Aerosol retrieval for APEX airborne imaging spectrometer: a preliminary analysis

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ABSTRACT

In order to achieve quantitative measurements of the Earth's surface radiance and reflectance, it is important to determine the aerosol optical thickness (AOT) to correct for the optical influence of atmospheric particles. An advanced method for aerosol detection and quantification is required, which is not strongly dependant on disturbing effects due to surface reflectance, gas absorption and Rayleigh scattering features. A short review of existing applicable methods to the APEX airborne imaging spectrometer (380 nm to 2500 nm), leads to the suggested aerosol retrieval method here in this paper. It will measure the distinct radiance change between two near-UV spectral bands (385 nm & 412 nm) due to aerosol induced scattering and absorption features. Atmospheric radiation transfer model calculations have been used to analyze the AOT retrieval capability and accuracy of APEX. The noise-equivalent differential AOT is presented along with the retrieval sensitivity to various input variables. It is shown, that the suggested method will be able to identify different types of aerosol models and to measure AOT and columnar size distribution. The proposed accurate AOT determination will lead to an unique opportunity of two-dimensional pixel-wise mapping of aerosol properties at a high spatial resolution. This will be helpful especially for regional climate studies, atmospheric pollution monitoring and for the improvement of aerosol dispersion models and the validation of aerosol algorithms on spaceborne sensors.

Keywords: Remote Sensing, Aerosol, Atmosphere, Climate, APEX

1. INTRODUCTION

The radiation budget on the Earth surface is one of the most fundamental factors in our climate system. It is strongly dependent on the optical influence of atmospheric aerosols. The measurement of aerosol parameter is an important subject in today's environmental and atmospheric sciences. Various ground based in-situ aerosol retrieval technologies present the best results in terms of accuracy, temporal resolution and type determination, while they cannot provide information on the spatial aerosol distribution. Many space-based imagers and sounders retrieve important operational data on a global scale, but it remains still a demand in higher spatial aerosol distribution information for regional climate studies and air pollution monitoring.

The Airborne Prism EXperiment (APEX)[1] will be one of the first imaging spectrometers for aerosol retrievals with high spatial resolution. This gives a new opportunity for studies of the local aerosol variability and for the mapping of source and sink regions. Even further investigation of the aerosol chemical composition, optical properties and interactions with water vapor and trace gases are conceivable.

This paper briefly assesses state of the art aerosol retrieval techniques with respect to a possible adaptation, modification and enhancement for the APEX instrument. Many available algorithms are based on the aerosol retrieval over ocean, while several challenges remain for land surface applications. The complex spectral and spatial ground reflectance makes it more difficult to decouple the signal at the sensor into the atmospheric and the surface contribution[2].

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2. APEX IMAGING SPECTROMETER

The dispersive pushbroom imaging spectrometer APEX will contribute to the simulation, calibration and validation of future space- and airborne optical sensors. Furthermore, APEX devotes unique hyperspectral datasets to various geo-physical and biochemical studies on land, water and atmospheric processes along with other applications.

APEX's broad spectral range from 0.38 to 2.50 microns splits into either 313 binned or 511 unbinned spectral bands. The ground pixel size varies from 2.5 to 8 meters depending on the flight altitude and spectral band setup. These spectral and spatial resolutions denote an opportunity to go beyond the limitations of available remote sensing platforms. Nevertheless the high spatial resolution of only a few meters introduces also new difficulties and uncertainties.

It is planned to operate APEX with a new calibration methodology for spectral, radiometric and geometric calibration and characterization[3,4]. This guaranties a high geometric, spectral and radiometric stability over a long period of time. The planned missions onboard the Earth observation and atmospheric research aircraft HALO[5], operated by the German Aerospace Center (DLR), can benefit from an onboard LIDAR and volatile organic compounds aerosol measurement system. This is a very promising setup for future aerosol research campaigns.

Table 1: Specifications of the APEX instrument

| Observation parameter	Carrying platform: DO-228 (DLR)	Carrying platform: HALO (DLR)	Platform independent specifications
Spectral range			380 nm to 2'500 nm
Spectral sampling			5 nm for VNIR 10 nm for SWIR
Flight altitude range	3000 to 7500 m	7500 to 15000 m	
Reference altitude (Alt.$_{ref}$)	5000 m	10000m	
Swath at Alt.$_{ref}$	2.5 km	5 km	FOV = 28 deg 1000 pixels cross track IFOV = 0.489 mrad
Ground pixel size in the spatial opt. mode at Alt.$_{ref}$	2.5 m	5 m	313 spectral bands (Normal operation mode)
Ground pixel size in the spectral opt. mode at Alt.$_{ref}$	4 m	8 m	511 spectral bands
Flight length	250 km	700 km	~60 min data on disk array
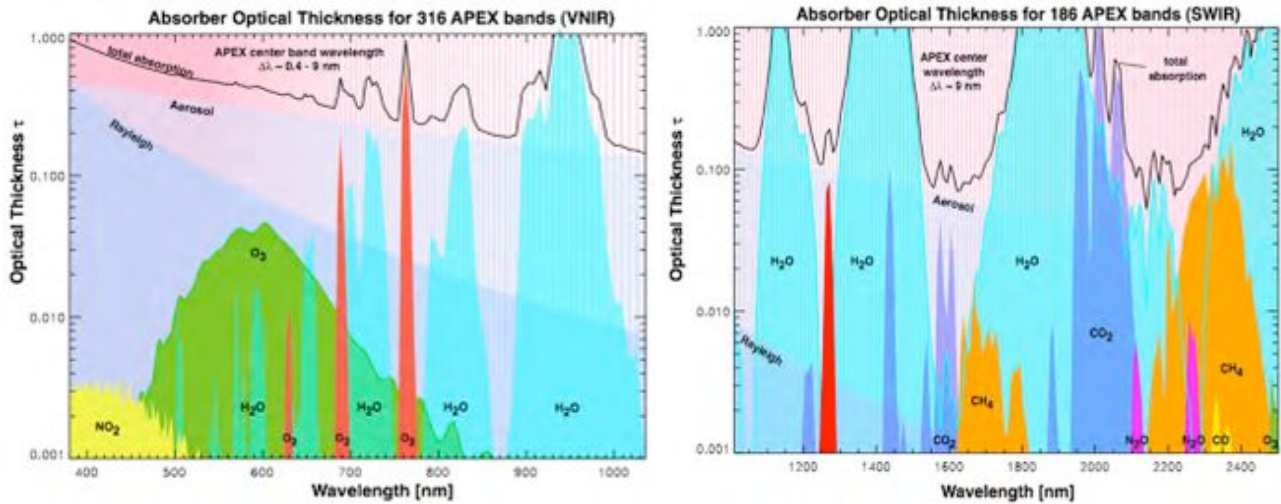
Figure 1: APEX's 316 VNIR (left) and 186 SWIR (right) spectral bands (narrow vertical lines) overlaid by the optical thicknesses of aerosol and Rayleigh scattering and atmospheric gas absorption.

3. REVIEW OF SELECTED RETRIEVAL METHODS

The first stage of evaluation for a future aerosol retrieval algorithm for APEX began with the study of existing retrieval methods on the following instruments: OMI[6] on Aura, MERIS[7] on Envisat, MODIS[8] on Terra and Aqua, TOMS[9] and GLI[10] on the former ADEOS-II spacecraft. They have been selected due to their technological comparability to APEX in terms of the aerosol retrieval. The following three approaches are described in more details.

3.1 MODIS Dark Target Approach or Kaufmann-Method

Kaufmann and Tanré[8] derived the AOT from the reflectance change between the blue and red channel, along with the surface reflectance retrieved from the 2.1 μm channel. The use of relatively dark targets over dense vegetation reduces the influence from the surface, while the 2.1 μm was assumed to be free from an aerosol signal. The ratio of the blue (0.47 μm) and red channel (0.66 μm) is corrected with the interfering surface contribution and used to choose an appropriate look-up-table (LUT), which provides the AOT. Since to was found that the 2.1 μm channel is not completely transparent to aerosol, the AOT and the fine mode fraction will be retrieved in the blue, red and mid-IR channel simultaneously. A further modified algorithm, called Deep Blue, introduced by Hsu[11], will be soon implemented for MODIS. This algorithm is now able to retrieve AOT and the Ångstrøm exponent over bright surfaces. It determines the surface reflectance in the 412 nm, 490 nm and 670 nm channels.

3.2 BEAR

The Bremen Aerosol Retrieval (BEAR)[12] has been developed to retrieve the AOT for land products of various spaceborne sensors, such as SeaWiFS, MERIS, MODIS and SCIAMACHY. It subtracts the surface and Rayleigh path reflectance and other non-aerosol contributions from the TOA reflectance. This "straightforward" approach keeps the algorithm remarkable adaptive to different sensors, because it does not depend on a specific channel setup. The AOT is then retrieved on the basis of precalculated LUTs. Since BEAR follows a multi-channel approach, where e.g. the first 7 MERIS bands (410 nm to 665 nm) are involved, there is an important dependency on accurate surface reflectance information. The normalized differential vegetation index (NDVI) controls a linear mixing model of vegetation and soil spectra to subtract the surface from the total reflectance.

3.3 Near-UV two-channel retrieval method

Using TOMS, GLI, or OMI data reveals the opportunity of spectral bands in the UV or near-UV region for the aerosol retrieval. The near-UV offers several advantages for the aerosol retrieval over land[10], such as low reflectance for most surfaces (around 5%), low absorption of trace gases, relatively weak bidirectional reflectance function (BRDF) effects and strong Rayleigh single and multiple scattering, which helps to identify absorbing aerosols. The occurrence of aerosols in the atmosphere alters the incident radiance at the sensor depending on its number concentration and its optical properties. The resulting distinct radiance change can be used to detect and distinguish different aerosol types and their loadings[9]. The retrieval problem simplifies by the fact that the surface reflectance contribution is low and can even be neglected under certain circumstances. On the other hand, Torres[9] showed that the height of the surface aerosol layer with absorbing particles has a significant effect on the measured radiance.

4. APEX AEROSOL RETRIEVAL

The main goal of the APEX aerosol retrieval is the determination of a robust AOT to be used as an input variable for an atmospheric correction algorithm (e.g. ATCOR[13]). Along with the geometric correction, the resulting Level-2 data provide satisfying surface reflectance information leading to the second main goal, the pixel-wise aerosol feature extraction. This second iteration of aerosol retrieval can rely on an accurate ground reflectance input acquired in the first iteration. This enables to subtract the surface feature of each pixel from the signal at sensor. Finally, the available zero- or one-dimensional aerosol data can be extended into a two-dimensional, vertically integrated aerosol distribution image.

The initial retrieval will be conducted over sampling regions of dark vegetation, where the ground reflectance is weak enough to prevent large errors from the assumption of the surface spectral behavior. Due to the high spatial resolution of APEX, there is also the possibility to outlay black ground-truth targets as sampling points. Since the imaging spectrometer will be used in semi-operational scientific campaigns, it is planned to run individual scene-specific

radiation transfer model (RTM) calculations with all available atmospheric, solar, elevation and viewing geometry input variables. The specific RTM calculations are now reduced to the residual uncertainty of the assumed aerosol model. If no aerosol vertical profile data are available, the uncertainty in the vertical distribution and concentration of absorbing particles[9] contributes to the retrieval accuracy.

Basically, the APEX aerosol retrieval follows the idea of a two-channel approach in the near-UV spectral region at 385 nm and 412 nm. This allows to identify the aerosol optical properties and to differentiate between different particle types. The RTM calculation yields the relation between radiance and AOT for the given observation parameters. This information is then used to invert the measured at-sensor radiance (ASR) to the corresponding AOT value. If there is no a priori information available (i.e. from AERONET), the retrieved radiances can be interpolated to precalculated LUT values to obtain both, τ_a and the single scattering albedo (ω_0). The ω_0 determines the aerosol absorption feature, which can thereby be related to an aerosol type. A given Ångstrøm wavelength exponent (α), which can also be obtained by AERONET, allows to extrapolate the spectral AOT from the near-UV region to the whole APEX spectrum according to $\tau_\lambda = \tau_{\lambda,0}(\lambda/\lambda_0)^{-\alpha}$, where τ_λ denotes the spectral optical thickness. It is even possible to estimate α with the ASR ratio between the two retrieval channels without AERONET. Further, linear inversion methods to solve the well-known Fredholm equation of the first kind can be used to determine the columnar aerosol size distribution, according to King[14].
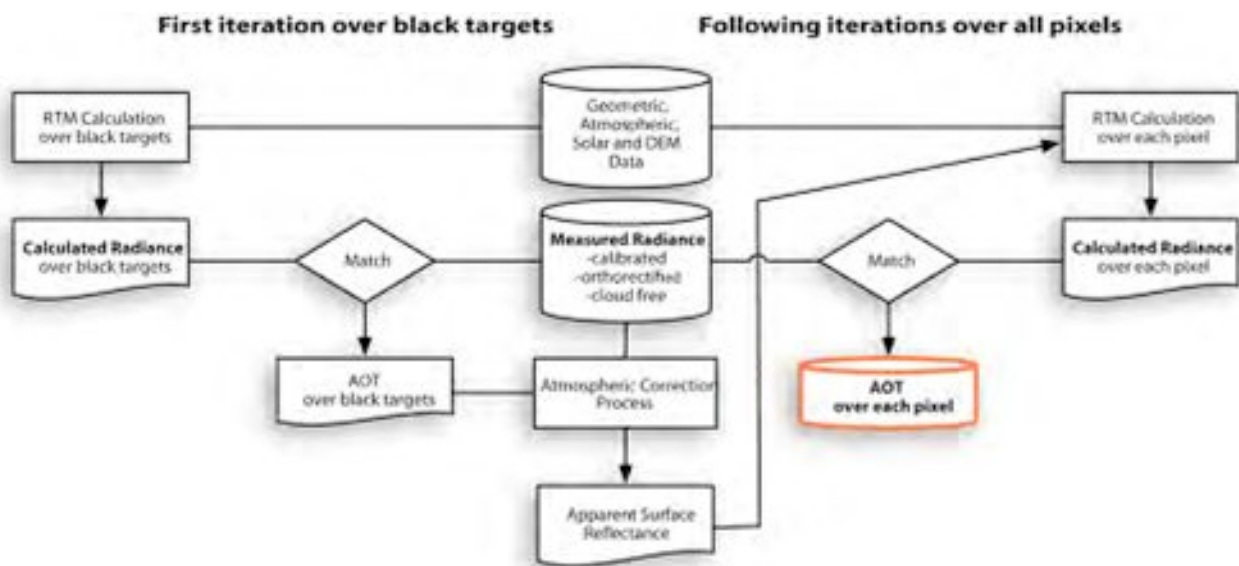

Figure 2: Flowchart of the suggested APEX aerosol retrieval procedure. It starts with a fist iteration of RTM calculation over black targets to calculate an expected radiance for various AOT. Where the calculated and the measured radiance match, the corresponding AOT will be retrieved. This AOT over black targets enables the atmospheric correction process to determine the apparent surface reflectance. Now, the following iterations over all pixels can rely on that "first-guess" surface reflectance and are therefore not limited to black targets. Finally, the AOT for each pixel is retrieved. It is now possible to achieve an accurate surface reflectance by feeding a second atmospheric correction run with the retrieved AOT over each pixel.

A constraint of many available aerosol retrieval algorithms is the quality of the cloud mask. Either there are many pixels masked out or even a small cloud contamination within a pixel significantly disturbs the aerosol retrieval. The high spatial resolution of the APEX imaging spectrometer helps to detect even small convective clouds and fog patches with a cloud-screening algorithm. Cirrus layers are expected above the airborne sensor, not interfering with the line of sight and their effects on the solar irradiance can be considered to a certain extend in the RTM calculations.

Along with the implementation of custom aerosol models, a further improvement in terms of accuracy of the RTM calculations comprises basic considerations of BRDF and polarization effects of the Rayleigh atmosphere.

This aerosol retrieval technique is adjusted for dark land surfaces, but it can be basically applied also over water bodies. It is planned to modify the outlined algorithm by the use of bands in the spectral regions of 860 nm and 2200 nm to benefit from very low surface reflectance over water surfaces.

5. PERFORMANCE AND SENSITIVITY ANALYSIS

The following analyses are based on expected standard atmospheric, surface and viewing geometry conditions for operations with the APEX airborne instrument. The RTM calculations are basically performed by the input parameters tabulated below. Some of them have been varied to show their effect on the RTM result.

It is planned to calculate the effect of polarization on the APEX aerosol retrieval result. It is expected that this effect can reach about 6% at 380 nm[10] for Rayleigh multiple scattering, while it is much smaller for the aerosol multiple scattering. The aerosols themselves depolarize the atmospheric and surface signal.

Table 2: Definition of the standard RTM boundary conditions. The solar geometry represents summer solstice condition in Zürich (Switzerland). ϕ_0=solar azimuth angle, θ_0=solar zenith angle, θ_s sensor zenith angle, $\rho_{s\lambda}$=spectral surface reflection.

ϕ_0 / θ_0 θ_s	Atmospheric-condition	Boundary-layer Temp.	Water Vapor-Column	Sensor Alt. Ground Alt.	Target $\rho_{s\lambda}$ Backgr. $\rho_{s\lambda}$	Aerosol-model
181° / 23.8° 180° (nadir)	Midlatitude-summer	293.0 K	1.7 g/cm^2	5000 m 400 m	BlackPaint Green Grass	Rural

5.1 Radiation transfer model

RTM calculations have been carried out with MODTRAN4 for the constructions of accurate LUTs and to test the sensitivity[15] of the suggested retrieval approach. The solar spectral irradiance is adapted from Thuillier[16]. For simplicity, the standard MODTRAN4 atmospheric profiles and aerosol models have been used. The layer structure and vertical distribution of the different gases and particles have not been modified for this study, but it would make sense to the APEX aerosol retrieval to adjust the lowest aerosol layer height depending on actual conditions. The molecular, temperature and humidity vertical distribution represent an average mid-latitude atmosphere adjusted by the season. Different aerosol models can be applied to the planetary boundary layer up to an altitude of 2 km, while the free troposphere assumes an invariant mixing ratio of 0.7 water-soluble (organic compounds, ammonium and calcium sulfate) and 0.3 dust-like aerosols in the small particle fraction. The background aerosols in the stratosphere consider sulfur and variable amounts of volcanic particle compounds. Molecules and aerosol multiple scattering is taken in account, along with the important effect of water vapor on the absorption and scattering properties of the aerosols due to particle growth[17]. The spectral lambertian surface reflectance considers adjacency effects by assuming a black painted target pixel within a green grass surrounding. The spectral reflectance behavior of such methods has been adapted from the established ENVI spectral libraries[18].

The user selects in MODTRAN4 the aerosol loading via the meteorological range, which is transformed with the traditional Koschmieder formula into the total atmospheric extinction coefficient ($k_{e,tot}$) at 550 nm. To obtain the τ_a values used in this paper, $k_{e,tot}$ is integrated over the optical pathlength between the surface and the sensor and corrected by the Rayleigh scattering at 550 nm and the NO_2 gas absorption in the near-UV, which is assumed to be small (~0.003). All τ_a values in this paper are therefore normalized to 550 nm, even if they are calculated in the near-UV spectral region. Upcoming refinements of the APEX aerosol retrieval will enhance the accuracy of τ_a by introducing a more sophisticated method with MODTRAN4 instead of relying on the empirical Koschmieder formula.

5.2 Minimum retrievable aerosol optical thickness

The APEX performance characteristics (refer to Table 3) promise successful aerosol retrieval with the suggested near-UV approach. The noise-equivalent differential aerosol optical thickness (NE$\Delta\tau_a$) describes the channel sensitivity to the aerosol loading. The sensor specific signal to noise ratio (SNR) at a given ASR defines the least measurable radiance difference (NEΔL), which yields the NE$\Delta\tau_a$. Figure 3 visualizes the effect of the NE$\Delta\tau_a$ for standard conditions on the at-sensor reflectance for different aerosol models.

Table 3: APEX Band specifications for low radiance levels. The noise equivalent $\Delta\tau_a$ has been calculated for standard conditions (refer to Table 2). These values represent the most recent sensor design status, which includes a removable optical filter. No-filter operations would improve the given values.

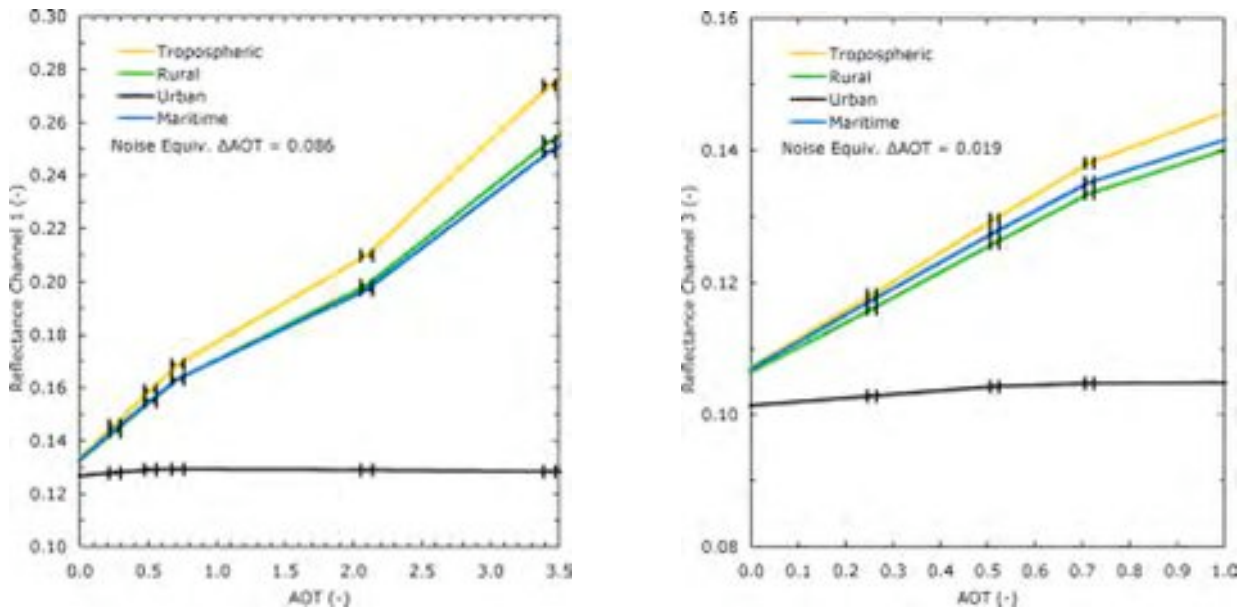| Band Number in VNIR Channel	Center Wave-length [nm]	Low Radiance [W m^{-2} sr^{-1} nm^{-1}]	SNR [-]	Noise Equiv. ΔL [W m^{-2} sr^{-1} nm^{-1}]	Noise Equiv. $\Delta\tau_a$ [-]
1	385	0.034	50	0.00072	0.086
2	398	0.033	108	0.00031	0.028
3	412	0.031	120	0.00026	0.019
4	425	0.029	123	0.00024	0.019
5	438	0.027	114	0.00024	0.018

Figure 3: The noise equivalent $\Delta\tau_a$ is plotted as an error-bar in channel 1 (left) and channel 3 (right) for each of the four different aerosol models.

5.3   Aerosol models and AOT variation

Four MODTRAN4 built-in aerosol models have been used for this preliminary study. The clean continental or rural type is composed of 70% water-soluble (organic compounds, ammonium and calcium sulfate) and 30% dust-like particles. The rural aerosol type mixes 56% water-soluble and 24% dust-like with 20% soot particles. Only the urban model contains soot particles, which introduce the absorbing feature of this aerosol model. A realistic aerosol model for medium populated areas should be defined somewhere in between the non-absorbing rural and the urban model, which applies only for a relatively strong polluted air mass. Those models are subject to further refinements in order to improve the representation of local aerosol conditions.

The resulting effect of aerosol loading is shown in Figure 4. Each dot represents a RTM reflectance output value for a specific τ_a, which are taken constant on the four different aerosol models. The spectral surface reflectance used for the RTM calculations is in accordance to Table 2 defined as a black paint spectrum in the target pixel, surrounded by a green grass spectrum. This ratio plot visualizes how the different aerosol loadings in different models are distinguishable from each other. The further the different models are spreading in such a plot, the easier they can be distinguished with measured ASR data. Since the rural model adds only the boundary layer to the tropospheric model with the same physical optical properties, the curves lie very close to each other. In that case, a distinct AOT retrieval would only be possible for high aerosol concentrations. The maritime and especially the partially absorbing urban models can easily be distinguished from each other, even for small aerosol loadings. Further, Figure 4 shows the

sensitivity of a two-channel retrieval approach to absorbing and non-absorbing aerosols, because the urban model does not induce a distinct at-sensor apparent reflectance change in one single channel. Generally, the reflectance changes gets less distinct with increased surface reflectance, which decreases the sensitivity to the aerosol type determination.
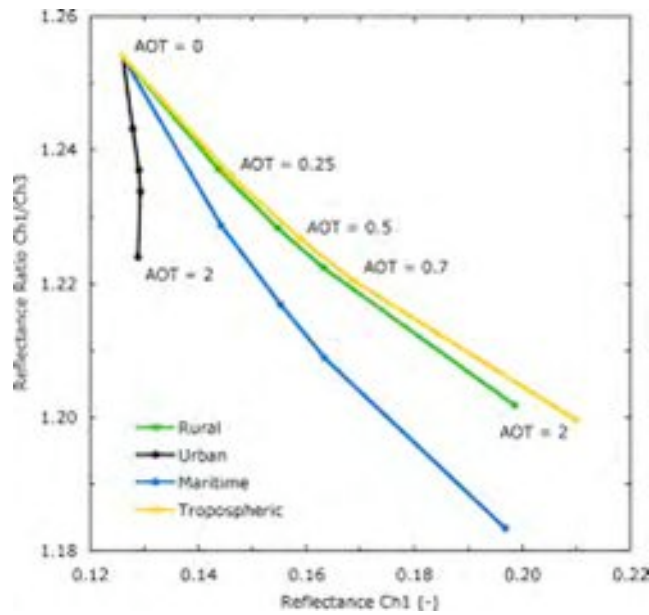

Figure 4: Relationship between the APEX Channel 1 (385 nm) apparent reflectance and the Channel apparent reflectance ratio 1 / 3 (385 nm / 412 nm) for four aerosol models. The dots represent varying at-sensor reflectance values due to different AOT. All four models were calculated with the same AOT under standard conditions (refer to Table 2).
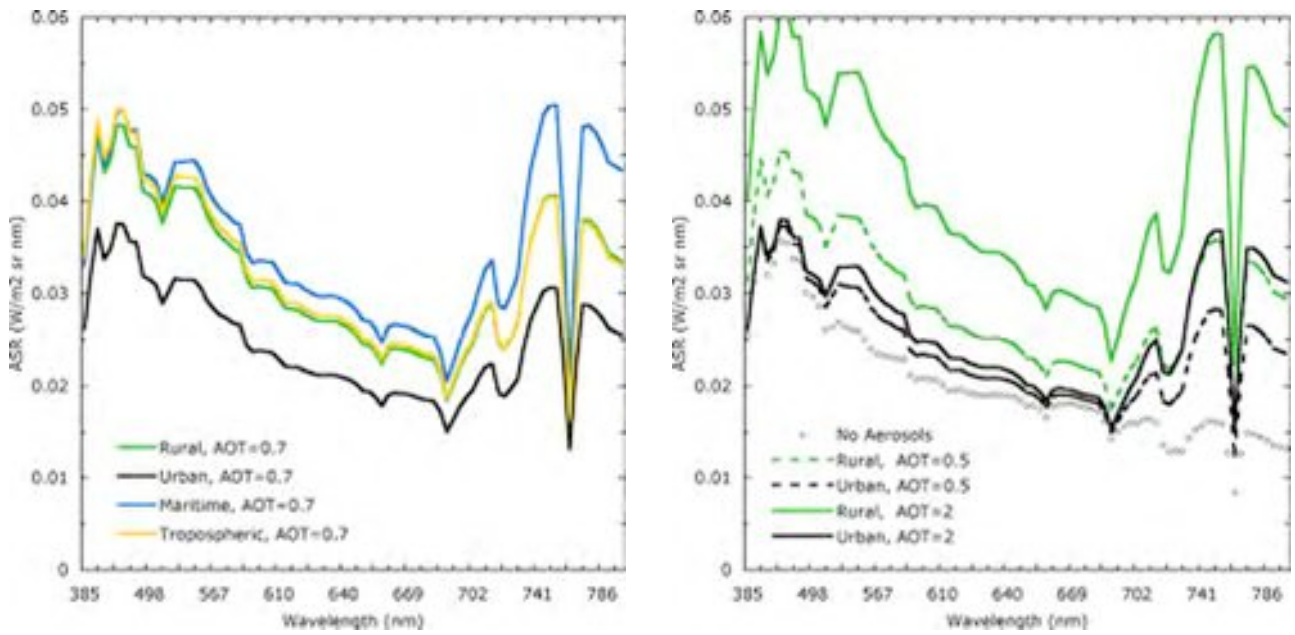

Figure 5: APEX at-sensor radiances (ASR) for different aerosol models and different AOT under standard conditions (refer to Table 2).

A further analysis of the effect of the aerosol model with different aerosol loadings is presented in Figure 5. The rural, maritime and tropospheric models produce nearly the same ASR signal for τ_a=0.7 in the near-UV region, while the maritime sea salt particles increase the signal around the O_2 absorption band at 765 nm. If τ_a is increased up to a value of 2, the rural model reacts with an increased signal due to increased scattering, while the urban model signal remains more or less the same. The increased absorption compensates the increased scattering completely in the near-UV spectral region. With the AOT setup in Figure 5 (right), the urban model with τ_a=2 creates the same ASR signal as the rural τ_a=0.5 case at wavelengths around 750 nm. This finding emphasizes that a one-channel retrieval procedure can provide ambiguous RTM solutions, which is followed by a misinterpretation of the aerosol conditions.

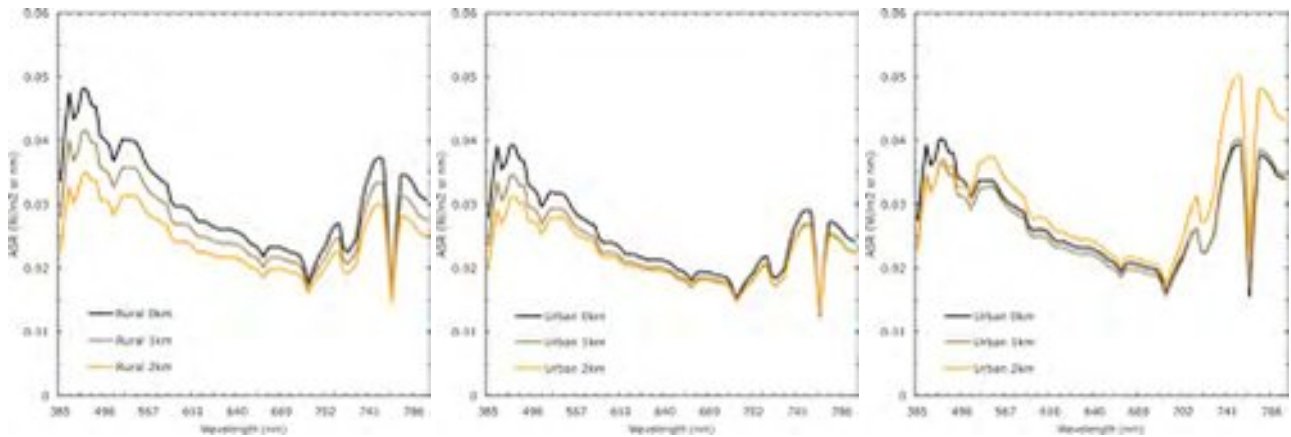## 5.4 Surface altitude and aerosol layer variation

Figure 6: APEX at-sensor radiances (ASR) under standard conditions (refer to Table 2) for different surface elevations and aerosol models: (left) rural, τ_a=0.5; (center) rural, τ_a=0.5; (right) τ_a=3.4.

Figure 6 plots RTM calculation results for three different ground altitudes, while the sensor was kept at 5 km. In case of an increase of the optical path length by 2000 m, when comparing the RTM run on 2000 m surface elevation to the RTM run on mean sea level, the ASR is increased by about 40% in the APEX 398 nm band. The radiance source of aerosol and Rayleigh scattering is dominating for rural aerosols within the first two kilometers above the mean sea level. The urban model with a relatively low aerosol loading (Figure 6 center) does not show such a strong optical path length sensitivity in contrast to the same model packed with absorbing particles (Figure 6 right). This case might suite to smoke plumes and shows an interesting local ASR peak around the 765 nm O_2 absorption. In good accordance to Torres[9], the ASR and therefore also the AOT are sensitive to the aerosol layer height, especially if absorbing soot particles are present. The findings above emphasize the importance of the implementation of digital elevation models in the future APEX aerosol retrieval algorithm.

ASR changes due to the max. +/-14°θ_s variations in the field of view have been neglected so far. They are expected to be small, compared to altitude variations of the surface and/or the sensor.

5.5 Seasonal variation

The RTM calculations have been tuned to match specific seasonal conditions. This comprises the boundary temperature, density, water vapor and top of atmosphere height. The solar geometry was chosen for solstice and equinox dates. The ASR level is consequentially correlated to the available solar irradiance. The varieties in Figure 7, between the spring and fall curves that basis on the same equinox irradiances arise from the differences in the columnar water vapor and seasonal atmospheric model defined by MODTRAN4. The summer irradiation results in an ASR that is twice as high as the winter radiance in the near-UV region. Nevertheless, the expected ASR for the APEX 385 nm band in wintertime (0.015 $Wm^{-2}sr^{-1}nm^{-1}$) provide still enough signal to exceed the noise level of 0.00072 $Wm^{-2}sr^{-1}nm^{-1}$ (refer to Table 3). The surface reflectance was considered to be constant over the four seasons. Aerosol detection over a terrain covered with snow is not considered so far, but a similar approach might be possible. Aerosols increase the apparent reflectance over dark targets due to particle scattering, while they might reduce the ASR over white surfaces.
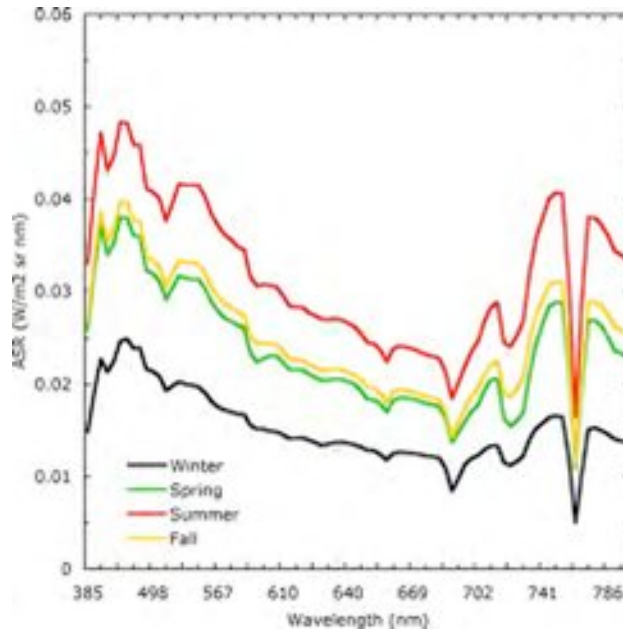
Figure 7: At-sensor radiances (ASR) of APEX for different seasons under standard conditions (refer to Table 2) with τ_a=0.7.

6. CONCLUSIONS

The retrieval of aerosol properties with imaging spectrometers and other sensors is known as a non-trivial problem. A recent study by Myhre et al.[18] identifies significant disagreements between different spaceborne aerosol retrievals over the ocean. Those differences are found to be larger as suggested in earlier studies. The aerosol retrieval over land is even more challenging due to the additional complexity of the surface reflectance.

An important reason for that is the large amount of degrees of freedom in RTM calculations, which are used to build the LUTs. This leads to a large number of assumptions and approximations. Further constraints are introduced due to sensor calibration as well as limitations in spatial and spectral resolution. The RTM calculations performed for this paper demonstrate the great importance of correctly determined input values. Only small perturbations of some variables can have large effects on the retrieved AOT.

This paper demonstrates that the setup of APEX and its operation on an aircraft platform promises various advantages for aerosol retrieval due to its high SNR along with a sophisticated combination of spectral and spatial high resolutions. Based on the presented RTM computations, the suggested aerosol retrieval technique shows promising performances under most conditions.

ACKNOWLEDGMENTS

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