A PORTABLE SPECTRO-POLARIMETRIC IMAGER: POTENTIAL MINE SAFETY AND GEOLOGIC APPLICATIONS

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ABSTRACT

A significant risk factor in assessing and modeling potential catastrophic slope movement in open-pit mines is the presence of argillic alteration in host rocks. High-resolution hyperspectral imagery operating in the visible to shortwave infrared can be a useful tool for identifying and mapping potentially dangerous argillic zones. We have conducted preliminary experiments with a new type of hyperspectral imager that employs an acousto-optic tunable filter, a variable retardation plate and a standard digital camera. The instrument we tested operates in the .5-1.0 micrometer range. A shortwave infrared instrument is planned, and mid-infrared instruments have been designed. An AOTF consists of an acoustic transducer that generates an acoustic wave that propagates through an attached crystalline substance. The wave sinusoidally modulates the refractive index of the crystal, selectively diffracting incident light according to its wavelength. The instrument also measures polarization signatures of reflecting surfaces as well as their spectral properties, opening up new areas of possible research. Images can be acquired and processed at 30 frames/second. The AOTF camera system offers numerous advantages to geologists. It can be used as an airborne imager or as a portable field device to image pit walls, outcrops, rock specimens or drill core. It can be adapted to image polished sections under a microscope, and it could be used in underground workings. Algorithms can produce processed images in real time (e.g., ratio images), and, because it is a camera system, aerial images can be orthorectified.

1.0 INTRODUCTION

The slope stability team at the National Institute for Occupational Safety and Health Spokane Research Laboratory has been investigating ways to detect and mitigate hazardous conditions that could lead to catastrophic slope failure in open pit mines. A contributing factor in many high-wall failures that we have investigated is the presence of mechanically incompetent argillically altered rock in pit walls. We are investigating imaging spectroscopy as a means of mapping the geology of active mines, especially argillic zones in open pit highwalls. Imaging spectrometers in use today operate exclusively as airborne instruments and lack the flexibility and cost effectiveness for operational use in a mine. Our investigations have led us on a quest for a field-portable imaging spectrometer capable of obtaining high-resolution imagery from a variety of platforms at any scale and in a wide range of environments.

The system that we describe in this paper is based on an acousto-optic tunable filter (AOTF), a device capable of obtaining spectral measurements for an entire scene at 30 microseconds per spectral band. The system uses an off-the-shelf CCD camera, which allows image rectification through standard photogrammetric techniques. It also includes an optional liquid-crystal phase retarder which allows independent filtering based on polarization signatures in a scene. Designed for operation as a field-portable device in demanding outdoor environments, the device is rugged, compact, and modular. Its design offers unprecedented flexibility and permits microscopic to telescopic imaging in a wide range of configurations under open sky or artificial lighting conditions.

2.0 AOTF SPECTRO-POLARIMETRIC IMAGER

The spectro-polarimetric imager (SPI) consists of three parts: the camera enclosure, the control electronics, and the host computer. It operates much like an ordinary CCD camera, except that the spectral and polarimetric content of light to be viewed is electronically controlled by a computer. During operation, the host computer sends commands to the controller to select the desired spectral and polarization parameters. The controller interprets the commands, generates the required analog signals, and passes them to the camera enclosure. Finally, the incoming image is optically filtered and sampled by the camera, and the resulting video signal feeds back to the host computer where it is digitized by a frame grabber. The resulting data cube can then be further processed by standard multispectral and hyperspectral techniques.

2.1 AOTF CAMERA

The hyperspectral capabilities of the imaging system rely on the AOTF located in the camera enclosure (Figure 1). The AOTF itself is a tellurium dioxide (TeO_2) crystal with acoustic transducers bonded to the surface on one side. A radio-frequency (RF) signal applied to the transducers creates a traveling acoustic wave inside the crystal. As light passes through the crystal, it is optically filtered and spatially separated into three components: two are bandpass filtered according to the frequency spectrum of the applied RF signal, and one is notch filtered using the complement of the RF spectrum. The bandpass filtered components are plane polarized orthogonally to one another. The AOTF can switch between two bands in 30 microseconds and operates with a 10-nm spectral resolution over a range from 450 to 850 nm, corresponding to the visible spectrum and near infrared. The operating range of the AOTF is

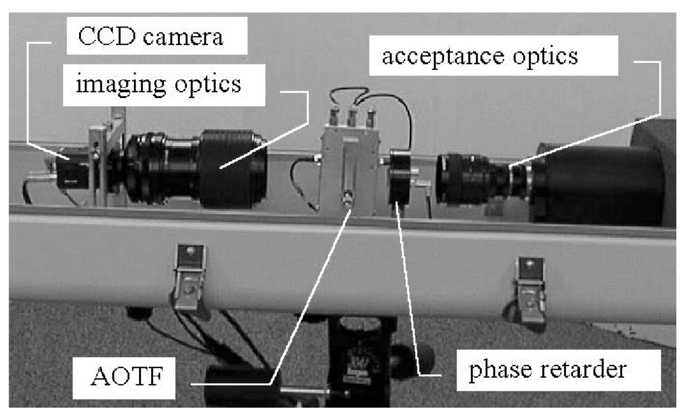

Figure 1. The AOTF camera in its housing (left), and the camera components within the housing (right).

chiefly determined by the choice of crystal material. We are currently investigating other materials that will extend the AOTF's range further into the infrared.

Following the optical path through the camera enclosure, incoming light first passes through the acceptance optics, which provide active zoom control and collimate the light before it passes through the phase retarder and AOTF. Using the active zoom on the acceptance optics, the camera's field of view is adjustable from 1.6 to 16 degrees. After passing through the phase retarder, light enters the AOTF, where it is decomposed into its three components. We align the imaging optics to focus the vertically polarized bandpass filtered image onto the CCD camera image plane while excluding the other two images.

2.1.1 Phase Retarder

The liquid crystal variable phase retarder provides optional polarimetric control for the imaging system. Conceptually, a retarder operates by resolving incident light into two orthogonal components with electric vectors oriented along what are called the fast and slow axes of the device. By varying the voltage applied to the retarder, we control the amount of phase delay between the components, achieving the overall effect of changing the polarization state of the incoming light. The AOTF acts as an analyzer by transmitting only vertically polarized light, and by varying the retardation, we change the intensity of light reaching the CCD camera.

For natural scenes in the visible spectrum, polarized light is predominantly linearly polarized, and under direct illumination from the Sun, Moon, or under overcast skies, the polarization of light is primarily horizontal. To observe the amount of horizontally linearly polarized light in a scene, we mount the retarder with the fast axis oriented 45 degrees from horizontal. If the input voltage to the retarder is set to achieve $\lambda/2$ phase delay, horizontally polarized light is rotated 90 degrees and becomes vertically polarized. In this case, the light would be transmitted by the AOTF. With no phase delay, the light is blocked by the AOTF. By switching between these two extremes, objects can be discriminated based on their polarization. By sweeping the retardation from 0 to $\lambda/2$, we can obtain polarization signatures of points in the scene including the polarization angle and magnitude.

2.2 CONTROLLER AND HOST COMPUTER

The controller acts as an intermediary between the host computer and the camera. Inside the controller, a Motorola 6816 microcontroller interprets the serial commands from the host computer and generates the necessary control signals for the retarder and the AOTF. The retarder voltage is controlled digitally using the manufacturer-supplied controller. However, generation of the RF signal for the AOTF is more complicated. The microcontroller programs up to four voltage-controlled oscillators (VCO), the outputs of which are combined and amplified to produce the RF signal. We control the frequency of each VCO independently, and amplitude control is achieved with a digital step attenuator.

Any computer with a serial port and a frame grabber can control the camera with no hardware redesign. Our goal is to use a laptop PC, making the system truly portable, but current bus bandwidth limitations on PCMCIA frame grabbers prevent video frame rate digitization. At this time, we are using a 200 MHz Pentium-Pro PC with an Image Nation PX500 frame grabber capable of capturing 30 frames per second.

2.3 OPERATIONAL MODES

The SPI offers unprecedented operational flexibility limited only by the imagination of the operator. Two control strategies lie at the extreme ends of this range of choices: sweep mode and switching mode. In sweep mode, we use a single VCO to perform a full spectral sweep over the functional range of the camera (450 to 850 nm), collecting 41 10-nm images. This method gathers the maximum amount of information in a scene. In switching mode, the camera alternates between a small number of parameter settings. The parameters for each image can use one VCO to acquire a single band in the scene, or they can be chosen to create more complex filters by combining multiple VCO's and the retarder. In the extreme, an arbitrary waveform generator could be used to generate arbitrarily complex filters. In switching mode, the system can be programmed to obtain real-time band ratio images.

3.0 ROCK SPECTRA

We obtained SPI data cubes at 10-nm resolution from a suite of rock specimens with spectral features or spectral contrast in the visible and near infrared. Various types of reflective surfaces were imaged as well, including metallic, glassy and granular surfaces. Foliated rocks, a slate and a mica schist, were also imaged to find out if rock fabric influences polarization signatures. Figure 2 shows reflectance spectra from four of these specimens: bastnaesite from Mountain Pass, California; azurite; dunite; and hematite stained tuff. Solid lines represent spectra extracted from SPI images, and dotted lines represent spectra measured with an ASD full-range spectrometer at one nm resolution and resampled to 10 nm resolution. We find good agreement between the SPI and ASD spectra, particularly in the 600 to 800 nm range, with a slight tendency of the two measurements to diverge below 600 nm and above 800 nm.

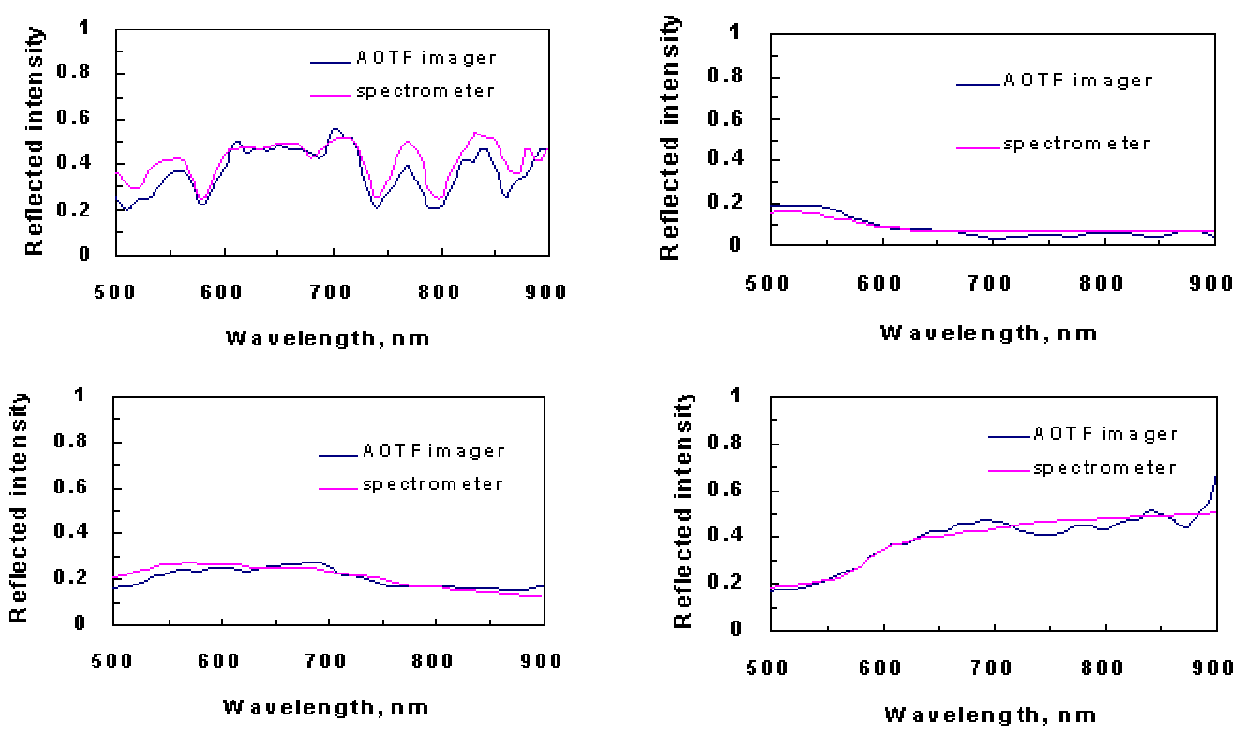

Figure 2. SPI and ASD spectra of bastnaesite from Mountain Pass, California (upper left); azurite (upper right); dunite (lower left); and hematite-stained tuff (lower right).

We did not find significant polarization differences in any of the specimens except from a metallic surface of pyrite where a slight difference was observed. Foliated specimens showed no polarization difference. This might be because the phase angle (the angle between line of sight of the camera and line of the illumination) was too small. We are planning further experiments to investigate possible relationships between polarization signatures and phase angle.

4.0 CONCLUSIONS

The current and planned versions of the SPI offer unprecedented imaging flexibility. The instrument can be adapted to operate as an aerial camera or as a field instrument where it could be used to image pit walls, outcrops, hand specimens and drill core. The device could also be used to map underground workings under artificial lighting, and it can be fitted to a microscope to image polished sections and drill cuttings. It is conceivable that a fiber-optic device could be adapted to be inserted into drill holes. Because it operates as a digital camera, standard photogrammetric techniques can be applied to the imagery, and because data are digital, conventional image processing and spectral matching techniques can be employed. Because the instrument is computer driven, spectral resolution can be pre-programmed and complex filters and specialized algorithms can be written to obtain band ratio or principal component images, for example, in near real time.

The SPI was designed to image dynamic scenes from moving battle field vehicles, so speed of data acquisition was paramount over noise and image fidelity. In most geologic applications other than aerial imaging, static scenes would be acquired. Noise and image contrast would therefore be more important necessitating longer exposure time or averaging multiple exposures.

We are developing designs to extend the spectral range of AOTF further into the infrared, particularly the all important 2-2.5 µm short wave infrared and 8-12 µm mid-infrared ranges where clays, carbonates and silicates can be mapped. This will require different crystalline substances to make the AOTF and different, and more expensive, focal plane arrays sensitive to these wavelength ranges.