

# Dealing with Cloud Shadows in Surface Reflectance Retrieval from Drone Hyperspectral Imagery

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## Abstract

Drone-based hyperspectral imaging is a powerful tool for environmental monitoring, yet its reliability in mid-latitude regions is often compromised by non-ideal weather conditions. Specifically, cloud shadows and light scattering by Cirrus clouds are influencing the irradiance and are difficult to parameterize. Standard atmospheric correction tools typically assume clear skies, leading to significant inconsistencies in retrieved surface reflectance values when clouds are present. This paper presents a new approach on the basis of the DROACOR atmospheric correction method which couples an empirical cloud detection routine with physical cloud transmittance calculations. For the detection of the spatially variable cloud shadows, an algorithm based on statistical analysis of spatially smoothed images is used. This is coupled with a physical model for cloud transmittance and spherical albedo retrieval. This combination is tested for the adjustment of reflectance in shaded areas to match illuminated conditions. Applied to data from HySpex VS620 and AVIRIS-4 systems, the method successfully retrieves surface reflectance values in the VNIR spectrum, comparable to fully illuminated areas. However, challenges remain in detecting faint shadows, correcting diffuse shadow borders, and retrieval of accurate surface reflectance in the SWIR spectral range.

## 1. Introduction

Drone-based imaging spectroscopy has grown to become a major remote sensing tool for environmental, agricultural and geological analysis. The data is easy to acquire at moderate costs per operation time. This bears the potential for regular monitoring of an area of interest. However, clear sky cases are rare in typical midlatitude situations. The solar illumination is often affected by scattering from thin clouds such as Cirrus or by shadows from thick clouds. So far, physical atmospheric correction tools are mostly reliant on a clear sky assumption which leads to inconsistencies in retrieved surface reflectance values due to cloud influences.

Retrieval of surface reflectances within cloud shadow areas or for data acquisitions below clouds is currently mostly done by empirical methods. The methods as implemented in ATCOR (Richter and Schlöpfer (2023)) and by Adler-Golden (Adler-Golden et al. (2002)) use a matched filter approach to retrieve surface reflectances in shaded areas by comparing the statistics of the shaded area to the directly illuminated area. Both methods rely on the availability of clear sky portions in the imagery which are not affected by cloud absorption and scattering effects. Drone imagery provides high resolution data while covering only small areas. Therefore, empirical methods are not always working satisfyingly as image statistics are normally not well comparable in small areas between various parts of an image. Furthermore, areas considered as 'clear sky' are normally still affected by increased diffuse illumination by clouds.

In this contribution, we first investigate the spectral variability of the illumination due to the presence of clouds. Based on radiative transfer methodology we then outline potential methods to dynamically retrieve surface reflectances within cloud

shadow areas. This includes the combination of shadow detection, cloud simulation and atmospheric correction for below-cloud situations.

## 2. Theory

For an appropriate surface reflectance retrieval below clouds, we have to analyze the effect of clouds on the ground irradiance as well as the optical properties of clouds, as shown hereafter.

### 2.1 Impact of Clouds on Irradiance

The impact of clouds on the solar flux at the ground has been modeled using the MODTRAN6 radiative transfer code (Berk et al. (2014)) for typical situations with solar zenith angle of 25 degrees and a constant Lambertian surface reflectance of 20%. Nimbus clouds base altitude was set to 5km with a thickness between 100 and 500m, while Cirrus were considered at high altitude. Results are shown in Fig. 1.

In the presence of Cirrus clouds, the total irradiance is hardly affected by the clouds, but the portion of diffuse irradiance is significantly increased between a factor of about 1.3 in the visible to a factor of almost 3 in the SWIR part of the spectrum. This has a significant impact for the analysis of areas shaded by terrain or by scattered clouds as the diffuse irradiance dominates the SWIR in the Cirrus case. Within the shadows of thick clouds, the direct irradiance is reduced to almost zero, whereas the diffuse irradiance dominates. This has considerable effects on the relation between the NIR and SWIR parts of the spectrum: the attenuation due to scattering is higher in the VNIR. This results in a higher relative irradiance in the SWIR compared to the VNIR below cloud as under clear sky situations.

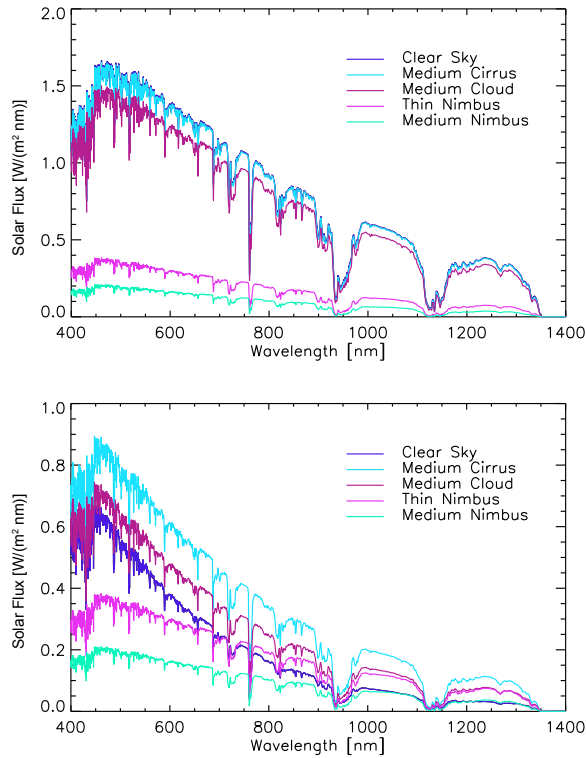


Figure 1. Total (top) and diffuse (below) solar flux on surface level for clear sky situation (blue) in comparison to the cases with Cirrus and with Nimbus clouds. RTC simulations are performed using Modtran6.

Both effects, i.e. the brightening of irradiance by scattering clouds as well as the attenuation due to clouds are to be analyzed carefully if the surface reflectance is to be retrieved under cloudy conditions.

For the practical simulation of the irradiance, we propose a new model for the solar light calculation at the ground in the presence of clouds that takes into consideration non-selective scattering. This model is directly applicable to below-cloud data acquisitions.

## 2.2 Irradiance Model

The total irradiance is calculated from direct, diffuse and adjacency contributions. Each of these components is highly dependent on the cloud type and coverage. The irradiance below clouds  $E_{g,c}$  can be written as a combination of the direct, adjacency and diffuse irradiance components ( $E_{g,c,dir}$ ,  $E_{g,c,adj}$ ,  $E_{g,c,dif}$ ), respectively as:

$$E_{g,c} = E_{g,c,dir} + E_{g,c,adj} + E_{g,c,dif} \quad (1)$$

$$E_{g,c} = (E_{dir} + E_{dif})(T_c + T_c * T_{adj} * r_c \rho_{adj}), \quad (2)$$

where  $E_{dir}$  = direct irradiance, top of cloud  
 $E_{dif}$  = diffuse irradiance, top of cloud  
 $T_c$  = cloud transmittance  
 $T_{adj}$  = adjacency path transmittance  
 $r_c$  = cloud spherical albedo

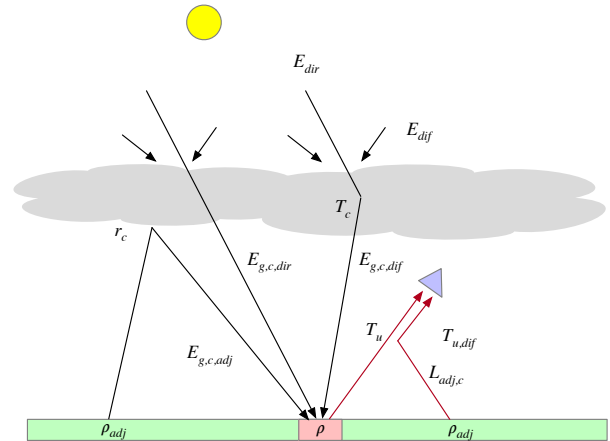


Figure 2. Below-cloud radiance components and relevant parameters.

$\rho_{adj}$  = adjacency ground reflectance

Compare Fig 2 for the definitions.

Using this formulation, reflectance can be retrieved below clouds as:

$$\rho = \frac{\pi L_s - \rho_{adj} E_{g,c} T_{u,dif}}{T_u E_{g,c}}, \quad (3)$$

where  $L_s$  = calibrated at-sensor radiance  
 $T_u$  = direct ground-to-sensor upward transmittance  
 $T_{u,dif}$  = diffuse (apparent) upward transmittance  
 $L_{adj,c}$  = below cloud directly scattered adjacency radiance  
 $\rho_{adj} = \rho_{adj} E_{g,c} T_{u,dif}$

The adjacency reflectance  $\rho_{adj}$  is a critical parameter in this retrieval process and is to be estimated iteratively from the image data.

## 2.3 Cloud Model

The current cloud model is based on the results of the asymptotic radiative transfer (ART) theory (Sobolev (1975), Zege et al. (1991), Kokhanovsky et al. (2020)). It is suggested in the framework of the ART that the reflection and transmission functions  $R$  and  $T$  of optically thick clouds, depending on the observation angles  $\mu$  and  $\phi$ , can be modelled as it follows:

$$R(\mu_0, \mu, \phi) = R_\infty(\mu_0, \mu, \phi) - T(\mu_0, \mu) e^{-\alpha s - k\tau} \quad (4)$$

and

$$T(\mu_0, \mu) = \frac{U(1 - e^{-\beta s})}{1 - e^{-2\alpha s - 2k\tau}} e^{-k\tau}, \quad (5)$$

where  $R_\infty$  is the reflection function of a semi-infinite cloud,  $U$  is the geometry parameter depending on the solar position  $\mu_0$ . The parameters  $\alpha = 10/7$ ,  $\beta = 8/3$  are derived from radiative transfer theory and  $k = \sqrt{3(1 - \omega_0)(1 - g)}$  is the diffusion exponent.  $g$  is the average cosine of single light scattering angle in the cloud,  $\omega_0$  is the single scattering albedo and  $s = k/(1 - g)$  is the similarity parameter,  $\tau = k_{ext} L$  is the

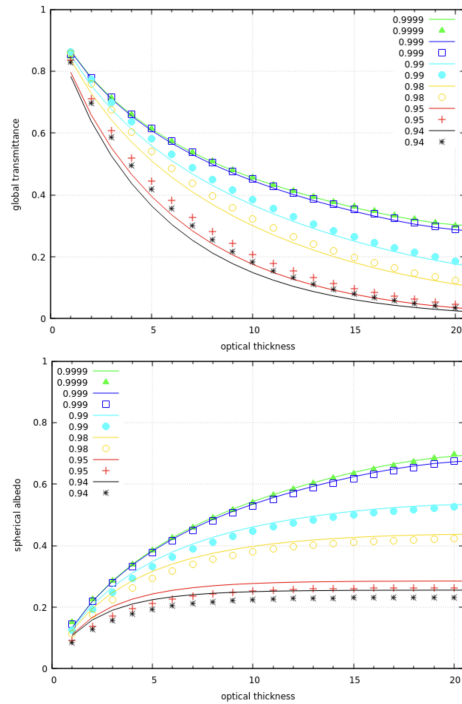


Figure 3. The dependence of the global transmittance and spherical albedo of plane-parallel clouds on the cloud optical thickness for the Henyey-Greenstein phase function with the asymmetry parameter  $g=0.85$  and various values of single scattering albedo. Exact radiative transfer calculations (Korkin et al. (2017)) are given by symbols.

cloud optical thickness,  $L$  is the cloud geometrical thickness, and  $k_{ext}$  is the cloud extinction coefficient. The parameters  $g$ ,  $\omega_0$ , and  $k_{ext}$  are calculated as the functions of the complex refractive index of water and the gamma droplet size distribution parameters in the framework of the geometrical optics with account for edge effects (Kokhanovsky (2006)). Eqs. 4 and 5 are particularly accurate in the visible and near - infrared regions of the electromagnetic spectrum, where  $\omega_0 \rightarrow 1$ .

Analytical approximations for the cloud diffuse reflection and transmission can be easily found by integration of Eqs. 4 and 5. In particular, it follows for the spherical albedo:

$$r_c = e^{-\beta s} - T_d e^{-\beta s - k\tau}, \quad (6)$$

where is the cloud diffuse transmittance under diffuse illumination is:

$$T_d = \frac{(1 - e^{-\beta s})e^{-k\tau}}{1 - e^{-2\alpha s - 2k\tau}}. \quad (7)$$

The cloud transmittance under direct solar light illumination given in Eq. 2 can be presented as:

$$T_c = T_d \frac{3 + 6\cos(\theta_0)}{7}, \quad (8)$$

where  $\theta_0$  is the solar zenith angle. The accuracy of these approximations for the diffuse transmittance under diffuse illumination conditions and also for the cloud spherical albedo is

illustrated in Fig. 3 as function of cloud optical thickness for different values of the single scattering albedo at the asymmetry parameter  $g = 0.85$  typical for water clouds. The exact radiative transfer results are calculated using the approach described by Korkin et al. 2017 are given by the solid lines.

### 3. Method

In recent years, we developed the DROACOR atmospheric correction method the surface spectral reflectance retrieval of short range, typically drone-based hyperspectral imagery. The method follows a radiative transfer code (RTC) based correction method (Schläpfer et al. (2020)) using Look-up Tables (LUT) simulated with libRadtran (Emde et al. (2016)). Calculations include consideration of the irradiance as consisting of direct, diffuse and adjacency components. DROACOR includes two models for cloud shadow correction: The first model is meant for partial cloud shadows, where the correction has to be adapted to the relative shading in the imagery. The presence of a cloud shadow is found by statistical analysis of spatially smoothed images or image mosaics, using a fixed set of spectral reference bands. A first order reflectance value is retrieved with the standard DROACOR atmospheric correction. The reflectance in shaded areas is then retrieved by adjusting the reflectance statistics under consideration to the conditions in non-shaded areas. The magnitude and the spectral shape of the latter depends on the cloud characteristics.

The second variation of the method is for data analysis of UAV based data taken under fully overcast conditions. The apparent reflectance statistics is analyzed in comparison to the expected brightness at selected wavelengths to get the cloud optical thickness. This parameter is then used to tune the cloud optical model for the approximative calculation of the irradiance below cloud and subsequent retrieval of the surface reflectance.

The implementation scheme of the method is shown in Fig 4. The surface reflectance is retrieved iteratively, starting with a clear sky assumption to estimate the shaded areas statistically. Using the cloud model presented in here, cloud transmittance  $T_c$  and cloud spherical albedo  $r_c$  can then be calculated. In a second step a first order reflectance below cloud is retrieved, which then can be used to get an estimate of the adjacency reflectance. This leads to a final reflectance product.

#### 3.1 Cloud Shadow Detection

A semi-empirical cloud deshading (i.e., spatial illumination based brightness adjustment) of images or image mosaics based on the averaged relative brightness to atmospherically corrected apparent reflectance data as included in DROACOR is used as input to the correction. It is based on apparent reflectance data retrieved by DROACOR under clear sky conditions. First, a subset of 5 bands at 580, 850, 1200, 1650, and 2100 nm wavelength is used for a generic brightness calculation. For overcast imagery, a reference reflectance value in these bands is used while for partially shaded imagery the directly illuminated areas serve as a reference. The brightness is created by a moving window technique with spatial smoothing within a specific radius according to the expected size of cloud shadows. The procedure follows the below steps:

1. calculate the statistics in reference wavelengths and assign reference reflectances applicable to the sensor at selected wavelengths.

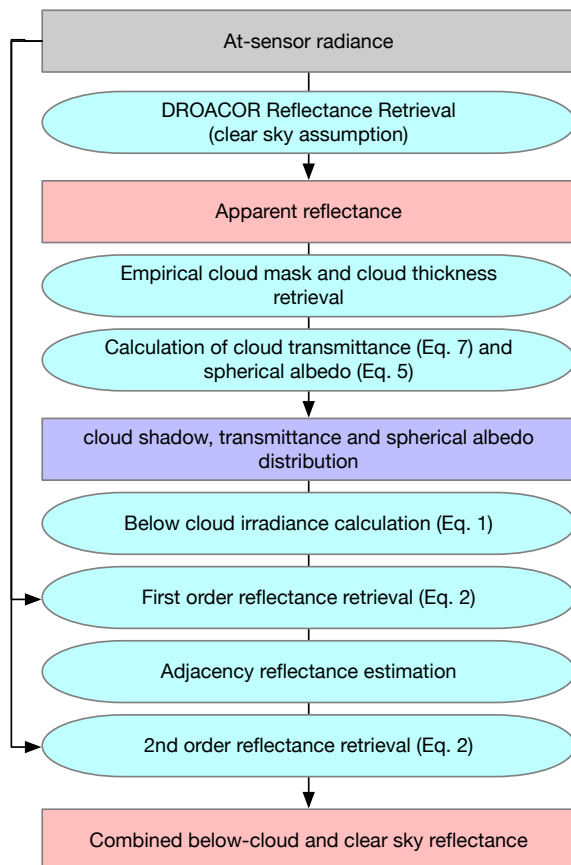


Figure 4. Below cloud reflectance retrieval scheme.

2. limit the range of reflectance between 2% and 90% (excluding very dark and bright pixels)
3. generate the brightness distribution map by averaging the values for all reference bands and divide by the reference reflectance.
4. scale the average relative brightness to a user-defined threshold.

The such derived shading distribution can be used as proxy for later shadow correction and for scaling of the cloud parameters to the spatial distribution of cloud thickness.

#### 4. Sample Results

The methods have been tested on a set of airborne and drone images from HySpex, Specim AFX systems, and on airborne data from AVIRIS-4 (Hueni et al. (2025)). An example of correction under partial cloud shadow for the HySpex VNIR1800 instrument is shown in Figure 5. The data was acquired in standard summer conditions with a solar zenith angle of 38°. For areas under relatively large and dark cloud shadows, the correction results in surface reflectance values comparable to those in directly illuminated areas. Problems occur for faint or small shadows, which are not detected by the filtering, and at the diffuse borders of the cloud shadows which can not be quantified easily. This method for cloud shadow removal has been mostly successful in the VNIR spectral range, whereas the reflectance retrieval for the SWIR spectral range could only partially be resolved.

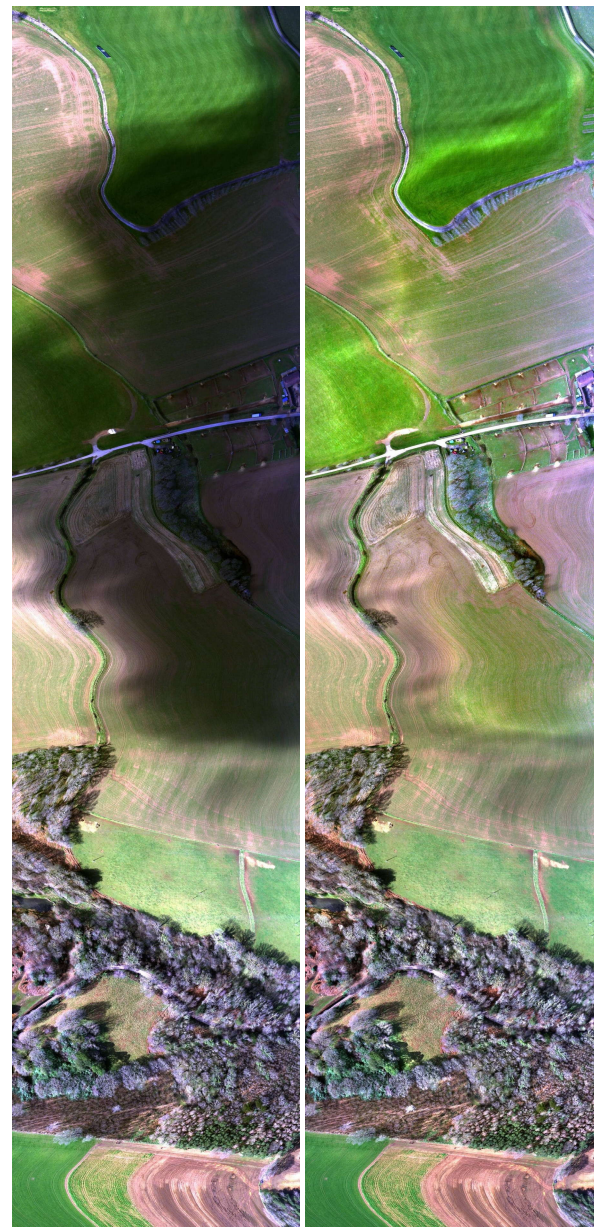


Figure 5. Semi-empirical correction of cloud shadow in HySpex VNIR spectral imagery. True color image (data courtesy of 2excelgeo UK).

For below cloud data acquisitions, no reference value from fully illuminated areas is available. The cloud thickness is to be derived in relation to reference reflectance values. Deriving the cloud optical transmittance and reflectance is crucial for the correction of such data. First tests on AVIRIS-4 imagery taken below cloud are promising (s. Figure 6). Vegetation spectra can be retrieved satisfyingly while high reflectances in the SWIR can not be retrieved yet correctly.

Figure 7 shows samples of retrieved reflectances from AVIRIS-4 data under sunny and cloud conditions without accounting for the attenuation by clouds. The spectra under clear sky conditions are as expected and show some artifacts due to spectral accuracy issues (no spectral filtering applied to the data). If assuming clear sky irradiance, the retrieved reflectances under cloudy conditions are lower by a factor of about two due to the attenuation by clouds. The spectral signatures in the VNIR



Figure 6. AVIRIS-4 data of the same area taken once under sunny conditions (left) and below fully overcast situation (right), scaled to the same brightness range; data courtesy of RSL Univ. Zurich.

spectral range are still realistic despite their lowered brightness. The SWIR spectra range apparent reflectance, on the other hand, is influenced strongly by the spectral absorption signatures of water and possibly ice in the cloud.

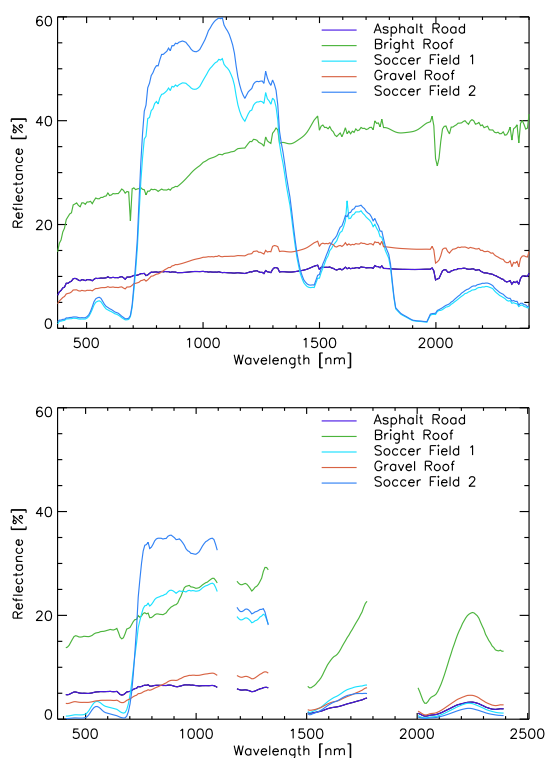


Figure 7. Reflectance spectra retrieved from AVIRIS-4 data. Top: under clear sky conditions with ATCOR; no filtering applied. Below: Under diffuse conditions without accounting for cloud influences, with water vapor bands masked out.

Using our model, the spectra can be improved by adjusting the irradiance. Correcting for the cloud transmittance and spherical albedo leads to improved results in the VNIR spectral range as shown in Figure 8. Realistic reflectance levels can be achieved up to 1000nm. In the SWIR spectral range, strong spectral ar-

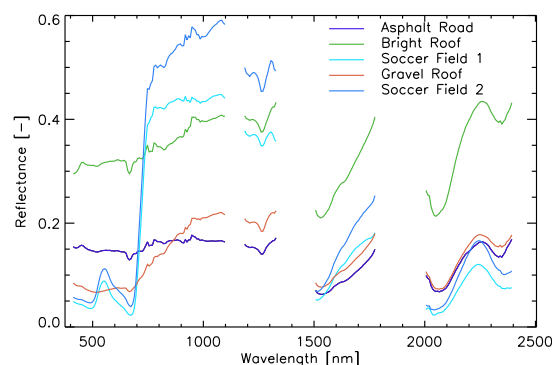


Figure 8. Tentative reflectance spectra retrieved from AVIRIS-4 data with liquid water based cloud transmittance and spherical albedo correction applied, with water vapor absorption bands masked out.

tifacts remain. The unexpected spectral shape above 1500 nm could be related to signatures of ice cloud absorption. Possibly, this has been caused by a Cirrus cloud layer above the Nimbus clouds which was not considered in the current corrections scheme.

A further test is done using retrieved AVIRIS-4 surface reflectances of the same targets (soccer fields) for the case of clean and cloudy sky measured in different periods of time. Although the measurements are from the same area, the complete spatial collocation has not been performed. It has been assumed that the adjacency reflectance coincides with the measurements for a clean day. Both theoretical calculations and measurements for a cloudy case show broad minima in the SWIR spectral range.

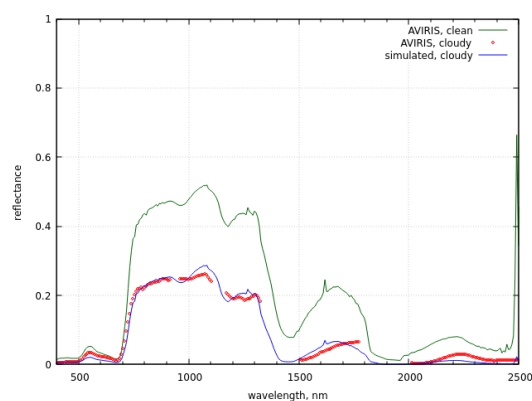


Figure 9. Measured reflectance for clean and cloudy sky. The simulated reflectance for the case of cloudy sky is shown as blue line. For the cloudy sky measurement, no interpolation of the measured spectra in the water absorption bands has been applied.

An optimization has been performed with respect to two cloud parameters (the liquid water path and effective radius of particles in a cloud). In this case, a path liquid water content of  $130\text{g/m}^2$  and an effective particle radius of  $12\mu\text{m}$  was estimated. This is the first retrieval of liquid water path and the effective radius of particles in clouds performed looking in cloud shadows. The accuracy of the technique must be further investigated. When applying the such derived parameters, the apparent reflectance below cloud can be simulated and compared to the measured apparent reflectance (see Fig 9). Spectra agree

very well in the VNIR spectral range, while the differences in the SWIR still remain. The shift of the measured spectra for the case of cloudy sky to longer wavelengths as compared to calculations requires further investigation.

The presented method has also been tested on satellite imagery where the removal of cloud shadows showed promising results. The respective results on ENMAP and Sentinel imagery will be presented in future publications.

## 5. Conclusions

The surface reflectance retrieval in imagery affected by cloud shadows is a problem which has not been addressed physically so far. We are proposing a method to allow reflectance retrieval using simple radiative transfer assumptions. This shall make it possible to retrieve surface reflectances below clouds in a fully automatic way. The cloud shading effect is retrieved semi-empirically by analyzing apparent reflectances calculated under clear-sky assumptions. Using the physical constraints one can show that reflectance retrieval is feasible across the full spectrum if both liquid water clouds and icy cloud absorption was considered. This method bears the potential for fully automatic reflectance retrieval under cloud coverage across the reflectivity spectrum in the VNIR spectral range, while further research is required for a fully automatic correction of the SWIR spectral range below clouds. Problems remain in areas of partial shading at the edges of clouds, which tend to be over- or under-corrected. Furthermore, areas with a significant portion of cast shadows (e.g. forests) are enhanced as well which can lead to overcorrection artifacts.

In this work we have tested a new system of equations, which can be used to simulate hyperspectral measurements underneath and also above clouds using fast analytical equations, which connect cloud reflectance and transmittance spectra with the cloud liquid/ice water path, shapes and sizes of cloud particles. The accuracy of all equations has been checked with the numerical calculations using the radiative transfer equation and Mie theory. The retrieval of the Lambertian ground surface reflectance for the case of the observer located under the cloud and looking downwards has been addressed for the case of extended cloud fields. The general equation for the ground reflectance function with account for the diverse illumination of a surface element from a broken cloud field is still to be implemented and tested. So, further development work is required for a stable solution for all kind of optical imagery.

For below cloud data acquisitions, it is possible to estimate the cloud transmittance from the relative brightness attenuation in the VNIR spectral range by inversion of the physical model presented in here. Our model can then be used to find the cloud transmittance and the albedo of the clouds and use these values for modeling the irradiance for the full imagery. The presented method will further be tested towards a fully operational and automatic cloud shadow correction in the DROACOR atmospheric correction procedure. Furthermore, first tests have shown that this method is also suited for the correction of cloud shadows in satellite imagery. Thus, we will investigate the possibilities to incorporate such methods for surface spectral reflectance retrieval in shaded areas in hyperspectral satellite imagery as part of the ATCOR method.

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