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OF MINERAL RESOURCES
EXPLOITATION

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WP5 - LIGHTWEIGHT AERIAL REMOTE SENSING

DELIVERABLE D5.1
REPORT ON THE LIMITATIONS AND POTENTIALS OF AIRBORNE EO DATA

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SEVENTH FRAMEWORK PROGRAMME

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MISSION STATEMENT:

D 5.1 Evaluation of the usability and feasibility of airborne systems in line with relevant GEO tasks:

- Evaluation how available Airborne and Hyperspectral systems can be used in an optimal manner to identify and monitor the various aspects of the mining-related disturbance of human and natural environment. The emphasis is on the employment of highly innovative “beyond state-of-the-art” lightweight systems, allowing highly cost effective and flexible operation.
- Identification of diagnostic geomorphologic, spectral, chemical and geophysical characteristics that can be detected using airborne hyperspectral and geophysical methods.
- Definition of the technical framework for harmonized cost effective monitoring including data of different scales (European, national, regional). This includes consideration of required ancillary data. Special emphasis will be drawn on the accuracy requirements of stakeholder organizations.

1. Introduction

The objective of ImpactMin is to develop new methods and a corresponding toolset for the environmental impact monitoring of mining and mining-related activities via airborne and geophysical remote-sensing methods. In WP5 the emphasis is derived from the information set forth by preceding work packages (namely WP4) and by generating a scientific knowledge pool of methods derived from mineral resource exploration and exploitation methods, airborne and EO-based environmental monitoring techniques, in-situ sampling/ground-truthing and adaptation of results and methods from other field of science with a possible applicability in ImpactMin, as discussed in previous WPs.

This report (D5.1) expands on the results of WP4.1 and WP4.2, dealing with spaceborne remote sensing and generates its own organic observables from WP5.1 and WP5.2, with an emphasis on airborne methods and innovative techniques. In WP5.1 the environmental variables associated with mining activities and detectable with airborne remote-sensing and geophysical data were examined and identified with attention given to the assessment of environmental variables and general observables. Furthermore, the WP had outlined certain sensor properties, advantages/disadvantages, limitations and approaches. WP5.2 focused on the generation of a knowledge-pool of successful airborne remote-sensing/geophysical methods, tools and algorithms. Existing tools and methods for the monitoring of mining impacts were compiled from the findings of WP4.2 and adjusted to airborne approach in WP5.2. Methods from different areas of environmental monitoring, other than mineral resources exploitation, were reviewed and, if possible, translated for applicability in monitoring mining impacts. Finally, the proper analysis software, algorithms and procedures needed to extract useful information from various datasets, in order to optimize the efficiency of the analytical procedures, were identified, upgraded and tailored. This report sets up elementary parameters for the phenomenology of airborne remote-sensing/geophysical data acquisition, processing and evaluation, and road-map to implementation of new technology and multiple geospatial data integration. The overall goal is to carry out successful imaging and classification of mineral occurrences, mining areas, mine waste within their surrounding area and ecosystem. Determination of observables is the main contribution of Hyperspectral Imagery (HSI) and Gamma-Ray Spectrometry (GRS) data through mineral-spectral, but also vegetative and man-made spectral endmembers present within the target areas, but also their distribution and dispersal of observables on land in water with possible effects to vegetation and overall ecosystem health.

2. Airborne remote sensing for environmental monitoring

Primary objective:
Evaluation how available airborne and hyperspectral systems can be used in an optimal manner to identify and monitor the various aspects of human and natural environment. The emphasis is on the employment of highly innovative “beyond state-of-the-art” lightweight systems, allowing highly cost effective and flexible operation.

Environmental monitoring is a system of observation, estimation and prognosis for the environment under the influence of natural and anthropogenic factors. This system must be realized in the frames of **air** monitoring, surface and ground **water** monitoring, **soil** monitoring, and **flora** and **fauna** monitoring. Remote sensing has enormous potential for this because it can minimize the intensive sample collection and the amount of people needed over a prolonged period to achieve the required spatial and temporal coverage. The case for supplementing satellite remote sensing with airborne measurements for environmental monitoring stems from an inadequate resolution (spatial, spectral and temporal) of satellite data to address observables in a relatively small and highly-detailed area. Even with the advent of new-generation hyperspectral satellites, the spatial resolution and atmospheric modeling remain obstacles in detecting discrete signatures necessary for successful monitoring. The role of airborne spectroscopic data therefore fits the niche between the regional satellite assessment and ground point-sampling.

2.1 Airborne optical sensors

The primary modus of operation for the optical sensors revolves around the ability of an instrument to record the solar energy reflected or re-radiated from the surface (Goetz, 1980, p.680; Taranik, 1988). As the energy in the form of photons is reflected or absorbed from the materials, it is possible to derive certain information about the material (shape, texture, chemical composition). Within the optical sensor the received energy is transformed into an electric impulse, which is then recorded as an array of digital numbers, ready for processing. The digital numbers are then converted to brightness values. The brightness values become the carriers of acquired information and can be used to generate digital images and subsequently spectral and topographic information (Sabine, 1999, p.383; Taranik, 1988). Clark (1999, p.4) defines the four general parameters that describe the capability of a particular sensor in deriving the information from an observed target:

• Spectral range which shows the values in which the given instrument can “see”, from visible and near-infrared (VNIR), shortwave-infrared (SWIR) to thermal infrared (TIR).
• Spectral bandwidth describes the width of the individual spectral channel, with narrower bandwidth being able to discern more subtle and narrower spectral features. As the bandwidth widens, some of the spectral detail is lost.
• Spectral sampling denotes the wavelength distance among the spectral bandpass profiles for each channel in the sensor. In order to resolve a spectral feature, there must be at least two samples close enough to measure the peak and valley locations.

• Signal to Noise Ratio (SNR) describes the ability of a sensor to measure a given phenomena with enough precision to record all of the significant details. Some features will require only a modest SNR, while some will require much higher.

Sabine (1999, p.384) describes the image analysis processes as a stream of recognition of spatial and spectral patterns in image data that through the use of appropriate models eventually evolves into interpretation of landscape attributes. The landscape attributes are then explained (through the geologic interpretative process) to develop geologic information pertinent to the geomorphology, lithostratigraphy or structure of the area. Ultimately, the information that can be derived from an image is related to the characteristics of the pixels comprising the image – where the group of pixels with the similar tonal attributes can be identified as a particular area of geologic interest (showing linear trends, bright areas and so on). The steps in the analysis and deriving geologic knowledge from the image can be summarized as following (Sabine, 1999 p.386): Radiance (Brightness) measurement -> Groups of Pixels -> Textural/Spectral units -> Landscape attributes -> Geologic Processes -> Geologic Models.

The reflectance region of electromagnetic spectrum has been demonstrated to hold permissive elements for identification of various targets on the basis of their particular physical properties. Hyperspectral imaging consists of quantitative measurements of the spectral characteristics of materials using a remote sensing system having greater than 60 spectral bands with a spectral resolution less than 10 nm producing a contiguous portion of the light spectrum which defines the chemical composition of the material through its spectral signature within the observed range of wavelengths. Various molecular vibration, charge and crystalline structure effects define the characteristics that become observables in the given region of the EM spectrum.

2.2 Airborne radiometric surveys

All rocks and soils are naturally radioactive, containing varying concentrations of a variety of elements exhibiting natural decay and emitting variety of types of radiation (alpha, beta, gamma) at specific energy levels. Natural gamma spectra emitted by minerals and other soil components are a sum of contributions from different radionuclides. At present, only the gamma-ray radiation has sufficient energy to be used in geophysical mapping or exploration and provides a method of measuring concentrations of individual radioactive elements (K, U, Th) as the foundation for differentiating lithologies and soils by their characteristic radioactivity-emissive signatures. A gamma spectrum measured in nature therefore yields information on the actual concentration of nuclides in the material sensed by the detector system. Most of the field systems used to record natural radiation consist of some kind of scintillation crystal setup coupled to a series of multi-channel analyzers (MCA's). Scintillation crystals 'translate" incoming radiation into flashes of light having an intensity proportional to the energy of the absorbed gamma photon. The light output of a scintillator is translated into an electric signal that is stored using a MCA. Generally 256 (or 512) channel spectra are collected and reduced, as recommended by the International Atomic Energy Agency, to four standard energy windows: potassium, uranium, thorium, and total count (Figure 2c).

Potassium abundance is measured directly as gamma-rays are emitted when ^{40}K decays to Argon. Uranium and Thorium cannot be measured directly. Daughter nuclides generated during the decay of parent elements are measured instead, and the abundance of parent elements is inferred. Distinct emission peaks associated with ^{208}Tl and ^{214}Bi are used to calculate the concentration of Th and U. Therefore, U and Th are expressed in equivalent parts per million (eU and eTh) or Bequerel per Kg. The radionuclide concentration is known to be specific for given rocks, minerals and soils types. Each mineral can be characterized by a radiometric fingerprint, or a concentration vector ($C^{40}K$, $C^{232}Th$, $C^{238}U$) (de Meijer, 1998). The energy distribution of gamma radiation is nuclide specific; each type of nuclide emits photons with one or more unique energies that can be recorded using gamma-spectrometer systems.

Airborne radiometric surveying can also be utilized in assessing overall as well as subtle observable characteristics of abandoned mine wastes and preliminary ranking of sites with regard to potential environmental quality impacts. The Gamma-ray Spectrometry (GRS) survey, used in the scope of WP5 can be applied to map possible surface and subsurface lithology, structure, possible ground water flow and/or sources of radioactive decay. Smith et al. (2000) described application of these techniques at both regional (e.g. state) and local (e.g. watershed) scales while overviews of geophysical techniques are provided by Campbell and Fitterman (2000) and Campbell et al. (1999). Airborne gamma-ray surveys have been applied to geological studies for more than 40 years, and are finding still finding their way into new applications such as exploration for mineral resources other than uranium (de Meijer et al., 1997; Tourliere et al., 2003; Shives et al., 1997; Ramadan et al., 2009; Porter et al., 2000; McAfferty et al., 2009,), environmental impact monitoring (Coetzee et al., 2009; Martin et al., 2006; Medusa white paper; Scott et al., 2004; Pollanen et al., 2009; Pfitzner et al., 2001; Winkelmann et al., 2001; Bierwirth and Brodie, 2005), land degradation and agricultural monitoring (Carrier et al., 2006; Street-2010), regolith mapping (Wilfort et al., 2002) .

Bierworth et al. (2005), used airborne gammaray data in combination with Aster imagery to identify acid sulfate soil hotspots.

GRS provides a direct measurement of the radioactivity on the surface of the earth, with no significant depth of penetration, but with possibility of inferring information at-depth through the surface emissions of radioactive decay (e.g. potassic hydrothermal alteration of the mineralized host rock manifested by the high K counts in GRS). The surface assessment of the observable characteristic allows fairly reliable quantification of the measured radioactive element emissions to mapped bedrock and overall surficial geology, and/or any alteration-assemblages associated with possible mineral deposits or mine-waste introduction. All rocks, and the materials derived from them are radioactive, containing detectable amounts of a variety of radioactive elements. A gamma-ray spectrometer has the ability to accurately differentiate the recorded gamma rays by their respective energies and bin the spectral information to particular regions in a similar approach to that of a reflectance spectrometer. Airborne methods provide valuable, systematic coverage of large areas and are best-suited for evaluating targets of possible environmental impact such as mine-lands and/or industrial accidents (e.g. Rangelov et al., 1993; Grasty, 1993).

2.3 Discussion on Novel Airborne Systems / Technology

Recent advances in technology (better detector material) and processing methods have allowed for marked improvements in data quality. The use of smart automated gain stabilization and high quality standard spectra in both HSI/GRS arenas, results in an even larger improvement.

2.3.1 Gamma-ray spectrometers

The recent and historical (1960-70s) acquisition and analysis of GRS data was mainly directed towards deconvolving information from the binned potassium (K), uranium (U) and thorium (Th) channels and their resulting ratios. The concept of the detector was primarily designed towards counting pulses of incoming radiation derived from the decay process of the U, K, Th gamma rays within the large crystal (usually NaI crystal). If a particular ray is

absorbed within the crystal, it would emit a pulse of light (scintillation), proportional to the energy level of the incident ray.
The full spectrum analysis in GRS sector is a novel advance resulting from the development of a new detector elemen, a CsI scintillating crystal, which has proven to be a valid replacement, and possibly even an improvement of a classical 4x4L NaI-based system, used in past. The use of a single scintillation crystal reduces the system complexity and allows for advanced interpolation and analysis techniques such as the ones used with HSI data. To arrive at a small system, a“full spectrum” analysis is combined with a high crystal type (CsI instead of NaI) and measures all of the incoming gamma rays over a particular spectral range, similar to the way a hyperspectral instrument would measure a refelected solar radiation. Fully automated software based stabilization and Monte Carlo simulation-based calibration complete the development. Full Spectrum Analysis (FSA) incorporates virtually all of the data present in the measured gamma spectrum allowing for the deconvolving of concentrations of the radionuclides that led to the measured spectrum (Hendriks et al., 2001). These recent developments in both the detector technology and the data analysis allow us to reduce an airborne system to a size and weight that opens up possibilities for operation on an ultralight aircraft or a helicopter drone. Succesful experiments for monitoring ^{137}Cs-fallout from the Chernobyl accident with a small CsI-detector mounted in an unmanned aerial vehicle were performed by Pöllänen et al. (2008).

2.3.2 Hyperspectral sensors

The new generation of airborne sensors operating in the VIS/NIR-SWIR range of 380 - 2500 nm, provides superior spectral and spatial imaging with negligible sub-pixel distortions (smile, keystone). The advanced sensor design has an excellent spatial resolution without compromising the imaging speed and signal-to-noise ratio. The advanced performance from a light weight sensor allows integration into variety of airborne platforms, some of them even unmanned. The compact new technology is particularly designed to increase the spatial resolution of push-broom hyperspectral imagers, and works with detector arrays up to 24 mm wide in the spatial dimension. The design is optimized for operation in harsh conditions, and provides the option of a user exchangeable foreoptic.

2.3.3 Optical systems on unmanned aircraft

Smaller size of modern-day sensing systems allows their integration into an Unmanned Aerial Vessel (UAV) / Unmanned Aircraft System (UAS) designed for aerial survey mapping. A relatively inexpensive, but high-resolution optical (visible-near IR) system is capable of acquiring imagery in 5-9cm resolution, from 200m above-ground level (AGL), allowing for identification of objects/surfaces in high resolution coupled with the ability to derive digital surface models (DSM) by an automated dense-stereo matching techniques at 5-10cm RMS.
Aerial mapping and survey using small electrical powered aircraft is economic and environmentally friendly when compared to conventional surveys. Smaller aircraft platforms, some of which are used in the scope of this project (e.g. Kristineberg, Sweden), are small and lightweight, and generally considered to pose minimal-to-very low danger to people/objects on the ground or manned aircraft, thus allowing its operation without restrictions and flight clearance procedures requires for regular aerial mapping operations.

2.4 Commercial applications of spectral imagery

Remotely sensed spectroscopy is becoming an affordable, rapid and efficient manner in which to characterize a variety of important materials that occur on the earth's surface. Numerous studies described in this report have been carried out to understand the meaning of infrared reflectance spectra and the implication of changes in spectra with respect to changes that occur within and between those materials, either in reaction to natural processes or as a result of human interference. The validity of spectroscopy is thus well proven, and should not need any additional explanation.

2.4.1 Historical development

The first imaging spectrometer was the NASA Scanning Imaging Spectroradiometer (SIS) built in the late 1970's, which provided image data in 32 contiguous spectral bands, each 15nm wide, in the spectral range of 0.43-0.8µ. Thereafter, an important development was the airborne spectroradiometer developed by the Geophysical Environment Research (GER) Company. It operated in one-dimensional profiling mode to acquire data in 576 narrow channels in the spectral range of 0.4-2.5µ A major advancement in instrumentation was the design of imaging systems with dispersing optics, which allowed acquisition of spectral data in a large number of discrete contiguous spectral channels. The Airborne Imaging Spectrometer (AIS) was designed and built at the NASA Jet Propulsary Laboratory (JPL) in the early 1980's. It acquired image data in 128 spectral bands and a 32-pixel swath. The next important development was the advanced Visible/Infrared Imaging Spectrometer (AVIRIS), which became operational in 1986. This sensor has been flown over numerous test-sites worldwide, and is still operational. Aviris images in 224 contiguous channels in the spectral range of 0.4-2.5µ, with a spectral bandwidth of 99.4 nm.

2.4.2 Commercialization

A number of private organizations have since recognized the immense potential of hyperspectral imaging. Among the more important commercial airborne imaging spectrometers were CASI/SASI, GERIS, HYDICE, HYMAP, HyperSpecTIR, SFSI and SPECIM instruments (AISA, Eagle, Hawk etc.). In the last 10-15 years the commercial exploitation of airborne hyperspectral imaging has found its way into many fields of application, such as forestry and vegetation monitoring, precision farming, environmental monitoring, identification of oil-impacted surfaces, land use management, mineral exploration, hazardous waste remediation and so forth.

Because of the high cost and complexity of the airborne systems in the past, most of the airborne hyper spectral surveying took place in the domain of scientific or governmental organisations, With the ongoing perfection and miniaturisation of the sensors and cameras as well as processing technology their operation and employment rapidly becomes much less complicated and cheaper, hence better cost-benefit rations, and as a result routine use of commercial airborne hyper spectral surveying is expected to take off significantly in the next decade. There is currently a significant growth in commercial applications of this technology and hence in the number of service providers (e.g. Hyvista, Spectir, ITRES etc.). Smaller hyperspectral camera systems allows for usage aboard the smaller aircraft that can be rented locally, implying less complex logistics and lower costs, and miniaturization has made such progress that the first hyper spectral systems that can be flown on a UAV are available on the market. An important implication of this process is that it is becoming feasible to survey relatively small areas that were previously, from a cost perspective, impossible to fly because mobilization costs were prohibitively high. The recent developments have thus brought the hyperspectral surveying into a realm of an efficient and relatively low cost technology for mapping complete areas. Table 1 outlines some of the commercial or semi-commercial systems currently available for tasking and data purchase in the VNIR-SWIR spectral region.

Sensor	Country	Age	Bands	Region (μ)	GIFOV (m)	Config.
AVIRIS	USA		224	0.4-2.5	3.6 – 20	Single
Hymap	Australia		128	0.45-2.45	2 – 5	Single
CASI/SASI	Canada		288+100	0.38-2.45	1 – 4	Dual
SpecIM	Finland		>500	0.4-2.45	0.4 – 3	Dual
HST-3	USA		230	0.43-2.55	0.5 – 4	Single

Notes:
GIFOV – Ground Instantaneous Field of View (ground resolution)
Config. – Instrument configuration whether is a single focal panel or two instruments
AVIRIS/HST-3 are under U.S. government control, but sometimes participate in commercial applications

Table 1 - Summarized airborne sensors and their characteristics

2.4.3 Considerations

The diameter of the surface covered by a spectral measurement varies between a few mm till a few m. depending on the type of spectrometer and fore-optics used. However, the problem with the earth's surface is that it is extremely inhomogeneous, and that processes that take place at surface often result in very diffuse transitions from one surface class to another. Often observed are the mixtures of materials and the proportions of materials in those mixtures can change, but also the spectral properties of the individual components.

Hence the difficult questions remain: What is the density of sampling? Where to sample, and how to treat the space in-between the samples. The denser the sampling grid, the more realistic the information, but also the more expensive the survey becomes. The cost of a spectral analysis lies between 10 and 20 EUR per sample, not including the sample collection. Sampling at a density of one sample per 10 m^2 (assuming more or less homogenous composition) would hence imply a cost between 10,000 and 20,000 EUR per Km^2, just for the analysis.

Obviously the sample density depends on the scope of the project, because this scope determines how much surface variation can still be regarded as "homogenous". In the case of a point measurement and one sample per $10m^{2,}$ this would imply that a surface measurement at about 4 mm^2 is representative for a surface of 10*10m. Tentatively one could seriously question whether this is a representative measurement. If an airborne hyperspectral survey is considered, the situation is entirely different. Depending on the flight altitude, the size of a measurement (pixel) would lie between 0.5 and 5 m (e.i: 0.25 m^2 - 25 m^2) In contrast to the field measurements, the spectrum for each grid really does represent all the materials within the grid-cell, which can a great advantage, especially in small areas where there is significant surface variability.

The cost of hyperspectral survey depends on the altitude (i.e: resolution) and flightline spacing, but usually varies between 250 and 500 EUR per Km^2 for large areas (depending on the location and size of the area). The size of the survey area is a very important parameter, because of the relatively high cost of mobilization. When large areas are flown, the mobilization costs are spread over a wider area, and hence lower the overall survey price per Km^2. One can imagine that in the case of small areas of interest, the mobilization costs could be prohibitively high, and this is exactly one of the goals addressed in this project: by using smaller, locally available aircraft, the mobilization cost can be reduced, and the cost of a survey would be much closer to the actual cost of flight acquisition.

3. Potential of airborne remote sensing for mineral resources exploitation monitoring

Primary objective:
Identification of diagnostic geomorphologic, spectral, chemical and geophysical characteristics that can be detected using airborne hyperspectral and geophysical methods.

Mining operations have a severe environmental impact, which can be monitored using extensive, labour-intensive and costly ground based field observations. However, based on the positive results found in literature on the monitoring of the environment with airborne remote sensing and geophysical data, significant potential lies in the application of these data to monitor the environmental impacts caused by mining operations. In §3.1, environmental variables, soil and surface variables associated with mining activities and detectable using airborne hyperspectral and geophysical data, are summarized. The following section, §3.2, gives an overview of the potential of airborne hyperspectral and geophysical data for the assessment of different environmental variables associated with mining. In the last section of this chapter, §3.3, limitations and possibilities, advantages and disadvantages, are reviewed.

3.1 Environmental variables associated with mining activities

The potential environmental effects associated with dormant or abandoned mines are a complex nexus of chemical and physical processes. The overview of available information in this report offers current state of knowledge on the physical and biogeochemical processes playing role in the mobilization, transport, reaction and dispersal of potentially hazardous elements/effects in the surrounding habitat. The current research in the matter (e.g. USGS circular 1328) highlights the importance of a) geologic sources of contaminants b) pathways that facilitate transport from the sources c) processes that control the interaction of the elements in the environment. Figure 1 gives an overview of a number of environmental variables and sensors best fitted to monitor the variables.

Applicability

■ strong
▣ moderate
□ none

Sensing System				Applications															
Hyperspectral Data	LIDAR Data	Geophysical Data	Observables	Conservation	GIS and Geometric Networks	Mobility, Accesibility, Evacuation	Mine Collapse Prevention	Damage Assessment	change Detection	3 Dimensional / Stereo Analysis	Environmental Monitoring	Agricultural Impact	Urban Analysis	Natural Hazards	Geologic / Pedologic Classification	Bio Diversity / Landcover	Wildlife Habitat Assessment	Consequence Assessment	Overall Baseline
■	▣	▣	Valley Lithology	▣	■	▣	■		■	■	▣			■	■		▣	■	■
▣	■	▣	Topography	▣	■	■			▣	■	■	▣	■	■	▣	■	■	▣	■
■	▣		Plant Health	■	▣				■		■	■		▣	▣	■	■		▣
■	▣		Land use/cover types	■	■	■	■		■	▣	■	■	■	■		■	■	■	■
■	▣		Vegetation Species Identification	■	■		■		■	▣	■	■		▣		■	■		■
■			Aquatic Flora Identification	■	■		■		■		■					▣	■		■
■	■		Surface Drainage	■	■	■			▣	■	▣	■	■	■	■	▣		■	▣
▣			Atmospheric gases and aerosols	■					▣		▣			■					
■	■		Underground fire venting/Fumaroles/Smoke	■		▣	■	■	■									■	
▣	■	▣	Bathymetry of the pit lake/river	▣					▣								■		■
■	■	▣	Slope stability (pit walls)	■	■				▣	■			■	■				■	▣
■	▣		Critical Infrastructure Monitoring	■	■	■		■			■		■	■				■	■
■		▣	Materials Identification	■			▣	■			▣		■		■	■		■	
▣	▣		Soil Moisture			■	■		■			■		▣	■	■	▣		
■			Soil Composition	■		■	■		■		■	■		■	■	▣			■
▣		■	Subsruface Fracture Systems			▣	■			▣	■		■		■			▣	■
■	▣		Surface run off	■	■		▣		■		■	■	▣						▣
■			Water Clarity/Quality	■					■		■						■		

Figure 1 – Logic path for implementation of airborne hyperspectral imagery with other remote sensing assets.

Based on a thorough literature study on the environmental impact of mining operations, the following variables were selected from Figure 1 as of being of "major importance" to the airborne campaign and monitoring of the mine-lands within the ImpactMin project:

<u>Air monitoring:</u>

- Atmospheric gasses and aerosol
- Underground fire venting/smoke

<u>Water monitoring:</u>

- Water quality
- Water turbidity and sediment load
- Heavy metal contamination
- Aquatic flora identification
- Surface drainage

Soil and mineral monitoring:

- Soil composition:
- Minerals : iron, clay, sulfate, carbonate
- Subsurface fracture systems

Vegetation monitoring:

- Plant health
- Land use/ Land cover
- Vegetation species identification

Except from the subsurface fraction systems, for which geophysical methods are more appropriate, all other selected variables allow monitoring with hyperspectral data (<5m). This, because all variables can be associated with observables having specific absorption characteristics (see Table 2, Figure 2a).

Observable	Observable chars.	Association
Soil and mineral monitoring		
Iron minerals (oxide/hydroxide)	350-700nm absorptions	Alteration, surface cap, rust, waste rock
Sulfate minerals	1700nm, 2100nm	Alteration, weathering, acid drainage
Clay minerals	2200nm	Alteration, rock units, unstable slope
Hydrocarbons	1200, 1700, 2300+nm	Pollution, resource dump, venting
Carbonates	2300nm	Buffering, host rock, remediation
Materials	500-700, 1500-1700	Waste, hazardous zones, cultural ftrs.
Discrete anomalies	Unusual absorptions	Explosives, artifacts, burning
Vegetation monitoring		
Vegetation stress	500-900, 2200nm	Pollution, water depletion, geology
Chlorophyll	300-900nm	Pollution, nutrient load
Air Monitoring		
Gas emissions	760, 1500, 2100nm	Pollution, fumaroles, burning
Atmosphere and aerosol	380nm, 600-1000nm, 1200-1400nm 1600-1900nm	Gas and water vapour absorptions, Rayleigh scattering of dust.
Water Monitoring		
Water turbidity and load	380-420nm, 550-800nm	Pollution, runoff
Sub aquatic vegetation	300-900nm	Pollution, nutrient load

Table 2 – Some of the observables detectable with reflectance spectroscopy

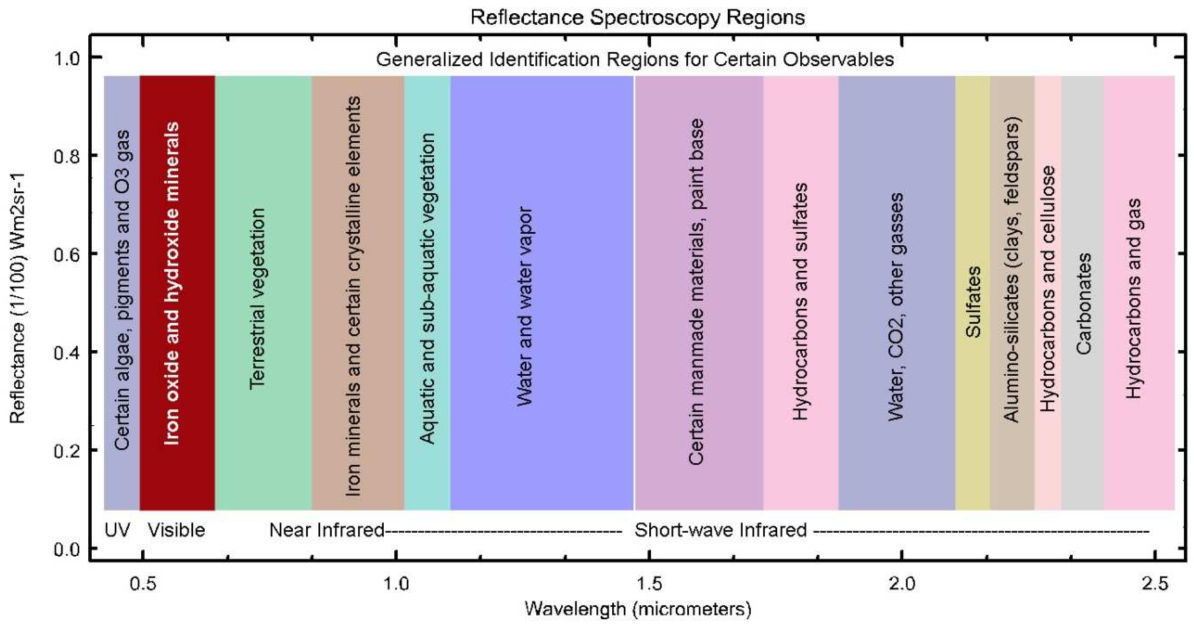

Figure 2a – Characteristic spectral regions for certain types of targets

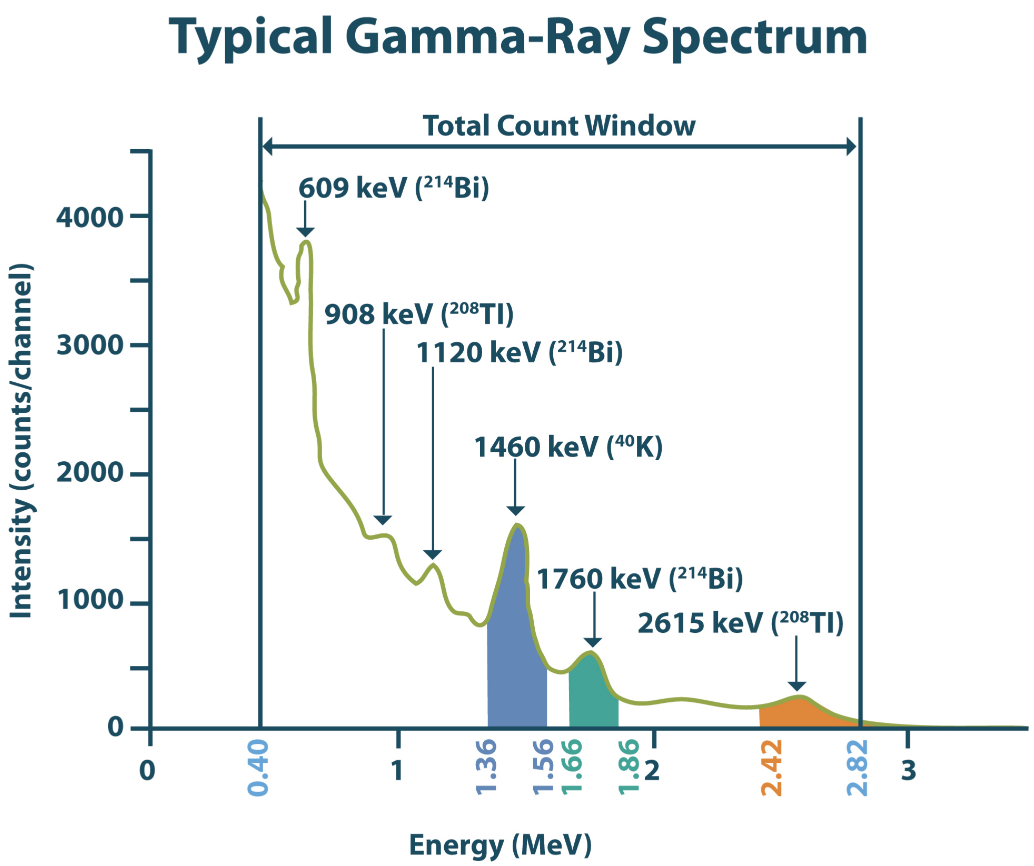

Figure 2b - Chareacteristic spectral regions for gamma ray emissions showing the count windows for K (purple), U (green) and Th (orange) – Courtesy of Natural Resources Canada: *http://gamma/gsc.nrcan.gc.ca;*

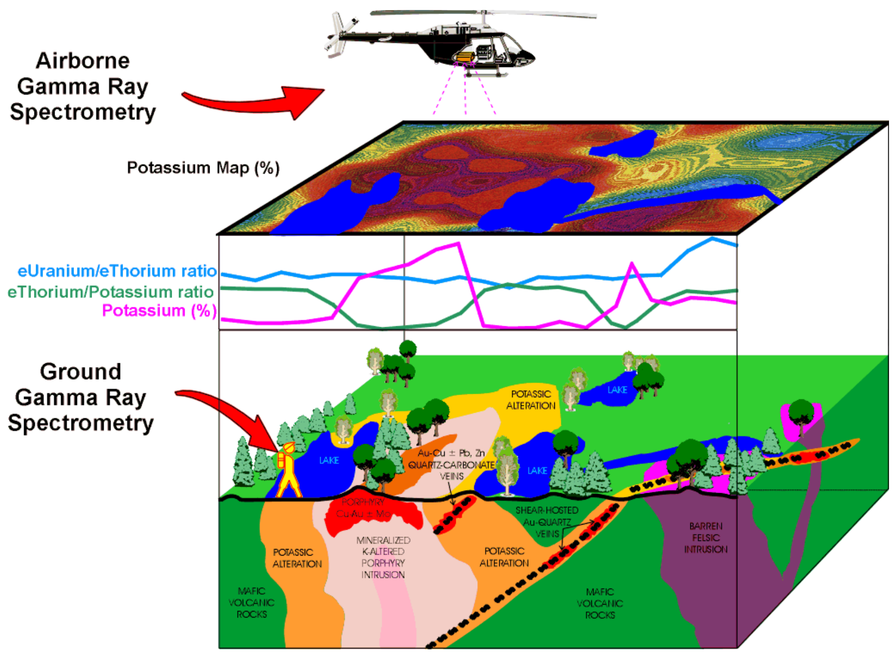

Figure 2c – Concept of Gamma ray spectroscopy and observables (adapted from Natural Resources Canada - http://gdr.nrcan.gc.ca/gamma/about_e.php)

Observable	Observable chars.	Association
Depleted uranium	U238 elevated value	Military operations, waste dumping
Phosphates	U238, K	Deposition env., fertilizer waste
Potassium	Elevated K	Alteration, rock units
Thorium	Elev Th., reduced U	Rock units
Hydrocarbons	Elevated U, Th	Contact, precipitation
Radioactivity	Elevated Total count	Radon gas, radioactive waste

Table 3 – Some of the observable features detectable with gamma-ray spectroscopy

Related variables for environmental impact (below) are linked to the table of observables (above) and the logic-path (Figure 1) to establish **direct (1)** or **indirect association (2)** with mining activities:

Air monitoring:

- Dust: Iron oxide (1), Atmosphere and aerosol (1)
- Fine particles: Emissions (1), Atmosphere and aerosol (2)
- Gas emissions – pollution, burning: Emissions (2)

Water monitoring:

- Acid mine drainage: Iron minerals (1), sulfate (1), clay minerals (2)

- Sediment yield and metal contamination: Water turbidity (1), vegetation stress (2)
- Water depletion: Vegetation stress (2), sub-aquatic vegetation (2)
- Water turbidity: Pollution/run-off (1), nutrient load (2), sub-aquatic vegetation (2)
- Heavy metal: sulfate minerals (2), iron minerals (1)

Soil and mineral monitoring:

- Minerals: Iron, clay, sulfate, carbonate, materials (1)
- Acid mine drainage: Iron, sulfate, clay minerals (1)
- Ferruginous materials: Iron (1)
- Heavy metals: Sulfate minerals, iron (2)
- Changes in soil moisture : Water, vegetation stress (2)

Vegetation monitoring:

- Land use and land cover change: Chlorophyll, materials, sub-aquatic vegetation (1)
- Vegetation stress: Chlorophyll (1), water, aerosol, sulfate minerals (2)

3.2 Compilation of existing methods for the monitoring of mining impacts

Below is the brief discussion on the existing information and literature review of the measured, investigated and inferred potential of airborne remote sensing in assessing different environmental variables, soil and surfaces parameters associated with mining activities. The literature review is based on the information pertinent to the named area of interest for airborne operations (primarily the target site of Mostar Valley in Bosnia and Herzegovina).

3.2.1 Air monitoring

Consult §3.2.1.c and §3.3.1c in ImpactMin D4.1 document regarding air monitoring because the airborne sensors are deployed from the lower altitudes (<1000m AGL) and lack regional extent to obtain meaningful and pertinent information. Only profound effects, tactical in scope (e.g. smoke, heavy dust, fumarole emissions) can be feasibly detected using HSI methodology in the reflected portion of the spectrum, while GRS is not suited for the task. For smoke/dust detection on a tactical-scale, Clark and others (2003) discussed the mapping of dust hazard following World Trade Center attack (Figure 3). A similar study by Swayze and others (2003) and the follow-up study on mapping asbestos-bearing minerals (Swayze et al., 2009) focused upon asbestos and fibrous dusts related to mining, mineral processing, or mineral products, with secondary study of potential health implications of other earth materials such as: metal-bearing mine wastes, mill tailings, and smelter emissions; dusts from dry lake beds; soils; volcanic ash; coal and coal fly ash; and dusts from building collapse. The studies identified many topics for a spectrum of earth materials where substantial further research is needed to address increasing societal concerns. Spinetti et al. (2003, 2008) obtained a volcanic plume CO_2 concentration map using airborne MIVIS and AVIRIS hyperspectral data. Salvador (2008) showed that it is possible to detect weak gas signatures in hyperspectral imagery for both airborne and spaceborne sensors, using the newly developed wavelet packet subspace method.

Figure 3 – Example of air-quality/dust-dispersal in the aftermath of World Trade Center collapse in New York City, USA observed with AVIRIS hyperspectral data (from Clark et al., 2003)

3.2.2 Water monitoring

During the water passage through new and/or old mine ground and mine wastes results in the mine water, which constitutes an integral part of the hydrologic cycle and frequently carry suspended solids and dissolved pollutants, such as heavy metals. Flowing along the hydraulic gradient through different groundwater and surface water pathways, the mine water affects and pollute other environmental water settings (groundwater, streams, lakes, coastal and marine water) across municipal, regional and national borders. As a result of this, some of these impacts can persist for centuries after mine closure. Classical practice in dealing with industrial pollution discharges may not be fully suited to regulation of the impacts of mining on the water environment.

Management of new and old (closed or abandoned) mines must deal with mine water management in the integral part of general water management regulated through the Water Framework Directive (WFD). This is a unified framework for management of Europe's surface and groundwater, which includes the pollution by mine waters. WFD considers water management in a coordinated way within the basic water management tasks of:

- Formulating water management plans and action programs
- Evaluating individual permit applications regarding new mining and mine waste disposal projects
- Remediation decisions for contaminated land

All of these different mining pollution issues (waste, water, soil) have one common question: *is there a need for and are there any technologically feasible and socio-economically sustainable measures to be taken (including environmental monitoring) for achieving long-term compliance with environmental standards?*

Water pollution caused by mine water and mine waste at any given water recipient downstream is determined by both the source emission and the subsequent hydrological transport and hydro geochemical retention/attenuation of emitted pollutants along various downstream water and solute flow pathways. These pathways comprise complex structure through soil water, groundwater and surface water systems. This further results in a coupled monitoring and prediction of water flow and pollutant transport with attenuation processes on a catchment scale. Since monitoring program for mining environmental impacts plays a crucial role in future water resources management (under WFD) and sustainable mining, the new innovative monitoring techniques must be carefully analyzed and proposed to decision makers for future environmental compliance of mining activities.

Extensive literature coverage and detailed synthesis of various mining impacts examples can be found in Younger et al. (2002a,b) or Lottermoser (2003 and 2003b) together with ERMITE (Environmental Regulation of Mine waters in the European Union) Consortium (2004) FP5 project which clearly addressed key mine water management problems specifically at the catchment scale. There are three general divisions in addressing the impact to water environment:

a. *Impact from mining activities*

   Mining activities inevitably disrupt preexisting hydrological pathways within the geologic strata. All types of mining have the potential to directly disrupt groundwater flow (Booth, 2002), which in turn can affect surface waters that are in hydraulic continuity with the affected groundwater system. In most cases the impacts on the natural water systems arising from the mining activities tend to be relatively localized and limited compared to other mining related impacts such as those associated with dewatering.

   Mine dewatering is essential in mining operations in order to secure access for miners and mining machinery to the mineral reserves, and to ensure safety of personnel working in mining areas. Dewatering environmental impacts are numerous:

   - Disposal of the pumped (usually saline) water

- Depression of water table around the dewatered zone (Younger et al. 2002)
- Decreased flows in streams, wetlands, and lakes that are in hydraulic continuity
- Lowering of the water table in the vicinity of water supply or irrigation wells.
- Land subsidence usually due to compaction of fine-grained sediments
- Surface water or groundwater pollution

Many of these impacts can be anticipated before they happen and mining companies should be able to mitigate them and provide detection based monitoring. Mining impact from mines which went through the closure process result from the seepage of contaminated leachate from waste rock piles and tailings dams is a significant cause of surface and groundwater pollution in many mining areas. The form, although possible during mine operation, can persist long after site operation cease. In many cases, previously created mine waste deposits have suddenly begun to generate acidic leachates many years after they have been left unattended.

The Impact coming from abandoned mines can eventually lead to renewed environmental impacts, following the recovery of groundwater levels (a process called "rebound") to the preexisting base level of drainage. The rebound process in subsurface mines commonly leads to a marked deterioration in the quality of mine water (Wolkersdorfer 1996: Younger, 2000). In case of surface mines, water quality can deteriorate when backfield materials are initially saturated after restoration. After completion of mine water recovery, the overspill of untreated waters after flooding can happen.

Very often the mine sites give a rise to heavy loadings of suspended sediments in receiving watercourses resulting in increased turbidity and decreased light penetration. This directly affects the primary producers in aquatic ecosystems like different algae by inhibition of photosynthesis, and in turn reduces the food availability for the macro invertebrate community in surface waters and alters the fish population that feeds on them (MacDonald et al. 1991). The use of hyperspectral sensors at different scales can provide innovative way of properly monitoring such important environmental impact of surface waters.

b. *Suspended sediments*

Very often the mine sites give a rise to heavy loadings of suspended sediments in receiving watercourses resulting in increased turbidity and decreased light penetration. This directly affects the primary producers in aquatic ecosystems like different algae by inhibition of photosynthesis, and in turn reduces the food availability for the macro invertebrate community in surface waters and alters the fish population that feeds on them (Newcombe and MacDonald, 1991). The use of hyperspectral sensors at different scales can provide innovative way of properly monitoring such important environmental impact of surface waters. At present, the results of spectroscopy are limited to measuring those substances or conditions that influence and change optical and/or thermal characteristics of the surface water properties. Suspended sediments, chlorophylls, dissolved organic matter DOM, temperature, and oil are water quality indicators that can change the spectral and thermal properties of surface waters and are most readily measured by remote sensing techniques. Substances (i.e. nutrients, metals) that do not change the optical and/or thermal characteristics of surface waters can only be inferred by measuring surrogate properties (i.e., chlorophylls) which may have responded to an input of chemicals. Sudduth el al. (2005) and Shafique et al. (2002) collected and analyzed hyperspectral water reflectance data with airborne and ground-based sensing systems for mapping and water-quality modelling. Deronde et al.(2006) focused on the use of airborne hyperspectral imagery to map the sediment characteristics of a tidal sandbank in the Westerschelde. Sterckx et al. (2007) produced suspended sediment maps which described successfully the known variation of sediment behaviour in the Lower Sea Scheldt area and contribute to the improvement of our knowledge of spatial and temporal sediment distribution in this complex river system. Heavy metal - sulfate pollution

Recently there are many examples of pollution originated by mine waters. For example, the Tinto-Odiel river basin (Huelva, South Spain) generate sulphates pollution discharged to the Sea to be estimated on 1,2 million tons per year and additional 20 000 tons of heavy metal. There are many entire rivers which have effectively been removed from the inventory of fresh water resources due to mine water pollution (i.e., 1000 km in the UK). In areas where water resources are already scarce this problem becomes growing issue as the climate changes. The ecological effects from mining activities can be summarized in hydrological impacts like disruptions of groundwater systems and flow patterns, water table affection, alteration of flow rates, changes in the natural running waters among others. Impacts of mining on water resources (both groundwater and surface water) occur at various stages of the mining cycle (ERMITE, 2004):

- The mining process itself
- Mineral processing operations
- Via the dewatering which is undertaken to make mining possible
- Seepage of contaminated leachate from waste rock piles and tailings dams
- Through flooding of workings after extraction has ceased
- Discharge of untreated waters after flooding is complete

Definition of the mine water adopted by the ERMITE project is that mine water is water which is in mined ground (including waste rock/tailings depositories) and /or which is now flowing from mined ground into adjoining waterbodies (such as streams, wetlands, lakes, aquifers and oceans). Mine waters are part of the water cycle but are rarely treated as such in regulatory frameworks. This is despite the fact that short- and long-term pollution from active and abandoned mines is still one of the most serious threats to the water environments. Mine water pollution differs sufficiently from other forms of industrial pollution and requires specific regulatory requirements quite distinct from those applicable to most other industrial processes.

Several studies relate to the problem of yesterday's mine-related point sources having become today's diffuse sources within the groundwater-soil-sediment system, and continuously loading the surface water system with heavy metals (Baresel et al. 2009; Olli and Destouni, 2008) Advanced models were tested in the follow-up studies and showed some physico-chemical mechanisms for such diffuse subsurface source accumulation (Malmstrom et al., 2004) and the possibility of load abatement success, minimization of abatement costs, and extra abatement costs implied by the uncertainties (Baresel and Destouni, 2007; Baresel et al. 2006).

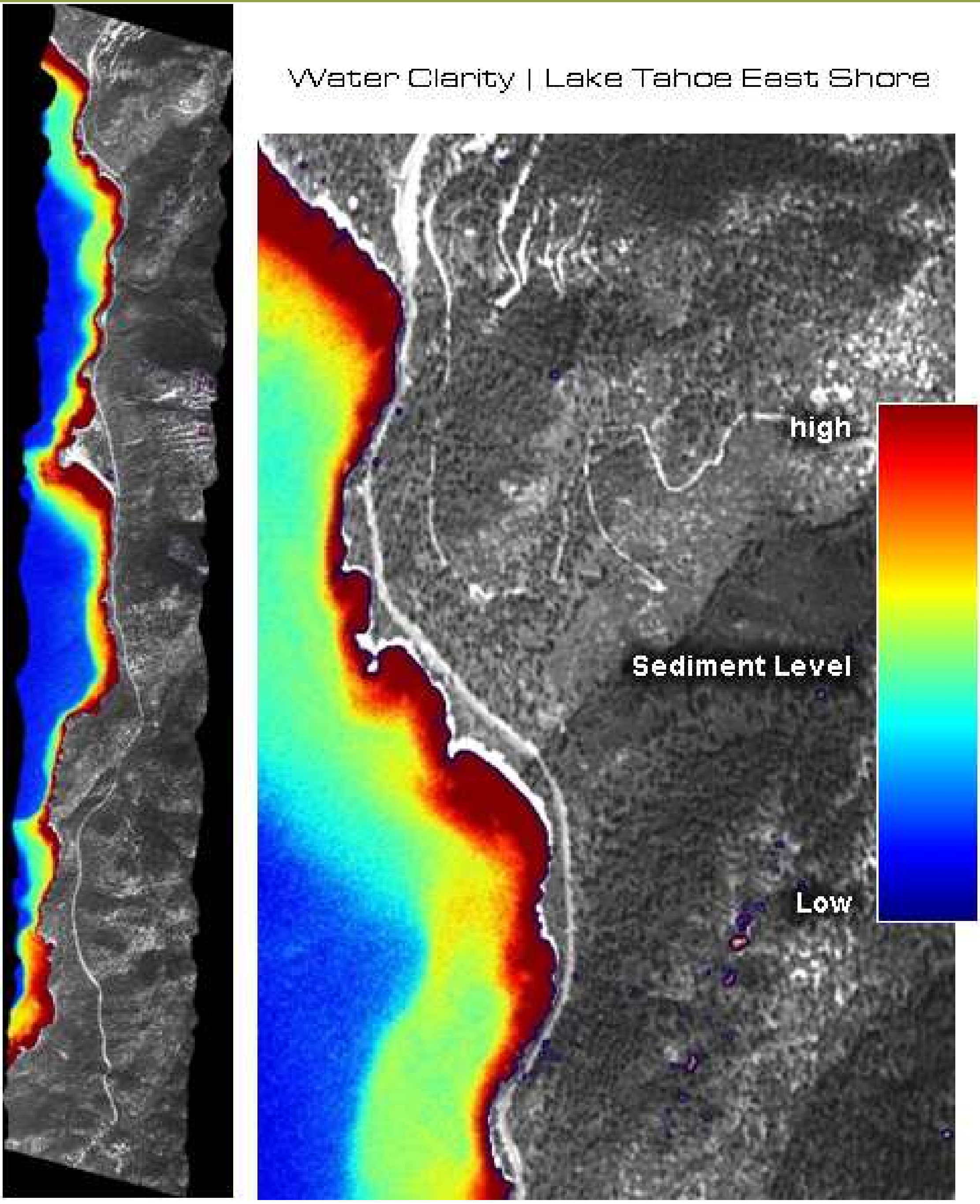

Figure 4 – Example of water turbidity monitoring with hyperspectral imagery (courtesy SpecTIR llc.).

Increases in water quality parameters such as chlorophyll a, turbidity, total suspended solids (TSS), and nutrients are symptomatic of eutrophic conditions (Figure 4). Concentrations of these parameters can provide insight on the extent of eutrophication and the potential impact on aquatic biota and overall water quality. The hyperspectral scanners are very sensitive to aquatic chlorophyll response at a wavelength of 700 nm, and can detect a very low density of chlorophyll in water (e.g. Jupp et al. 1994). In addition, decrease of water clarity can also be mapped by observing the peak water transmittance around 400-500nm thus determining overall load of suspended sediment.

As such, by acquiring imagery over the entire water body, it would be advantageous to resource manager to be able to detect eutrophic conditions using the system as a whole without relying on field measurements.

c. Mine-water Environmental Monitoring

To obtain the reliable measurements of mine water and hydro-geochemistry is prerequisite for environmental impact assessment (EIA) and for the design of mine water remediation facilities. The importance of collecting synchronous measurements of flow and water quality can never be overemphasized. This is because the ecological impact assessment and future decisions on mining prospective are most usefully based on contaminant loadings rather than simple concentrations. Loadings are calculated by multiplying flows [L^3/T] with concentration [M/L^3] yielding loading in units [M/T]. Importance of loading can be seen from the conclusion that low concentrations of pollutants at high flow conditions can be just as damaging ecologically as high concentrations under low flow conditions.

Beside the classical physical flow measurements the tracer tests offer a means of deducing hydrological subsurface flow paths. The application of tracer testing can only been used to directly quantify flows between two points on the same watercourse. In a complex mined systems these flow paths are not known and tracer testing is used to detect flow paths. Tracer test are most commonly applied in relation to mine water systems to indentify surface-subsurface flow pathways and they can be utilized in development of precautions against dangerous inrushes to working mines, to evaluate feasibility of backfill, mine subsidence investigations, and design of treatment or remedial strategies for polluted mine waters.

3.2.3 Soil and mineral monitoring

An important element of environmental monitoring in/around former and current mining operations is mineral mapping. The use of Hyperspectral imagery (HSI) for mineral mapping and identification is becoming more accepted, following almost two-decades of work over mineralogical sites of interest such as Cuprite and Virginia City, Nevada (Swayze, 1997; Kruse,1988; Kruse, 1999) and work by the USGS spectral laboratory (Clark et al., 2003; Rockwel et al., 2000). Taranik and others (2007) have defined the elements of the natural background (landscape surface cover composed of consolidated rocks, unconsolidated rock weathering products, soils, coatings on rock materials, vegetation, water, materials constructed by humans, mixtures, anthropogenic gases indicative of industrial processes) using various HSI sensors and methods.

The alteration minerals targeted for detection with hyperspectral airborne sensors minerals have abundant spectral absorption features throughout the visible/near-infrared (VNIR, 0.4-1.0 μm) and short-wave infrared (SWIR, 1.0-2.5 μm) wavelength ranges (Hunt, 1980, p.35). These phenomena result from the interaction of electromagnetic (EM) energy with the atoms and molecules which comprise the minerals (Hook and others, 1999 p.59). Many iron minerals have subtle spectral features in the 0.4 to 0.9 μm range caused by the electronic processes of Fe-ions. Charge transfer phenomena cause strong absorption in iron minerals at wavelengths smaller than 0.5 μm (Hunt, 1980, p. 32; Clark, 1999, p.16). The minerals containing hydroxyl (OH) group have characteristic spectral absorption features in the 2.1 to 2.4 μm wavelength range, which are caused by the vibrational processes in the crystal lattice; in this case stretching of the hydroxyl (OH) ion (Clark, 1999, p.27; Hunt, 1980, p.33) in combination with metal-OH bands, which vary (Figure 5).

Combination of remote sensing methods with field ground-truthing is already showing signs of promise in discerning natural resources at the numerous localities in the world (e.g. Bedell, 2004). Combined insight into the soil mineralogy is allowing geologists to explore the new sites of potential interest (shown as anomalous areas on remote sensing imagery) and also work in assaying and localizing the exact areas of mineralization. The analysis of multiple high-resolution datasets, including hyperspectral imagery and ground-based spectroscopic surveys can confirm the presence of hydrothermal alteration aureoles (associated with epithermal precious metal deposits), but also secondary surface factors which may be associated with petroleum basin formation. The previous case studies have shown that by understanding the mineralogical profile of the target area, one can significantly economize the exploration effort.

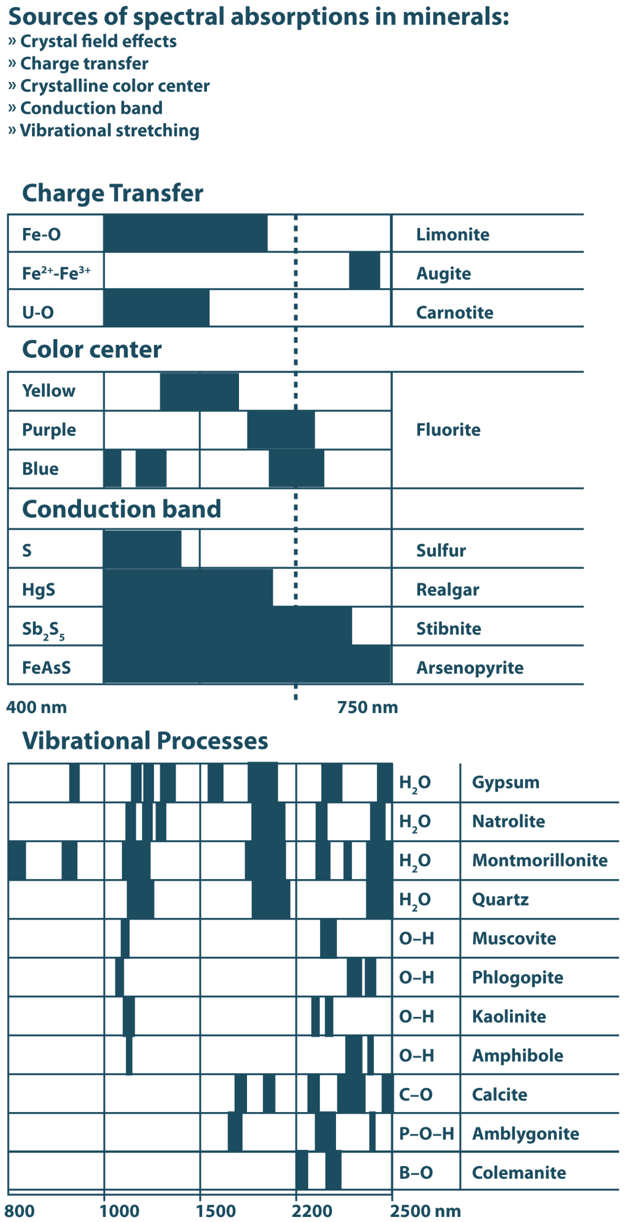

Figure 5 – Absorptive regions and cause of absorption for certain minerals (adapted and modified from the original figure by Hunt, 1980).

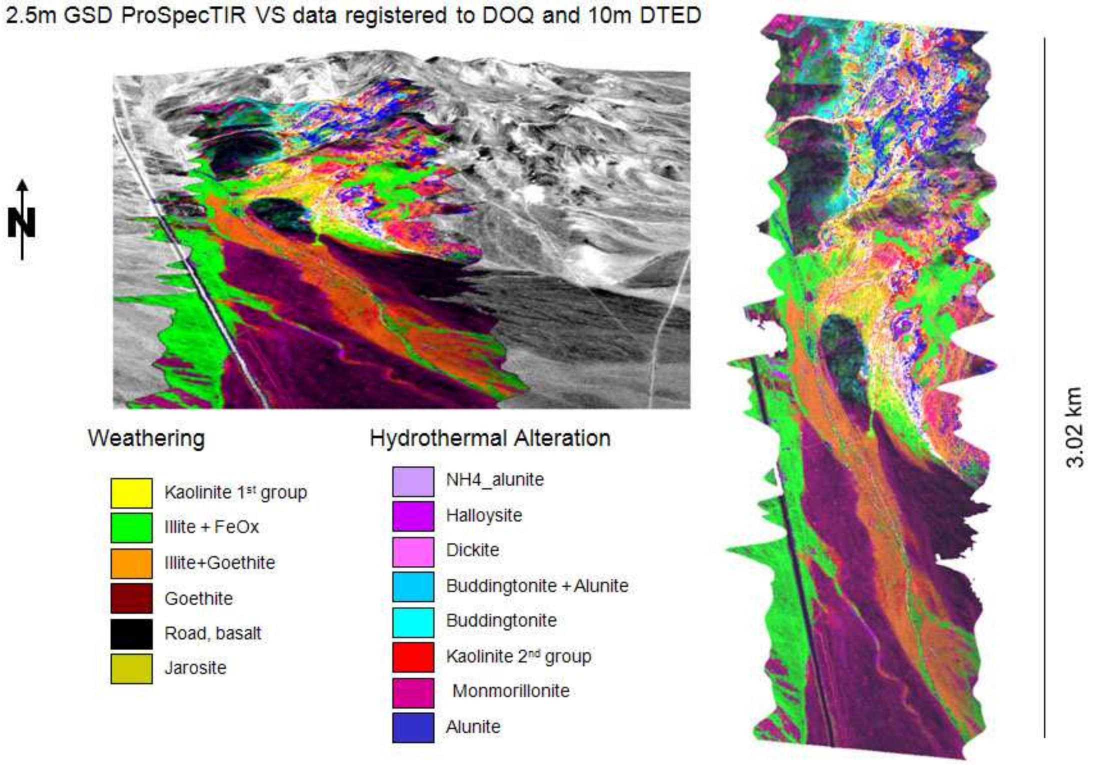

Figure 6 – Example of hyperspectral mineral mapping in Cuprite, Nevada (Smailbegovic, 2006).

The intimate mixtures (Figure 7) of minerals in the soils give the particular characteristic to soil types. The underlying mineralogy and structure often determine the observable characteristic of the soil (e.g. color, texture). In the particular case of Southern Dinarides (Herzegovina, Dalmatia), the red color of "terra-rossa" soils is a direct effect of its particular complex relationship of iron oxide mineralogy (e.g. Singer et al., 1998; Boero and Schwertmann, 1989; Durn et al., 2001). Previous studies have utilized XRD, ICP and elements of spectroscopy to discern the underlying mineralogy of soil composition. The common analysis methods are usually laboratory-intensive and require detailed and rigorous sample preparation, opening up a need for quick in-situ characterization of the soils and its content. Several authors (e.g. Goldshleger, N. et al., 2004) have explored the opportunity of soil reflectance mapping for the possibility of remotely sensed soil crust-related properties such as water infiltration. They have concluded that mineral constituents of soils can be detected with the use of reflectance spectroscopy and can be used to predict the soil characteristics and behaviour.

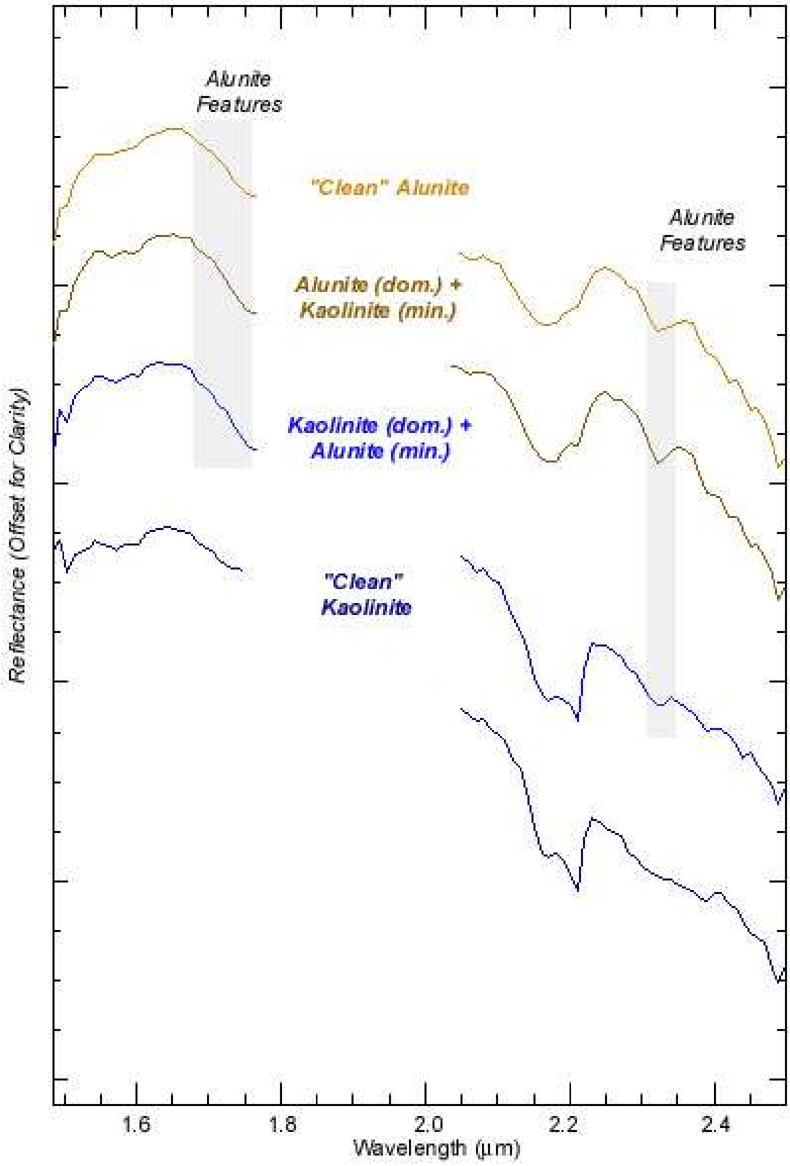

Figure 7 – Spectra of alteration minerals and their mixtures

With particular attention to the former mine lands are reports prepared in the course of MINEO program (Assessing and monitoring the environmental impact of mining activities in Europe using advanced Earth Obsrervations techniques) in 2002, with hyperspectral data collected to monitor lithology, suspended matter, tailing mapping, vegetation stress. The reports outlined the strategies for mineral mapping in the alpine environment and determining permissible lithologies for re-vegetation efforts, mineralogical/chemical dispersion of waste material in the acid mine drainage in the Mediterranean environment and dispersal/mapping of mine-waste tailings in the sub-arctic environment (see collated MINEO 2000 and 2002 reports on Contamination/impact mapping and modeling). The findings of the MINEO project present a starting point for the subsequent implementation of ImpactMin airborne campaign goals and expansion of already established hyperspectral observation strategies with higher resolution, horizontally-integrated remote sensing approach.

a. *Mercury pollution*

The method builds upon a regional space-borne satellite data to identify the areas of likely mineral occurrence and then task an airborne hyperspectral sensor to evaluate those areas for possible anomalies. Mercury becomes dangerous to ecosystems through a two-step transformation to the most toxic and bioaccumulative form of mercury, methylmercury (MeHg). Elemental mercury in the atmosphere and in watershed runoff is first oxidized by complex organic and inorganic reactions into its reactive, water-soluble form (Hg2+). Only reactive mercury can undergo “methylation,” the second set of reactions necessary to form methylmercury from elemental mercury. Methylation is a microbial process controlled by sulfate-reducing bacteria and a handful of other chemical and environmental factors. It is only once mercury is methylated that it enters the ecosystem, traveling up the food chain to humans through the consumption of affected fish. Studies show (Wu et al., 2005) that mercury absorption into soils is heavily depended on the soil mineralogy and local environmental factors. The researchers have demonstrated that high-resolution, hyperspectral imaging is sufficient in identifying soil types and minerals (clay and iron minerals) which have close relationship with mercury absorption. Hence being able to positively identify the areas with highest affinity for mercury concentration can delineate trouble-prone areas and limit the levels of human interaction (e.g. limit agricultural production in such areas).

b. *Radionuclides*

Remote sensing of radionuclides and occurrences of radionuclides in association with other elements (e.g. evaporites, hydrocarbons, organic sediments) with remote sensing spectroscopy is a relatively novel idea and yields possibilites worth exploring, especially with regards to the use of GRS methods. Several studies, carried out in the abandoned uranium mines in Australia (e.g. Martin et al., 2006), phosphate/gypsum production areas (Haridasan et al., 2001), sediments (van Wijngaarden, 2002) and naturally occurring regions (Thinova et al., 2006) have demonstrated that GRS is capable of identifying the distribution and spectral signature contributions of individual radionuclides on the surface as well as in aquatic environment. Kluson (2010) states that spectrometric data provide not only qualitative information (identification of radionuclides by the corresponding peak positions), but also provide quantitative information (photon flux energy distribution at the point of measurement). It is notable that coal and phosphate mining areas have been exhibiting elevated levels of radionuclides, particularly in Eastern Europe and former Yugoslavia (e.g. Ivan et al., 1990, Barisic et a., 1992). Identifying possible radionuclide anomalies associated with post mining areas can therefore offer an additional validation element and assessment tool for both natural and anthropogenic radiation assessment.

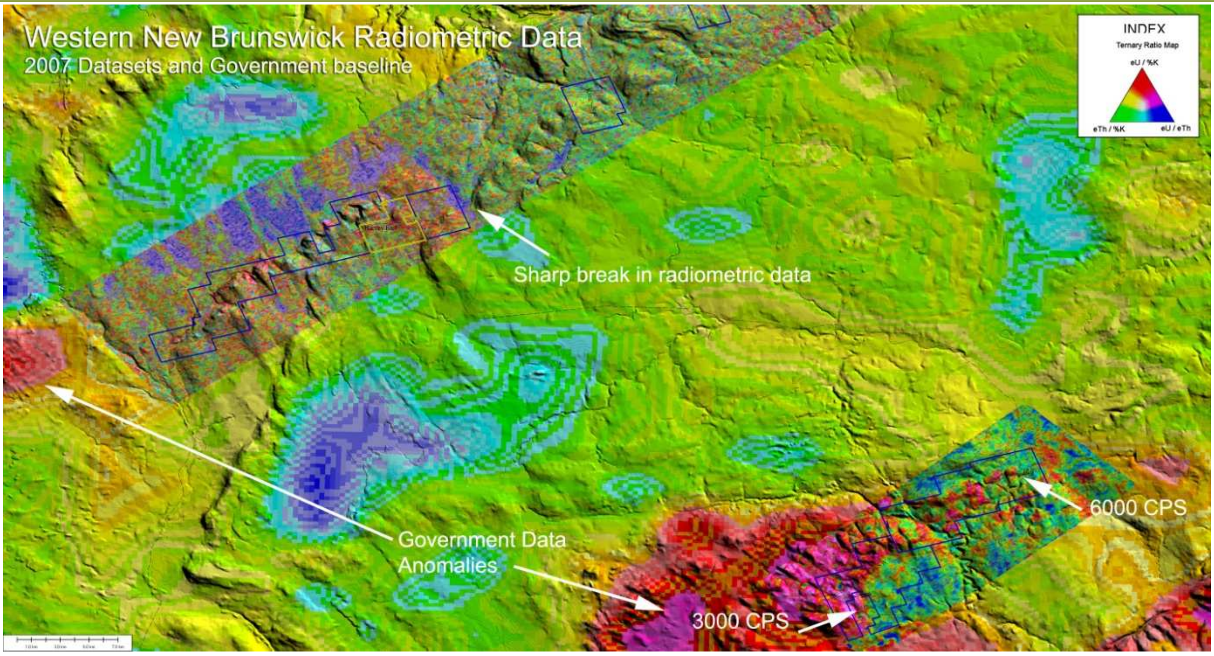

Figure 8 – Example of radiometric data use in characterization of radionuclide occurrences

c. Acid mine drainage

The acid mine drainage is a recurring problem in numerous former mine lands and has been a subject of numerous studies with muiltispectral and hyperspectral remote sensing. The most notable efforts were carried out as a part of USGS and NASA investigation of the abandoned mine lands (e.g. Swayze et al., 1998; Hauff et al. 2000, Peters et al., 2000; Swayze et al. 2008) and the subsequent MINEO project in Europe (2002). The problem is caused by rapid oxidation and evaporation of sulfides on mine waste tailings resulting in occurrences of iron-sulfate minerals (e.g. jarosite). The use of hyperspectral imagery had allowed generation of environmental baselines and evidence for predicting contaminant concentration and acid drainage on the variety of surfaces (Mars and Crowley, 2003; Ong et al, 2003; Riaza et. al, 2008;). The hyperspectral data can be used to effectively map the distribution and the oxidation stage of the various sulfide-bearing waste products, mainly through the distribution of jarosite, but also additional secondary minerals suggestive of weathering phenomena (e.g. Farrand and Harsanyi, 1995; Crowley et al., 2003)

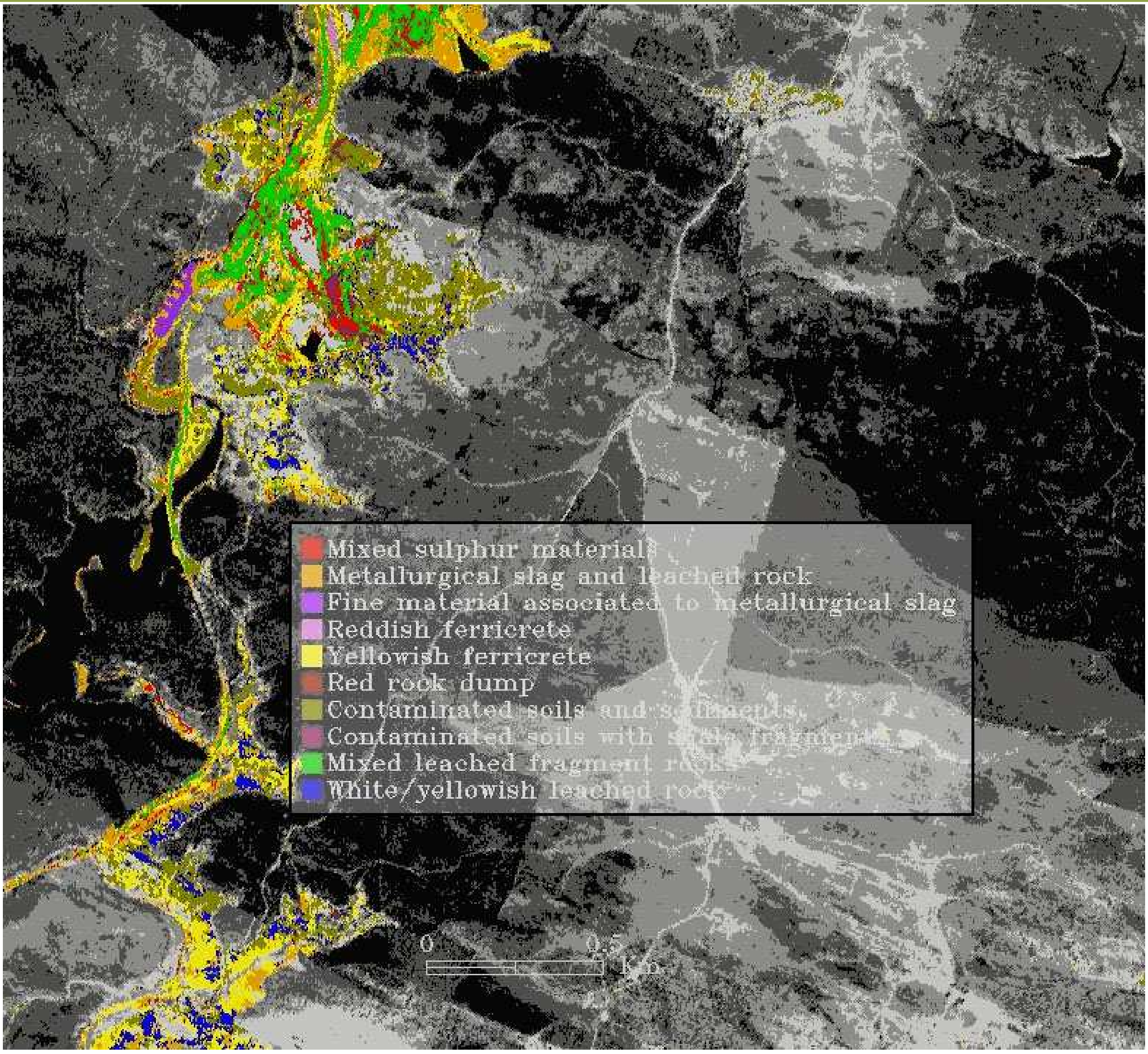

Figure 9 – Acid mine drainage identified through processing of hyperspectral data (MINEO, 2002)

3.2.4 Vegetation monitoring

a. Ecosystem health

Remote sensing spectroscopy is an effective tool for synoptic monitoring of ecosystem health. Even limited spectral information or coverage may be considered as useful aids in the design or improvement of point sampling programs, often through highlighting the best locations and timing for other types of sampling and/or monitoring. The strength of remote sensing techniques lies in their ability to provide both spatial and temporal views of surface water quality, atmospheric and or vegetation parameters that are typically not possible from in situ measurements. The high-resolution remote spectroscopy allows for monitoring of the landscape in an effective and efficient manner by identifying areas with parameters of concern. These quality parameters, often, can be quantified using remote sensing techniques allowing management plans to be formulated to reduce movement of substances from watersheds to water bodies or containment zones beyond containment thus reducing the effects of the pollutant on water quality and/or complete ecosystem (e.g. vegetations stress and health, food sources etc.).

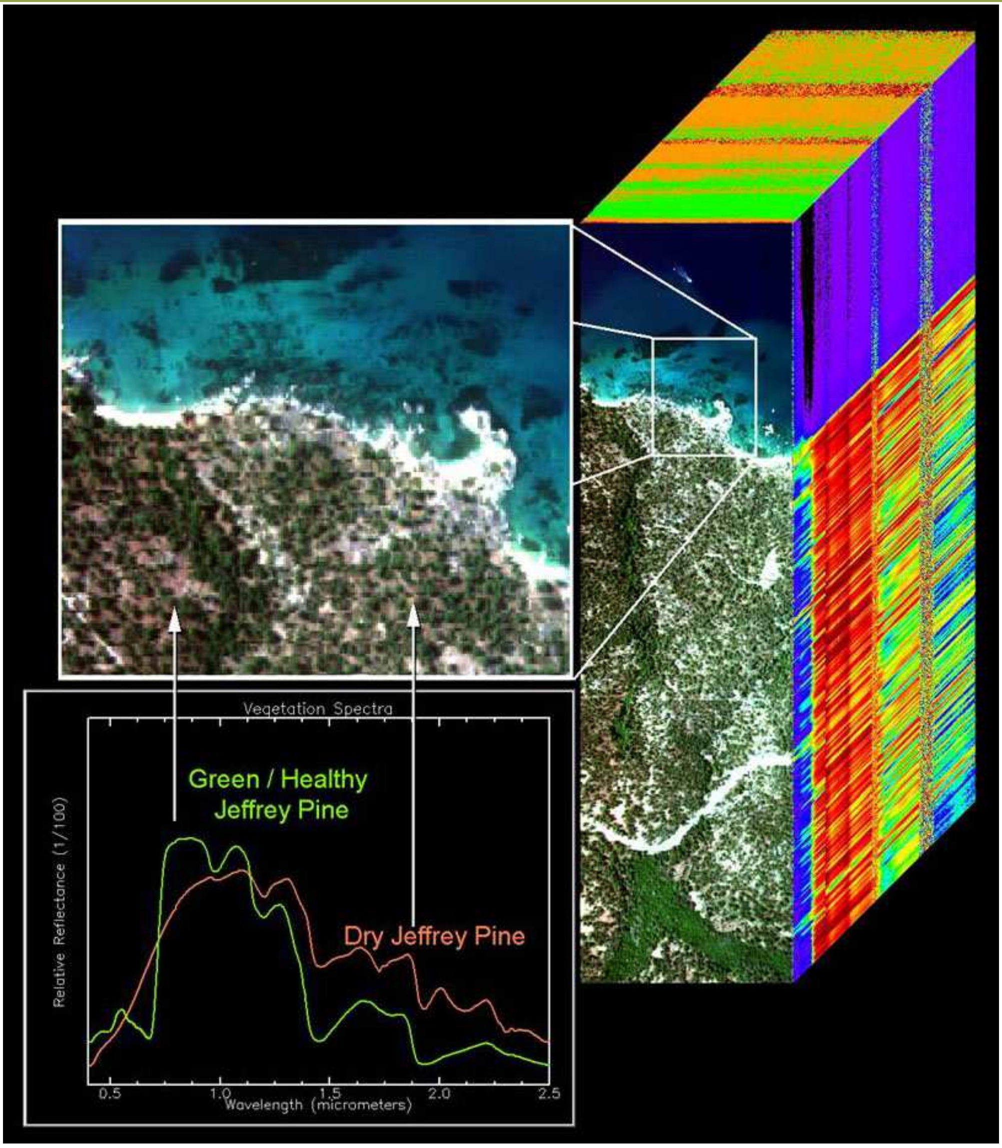

Figure 10 – Ecosystem health derived from hyperspectral imagery (image courtesy SpecTIR llc.).

b. Vegetation stress

A number of recent studies have indicated the advantages of using discrete narrowband data from specific portions of the spectrum, rather than broadband data, to obtain the most sensitive quantitative or qualitative information on crop or vegetation characteristics (Thenkabail et al., 2002).

Due to the specific changes of pigment concentrations and structure characteristics of plants under stress conditions and the related changes in the plants' spectral behaviour, multispectral and hyperspectral band intensities and ratios have been thoroughly investigated for plant stress detection. In the past, researchers have used reflectance from individual narrowbands (Mariotti et al., 1996), various ratio indices (Aoki, 1981;

Buschmann & Nagel, 1993, Carter, 1994; Gitelson, 1988; Lichtenthaler et al., 1996; Lyon et al., 1998), derivatives of reflectance spectra (Curran et al., 1991; Elvidge and Chen, 1995) or a combinations of these (Thenkabail et al., 1999), principal component analysis (Clevers, 1989; Asner et al., 2000; Thenkabail, 2002), discriminant analysis (Thenkabail, 2002), and the linear mixture modeling approach (Elmore et al., 2000; Mass, 2000). For example, leaf reflectance at visible wavelengths (475, 550, and 660 nm) increased and leaf reflectance at infrared wavelengths (850, 1600, and 2200 nm) decreased as concentrations of the heavy metals Cd, Cu, Pb, or Zn increased in plants grown in metal-contaminated soils (Horler et al., 1983).

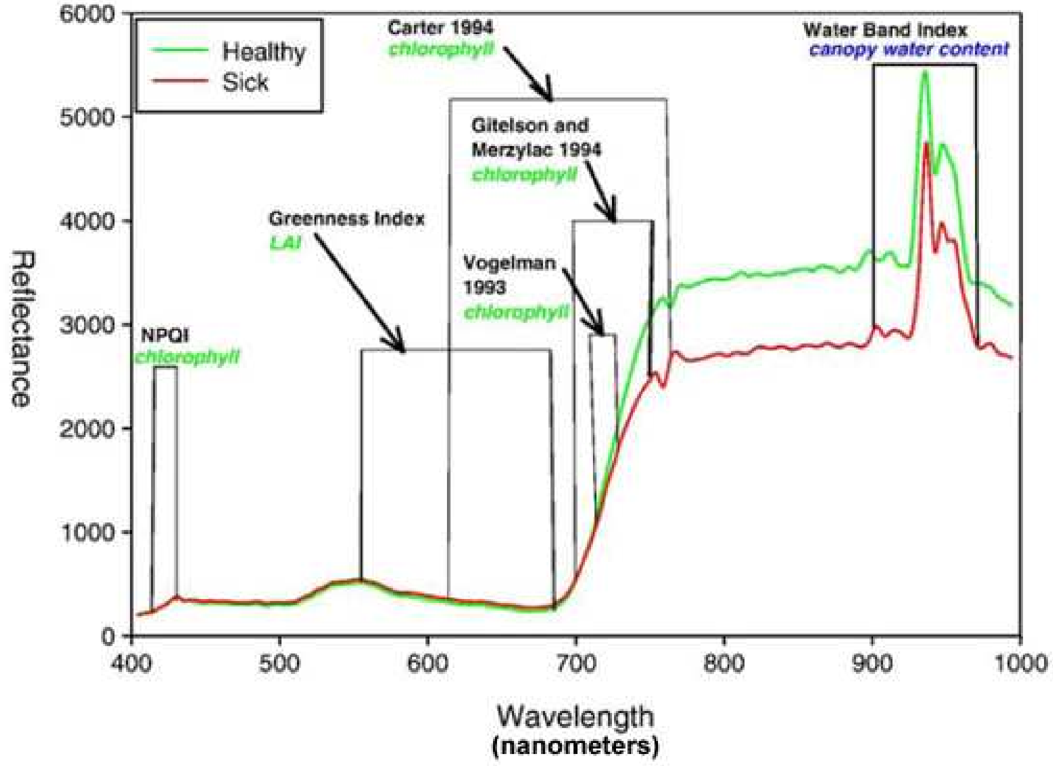

Figure 11 – Spectral observables of vegetation stress (modified from Pontius et al. 2008).

The normalized difference vegetation index [(NDVI=(NIR−Red)/(NIR+Red)] is positively correlated to total chlorophyll levels in plants. Generally, as plant stress levels increase, chlorophyll levels tend to decrease and NDVI values become lower (Gitelson et al., 2002; Gitelson, 2004).

Mining operations often result in limiting location factors like reduced water and nutrient supply which inhibit a natural succession. However, by abandoning these mine sites, remaining holes fill with ascending groundwater and surface water. This in turn leads to an unexpectedly strong groundwater rise and consequently to changes in species composition and vegetation vitality as well as to severe damage of reclaimed forested areas. Therefore, studies investigating water stress using airborne hyperspetctral data can be of great value to the mining industry. Götze and Glässer (2007) tested different parameters of plants such as chlorophyll content (NDVI, RVI, SAVI), pigment relationship (PRI, PSRI), water content (MSI, NDWI, RATIO975, WBI) and red edge (RVSI) for the detection of physiological stress due to water surplus. All indices used in their study were extracted from hyperspectral Hymap data.

Several other researchers have reported stress effects in vegetation due to leaking gas with symptoms including reduced emergence, yellowing of the leaves or a shift in the developmental stage (Arthur et al., 1985; Pysek & Pysek, 1989; Godwin et al., 1990; Smith et al, 2004). However, vegetation change due to gas leakage is likely to be slow in developing; and so hyperspectral remote sensing is more suitable for detecting prolonged leaks in isolated regions rather than as an early warning system. Smith et al. (2004) detected changes using a hyperspectral spectroradiometer with a spectral resolution of 3 nm, but similar effects have been identified by Smith et al. (2004) using an instrument with a spectral resolution of 4 nm and by Zarco-Tejada et al. (2003) using an instrument with a spectral resolution of 7.3 nm.

Kancheva and Borisova (2008) used the airborne HSI approach to describe the elements of spectral response associated with vegetative stress while Gotze and Glasser (2007) have used the advanced algorithms and airborne HSI data to characterize the vegetation stress in a lignite mining area. Kusomanen (2005) has demonstrated the ability to correlate spaceborne and airborne HSI data to map contaminated vegetation and soils.

Most of the research carried out in the first decade (1990-2000) was by investigators working with the data have been from academic institutions and government research agencies. However, the second decade (2000-2010) saw an increasing number of commercial applications of HSI, coupled with the arrival of new generation of commercial HSI-airborne instruments for routine operations. Multiple studies of HSI-potential for the use in mine-waste mapping operations have demonstrated the abilities of high-resolution, high-fidelity instruments to detect subtle indicators (e.g. acid-drainage, vegetation stress), which may yield important clues towards understanding the overall impact to the area (e.g. Farrand, 1999; Hauff et al., 2005; Vaughan, 2004; Crosta and Filho, 2005; Smailbegovic, 2005; Chevrel, 2005; Gotze and Glasser, 2007).

Vegetation has unique spectral characteristics which makes hyperspectral imagery so attractive (e.g. Rock et al., 1988; Roberts et al. 1993; Roberts et al., 1997). Vegetation has a high absorption in red wavelengths and a strong emission in near infrared. This allows it to be separated from other ground-surface covers because non-plant material absorbs and reflects infrared energy at a different rate. Differences in foliage, branches and architecture as well as branch angles, leaf shape and branch surface roughness cause individual tree species to reflect light differently and be individually mapped (e.g. Ustin et al., 1998). Furthermore, any external stress factors to the plant itself (damage, pollution, drought etc.) will result in chlorophyll attenuation, which in turn can be detected by the sensor and thereby help identify healthy from stressed plants.

3.3 Limitations

There are several challenges in obtaining precise, remotely sensed measurements from the surface. Some of the main obstacles are the atmosphere, mixtures and vegetative cover. Even though some of the factors limiting the efficiency of remotely sensed data are beyond control, proper planning of the data acquisition process may allow for their mitigation. Additionally, some factors can be mitigated with ground support during overflights and field validation to improve statistical mapping methods.

3.3.1 Atmospheric Effects

The atmosphere can interfere with the measurements in several ways: through scattering, absorption by the gasses comprising the atmosphere or through meteorological factors (wind, moisture etc.). The atmospheric constituents (primarily water, CO2 and Ozone) can entirely block the flux of radiation at certain wavelengths, leaving only a couple of "windows" for remotely sensed measurements. The presence of aerosols is responsible for the scattering in the visible region by suppressing reflectance from 0.4 to 0.8 µm (Zhengming and Li, 1997). The principal absorbing gasses in the spectral range of hyperspectral datasets are Ozone (0.35 µm), Oxygen (0.76 µm), CO2 (weak 1.56 µm doublet, 2.01 and 2.08 µm), Methane (2.35 µm) and water (0.73, 0.83, 0.94, 1.14, 1.38 and 1.88 µm) (Zhengming and Li, 1997) (Figure 7.3 b). In addition to general atmospheric chemistry, meteorological factors can seriously degrade the quality of measurements as well. Clouds can cause areas of low reflectance in the VIS-SWIR data. Rain showers can cause a pattern of streaks on the imagery. Ground moisture usually introduces heavy waterabsorption features in SWIR. Overcast conditions reduce the amount of received energy in SWIR (Clark, 1999 p. 6, 63)

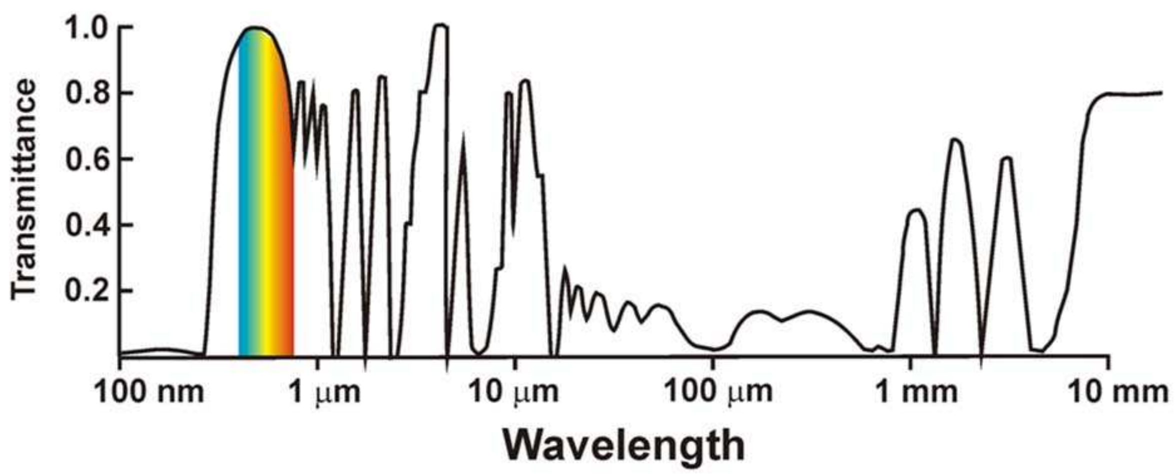

Figure 12 – Atmospheric transmittance windows and absorptions over EM spectrum.

3.3.2 Spectral Mixing

Very few pure surfaces exist at spatial scales available to geologic remote sensing. The acquired spectral measurements are bound to be in the form of spectral mixture, on a large or small scale. The measurements reflect the mixed nature of an imaged target by giving a combined measurement of all of its constituents (e.g. Goetz et al., 1985). Clark (1999, p. 36) outlines four main types of mixtures:

- Linear mixture described the situation in which the materials in the Field of View (FOV) are optically separated, so there are no multiple scattering among different constituents. The resulting signal is the sum of the "fractional area times the spectrum of each component."
- Intimate mixture is a result of different materials being in a direct or intimate contact within the surface (different minerals in a same rock for example). The resulting measurement is a "highly-nonlinear combination" of each material's unique spectra.

- Coatings result when one element coats another, where each coating layer presents a "scattering-transmitting layer" which may alter the spectral measurement of the underlying layer.
- Molecular mixtures describe the interaction of two materials on a molecular level (such as water adsorbed onto a mineral), where the molecular-interdependency of the components can cause band-shifts in the observed material (e.g., water content in the montmorillonite clay mineral).

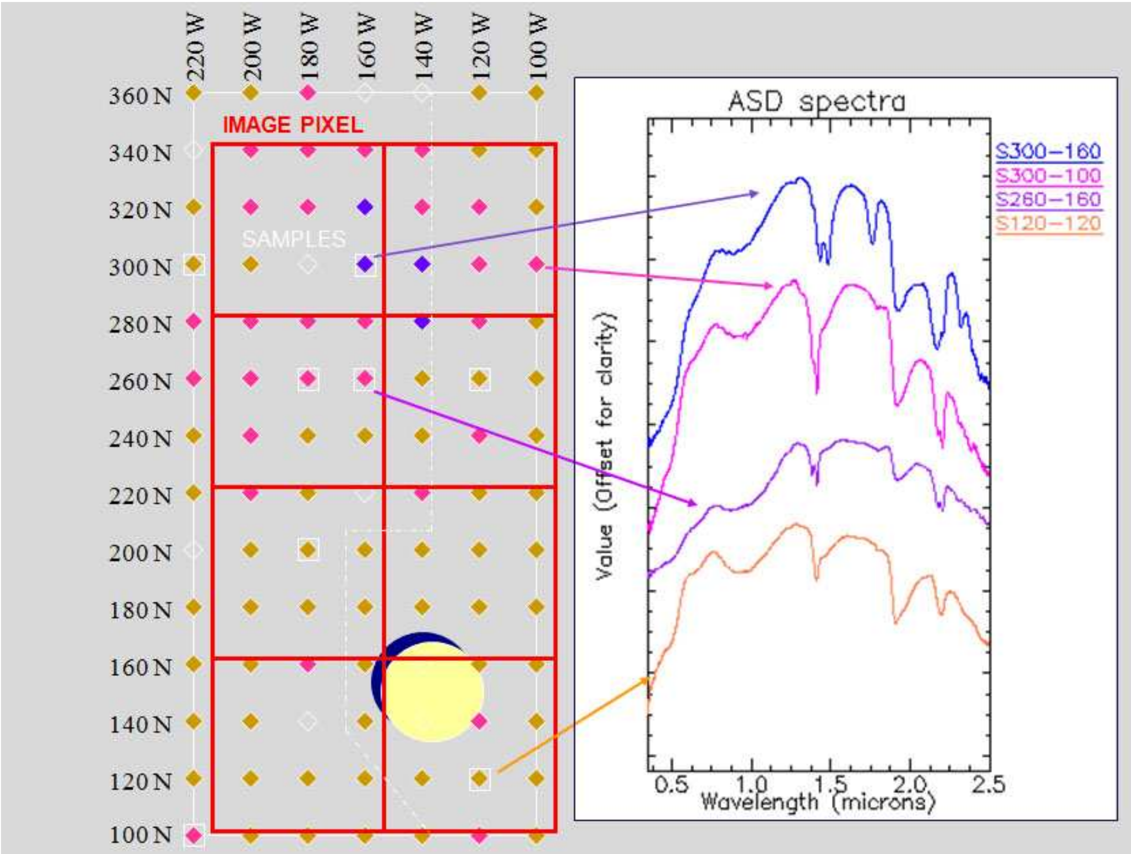

Figure 13 – Concept of mixed pixel (areal) problem, adapted from Vaughan, 2004.

3.3.3 Vegetative Cover

In geologic remote sensing, the issue of vegetative cover is important because vegetation tends to obscure the rock and soil surfaces. Siegal and Goetz (1977) emphasizes that the effect of naturally occurring vegetation on spectral reflectance of Earth material is a subject that deserves attention. The spectral region from 0.68 to 1.3 μm is heavily influenced by the chlorophyll absorption of the green plants (a steep rise in reflectance known as the "red edge."). Dry vegetation has minor spectral features in SWIR, related to cellulose and lignin around 2.2 μm (Ustin et al., 1998). It has been shown that vegetation cover has a profound effect on the spectral features of underlying and adjacent rock materials, particularly in the realm of hyperspectral remote sensing. When the vegetation component of a mixed pixel exceeds 20%, it degrades the ability to identify some mineral end-members, and when in excess 40%, variations in the reflectance of underlying rock materials are very difficult to detect (Taranik, 1988). In direct application to mining-related activities, Swayze et al. (2009) note that the vegetation categories are an important component of spectral maps because vegetation and mineral/grass mixtures often cover considerably more area than is covered by mineral-related pixels on the maps. The authors note that spectral maps that integrate information from substrate-dependent vegetative classification and lithologically independent mineral identification can be used as a tool for delineating areas more likely to contain particular mineral endmembers and locate areas in need of dust control, and help fill gaps in geologic mapping where access is limited.

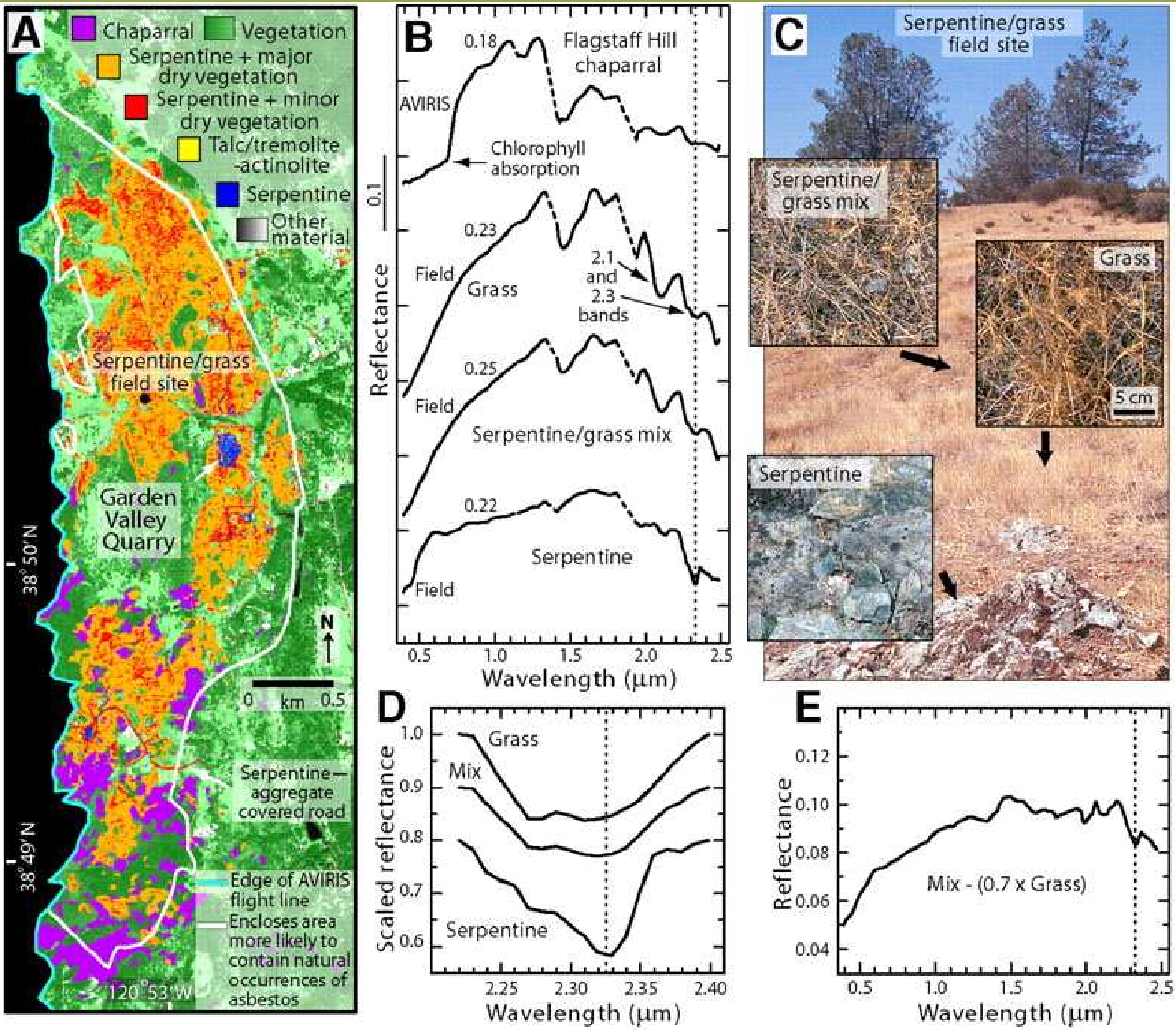

Figure 14 – Effects of vegetation to mineral mapping of asbestos minerals (Swayze et al., 2009)

3.3.4 Bi-directional reflectance distribution function (BRDF) effects

The BRDF effects (e.g. *specular* reflection for forward scattering or *hot spot* for backward scattering) can lead to incorrect classification results. Most surfaces on earth expose a relationship between the amount of reflected radiance and the directions of irradiance and viewing. According to a specific viewing and irradiance geometry an object appears brighter or fainter. Bidirectional effects affect remotely sensed observations in several ways. As soon as viewing and/or irradiance geometries within a single scene, or a series of scenes, are altered, the spectral reflectance signature of the sensed objects changes according to their object-specific BRDFs.

Generally, the world has been considered to be a lambertian-scattering surface, however there are numerous materials which exhibit non-Lambertian reflectance behavior. Many man-made materials appear glossy and exhibit a strong reflectance value in the specular direction (view direction has the same zenith as the incident angle, but are rotated 180 degrees apart in azimuth) while many natural materials (e.g. grass and soil) exhibit a strong reflectance value in the backscattering geometry (view direction has the same zenith and azimuth as the incident direction). These cases require a non-constant BRDF value to accurately predict how the materials will appear in a remotely sensed scene (Lentilucci and Gartley, 2009). This is also true when attempting to compare images from different sensors, or from the same sensor taken at different times (White et al., 2002; Sandmeier et al., 1998).

The research had shown that the spectral character of materials tends to converge to the illuminating source spectrum as the specularity of the material increases, with the limiting case being a perfect mirror. The results indicate that different material spectra, examined in the specular lobe, tended to converge: not only did the spectral character of the colored materials change, but they started to look similar. Therefore, the spectral reflectance (i.e., the BRDF) for materials does change as a function of wavelength and could (theoretically) cause potential false alarms in collected imagery (Lentiluci and Gartley, 2009; Sandmeier et al. 1998).

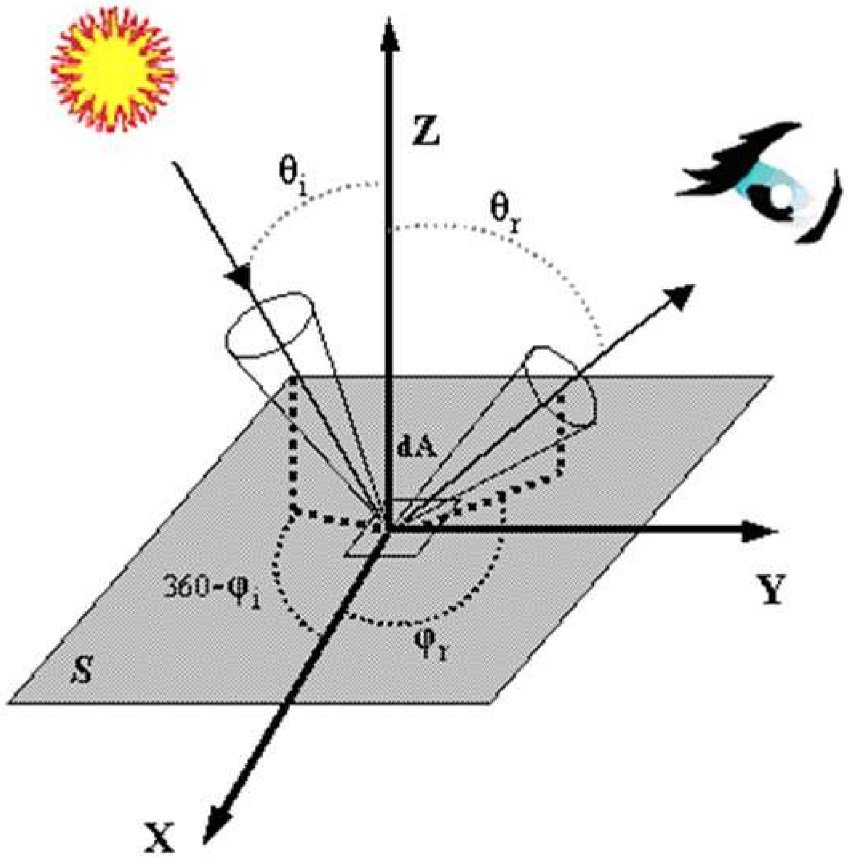

Figure 15 – Concept of Bi-direction reflectance distribution function (BRDF)

3.3.5 Shadowing

The interpretation of hyperspectral imagery can be further complicated or hindered by illumination variations due to shadowing, sloped terrain, or causes described above (e.g. vegetation, clouds). In atmospherically-calibrated data these variations in illumination are expressed as oscillations in overall spectral amplitude and signal response. In the deeper shadows where the illumination is derived from scattered skylight, the observed spectra are not only dimmer but also exhibit skewing towards shorter (blue-deep blue) wavelengths: these effects can impede the classification of surface materials and the detection of targets with standard methods (Adler-Golden et al., 2001). Several classification and detection algorithms have been developed that are insensitive to illumination (Healy and Slater 1999; Adler-Golden et al., 2001), but for numerous applications it is considered advisable to normalize all the pixels to a common illumination, such as full sun and skylight. The procedure calls for an ability to characterize the illumination-levels (brightness values) for each pixel, and in particular to identify shadows and quantify their depths, which can also contribute elevation information for terrain, surface objects, and clouds.

Several methods have been discussed for identifying and correcting for shadowing ranging from linear unmixing of atmospherically corrected data (Boardman, 1993) using spectral endmembers to more simplified varieties of matched filtering (Adler-Golden, 2001). The linear method using spectral endmembers defines shadows as a “black” (zero reflectance) endmember, and a sum-to-unity constraint is imposed on the endmember weights. The iterative matched filtering method a purely spectrally-based approach, which does not take advantage of spatial context or ancillary information that might distinguish between shadowed and fully lit surfaces that are spectrally similar, but delivers quick and on-the-fly results that may aid in correcting the illumination differences.

3.3.6 Radiometric considerations (GRS)

Measured gamma-ray spectra represent a complex function of many variables (Minty 1997). In addition to the concentration and geometry of the source, they are also functions of the height of the detector above the ground, thickness of non-radioactive overburden (Schetselaar et al., 1997), air temperature and pressure, precipitation, temperature inversion layers and air movements in the lower atmosphere, as well as soil moisture.

Barren overburden, because of its high density, can dramatically reduce the radiation output from the earth's surface. Just 2cm of surface cover can reduce the resulting signal by as much as 35 percent. In some areas, dense vegetation may have the same capacity to shield the source of radiation as 50m of air. The trunks of tress in a dense forest will have a collimating effect on radiation from the ground. Changes in temperature and pressure can also lead to a change in air density by up to 30 percent. The effect of Rn (radon gas) trapped in temperature inversion layers close to the ground under early morning still-air conditions can adversely affect estimates of background.

Airborne spectrometry measures surface radioelement concentrations to a maximum depth of about 40cm. uranium or radioactive element mineralization which is deeper than 40cm will not be detected by the airborne spectrometers. Spectrometric mapping of uranium also assumes an overall equilibrium in the $_{238}$U decay chain. Disequilibrium can occur where the daughter products above the measured Bismuth ($_{214}$Bi) in the decay chain are either enriched or removed, thereby giving either an over- or under-estimate of uranium. For example, uranium anomalies can be caused by the accumulation of radium ($_{226}$Ra) in ground waters. Dickson (1995) showed that disequilibrium effects in soils were not large. Soil disequilibrium together with generally low count rates are significant factors that contribute to the noise in uranium channel data.

Uranium concentrations derived from gamma-ray spectrometry are normally expressed in units of 'equivalent' parts per million (ppm eU) as a reminder that these estimates are based on the assumption of equilibrium in their respective decay series. False uranium anomalies can result from disequilibrium processes and it is essential that anomalies identified using airborne data are verified by soil and bedrock geochemistry. Correlation of airborne radioelement values with soil and rock geochemistry (Wilford et al. 2009) is currently being investigated as a means of better understanding issues around disequilibrium, scale and accuracy of the spectrometric method.

Spatial resolution of gamma-ray data largely depends on the line spacing and distance to ground of the airborne survey. Aircraft velocity and count-rate determine the resolution in the direction of the flight. The latter is usually between 25 and 100m. Flight line spacing and ground-distance are strongly related, and are usually a compromise between data resolution and acquisition costs.

A Gamma-ray sensor collects data from the ground in a circular area of influence. The further away from the nadir-point (and the larger the radius of the circle on the ground), the smaller the contribution to the total number of counts. This is illustrated in Figure 16. The figure shows the relationship between the radius of circle of influence on the ground and the cumulative proportion of total signal at a sensor at a altitude *H*. For example, for an aircraft flying at 60m altitude, 40% of the total signal comes from within a circle of influence with a radius of 50m.

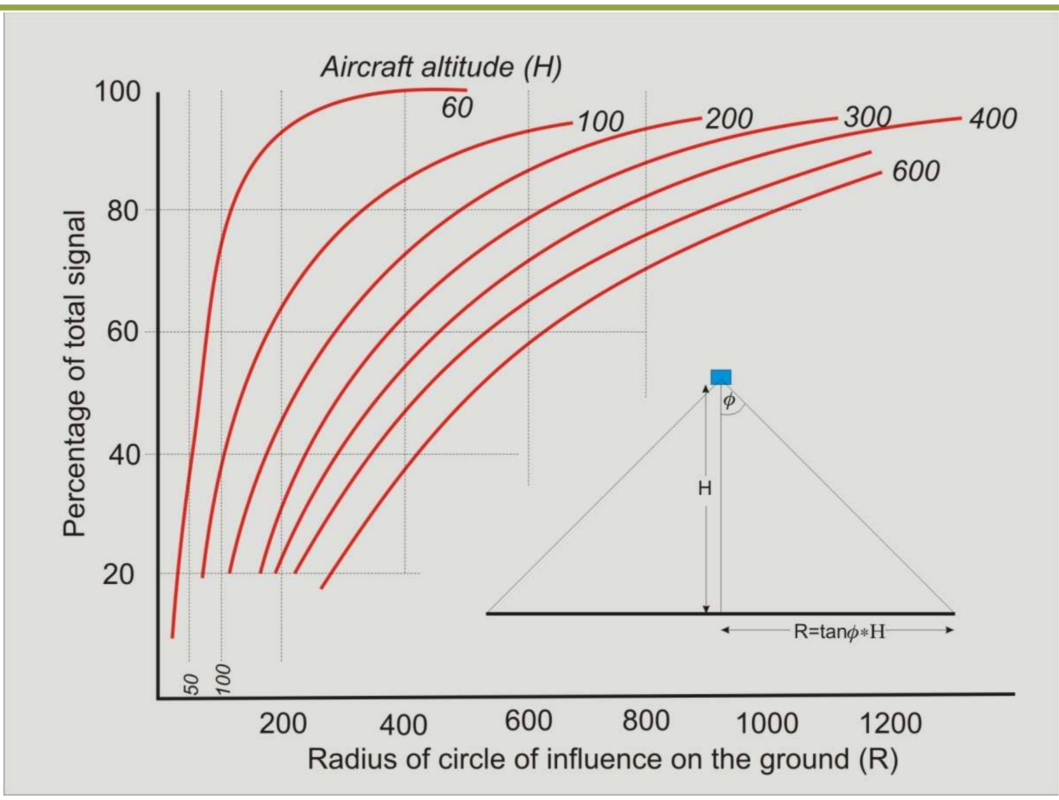

Figure 16- Radius of circle of influence versus percentage of total signal, as a function of different aircraft altitudes (after Uruqhart, 2004 and Grasty et al., 1995)

The figure implies that if the objective is to resolve small features on the ground, the survey should be performed at very low altitude (<50m) and low aircraft speed (< 100 km/hr). In the mining industry, such detailed surveys (altitude <30m, linespacing < 50m) are not uncommon to map geology at a prospect scale.

4. Inventory of field observation methods

Primary objective:
Inventory of field observation methods (geochemical, spectral, geophysical) needed to support and complement the airborne survey.

Airborne measurements are often supplemented with in-situ field measurement methods as an added element of ground-truthing and validation of the airborne measurements. By collecting point-measurement, it is possible to examine certain features in greater detail, discern mixtures and use them as a method for atmospheric calibration of airborne data.

4.1 Spectral

The role of point-spectroscopy in validation and calibration of airborne hyperspectral data has been described in great detail by Clark et. al (1993, 1995 and 2002). Calibrating imaging spectroscopy data to surface reflectance is an integral part of the data analysis process, and is vital if accurate results are to be obtained. The main importance lies in greater confidence that may be placed in the maps of derived from calibrated reflectance data, in which errors may be viewed to arise from problems in interpretation rather than incorrect input data.
There are several ways to derive usable surface reflectance from the acquired hyperspectral data (discussed in detail in §6.2). The field-calibration method can be two-fold: a) selection and spectral measurement of a suitable “field-calibration” site b) recording of the solar irradiance over period the data is acquired. These measurements can aid in comparison of the field or lab spectral measurements with the corresponding spectra from the airborne imager over a particular area. The radiance (irradiance measurements) or reflectance (field-calibration) data may show differences which indicate that additional corrections are necessary to be applied on the airborne measurements. On the basis of the comparison, a set of multipliers (gains) can be derived to modulate the airborne measurements with the high-fidelity spectral measurements. When the corrections are applied to the data, the resulting spectra are similar in quality to the laboratory reflectance spectra (Clark, 2002). Additional areas in the data set can be used to verify and further refine the accuracy of the multipliers and to derive any residual path radiance correction.

Figure 17 – Acquisition of field/calibration spectral measurements with spectroradiometer

The hyperspectral sun photometer calculation of solar irradiance is based on the concept vicarious calibration of optical remote-sensing systems. Sun photometer measurements at various wavelengths can be analyzed to estimate molecular scattering, aerosol extinction, and columnar concentrations of water vapor, ozone, and trace gases in the atmosphere. The approach uses a spectroradiometer (point-spectrometer) calibrated to standards traceable to the National Institute of Standards and Technology and a reflectance standard panel that exhibits nearly Lambertian 99-percent reflectance. The spectroradiometer is positioned above, and aimed downward at, the panel. The procedure for operating this instrument calls for a series of measurements: one in which the panel is fully illuminated by the sun, one in which a shade is positioned between the panel and the sun, and two in which the shade is positioned to cast a shadow to either side of the panel. The total sequence of measurements can be performed in less than a minute. From these measurements, the total radiance, the diffuse radiance, and the direct solar radiance are calculated. The direct solar irradiance is calculated from the direct solar radiance and the known reflectance factor of the panel as a function of the solar zenith angle. Atmospheric characteristics are estimated from the optical depth at various wavelengths calculated from (1) the direct solar irradiance obtained as described above, (2) the air mass along a column from the measurement position to the Sun, and (3) the top-of- atmosphere solar irradiance (NASA Stennis Space Center, 2008 Tech Brief).

4.2 Geochemical

Previous studies have investigated environmental impacts from historic mining and ways to distinguish problem sites from innocuous sites (Hauff et al., 2005; Chevrel, 2005; Zabcic, 2005; Swayze et al, 2000). Conventional ground methods to find and evaluate wastes have been found to be too time consuming and expensive, while the remote sensing offered a potential alternative. Overall, the discrimination of the mine waste or impact is focused on the subtle changes in mineralogy and what are considered to be waste materials. This directly correlates to the requirement for smaller pixel size and finer spectral resolution to resolve the apparent observables (e.g. Vaughan, 2004). However by implementing this approach, often very large data sets are obtained which have to be handled efficiently and rapidly. Processing has to be faster, more accurate, and consistent with the development of new mineral identification algorithms. Another important issue is the level of accuracy assessment; the studies suggest that field-checking with field spectrometers and X-Ray Fluorescence (XRF) and or X-Ray Diffraction (XRD) when metals are involved (Hauff, 2005; Vaughan, 2004, Swayze, 2002).

Another important element is water sampling in the vicinity of the mine area and associated watershed / proximal waterbodies. The effect is sometimes direct (e.g. acid mine drainage, waste pile leakage), but is mostly indirect and affects nearby waterbodies through groundwater percolation/discharge. The water samples are often analyzed for pH values, concentration of heavy metals and/or presence of nutrients, which may suggest potential contamination.

Figure 18 – Geochemical and pH sampling of the area affected by toxic waste flood.

4.3 Geophysical

As with any remote sensing technique, calibration and verification of the airborne gamma-ray data by means of ground surveying is essential.

However, comparisons between the airborne and ground based readings should be treated with caution (Martin et al., 2006) since the footprints of the two techniques are quite different. Portable field measurements are often made at about 1m height at fixed locations. Assuming a planar ground source with a homogeneous activity concentrations, then approximately 56% of the acquired signal would come from within the immediate 2m radius envelope, while approximately 92% of the overall would be derived from within the 10m radius (IAEA 1989), hence the resulting measurement would appear to be quite localized (Figure 19).

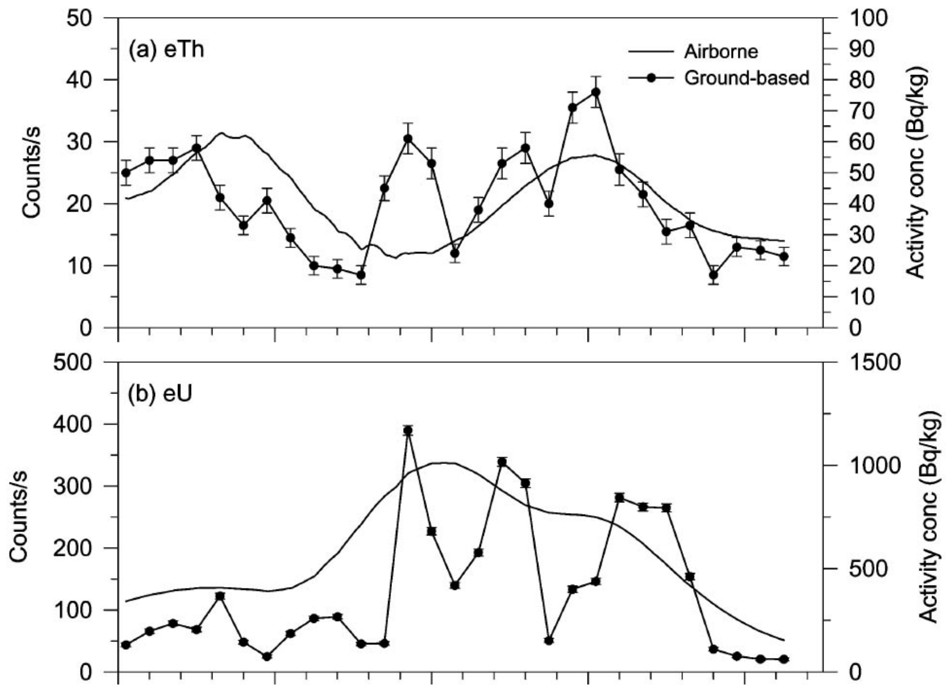

Figure 19 – Comparison of airborne and ground gamma-ray measurements along a profile (Martin et al., 2006)

By contrast, an airccraft flying an average ground height of approximately 60m during one measurement, and nominal line spacing of 100m would yield a spatial resolution of 60 x 100m. Further, at a relative height of ~50m, about 60% of the signal would be derived beyond the radius circle envelope of 50m. This would means that a significant fraction of the signal would be from beyond the nominal 60x100m measurement strip.

Another considerable difference may be that the counting period for the ground-based measurements may vary, allowing for longer count times and hence improved overall statistics for the low-activity regions, whereas the counting period for airborne methods is largely fixed.

Figure 20 – Geophysical ground verification with field gamma-ray spectrometers.

5. Focus on demo-site specifics and problems

Primary objective:
Summary of the most important characteristics, challenges and required tools pertaining to test-sites evaluated in the course of ImapactMin airborne campaign.

Each of the test sites encompassed in the campaign exhibit particular traits that are intended to be evaluated by an airborne remote-sensing method. The unique parameters also call for special challenges to be overcome in order to collect, analyze and implement the acquired data. The nature of the challenge also dictates the follow-up activities and the methods chosen in data acquisition.

5.1 Kristineberg, Sweden

Airborne remote sensing from an UAV can offer important high resolution information on ecological processes (mainly related to vegetation, barren ground and tailings) at the mine site. The Kristineberg mine is a massive-sulfide base and precious metal mine located in the Northern Middle Boreal sub-zone. The thick vegetative cover, lack of clear days and low sun angle in the northern latitudes presents a challenge to using standard airborne spectral surveys. By implementing the UAV platform, which can fly “under-the-weather” with a light-weight, high resolution digital camera, the objective is to acquire the imagery at high-spatial resolution, and determine vegetation to the species level and quantify the cover and biomass of different plant species in the mine area. This information can be used to quantify the vegetation succession in short- and long-term. Combining the information (plant biomass) from the UAV with field sampling (analysis of trace element concentrations in vegetation), it may be possible to assess the amount of trace elements (including heavy metals) accumulated by different plant species, which is an important for remediation processes.
Analyzing vegetation in running waters along a spatial gradient from the mining area offers information on the impact of mining on plant species composition in the riparian zone. The analysis of species composition might result in the identification of indicator species for certain mining related environmental conditions. Analyzing aquatic vegetation (macrophytes) along such spatial gradients is also important for the determination of the ecological status of waterbodies in accordance with the EU Water Framework Directive.

5.2 Mostar Valley, Bosnia & Herzegovina

The ‘Vihovici Coal Mine’ is located in the Mostar Valley, Bosnia and Herzegovina. The mine was exploited by ‘Rudnici mrkog uglja’ (Brown coal mines of Mostar), a state-owned company, but is inactive since 1991. The mine had entered production in 1901, first as an underground operation, but from 1963 on, open pit mining was performed. In total, 11 million tons of brown coal (lignite) were extracted from the mine. 3.5 million tons were produced by surface exploitation (open pitting). The total area of the mine site is 76 ha, with 43.2 ha surface operations and an open pit of 7 ha. The mine was used as public solid waste dump from 1992 – 1995. Illegal waste dumping continued until 2007, when a remediation program was started and in 95% of the mine area some of the surface waste was removed. Underground coal fires were (apparently) extinguished by water and fly-ash pumping.
The mine is located in a karst landscape, with associated typical structures (e.g. caverns, sinkholes, dolines). Geomorphology of the region is also dominated by alluvial formations along the Neretva River. The climate is a semi-arid, Mediterranean climate. Surface cover is sparse and consists of low-lying Mediterranean shrubs (wild pomegranate mainly). There are

five general zones of Neogene layers: sandstone, breccia, sand-gravel clays, sand marls and limestone. The main carbon-coal seam is composed of direct bottom and roof layers and a carbon layer with interlayer and refills of muck. The geology of the area consists of Perm-Triassic strata, ranging from plaster-anhydrites, unconsolidated limestone, clay and mudstones, which are compressed during folding episodes and exposed on the surface and thrusted upon Mesozoic rocks

Combined high-resolution hyperspectral/gamma-ray survey is intend to classify the areas of interest at Vihovici abandoned brown-coal mine near Mostar, Bosnia and Herzegovina with regards to the surface mineralogical, vegetative, hydrologic and anthropogenic cover. The narrow band-passes (5-10nm) and high spatial resolution (1m or better) of the hyperspectral imager is expected to allow definition of the discrete observables parameters of surface materials, in particular contaminants related to mining (clays, sulfates), organic materials (hydrocarbon polution) and overall surface-waste composition of the mine closure area near Vihovici (some of the surface refuse is mine-related and some of it is municipal in origin).

Furthermore, by using better-defined atmospheric parameters and narrow band-pass of the instrument, the intent is to map the distribution and location of possible toxic-gas emitting fumaroles (CO, H2S, CO2, SO2) which may still be present as a result of underground burning of coal seams in Vihovici region.

Lastly, any effluence of toxic substances into Neretva river, via surface or subsurface pathways is bound to generate detectable response, particularly because the rivers are fairly clean. Using the UV and deep blue regions of EM spectrum covered by the hyperspectral imager, it is intended to identify the zones of increased nutrient load, increase in dissolved solids or other phenomena suggestive of surface or subsurface contamination of the karst watershed.

Gamma-ray spectroscopic data can be flown in conjunction with hyperspectral data to offer additional information about the overall geology, but also identify hot spot zones indicative of industrial and military waste deposition at 1:10000 scale. There are anecdotal reports of radioactive waste dumped at Vihovici region before, during and after the 1992-95 war (e.g. Fichtner report, 2006), especially as a product of weapons testing and manufacturing of a nearby Soko industrial facility. Additionally there are anecdotal reports of both Yugoslav and intervening NATO forces using depleted-uranium munitions in the wider region, which have been a topic of specialized environmental and health studies (e.g. Jia et al., 2006, Sumanovic-Glamuzina, 2003). Using a high resolution, densely-spaced radiometric survey, possible presence of radioactive materials present in or around Mostar could be detected and further substantiated or disregarded. In addition, the coals-sequences and other occurrences of hydrocarbon deposits in the Central Dinarides region, reportedly contain above-average radiation levels (e.g. Kljajic et al., 1996, Hrvatovic, 1999) as a result of uranium deposition as a result of precipitation from the surrounding geological strata in the vicinity of hydrocarbon contacts.

The main challenges to the Mostar site are the low-altitude of required airborne operations and data acquisition over a heavily urbanized area. Operating in a congested area, with overhead infrastructure (e.g power-lines) in a relatively narrow mountainous valley, requires careful mission planning and safety considerations to minimize any potential risk on the ground.

The airborne campaign will be complemented by the ground truthing, ground sampling and water quality campaign on the ground, which will be determined and adjusted with the progress of the airborne operations in the area.

5.3 Rosia Montana, Romania

From 1970 till 2006, the Rosia Montana mine was owned and operated by the state. Currently, S.C. Rosia Montana Gold Corporation S.A. (R.M.G.C.) is trying to obtain the permits in order to again start operation (the so called ‘Rosia Montana Project’). Gold mining in Rosia Montana has occurred almost continuously over the last 2000 years and has influenced the social, economic, cultural and environmental conditions of Rosia Montana. Only underground mining operations were functioning before 1970. About 140 km of galleries were dug in the area in nearly 2000 years of mining. Later on, the open pit mines Cetate and Carnic were setup. The area of the open pits is 19.75 ha (Cetate) and 5.2 ha (Carnic). there have been no significant attempts at environmental rehabilitation and no effective environmental controls to reduce the impacts. The current situation is therefore progressive: if no remediation actions are done, continued pollution of streams and soil within the area can be expected, primarily from uncontrolled run-off and seepage from the former operations (activity closed in May 2006, site not rehabilitated), historic mine workings, and uncontrolled waste disposal practices.

At the time this report was written, only limited airborne LIDAR coverage over Rosia Montana mine in Romania was planned, acquired by a third party and integrated to the project as a courtesy of data contribution from the Rosia Montana Gold Corporation (RMGC). Rosia Montana region presents a complex geological-mining environmental interaction area, exhibiting over two millennia of surface and underground mining and milling operations. Mountainous, vegetated and water-saturated setting of the area gives additional complexity in characterizing the area from the environmental standpoint.

Data acquisition and overflight permits in Romania are considered to be the greatest challenge in successful airborne campaign. Based on the anecdotal information available from geophysical and geospatial survey providers, the issuance of permits is a lengthy and laborious process, which may extend beyond the duration of the ImpactMin project. The planned LIDAR survey over Rosia Montana was reportedly negotiated far in advance, and even though an effort was made to “piggyback” ImpactMin survey equipment on the existing survey, the request was declined by the provider. A tentative agreement between the ImpactMin project coordinator and representatives from RMGC exists to explore the feasibility/possibility of acquired airborne LIDAR (and/or other data) integration into the analysis and evaluation nexus of ImpactMin.

6. Tools for airborne remote sensing for mineral resources exploitation monitoring

Primary objective:
Evaluation the limitations of available data processing techniques. Development of new ways of processing the geophysical and hyperspectral data. If necessary, current software needs to be modified, and new software may need to be developed.

The analytical methodology presented is primarily geared towards analysis and interpretation of hyperspectral datasets, but some elements can also be used in the evaluation of supporting datasets (e.g. multispectral, radiometric, aeromagnetic). Furthermore, the integral part of analysis is the horizontal integration and cross-analysis of all available data to reveal subtle observables that can be used in identification of an informational "super-spectrum," a combined observable spanning multiple sets of data.
Some of the general guidelines in the pre-processing and analysis of hyperspectral data were described in the MINEO (2003) report and remain pertinent to the present day with the need for accurate atmospheric corrections, geometric correction and clearly established chain of processing and data reduction methods.

6.1 Pre-processing and radiance

The first element of hyperspectral data exploitation is the calibration of raw data to radiance-at-sensor and eventually reflectance, which can be correlated with various other physical elements of given observables (e.g. spectral absorptions and emissions). This step is usually undertaken by the provider of HSI-data and is generally instrument dependent, taking in account various elements of instrument noise (dark current subtraction), spectral and radiometric calibration, focal plane adjustments (e.g. bad pixel problem), geometric distortions etc. The most important element in deriving radiance-at-sensor is a sound radiometric, and consequently spectral calibration. Generally, the most widely used solution is based on the fact that the radiometric calibration is predictable and slowly varying as a function of wavelength and this allows the use of an iterative procedure to adjust the instrument gains and signal response. Ultimately, a good radiometric calibration allows for the mitigation of so-called "bad-pixel" problem often encountered in complex SWIR focal plane arrays. Minor voltage fluctuations, saturations, under-scans and similar effects results in visible data-artifacts which are mitigated using simplified physical model. The pixel is assumed to be made of 3 components: a bright component having reflectance of 1, a dark component having a reflectance of 0 and a variable component which has reflectance that varies between 0 and 1 in the region under consideration. The scanning and geometric effects are addressed by tagging each scan line with differential GPS measurement and then post-processing scan and geometric distortions to produce sensor input geometry maps. The end-result of the pre-processing is a solid radiance-at-sensor data, free of distortions and ready for input into further calibration algorithms and in certain cases, radiance-based target detection (e.g. ITTVS' BandMax algorithm).

6.2 Reflectance calibration.

For the atmospheric correction of hyperspectral data a radiative transfer modelling approach is the preferred method used. Several different methods have been used for HSI calibration in the past: Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes(FLAASH) (e.g. Adler-Golden et al., 1999) and the Moderate Resolution Atmospheric Radiance and

Transmission (MODTRAN) model (Berk et al., 1998; Matthew et al., 2000). These transformations are based on the model and are considered relatively hands-off in the approach.
Another method is based on the retrieved surface reflectance method where image spectra are directly compared to reference spectra for pure minerals that are archived in spectral libraries. Both the USGS and JPL have spectral libraries available via the Internet and contain VNIR/SWIR spectra for over 2000 minerals and rocks combined (e.g. Clark et al., 2003). For calibration sites, large (multi-pixel), flat areas that are mineralogically homogeneous and free of vegetation are chosen for field spectrometer measurements. A point-spectrum spectroradiometer is used in the field for mineral identification and calibration of remote sensing data sets, as well as in the laboratory for high-resolution characterization of field samples (Curtiss and Goetz, 1994). The data are calibrated to reflectance by measuring a dark current to define detector "noise" that contributes to the incoming signal, and by measuring the radiance from a white spectralon® (Labsphere, Inc.) reference panel of known reflectance. The field data are then compared against the sensor data for the same target to derive the empirical-line reflectance (see Baugh and Groeneveld, 2008 and references within).
Recently, another method was described by Peppin (2009) to handle reflectance calibration of high-spectral resolution (e.g. 5 nm or better) datasets and address the inadequacies of MODTRAN-based applications. The Virtual Empirical-Line Calibration (VELC) method presents an alternative method by using obtained airborne imagery for a “generic” spectra and produced a calibration spectrum that can be used in lieu of flat-field or empirical-line spectra, usually obtained through ground measurements.

6.3 Data analysis

There are numerous ways to approach the analysis and classification of airborne measurements. Many techniques already exist in the image processing and some are integral part of various image processing software packages (e.g. ENVI, IDRISI etc.), but certain may not be effective when they are directly applied to hyperspectral imagery and hyperspectral imagery containing variety of linear and areal mixtures. Overall the hyperspectral data processing is more demanding and non-linear than multispectral data discussed in D4.1. The term “classification” itself can be considered to be as a statement of odds: the probability of finding a desired target or spectral match. Generally, the classification can be subdivided into two distinct methods:

a) Supervised classification in which the targets for the classification are known at start
b) Unsupervised classification, in which the statistics of the entire image are computed and binned into a number of groups chosen by the user that are statistically distinct.

In the realm of hyperspectral image analysis, the analyst often has some idea what the goal of classification is, the information can be used to deinfe, steer and supervise the targets being classified, hence favoring the methodology of supervised classification. The techniques discussed below outline some of the recent advances and accepted methods of hyperspectral data processing, but are by no means limited to only them.

6.3.1 Spectral hourglass method

One of the most-often used analysis/interpretation methods is the “spectral hourglass method” in ways to find pixels that represent spectral end members (Kruse et al., 2003). The Spectral hourglass method provides a consistent way to extract spectral information from hyperspectral data without a priori knowledge or requiring ground observations. Key point of the methodology is the reduction of data in both the spectral and spatial dimensions to locate, characterize, and identify a few key spectra (endmembers) in the hyperspectral image data that can be used to explain the rest of the hyperspectral dataset. Once the endmembers are selected, their location and abundances can be mapped from the linearly transformed or original data. These methods derive the maximum information from the hyperspectral data themselves, minimizing the reliance on a priori or outside information. The hour-glass method heavily relies on the Pixel Purity Index (PPI) computation and spectral dimensionality analysis described by Boardman et al. (1995) can be used to find spectrally “pure” pixels (target spectra), which represent compositionally distinct areas (Kruse, 1988; Boardman and Kruse, 1994; Kruse et al., 1996). The approach significantly reduces the number of pixels that need to be searched for mineralogic spectral information, but it also finds pixels that are not necessarily of geologic interest e.g. urban/ cultural features, and vegetation. The second method is similar, except the pure pixels are chosen by defining regions of interest around obvious geologic targets (e.g., non-vegetated and non-urban areas) and these pixel spectra were viewed as points in n-dimensional space to select the outliers (Vaughan, 2004). Each spectral end member is used as a target spectrum, to "train" the pixel classification method described next. The derived endmember pixels are classified using two different supervised classification methods: 1) Spectral Angle Mapper (SAM) (Kruse et al., 1993) and Mixture Tuned Matched Filtering (MTMF) (Boardman et al., 1995).

SAM classifies pixels together based on their spectral similarity by treating spectra as vectors in n-dimensional space and calculating the angle between them. Spectral Angle Mapper differs from standard classification methods, because it compares each pixel in the image with every endmember for each class and assigns a ponderation value between 0 (low resemblance) and 1 (high resemblance) (Girouard et al., 2004). SAM measures spectral similarity by calculating the angle between the two spectra, treating them as vectors in an n-dimensional space: small angles between two spectra indicate high similarity. The method is not affected by solar illumination factors, because the angle between the two vectors is independent of the vectors length (Crósta et al., 1998).

SAM has been used successfully in the past for geological mapping and for identifying potential mineral exploration sites, using the USGS Spectral Library as reference spectrum (Crósta et al., 1998).

The MTMF method generates proportional spectral end member abundance maps based on partial unmixing of image target spectra (Boardman et al., 1995). For each end member mapped, a region of interest (ROI) is defined by selecting a threshold range of values from the abundance maps that corresponded to the highest abundance. In the approach, only the user-defined targets are mapped where the pixel value in the output image is proportional to the fraction of the pixel that contains the target material. Any pixel with a value of 0 or less would be interpreted as a “background.” The MTMF also derives an “infeasibility” image, which is based on both noise and image statistics and indicates the degree to which the matched-hit is a feasible mixture of the target and the background. Pixels with the high infeasibility are likely to be false positives, and can be eliminated from the classification.

An alternate method, described by Coulter (2006) is using shape based classification and partial unmixing. The spectral curve similarity classification is obtained by using Spectral Correlation Mapper (SCM) (de Carvalho and Meneses, 2004). A partial unmixing of the spectral data is performed using Optimized Cross Correlation Mixture analysis (OCCM) (Coulter, 2006) while the particular absorption band position analysis is performed using Gaussian fitting (Brown, 2006). The SCM algorithm is implemented by using library spectra of the candidate observables; the “best” locations identified by SCM are inspected in the image; and the best image endmembers are identified and extracted.

6.3.2 Non-Gaussian methods

A somewhat opposite approach is to develop techniques from a hyperspectral imagery viewpoint where noise is generally considered as a non-Gaussian element and interference plays a more dominant role than apparent noise in hyperspectral image analysis. More importantly, the detection and classification is performed and carried out by targets of interest rather than pattern classes. Stemming from the principle that the end-members define the simplex of greatest volume is the underlying basis for this algorithm. The rotation of the data cloud, which is the main component in a traditional method does not change the identity of the end-members, which is of paramount importance since it allows the use of orthogonal subspace projections (OSPs) for the reduction of hyperspectral image dimensionality (Harasanyi and Chang, 1994) . Dimension reduction via OSP (i.e. Principal Components transform, MNF transform, or singular value decomposition) is considered necessary to reduce the overall number of bands in an image to be one less than the final number of end-members sought. The algorithm views the hyperspectral image as a mixture of several mutually exclusive classes. Each of these classes is described by a linear combination of independent components with non-Gaussian (sub-Gaussian or super-Gaussian) probability density functions and in turn allocating particular endmember into a particular class on the basis of probability. There are variations of the non-linear method, such as Constrained Energy Minimization (CEM) which take advantage of particular image endmember elements rather than the entire set of image endmembers, thereby minimizing the need for a-priori knowledge of observable characteristics (Harsanyi, 1993; Farrand and Harsanyi, 1997). The CEM approach is preferred over other multi-dimensional algorithms because the intent is to classify all of the pixels in an unknown hyperspectral scene. The other OSP target detectors are only effective against small targets. In other words, an advantage of CEM is that the low occurrence constraint required by the other detectors is eliminated. The primary disadvantage is that the dominant subspace is not completely eliminated as in some of the other tools (e.g. Dominant Subspace Project detection).

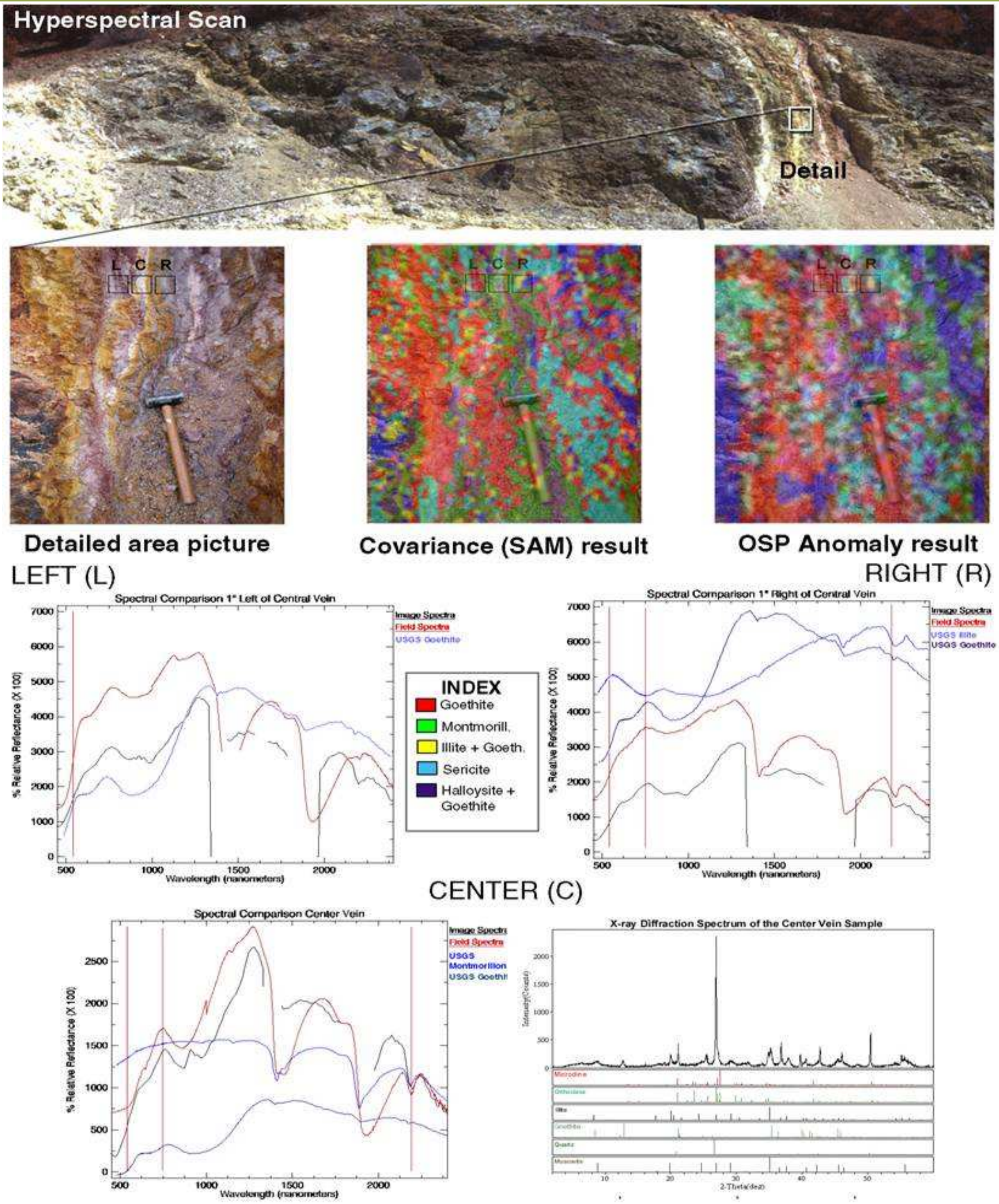

Figure 21 – Differences in covariance and CEM-based analysis of hyperspectral data (from Smailbegovic et al., 2005).

6.3.3 Sub-pixel classification

The sub-pixel classification procedure tries to reveal possible mixtures of classes and defines for each pixel the area fractions covered by the different cover types. A number of fuzzy classification techniques have been investigated for this purpose with the most widely used being Artificial Neural Networks (ANN) (Atkinson et al., 1997) (see 5.2.3) and Spectral Mixture Analysis (SMA) (Adams et al., 1993). The major advantage of an ANN is that it is able to address non linear mixing effects caused by multiple scattering of photons (Mas et al., 2004). The disadvantages of ANN's are the requirement of obscure initialization values (Varshney et al., 2004) and their sensitivity to ill-posed problems (Kulkarni et al., 1991). ANN's moreover act as a black box (Benitez et al, 1997) and are very computer and time intensive. On the contrary, SMA is directly driven by the physically explicit mixture models. Linear SMA techniques first identify a collection of spectrally pure constituent spectra or endmembers (VanderMeer et al., 1995, Lobell et al., 2004). Each measured spectrum of a mixed pixel is then expressed as a linear combination of endmembers weighed by fractions or abundances that indicate the proportion of each endmember present in the pixel (Adams et al., 1993). The abundances are typically estimated using the least squares estimation (LSE) method (Barducci et al., 2005). The quality of the endmembers will as such drive the success of the unmixing approach. Pure spectra can be obtained by spectrally measuring different ground cover materials in the field or laboratory, or automatically extracting them from the imagery. The most widely used automatic techniques for endmember extraction include the pixel purity index algorithm (Boardman et al., 1993), the N-FINDR software (Winter et al., 1999), or the iterative error analysis algorithm (Neville et al., 1999). A number of new endmember extraction methods are presented (Sequential Projection Algorithm (Zhang et al., 2008), Vertex Component Analysis (Nascimento et al., 2005), Sequential Maximum Angle Convex Cone (Gruninger et al., 2004), Iterated Constrained Endmembers (Berman et al., 2004), Simplex Growing Algorithm (Chang et al., 2006)).

6.3.4 Wavelet transforms

Wavelet transforms have been increasingly used for dimensionality reduction (Bruce et al., 2002). A wavelet is a mathematical function used to divide a continuous spectral signal into different frequency components and study each component with a resolution that matches its scale. Wavelets have advantages over traditional Fourier transform for representing functions that have discontinuities and sharp peaks. Wavelets also have advantages for deconstructing and reconstructing a signal. Discrete Wavelet Transform (DWT) and Continuous Wavelet Transform (CWT) are two types of wavelet transformations. Salvador (2008) illustrated that the application of the wavelet packet transform to the spectral space of hyperspectral and ultra-spectral imagery data improved the computational tractability and the detection of trace gases in airborne and spaceborne spectral imagery.

6.3.5 Classification tools for Gamma-ray data

The most common approach for interpretation of gamma-ray data is to produce a ternary plot for the three elements K, eU and eTh (Figure 22). The common ratios are U/Th and Th/K which tend to highlight particular emissive characteristics. Better visual interpretation can often be achieved when integrating the ternary radioelement map with other data, such as optical satellite, radar or digital elevation data (see Figures 23a-f). Subtle variations in the measured radio-elements can be enhanced using maps of ratios of the different elements. For example, the ratio Th/U has important applications to mineral exploration and for mapping igneous intrusions and potassic alteration (Dickson et al., 2004). This ratio may be used to discriminate between different magmatic rocks. K/Th ratios can be used as indicator for the degree of weathering within saprolite profiles (Carrier-2006), as well as detection of K-alteration (GSC-2007). Huston et al (1998) use these ratios to map both primary geological features and alteration facies in Massive Sulphide districts (Figure 24). De Quadros et al.(2003) used a variety of ratios to map hydrothermal alteration related to lode gold deposits in Brazil. Andreoli et al (2006) use several ratios to characterize different metamorphic grades in the Western Namaqualand Belt, South Africa

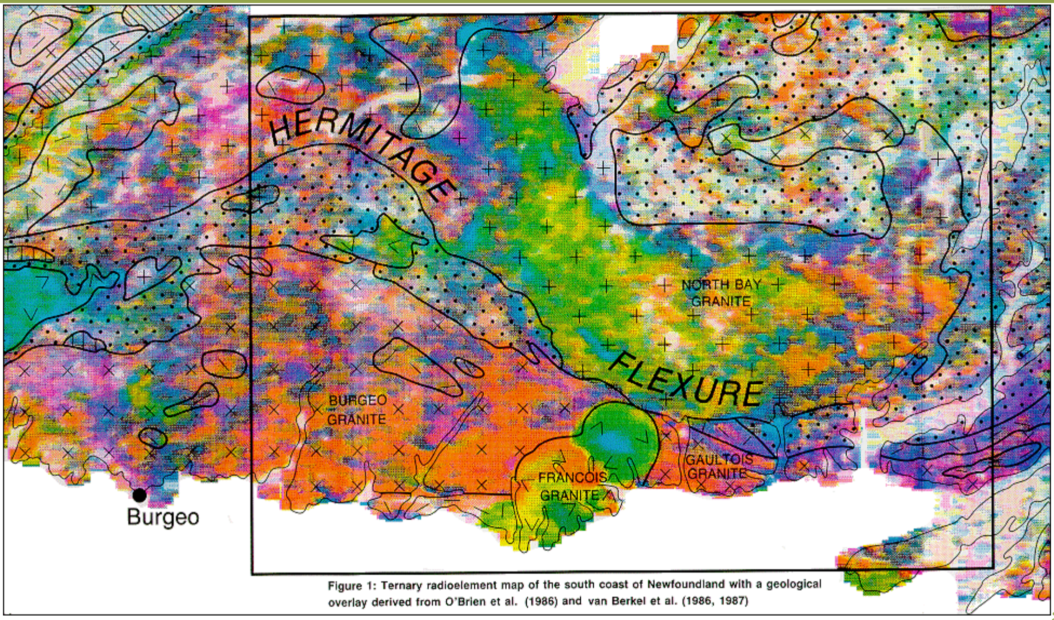

Figure 22 – Ternary radioelement map of the south coast of Newfoundland. Courtesy: Natural Resrouces Canada - *http://gsc.nrcan.gc.ca/gamma/appgeo_e.php*

However, with the greater use of additional spectral information derived from the gamma-ray channels using the full-spectrum analysis, some of the image-statistical tools can also be implemented to obtain additional information from the data. Principal component analysis (of wich the so called MNF is a special case, often and used to remove noise from the data) is an effective way to enhance the visibility of subtle variations in gamma-ray data. The technique can be applied to both conventional three-channel K-U-Th data (IAEG, 2003) and to multi-channel radiometric data (Minty, 1998).

Multivariate analysis techniques such as Supervised and Unsupervised classification provide powerful means to understand the information contained in the data, both with respect to the spatial and spectral patterns relationships that exist within the dataset (IAEG-2003). This is instrumental to the understanding of the meaning of the data in terms of processes such as geology, hydrothermal alteration, erosion, weathering, regolith formation, soil degradation, environmental impact, etcetera. Good examples of such classifications are provided by e.g. Anderson (1998), Martelet et al (2006), Roberts et al (2004), Goossens (1992).

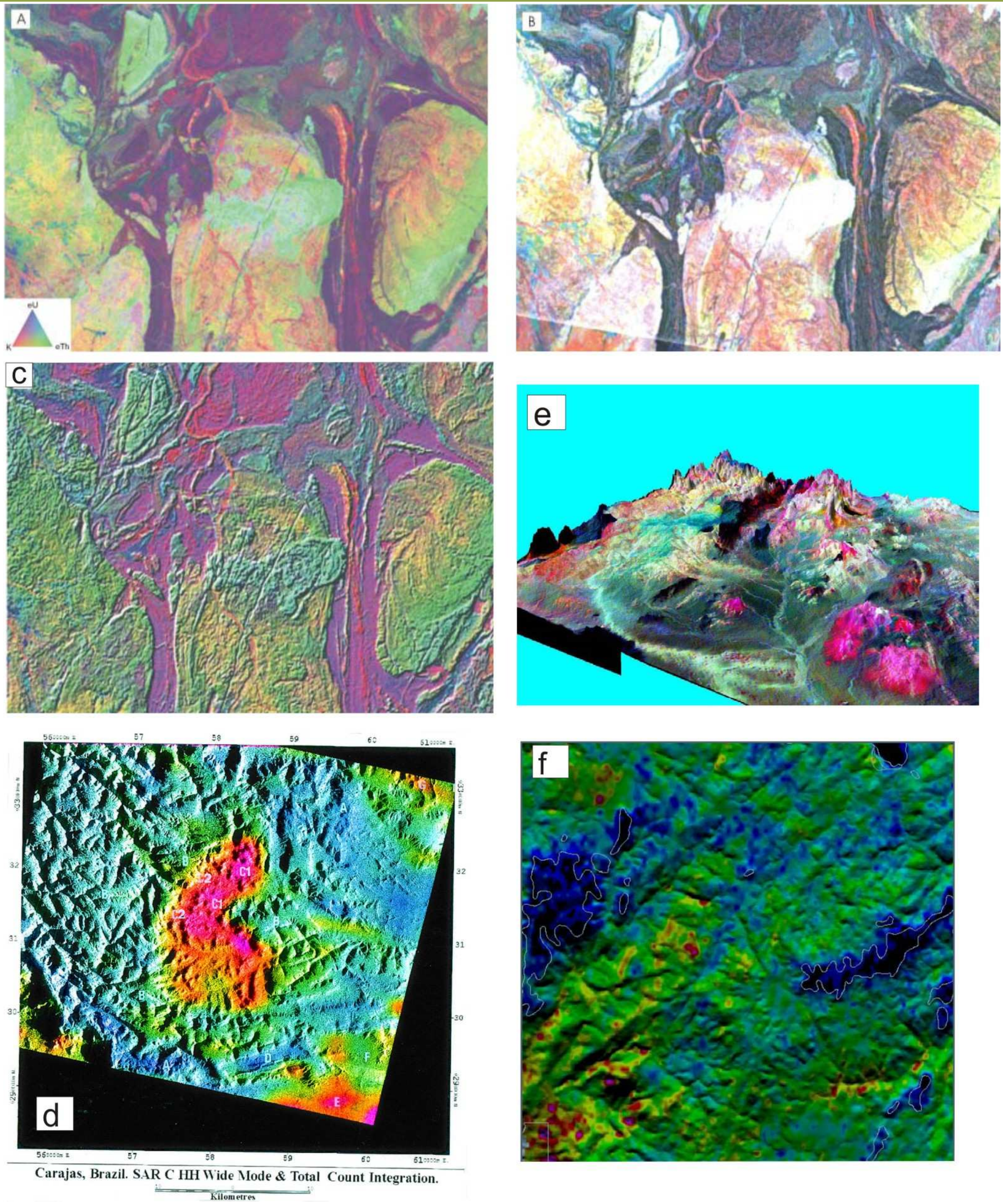

Figure 23a - Ternary relative radio-element abundance map; **b -** Image sharpened with high-pass filtered Landsat band TM5; **c**- Image integrated with relief shaded total count data (IAEA, 2003); **d-** Airborne SAR/gamma total count integrated product (Paradella et al., 1997); **e-** Combined gamma-ray ternary image with DEM as 3D-perspective enables the visualisation of complex relationships between the gamma-ray response and terrain morphology attributes (Wilford et al., 2002); **f-** Airborne potassium overlain on a hillshaded DEM for in a forested area near Batlow, NSW. Outlined dark blue areas correspond to basalt flows (Bierwirth et al., 1999)

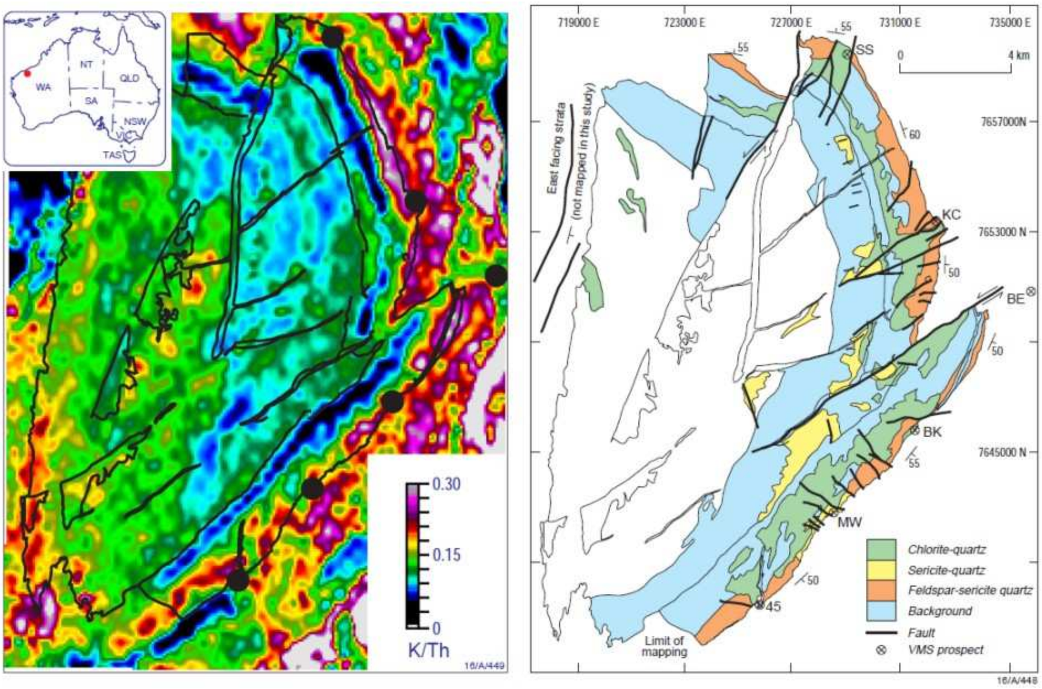

Figure 24 – Maps of the Panorama Massive Sulphide district with distribution of alteration facies (right) and the K/Th ratio from airborne Gamma-ray spectrometric data; from Huston et al. (1998)

6.3.6 Data Integration

The term "horizontal-data integration" is a more accepted term than the "data-fusion" commonly used before to denote methodology of employing combination of multi-source data to derive particular set of observables used in target detection. The main reason is that no data is actually fused, but is integrated in the variety of layers or defined observables to accurately account for all of the imaged target characteristics (e.g. shape, texture, spectral features). The need to seamlessly integrate various datasets stems from the increasing types of sensing systems used, differences in spatial, spectral and radiometric resolution and the modes of acquisition (active, passive, nadir-looking, off-nadir, horizontal etc.). Integrating remotely sensed data, especially multi-source remains challenging particularly in regards to viewing geometry, nature of the target observed and characteristic observables that may or may not be present under all observation conditions. Detailed discussion of horizontal data integration is presented in D4.1, §5.5.

The primary path of data integration presented in the ImpactMin project revolves along merging multispectral/hyperspectral satellite with airborne hyperspectral data, and to a lesser extent merging airborne hyperspectral with gamma-ray spectroscopic data. The primary concerns are the issues of scale/resolution and their effects on the detectability of particular targets. In any data integration, being able to resolve particular targets in varying imaging parameters becomes of crucial importance. Smailbegovic (2006) has presented a study on analyzing available radiance and reflectance data (and ancillary sets) on ProSpecTIR, HyperSpectir (HST), HyMap, Low and High altitude AVIRIS and Hyperion hyperspectral data over a cross-correlated discrete target-area present in all of the sets gathered in the geospatial database (i.e. *Buddingtonite Bump* area in Cuprite, NV). The goal was to demonstrate at what spatial or spectral resolution, comparable to the available sensor data, the target signal would become overwhelmed by the noise. However, it was demonstrated that the majority of hyperspectral sensors produce comparable results and can identify characteristic signature of buddingtonite mineral at spatial resolutions ranging from 1m to 30m, sampling interval ranging from 5 to 16nm and airborne to spaceborne mode of operation. Furthermore, it was demonstrable that the same area yielded very similar results regardless of airborne imager used. Improved spatial resolution allows for the spectrally unique areas to be resolved and constrained better, while improved spectral resolution allows for sub-classification of a particular endmember with regards to minute differences in the type, purity, composition, but also illumination, imaging geometry and so on.

In the course of ImpactMin project, the intent is to repeat this detectability threshold over variety of sensing systems used and determine at what spatial/spectral resolution the particular target observable disappears or becomes enhanced with an influx of an additional data element.

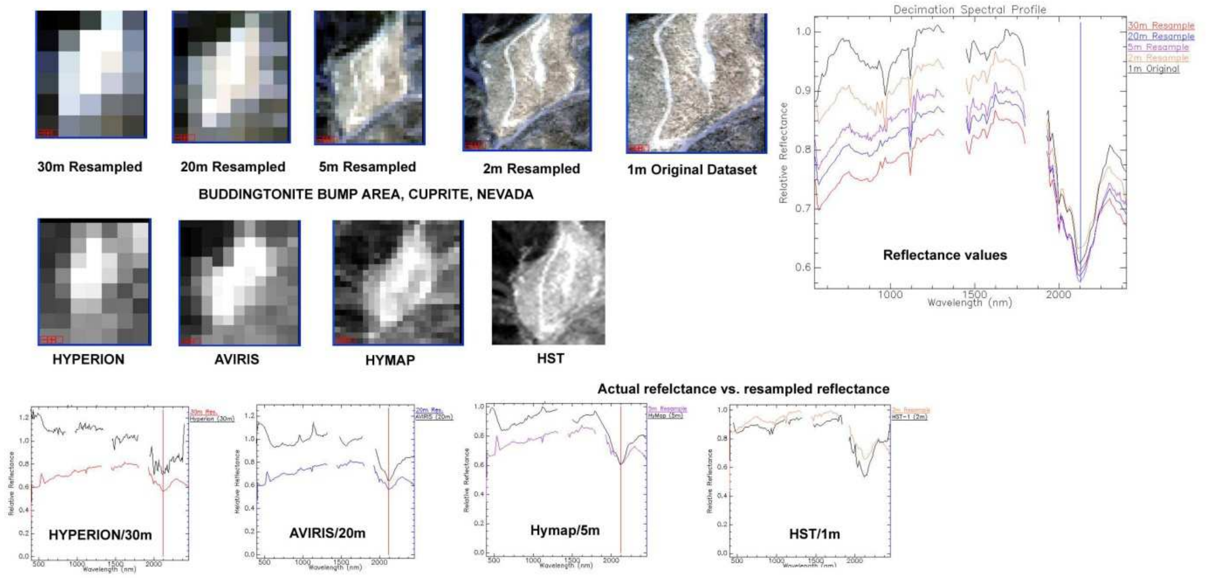

Figure 25 – Analysis of target detectability as a function of spatial and spectral resolution: important parameters in any data-integration (adapted from Smailbegovic, 2006).

7. Conclusions

The imaging and analysis of environmental factors related to mineral extraction with airborne HSI/GRS remote sensing is a complex task of resolving targets and observable characteristics coupled with the inherent dimensionality of spectral data. Ultimately, the ability to resolve the subtle indicators and clues is directly proportional to the quality of data collected, but also the premises and parameters determined in data acquisition and analysis. In conjunction with all other available methods, the airborne spectral imagery yields the highest score in the quantity and usability of data collected. Furthermore, by using the sheer quantity and redundancy of HSI/GRS data, it is possible to increase the level of confidence in target unmixing and detection, reinforcing the advantage over other sensing methods in the terms of confidence, time and overall cost effectiveness. Therefore, the airborne component fills the important niche situated between in-situ measurements and spaceborne sensing.

The main advantages of the airborne approach is the ability to resolve the surface detail in high spatial and spectral resolution, over relatively wide area and low-to-moderate overall cost of acquisition. These qualities make it increasingly popular with the industry in appraising mineralization potential of the area, types of surface cover, distribution of pollutants, anomaly identification and search/recovery. The spectral information provides a fairly robust approach in extrapolating composition of the particular imaged target and its classification or isolation from the background.

The main disadvantages of the approach are the requirements for nearly ideal acquisition conditions: clear weather and abundant sunlight for hyperspectral and low/level-flight for gamma ray sensors. The secondary disadvantages are the relatively high cost of mobilization and the amount of data generated that requires considerable technical proficiency in analysis and interpretation.

Some of these obstacles can be tackled by using novel methods in acquisition (e.g. use of unmanned aircraft, smaller sensors etc.), but also in supporting the airborne data with other types of in-situ or satellite data to achieve better calibration, in-fill the coverage gaps, or most importantly precisely target the airborne data to the areas where increased spatial/spectral detail is required.

The study sites presented in this report present an ideal testing ground in appraising capabilities of an integrated airborne collection approach with the other types of data because of their environmental diversity, presence of particular signatures characteristic of mineral exploration and exploitation and different strategies required or available to collect the necessary information.

8. References/Works Cited:

Adams, J., Smith, M. and Gillespie, A., 1993. Imaging spectroscopy: interpretation based on spectral mixture analysis. In: C. Pieters and P. Englert (Editors), Remote Geochemical Analysis, Topics in Remote Sensing 4. Cambridge University Press, U.K., pp.145-166.

Adler-Golden, S.M., M.W. Matthew, L.S. Bernstein, R.Y. Levine, A. Berk, S.C. Richtsmeier, P.K. Acharya, G.P. Anderson, G. Felde, J. Gardner, M. Hoke, L.S. Jeong, B. Pukall, A. Ratkowski and H.K. Burke, 1999, "Atmospheric Correction for Short-wave Spectral Imagery Based on MODTRAN4," in Summaries of the Eighth Annual JPL Earth Science Workshop, Vol. I, available at http://makalu.jpl.nasa.gov.

Anderson-Mayes, A.M., 1998; Simple spatial analysis of complex multivariate airborne geophysical data. http://www.geocomputation.org/1998/29/gc_29.htm

Andreoli M.A.G., Hart, R.J., Ashwal, L.D., Coetzee, H. 2006, Correlations between U, Th content and metamorphic grade in the Western Namaqualand Belt, Soth Africa, with implications for radioactive heating of the crust/ Journal of Petrology 47:6, 1095-1118

Aoki, M., Yabuki, K., and Totsuka, T. 1981, An evaluation of chlorophyll content of leaves based on the spectral reflective ity in several plants. Res. Rep. Natl. Inst. Environ. Stud. Jpn. 66:125–130.

Arthur, J., Leone, I., & Flower, F. 1985. The response of tomato plants to simulated landfill gas mixtures. Journal of Environmental Science and Health, A20(8), 913-925.

Asner, G.P., Hicke, J.A. and Lobell, D.B., 2003. Remote sensing of forest environments: concepts and case studies. Kluwer Academic Publishers.

Atkinson, P. and Tatnall, A., 1997. Introduction - Neural networks in remote sensing. International Journal of Remote Sensing, 18(4): 699-709.

Baresel C., Destouni G., Diffuse subsurface zinc loads from mining areas in the Dalälven River Basin, Sweden, Hydrology Research, 40(5), 445-453,doi:10.2166/nh.2009.013, 2009

Baresel C., Destouni G., Uncertainty-Accounting Environmental Policy and Management of Water Systems, Environ. Sci. Technol., 41(10), 3653–3659, doi:10.1021/es061515e, 2007

Baresel C., Destouni G., and Gren I.M., The influence of metal source uncertainty on cost-effective allocation of mine water pollution abatement in catchments, Journal of Environmental Management, 78(2), 138-148, 2006

Barisic, D., Lulic, S., & Miletic, P. 1992. Radium and uranium in phosphate fertilizers and their impact on the radioactivity of waters. Water Research, 26, 607±611

Baugh, W.M. and Groeneveld, D.P. 2008. Empirical proof of the empirical line. International Journal of Remote Sensing, 29:3, p.665-672.

Bedell, R.L. 2004. Remote Sensing in Mineral Exploration; Society of Economic Geologists Newsletter, Number 58, July, 2004, 8 p.

Benitez, J. M., Castro, J. L., and Requena, I., 1997, Are artificial neural networks blackboxes? IEEE Transactions on Neural Networks, 8, 1156–1164.

Berk, A., L.S. Bernstein, G.P. Anderson, P.K. Acharya, D.C. Robertson, J.H. Chetwynd, and S.M. Adler-Golden, 1998, "MODTRAN Cloud and Multiple Scattering Upgrades with Application to AVIRIS,' Remote Sens. Environ., 65, 367-375.

Berman, M., Kiiveri, H., Lagerstrom, R., Ernst, A., Dunne, R. and Huntington, J., 2004. ICE: an automated statistical approach to identifying endmembers in hyperspectral images. IEEE Transactions on Geoscience and Remote Sensing, 42: 2085-2095.

Bierwirth PN, Aspin SJ, Ryan PJ, McKenzie NJ, 1999; Gamma-ray remote sensing of soil properties in a forested area near Batlow, NSW

Bierwirth PN, Brodie RS, 2005; Identifying acid sulfate soil hotspots from airborne gamma-radiometric data and GIS analysis; Australian Governmnet-Bureau of Rural Sciences report.

Billings S, Hovgaard J, 1999; Modelling detector response in airborne gamma-ray spectrometry. Geophysics, 64 (5) 1378-1392

Boardman, J.W., 1993, “Automated Spectral Unmixing of AVIRIS Data Using Convex Geometry Concepts,” in Summaries, Fourth JPL Airborne Geoscience Workshop, JPL Publication 93-26, v. 1, pp. 11-14.

Boardman J.W. and Kruse, F.A. 1994. Automated spectral analysis: A geologic example using AVIRIS data, north Grapevine Mountains, Nevada. Proccedings of the 10th Thematic conference on Geologic Remote Sensing, Environmental Research Institute of Michigan, Ann Arbor, MI., p.407-418.

Boardman, J.W., Kruse, F.A. and Green, R.O.. 1995. Mapping target signatures via partial unmixing of AVIRIS data: Summaries of the 5th Airborne Earth Science Workshop, JPL Publication 95-1, v.1., p23-26.

Bodorkos S, Sandiford M, Minty BRS, Blewett RS 2004; A high resolution, calibrated airborne radiometric dataset applied to the estimation of crustal heat production in the Archaean northern Pilbara Craton, Western Australia. Precambrian Research 128, 57- 82

Boero, V. & Schwertmann, U. 1989: Iron oxide mineralogy of terra rossa and its genetic implications.– Geoderma, 44, 319–327.

Booth CJ, 2002, The effects on long-wall mining on overlying aquifers, Mine water hydrology and geochemistry, Geological Society, London, Special publication, 198: 17-45.

Thinova, L., Cechak, T., Kluson, J., Trojek, T., 2006. Use of Gamma Spectro- metry Method for Environmental Monitoring in the Area of NPP. Journal of Physics: Conference Series, vol. 41, no. 4, London, pp. 569–572, ISSN 1742-6596.

Bruce, L. M., C. H. Koger, and J. Li. 2002. Dimensionality reduction of hyperspectral data using discrete wavelet transform feature extraction. *IEEE Trans. Geoscience and Remote Sens* 40(10): 2331-2338.

Buschman, C. and Nagel, E., 1993. In vivo spectroscopy and internal optics of leaves as a basis for remote sensing of vegetation.International Journal of Remote Sensing, 14: 711-722.

Carrier F, Bourdon B, Pili E, Truffert C, Wyns R 2006; Airborne gamma-ray spectrometry to quantify chemical erosion processes. Journal of Geochemical exploration 88, 266-270

de Carvalho, O.A. and Meneses, P.R. (2000). Spectral Correlation Mapper (SCM); An Improvement on the Spectral Angle Mapper (SAM). Summaries of the 9th JPL Airborne Earth Science Workshop, JPL Publication 00-18, 9 p.

Carter, G.A., 1994. Ratios of leaf reflectances in narrow wavebands as indicators of plant stress. International Journal of Remote Sensing, 15: 697-703.

Campbell, D.L., Horton, R.J., Bisdorf, R.J., Fey, D.L., Powers, M.H., Fitterman, D.V. 1999. Some geophysical methods for tailings/mine waste work. In Tailings and Mine Waste ‘99 – Proceedings of the Sixth International Conference on Tailings and Mine Waste, Fort Collins, CO, January 24-27,1999. Rotterdam, A.A. Balkema, p. 35-43.

Campbell, D.L., Fitterman, D.V. 2000. Geoelectrical methods for investigating mine dumps. In Proceedings of the Fifth International Conference on Acid Rock Drainage. SME, Littleton, CO. p. 1513-1524.

Carter, G.A. 1994. Ratios of leaf reflectance in narrow wavebands as indicators of plant stress. International Journal of Remote Sensing, 15, 697-703.

Chang, C.-I., Wu, C.-C., Liu, W.-W. and Ouyang, Y.-C., 2006. A new growing method for simplex-based endmember extraction algorithm. IEEE Transactions on Geoscience and Remote Sensing, 44(10): 2804-2819.

Chevrel, S., 2005. MINEO two years later - did the project impulse a new era in imaging spectroscopy applied to mining environments? In: Proceedings of the 4th Workshop on Imaging Spectroscopy, Imaging Spectroscopy. New quality in environmental studies. 26-29 April 2005,Warsawa, pp. 389-395.

Clark, R.N., Swayze, G.A., Hoefen, T.M., Livo, K.E., Sutley, S.J., Meeker, G.P., Plumlee, G.S., Brownfield, I.K., Hageman, P.L., Lamothe, P, Gent, C., Morath, L.C., Taggart, J., Theodorakos, P.M., Adams, M., Green, R.O., Pavri, B., Sarture, C., Vance, J.S., and Boardman, J., 2003, Environmental mapping with imaging spectroscopy of the World Trade Center area after the September 11, 2001 attack, in Natural science and public health; prescription for a better environment; conference abstracts: U.S. Geological Survey Open-File Report 03-0097,p. 49.

Clark, R.N., Swayze, G.A., Heidebrecht, K.B., Goetz, A.F.H., and Green, R.O. 1993, Comparison of methods for calibrating AVIRIS data to ground reflectance. InSummaries of the Fourth Annual JPL Airborne Geoscience Workshop (R.O. Green, Ed.), JPL Publ. 93-26, Jet Propulsion Laboratory, Pasadena, CA, pp. 35-36.

Clark, R.N., Swayze, G.A., Heidebrecht, K.B., Green, R.O., and Goetz, A.F.H. 1995, Calibration to surface reflectance of terrestrial imaging spectrometry data: Comparison of methods. In Summaries of the Fifth Annual JPL Airborne Earth Science Workshop (R.O. Green, Ed.), JPL Publ. 95-1, Jet Propulsion Laboratory, Pasadena, CA, pp. 41-42.

Clark, R.N. 1999, Chapter 1: Spectroscopy of Rocks and Minerals and Principles of Spectroscopy, Manual of Remote Sensing (Invited), (A.N. Rencz, ed.) John Wiley and Sons, New York, p 3- 58.

Clark, Roger N; Swayze, Gregg A; Gallagher, Andrea J; King, Trude V V; Calvin, Wendy M. The U.S. Geological Survey digital spectral library; version 1:0.2 to 3.0 µm. Open-File Report - U. S. Geological Survey, Report: OF 93-0592, 1326 pp., 1993

Clark, R.N., Swayze, G.A., Heidebrecht, K.B., Green, R.O., and Goetz, A.F.H. 2002, Calibration to surface reflectance of terrestrial imaging spectrometry data: A Tutorial using AVIRIS. AVIRIS Workshop Proceedings, 2002: http://speclab.cr.usgs.gov/PAPERS.calibration.tutorial

Clevers, J.G.P.W., 1989. The application of a weighted infrared-red vegetation index for estimating leaf area index by correcting for soil moisture. Remote Sensing of Environment, 29: 25-37.

Coutzee H, Larkin J, 2009; Application of the airborne radiometric method in radiation protection applications. 11th SAGA Biennial Technical Meeting and Exhibition Swaziland, 16-18 September 2009, 453-455

Coulter, D.W., Hauff, P.L and Peppin, W. 2008. The use of high spatial and spectral resolution airborne imagery for alteration mapping and waste characterization at the Comstock Lode, Nevada. IGARSS 2008. www.igarss08.org/Abstracts/pdfs/3657.pdf

Crósta, A. and de Souza Filho, C., 2005. Remote sensing in mineral exploration: South American examples of benefits gained from recent advances in sensor and processing techniques. In: H. Rhoden, R. Steininger and P. Vikre (Editors), Window to the World. Geological Society of Nevada, Reno, Nevada, USA

Crosta, A.P., Sabine, C. and Taranik, J.V. 1998. Hydrothermal Alteration Mapping at Bodie,California, using AVIRIS Hyperspectral Data.Remote Sensing of Environment, Vol. 65, p. 309-319.

Crowley, J.K., Williams, D.E., Hammarstrom, J.M., Piatak, N., Chou, I-M. and Mars, J.C., 2003. Spectral reflectance properties (0.4–2.5 m) of secondary Fe-oxide, Fe-hydroxide,and Fe-sulphate-hydrate minerals associated with sulphide bearing mine wastes. Geochemistry: Exploration, Environment, Analysis, 3- 3, pp. 219-228(10).

Curran, P. J., Dungan, J. L., Macler, B. A., and Plummer, S. E. (1991), The effect of a red leaf pigment on the relationship short-wave infrared region.. Remote- Sens. Environ. 35:69–75.

Curtiss, B., AND A. F. H. Goetz. 1994. Field spectrometry: Techniques and instrumentation, p. 195–203. In R. B. Gomez [ed.], Proc. Int. Symp. Spectral Sens. Res.

De Meijer, R. J. (1997). Heavy Minerals: From 'Edelstein' to Einstein. Journal of Geochemical Exploration, 62(1-3): 81-103.

Deronde, B., Kempeneers, P. and Forster, R., 2006. Imaging spectroscopy as a tool to study sediment characteristics on a tidal sandbank in the Westerschelde. Estuarine, Coastal and Shelf Science, 69: 580-590.

Diakow LJ, Shivers RBK 2003; Geoscience parnership in the Toodoggone river and McConnell Creek map areas, North Central British Columbia. Contribution of the Federal-Provincial Targeted Geoscience Initiative-II (TGI-II)

Dickson BL 2004; Recent advances in aerial gamma-ray surveying. JOurnal of environmental radioactivity 76. 225-236

Durn, G., Slovenec, D. & Čovic, M. 2001: Distribution of iron and manganese in Terra Rossa from Istria and its genetic implications.– Geologia Croatica, 54/1, 27–36

Elmore, A. and Mustard, J., 2003. Precision and accuracy of EO-1 Advanced Land Imager (ALI) data for semiarid vegetation studies. IEEE Transactions on Geoscience and Remote Sensing, 41: 1311-1320.

Elvidge, C.D. and Chen, Z., 1995. Comparison of broad-band and narrow-band red and near-infrared vegetation indices. Remote Sensing of Environment, 54: 38-48.

ERMITE Consortium. 2004. Mining Impacts on the Fresh Water Environment: Technical and Managerial Guidelines for Catchment Scale Management. Younger, P.L. & Wolkersdorfer, C. (eds). Mine Water and the Environment 23A: S2-S80

Farrand, W.H. and Harsanyi, J.C. 1995. Mineralogic Variations in Fluvial Sediments Contaminated by Mine Tailings as Determined From AVIRIS Data, Coeur d'Aldene River, Idaho. AVIRIS Workshop, pp. 47-50, JPL Publication.

Farrand, W.H., and J.C. Harsanyi, 1997, "Use of a Modified Constrained Energy Minimization Technique to Map Ferruginous Sediments Along The Alamosa River, Colorado", Twelfth International Conference and Workshops on Applied Geologic Remote Sensing, Denver, Colorado, 17-19 November 1997, Vol.2, pp. 385-392.

Farrand, W., Stewart, R. and Vance, L., 1999. Preliminary results from a comparative mapping analysis in the Tintic Mining District using AVIRIS and ESSI-PROBE 1 data.

Fichtner consortium. Feasibility Study, November 2006, KfW Bankengruppe, City of Mostar Rehabilitation of the Coal Mining Complex Vihovici in Mostar - Bosnia and Herzegovina, Preparatory Stage Report

Girouard, G., Bannari, A., El-Harti, A, and Desrochers, A. (2004) Validated Spectral Angle Mapper for Geological Mapping: Comparative Study Between High and Medium Spatial Resolutions. ISPRS, Istanbul, Turkey, 10-23 July 2004, Actes sur CD, papier-599, commission-7.

Gitelson, A., 2004. Wide dynamic range vegetation index for remote quantification of crop biophysical characteristics. Journal of Plant Physiology, 161: 165-173.

Gitelson, A., Gritz, Y. and Merzlyak, M., 2003. Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll assessment in higher plant leaves. Journal of Plant Physiology, 148: 271-282.

Gitelson, A., Kaufman, Y., Stark, R. and Rundquist, D., 2002. Novel algorithms for remote estimation of vegetation fraction. Remote Sensing of Environment, 80: 76-87.

Gitelson, A.A. and Merzlyak, M.N., 1998. Remote sensing of chlorophyll concentration in higher plant leaves. Remote Sensing of Environment, 22: 689-692.

Gitelson, A.A. and Merzylak, M.N. 1994. Quantitative estimation of chlorophyll-a using reflectance spectra: Experiments with autumn chestnut and maple leaves. Journal of Photochemical Phytobiology, 22, p. 247-252.

Goetz, A.F.H.1980. Geological Remote Sensing in the 1980s. In Remote Sensing in Geology. Barrys S. Seigal and Alan R. Gillespie, Ed.p.679-687. 1980.

Goetz, A.F.H., Vane, G., Solomon, J.E., Rock, B.N. 1985. Imaging spectrometry for earth remote sensing, Science, 228:1147-1153.

Goldshleger, N., Ben-Dor, E., Benyamini, Y. and Agassi, M. 2004. Soil reflectance as a tool for assessing physical crust arrangement of four typical soils in Israel. Soil Science, 169, pp. 677-687.

Godwin, R., Abouguendia, Z., & Thorpe, J. (1990). Response of soils and plants to natural gas migration from two wells in the Lloydminster area (No. E- 2510-3-E-90): Saskatchewan Research Council.

Goossens, MA 1992; Petrogenesis of the mineralozed granitic intrusion near Los Santos, Western Spain and Remote sensing and Data Integration as a tool in regional exploration for granite related mineralization. PhD-thesis GeologicaUltraiectina. ISBN 90-71577-43-0

Goossens MA 1994: in IAEA-tecdoc-782: Spatial data integration for mineral exploration, resource assessment and environmental studies; A guidebook. International Atomic Energy Agency, 151- 160

Götze, C. and Glässer, C., 2007. Detection of vegetation stress characteristics in the open cast lignite mining area Goitzsche/Central Germany using hyperspectral remote sensing data, 5the EARSeL Workshop on Imaging Spectroscopy, Bruges, Belgium.

Grasty, R.L., 1993 Environmental Monitoring by Airborne Gamma-ray Spectrometry, Experience at the Geological Survey of Canada; in Application of Uranium Exploration Data and Techniques in Environmental Studies, Proceedings of a Technical Committee Meeting, November 9-12, 1993, International Atomic Energy Agency, Vienna, IAEA TECDOC-827.

Grasty RL, Minty BRS 1995; A guide to the technical specifications for airborne gamma-ray surveys. Austrailan Geological Survey organisation. Record 1995/60

Gunn PJ, Minty BRS, Milligan PR 1997; The airborne gamma-ray spectrometric response over arid Australian terranes. In: Proceedings of Exploration97: Fourth decennial iInternational Conference on Mineral Exploration. Ed. Gubis AG. pp 733-740

Guogang Jia, Maria Belli, Umberto Sansone, et al., 2006. Concentration and characteristics of depleted uranium in biological and water samples collected in Bosnia and Herzegovina, in: *Journal of Environmental Radioactivity* Vol. 89 (2006), No. 2, p. 172-187

Harsanyi, J.C., 1993, "Detection and Classification of Subpixel Spectral Signatures in Hyperspectral Image Sequences",Ph.D. Dissertation, University of Maryland, Baltimore County, 116 pp.

Harsanyi, J. C. and C. -I. Chang, 1994. Hyperspectral image classification and dimensionality reduction: An orthogonal subspace projection, IEEE Transactions on Geoscience and Remote Sensing, vol. 32, pp. 779-789

Hauff, P., Coulter, D., Peters, D., Sares, M., Prosh, E., Henderson, F. and Bird, D., 2005. Using AVIRIS in the NASA BAA project to evaluate the impact of natural acid drainage on Colorado watersheds, 12th JPL Airborne Earth Science Workshop.

Hauff, P.L., D.C. Peters, G.A. Borstad, W.A. Peppin, E. Dillenbeck, L.G. Closs, and E.C. Prosh, 2000, Hyperspectral investigations of mine waste and abandoned mine lands – The Dragon calibration site case study, in Proceedings of the Ninth JPL AVIRIS Workshop, February 23-25, 2000, Pasadena, California: Jet Propulsion Laboratory.

Healy, G. and D. Slater, 1999, “Models and Methods for Automated Material Identification in Hyperspectral Imagery Acquired Under Unknown Illumination and Atmospheric Conditions,” IEE Trans. Geosci. Remote Sensing, Vol. 37, pp. 2706-2717.

Hendriks, P.H.G.M., Limburg, J. and de Meijer, R.J. 2001. Full-spectrum analysis of natural[gamma]-ray spectra. Journal of Environmental Radioactivity, 53: 365-380.

Hook, S.J.; Abbot, E.A.; Grove, C.; Kahle, A.B. and F. Palluconi, “Use of Multispectral Thermal Infrared Data in Geological Studies”, in Remote Sensing for the Earth Sciences: Manual of Remote Sensing, 3rd ed., vol. 3, A. N. Rencz, Ed., pp. 59-110, 1999.

Horler, D.N.H., Dockray, M. and Barber, J., 1983. The red edge of plant leaf reflectance. International Journal of Remote Sensing, 4: 273-288.

Hunt, Graham, R. 1980. Electromagnetic Radiation: The communication Link in Remote Sensing. In Remote Sensing in Geology. Barrys S. Seigal and Alan R. Gillespie, Ed.p.6-45. 1980.

Huston DL, Brauhart CW, Wellman P, Andrew AS 1998; Gamma-ray spectrometric and oxigen-isotope mapping of regional alteration halos in massive sulphide districts: an example from Panorama, centra Piblara Craton. AGSO Research newsetter 29

Hyvonene E, Turunen P, Vanahanen E, Arkimaa H, Sutinen R 2005; Airborne gamma-ray surveys in Finland. Geological Survey of Finland, special paper 39 119-134

International Atomic Energy Agency-tecdoc-1363, 2003; Guidelines for radioelement mapping using gamma-ray spectrometry data

Isaksson H, Thunbed H, Keisu M, 2004; Forsmark Site investigation. Intrpretation of airborne geophysics and integration with topography. Report Svensk Kämbränslehantering AB, Swedish Nuclear Fuel and waste management Co.

Ivan, K., Dusan, B., Franc, K., & Milos, V. 1990. Radionuclides in e.uent from coal mines, a coal fired power plant and a phosphatic fertilizer plant in Zasavje, Slovenia (Yugoslavia). Health Physics, 58, 81±85.

Jia G, Belli M, Sansone U, Rosamilia S, Gaudino S. 2006. Concentration and characteristics of depleted uranium in biological and water samples collected in Bosnia and Herzegovina. J. Environ.Radioactivity. 89: 172-187.

Jupp, D. L. B., Kirk, J. T. O. & Harris, G. P. 1994. Detection, identification and mapping of cyanobacteria. using remote sensing to measure the optical quality of turbid inland waters. Aust.
J. Mar. Freshwater Res., 45, 801.828.

Kancheva, R. and Borisova, D., 2008. Vegetation spectral response to stress conditions, Fundamental Space Research, Sunny Beach, Bulgaria.

Kettles IM, Rencz AN, Bauke SD 2000; Integrating Landsat, geologic and airborne gamma-ray data as an aid to surficial geology mapping and mineral exploration in the Manitouwadge area, Ontario. Photogrammetric Engineering and Remote Sensing 66 (4) 437-445

Kettunen MJ, Nikkinen MT 2005; Fixed-wing gamma measurement for the detection of radioactive materials. Journal of Radioanalytical and Nuclear Chemistry 263 (1) 241-243

Kljajić R., Mašić Z., Žunić Z., Pavlović S., Tošić M., Mandić M., Gordanić V., Polić P.: Natural radionuclide emission from a coal power plant and the population exposure to external radiation in its vicinity.Environment International, 22, Suppl.1, S227-S235, 1996 , R51 5,0

Kruse, F. A., 1988, Use of Airborne Imaging Spectrometer data to map minerals associated with hydrothermally altered rocks in the northern Grapevine Mountains, Nevada and California: Remote Sensing of Environment, V. 24, No. 1, p. 31-51.

Kruse, F. A., and Lefkoff, A. B., 1993, Knowledge-based geologic mapping with imaging spectrometers: Remote Sensing Reviews, Special Issue on NASA Innovative Research Program (IRP) results, v. 8, p. 3 - 28.

Kruse, F. A., Huntington, J. H., and Green, R. O, 1996, Results from the 1995 AVIRIS Geology Group Shoot: in Proceedings, 2nd International Airborne Remote Sensing Conference and Exhibition: Environmental Research Institute of Michigan (ERIM), Ann Arbor, v. I, p. I-211 - I-220.

Kruse, F. A., 1999, Visible/Infrared Sensors and Case Studies, Chapter 11, in Rencz, A., (ed.), Remote Sensing for the Earth Sciences, Manual of Remote Sensing, Volume 3, p. 567 – 606.

Kruse, F. A., Boardman, J. W., and Huntington, J. F., 2003, Comparison of Airborne Hyperspectral Data and EO-1 Hyperion for Mineral Mapping: in Special Issue, Transactions on Geoscience and Remote Sensing (TGARS), IEEE, v. 41, no. 6, June 2003, p. 1388 - 1400.

Kulkarni, A.D., Giridhar , G.B. and Praveen Coca, Neural network based fuzzy logic decision systems for multispectral image analysis, Neural, Parallel & Scientific Computations, v.3 n.2, p.205-218, June 1995

Kuosmanen, V., Laitinen, J. and Arkimaa, H., 2005. A comparison of hyperspectral airborne HyMap and spaceborne Hyperion data as tools for studying the environmental impact of talc mining in Lahnaslampi, NE Finland. In: B. Zagajewski, M. Sobczak and M. Wrzesien (Editors), 4th EARSel Workshop on Imaging Spectroscopy. New quality in environmental studies, Warsaw, Poland.

Lentilucci, E.J. and Gartley, M. Impact of BRDF on Physics Based Modeling as Applied to Target Detection in Hyperspectral Imagery. Proceedings of SPIE, Vo. 7334. Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery XV, edited by Sylvia S. Shen, Paul E. Lewis, Proc. of SPIE Vol. 7334, 73340T

Lobell, D. and Asner, G., 2004. Cropland distributions from temporal unmixing of MODIS data. Remote Sensing of Environment, 93(3): 412-422.

Lottermoser, B., 2003. Tailings, Mine Wastes. Springer, Berlin, pp.153-182.

Lottermoser, B., 2003b. Sulfidic Mine Wastes, Mine Wastes. Springer, Berlin, pp. 33-90.

Malmström M., Destouni G., and Martinet P., Modeling expected solute concentration in randomly heterogeneous flow systems with multi-component reactions, Environmental Science and Technology, 38, 2673-2679, 2004

Mariotti, M., Ercoli, L., and Masoni, A. 1996, Spectral properties of iron-deficient corn and sunflower leaves. Remote Sens. Environ. 58:282–288.

Mars, J.C. and Crowley, J.K., 2003. Mapping mine wastes and analyzing areas affected by selenium-rich water runoff in southeast Idaho using AVIRIS imagery and digital elevationdata. Remote Sensing of Environment, 84, 3, pp. 422-436.

Martelet G, Truffert C, Tourleère B, Ledru P, Perrin J, 2006; Classifying airborne radiometry with Agglomerative Hyrarchical Clustering: A tool for geologic mapping in context of rainforest (French Guiana. International Journal of Applied Earth Observation and Geoinformation 8, 208-223

Martin, P., Tims, S., McGill, A., Ryan, B., Pfitzner, K., 2006. Use of airborne g-rayspectrometry for environmental assessment of the rehabilitated Nabarlek uranium mine, Northern Australia. Environmental Monitoring and Assessment 115, 531–553.

Mas, J.-F., Puig, H., Palacio, J. and Sosa-López, A., 2004. Modelling deforestation using GIS and artificial neural networks. Environmental Modelling & Software, 19(5): 461-471.

Matthew, M.W., S.M. Adler-Golden, A. Berk, S.C. Richtsmeier, R.Y. Levine, L.S. Bernstein, P.K. Acharya, G.P. Anderson, G.W. Felde, M.P. Hoke, A. Ratkowski, H.-H Burke, R.D. Kaiser, and D.P. Miller, 2000, “Status of Atmospheric Correction Using a MODTRAN4-based Algorithm,” SPIE Proceeding, Algorithms for Multispectral, Hyperspectral, and Ultraspectral Imagery VI, Vol. 4049, pp. 199-207.

McCafferty AE, van Gosens BS, 2009; Airborne gamma-ray and magnetic anomaly signatres of serpentinitte in realtion to soil geochemsitry, Northern California. Applied Geochemistry 24, 1524-1537

MINEO: MINEO Assessing and monitoring the environmental impact of mining activities in Europeusing advanced Earth Observations techniques; Annex 1: Description of Work. Shared-costRTD, Contract no.: IST-1999-10337.

MINEO: MINEO Hyperspectral Airborne Survey. Survey Report. http://www.brgm.fr/mineo; 2000.

MINEO Final Report 2003: http://www2.brgm.fr/mineo/final.htm

Minty BRS 1997; Fundamentals of airborne gamma-ray spectrometry. AGSO Journal of Australian Geology and Geophysics 17 (2) 39-50

Minty BRS, Luyendijk APJ, Brodie RC 1997; Calibration and data processing for airborne gamma-ray spetrometry. AGSO Journal of Australian Geology and Geophysics 17(2) 51-62

Minty BRS, McFadden P, Kennet BLN 1998: Multichannel processing for airborne gamma-ray spectrometry. Geophysics 63 (6) 1971-1985

NASA Space Flight Center, Tech Brief. http://www.techbriefs.com/component/content/article/2890

Nascimento, J. and Dias, J., 2005. Vertex component analysis: a fast algorithm to unmix hyperspectral data. IEEE Transactions on Geoscience and Remote Sensing, 43: 898-910.

Neville, R., Staenz, K., Szeredi, T., Lefebvre, J. and Hauff, P., 1999. Automatic endmember extraction from hyperspectral data for mineral exploration, International Airborne Remote Sensing Conference and Exhibition, 4th/21st Canadian Symposium on Remote Sensing, Ottawa, Canada, 21-24 June, 1999.

Newcombe, C.P., and MacDonald, D.D., 1991, “Effects off suspended sediments on aquatic ecosystems,” North American Journal of Fisheries Management, Vol. 11, pp. 72-82.

Olli G., Destouni G., Long-term heavy metal loading to near-shore sediments, Water, Air, and Soil Pollution, 192, 105-116, DOI 10.1007/s11270-008-9638-7,

Ong, C., Cudahy, T.J. and Swayze, G., 2003. Predicting Acid Drainage Related Physicochemical Measurements UsingHyperspectral Data. Proc. 3rd EARSeL Workshop on Imaging Spectroscopy, Herrsching, 13th-16 th May 2003, pp. 363-369.

Paradella WR, Bignelli PA, Veneziani P, Pietsch, RW, Toutin T 1997; Airborne and spaceborne Synthetic Apertur Radar (SAR) integration with Landsat TM and gamma ray spectrometry for geologcal mapping in a tropical rainforest environment, the Carajás Mineral Province, Brazil. International Journal of Remote Sensing 18 (7) 1483-1501

Peppin, W. 2009. White Paper: An investigation of hyperspectral imagery over Cuprite, Nevada. At: http://www.spectir.com/assets/Text%20Files/AnInvestigationOverCuprite_BPeppin.pdf

Peters, D.C., P.L. Hauff, G.A. Borstad, F.B. Henderson III, W.A. Peppin, E. Dillenbeck, E.C. Prosh, L.G. Closs, J.L. Thiros, D.W. Coulter, K. Lee, D.A. Robbins, and K.W. Wangerud, 2000, Mine and mill waste characterization using CASI/SFSI hyperspectral data: Utah abandoned mine lands study areas, in Proceedings of the 14th International Conference and Workshops on Applied Geologic Remote Sensing, November 6-8, 2000, Las Vegas, Nevada: Ann Arbor, Environmental Research Institute of Michigan, p. 54-61.

Pfitzner K, Martin P, Ryan B, 2001; Airborne gamma survey of the upper South Alligator River valley, second report 2001; Report: Environmental Research Institute of the Supervising Scientists (eriss)

Pöllänen R, Toivonen H, Peräjärvi K, Karhunen T, Ilander T, Lethinen J, Rintala K, Katajainen T, Niemelä J, Juusela M 2009; Radiation surveillance using an unmanned aerial vehicle.. Applied Radiation and Isotopes 67, 340-344

Pontius, J., Martin M., Plourde, L. and Hallet R. 2008. Ash decline in emerald ash borer-infested regions: A test of tree-level, hyperspectral technologies. Remote Sensing of Environment.

Porter JK, Lowe C 2000; Airborne Gamma-ray spectrometry over the Endako porphyry molybdenum district in Central British Columbia. Geological Survey of Canada. Contribution to the Nechako NATMAP project.

Pysek, P., & Pysek, A. (1989). Changes in vegetation caused by experimental leakage of natural gas. Weed Research, 29(193-204).

Quadros TPF de, Koppe JC, Strieder AJ, Costa JFCL 2003; Gamma-ray processing and intergration for lode-Au deposites exploration. Natural Resources Research 12 (1) 57-65

Ramadan TM, El Mongy SA, Salah el Dein S 2009; Exploration for Uranium mineralisations at Wadi Um Laseifa area, Central Eastern Desert, Egypt: Using remote sensing technique. Australian Journal of Basic and applied Sciences 3 (2) 689-697

Rangelov, R., Hetu, R., Grant, J.A. and Grasty, R.L., 1993 Monitoring Man-made Radiation by Airborne Gamma-ray Spectrometry, Kozloduy Area, Bulgaria, Geological Survey of Canada, Open File 2573, 10 pages.

Rock, B. N., Hoshizaki, T., & Miller, J. R. (1988). Comparison of In Situ and airborne spectral measurements of the blue shift associated with forest decline. Remote Sensing of Environment, 24, 109-127.

Roberts, D.A., Adams, J.B., and Smith, M.O., 1993, Discriminating Green Vegetation, Non-Photosynthetic Vegetation and Soils in AVIRIS Data, Rem. Sens. Environ., 44: 2/3 255-270.

Roberts, D.A., Green, R.O., and Adams, J.B., 1997,Temporal and Spatial Patterns in Vegetation and Atmospheric Properties from AVIRIS, Remote Sens. Environ 62: 223-240.

Robers LM, Wilford JR, Field JB Greene RSB 2004; High resolution ground based gamma-ray sectrometry and electromagnetics to assess regolith properties, Boorowa, NSW. Advances in Regolith 352-357

Sabine, Charles. 1999 Remote Sensing Strategies for Mineral Exploration. In Manual of Remote Sesning. Vol. 3. p.379-449 Edited by Rencz, Andrew, N.; ASPRS & John Wiley and Sons, Inc., New York.

Salvador, M.Z., Resmini, R.G. and R. B. Gomez, “Hyperspectral trace gas detection using the wavelet packet transform,” in Proc. SPIE'08, 2008, pp. 69661T.1-69661

Sanderson DCW, Cresswell AJ, Whit DC 2008; The effect of flight line spacing on radioactivity inventory and spatial feature charactersistics of airborne gamma-ray spectrometry data. International Journal of Remote Sensing 29 (1) 31-46

Sandmeier, Ch. Mueller, B. Hosgood and G. Andreoli, 1998, Sensitivity Analysis and Quality Assessmentof Laboratory BRDF Data, Remote Sensing of Environment,vol. 64, no. 2.

Schetselaar EM, Rencz AN 1997; Reducing the effects of vegetation cover on airborne radiometric data using Landsat TM data. International Journal of Remote Sensing 18 (7) 1503-1515

Scott EM, Sanderson DCW, Cresswell AJ, Lang JJ 2004; Spatial scale and its effects on comparisons of airborne and ground-based gamma-ray spectrometry for mapping environmental radioactivity.

Siegal, B.S., and A.F.H. Goetz, 1977. Effect of vegetation on rock and soil type discrimination, Photogrammetric Engineering Remote Sensing, 43(2):191-196.

Singer, A., Schwertmann, U. & Friedl, J. 1998: Iron oxide mineralogy of terre rosse and rendzinas in rela-tion to their moisture and temperature regimes.– European Journal of Soil Science, 49, 385–395.

Shafique, N.A., Fulk, F., Autrey, B.C., and Flotemersch, J. 2002. Hyperspectral Remote Sensing of Water Quality Parameters for Large Rivers in the Ohio River Basin. Available at: http://www.tucson.ars.ag.gov/icrw/Proceedings/Shafique.pdf.

Shives RBK, Ford KL 1997; The detection of potassic alteration by gamma-ray spectrometry-recognition of alteration related to mineralisation; In: Exploration 97: Geophysics and Geochemistry at the Millennium

Smailbegovic, A., Taranik, J., Silberman, M. and Oppliger, G., 2005. Regional and local constraints on metallogenesis in the Bodie Hills of Nevada and California - A case history on horizontal integration of geospatial data sets. In: H. Rhoden, R. Steininger and P. Vikre (Editors), Window to the World. Geological Society of Nevada Symposium 2005, Reno, Nevada, pp.1023-1033.

Smailbegovic, A. 2006. Analysis of multiple hyperspectral datasets over Cuprite, Nevada. Report to the DOE Na-22 proposal.

Smith, B.D., McCafferty, A.E., McDougal, R.R. 2000. Utilization of airborne magnetic, electromagnetic, and radiometric data in abandoned mine land investigations. In Proceedings from the Fifth International Conference on Acid Rock Drainage. SME, Littleton, CO. p. 1525-1530.

Smith, K., Steven, M. and Colls, J., 2004. Use of hyperspectral derivative ratios in the red-edge region to identify plant stress responses to gas leaks. Remote Sensing of Environment, 92(5): 207-217

Smith, K. L. (2002). Remote sensing of leaf responses to leaking underground natural gas. Unpublished PhD, University of Nottingham, Nottingham, UK

Smith, K. L., Steven M. D., & Colls J.J (2004). Spectral responses of pot-grown plants to displacement of soil oxygen. International Journal of Remote Sensing In press.

Spinetti, C., Buongiorno, M.F., Lombardo, V. and Merucci. L. 2003. Aerosol optical thickness of Mt. Etna volcanic plume retrieved by means of the Airborne Multispectral Imaging Spectrometer. Annals of Geophysics, Vol. 46, N. 2.

Spinetti, C., Carrère, V., Buongiorno, M. F., Sutton, A. J. & Elias, T., 2008. Carbon dioxide of Pu`u`O`o volcanic plume at Kilauea retrieved by AVIRIS hyperspectral data. Remote Sensing of Environment 112: 3192-3199.

Street GJ; Spatial tools for land management: The regional institute Ltd. http://www.regional.org.au/au/gia/01/002street.htm

Sumanovic-Glamuzina, D. Violeta Saraga-Karacic, Zeljko Roncevic, Aleksandar Milanov, Tomica Bozic, Milivoj Boranic; 2003. Incidence of Major Congenital Malformations in a Region of Bosnia and Herzegovina Allegedly Polluted with Depleted Uranium, in: *Croatian Medical Journal* Vol. 44 (2003) No. 5 (October), p. 579-584

Sudduth, K.A., Kitchen, N.R., Wiebold, W.J., Batchelor, W.D., Bollero, G.A., Bullock, D.G., Clay, D.E., Palm, H.L., Pierce, F.J., Schuler, R.T., Thelen, K.D., 2005. Relating apparent electrical conductivity to soil properties across the North-Central USA. Comp. Electron. Agric. 46, 263–283.

Sterckx, S., Knaeps, E., Bollen, M., Trouw, K. and Houthuys, R., 2007. Retrieval of suspended sediment from advanced hyperspectral sensor data in the Scheldt estuary at different stages in the tidal cycle. Marine Geodesy, 30: 1-12.

Swayze, G.A. R. F. Kokaly, C. T. Higgins, J. P. Clinkenbeard, R. N. Clark, H. A. Lowers, and S. J. Sutley, 2009. Mapping potentially asbestos-bearing rocks using imaging spectroscopy Geology (Boulder) (August 2009), 37(8):763-766

Swayze, G.A., Kokaly, R.F., Higgins, C.T., and Churchill, R.K., 2003, Mapping natural occurrences of potentially asbestos-bearing serpentine rocks in the foothills of the Sierra Nevada, California using imaging spectroscopy, in Natural science and public health; prescription for a better environment; conference abstracts: U.S. Geologial Survey Open-File Report 03-0097, p. 70.

Swayze, G.A., Clark, R.N., Smith, K.S., Hagemann, P.L., Sutley, S.J., Pearson, R.M. 1998: Using ImagingSpectroscopy to Cost-Effectively Locate Acid-Generating Minerals at Mine Sites: An Example from the California Gulch Superfund Site in Leadville, Colorado. - Summaries of the 7th JPL Airborne Earth Science Workshop, JPL Publ. 97-21, Vol. 1: 385-389

Swayze, G.A., 1997, The hydrothermal and structural history of the Cuprite Mining District, Southwestern Nevada: An integrated geological and geophysical approach, Ph. D. Dissertation, University of Colorado, Boulder, Colorado, p. 399. Available from University Microfilms Inc., Ann Arbor, Michigan, USA (313) 761-4700 or 1-800 521-3042 Catalogue no. 9725795 Color figures and plates can be downloaded from our ftp site: ftp://ftpext.cr.usgs.gov/pub/cr/co/denver/speclab/pub/cuprite/

Taranik J.V. 1988, "Application of Aerospace Remote Sensing Technology to Exploration for Precious Metal Deposits in the Western United States," Bulk Mineable Precious Metal Deposits of the Western United States, Symposium Proceedings, GSN, Ed. Robert W. Schafer, 1988.

Thenkabail, P., Smith, R. and De Pauw, E., 2002. Evaluation of narrowband and broadband vegetation indices for determining optimal hyperspectral wavebands for agricultural crop characterization. Photogrammetric Engineering and Remote Sensing, 68(6): 607-621.

Toulière B, Perrin J, Le Berre P, Psquet JF 2003; Use of airborne gamma-ray spectrometry for kaolin exploration. Journal of applied geophysics 53, 91-102

Truffert C, Perrin J, Martelelt G, Deparis J, Duffy A, Eberle D 2009; Airborne gamma-ray spectrometry- How to settle Rn atmospheric correction. 11th SAGA Biennial Technical Meeting and Exhibition Swaziland, 16-18 September 2009, 450-452

Urquhart WES, 2004; Airborne gamma-ray spectrometry surveys. Geoexplo Ltda. http://www.geoexplo.com/airborne_survey_workshop_rad.html

Ustin, S.L., Roberts, D.A., Pinzon, J., Jacquemoud, S., Gardner, M., Scheer, G., Castaneda, C.M. and Palacios, A., 1998, Estimating Canopy Water Content of Chaparral Shrubs Using Optical Methods, Rem. Sens. Environ. 65:280-291.

Varshney, P. and Arora, M., 2004. Advanced image processing techniques for remotely sensed hyperspectral data. Springer, pp.322.

Vaughan, R.G. 2004. Surface Mineral Mapping at Virginia City and Steamboat Springs, Nevada with Multi-Wavelength Infrared Remote Sensing Image Data. unpublished PhD Dissertation, University of Nevada. Reno, 259 p.

Vaughan, R. Greg, and Calvin, Wendy M., 2005, Mapping weathering and alteration minerals in the Comstock and Geiger Grade areas using visible to thermal infrared airborne remote sensing data, in Rhoden, H.N., Steininger, R.C., and Vikre, P.G., eds., Geological Society of Nevada Symposium 2005: Window to the World, Reno, Nevada, May 2005,

Vogelmann J.E., Rock, B.N. and Moss, D.M. (1993). Red edge spectral measurements from sugar maple leaves. International Journal of Remote Sensing, 14, p.1563-1575.

Van der Meer, F., 1995. Spectral unmixing of Landsat Thematic Mapper data. International Journal of Remote Sensing, 16(16): 3189-3194.

Younger PL, 2000, predicting temporal changes in total iron concentration in groundwater flowing in abandoned deep mines: a first approximation. Journal of Contaminant Hydrology, 44(1), 47-69.

Younger PL, 2002, Mine water pollution from Kernow to Kwazulu-Natal: geochemical remedial options and their selection in practice. Geosciences in Southwest England, proceedings of the Ussher Society, 10, 255-266.

Wilford JR, Bierwirth PN, Craig MA, 1997; Application of airborne gamma-ray spectrometry in soil/regolith mapping and applied geomorphology. Journal of Astralian Geology and Geophysics, 17 (2), 201-216

Wilford JR 2002; Airborne gamma-ray spectrometry. In: Papp E (editor) 2002, Geophysical and Remote Sensing Methds for Regolith Exploration. CRCLEME open file report 144, 46-52

Wilford F, Murphy B, Summerell G 2008; Delineating reolith Materials using multi-scaled terrain attributes and Gamma-ray imagery- applications for updating soil-landscape maps and managing dryland salinity. Geoscience Australia/ CRC LEME-Canberra

Wilford JR, Worral L, Minty B, 2009; Radiometric map of Australia provides new insights into uranium prospectivity. AUSGEO news, 95

Winkelman I, Thomas M, Vogl K, 2001; Aerial measurements on uranium ore mining, milling and processing areas in Germany. Journal of environmental radioactivity 53, 301-311

Winter, M., 1999. N-FINDR: an algorithm for fast autonomous spectral end-member determination in hyperspectral data. Proceedings SPIE, 3753(266).

Wolkersdorfer Ch, 2002, mine water tracing. Geological Society, London, Special Publication, 198, 47-61.

van Wijngaarden, M., Venema, L.B. en de Meijer, R.J. 2002. Radiometric sand mud characterisation in the Rhine-Meuse Estuary. Part B: in situ mapping. Geomorphology, 43: 103-116.

White, H.P.; Lixin Sun; Champagne, C.M.; Staenz, K.; Leblanc, S.G.; 2002. BRDF normalization of hyperspectral image date. Geoscience and Remote Sensing Symposium, IGARSS'02. IEEE International, vol4, pp.2572-2574.

Zabcic, N., Ong, C., Müller, A., Rivard, B., 2005. Mapping pH from airborne hyperspectral data at the Sotiel-Migollas mine; Calanas, Spain, Proceedings 4th EARSeL Workshop onImaging Spectroscopy, 27th-29th April 2005, Warsaw (Poland),

Zarco-Tejada, P. J., Pushnik, J. C., Dobrowski, S., & L, U. S. (2003). Steady-state chlorophyll a fluorescence detection from canopy derivative reflectance and double-peak red-edge effects. Remote Sensing of Environment, 84, 283-294.

Zhang, J., Rivard, B. and Rogge, D., 2008. The Successive Projection Algorithm (SPA), an algorithm with a spatial constraint for the automatic search of endmembers in hyperspectral data. Sensors, 8: 1321-1342.

Zhengming, W. and Li Zhao-liang, 1997, "A Physics based algorithm for retrieving land surface emissivity and temperature from EOS/MODIS data ",IEEE Transactions. Geoscience and Remote Sensing, Vol. 35, No.4, pp. 980-996