DROACOR® REFLECTANCE RETRIEVAL FOR HYPERSPECTRAL MINERAL EXPLORATION USING A GROUND-BASED ROTATING PLATFORM

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ABSTRACT:

The acquisition of imaging spectroscopy data from ground based rotating stages is a novel approach which is more and more used in open pit mines for prospection and controlling. The special radiometric situation of such data sets asks for new processing approaches for geometric processing as well as for reflectance retrieval. Herein, a new method for atmospheric correction and relative reflectance retrieval is presented which is optimized for the special horizontal scanning situation by hyperspectral instruments from rotating ground based platforms. The method is implemented within the recently developed drone atmospheric correction framework DROACOR®. It combines a physical inversion of a radiative transfer code with semi-empirical correction approaches for illumination and spectral absorption. Sample results from two open pit mines show that mineral detection after reflectance retrieval allows the discrimination of iron minerals and that the retrieved spectra are well comparable to standard library spectra.

1. INTRODUCTION

The deployment of ground-based imaging spectrometers is a relatively new application of remote sensing where the sensor is mounted on a fixed platform using a horizontal scan system to monitor, e.g., a mining target area. The instruments applicable for these applications (e.g. SPECIM Fenix (SPECIM Spectral Imaging, 2021), Headwall Hyperspec (Headwall Photonics Inc., 2021), Hyspex Mjolnir (Norsk Elektro Optikk AS, 2021)) may cover the spectral region from 400 nm up to 2500 nm. This technique has been applied for short distances, typically 50 - 500 m, to identify minerals from their spectral features in open pit mines.

However, the recorded data is proportional to the measured radiance and a direct comparison with library reflectance spectra of minerals is not possible – new reflectance retrieval approaches are to be developed. The presented atmospheric correction method for ground based horizontal scanning uses the LibRadtran radiative transfer code (Mayer et al., 2019) to convert the radiance data into relative reflectance data, which can be compared to libraries of mineral reflectance spectra, e.g., from the USGS spectral libraries (Kokaly et al., 2017).

Radiative transfer codes have been traditionally used for atmospheric correction of optical data from airborne and spaceborne platforms such as in the ATCOR® method (Richter, 1998, Richter, Schläpfer, 2002). However, these methods are based on a nearly vertical or slant viewing direction with long distances, and they are not suitable for short horizontal distances. The major differences between horizontal and vertical viewing geometries from a radiative transfer point of view are:

- Capabilities of Radiative transfer (RT) codes such as LibRadtran or MODTRAN® (Berk et al., 2004) for atmospheric correction were developed for a layered atmosphere and airborne or spaceborne radiance simulations. The calculations of path radiance and diffuse solar flux depend on this assumption. Only the direct (beam) solar irradiance on the ground can be used for applications with a horizontal view direction.

- For mining applications the observed target usually is a wall or hill with many small-scale facets and not a flat surface. Therefore the RT output of the downwelling diffuse flux on a flat horizontal surface cannot be applied. Even the use of a DSM (Digital Surface Model) will not help, because of the small pixel size (typically 5 - 20 cm) and the many orientations of the rugged terrain.

Therefore, the challenge in atmospheric correction for short horizontal distances with a large scan angle range is the unknown path radiance and diffuse solar flux. Additional problems are caused by the bidirectional reflectance properties of surfaces and the irregular shapes of pebbles and stones in mining areas. Another complicating factor is the often complex topography with vertical walls, small valleys, and reflection from opposite walls or hills.

Recently, the atmospheric correction methods have been further evolved for close range UAV based remote sensing by the DROACOR® method (Schläpfer et al., 2020), but still that method relies originally on vertical observation geometry. The capabilities of the method have now been extended for short distances and nearly horizontal viewing conditions; denominated as 'DROCOR-H' in this paper. The novel features are the use of restricted information from a RT code, namely solar beam irradiance and transmittance of the horizontal optical path, coupled with a statistical correction of the scan angle influence, an automated retrieval of water vapor, an automatic absorption feature adjustment, and a spectral re-calibration with oxygen and CO_2 absorption features. Optionally, a spectral polishing can be applied for post-processing to smooth remaining small spectral artifacts.

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2. GROUND-BASED REMOTE SENSING REFLECTANCE RETRIEVAL

The geometry of ground based data acquisitions as shown in Figure 1 differs significantly from airborne remote sensing: the illumination of the sun shows high variability on the typically steep targets and the horizontal observation distance has to be modeled differently than with vertical observations.
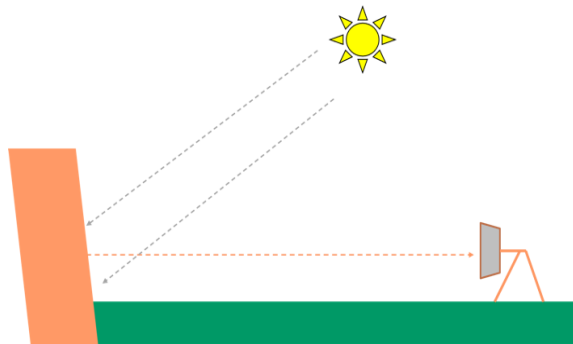

Figure 1. Horizontal scan geometry.

The method implemented as part of the DROACOR® software uses some approximations to calculate a relative reflectance cube. The intrinsic problems with a short-distance horizontal viewing geometry are:

- The pixel size is small (typically 5 - 20 cm), and the target is a rugged surface with many small facets oriented in different directions, aggravating BRDF effects.

- The scan azimuth angle range is large, typically up to 90°, which can include the solar principal plane.

- The foreground of the scene is also illuminated and the reflected foreground radiation influences the reflected target (wall /hill) radiance.

- The scene usually also contains a sky background, another factor influencing the target signature.

- The solar elevation angle is often low (high zenith angle), implying a low signal and signal-to-noise ratio.

- Employing an in-scene reference panel is not always practically feasible and of limited value.

For these reasons, a strictly physical approach to convert the radiance into surface reflectance data seems very challenging if not impossible. Some compromises and approximations have to be made to obtain a practical solution. Factors considered in the correction by the presented method are the gaseous absorption along the optical path, the relative illumination strength (solar beam irradiance) and the impact of the observation scan angle. Factors which can not be taken into account easily are the diffuse solar radiance, the adjacency effect, the complex topography, and the bidirectional reflectance variations. The resulting product is not an absolute reflectance product, but rather a relative reflectance cube, which is still sufficient for a comparison with library spectra.

3. METHOD

The DROACOR-H reflectance retrieval method follows the steps as shown in Figure 2. The process starts with laboratory calibrated radiance imagery. Radiometric calibration may optionally be achieved based on standard reflectance panels, but this is not recommended due to these only covering few pixels of the full image and thus not representing the truth for the rest of of the scan geometry. There are also other reasons that render in-scene reflectance panels non-practical; worst of them being that close to 100% reflective white panels are usually far above the scene reflectivity and thus force reducing the sensor dynamics to prevent saturation, which means loss of available scene SNR. Grey panels can be used, but they often are not as well characterized as the white Spectralon and may result in extrapolation artifacts for bright minerals. Moreover, the strict safety regulations of an active mine often hinder setting the panels close to the wall, and leave short time windows for scans conducted in the same pits with active heavy goods vehicles. The only practical approach for applying hyperspectral outcrop mineral scanning as a support of active mining is to use algorithmic atmospheric correction routine such as DROACOR-H.
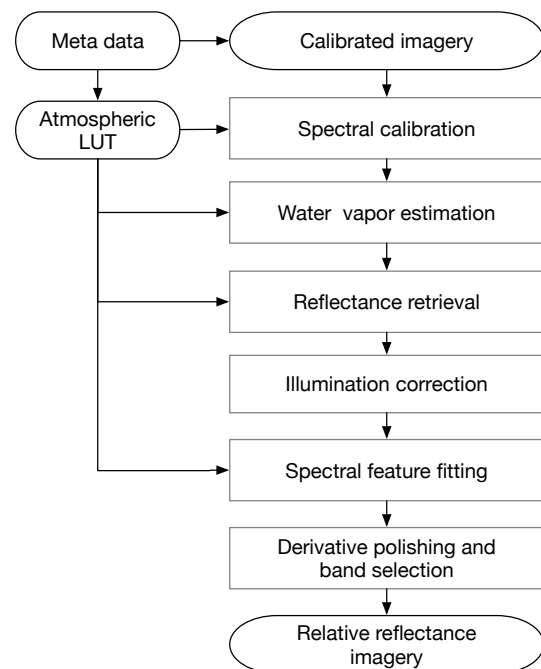

Figure 2. Process flowchart for DROACOR-H ground based horizontal reflectance retrieval.

The meta data required for the processing are solar zenith angle (based on time and location), ground altitude, and average distance to the observed object. A precalculated LUT based on the LibRadtran radiative transfer code (Mayer et al., 2019) is used for the further calculations. It contains the necessary parameters with a solar zenith angle between 10° and 70° for ground altitudes up to 3000m and sensor-to-target distances from 50 m up to 500 m. The spectral range covered is 350 - 2550 nm at a spectral sampling distance of 0.4 nm (FWHM=0.8 nm). In addition, the extraterrestrial solar irradiance spectrum at medium solar activity based on Fontenla (Fontenla et al., 2011) is used. Our own comparisons between the LibRadtran spectra and MODTRAN® have shown a good agreeement of the two

radiative transfer codes within a 1% margin for the parameters used in the DROACOR-H routine.

The processing starts with a spectral re-calibration using known atmospheric oxygen absorption features at 760 and 1268 nm. This step is required due to temperature-dependent spectral shifts in most standard imaging spectrometers. A sensor specific LUT is then generated based on the shifted positions and the spectral information from the image meta data. A water vapor estimate is found by spectral feature fitting to the water vapor absorption band, and is used as one value for the whole image for the further processing. The reflectance retrieval is a straight forward process, where the water vapor amount and the geometric information are used to find the appropriate atmospheric transmittance and the scattering parameters from the LUT for calculation of pixel reflectances. The reflectance at the target is then derived as relation between at-target radiance to an estimate of the irradiance.

Due to the large scan angle range, typical mine face scanner scenes contain strong brightness variations. These are caused by changes in illumination and bidirectional reflectance (BRDF) effects. In addition, the diffuse atmospheric radiation components (path radiance and adjacency effect) are geometry dependent. A simplified scan angle correction approach has been included which adjusts the scan-dependent brightness per channel to the maximum brightness. The method neglects BRDF effects and the diffuse radiation components.

The next processing steps are added to achieve realistic reflectance spectra, also in atmospheric absorption regions. First, known atmospheric absorption bands are analysed to find a best fitting absorption curve based on the radiative LUT in an iterative approach. By applying this best fit, remaining artifacts in the spectrum can be removed. This technique is applied to all water vapor absorption bands, the oxygen absorption features, the CO_2 absorption bands and to spectral bands below 430nm and above 2430nm, respectively, where strong atmospheric absorption often leads to spectral artifacts. Spectral bands with little signal, i.e. below a given threshold of transmission are linearly interpolated in order to support the subsequent spectral polishing.

The such filtered spectra are then polished using a derivative polishing approach (Schläpfer, Richter, 2011). This process uses a number of 7-11 spectral bands to find a trend for the center band by spectral derivatives on both sides while preserving absorption features. Finally, bands with very low transmittance and noisy bands at the edges of the detector are excluded from the final outputs, using a combination on sensor specific user configuration and automatic spectral adjustments. Examples of the finally achieved spectra can be seen in the two examples validated in the following section.

4. RESULTS

The method has been validated on a variety of 10 sample images of ground based imaging spectroscopy in various mining areas. A first example of DROACOR-H-retrieved image outputs is shown in Figure 3. These images show false color composites of the original scene and the scan-angle corrected relative reflectance image. The data has been acquired with the SPECIM Fenix system (SPECIM Spectral Imaging, 2021) using a rotational stage. It has 384 across track samples, with 1547 scan lines and 362 spectral bands covering the full spectral
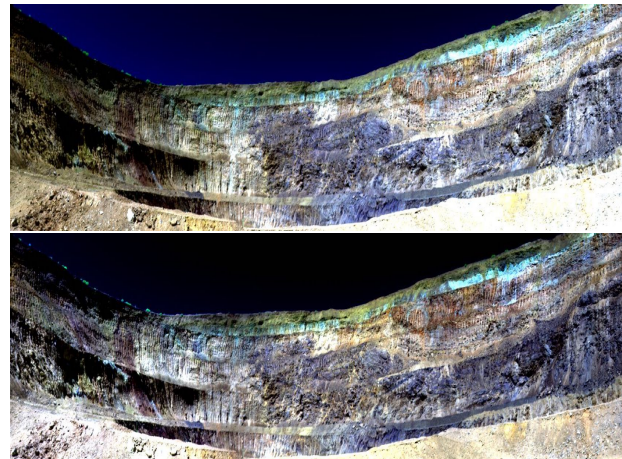

Figure 3. SPECIM Fenix mine face scanning scene, example 1, false color composite (R:2200nm, G: 1050nm, B:610nm).

range between 400 and 2450 nm, The scan angle swath is 90°, the solar zenith angle was at 38.7°, and the average observation distance between sensor and mine face was approximately 150 m. The image results show that the variability of the illumination in dependency of the observation direction can be mostly reduced by statistical means.
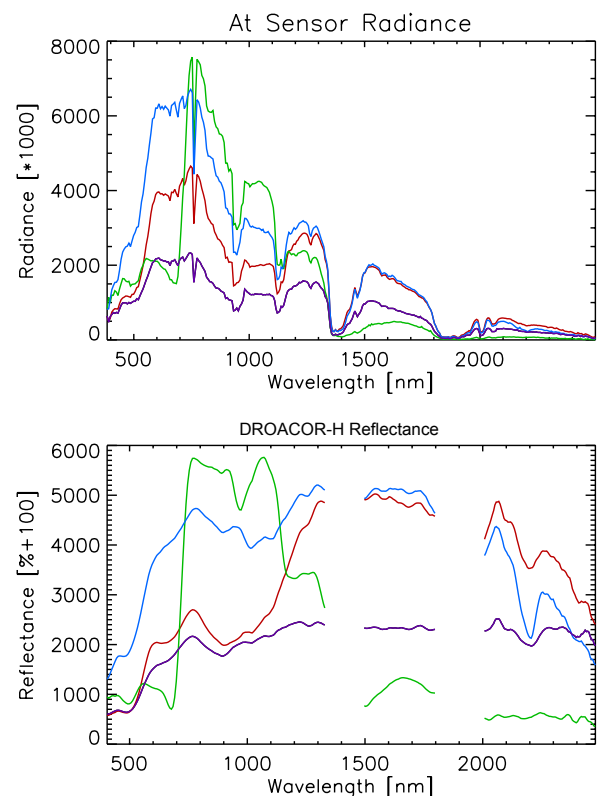

Figure 4. Spectra taken from sample image, before and after DROACOR-H processing: one vegetation spectrum (green) in comparison to three mine face mineral spectra.

Figure 4 shows the radiance and reflectance spectra of selected single-pixel spectral samples. One can clearly see the iron absorption features in the blue-green and the near infrared wavelength regions of the mineral spectra. Also, the mineral absorption features around 2100 nm and 2200 nm are well pro-

nounced. The results show the applicability of the proposed method to the horizontal mine face scanning setup. Very reasonable relative reflectance spectra results can be achieved which only exhibit small residual variations wich can be atributed to atmospheric variations, e.g. at the 940nm water vapor band.

In order to test the quality of the image product, a spectral angle mapping with spectra of minerals known for being present in the imagery has been performed. Three mineral spectra have been selected from the USGS spectral library (Kokaly et al., 2017), as shown in Figure 5, which are likely to occur in this open pit mine.
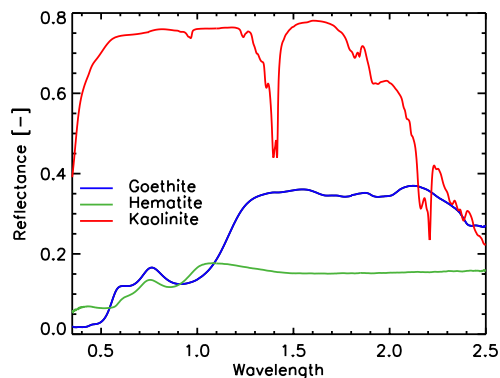

Figure 5. Selected USGS mineral spectra used for spectral angle mapping.
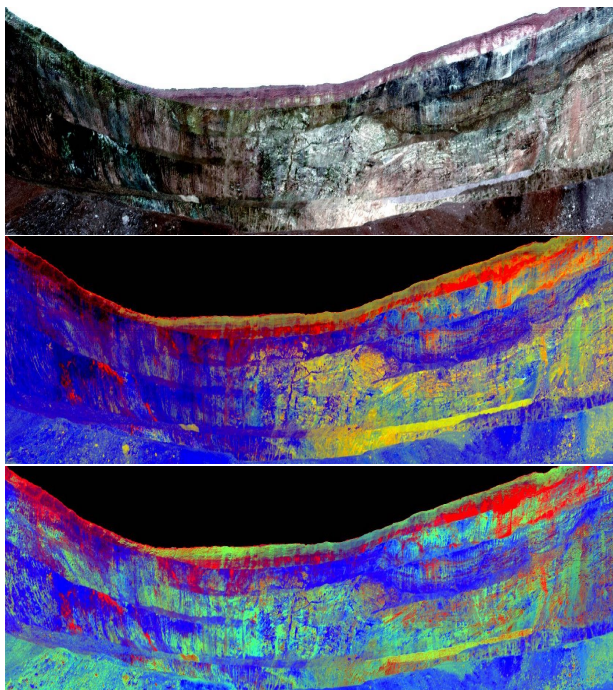

Figure 6. Inverse SAM image for mine face example 1: R: Kaolinite, G: Hematite, B: Goethite. Top: based on radiance image, Middle: based on apparent reflectance, Bottom: based on DROACOR outputs

The spectral angle mapping (SAM) as implemented in the GLIMPS software (Schläpfer et al., 2021) has been applied using the three spectra. For validation purposes, the same spectral

angle mapping has been applied to the raw radiance image L_s and to an apparent reflectance image ρ_{app}. The latter is calculated by dividing the calibrated at sensor radiance by the average estimated ground irradiance E_g; i.e. $\rho_{app} = \pi L_s / E_g$. The inverse spectral angles for each of the spectra are then displayed as RGB values in the three images respectively; see Figure 6. Inverting the spectral angle results shows the relative occurrence of hematite, goethite and kaolinite by the respective RGB-colors. Applying the SAM method with reflectance spectra on radiance data does not lead to useful results; this is to be expected as the spectral shapes of radiances are completely different than the library reflectance spectra (compare Figures 5 and 4). On apparent reflectance data, results are more realistic. However, a strong gradient in dependence of observation azimuth and illumination can be observed. As the SAM method is not sensitive to spectral brightness, this effect has to be attributed to the unrealistic spectral shapes of the apparent reflectance spectra.. Figure 7 shows three sample spectra of apparent reflectance in comparison to DROACOR-H reflectance. No spectral polishing has been applied to the these spectra to show the small spectral variations present directly after atmospheric compensation. The stronger disturbances in the vicinity of water vapor absorption bands may have led to the poorer performance of the SAM quantification for the apparent reflectance data.
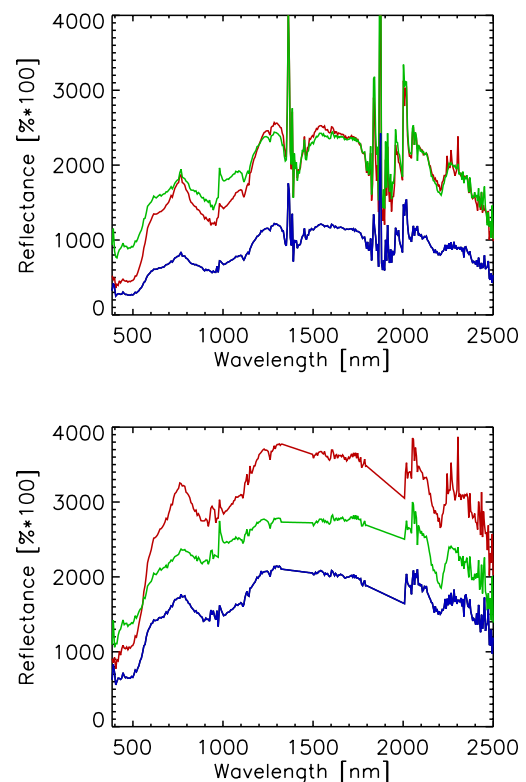

Figure 7. Comparison of three arbitrarily chosen, unfiltered reflectance spectra on single pixels (same pixels in both figures; top: apparent reflectance; bottom: DROACOR-H reflectance.

As a second check, the mineral reflectance spectra in Figure 5 are compared to scene-derived spectra as shown in Figure 4. The mine face spectral samples in Figure 4 have been taken at spots of relatively high occurrences for each of the minerals based on the SAM results. The spectral shapes are well
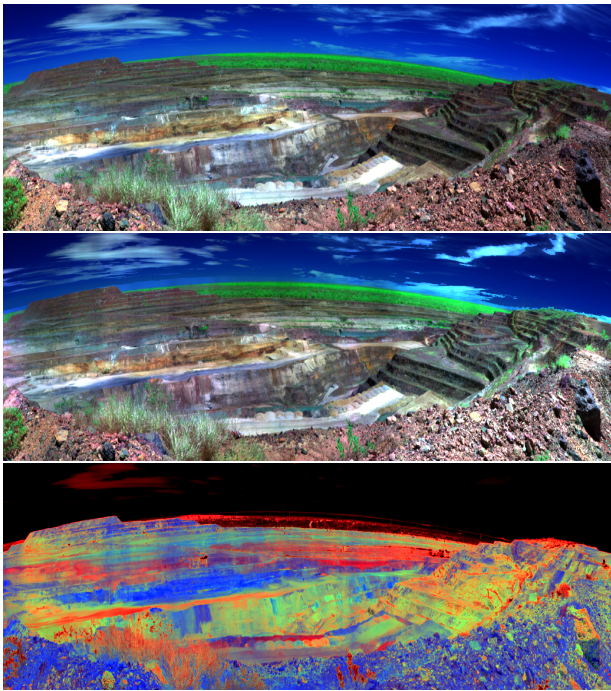
Figure 8. Open pit mine example 2, top: false color radiance ((R:2200nm, G: 1050nm, B:610nm); middle: DROACOR-H reflectance output, same spectral bands; bottom: inverse SAM quantification with: R: Kaolinite, G: Hematite, B: Goethite.
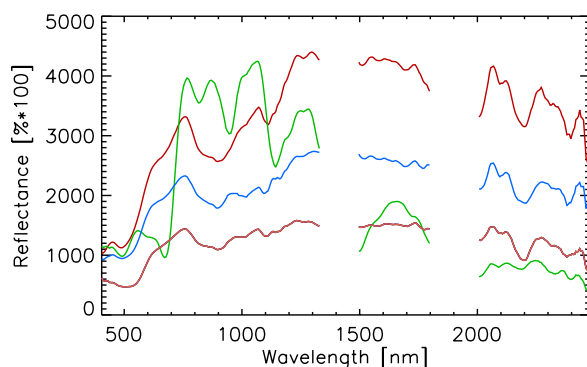

Figure 9. Spectra taken from 2nd example image. The green curve is a vegetation spectrum whereas the other spectra have been taken from within the open pit mine area.

reproduced after DROACOR-H correction: the purple curve in Figure 4 corresponds to Hematite, the red curve to Goethite and the blue curve to a formation with high Kaolinite abundance.

A second example scene is from an open pit mine imaged from variable distance between 20 and 800 m, scanned with the same setup as in the first example. The solar zenith angle was at 20° and the ground elevation is 540 m. The resulting DROACOR-H image is shown in Figure 8. It uses the same mineral reference spectra (Goethite, Hematite, Kaolinite; see Figure 5) for the SAM classification as in the first example. The inverse SAM classification image shows significant differences in detection of the various materials. If evaluating the spectra visually (see Figure 9), the resulting spectra are well comparable to the first example. However, the variable distances results in overcorrec-

tion of spectra in the foreground and some under-corrections at the farthermost distances within atmospheric absorption features. This is due to the fact that most spectral corrections implemented in DROACOR® are based on average image spectra which exhibit highly variable absorptions if the observation distances vary by more than 100 m.

5. DISCUSSION

The currently implemented procedure is based on a number of rough approximations in order to get reasonable relative reflectance spectra. The reflectances are 'relative' as the absolute brightness is not known. Even though, the presented results show that the such processed data may lead to improved and more stable mineral detection results. Specifically, methods based on spectral shape such as the spectral angle mapper are well suited to be used with DROACOR-H reflectances. Retrieving absolute reflectances on a per pixel basis would require an accurate prediction of the total direct and diffuse irradiance for every facet of an image. More and more, the hyperspectral data acquisitions are accompanied with laser scanners. This would allow to derive the accurate irradiance angles for the observed mining areas. Theoretically, such data sets would allow the retrieval of absolute reflectances. Problems to overcome are strong cross sensitivities by terrain irradiance, the extreme illumination and observation angles variations, and the related strong BRDF effects. So, suited BRDF models coupled with true 3-dimensional ray tracing would be required to solve that problem. From current point of view, in-depth new research is required to overcome these problems.

Instead of heading for a complete physical solution, one may also try to go for a purely empirical reflectance retrieval approach. There are two solutions which may be successful: either using in-situ reflectance panels or using image statistics. The use of in-situ panels is common practice for ground based imaging spectroscopy and also for drone imagery. Our analysis have shown that if observation distances are larger than 100m, the atmospheric effects are becoming significant, i.e. above approximately 5% relative differences in relevant spectral bands. Spectral ranges affected are specifically the 800-900nm range, where iron absorption features may be masked by atmospheric effects. Therefore, panels would need to be at the very same distance as the observed object for accurate reflectance retrieval. For images with highly variable distances as in mining this is hardly feasible. For this reason and for the reasons already mentioned in Section 3, the use of reflectance panels is of doubtful value.

Using image statics for reflectance normalisation is an approach which is applied QUAC reflectance normalisation method (Bernstein et al., 2008). For medium to large scale imagery, this method can lead to good quality relative reflectance spectra. The problem with its application in close-range imaging spectroscopy is the highly variable statics between imagery and scenes. Each mining site is different and it is hardly feasible to define comparable metrics for relative reflectance retrieval based on spatial averaging. Therefore, the method is not well applicable for the posed problem of ground based horizontal mine scanning. What remains is the presented semi-empirical method where physical modelling is coupled with automatic iterative spectral optimization processes.

6. CONCLUSIONS

The concept, the methodological background, and two example results of the DROACOR-H reflectance retrieval method have been presented. It shows that the tool allows realistic reflectance retrieval from calibrated imagery even for the radiometrically challenging case of horizontal scanning.

A first operationally usable version is ready to be used now, but further improvements are about to be developed. One possible additional feature will be an adaptive illumination correction, based on shadow analysis or using a 3D digital surface models. For the atmospheric parameters, the variable observation distances for water vapor correction and a rough quantification of the diffuse irradiance part could be helpful. Furthermore, masking of vegetation signatures and the transition from the relative reflectances to spectral albedos using BRDF models would have to be investigated in detail.

The methods developed in DROACOR® are well suited for applications other than mineral exploration. Typical applications would be vegetation, tree and forest border analysis. Furthermore, there are many potential applications in urban environments, where building faces and other built-up constructions could be checked for damages by hyperspectral horizontal scanning without the complexities always involved with airborne operations. Even the use of horizontal scanners from cars or drones would be a potential applications, specifically if the capability of taking the observation distance into account was added to the method.

The first version of DROACOR-H will be available for regular use by fall 2021. The module will be part of the the DROACOR® software package and shares data import and handling routines. An additional module for the processing of thermal hyperspectral data for mineral exploration is planned soon after. Thus, the DROACOR® software will soon help to process close range imaging spectroscopy data to reflectance quantities with higher reliability and repeatability than standard reflectance normalisation approaches.

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