



## Evaluation of complex copper ore sorting: Effect of optical filtering on particle recognition

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### ABSTRACT

In mixed and multi-component mineral systems, the reflectance spectra of individual minerals interfere with the reflectance/absorbance features of other minerals and random spectra can form. This contradictory case causes difficulty in implementing ore sorting to certain minerals. Hence, filtering out certain wave lengths may prevent this situation which makes it difficult for an ore sorter to perform a selective and efficient separation. The scope of this study is to investigate the feasibility of the optical filtering to enhance the differences in the reflectance features of mineral grains, and to compare the possible separation performances of the ore sorters under the best filtered and unfiltered conditions.

Within the experimental studies, a new experimental setup which runs its uniquely coded software was designed. Additionally, an adjustable filter cartridge apparatus was developed enabling to mount the wavelength specific filters in front of the conventional sensors which support universal f-mount type lenses. A representative sample batch consisting of 31 grains of complex copper ore was prepared. Filtered and unfiltered images of each grain in between 450 and 1650 nm wavelength range were acquired carefully with the designed experimental setup. Following the data extraction by imaging studies, each particle was weighed, ground, and analyzed to determine chemical compositions. Thus, the reflectance values and chemical analysis data of each particle with each filter were obtained. Principal component analysis (PCA), partial least square analysis (PLS) and stepwise multiple linear regression (SMLR) methods were used to evaluate the resulting data in order to establish meaningful relationships between dominant chemical contents and reflectance values of each individual particle. Hence, the effect of using optical filters in altering the differences among the reflectance values of complex copper ore grains has been determined. Following the determination of best filters and wave lengths, projected product qualities of a conjectural optical sorting operation integrated with optical filters have been analytically investigated. It was concluded that an alteration in the relationship between % sulphide content and reflectance values was observed over 1500 nm wavelengths in comparison to the unfiltered and other filtered conditions. Evaluation of the overall results showed that up to 73.30% of Au, 96.14% of Ag, and 86.24% of CuFeS<sub>2</sub> in feed can be recovered when a long-pass 1500 nm filter was used.

### 1. Introduction

The electromagnetic spectrum is the corporate term that includes all known wavelengths of the electromagnetic radiation (Workman and Weyer, 2007). The widely accepted spectral ranges are as follows (Clark, 1999):

1. Ultraviolet, UV, up to 400 nm
2. Visible, VIS, 400–700 nm
3. Near Infrared, NIR, 700–3000 nm
4. Medium Infrared, MIR, 3000 nm–30 μm
5. Far infrared, FIR, 30 μm–1 mm

Reflectance/absorbance spectroscopy is a class of methods that offers graphical representation of the reflection characteristic of a material in different wavelengths on the electromagnetic spectrum (Hunt, 1977; USGS, 2017). The absorption and reflection bands on the spectrums are highly sensitive to small changes in chemical content and crystal structure. The reflectance spectroscopy is widely used for identification of pure minerals in the laboratory environment and for remote sensing in geological discovery studies (Shankar, 2015). Detailed information on the reflection and absorption properties of materials and their evaluation in terms of physical and optical laws can be found in the literature (Clark, 1999; Wooten, 1972).

Sensor based sorters (which is an umbrella term covering ore sorters

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and optical sorters (Cutmore and Eberhardt, 2002) take the advantage of individual responses of specific minerals to different levels of electromagnetic radiation (Robben et al., 2011). XRT (X-ray transmission) (Kleine, 2010), XRF (X-ray fluorescence), VIS (Visible light, color), PM (Photometric), NIR (Near-infrared), IR (Middle and far infrared), and MW/IR (Microwave heating combined with IR) sorters have been conveniently used in the mining industry to separate valuables from barren rock. VIS and NIR sorting are the most common applications in ore sorting practices (Daljmin et al., 2003; Anselmi and Habeck, 2000; Dehler, 2003; von Ketelhodt, 2009; Gülcan et al., 2012). One of the major drives in leading to this situation is because, the specific differences in molecular and crystal structures of known minerals can be clearly observed in the spectrum of VIS and NIR wave lengths (Wotruba et al., 2010). Minerals reflect/absorb electromagnetic radiation in different amounts depending on their crystal structures. Hence, each individual particle's response to VIS and/or NIR radiation is used as an indicator for implementing ore sorters. It is important to note that VIS sorters are easy to use, simple in principle and refined in comparison to NIR sorters. Unfortunately, they only detect the surface color differences among mineral grains. On the other hand, a fingerprint scan of the mineralogical structure of a particular mineral can be obtained with the near infrared spectroscopy (NIRS) (Clark, 1999; Richards, 2001; Stuart, 2004; Dalm et al., 2014). The application areas of NIR systems combined with sensor based sorters are quite broad, especially for recycling purposes (Feldhoff et al., 1997). The reason for the NIR reflectance pattern being specific to individual minerals, such as a fingerprint, is the electronic and vibrational transitions between molecules. Accordingly, the mineral reacts to the NIR radiation and a spectrum of different absorption bands forms (Clark, 1999; Atkins and De Paula, 2006).

The majority of the minerals that are subjected to mineral processing are naturally multi-component and complex. In multi-component mineral systems, each individual spectrum could shade the other and unreasonable spectrums could be formed. The reason for this situation is not fully explained yet. This phenomenon in the spectrum of multi-component minerals can be attributed to the bonds in linkages of the different rocks, the proportions of mineral contents, or water-based components in crystal structures (Wetzel, 1983). In effect, there is a lack of a reference spectrum when working with the NIRS of multi-component minerals. However, presence of active groups and their known location in the spectrum allows interpretation of the NIR spectrum most of the time (Chang et al., 2001). In addition to the chemical structure, reflectance spectrum is also affected by physical properties. Grain size, shape, structural voids, thickness and light transmittance are among the other factors affecting NIRS. In multi-component minerals, overall reflectance spectrum can be substantially different from each individual component's and active groups' spectrum. For example, Clark (1999) compared the NIR spectrums of calcite, dolomite, beryl, gypsum, and alunite. Results showed that the absorbance intensities of common NIR active groups (OH, CO<sub>3</sub>, H<sub>2</sub>O, etc.) varied resulting with the molecular differentiation of host mineral compositions (Clark, 1999). Reflectance spectrum can also be affected independently of the predominant NIR active mineral's concentration in the sample. Fe<sup>+</sup> is known to interfere with the spectral features of other minerals in the system, and lower their intensities. King and Ridley (1987) observed disparate spectral signatures of similarly sized two olivine samples of which FeO contents were 53.65% and 7.93%, respectively (King and Ridley, 1987). Theoretically, interaction with NIR should not change with the varying grain size and thickness of the same mineral. However, there are also many findings in the literature that contradict it (Wetzel, 1983). Iyakwari and Glass (2014) discussed the NIR reflectance spectra of chlorite, muscovite and hematite having different particles sizes (Iyakwari and Glass, 2014). Consequently, larger particle sizes delivered higher spectral features across the wavelength range compared to the smaller particle sizes. For these reasons, strong, mineral-specific and detectable properties are emphasized while commenting on reflectance

spectrum of multi-component minerals.

The variability in reflectance values resulting from above mentioned factors makes it difficult to relate reflectance properties directly to the mineral properties. For this reason, it is necessary to develop a calibration model for characterization when working with reflectance spectrums (Mevik and Wehrens, 2007). Some of the most basic statistical efforts to associate especially NIRS with the mineral's measured feature are: principal component analysis (PCA), stepwise multiple linear regression (SMLR), partial least square regression (PLSR), Fourier regression (FR), locally weighed regression (LWR), and artificial neural networks (ANN) (Chang et al., 2001; Mevik and Wehrens, 2007; Creaser and Davies, 1988; Holst, 1992; Dalal and Henry, 1986). The difference between PCA and PLS is that while former finds planes of maximum variance between the reflectance values and chemical content, the latter finds a linear regression by projecting the actual and the calculated responses to a new space (Mevik and Wehrens, 2007). Reflectance values of multi-component minerals show collinearity and SMLR is particularly a suitable statistical method when one of the multiple variables can be linearly predicted from the others with a substantial degree of accuracy.

Uncertainties in the examination of the spectra of multi-component minerals are problematic in terms of the more widespread and efficient use of sensor based sorters in ore sorting. Although current VIS and NIR sensors could obtain full spectrum and can operate selectively based on the spectral signatures, the problems due to the spectral interferences are unfortunately still existed. Therefore, physically filtering narrow or board bandwidths is inherently more accurate than using reference spectrum for fast and reliable intervention to the ore sorting process. The purpose of this study is to highlight the effect of physically implementing optical filtering in altering the reflection difference between the particles in VIS and NIR regions. Therefore, a new system was configured facilitating to apply various optical filters to a given VIS/NIR sensor configuration. In the new system, a filter cartridge apparatus is used to mount the optical filters to a standard VIS or NIR sensor/camera. System allows to change optical filters in accordance with the operational specifications, to use one or more filters together in a single sensor, or to use more than one sensor with different filters. As one might expect, the main rationale for the filter use is to eliminate overlaps and shadows in the reflectance spectrum by allowing only certain wave lengths to pass through. Hence, target mineral grains can be detected by filtering certain wave lengths more precisely and cost effectively. Due to the complex nature of reflectance properties of multi-component minerals, experimental studies were carefully focused on collecting reflectance values of individual stones of a complex copper ore with each filter precisely. Following the data collection, chemical components of each stone and their possible impact on overall reflectance behavior was investigated.

## 2. Effect of optical filtering on sorting threshold selection

A potential linear relation between reflectance value and target mineral content benefits two important consequences: determination of the approximate mineral content by using individual reflectance values, and specifying the ore sorting threshold at a given sorting operation. A sorting threshold can be described as the "cut reflectance value" which directly effects the sorting products' quality (Fawcett, 2006; Pascoe et al., 2010). Different thresholds on the reflectance value axis could be set during sorting. Therefore, desired mass pulls and valuable amounts in conjectural accepted/rejected products could be established. The best threshold can be chosen whether to maximize the mineral recovery or to best the mineral grade. In effect, the selective sorting with an ore sorter is directly related to the reflected/absorbed amount of electromagnetic radiation. This quantitative value is translated to a numeric number ranging from 0 (all radiation is absorbed) to 255 (all radiation is reflected) on the gray scale. The longer the distances between the regions where the reflectance histograms are intensified, the better the

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