EFFICIENT RADIATIVE TRANSFER CALCULATION AND SENSOR PERFORMANCE REQUIREMENTS FOR THE AEROSOL RETRIEVAL BY AIRBORNE IMAGING SPECTROSCOPY

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ABSTRACT:

Detailed aerosol measurements in time and space are crucial to address open questions in climate research. Earth observation is a key instrument for that matter but it is biased by large uncertainties. Using airborne imaging spectroscopy, such as ESA's upcoming airborne Earth observing instrument APEX, allows determining the widely used aerosol optical depth (AOD) with unprecedented accuracy thanks to its high spatial and spectral resolution, optimal calibration and high signal-to-noise ratios (SNR).

This study was carried out within the overall aim of developing such a tropospheric aerosol retrieval algorithm. Basic and efficient radiative transfer equations were applied to determine the sensor performance requirement and a sensitivity analysis in context of the aerosol retrieval. The AOD retrieval sensitivity requirement was chosen according to the demands of atmospheric correction processes. Therefore, a novel parameterization of the diffuse path-radiance was developed to simulate the atmospheric and surface effects on the signal at the sensor level.

It was found for typical remote sensing conditions and a surface albedo of less than 30% that a SNR of circa 300 is sufficient to meet the AOD retrieval sensitivity requirement at 550nm. A surface albedo around 50% requires much more SNR, which makes the AOD retrieval very difficult. The retrieval performance is further analyzed throughout the visual spectral range for a changing solar geometry and different aerosol characteristics. As expected, the blue spectral region above dark surfaces and high aerosol loadings will provide the most accurate retrieval results. In general, the AOD retrieval feasibility could be proven for the analyzed cases for APEX under realistic simulated conditions.

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1. INTRODUCTION

The simulation of the light propagation through the atmosphere is a very important prerequisite for the scientific and quantitative use of remote sensing data. Radiative transfer models, such as MODTRAN (Berk et al. 1989) or 6S (Vermote et al. 1997), are often used therefore. They allow calculating the apparent signal at the sensor level with all its components of atmospheric extinction and surface interactions. Unfortunately, these models are rather complex and involve the risk of undetected operating errors. Furthermore, they are not optimized for aerosol remote sensing and are in need of intensive computational time. The use of look-up-tables (LUT) helps to circumvent these problems, but it is inflexible and depends on the LUT's limitations.

This paper introduces the Simple Model for Atmospheric Radiative Transfer (SMART). It is based on streamlined radiative equations and parameterizations, and yet accurate enough for most needs in aerosol remote sensing. In other words, it is a trade-off between performance, versatility, operator convenience and accuracy.

2. RADIATIVE TRANSFER

A simplified derivative of the radiative transfer equation (RTE) (Chandrasekhar 1960) provides a reasonably general and nevertheless powerful approximate of the interaction of light with particulate media (Kokhanovsky 2008). The use of the so-called single-scattering approximation (SSA) isolates the very complex problem of multiple scattering. A parameterization of the discrete ordinate radiative transfer code DISORT (Stamnes et al. 1988) is used to estimate the latter. A further help provides the breakdown into a part, which is either purely influenced by the atmosphere or by the surface.

2.1 SMART

SMART simplifies the atmosphere by two-layers (Fig. 1). It is assumed, that all aerosols are trapped within the lower layer, the so-called planetary boundary layer (PBL) or mixed layer.

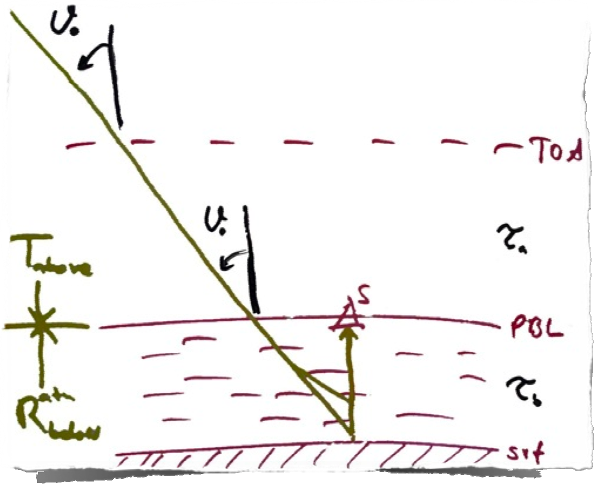

Figure 1: SMART atmosphere. The sensor (S) is situated between the PBL and the free atmosphere.

The resulting value from SMART is the apparent reflectance at the airborne sensor level (R_S):

$$R_\lambda^{sensor} = T_\lambda^{\downarrow 1}\left(R_\lambda^{\uparrow 2} + R_\lambda^{sfc}\right) \tag{1}$$

where T^1 denotes the transmittance between top-of-atmosphere and the sensor level, R^2 the reflectance function of the PBL and R^{sfc} the reflectance function of the surface contribution. The subscript λ refers to the spectral dependence. T^1 comprises a direct and a diffuse component:

$$T_\lambda^{\downarrow 1} = e^{-\frac{\tau_\lambda}{\mu_0}} + T_\lambda^{1\downarrow\, dfs} \qquad (2).$$

The calculation of R^2 makes use of the SSA and the correction factor f^{corr} in order to consider for higher orders of scattering:

$$R_\lambda^{\uparrow 2} = R_\lambda^{\uparrow 2\, SSA} * f_{\mu_0}^{corr}(\tau_\lambda) \tag{3}$$

The PBL reflectance with the SSA can be written as (Kokhanovsky 2004):

$$R_\lambda^{\uparrow 2\, SSA} = \left[1 - e^{-\tau_\lambda\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)}\right] \frac{\omega_0 P_\lambda(\Theta)}{4(\mu+\mu_0)} \tag{4}$$

where τ is the total optical depth (molecules and aerosols), μ_0 is the cosine of the solar and μ the cosine of the sensor zenith angle, ω_0 is the single scattering albedo and P(Θ) is the phase-function.

The remaining multiple scattering is considered by the use of a third order polynomial parameterization of the ratio between the MODTRAN total atmospheric reflectance and the result of Eq. (4) as follows:

$$\frac{R_{\lambda,\mu_0}^{atm,MODTRAN}}{R_{\lambda,\mu_0,SSA}^{atm}} \approx \sum_{m=0}^{3} c_m(\mu_0)\,\tau_\lambda^m = f_{\mu_0}^{corr}(\tau_\lambda) \tag{5}$$

The remaining R^{sfc} is calculated by:

$$R_\lambda^{sfc} = \frac{\rho_\lambda^{sfc} T_\lambda^{\updownarrow 2}}{1 - s_\lambda \rho_\lambda^{sfc}} \tag{6}$$

where ρ^{sfc} denotes the albedo or bihemispherical reflectance of the surface, T is the total transmittance (Kokhanovsky et al. 2005) and s is the spherical albedo.

The altitude of the aircraft can be adjusted via the air pressure at the surface, respectively at the sensor.

The values of the main input variables for SMART, which were used for this paper, are given in Tab. 1.

solar zenith angle	40°
aerosol model	average rural
sensor zenith angle	nadir
air pressure at surface level	1013 mbar (sea level)
air pressure at sensor level	506 mbar (5500 m above sea level)

Table 1. Radiative transfer variables used for this paper.

2.2 Aerosol retrieval

The principle of the AOD retrieval by inversion of SMART is shown in Fig. 2. A measured reflectance at the sensor level (red curve) is compared to the result of Eq. (1). In this example, an AOD of 0.4 in SMART reproduces the measured signal and is therefore assumed to be the correct AOD value.

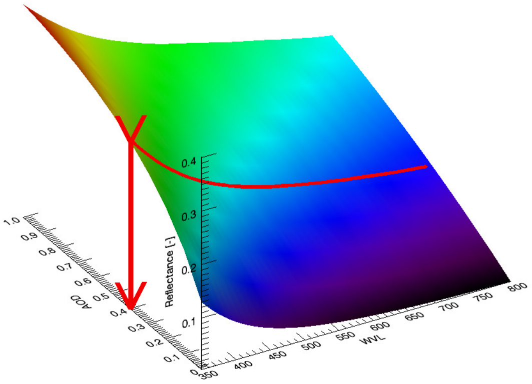

Figure 2: SMART inversion to determine the AOD.

2.3 Accuracy assessment of SMART

A comparison of SMART against MODTRAN4 was performed to assess its accuracy. The atmosphere and the aerosol model were adjusted in MODTRAN4 to represent the same two-layer scenario and the average rural aerosol model (d'Almeida et al. 1991) as it is currently used in SMART. A black surface was assumed to focus on the pure atmospheric influence. Fig. 3 shows the direct comparison between R_S from MODTRAN4 (rainbow-colored surface) and from SMART (yellow surface).

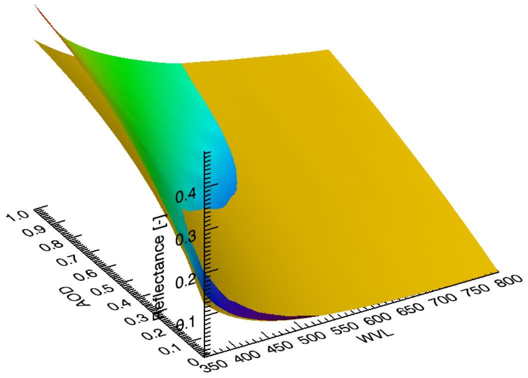

Figure 3: Comparison of R_S from MODTRAN4 (rainbow-colored surface) against SMART (yellow surface), plotted over wavelength [nm] and AOD.

The absolute difference of the resulting R_S between those two models is given in Fig. 4. It can be interpreted as the absolute error of SMART, given that MODTRAN4 provides the truth. The error is less than 0.02 reflectance values throughout the visual spectral range. The largest error, which is still below 0.1 reflectance values, is found for an unusual high AOD below 400 nm.

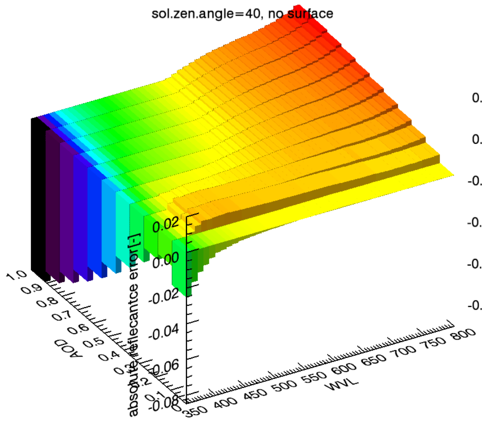

Figure 4: Absolute difference of R_S between MODTRAN4 and SMART, plotted over wavelength [nm] and AOD.

3. RESULTS

SMART can be used also to study the influence of different variables on the R_S. The following results illustrate its dependency on the surface albedo and AOD.

3.1 Artificial surface albedo

Artificial, spectrally flat surface albedo values were chosen to study their effect on R_S as a function of AOD. The pure influence of the atmosphere is given in Fig. 5. A clean atmosphere without any aerosols is purely Rayleigh or molecular scattering. It is therefore almost non-reflecting above 600 nm. The reflectance is increasing simultaneously with AOD due to additional Mie scattering of the particles. The effect of AOD is pronounced in the near-UV/blue part of the visible spectrum because scattering is most effective there. This translates into a well-defined gradient of R_S towards AOD. A small change in AOD produces a relatively strong change in the measurable signal, which is a strong asset for the aerosol retrieval.

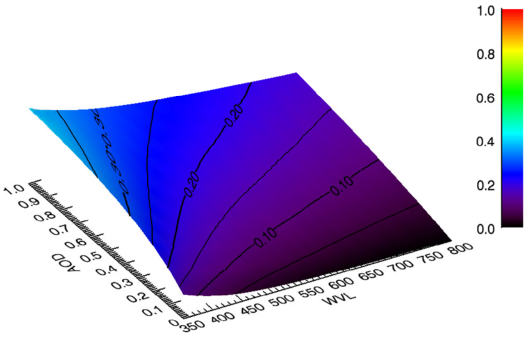

Figure 5: R_S with $\rho^{sfc} = 0\%$

A bright surface (albedo of around 0.4) decreases this gradient drastically (Fig. 6).

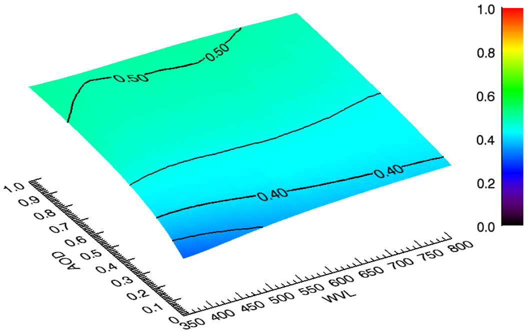

Figure 6: R_S with $\rho^{sfc} = 40\%$

An almost white surface makes the AOD retrieval even impossible. Even a string change in AOD does not produce any change of the signal at the sensor level (Fig. 7).

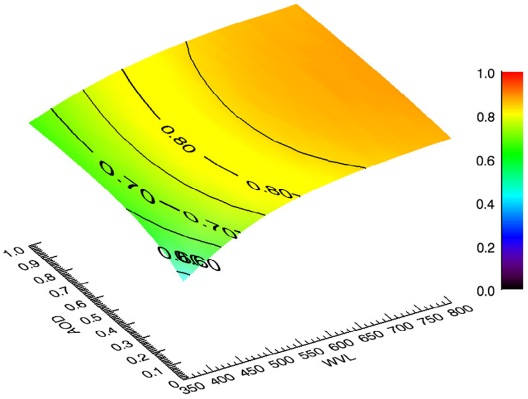

Figure 7: R_S with $\rho^{sfc} = 90\%$

3.2 Real surface albedo

A realistic surface albedo can also be used in SMART. The black surface in Fig. 8 shows a lemonwood-vegetation spectrum, which was taken from SPECCIO (Hueni et al. 2009). On top of that, the rainbow colored surface visualizes the influence of the atmosphere with respect to AOD. Again, Rayleigh scattering does not alter the red part of the visible spectrum and the most dominant influence of the Mie scattering is in the blue. The green-peak is still recognizable at high AOD, but it is less distinct and the blue is dominating. This corresponds to a decrease in the color contrast.

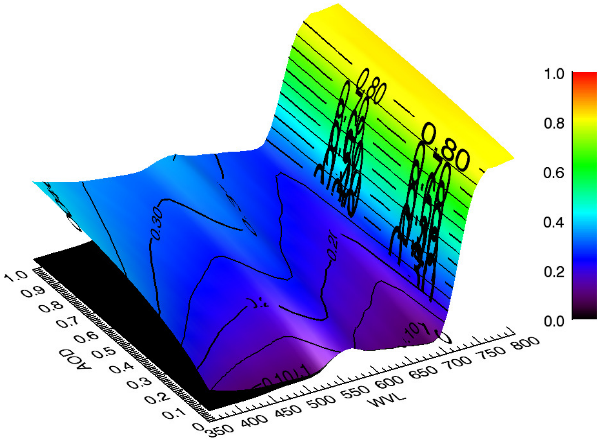

Figure 8. Visualization of influence of the atmosphere on R_S with respect to AOD over a vegetation target.

4. REQUIRED SENSOR PERFORMANCE FOR THE AOD RETRIEVAL

SMART was used additionally to assess the required sensor performance for the AOD retrieval in terms of SNR. It provides the interrelation between AOD and the measurable signal at the sensor, translated into SNR. It was found for a surface albedo of 0.1 that an SNR of 100 or better is required to be able to distinguish differences of about 0.01 AOD values. This demanded sensitivity, expressed in noise-equivalent differential AOD ($NE\Delta\tau^{aer}$) at 550 nm, is given by the violet line in Fig. 9. The yellow area indicates the fulfilled requirement. In the red area, the AOD retrieval is impossible. Brighter surfaces would require higher SNR values, according to the decreasing gradient of R_S in respect to AOD. This effect is further discussed in subsection 3.1. Please refer to (Seidel et al. 2008) for further details.

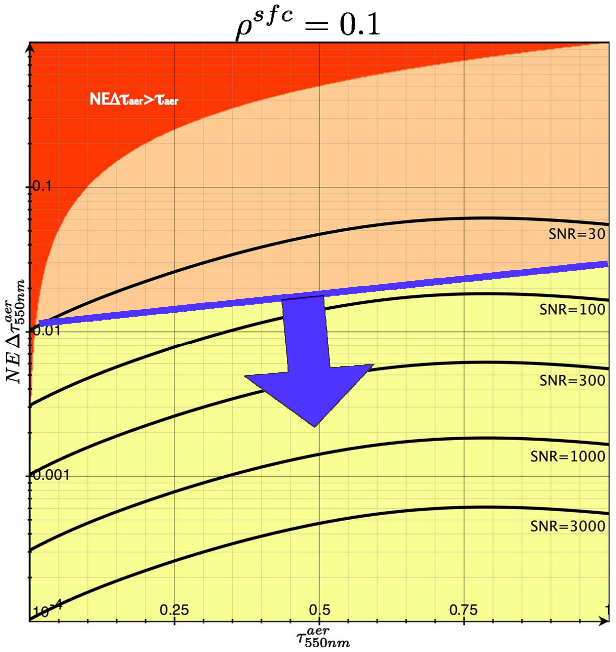

Figure 9. Visualization of SNR requirements for the aerosol retrieval as a function of AOD and $NE\Delta\tau^{aer}$. The yellow area fulfills the AOD retrieval accuracy requirement for a surface albedo of 0.1.

5. CONCLUSIONS

This study aimed at estimating AOD by the use of a radiative transfer model, which is relatively simple and still accurate enough for various applications. For typical remote sensing cases, the proposed SMART can reproduce the MODTRAN4 calculations quite well in terms of R_S. It could be used therefore as a replacement for MODTRAN4, whenever speed, flexibility and ease of use are important. SMART allows live calculations, helpful for the interpolation of a LUT or for visualization and educational purposes.

SMART was demonstrated by studying the interesting interrelation of the surface albedo and AOD on R_S. Further, it was used to connect SNR to AOD and assess the minimal

SNR, which is required to retrieve AOD by the requested accuracy. This leads to the conclusion, that theoretically it will be possible with ESA's upcoming airborne Earth observing instrument APEX (Itten et al. 2008) to retrieve AOD unprecedentedly accurate.

In the near future, SMART will be tested on airborne imaging spectroscopy data and validated against in-situ AOD measurements. SMART could be enhanced later by taking gaseous absorption; polarization and directional surface properties, as well as the terrain into account.

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