A Real-Time Coal Content/Ore Grade (C^2OG) Sensor

Final Report

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ABSTRACT

This is the final report of a three year DOE funded project titled “A real-time coal content/ore grade (C^2OG) sensor”. The sensor, which is based on hyperspectral imaging technology, was designed to give a machine vision assay of ore or coal. Sensors were designed and built at Resonon, Inc., and then deployed at the Stillwater Mining Company core room in south-central Montana for analyzing platinum/palladium ore and at the Montana Tech Spectroscopy Lab for analyzing coal and other materials. The Stillwater sensor imaged 91’ of core and analyzed this data for surface sulfides which are considered to be pathfinder minerals for platinum/palladium at this mine. Our results indicate that the sensor could deliver a relative ore grade provided tool markings and iron oxidation were kept to a minimum. Coal, talc, and titanium sponge samples were also imaged and analyzed for content and grade with promising results.

This research has led directly to a DOE SBIR Phase II award for Resonon to develop a down-hole imaging spectrometer based on the same imaging technology used in the Stillwater core room C^2OG sensor. The Stillwater Mining Company has estimated that this type of imaging system could lead to a 10% reduction in waste rock from their mine and provide a $650,000 benefit per year. The proposed system may also lead to an additional 10% of ore tonnage, which would provide a total economic benefit of more than $3.1 million per year. If this benefit could be realized on other metal ores for which the proposed technology is suitable, the possible economic benefits to U.S. mines is over $70 million per year. In addition to these currently lost economic benefits, there are also major energy losses from mining waste rock and environmental impacts from mining, processing, and disposing of waste rock.

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INTRODUCTION

Problem addressed. An inexpensive, real-time instrument needs to be developed for dual use in process streams and at the working face to analyze solid materials for grade and content. This lack of information during the mining and processing phases negatively impacts the exploration, mining, and processing phases of mineral extraction and is a general problem in nearly all types of mining from coal to platinum and talc. Based on estimates compiled by Stillwater Mining Company in 2000, a real-time ore grading instrument could lead to the decrease in the amount of rock mined by 7% and the amount of waste rock by 25%. This would correspond to a 22% decrease in the amount of energy required for the mine's operation. Subsequent more conservative estimates of only a 10% reduction in waste rock would provide an estimated energy savings of 1.78×10^{11} BTU per year in the Stillwater Mine alone. Thus, even with the lower estimate and only moderate adoption, hyperspectral imaging based technology could easily provide savings well over 1×10^{12} BTU per year. With rising energy costs, these benefits are even greater today than when this project began.

Solution. In many cases an expert can reasonably estimate coal content or ore grade by visual inspection. For example, the core room Geologists at the Stillwater Mine routinely visually inspect and grade exploratory core drilled from or near the working mine face. They do this by estimating the amount of sulfide that is visible on the surface of the core. This suggests that a machine vision system might also be able to make the same ore grade estimate as the human expert.

Additionally, improvements in computer speed, decreasing costs for CCD cameras, and continual advancements in hyperspectral image analysis have made low-cost, spectral imaging solutions possible for a wide range of applications. Moreover, hyperspectral data can be used to distinguish between materials with colors of nearly identical shades and brightness. Although a substantial community recognizes the potential of spectral machine vision, we are not aware of hyperspectral imaging being applied to real-world industrial environments or for any applications requiring continuous (or even very frequent) operation, expect for experimental testing. Thus, hyperspectral imaging is a largely untapped technology for machine vision in industrial applications.

To exploit the opportunity presented by hyperspectral imaging, we originally proposed to design and implement a machine vision system for real-time analysis of solid materials. Although this type of system could never entirely replace the expert, it would have a number of advantages over its human counter part including better spectral resolution than the human eye, greater spectral range, and repeatability. These imaging systems could also be deployed in situations where it is either too expensive or where humans introduce errors due to fatigue, such as over conveyor belt systems for continual monitoring and sorting, and in places where people can not go, such as blast holes, or where it might be too hazardous.

The machine vision system designed, fabricated and deployed for this research project utilizes imaging spectroscopy technology (also called hyperspectral imaging). This type of imager acquires a digital image of a surface while simultaneously measuring the reflectance spectrum of each pixel in the image. Using the same CCD based imaging technology as digital video, imaging spectrometers can be designed to provide spectral information over hundreds of very narrow bands ranging from the ultraviolet (UV) region, through the visible and into the infrared (IR). Just as color can often be a distinguishing characteristic of some minerals, the spectral signatures obtained with an imaging spectrometer can be very distinctive for a number of rock forming minerals.

Not surprisingly, the high spectral resolution possible with modern spectrometers allows them to be used to determine mineral content in situ and in remotely sensed images. Large libraries of mineral spectra are presently being compiled.[1] Others have noted that artificial vision utilizing color cameras can be useful for real-time ore grading, and a hand-held spectrometer has been developed for real-time ore evaluation purposes.[2,3]

Research Objectives: As noted above, despite its promise, hyperspectral imaging had not been utilized in working mines when this project started. Consequently, our primary goal was to develop an imaging system for real-time analysis of coal and ore. The objectives we originally outlined in order to achieve this goal are listed below by year:

- **Year 1:** Identify and optimize the signals that would be used to sense the minerals of interest and develop the computer algorithms required to recognize the spectral signatures in the data. This information was critical in helping to determine key details in the design of the sensor and software. Real time operation also meant optimizing and economizing on the algorithm design. Algorithm exploration, development, verification and implementation actually extended over the full three years of the project as we learned more about the variability in the ore and coal and the types of problems that can be encountered in a less than ideal environment and target for imaging.

- **Year 2:** Design and fabricate one or more sensors for calibration, testing and evaluation. The objective of this phase of the effort was to design an imaging instrument that would accurately differentiate the signature spectra of interest from the host rock. The problem was to determine the most economically feasible imaging system with sufficient spectral and spatial resolution necessary to accurately and quickly determine mineral content in the samples after the appropriate data manipulation.

- **Year 3:** Deploy a real-time C^2OG sensor in a working mine for long term monitoring and evaluation. It would be one thing to have an instrument that could operate in the laboratory, but quite another for it to operate in a working mine environment. To accomplish this objective, the instrument was set up to scan and grade drill core at the Stillwater Mine near Nye, Montana. For the proposed instrument to be marketable to mining companies, it would need to be able to operate for extended periods of time in mining environments. This would require the development of maintenance schedules and troubleshooting any problems that develop after extended use.

Achievement of Objectives. As discussed in more detail in the main body of this report, all but a couple of the objectives outlined above were achieved to our satisfaction. In the first and second year of the project we found that a line scanning imaging spectrometer system provided the most accurate method of analyzing ore. Although more expensive than a digital color camera (~$10,000 vs. ~$1,000), it was clear that the added spectral resolution was critical to obtaining the data required to accurately image and grade the core. (Color cameras provide 3 spectral bands, whereas the spectral imaging camera developed and used by Resonon provides 213 spectral bands.) It was also clear that a scanning hyperspectral imager with 200+ narrow contiguous spectral channels could be built at the same cost or cheaper than a multi-spectral system with only a half dozen broad spectral channels.

We found that the spectral angle mapping (SAM) algorithm provided a quick and efficient analysis of the spectrometer data and could easily be implemented in a real-time scanning system. (It should be noted that there are numerous algorithms currently available and many more will likely be developed that have greater capabilities than SAM, but currently are too slow to utilize for real-time applications. With improvements in computer speed and more efficient coding, it is clear that these algorithms will provide improved functionality for hyperspectral machine vision applications in the future.) Several C^2OG sensor systems with imaging spectrometers were designed and fabricated at Resonon, and then used at Montana Tech for characterizing Stillwater ore as well as other material with potential applications such as coal, talc, titanium sponge, wheat grass, and biofilms. In addition to the hardware, the software interface was engineered and beta tested at both Resonon and Montana Tech. The software provided a human interface with the imaging system, as well as controlled the data acquisition, performed the data analysis, provided data visualization and logged the results. The eventual marketing of the C^2OG sensor by Resonon required that the software interface be straight forward and intuitive for people who were not experts in imaging spectroscopy. In the second and third years, a core imaging system was designed, fabricated and then deployed at the Stillwater Mine core room. During what amounted to about two weeks of operation at the mine, we did not experience any system breakdowns. Although this made it impossible to establish a maintenance schedule, overall it is good news.

The objective of implementing real-time analysis was achieved in the laboratory. It was not implemented at the mine due to some quality control problems discussed below, but there do not appear to be any fundamental hurdles to deploying it in a mine. Real-time data analysis is planned for the SBIR Phase II project that resulted from this effort. The data acquired during the third year at Stillwater was processed at Montana Tech and Resonon. This situation presented another interesting hurdle during the third year of the project. The volume of hyperspectral data acquired during the two weeks at Stillwater required that batch processing software be written and implemented. Although not initially planned, this software was essential for data analysis and significantly advanced the technology for mining applications.

Technical Results. Hyperspectral data was collected and analyzed for three possible mining applications during this effort: (1) identifying defects in titanium sponge in samples from Timet, Inc.; (2) grading coal ore by identifying pyrite (associated with sulfur) and shale (associated with ash) in samples from the Rosebud mine in south-eastern Montana; and (3) measuring sulfides in platinum/palladium (Pt/Pd) ore from the Stillwater mine in south-central Montana. Hyperspectral data was successfully used to identify the defects in sponge, the pyrite and shale in coal, and sulfides in the Pt/Pd ore. Thus, in principle hyperspectral machine vision could potentially be used for all three of the potential applications tested for.

For reasons discussed below, the majority of this effort concentrated on sulfide detection in Pt/Pd ore. The primary technical results for the measurements taken on Pt/Pd ore are shown in the scatter plot of Figure 11. In brief, Figure 11 shows a positive correlation between the sensor ore grade estimate (% visible sulfides) and the mine's assay of the same ore. Although the sensor and acquisition software worked flawlessly after some minor adjustments, we did encounter the type of "real world problems" one expects, but can not easily predict. Once in the core room, we found that the SAM algorithm was prone to mistaking yellow chalk marks, iron oxide stains, and tool burnishings for pathfinder sulfides. Although once this type of commission error is recognized, the algorithm can be modified to minimize the misclassification. However, even with 95% removal of these errors, the problem was so pervasive on some core that about 33% of the data we recorded was discarded. This did tell us, however, that most of the problems we encountered were associated with the extraction, handling and storage of the core and not the mineralogy of the ore itself. These are problems which can be greatly minimized simply by cleaning off the core before scanning. More importantly, these problems will also be less prevalent or non-existent at the working face and in the borehole where the sensor is most likely to be deployed in the future.

Assessment of Commercial Potential. The commercial potential for hyperspectral imaging requires could be called "fair" in that it has strong positive features: (1) there is no direct competition and very little indirect competition; and (2) the mining industry is receptive and tolerant to new technology; and strong negative features: (1) the mining market is highly volatile; and (2) the mining market is relatively small and highly fractured (every mine requires unique R&D). Because mining provides a good development platform for new technology, Resonon will continue to pursue it via: (1) an SBIR Phase II to deploy the technology in blast holes (Mount Sopris, a leading borehole instrumentation company, will likely market the instrument); and (2) we are exploring the utilization of the technology in surface mining with Barretts Minerals (talc) and Phelps Dodge (sulfides). (It is unfortunate that the DOE Mining program is no longer available to assist in the development of this promising technology for mining applications.)

In a broader perspective, advances made during this effort have helped Resonon obtain funding for other applications of hyperspectral imaging, including: several commercial sales; an NSF STTR Phase I for proteomics research; and DOD SBIR Phase I and Phase II awards for Unmanned Airborne Vehicle (UAV) remote sensing applications. Additionally, we are now getting requests for quotes nationally and internationally for our systems.

Considerable additional detail on the benefits and market for a hyperspectral down-hole probe are provided later in this report.

EXECUTIVE SUMMARY

Project Objective. The primary goal of this research was to develop a real-time coal content/ore grade (C^2OG) sensor that could be used for exploration, mining, and processing. The C^2OG sensor is built around hyperspectral imaging technology which utilizes the unique reflectance spectra of the minerals of interest to quantify coal content and ore grade. The project team at Resonon, Inc., Montana Tech and Stillwater Mining Company took this idea from concept to the design, fabrication, and deployment of an instrument in the Stillwater Mine core room (see Figure 1). A similar system has been set up at Montana Tech to analyze coal, talc and other materials from mining and industry for content, grade or quality. The system uses digital imaging technology that can generate a map in real-time indicating ore grade or coal content (see Figure 2). With modifications this instrument can be made suitable for use in both open pit and underground mining operations either at the working face or where particulate matter is being processed.

Figure 1. The C^2OG machine vision system. The imaging spectrometer is the black box near the top of the tower. The translation stage just below the spectrometer emulates conveyor belt motion. The C^2OG sensor is a scanning system requiring the sample and imaging spectrometer to be in relative motion. The sensor deployed in the Stillwater Mine core room uses a core roller rather than the translation stage. Any laptop or desktop computer with a firewire (IEEE1394) port can run Hyperfire, the control and data acquisition software written at Resonon for its imaging spectrometers. Since starting this project, Resonon has begun modifying this system for other applications in mining as well as applications in remote sensing, agriculture and microscopy.

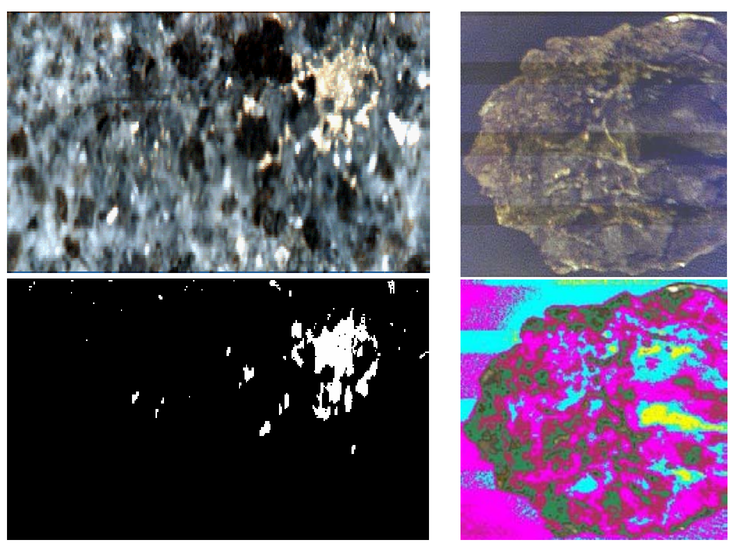


Figure 2. C^2OG images of Stillwater core (left) and contaminated coal (right) (vertical dimension is about 7 cm in each image). Below each image is the corresponding classification map result. For the Stillwater core, white indicates sulfide and black indicates non-sulfide. For the coal, green, brown, pink and maroon indicate impurities such as pyrite and shale. Aqua and yellow indicate regions of good coal. Note that some of the background has been misclassified. Using a different background material can eliminate this artifact.

Experimental Results. To assess the performance of the C^2OG sensor, we worked from the premise that the amount of visible sulfides in the Stillwater ore is an indicator of platinum/palladium (Pt+Pd) ore grade. The scatter plot in Figure 3 was obtained after imaging 91' of core at the Stillwater Mine. It shows the correlation between sensor result (% surface sulfides) versus the corresponding platinum/palladium assay. This analysis of sensor data shows a positive correlation and supports the premise that machine vision can deliver an indication of ore grade in real-time. The system did have problems mistaking some of the Geologists' yellow chalk marks, iron oxide stains, and tool burnishings for sulfides. It was clear that these problems were due to the extraction, handling, and storage of the core, which means that they may be much less prevalent or non-existent at the working face or in a borehole where the sensor is most likely to be deployed. .

Future Research. Interest in Resonon's machine vision approach for mining has increased as the technology has been pushed forward. Evidence of this includes the willingness of the Stillwater Mining Company to provide a platform for further development. Barretts Minerals, Dillon, Montana, and Phelps Dodge, Tucson, Arizona, have also expressed interest in developing an imaging system for real-time grade analysis at the working face of their mines. Resonon was awarded a SBIR Phase II last year from DOE to develop a probe based on the C^2OG hyperspectral imaging technology for down-hole ore-grading.

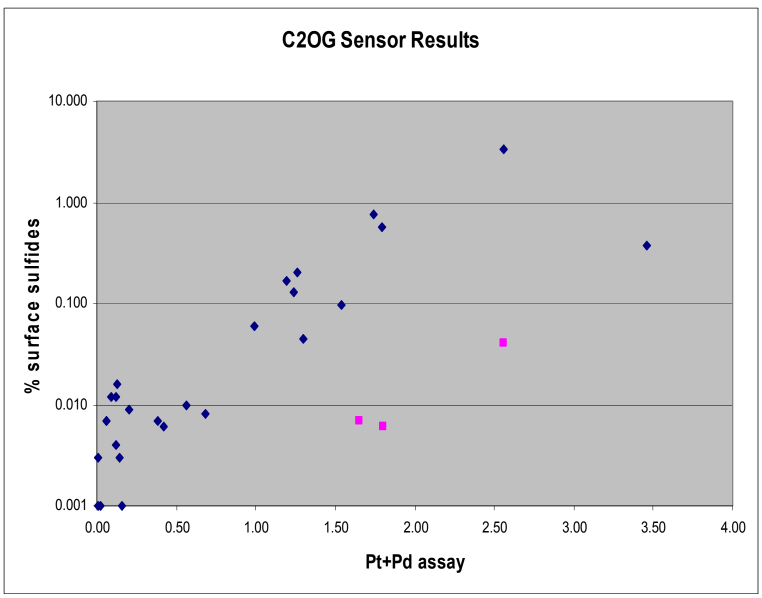
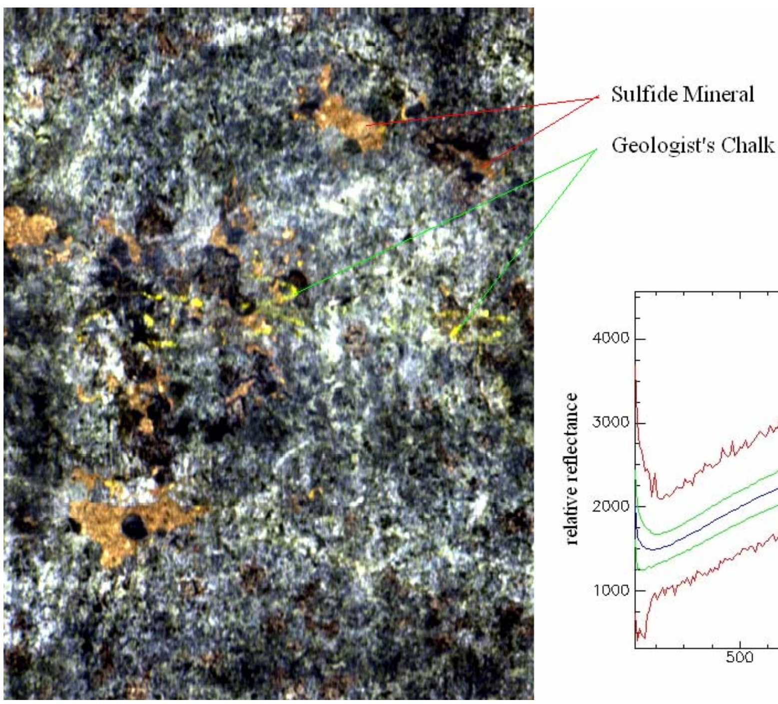
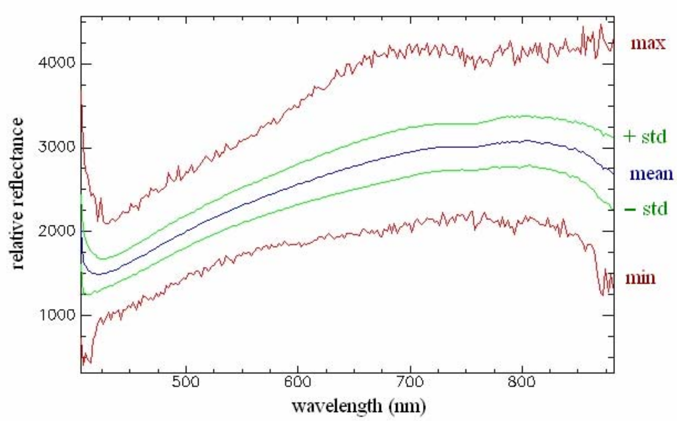


Figure 3. This scatter plot shows the correlation between surface sulfides and platinum/palladium ore grade (Pt+Pd assay). The blue data points support the hypothesis that sulfide minerals are positively correlated with ore grade. The pink data points are interesting outliers because they are from images where the sensor did not pick out the smallest sulfide flecks visible to the mine geologists. Although issues like these still need addressing, the implications with regards to robotics and machine vision applications in mining are far reaching.

EXPERIMENTAL

Year 1. Identify target spectra and explore algorithms. In year 1, we looked for distinct spectral signatures that could be used for mineral analysis in coal or ore. The pathfinder sulfides of the Stillwater platinum/palladium ore have a simple reflectance spectrum in the visible and near infrared (VNIR) that is distinct from most of the other minerals in the ore. Geologists at the Stillwater Mine use the sulfide minerals chalcopyrite, pyrrhotite, and pentlandite to obtain a visual assay of their ore for quality control during the mining process. Figure 4a shows an enhanced image from a C^2OG core scan with visible sulfides. Scans like this were used to calibrate the sensor for picking out sulfides in other Stillwater ore. Figure 4b shows the mean spectrum for the sulfide minerals in 4a. Much of the first year's effort is documented in the paper "Sulfide detection in drill core from the Stillwater Complex using visible-near infrared imaging spectroscopy", *Geophysics* , 68:1561-1568 (September-October 2003) by Brock Bolin and Tom Moon.



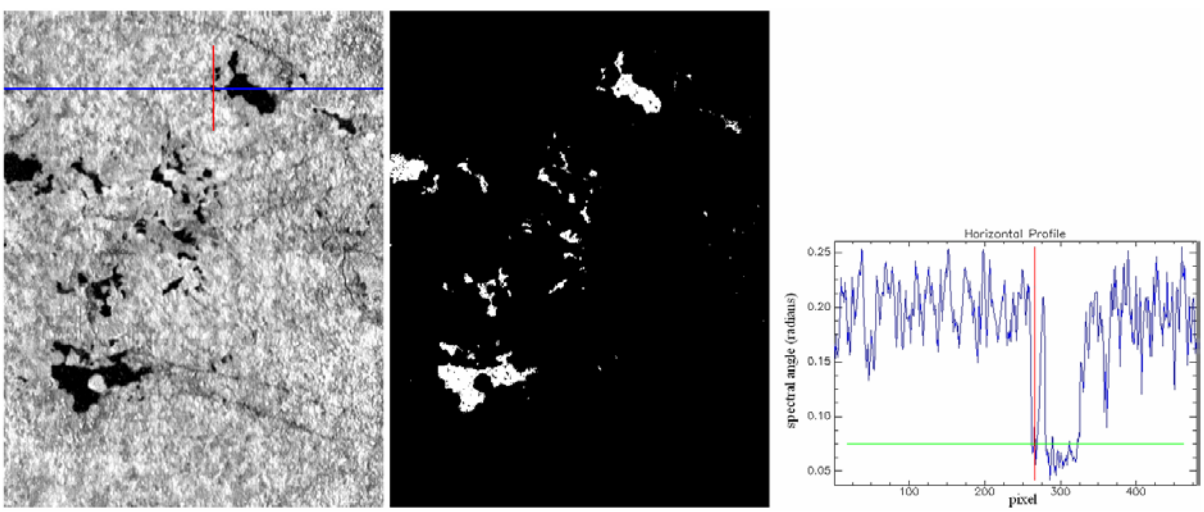


4a. 4b.

Figure 4. Image of Stillwater core from C^2OG scan (4a) and graph of mean spectrum of sulfide minerals in the image (4b). Each pixel in the scan has a 213 channel spectrum from about 405 nm to 882 nm (visible spectrum is from 400 nm to 700 nm). Several hundred of the gold sulfide pixels in 4a were manually selected for the calculation of the statistics shown in 4b. Even with uniform lighting, the sulfides showed enough variability to warrant the use of the full spectrum for accurate analysis of the data. Note the presence of the Geologist's chalk in the image which is part of their visual assaying. The horizontal dimension of the image in 4a is parallel to the center axis of the cylindrical core and is approximately 9 cm (480 pixels). The vertical dimension of the image is along the circumference of the core and is approximately 12 cm (625 pixels). The diameter of the cores is approximately 3.8 cm.

Algorithm development and implementation began in the first year and continued throughout the project. It was found that using spectral angle mapping (SAM) after a flat field correction for source removal was an efficient means of analyzing for sulfides [4]. It was found that the benefits gained by using more sophisticated algorithms were not significant and were offset by the additional time required for analysis, which was unacceptable for a real-time sensor. After deployment of the system in the third year of the project, however, it was clear that a simple application of the SAM algorithm may not be enough.

The SAM algorithm treats an n-band spectrum as a position vector in an n-dimensional space. It finds the angular distance between each spectral vector and a target vector using the dot product of linear algebra. For example, each pixel in Figure 4a has a 213 band spectrum (or 213 component position vector) and the mean sulfide spectrum in Figure 4b is the target vector. Figure 5a shows the angular distance between each of these spectral vectors and this target vector. The smaller the angular distance the darker the pixel in 5a and the more likely the pixel is a sulfide. The classification map in 5b shows the final result where sulfide pixels (white) are distinguished from the non-sulfide pixels (black). This result is obtained by thresholding the angular distance as indicated by the green line in 5c. In this case, only spectral vectors with angular distances less than the threshold value of 0.065 radians are classified as sulfide. Choosing the threshold was not always as straightforward as the data used in Figures 4 and 5 might indicate. Thresholds depended on lighting, the type and amount of sulfides in the core and the type of background minerals that are present.



5a. 5b. 5c.

Figure 5. Spectral angle mapping results for the pixels in the core scan of Figure 4a. Figure 5a shows the angular distance between each pixel in the scene and the mean spectrum of Figure 4b. The smaller the angular distance the darker the pixel in 5a and the more likely the pixel is a sulfide. A horizontal profile of the angles along the blue line in 5a is plotted in 5c. The vertical red line in 5a shows the location of a small sulfide bleb transected by the blue line. The classification map in 5b shows the final result were pixels are mapped as either sulfide (white) or non-sulfide (black). This result is obtained by thresholding the angular distance as indicated by the green line in 5c. Only the pixels with angular distances less than the threshold value of 0.065 radians are classified as sulfide. Choosing the threshold was not always as straight forward as the data used in Figures 4 and 5 might indicate.

Year 2. Design, fabricate and test sensor. The initial sulfide spectra that were acquired in year 1 suggested that a color digital camera might be sufficient for distinguishing sulfides from the host rock. Early trials quickly indicated that the variability in the sulfide and host rock minerals meant that more than the three bands from a digital color camera (visible red, green and blue) were needed to accurately and consistently image sulfides. It was also decided that wavelengths in the visible and near-infrared (VNIR) range would be sufficient for the imaging spectrometers. This allowed the use of common and relatively inexpensive Si based detector arrays used in analog and digital video cameras. To go further into the infrared would require an InGaAs based imaging system with more than a ten fold increase in cost. It was also found that a scanning imaging spectrometer with several hundred spectral bands could be built for about the same cost as a multispectral system with only four or five bands. The optical design of the imaging spectrometers built at Resonon for this project are based on a "push broom" scanner design used in a number of airborne sensors for remote sensing applications [5]. A cartoon diagram of the basic design is shown in Figure 6. This type of push broom scanning system requires relatively inexpensive fore-optics and only a single detector array to obtain hundreds of bands. A multispectral system would either require a detector array for each band with relatively expensive prism array fore-optics or a single detector array with a variable band filter, again a relatively expensive component. The Resonon imaging spectrometers based on the design used for this project are now being marketed for about $12,000. Their nearest competitor sells an imaging spectrometer system for about $50,000. A scratch built multi-spectral system would likely be at least $10,000 and possibly much higher.

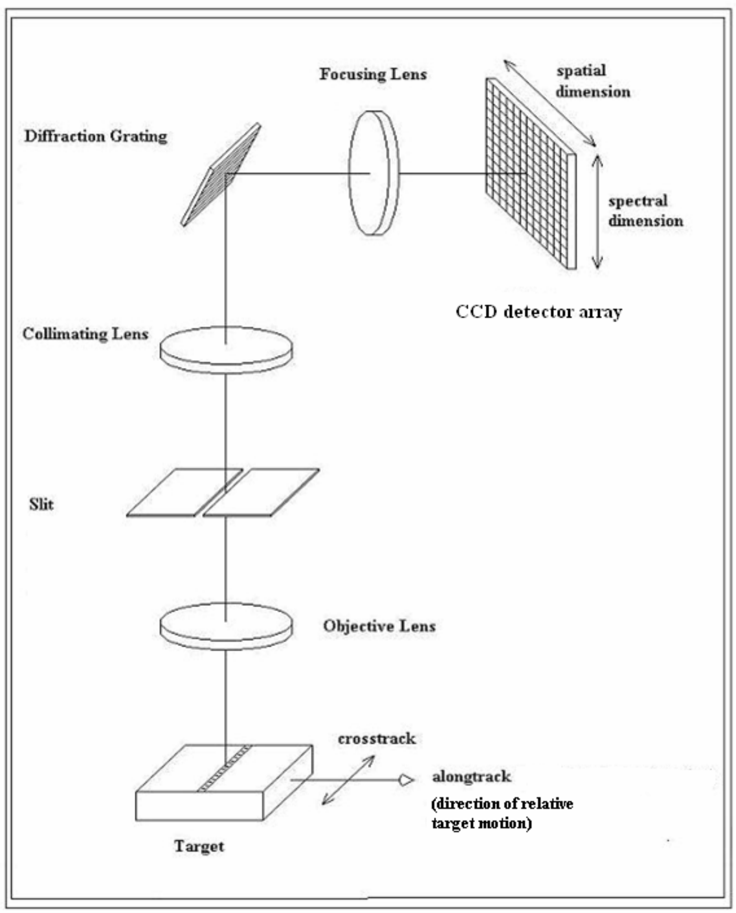


Figure 6. Cartoon of the "push broom" scanner imaging spectrometer system used in the C^2OG sensors. The scanner images only a single line of the target material at a time. Light from each pixel in the line is dispersed by a diffraction grating in order to image its spectrum on the CCD detector array from a digital video camera. In effect, hundreds of images are made of the line simultaneously with each image being made from light at a different wavelength. Aside from choosing and aligning the optical elements, the only other complication is building the image from each line scan. Since only one line of the target material can be imaged at a time, the target and spectrometer must be in relative motion. In remote sensing systems the spectrometer is on an airborne platform that moves over the ground. For this project the spectrometer was fixed while the target material was moved on a translation stage or rolled in the case of the Stillwater core.

Much of the early work in software and algorithm development with prototype imaging spectrometers was performed at Montana Tech of the University of Montana. Figure 7 shows one of the early prototype Resonon imaging spectrometers in the Montana Tech Spectroscopy Lab. The Tech team was tasked with looking at platinum/palladium ore and coal, and exploring other possible applications in talc, biofilms, titanium sponge, and wheat grass. Three master theses were completed by graduate students who were supported by DOE and Montana Board of Research Commercialization Technology (MBRCT) funding for this project (see Bibliography). The work on coal parallels the discussion on platinum/palladium ore with an emphasis on coal quality with regards to ash, pyrite and other impurities (see Figure 2). The results of the coal research are discussed in the following section.

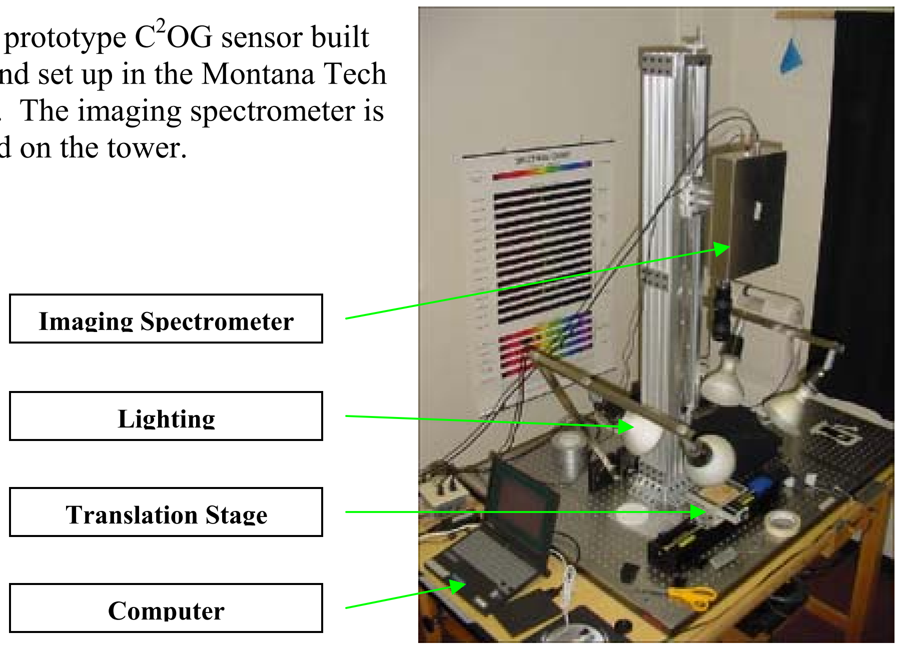


Figure 7. An early Resonon prototype C^2OG sensor built during year 2 of the project and set up in the Montana Tech Spectroscopy Lab for testing. The imaging spectrometer is in the aluminum box mounted on the tower.

Year 3: Deploy a real-time C^2OG sensor in a working mine. During year 2 several push broom scanner type imaging spectrometers with various design modifications and versions of control and acquisition software were fabricated at Resonon for this project (see Figures 1 and 7 for example). The imaging spectrometer eventually deployed at the Stillwater Mine during year 3 had a spectral range from 405 nm to 882 nm and a spatial resolution of about 0.2 mm. This configuration delivered a datacube having 213 spectral bands with a nominal bandwidth of 2.25 nm (see Figure 8). While the swath is presently fixed at 480 pixels, the length of the datacube in the image plane is only limited by the size of the hard drive of the computer running the control and acquisition software.

The complete C^2OG sensor system includes imaging spectrometer, software, computer, lighting, and translation stage. As mentioned in the previous section, the stage is necessary because the imaging spectrometer is a push broom scanner that requires the target and spectrometer to be in motion relative to each other. For desktop units like the one in Figure 1, the spectrometer is fixed while the sample is placed on the carriage of the translation stage which is in motion during the scan.

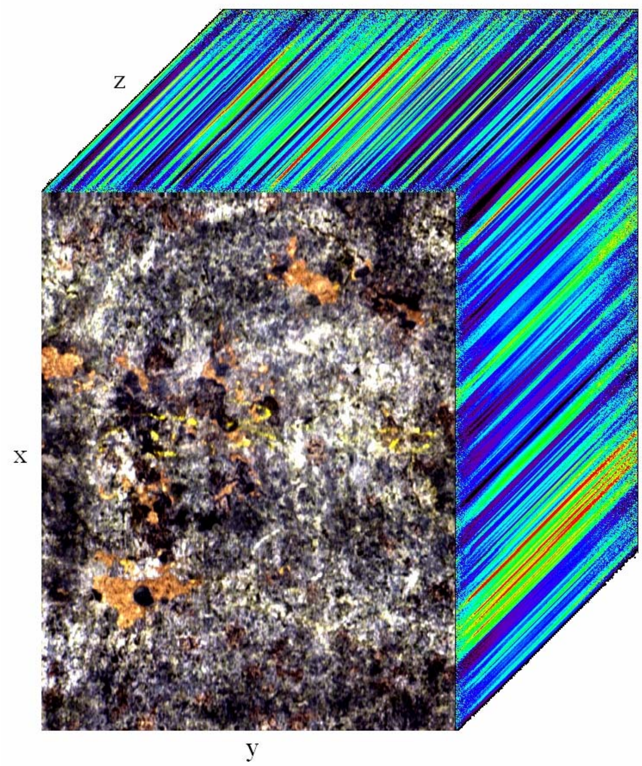


Figure 8. This is a graphical representation of the C^2OG imaging spectrometer's 3-D data product or datacube for the core scan of Figures 4 and 5. The Z dimension is the spectral or band dimension while X and Y are the spatial or image plane dimensions. Scanning proceeds in the X direction. Y is the cross track dimension or swath. Each pixel in the X-Y image plane has a spectrum in the Z dimension. Each row parallel to the Y dimension is called a line. The spectrometer builds the datacube one line (Y - Z plane) at a time. This datacube has 625 lines along the X dimension and a Y dimension swath of 480 pixels. A maximum scan rate of 30 lines per second was used for this project. Between line acquisitions, the C^2OG sensor software can flat field correct the data and obtain the SAM result. Scanning can continue indefinitely and is only limited by the size of the computer's hard drive.

The control and acquisition software developed at Resonon, called Hyperfire, utilizes a firewire (IEEE 1394) interface. Figure 8 shows a screen shot of the Hyperfire Graphical User Interface (GUI). The software is icon driven and was designed with the objective of being straightforward for the non-expert to navigate. Stage control and preview functions are available through the interface. The "running man" icon on the toolbar is used to initiate a scan. Hyperfire can be set up to acquire datacubes of any length with the only limitation being the size of the computer's hard drive and how much is stored with each scan. Source removal and SAM can be implemented in real-time as data is acquired up to 30 lines per second (one line is 480 pixels). Real-time acquisition can be set up to run indefinitely.

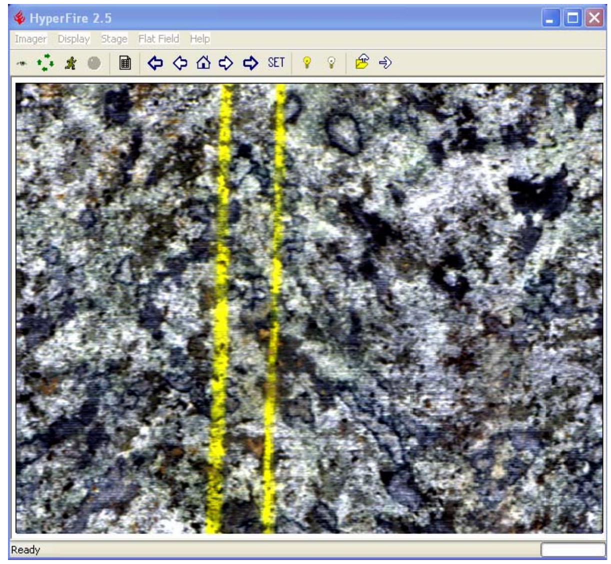


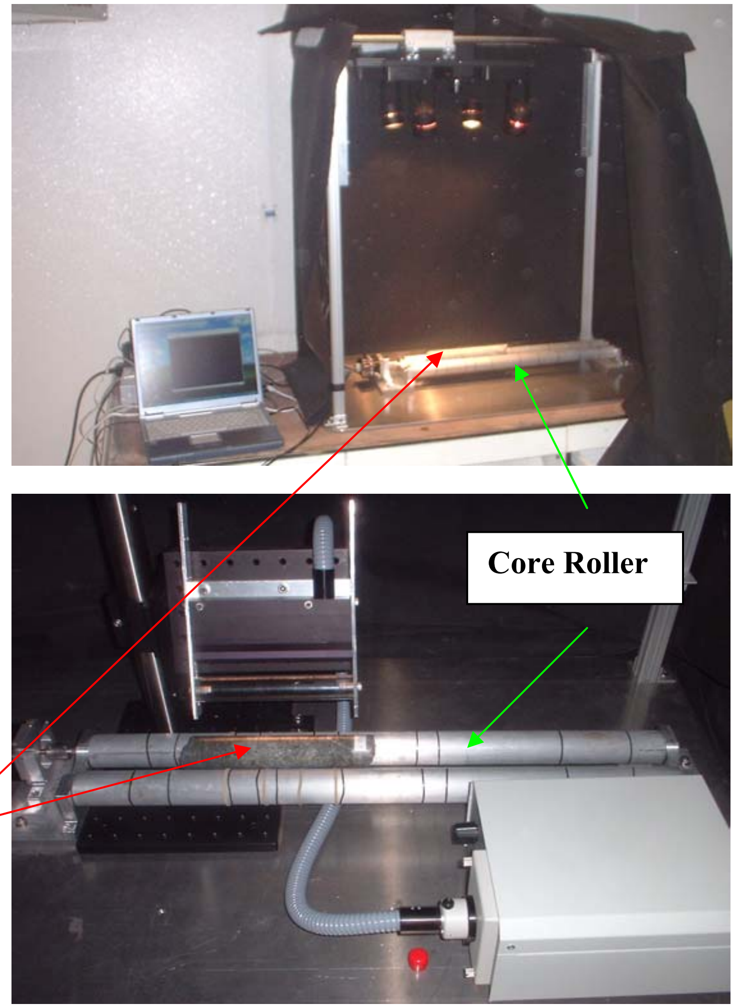
Figure 9. A screen shot of the Hyperfire control software developed by Resonon for its imaging spectrometers and the C^2OG sensor. The preview image is from a scan of Stillwater core in the mine's core room. Note the two Geologist's chalk lines indicating the presence of sulfides. Sulfide minerals are also visible in the preview image and appear dark orange in this figure. This image is formed in a waterfall display as the core is being scanned making on-site quality control straightforward.

Deployment of a C^2OG sensor in a working mine was the project objective of the third year. Figure 10 shows the instrument set up with laptop, imaging spectrometer, lighting and core roller in lieu of a translation stage. About a 10 cm section of core could be imaged at a time to obtain a pixel size of about 0.2 mm as suggested by the Stillwater core room Geologists. The core imaging data shown in Figures 4, 5, 8, 9 and 12 were acquired with this system. The system was operated at the Stillwater Mine for approximately 6 hours a day continuously for 10 days without breakdown and showed no special maintenance requirements beyond set up and daily lens cleaning.

From the beginning of the project it was clear that light needed to be delivered to the ore from as many directions as possible. Sulfides, like most rock forming minerals, reflect light differently depending on the angle of the incident light and the angle of the reflected light that is gathered by the instrument. Our solution was to develop an "integrating" cylinder that delivers light from a wide range of angles to the core surface being imaged. Ideally, the reflected light is the average of all the possible reflected angles off the surface of the sulfide minerals. The result is a sulfide signature that is less variable from mineral to mineral. This approach also allowed us to put more light on the target and increase the instrument signal-to-noise ratio.

The problems discussed in the Results and Discussed section that follows kept us from implementing the real-time feature of the C^2OG sensor. Instead of being able to analyze the core on the fly as scanning took place, the datacubes acquired in the Stillwater core room were taken back to Montana Tech and Resonon for analysis. This situation presented another interesting hurdle during the third year of the project. The volume of hyperspectral data acquired during these two weeks at Stillwater (320 datacubes) required that a batch processing software be written and implemented since this type of hyperspectral analysis software is not generally available. As it turns out, batch processing of large datacube sets is atypical in hyperspectral remote sensing applications where fewer than 10 datacubes or "scenes" might be analyzed during a project. Although real-time processing is the goal, this extra task did leave us the necessary tools and understanding for processing large sets of datacubes.

Figure 10. These two pictures show the C^{2}OG sensor set up in the Stillwater Mine core room. The imaging spectrometer is only visible in the top picture, but is difficult to see. It is in a black box just above the four halogen lights at the top of the frame and is essentially identical to the one shown in Figure 1. The cores were imaged by rolling them like hotdogs. Several lighting arrangments were tried. Halogen track lights are shown in the top picture while a fiber optic line lighting system is shown in the bottom image. The final solution was a line light and integrating cylinder made from a 15 cm section of 10 cm diameter PVC pipe coated with Avian white reflectance coating (not shown).



RESULTS AND DISCUSSION

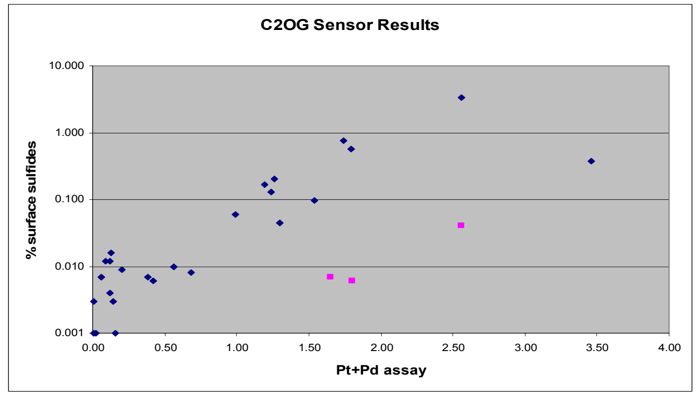
The question we will attempt to answer here is: Does the C^2OG sensor system that was deployed at the Stillwater mine solve the problem for which it was designed? We recognized that an inexpensive, real-time instrument or sensor was needed in the mining industry to analyze solid materials for grade and content. Our solution was to design and implement a machine vision system based on spectral imaging for real-time analysis of solid materials. The cost issue will be answered first, and then the more technical question as to whether or not the C^2OG sensor can deliver an analysis of grade or content in real-time will be addressed.

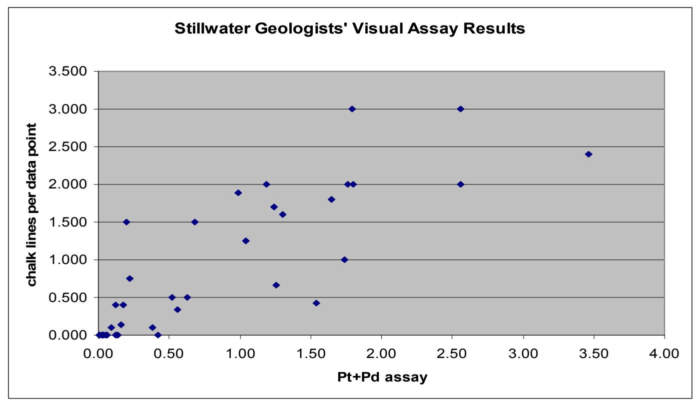
Instrument Cost. Largely, as a result of the research done for this project, Resonon presently offers a desktop hyperspectral imaging based unit like the one in Figure 1 for $12,000. The cost for configuring this system for different applications, such as core scanning as shown in Figure 10, would be approximately the same. Although core scanning was an important test of the instrument's capabilities, as discussed below, it is probably not how this technology will be implemented in the immediate future. Last year, Resonon was awarded an SBIR Phase II from DOE to build a down-hole imaging spectrometer for ore grading. The cost of this instrument is likely to be in the $50,000 range. Stillwater estimates they could utilize 3-4 of these borehole imaging/IP probes in their operations. Provided they reduce the amount of low grade ore that is extracted by 10%, and increase the amount of high grade ore by 10%, Stillwater estimates that the probes would pay for themselves in about 1 ½ months. If the probes just lower the amount of extracted low grade ore by 10%, then it would take about 6 ½ months for the probes to pay for themselves. Given the environment in a mine, a plausible average lifetime of the sensor system is 2 years, and therefore represents a cost effective investment for the Stillwater mine.

Instrument Performance. Of course, cost is irrelevant if the instrument can not do the job for which it was designed. The sensor's performance as a visual ore grader and coal content analyzer was evaluated by scanning Stillwater core in the Stillwater Mine core room and by scanning coal samples from Western Energy at Montana Tech. In both cases, a correlation was obtained between the C^2OG sensor results and an independent ore or coal analysis result. Although some problems were encountered that still need addressing, both cases suggest a positive result for the sensor. These results are discussed in more detail below.

Platinum/palladium ore grading. During the third year of the project, the C^2OG sensor system was set up in the Stillwater Mine core room where it scanned 91'of core. These scans were analyzed for surface sulfides as described in the EXPERIMENTAL section given above. The working assumption at Stillwater is that the amount of visible sulfides is an indicator of ore grade. Consequently, the sensor data provided an estimate of percent surface sulfide for the core that can be compared with the mine's assaying of this core. The results of this analysis are shown in the top scatter plot of Figure 11. For comparison, the results of the Geologists' corresponding visual assay of the same core are seen in the bottom scatter plot in Figure 11. Both plots qualitatively support the assumption that visible sulfides are indicators of platinum/palladium (Pt+Pd) ore grade. This is an important result and shows that the instrument can deliver an ore grade at least as accurately as its human counterpart. There are, however, some key issues that still need resolving.

Figure 11. These two graphs show the correlation between visible surface sulfides and platinum/palladium ore grade (Pt+Pd assay). The top graph correlates the Pt+Pd assay with the C^2OG sensor measurement of % surface sulfides. The bottom graph correlates Pt+Pd assay data with the visual assaying done by Stillwater Geologists ("chalk lines" per data point). Both graphs support the hypothesis that sulfide minerals are positively correlated with ore grade. The pink data points in the top graph are interesting because they are outliers from the general trend and are from images where the sensor did not pick out sulfide flecks that were seen by the Geologists. Although some issues like these need to be addressed with regards to the acquisition and analysis of C^2OG sensor images, the implications are far reaching with regards to robotics and machine vision applications in mining





Figures 4, 9, and 12 are images from the datacubes of core scanned at Stillwater. In each image yellow chalk lines can be seen. These are placed there by the core room Geologists who do the visual assay of the core. No lines mean very low grade (no visible sulfides), and one to three lines indicate increasing amounts of visible sulfide. It was clear from the beginning of the core scanning that the amount of yellow chalk, tool marks and iron oxide being mistaken for sulfides meant we had to take the data back to Montana Tech and Resonon rather than using the sensor's real-time feature. Real-time analysis requires *a priori* knowledge of the spectral signatures of the problem areas. Although we eventually had success distinguishing most of these error classes from sulfides using the SAM algorithm, some images still showed too many obvious misclassifications to be usable.

The scan shown in Figure 12 is a good example of some of these problem areas. The datacube this image came from was unusable because of the tool markings. In addition to the commission errors due to the markings, this core section produced one of the few datacubes that had omission errors. In this case the sensor did not resolve the smallest sulfide flecks visible to the Stillwater geologists. This type of omission error could be corrected by moving the imager closer to the core and thereby decreasing pixel size and increasing the spatial resolution. The trade off would have been more scans to cover a given length of core and consequently slow down the imaging process. Another option would be to add a mixed-pixel algorithm to the analysis that would most likely slow down the real-time processing. The instrument could be redesigned to use a detector array with more pixels, but would result in a much more expensive imager. None of these options have been fully explored.

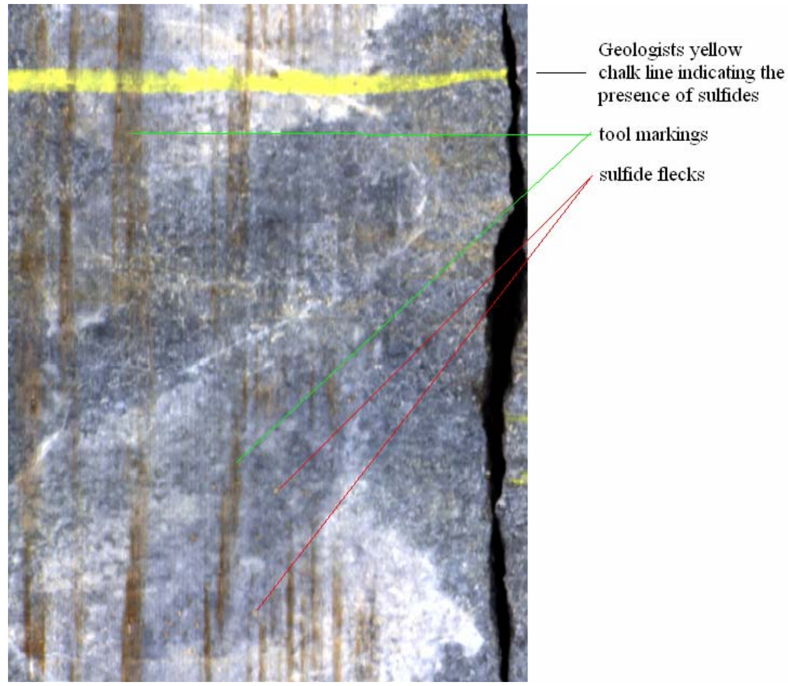


Figure 12. This core image from the Stillwater sensor data is a good example of some of the problems we encountered with the Stillwater ore. The Geologist chalk mark was the easiest problem to correct; however, too many of the red tool markings (the reddish vertical striations in this image) were misclassified as sulfides even after a 95% removal. Many of the small visible sulfides in this image, which were seen by the Geologists as evidenced by the yellow chalk line, were not seen by the sensor due to resolution issues. Stillwater Geologists mark the core with 1, 2 or 3 yellow lines to indicate a relative ore grade (3 lines means highest grade, no lines means lowest grade)

The problems discussed above did suggest to us a better experimental design for obtaining the data in Figure 11. We found that we were trying to answer several critical questions simultaneously:

- How well does the C^2OG sensor map sulfides?
- How well do surface sulfides correlate with ore grade?
- How well does the C^2OG sensor map sulfides in a real world application?

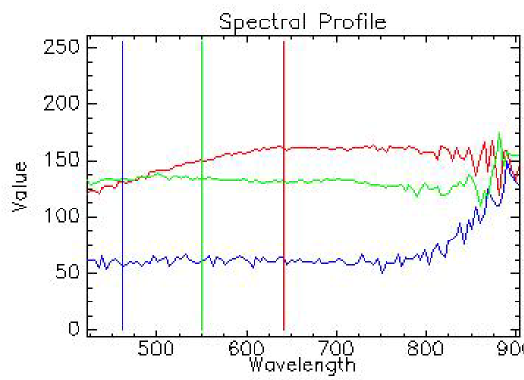
These are independent questions that should be addressed separately. An experiment could be designed whereby the sensor would image a rough polished section of Stillwater ore approximately 4 cm^2 in size. This would be a large enough target for the sensor, but small enough that it could be scanned with the SEM-EDX at Montana Tech. The corresponding sulfide maps could be registered and compared and an assessment could be made regarding the accuracy of the sensor. Once satisfied that the sensor could accurately map sulfides, it would be taken to the Stillwater core room to answer the second question. To do this properly, the core would be cleaned of chalk, rust and tool markings introduced during the extraction and storage of the core. A more accurate scatter plot correlating % sulfide and assay results without these problems. The overall benefit would have been more efficient data acquisition and much less time spent on data analysis if the real-time feature could have been employed. After sufficient data for the correlation plot was gathered, then we would assess whether or not the introduction of chalk marks, tool burnishings and rust stains are necessary before deployment of the sensor in its working environment.

It is clear that the work at Stillwater could have proceeded much more efficiently. Presently, Stillwater uses one to three feet of core for each assay. To obtain the required spatial resolution, the scanner could only scan about 3.5 inches of core at a time. This meant about 4 to12 scans for each data point in Figure 11. Although, it would have been more costly to assay each 3.5 inch section of scanned core, it would have required much less of our time to generate the data points for the correlation plot in Figure 11. This might have allowed us more time to train some of the Stillwater geologists on the instrument and perhaps an opportunity to assess its real-time performance.

Coal content analysis. Coal samples from Western Energy's Rosebud Coal Deposit located near Colstrip, Montana, were analyzed with a C^2OG sensor at Montana Tech for coal content. Although Rosebud coal is noted for its low sulfur and ash content, even clean coal contains some sulfur and ash associated with mineral impurities. Minerals associated with sulfur consist of metal sulfides, mainly pyrite-marcasite (FeS_2), and organic sulfur and sulfates. Those associated with ash are shale and clay. Pyrite-marcasite (FeS_2) also contributes ash.

Pyrite-marcasite, shale-clay minerals, and coal from the Rosebud deposit show no specific diagnostic features in the VNIR range as seen in Figure 13. Shale-clay minerals are white, light gray or light yellow in color while pyrite-marcasite minerals are yellow or gold.

Figure 13. Sample reflectance spectra for coal (blue line), pyrite-marcasite (red line) and shale-clay (green line) in the VNIR region. Although the shapes of these spectra are somewhat distinctive, the greatest diagnostic feature between coal and these impurity minerals is their relative brightness or albedo. The red, green and blue vertical lines are the three bands selected for generating a color composite image of the sample (see Figure 14).



Since brightness or albedo is the most important diagnostic attribute for coal and the coal related sulfur and ash minerals, application of the SAM algorithm directly to the spectra was not appropriate. SAM looks for the angular distance between spectra and effectively removes the overall pixel brightness information from the analysis. Spectra were first transformed by a minimum noise fraction (MNF) rotation which puts overall pixel brightness in one MNF band. Afterwards a SAM analysis can be applied which emphasizes pixel brightness [6]. Although computationally intensive, one benefit of the MNF transform is the significant reduction in the number of bands that are needed to apply the SAM algorithm. Rather than using the full 213 bands in the original datacube, only the first few bands of the MNF transformed datacube typically contain information about the scene regarding brightness and color. Figure 14 shows a typical result of this MNF-SAM algorithm. This algorithm was used almost exclusively for the C^2OG coal analysis. Plans are presently underway to implement this algorithm in real-time analysis.

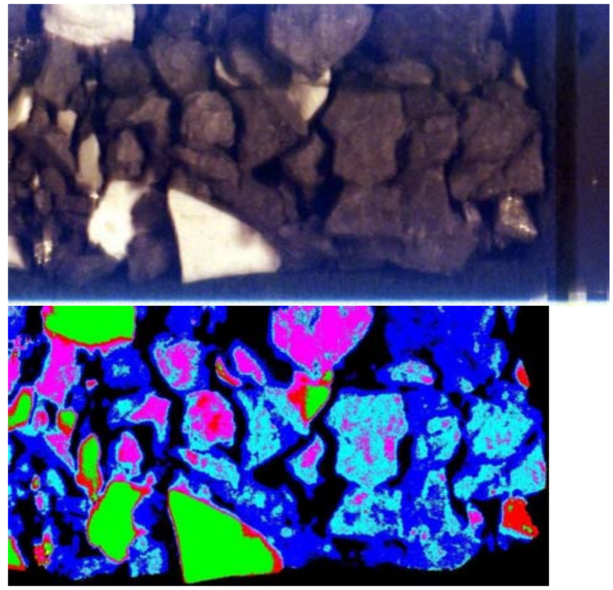


Figure 14. C^2OG scan of particulate coal and coal related minerals. Vertical dimension of each image is approximately 5 cm. The top image is a color composite using the three bands designated in Figure 13. The bottom image is a classification after an MNF rotation and SAM classification. The blue, cyan and magenta regions in the bottom image are classified as coal material. The red and yellow regions have been correctly classified as pyrite-marcasite. The green regions have been correctly classified as shale-clay minerals. Black regions are unclassified or background pixels.

C^2OG analyses of individual samples like the one shown in Figure 2 have been compared to LECO® Carbon/Sulfur (C/S) Analyzer results (see Figure 14). The C/S analysis measures volume or weight percentages for carbon (coal content), sulfur, and ash while the C^2OG analysis measures the area fraction or percent. The correlation R^2 values varied from 0.65 to 0.91 (1 being a perfect correlation) indicating a positive result for the C^2OG sensor at least for the ash content. This provides some incentive to explore where this technology could be implemented in coal fed power plants, process operations, or at the working face. Analysis of particulate matter has given similar results with the smaller particles showing the best correlations with the bulk properties measured by C/S analysis.

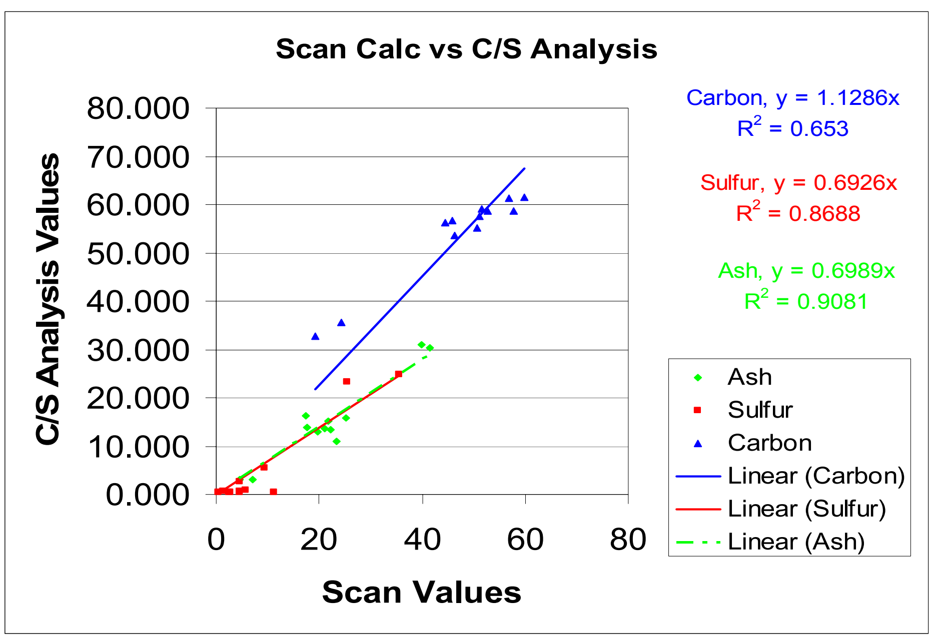


Figure 15. Graphical representation of SAM classifications versus C/S analysis results. The horizontal axis (Scan Values) are C^2OG sensor results indicating percent pixels imaged for the type of material (coal, sulfur, or ash). The C/S Analysis Values are weight or volume percentages.

Defects in titanium sponge. Samples of titanium sponge and typical defects were provided by TIMET for analysis. Currently defects in the sponge are removed manually from a conveyor belt, making it a highly labor intensive procedure. Additionally, the defect removal process is subject to human fatigue and variations due to the qualitative nature of material classification by humans.

Titanium defect classification using hyperspectral imaging was done quite early in the 3-year effort. For this work, samples that included normal titanium sponge were mixed with defects and imaged in the imaging spectroscopy laboratory at Montana Tech. The imaging spectrometer scanned an area about 3 cm x 3 cm to form 480 x 480 pixel images. Consequently, each pixel in the images you see here is about 63 μm x 63 μm in size. The spectral range is from about 460 nm in the visible to about 950 nm in the near infrared (visible light is 400 nm to 700 nm).

Figure 16 shows images of 5% N defects mixed in with normal titanium. The left image is "seen" at just one wavelength and the defect samples are labeled. There was considerable variability in the 5% N defects, which is evident in the image. Note that some of the defects can hardly be distinguished from the normal titanium in the left image. The right image is a false-color image that classifies objects by color and brightness. The pink-maroon color is "seen" as normal titanium and the other colors are the defects or background. Note that not all pixels are correctly identified, but the vast majority are and it is quite easy to distinguish between defects and the normal sponge.

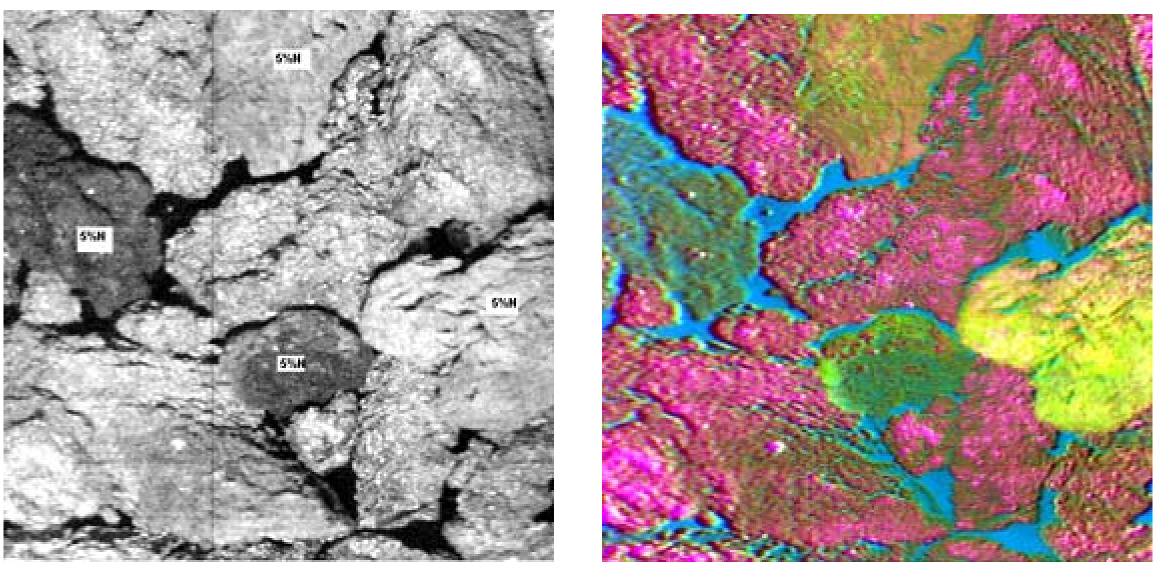


Figure 16. The left image shows normal titanium and 5% N defects mixed together as seen at a single wavelength with the imaging spectrometer. The defects are labeled in the left image. The right image is a false color mapping to indicate how the machine vision would identify the objects. The normal titanium is maroon.

The images in Figure 17 show blue sponge defects mixed in with normal sponge. Again, the image on the left is a single wavelength and has the defects labeled. The blue sponge is false colored in green and blue. The blue false color is quite similar to the background mapping in this case. Again, one can see that the system picks out the defects quite well.

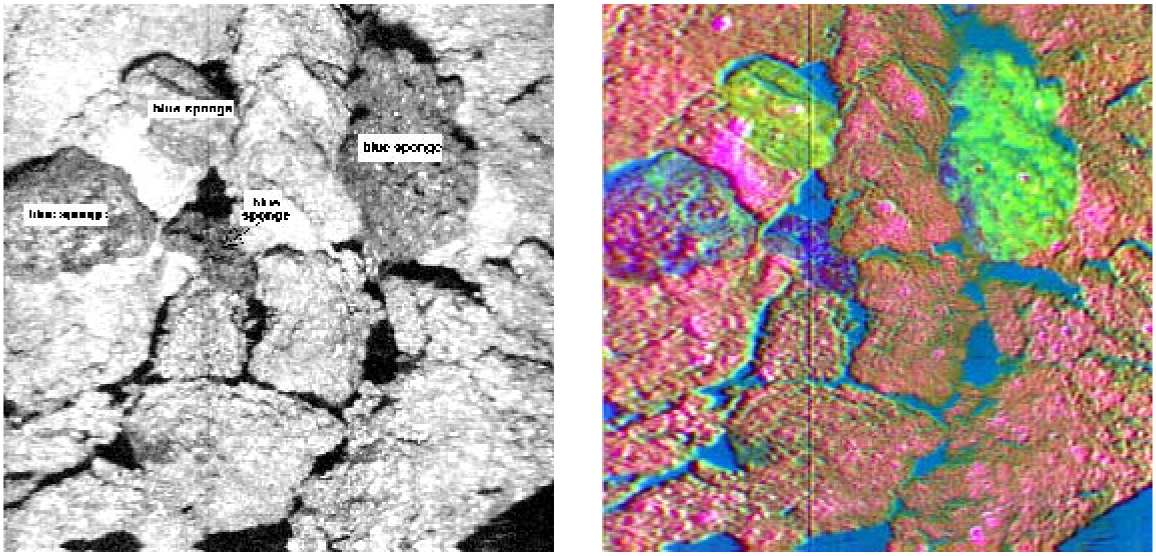


Figure 17. The left image is shown at a single color with labeled defects. The right image is a false color mapping, where the normal sponge is maroon.

The final images shown below are of normal titanium with no defects. The purpose of this test was to make sure the system did not find defects when there were none to be found.

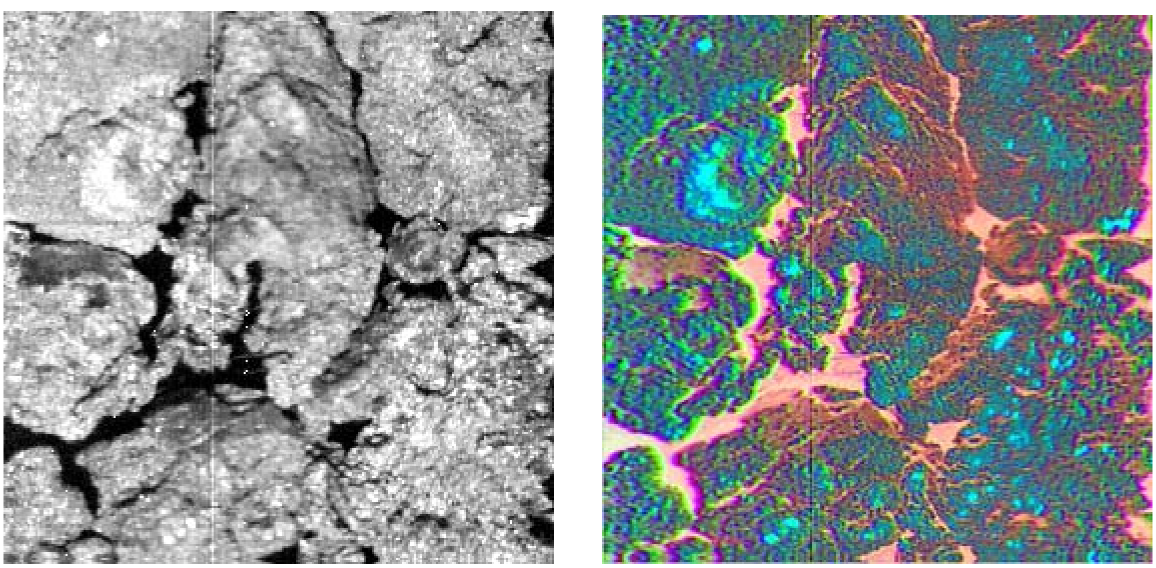


Figure 18. The left image shows an image of normal titanium sponge with no defects. The right image maps normal titanium to turquoise. This result indicates there will not be a serious problem with false positives.

Data was also for 1% N, 2% N, and 3% N defect samples. These defects were detected with good success, roughly similar to what is shown above. The classification techniques were unsupervised, which means a human did not need to pick out a typical pixel of the defect and then tell the system to find similar pixels. The results shown here do not incorporate spatial effects. For the results provided here, the machine vision system utilizes only the data from a single data cube. With a "real" system, a spectral library would probably be generated.

Results on the identification of titanium sponge were provided to TIMET. They were concerned about the immaturity of the technology and consequently did not pursue implementing a hyperspectral machine vision system for identifying defects.

CONCLUSION

Project overview. The coal content/ore grade (C^2OG) sensor is a machine vision system based on remote sensing technology known as hyperspectral imaging and imaging spectroscopy. The design and manufacture of imaging spectrometers is the central technology of Resonon, Inc. (www.resonon.com), an electro-optic sensor company located in Bozeman, Montana. Sensors were designed and built at Resonon, Inc., and then deployed at the Stillwater Mining Company core room for analyzing platinum/palladium ore and at the Montana Tech Spectroscopy Lab for analyzing coal and other materials. Key results were presented in Figures 11 and 15 that show the viability of this technology for machine vision applications in mining. These results have directly led to the development of a down-hole sensor based on this technology and that has been awarded DOE SBIR Phase II funding to continue.

Project objectives and results. For the Stillwater platinum/palladium ore, the technical objective was to obtain an estimate of ore grade by accurately measuring the percent surface sulfides with a sensor deployed at a working mine. 91' of Stillwater core were scanned at the Stillwater core room. Sensor results were correlated with the assays of the core in Figure 11. Although this correlation is a positive result for the sensor, there were a number of significant problems with ore that had iron oxide residues, tool markings and tool burnishings. It is important to note that most of these problems are due to the handling and storage of the core and would be minimal at the working face or in a borehole where the sensor is most likely to be deployed.

A C^2OG sensor system was set up at Montana Tech to analyses particulate coal from Western Energy. Analysis of individual samples like the one shown in Figure 2 were compared to LECO® Carbon/Sulfur (C/S) Analyzer results to assess the performance of the C^2OG sensor. The correlation plots in Figure 15 indicate a positive result for the C^2OG sensor at least for the ash content. This provides some incentive to explore where this technology could be implemented in coal fed power plants, process operations, or at the working face. Additional work demonstrated that the technology could identify titanium sponge defects.

Despite the positive results discussed, we recognize that there are some areas that still need further exploration.

- Extend the period of sensor operation at the mine. A full assessment regarding sensor maintenance and amortization still needs to be done.
- Real-time operation at the mine. Although the sensor can operate in a real-time mode that implements the SAM algorithm, the accuracy of its analysis can decrease when unanticipated error classes (e.g., tool burnishings) are present. Since these problems are

often impossible to predicted, it is clear that more sophisticated or intelligent algorithms need to be implemented. Since time is critical, it is possible that a hardware solution like embedded processing may also be required.

- Assess how easy it would be for a non-expert to use the instrument and control software. Good interface design is critical for marketing. This is a new technology for most mine operators and its correct implementation and usage can only occur if they are comfortable with the sensor and its human interface. The other aspect of this is increasing the control and analysis software's functionality. This is particularly important for expanding the market into different areas both inside and outside of mining.

Benefits. Providing real-time ore-grade assessment of the material behind a mine face will yield major economic, energy, environmental, and safety benefits, as discussed below.

Economic benefits. Real-time mapping of the ore body will allow miners to (1) reduce the costs associated with waste rock removal and (2) improve the recovery and sorting of the ore. It should be noted that not all waste rock can be left in place in normal operating conditions. However, some waste rock can be left by dropping holes, and Stillwater Mining Company estimates that the probable impact of the down-hole sensor system will be a 10% reduction in waste rock [7]. This would provide an economic benefit of over $650,000 per year. If a 10% improvement in recovered ore can be achieved, there would be an additional benefit of over $2.4 million per year. Thus, on an annual basis for the Stillwater mine alone, the combined economic benefit could exceed $3.1 million, or approximately 1.1% of total revenues. Extrapolating this to all U.S. mines where this technology could be used, the economic benefit could be as high as $72 million per year.

Energy benefits. Additional benefits will accrue by (1) reducing the energy used for removing, sorting, and disposing waste rock; (2) allowing the ore to be properly sorted and blended, thereby providing more efficient processing; and (3) increasing the overall grade of ore removed from the mine, thereby decreasing the amount of energy needed per pound of product. Stillwater Mining Company estimates that a 10% decrease in waste rock would also provide approximately a 10% savings in energy usage, which corresponds to 1.78×10^{11} Btu/year savings for one mine. Due to the vastly different mining techniques used in different mines, it is difficult to accurately estimate the total U.S. energy savings, but for reasonable adoption, it would easily exceed 10^{12} Btu/year.

Environmental benefits. The predicted 10% reduction in waste rock would lessen the environmental impacts associated with mining, processing, and disposing of waste rock. The benefits for other mining companies depend on the nature of the mining activity, but it is plausible that other underground mining companies would realize comparable benefits and open pit mining companies would realize more limited benefits.

Safety benefits. The Mining Safety and Health Administration reports there was an average of 343 registered injuries and 5 fatalities at US metallic mining operations during the last three years [8]. Although this represents a significant improvement in mining safety rates relative to historical norms, the Administration seeks further improvement [9]. The proposed look-ahead mining device has promise for improving worker safety in the metallic mining environment because it (1) minimizes rock disturbance and the hazards of removing waste rock and (2) provides improved information on the nature of the rock ahead of the excavation activities. This in turn reduces cave-ins and other injuries occurring in the excavation process.

Energy benefits. Additional benefits will accrue by (1) reducing the energy used for removing, sorting, and disposing waste rock; (2) allowing the ore to be properly sorted and blended, thereby providing more efficient processing; and (3) increasing the overall grade of ore removed from the mine, thereby decreasing the amount of energy needed per pound of product. Stillwater Mining Company estimates that a 10% decrease in waste rock would also provide approximately a 10% savings in energy usage, which corresponds to 1.78×10^{11} Btu/year savings for one mine. Due to the vastly different mining techniques used in different mines, it is difficult to accurately estimate the total U.S. energy savings, but for reasonable adoption, it would easily exceed 10^{12} Btu/year.

Commercial potential. From a broad perspective, the commercial potential of hyperspectral imaging for mining and other applications should be excellent. Human vision is one of our best developed senses and we constantly use color and spatial patterns to recognize and distinguish objects. Consequently, one would expect a machine vision system that provides both spectral and spatial information to have a wide range of applications. Moreover, spectral machine vision has not been widely exploited and it is clear that there are numerous options to pursue.

During this project, Resonon targeted innovative uses of hyperspectral imaging in the mining industry. In addition to advancing the technology, this also helped us identity strengths and weaknesses of the technology to exploit and work around. Strengths include the ability to differentiate between objects that have extremely similar colors, excellent repeatability, quantitative results, and minimal need for maintenance. Weaknesses include a substantial sensitivity to illumination variations, a need for new and/or specialized algorithms that utilize both spectral and spatial information, and poor depth of field (at least in near-field applications).

As with many emerging technologies, multiple applications should be pursued to discover where the technology will be useful. Unfortunately, it is impossible for a small company to effectively pursue too many applications at once. (Many would argue the same is true with large companies.) Therefore, we identified the area of application that appeared to have the most promise for our SBIR effort based on this technology. In particular, we chose to pursue a down-hole instrument for sulfide detection for the following reasons: (1) sulfides have no distinct shape, which minimizes the need for including spatial dependence (this is the case for most mining applications and is not specific to sulfide detection); (2) the down-hole environment is dark so lighting can be completely controlled; (3) the surface of a borehole is smooth and a centralized bore-hole instrument will have minimal depth of field issues to contend with; (4) we have a strong and enthusiastic partner, Stillwater Mining Co., who understand the technology and are willing to work with us; and (5) the pay-back potential for even slight gains in mining productivity is large due to the large expense of underground mining and the high value of platinum and palladium.

Although our initial target is underground mining, we have also received interest in using the technology in surface mines from Barretts Minerals and Phelps-Dodge. Although surface mines have the advantage of easier access, variations in lighting will likely require significant developmental work. No funding is available for surface mining projects currently; what is significant is that there is interest in the technology even in its relatively undeveloped stage. Some preliminary work has been done for talc ore and is shown in Figure 19. The classification maps clearly indicate that talc can be classified within a background of usual waste rock, even using natural solar lighting.

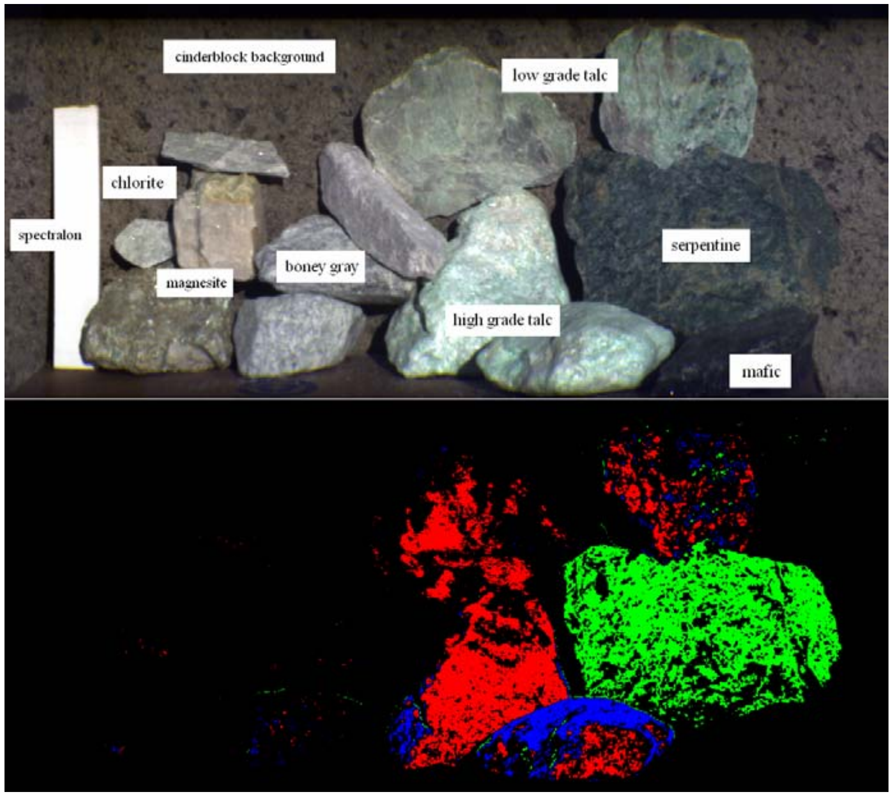


Figure 19. The top image is from a scan of talc with some of its associated low grade and non-talc byproducts. The bottom image is a classification map showing the location of high grade talc (red and blue), serpentine (green) and all other non-talc rock and background (black). The low grade talc shows a mixture of high grade and non-talc rock which is an obvious problem area in talc mining and processing. The rectangular spectralon strip at the far left of the image was used as a white target for light source removal allowing the analysis to work with reflectances which are a material property independent of the lighting. A similar procedure is followed for all C^2OG scans.

Metallic minerals that correlate with sulfides will be the focus of Resonon's commercialization efforts in the near term, primarily platinum/palladium, with secondary attention to gold. Underground mines are particularly promising potential users of the Resonon instrument due to the high cost of moving material. Underground mining is used in the U.S. to extract platinum, gold, lead, silver, zinc and a few other primarily non-metallic minerals [10]. The device also has potential for use in open pit mining of the metals mentioned above as well as for copper and nickel. In addition, a modified version of the device would have commercial promise for coal mining and some non-mining applications. A brief discussion of several metals associated with sulfides is provided below to provide an indication of the potential market for our down-hole sensor that is in development.

Platinum group metals. Platinum group metal (PGM) mining usually takes place underground. The U.S. platinum/palladium mining industry consists of Stillwater Mining Company, which generated $276 million in revenues and employed 1,575 workers in 2002 [11]. Stillwater's production amounts to roughly 5% of world output. Other major producers are Russia, South Africa, and Canada.

Stillwater estimates they could utilize 3-4 borehole probes in their operations, which would provide $270,000 to $360,000 in original equipment sales. Stillwater estimates that the probes would pay for themselves in a period between 1.4 and 6.7 months. Given the environment in a mine, a plausible average lifetime of the sensor system is 2 years, which would generate average annual follow-on sales of $135,000 or more.

Gold. Gold mining is the largest segment of the U.S. nonferrous metal mining industry, with $2.9 billion in annual revenues and 7,000 employees [12]. The gold mining industry makes widespread use of underground mining, and gold market fundamentals have improved dramatically in recent years. Consequently, the gold mining industry is one of the most promising commercial targets of the Resonon borehole probe.

There are 12 active underground gold mines in the United States [12]. If half of these mines purchased 2 probes apiece, system sales in excess of $1,000,000 would result. Bearing in mind that the U.S. accounted for 10 percent of world gold output in 2003, international sales of the Resonon probe are potentially much larger.

Lead. The U.S. lead market was $435 million, or about 15% of world output in 2003 [13]. For the most part, future U.S. lead mining will be conducted in increasingly deep and difficult-to-extract veins of ore, and hence is well suited for adoption of the Resonon borehole probe. Business fundamentals are good for lead mining. Average lead prices on the London Metals Exchange increased more than fifty percent in the past year [14]. If the price increases can be sustained, investment in mining equipment will undoubtedly rise sharply, with a corresponding increase in interest in new efficiency enhancing technology such as the Resonon borehole probe.

Silver. Although silver is a primary metal in the Helca and Coeur d'Alene mines of Idaho, silver is typically mined jointly with gold, lead, zinc, and copper, and is usually a secondary byproduct of these mining operations. Accordingly, the size of the U.S. silver mining industry is relatively small, with $184 million and 980 employees in 2003 [15]. The Resonon borehole probe should be well suited for mining silver due to the industry's frequent use of underground mining.

Zinc. Zinc mining could utilize the Resonon probe. The U.S. zinc mining market is more important than silver in terms of revenues and employment ($664 million and 1400 employees respectively in 2003 [16]). Unfortunately, the worldwide zinc market has been very weak for over a decade, as reflected by the fact that U.S. production has been decreasing for the past five years and worldwide production has been characterized by over-capacity [16]. In this environment, companies involved in zinc mining are unlikely to invest much in new mining technology, unless it is also used for identifying more lucrative minerals such as lead and silver. Thus we view zinc mining as a potential target for the hyperspectral technology, but one that may require stronger market fundamentals.

Copper. U.S. copper mining companies have historically utilized both underground and open pit mining, but open pit mining is now used exclusively owing to its lower cost, lower complexity, and greater safety. This situation will change in the future as the open pit reserves are used up [17]. For example, Kennecott is proposing an underground mine for its new discovery in Arizona. Copper is one of the more important segments in the U.S. metallic mining industry, with $2 billion in sales and 6,800 employees in 2003. Open pit copper mines use sulfides as indicator minerals in core samples, so there is some current potential market with copper mining. This potential will increase as underground copper mining increases. Informal discussions with representatives from Phelps Dodge at the International Symposiom on Computer Applications in the Minerals Industry in Tucson, Arizona, this April have also indicated the need for a machine vision solution at the working face of at least one of their copper mines.

Other metallic minerals. Other metallic minerals, such as molybdenum, nickel, tin, and titanium, are also candidates for the Resonon borehole probe. Molybdenum mining is conducted mostly in an open pit environment, and the U.S. presence in nickel, tin, and titanium is small or nonexistent, so these industry sectors are not near term targets of the Resonon device.

Market projections. Systematic estimates of the market potential for a down-hole hyperspectral imaging probe are provided in Table 1. These projections are for annual sales in 2009, five years from the beginning of the Phase II project. Table footnotes explain the procedures used to obtain the projections. The estimates reflect current market conditions and exclude potentially important markets, such as copper, nickel, underground surveying, and open pit mining in general.

Table 1: Estimated Near Term Potential Sales of the Resonon Borehole Probe

Metal	U.S. Sales[1]	Foreign Sales[2]	Comment
PGMs	$270,000	$540,000	Primary Phase II target.
Gold	1,080,000	1,080,000	Secondary Phase II target.
Lead	540,000	324,000	
Silver	270,000	405,000	
Zinc	180,000	198, 000	Market fundamentals comparatively weak.
Total	$2,340,000	$2,547,000	

1. Sales estimates for the U.S. PGM industry come from Stillwater Mining. Sales estimates for the U.S. gold, lead, and silver mining industries are based on the following formula:
sales = (probe price) ∗ (number of active U.S. underground mines in sector) ∗ (percentage of mines that would buy instrument) ∗ (number of instruments purchased per mine). The last two factors in the formula are 50% and 2, respectively. U.S. zinc market estimates are computed using the same formula except that percentage of mines that would buy the instrument is assumed to be 25%.
2. Sales estimates for foreign markets are based on the following formula: sales = (ratio of world output of mineral to U.S. output) ∗ (U.S. sales) ∗ (international market penetration factor). The last factor is assumed to be 10%, representing an international market penetration of one tenth the U.S. market penetration level.

Other opportunities. The markets noted above could potentially utilize a hyperspectral imaging based device for detecting sulfides. It is likely that there are numerous other objects of interest – in fact it is likely that materials other than sulfides will be more lucrative. Because down-hole hyperspectral imaging is an emerging technology, potential markets are not yet aware of its capabilities. Therefore, one of the reasons to develop hyperspectral imaging for mining is that it will demonstrate the technology's value in an industrial atmosphere, thereby likely opening up future markets in mining and elsewhere.

REFERENCES

1. See the websites: http://speclab.cr.usgs.gov, http://speclab.jpl.nasa.gov, and http://minerals.gps.caltech.edu. for example.

2. G. Bonifazi, F. La Marca, and P. Massacci, "Raw Ore Selection by Artificial Vision," SME Annual Meeting, Preprint 99-57, March 1-3, 1999.

3. See for example the handheld spectrometers marketed by Integrated Spectronics, web address http://www.intspec.com. Another manufacturer is Analytical Spectral Devices, Inc., web address http://www.asdi.com/asq.

4. For an example of the SAM algorithm see, F. A. Kruse, A. B. Lefkoff, J. W. Boardman, K. B. Heidebrecht, A. T. Shapiro, P. J. Barloon, and A. F. H. Goetz, "The spectral image processing system (SIPS) – interactive visualization and analysis of imaging spectrometer data," Remote Sensing of the Environment, 44:145-163, 1993.

5. Alexander F. H. Goetz, Gregg Vane, Gerry E. Solomon, and Barrett N Rock, "Imaging Spectrometry for Earth Remote Sensing, Science," 7 June 1985, Volume 228, Number 4704.

6. J. W. Boardman and F. A. Kruse, "Automated spectral analysis: a geological example using AVIRIS data, north Grapevine Mountains, Nevada," in Proceedings, ERIM Tenth Thematic Conference on Geologic Remote Sensing, Environmental Research Institute of Michigan, Ann Arbor, MI, pp. I-407 - I-418 , 1994.

7. Personal communications with Matt Knight and Ennis Geraghty from Stillwater Mining Company.

8. www.msha.gov/stats

9. www.msha.gov

10. USGS underground mines list found at http://minerals.usgs.gov/minerals.

11. Stillwater annual 10-K report for 2002 as reported in the SEC Edgar database, www.sec.gov/edgar.

12. USGS gold industry report found at http://minerals.usgs.gov/minerals/pubs/commodity/gold/index.html#mcs.

13. USGS lead industry report found at http://minerals.usgs.gov/minerals/pubs/commodity/lead/index.html#mcs

14. London Metals Exchange address is: http://www.lme.co.uk

15. USGS silver industry report found at http://minerals.usgs.gov/minerals/pubs/commodity/silver/index.html#mcs

16. USGS zinc industry report found at http://minerals.usgs.gov/minerals/pubs/commodity/zinc/index.html#mcs

17. USGS Copper industry report found at http://minerals.usgs.gov/minerals/pubs/commodity/copper/index.html#mcs.

BIBLIOGRAPHY

C. Smith, R. Swanson, M. Kehoe, T. Moon and B. Bolin, Hyperspectral imaging for real-time ore grading, accepted for the APCOM 2005 32nd International Symposiom on Computer Applications in the Minerals Industry, Tucson Arizona, March 30 – April 1st, 2005.

R. Swanson and C. Smith, Deployment of a real-time Coal Content/Ore Grade sensor at the Stillwater Mine, Montana Board of Research and Commercialization Technology Poster Session, Capitol Rotunda, Helena, Montana, Monday, February 9, 2005.

Rand Swanson, Hyperspectral Imaging for the Mining Industry, MINExpo International 2004 Poster Session, Las Vegas, Nevada, September 27-30, 2004.

T. Moon, R. Swanson, C. Young, R. Johnson, C. Smith, A real-time Coal Content/Ore Grade sensor, Montana Board of Research and Commercialization Technology Poster Session, Capitol Rotunda, Helena, Montana, Monday, February 3, 2003.

Brock Bolin and Tom Moon, Sulfide detection in drill core from the Stillwater Complex using visible-near infrared imaging spectroscopy, Montana Academy of Sciences 61st Annual Meeting, Environmental Sciences and Engineering, Great Falls, Montana, April 20, 2002.

Brock Bolin and Tom Moon, Sulfide detection in drill core from the Stillwater Complex using visible-near infrared imaging spectroscopy, *Geophysics* , 68:1561-1568 (September-October 2003).

Brock J. Bolin, Sulfide detection in drill core from the Stillwater Complex using visible-near infrared imaging spectroscopy, Masters Thesis, Geophysical Engineering, Montana Tech of the University of Montana, May 2002.

Kathleen J. Miller, Development and implementation of a user interface and preprocessing software for Resonon hyperspectral imagers, Masters Thesis, Geophysical Engineering, Montana Tech of the University of Montana, December 2003.

Ronald G. Johnson, Sulfur and ash determination using visible-near infrared imaging spectroscopy for pyrite-marcasite and shale-clay mineral detection in Rosebud coal, Master Thesis, Metallurgical and Materials Engineering, Montana Tech of the University of Montana, May 2004.

LIST OF ACRONYMS AND ABBREVIATIONS

CCD	charge coupled diode array
C^2OG Sensor	Coal Content/Ore Grade Sensor
C/S	carbon/sulfur
MBRCT	Montana Board of Research Commercialization Technology
MNF	Minimum Noise Fraction transform
Pt+Pd	platinum/palladium
SAM	Spectral Angle Mapping algorithm
VNIR	Visible and Near Infrared