Paper 22

Airborne Hyperspectral Remote Sensing

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ABSTRACT

Airborne Hyperspectral Imagery (HSI) provides high spectral and spatial resolution data that may be used to map a broad range of mineral species associated with alteration and mineralization. The method makes contiguous, finely sampled, measurements of reflected solar radiation in the visible through infrared regions of the electromagnetic spectrum. The measurements are geometrically and radiometrically corrected to apparent surface reflectance. The reflectance data may then be inverted to the dominant mineral in each pixel or a linear mixture of minerals for each pixel. Airborne operations for HSI data collection are similar to other fixed wing geophysical surveying methods. Aircraft typically operate at 1,000 m to 5,000 m above the average ground elevation to produce 1 m to 5 m pixels but fly at a fixed barometric altitude for each flight line. The primary limiting factors on the use of HSI are weather conditions and ground exposure. The methods must be flown under clear sky conditions and adequate surface exposure of rocks is essential.

INTRODUCTION

Hyperspectral imagery (HSI) remote sensing is the only airborne exploration method that directly maps a wide range of minerals associated with alteration and potential economic mineralization. It is poised to be one of the most significant new technologies to see broad acceptance by the exploration industry. Widely used in the forestry, agricultural, oceanographic, and intelligence communities, HSI has been slow to gain wide use in exploration. A few exploration companies have embraced the technology, and even built and operated proprietary instruments, but widespread acceptance has been limited by relatively high cost of the surveys (and limited exploration budgets for much of the late 1990's and early 2000's), minimal competition amongst survey operators, lack of robust inversion methods, and limited understanding of the technology by explorationists. The widespread adoption of field spectrometers for sample and core analysis has impressed on practitioners the importance of spectroscopic mineral analysis for developing a greater understanding of alteration mineralogy. This has begun a wider recognition that airborne spectroscopic mapping has an important place for exploration in settings that have adequate exposure.

Alteration mineral mapping is an essential tool for identifying, mapping, and understanding exploration targets on regional and local scales. The pressure, temperature, and chemistry of hydrothermal fluids directly control mineral stability fields. Satellite multispectral imagery, such as ASTER, is often the primary tool for regional exploration early in the exploration cycle in semi-arid to arid regions. Whereas ASTER identifies general alteration mineral families at moderate spatial resolutions (15-90m pixels), hyperspectral imagery can be used to map specific minerals and mineral variations at high spatial resolutions (1-5 m pixels).

Hyperspectral imagery is relatively new technology that has emerged for commercial use in exploration largely in the last 10 years. Although a single experimental spaceborne HSI system is available (NASA's Hyperion), the vast majority of HSI is collected from airborne platforms. Like conventional multispectral imagery (MSI), HSI is collected as a grid of measurements over the entire surface under investigation. HSI has, however, extremely dense spectral sampling of reflected electromagnetic radiation. MSI instruments like Thematic Mapper (TM) and ASTER have relatively few, non-contiguous, spectral band passes over broad wavelength windows (typically 50 to 100 nanometers (nm)), whereas HSI instruments have hundreds of continuous narrow wavelength bands (typically 5 to 20 nm) (Figure 1). The goal of HSI is to collect the spectral signature of each image pixel over the surface.

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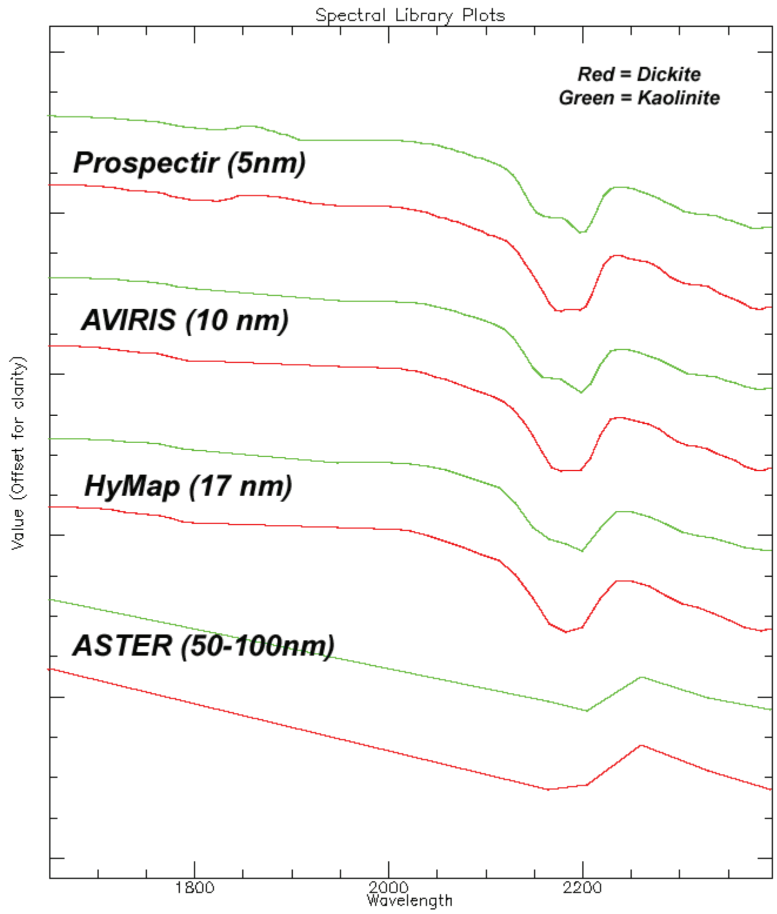

Figure 1: Comparison between the spectra of dickite and kaolinite for the ASTER multispectral instrument and several hyperspectral instruments.

Commercial HSI systems primarily operate in the visible to shortwave infrared region of the electromagnetic spectrum (~400 nm to 2500 nm). Some systems make a limited number of measurements in the thermal infrared as well. The visible to near infrared (VNIR – 400 nm to 1100 nm) region is used primarily to map metal oxides, oxyhydroxides, and vegetation. This region is critical for mapping minerals associated with leach caps, gossans, skarns, laterites, and acid drainage systems. The shortwave infrared (SWIR – 1100 nm to 2500 nm) region is used to map phyllosilicates, sulfates, carbonates, and ammoniated minerals. Many of the minerals associated with hydrothermal alteration systems, especially epithermal gold, porphyries, IOCG (iron oxide copper gold), kimberlites, unconformity uranium, and laterites are mapped in this region.

While HSI instruments have been operated since the 1980's, these were primarily used for scientific studies. Commercial HSI systems began to appear in the 1990's and began to operate on a production basis for exploration in the late 1990's and early 2000's. As with any technology, the earliest instruments suffered from limitations, including poor radiometric calibration, low geometric fidelity, and low signal to noise (S:N). Improvements in electronic and positioning technologies have brought about significant improvements in the quality of data produced by HSI instruments.

HSI surveys are primarily conducted from fixed wing aircraft. The optical characteristics of each instrument control the relationship between the ground clearance and pixel size. Most instruments range between 1000 to 1 and 2000 to 1 ratios. Thus a system with a 1000:1 optical ratio flying at 1000 m above the ground produces 1 m pixels. Early HSI surveys were flown with pixels sizes of around 10-20 m whereas current surveys are typically flown with pixels smaller than 5 m.

The processing of HSI data has evolved significantly in recent years. Since the data are collected though the Earth's atmosphere the effects of atmospheric gasses, and more importantly water vapour, must be removed. A number of commercial packages to accomplish atmospheric correction have become available. In addition, the growing experience of research and commercial HSI users has produced an improved understanding of the best practices for accomplishing accurate corrections. The analysis and exploitation of HSI has seen significant improvements as well, with advancements in methods for semi-quantitative inversion of the data to mineral species.

OVERVIEW

The ability to accurately map minerals from the air has been a goal of geologic remote sensors for many years. A series of papers by Hunt and Salisbury (with additional authors over the years) in the early 1970's documented the visible and infrared signatures of all the important mineral species using laboratory methods. The translation of this ability to an airborne platform took a few more years. Geophysical Environmental Research (GER) first developed a airborne profiling spectrometer that measured a single line of spectra below an aircraft. The company went on to field the first commercial imaging spectrometer in the mid 1980's, the 63 channel GERIS system. This system pushed the limits of the technology but suffered from a low signal to noise and calibration issues. It was also not a true imaging spectrometer in that some regions of the electromagnetic spectrum were not sampled. Regardless of the enthusiasm of exploration remote sensing geologists for imaging spectroscopy, the focus of imaging spectrometer development for many years switched to the government. JPL was at the center of this with the development of the Airborne Imaging Spectrometer (AIS) and then the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) in the 1980's (Figure 2). AIS was a short lived "proof of concept" instrument but AVIRIS became, and continues to be, the gold standard for scientific HSI. Since its initial flights in 1987, AVIRIS has been continuously updated to improve the signal to noise and operational flexibility. AVIRIS is a true HSI system in that it collects 224 continuous channels of data between 400 and 2500 nm. The continuity of data, even in EMR regions that have significant atmospheric absorptions is critical for accurately correcting the data for atmospheric interference (more on this later). AVIRIS has been flown on four platforms: an ER-2 (a civilian version of the U-2), a Proteus, a WB-57 (all high altitude aircraft), and a Twin Otter (a low altitude aircraft)(Lundeen, 2006). Pixel sizes vary between 20 meters for high altitude missions and 3-5 meters for low altitude missions. While AVIRIS data are occasionally collected over mineralized systems, the instrument is used in support of scientific research, not commercial exploration interests. Additionally, because it is a government owned and subsidized instrument, the data collected with AVIRIS are non-proprietary.

The appearance of commercial true HSI systems began in the late 1980's. The ITRES Research Ltd. Compact Airborne Spectrographic Imager (CASI) appeared on the scene but covered only the visible to near infrared, not the shortwave infrared needed for mapping many alteration minerals. (ITRES has subsequently released SWIR and TIR region sensors, which they call SASI and TASI.) The Canada Center for Remote Sensing (CCRS) addressed this with the development of the SWIR Full Spectrum Imager (SFSI). SFSI covers the range of 1230 to 2380 nm and is often flown in tandem with CASI. SFSI is a push broom design and was one of the first commercial sensors to utilize a 2-D detector array. In the 1990's an imaging spectrometer designed specifically to target the exploration market was developed by Integrated Spectronics Pty Ltd. This sensor, HyMap (Figure 3) (and its variants) was the standard for exploration HSI from the late 1990's into the 2000's.

Figure 2: The AVIRIS instrument in the laboratory.

Figure 3: The HyMap instrument mounted in a survey aircraft. The lower part of the system is a stabilized platform.

One mining company in particular, Noranda, made a strong commitment to the use of hyperspectral data for exploration. In 1997 Noranda partnered with Falconbridge and Earth Search Sciences Inc. (ESSI) to fly the Probe 1 sensor (a variant of HyMap) on a routine basis (Gingerich and Peshko, 2000). They often were able to acquire imagery covering 2,000- 2,500 km^2 per day with a ground resolution of 10m. These data provided rapid, objective, mineralogical mapping of large areas that would have been prohibitively expensive using conventional field techniques. The Noranda experience showed that rapid processing and exploitation of the HSI data were critical for success (Gingerich and Peshko, 2000) and Noranda partnered with a variety of commercial, scientific, and academic organizations to develop efficient methods of inverting the data to mineral abundances.

As we entered the 21st century the focus of instrumentation became improvements in size and weight, operational simplicity, data quality (signal to noise), and spatial and spectral resolution. While AVIRIS and HyMap had the capability to fly low altitude missions, the limit of resolution was around 3-5m with most missions flown at 20m pixel resolution (Instantaneous Ground Field Of View or IGFOV)for AVIRIS and 10m IGFOV for HyMap. In 2002, Spectir Corp. began flying the HyperSpectral Technology sensor (HST) (Figure 4). The design of this instrument permitted very high spatial resolution data (< 1 m) to be collected. High spatial resolution can be invaluable in certain terrains. The small pixel size reduces issues of mixed pixel signatures and allows better resolution of exposed outcrop in lightly forested areas. Advanced hyperspectral camera technology has permitted spectral resolution to improve as well. The AISA cameras (Figure 5) from Spectral Imaging Ltd. (SPECIM) permit spectral resolutions as high as 5 nm to be acquired (as compared with 10 nm for AVIRIS and 11-18 nm for HyMap). This system is currently operated by Spectir Corp. as the HST instrument has been retired from airborne operation. A similar system called HySpex (Figure 6) is available from Norsk Elektro Optikk but is not yet being flown by contractors (an Australian survey company will reportedly soon be flying HySpex). High spectral resolution is often critical for mapping hydrothermal minerals (Figure 1).

Figure 4: The HST instrument

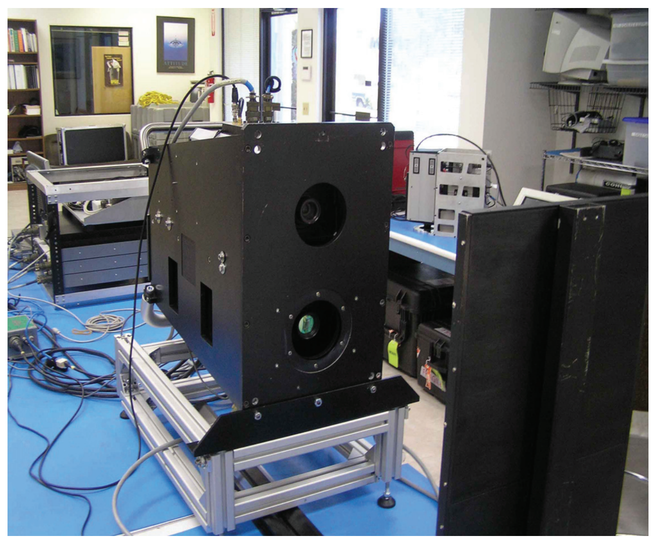

Figure 5: The ProSpecTIR dual HSI camera system (AISA cameras) on a workshop bench

Figure 6. An operational prototype of the HySpex system mounted in an aircraft.

SPECTROSCOPY

The basis of the usefulness of HSI for exploration lies in the spectroscopy of minerals associated with alteration. A full discussion of spectroscopy as it applies to mineral exploration may be found in Hauff (2007) within this volume. A brief overview of spectroscopy is, however, provided here. Until the 1980's, mineral spectroscopy was primarily a laboratory method. The introduction of the PIMA and ASD field spectrometers brought about a revolution in the use of mineral spectroscopy for exploration. These lightweight portable instruments permit the rapid identification of mineral species. Most exploration geologists have some experience with a PIMA or ASD TerraSpec™.

The interaction between electromagnetic radiation and matter is wavelength dependent; some EMR is absorbed through various mechanisms and some is reflected. Measurements of the reflectance spectra of materials can be used to identify many materials. This is the foundation of reflectance spectroscopy and hyperspectral imaging.

The mechanisms that cause EMR to be absorbed by materials are wavelength dependent. Electron transition effects are dominant at short wavelength, lattice vibrations at intermediate wavelengths, and molecular rotations at long wavelengths. Electron transitions may take the form of color centers, crystal field effects, charge transfer, excitons, and interband and impurity transitions (Hapke 1993). For the iron minerals that are important for alteration mapping, crystal field effects and charge transfer are the primary mechanisms of electron transitions (Hapke 1993). Lattice vibrations take the form of stretching and bending of molecular bonds in which the dipole moment of the bond is changed (Hapke 1993; King et al.

1995). Electromagnetic radiation may cause a bond vibration to switch from a lower to higher vibrational energy state and thus absorb energy (Hapke 1993). The primary absorption bands resulting from this are centered at thermal wavelengths but have overtones in the shortwave infrared (SWIR). For alteration minerals, Al-OH, Fe-OH, CO3 and Mg-OH bonds are the most important and produce absorption bands near 2200 nm and 2300 nm respectively.

INTRUMENTATION

HSI instruments fall into two basic categories: whiskbroom and pushbroom (Figure 7). Whiskbroom scanners, such as AVIRIS and HyMap, utilize a rotating mirror to progressively scan each pixel across the flight path. The image is built up scan line by scanline as the aircraft flies. The light from each pixel is passed through a dispersion element (grating or prism) and measured in spectrographs using 1-D electro-optical arrays. These arrays turn the light energy that falls on them into electrical signals. There are typically multiple spectrographs to cover different parts of the electromagnetic spectrum. Pushbroom sensors measure all of the pixels across the flight path simultaneously. HSI pushbroom systems, such as ProSpecTIR, HySpex, and SFSI utilize 2-D electro-optical arrays. One dimension of the array is spatial (across track) and the other dimension is spectral, light is dispersed in the along track direction (Figure 8). Effectively, pushbroom HSI systems utilize technology similar to that which is used in digital cameras except that light is dispersed in one dimension. All sensors utilize optics to focus light onto the dispersion element. The geometry of the optical path is shown in Figure 9. Rather than providing a focal length, sensors are rated in terms of the Instantaneous Field of View (IFOV) angle which is given in milliradians (.001 radian). This allows a simple calculation to be used to determine pixel size:

pixel size(meters) = altitude(meters AGL) * IFOV(radians)

So a system with a 1mr IFOV will produce 1m pixels at an altitude of 1000m (1000m * .001 = 1).

The HyMap sensor collects 128 spectral channels in the range of 420 nm to 2500 nm with a spectral resolution ranging from 11 nm to 18 nm (Cocks et al., 1998). The thermal infrared (TIR) range may also be collected with 32 channels in the 8 to 12 um (8,000 to 12,000 nm) with a resolution of 200 nm. The HyMap system is normally mounted in a geostabilized platform to minimize aircraft motion (Figure 3). The IFOV is selectable between 1 and 3 mr providing ground resolutions between 3 and 5 m. The swath width is a function of the IFOV and altitude.

The ProSpecTIR sensor is highly configurable. Two data collection modes are typically used for exploration. A nominal 10 nm sampling mode results in 187 spectral channels between 400 and 2450 nm, whereas the nominal 5nm sampling mode results in 374 channels. Thermal IR capability is available but not typically flown on exploration projects. The system is hard mounted to the aircraft and geometric corrections are performed in software based on GPS/INS information. The IFOV is selectable but typically flown at 1.2 mr. The instrument is normally flown at ground resolution of 1 to 5 m. The swath width is fixed at 320 pixels but will be upgraded to 1024 pixels in the near future.

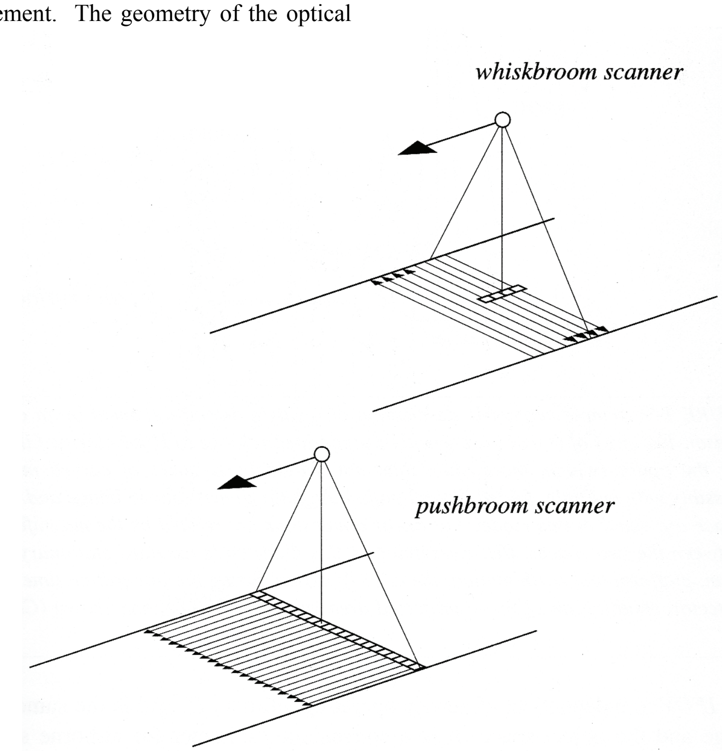

Figure 7: The acquisition geometry of whiskbroom and pushbroom instruments.

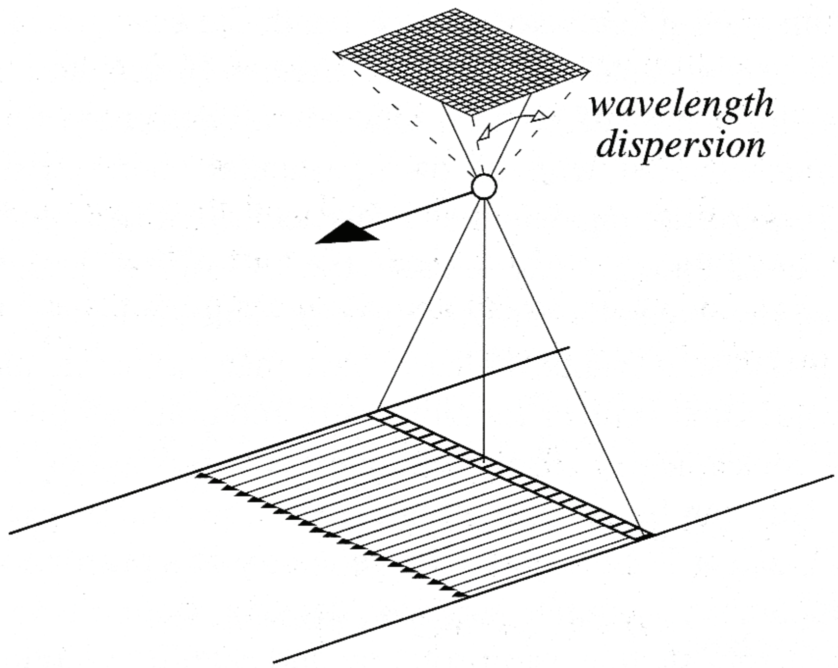

Figure 8: Spatial and spectral acquisition geometry of 2-D pushbroom HSI systems.

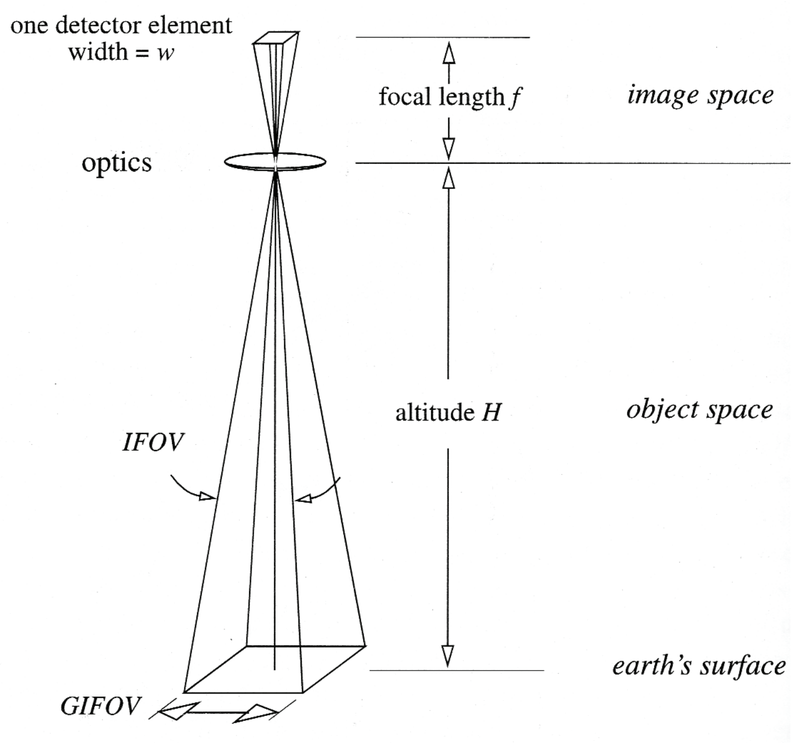

Figure 9: Generalized optical path for remote sensing instruments.

Whiskbroom and pushbroom issues

Whiskbroom and pushbroom sensors each have benefits and drawbacks. Whiskbroom technology is more mature than pushbroom primarily because the 2-D detector arrays required for a pushbroom HSI system (particularly arrays responsive to the SWIR) are relatively new.

Image striping is an issue with all remote sensing systems. Whiskbroom sensors tend to have minimal striping as the same 1-D array is used for all measurements. When striping is present, it is in the across track direction. Pushbroom sensors almost always posses some striping as each image column is measured by a different column on the 2-D array. Striping is always along track.

The most serious issue with pushbroom technology is that the sensors tend to be prone to "spectral smile" and mis-registered spectra. These are inherent problems with slit based spectral systems. Spectral smile (or conversely and equally as bad spectral frown) is a shift in channel band centers across track. For example, channel 100 will be centered at 1000 nm at the center of the image and 1020 nm at the edges (this is a dramatic example but has occurred on at least one spectrometer destined for Mars (Green, 2007a)). The second problem is that of spatially mis-regestered spectra. In this situation, part of a spectrum comes from one pixel and another part from a different pixel. While technically challenging, these issues can be addressed by careful design of the instrument (Mouroulis, 2005) or characterized and partially corrected by post processing.

The primary advantages of pushbroom sensor are compact size, low weight, simpler operation, higher signal to noise. The drive toward the use of pushbroom sensors by survey companies is primarily motivated by their small size, low weight and simple operation. The absence of a scanning mirror and lack of moving parts are primarily responsible for this. At one extreme, a visible to near IR hyperspectral camera designed for unmanned aerial vehicle use is currently available that weighs less than ½ Kg. (Figure 10). The ProSpecTIR system, while much bulkier, can still be transported to a survey site as checked airline baggage. Finally, pushbroom sensors tend to have higher signal to noise because the per pixel integration time is many times longer than whiskbroom sensors.

Figure 10: A miniature VNIR HSI camera designed for use in UAV's.

SURVEY METHODS

Hyperspectral surveys have much in common with fixed wing geophysical surveys. The nature of the measurements and types of corrections needed, however, introduce some special factors that need to be addressed. The primary issues are extent and type of ground cover, ground albedo ("brightness" of the surface material), weather conditions, solar factors, and atmospheric calibration requirements.

All optical remote sensing methods are non-penetrating. The optical depth measured is on the order of a few microns. Thus we measure only what is on the surface. The decision to undertake an HSI survey requires careful consideration of the surface conditions. Zhou (2004) found that rock exposure should exceed 20% for remote sensing of high albedo epithermal systems with ASTER to be effective. But she notes that one must be careful about what is defined as exposure. Outcrops covered in lichen or moss are effectively masked and will not be "seen" by the instrument. High spatial resolution HSI surveys (pixel size < ~3m) may modify this limitation as outcrops and bare patches that would be mixed with cover at ASTER resolutions may be resolved at high resolutions (Figure 11). Forested alpine environments should not necessarily be ruled out as alteration above timberline, or mineralized systems are often un-vegetated due to climatic conditions or toxic soils (Figure 12).

The second issue for airborne hyperspectral methods are the weather conditions. The sun is the only source of energy available for the optical measurements. Thus, clear sky conditions are necessary for survey operations. Even high thin clouds and haze can seriously degrade the quality of the data (Salisbury, 1998).

The angle between the sun and the earth (the solar angle) is also an important factor in operating HSI surveys. High signal is critical for producing quality results. The nearer the sun is to overhead, the greater the energy is per unit area. This imposes seasonal and daily windows when survey conditions are optimal. At mid latitudes the seasonal window is approximately 3 months on either side of the Summer Solstice. This is narrower at high latitudes and broader at low latitudes - one can fly year around at the equator and perhaps for a month in polar regions. The daily window at mid latitudes is approximately 2 hours on either side of solar noon (4 hour total "on line" survey day). This is also a bit wider at lower latitudes. It is important to note that solar noon is longitude dependent – there are websites that may be used to calculate the local time of solar noon for a given longitude and date. The daily time window may also have to be reduced in areas of extreme relief to avoid imaging steep terrain in shadow.

The albedo or average brightness of the ground surface must also be taken into consideration. Bright material with a high overall signal will produce better results than dark material. This is because the instrument noise has a much lower proportional contribution to bright, high signal, measurements.

Finally, the local variations in the atmosphere must be taken into account. Whereas atmospheric gases are mixed relatively uniformly, water vapour and dust are subject to significant spatial and temporal variations. A full discussion of the methods used for corrections of the atmosphere may be found below in the section on processing. As an aid to both atmospheric calibration and as a quality check on the data, field measurements during data acquisition are highly desirable. The recommended procedure for local calibration (and quality checks) is the use of a natural or artificial reflectance target (Clark et al., 2002). A discussion of field procedures for setting up reflectance target is provided here.

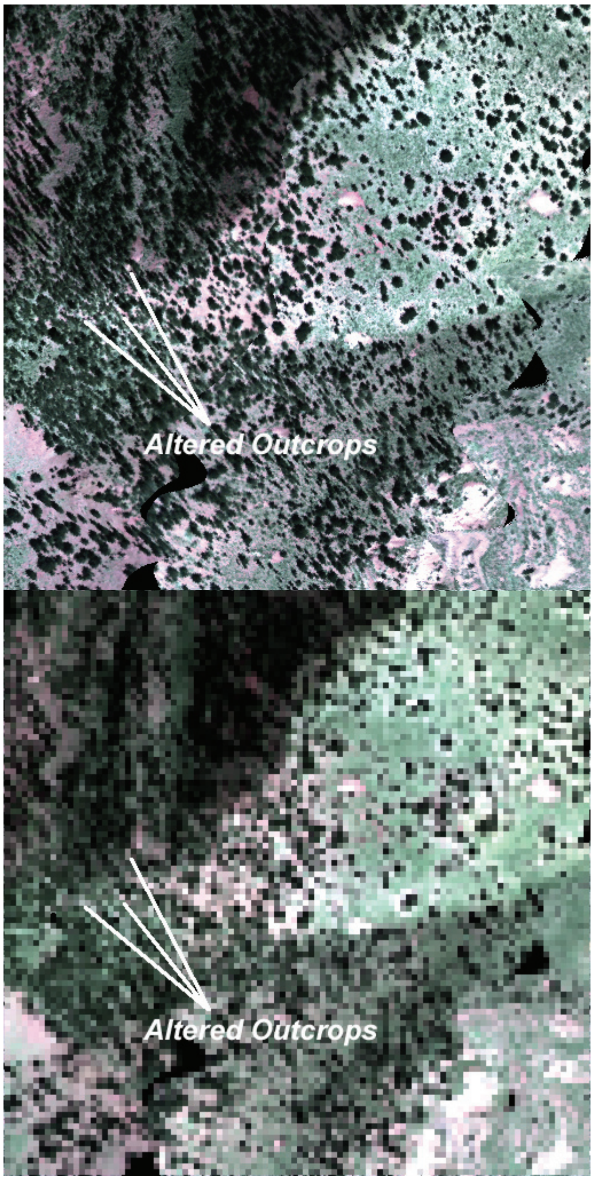

Figure 11: Comparison between 1 meter data (top) and 5 meter data (bottom) showing alteration (pink) in a lightly to moderately forested area. Individual altered outcrops that are visible in the 1 meter data are mixed with vegetation in the 5 meter data.

Whether natural or artificial, reflectance targets should be extensively measured with a field spectrometer during data acquisition. A natural reflectance target needs to be homogenous, have minimal absorption features, and be relatively bright. A dark target is also useful for determining atmospheric scattering. Typical targets include playas or concrete parking lots as bright targets and deep water bodies or deeply shadowed canyons as dark bodies. The exact location of the bright calibration site should be identified with 2 tarps that are at least the size of 4 pixel set at least 8 pixels apart (this allows the target to be easily seen in the imagery). The area between the tarps is measured extensively with a field spectrometer (1,000's of measurements, typically). The average spectrum of this calibration area may then be compared with the airborne spectrum and used to correct the airborne data. In many cases artificial calibration targets may be more practical. They are more uniform and may be moved periodically if field access permits. The most logistically practical targets are 2 large tarps (at least 4x4 pixels in size) that are painted with black and white flat paint. The white target may be painted with standardized spectral calibration paint if desired (this is quite expensive). As long as the paint is well mixed and thoroughly measured spectrally, the results for standard paint should be adequate. Ideally each flight line should have a pair of targets placed at the elevation of interest. For high spatial resolution surveys with many flight lines this is logistically impractical. A single pair of targets for each survey day is adequate for most situations. For areas with significant elevation differences 2 pairs of targets, one near the elevation maximum and one near the elevation minimum, are preferred.

Hyperspectral aircraft survey operations function much as any geophysical survey. HSI surveys are flown barometric (fixed altitude MSL) with the flight altitude set so the mean elevation of the line has the desired pixel size. Survey lines are planned to minimize topographic variation on each line as much as possible. Normal medium resolution regional exploration surveys are flown with a nominal pixel size of 2-5m. The results in a nominal ground clearance of 2000 – 5000 m for an instrument with a 1 mr IFOV. Surveys are typically flown in an unpressurized aircraft with an open photographic belly port. This is due to the fact that glass covers on photographic ports significantly attenuate SWIR light. Specialized crystal windows are available that permit pressurized operation and are utilized by some survey companies for high altitude surveys. Line spacing is a function of IFOV, instrument swath width, altitude, and along line topography. In whiskbroom scanners the swath width is a function of the aircraft altitude and speed, in pushbroom systems it is a function only of altitude. In low relief terrain lines are flown with 30% overlap. This may increase to 40% overlap in high relief areas. As an example, the ProSpecTIR system when collecting 3 m resolution data in moderate terrain would fly approximately 600 m lines. Survey efficiency (total data acquisition time/total time in air) is a function of commute time to the survey area and, more importantly, survey geometry. Survey aircraft normally operate at approximately 200 km/hr (3.33 km/min) and the normal return to line time (turning the aircraft, lining up, and getting the instrument ready for data collection) is approximately 7 minutes (Wright, personal communication). The turn at the end of each line is equivalent to 23 km of data acquisition. Thus flight lines should be designed to be as long as possible. Complex survey shapes should be avoided: salients and re-entrants are inefficient – it is more productive to fly unneeded data than to fly a complex shape that matches a project area. Long rectangular surveys are the most efficient shape.

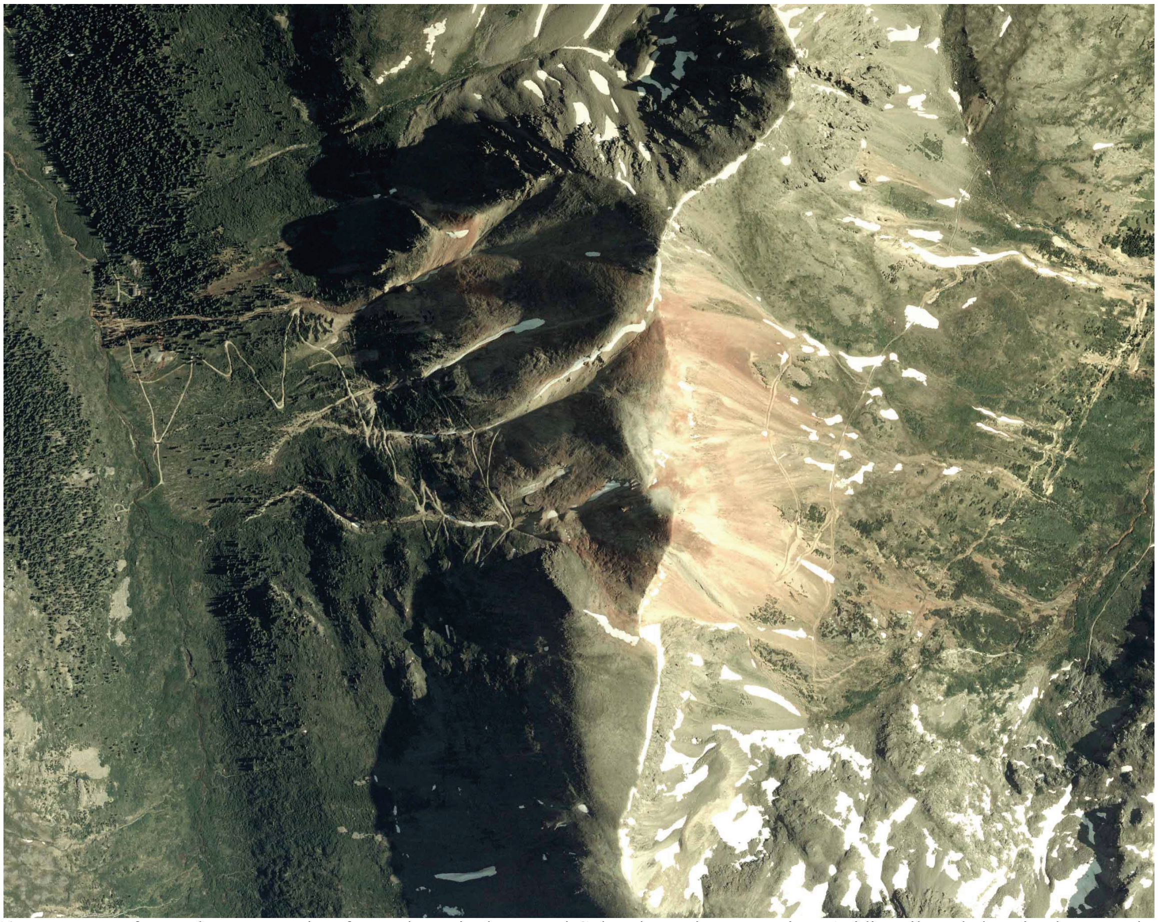

Figure 12: Exposure of a porphyry system in a forested area in the central Colorado Rocky Mountains. Acidic soils and elevation have resulted in the system being well exposed.

PROCESSING

Data processing methods for airborne HSI data have typically played catch-up to the data acquisition methods. Engineers design new instrumentation and the data analysts wait for operational surveys to figure out the best processing methods for the data. HSI data are subjected to three basic processing steps: radiometric calibration, geometric correction, and data inversion to mineral components through classification or unmixing. These topics are discussed in detail in Agar and Coulter (2007) in this volume but are summarized here.

Radiometric calibration is the process of converting the HSI instrument measurements to reflectance measurements that are as similar to laboratory reflectance measurements as possible. The first step in the process is the conversion of raw instrument data to the physical quantity of radiance at sensor (which is given in watts per steradian per square meter per micrometer – W sr-1 m-2 um-1). For compactness of storage, this is usually rescaled to a 16-bit integer and stored along with offset and scaling factors. As this correction is instrument dependent, it is always performed by the survey operator and is the lowest level dataset delivered. Radiance at sensor is the wavelength dependent light measured. It is, however, a convolution of solar energy, atmospheric effects (scattering and absorption), and ground reflectance (Figure 13). Since our interest is the ground reflectance, we must deconvolve the solar and atmospheric effects. This correction may be accomplished in a number of ways: data driven empirical methods, ground based empirical methods, model based methods, or hybrid methods. Data driven approaches are the simplest to use. The assumption is that by averaging the spectra of many pixels, the value converges on the average atmospheric spectrum. The data are then normalized to remove the average atmosphere. Internal Average Relative Reflectance (IARR) and Log Residual methods are based on this. While these methods are simple, they often are inadequate for airborne HSI data – particularly high resolution data as the spatial sample is small.

Ground based empirical methods require knowledge of the spectroscopic signature of identifiable locations on the ground surveyed. The Empirical Line correction method is used where a natural or artificial target with known spectrum is located within a survey area (the field methodology was described above). The method fits a channel by channel transfer function that converts the sensor radiance to the known ground response. This function is then applied to all pixels in the image. Dark targets are used to define and remove the scattering component (which is additive) and bright targets the absorption component (which is multiplicative). This approach may be affected by significant changes in atmospheric conditions between the time and location of the target overflight and data collection. Significant elevation differences between the calibration target and measured ground will cause problems as well as changes in weather (particularly the relative humidity). The Flat Field method is similar to Empirical Line except that a target with a known relatively flat spectral response is identified in the image. Relatively clean quartz exposures are good Flat Field targets.

Model based correction methods utilize a mathematical and/or empirical model of the atmosphere to calculate local atmospheric composition. A number of software packages are available to accomplish this including: MODerate spectral resolution atmospheric TRANSmittance (MODTRAN), Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH), ATmosphere REMoval program (ATREM), Atmospheric COrrection Now (ACORN), and High-accuracy Atmospheric Correction for Hyperspectral data (HATCH). All of the model based corrections require knowledge of the location, altitude, date, and time of image acquisition. When correcting hyperspectral data the local atmospheric conditions (primarily water vapour content of the atmosphere) are estimated from the data as the atmospheric absorptions are contained in the spectra. Typically, the estimated water vapour is calculated for each pixel in the image. The atmospheric model is then removed from each pixel in the image. Model based approach may be constrained to produce “realistic” looking spectra (i.e., minimize atmospheric artefacts), by a process called spectral polishing. Almost all model based corrections produce atmospheric artefacts due to slightly inaccurate estimates of the atmospheric parameters and instrument specific artefacts.

Hybrid corrections utilize a combination of model based correction and the empirical line method. This approach is preferred by the US Geological Survey (Clark et al., 2002). The approach involves application of an atmospheric model to get a first approximation of the reflectance. The empirical line method is then applied to “tweak” the data for residual atmospheric and instrument errors. When applied properly, this method produces the best possible results.

The final processing step for HSI data is the generation of mineral maps. These may consist of classifications and/or mixture analyses. Classification produces a single dominant mineral for each pixel in the image whereas mixture analysis produces an estimate of the apparent concentrations of minerals in each pixel. Software tools to accomplish these tasks are available from a number of commercial software vendors as well as academic and scientific organizations. The ENVI software package, however, is favoured by most hyperspectral analysts.

The most popular classification methods for mineral analysis are Spectral Angle Mapper (SAM), Spectral Feature Fitting (SFF), and Spectral Correlation Mapper (SCM). SAM is a simple calculation that treats the n-dimensional spectral channel space as a Euclidean space. The angle between a target mineral spectrum and the spectra of every image pixel is calculated. A value of 0 indicates that the shape of the target and unknown spectra are the same. SFF is a more complex analysis that involves analysis of the shape of selected specific spectral absorption features. Metrics of absorption features for target mineral spectra are generated; typically depth, width, and asymmetry. These are compared with the metrics for the same absorption features from each image pixel and the best match is selected as the classification mineral. The USGS uses a customized version of SFF within an analysis package they call Tetracorder (Clark et al., 1999). SCM is similar to SAM in that it is a shape matching approach. The difference is that SCM calculates the cross correlation between the each target mineral spectrum and each image pixel spectrum; a value of 1 indicates that the shapes are the same and a value of -1 indicated the shapes are mirror images. SCM is particularly useful for smaller numbers of bands (e.g., a subset of the hyperspectral data or multispectral data) as SAM will indicate a match for spectra that are mirror images whereas SCM will differentiate these cases (Carvalho and Meneses, 2000).

A critical problem with classification methods for HSI data is that virtually no pixels contain a single mineral. The measured pixel spectra are most often a mixture of mineral spectra. Thus, spectral unmixing methods are preferred in most cases. The goal of unmixing is to separate the mineral spectra and assign a proportion for each mineral spectral component. It is important to note that the result of this process is the apparent concentration of minerals, as minerals with no spectral character may be present on the ground and are not represented in the spectral measurement. In addition, the relationship between the physical proportions of minerals and their spectral response is often non-linear (Clark 1983; Hapke, 1993), but modelled in most cases as linear. One of the most popular tools for spectral unmixing for geologic problems is Mixture Tuned Match Filtering (MTMF) (Farrand, 2001). This approach involves the calculation of an orthogonalized version of the n-dimensional spectral data that is ordered in terms of increasing random noise through a transformation called Minimum Noise Fraction (MNF)(Greene et al., 1988). After the MNF transformation is applied, the higher (noisier) MNF images are pruned. Finally, a common signal processing method called Match Filtering (MF) is applied to determine the approximate contribution of each candidate mineral spectra to each pixel spectrum (Farrand, 2001). The MF approach may be applied directly to the raw data but is unstable due to the highly correlated nature of hyperspectral bands (i.e., HSI bands are not linearly independent) which results in singular matrices that must be inverted as part of the calculation. Methods are also available to perform a direct inversion of the linear unmixing problem with matrix algebra (the problem is effectively one of simultaneous linear equations). Full unmixing approaches are often cumbersome in that they require that the spectra of every possible surface material be known. A different approach to unmixing called Optimized Cross Correlation Mixture (OCCM) analysis was presented by Coulter (2006) (also described in Agar and Coulter in this volume). This approach utilizes constrained optimization methods to identify the mixture of mineral spectra that most closely matches each image pixel spectrum.

New approaches to the complex problem of HSI data inversion are appearing regularly in the literature. The journals, IEEE Transactions on Geoscience and Remote Sensing and IEEE Geoscience and Remote Sensing Letters are common publishing points for new methods and algorithms.

COSTS

The cost of acquiring and processing HSI data varies with aircraft and instrument utilized, location, and survey specific geometry. Costs are reasonably accurate for the summer of 2007 but will vary with fuel cost changes and other factors over time. Twin engine aircraft are typically utilized and range from Cessna 320 class aircraft for moderate terrain to Learjets for extreme terrain. The type of aircraft used has less of an impact on costs than survey geometry as higher cost aircraft are faster and more efficient (e.g., can attain survey altitude faster and fly faster). The details of survey pricing are proprietary to the survey companies but some of the factors can be related here. There are the following basic operating costs: instrument cost (priced per day), aircraft and fuel costs (priced per hour including pilot), personnel costs (typically 1-2 operators and possibly a relief pilot – priced per day), and living expenses (priced as per diem per person). Weather stand-down days typically have a fixed price; mechanical and instrument down days are absorbed by the survey company. Some survey companies factor in weather delays and provide an all inclusive contract (“fly until completion”) while others allow the client to pay for weather days and take the risk of a partial survey (pay as you go contract or “fly until the money runs out”). All inclusive contracts are priced higher than pay as you go contracts but the risk of delays are borne by the survey company. The cost of all inclusive contracts ranges from $US100/ Line km (a project with moderate relief, predictable clear skies, and good infrastructure – e.g., many areas in N. America) to $150 / Line km (projects with high relief, unpredictable weather, and/or poor infrastructure – e.g., many parts of the Andes). The amount of ground covered is a function of the pixel resolution acquired and the sensor used. For the Spectir system flying 3 m pixels, a Line km covers approximately 1 km^2. These prices assume a reasonably large survey area – at 3 m resolution a survey should be at least 1000 km^2 – smaller surveys will result in significantly higher Line km costs. Acquisition costs include radiometric and geometric corrections and delivery of flight line data. The costs do not include mobilization and demobilization. These latter costs can very from a few thousand dollars to over one hundred thousand dollars depending on the country location, flight planning, permits, insurance, customs bonds, personnel transportation to country and logistics (the high end cost assumes a plane must be ferried considerable distance).

Higher level processing and data inversion costs vary significantly depending on the level of detail desired by the client. Basic analysis which includes mosaicing of flight lines to map sheets and generation of mineral maps for common alteration minerals is typically priced per square kilometre but is a function of the ground resolution. Pricing in the range of $30-$50 per km^2 for 3 m data is typical (1 m data will be about 10 times this per km^2 and 10 m data will be about 1/10). Advanced analysis which includes interpretation, integration with ground measurements and other data, and target generation is typically undertaken on a consulting basis.

CONCLUSIONS

Airborne hyperspectral imaging methods facilitate the identification and mapping of minerals directly associated with alteration and mineralization over exposed ground. No other airborne method used in exploration has this capability. While often ignored in the past due to high cost, limited availability, and lack of understanding of the method, HSI is undergoing renewed interest as advanced technology is making the method cheaper and more available. The maturing of data correction and inversion methods permits analysis of the data to be undertaken more rapidly and accurately.

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