Influence of cloud edges on atmospheric radiative transfer and its consequences for satellite retrievals

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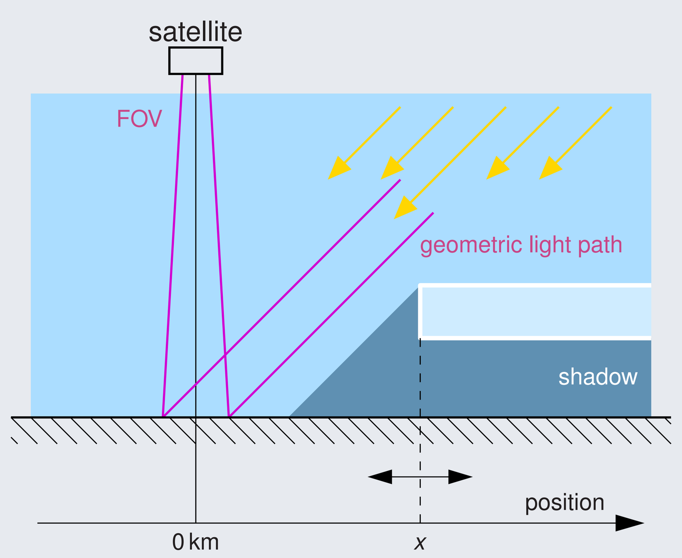
Abstract

Clouds have a strong influence on uv/vis satellite measurements in general and the analysis of absorbing trace gases and aerosol optical depth in particular. Effects of 3D features like spatial heterogeneities and structured cloud boundaries increase when the spatial resolution of the instruments approaches the dimensions of cloud features and if the vertical and horizontal dimensions of clouds are similar: at coarser resolution opposing effects average out whereas at finer resolution 3D effects may be fully resolved. Hence, measurements by future satellite-borne spectrometers, like the Tropospheric Monitoring Experiment (TROPOMI) designed to resolve horizontal features of 7×7 km^2, will be strongly influenced by 3D cloud effects. This type of spectrometer is primarily used to measure trace gases, but aerosol properties may be retrieved as well. Here, the influence of important 3D effects on atmospheric radiative transfer are investigated using Monte Carlo simulations, e. g. cloud shadows and illuminated cloud sides. Additionally, the influence of cloud parameters (e.g. cloud top height, cloud optical density) and observation geometry are studied.

Radiative transfer (RT) model setup



RT-model: McArtim v3, Deutschmann et. al (2011)

- spherical model domain
- polarisation enabled
- nadir observation geometry
- 1×1 km^2 square MODIS-like field-of-view (FOV)

cloud parameters (Mie cloud):

- cloud medium evenly distributed
- cloud base at 2 km altitude
- Henyey-Greenstein param: 0.85
- single scattering albedo: 1

aerosol parameters (Mie aerosol):

- constant layer between surface and 1 km altitude
- Henyey-Greenstein param: 0.68
- single scattering albedo: 1 or 0.9

Base-case settings:

- wavelength: 360, 440, and 870 nm
- solar zenith angle: 50°
- albedo: 0.05
- cloud top height: 3 km
- cloud optical thickness: 10
- cloud geometric height: 1 km
- aerosol optical thickness: 0

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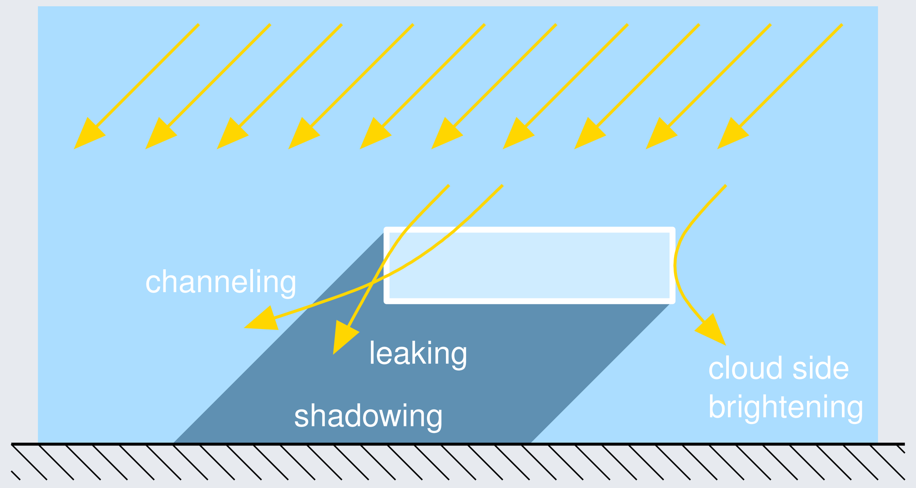
Introduction



3D clouds introduce effects not captured by 1D RT (cf. Nikolaeva et al., 2005):

channelling: cloud outside geometric light path towards sun forward-scatters towards the sun-averted side
→ intensity increases

shadowing: cloud within geometric light-path towards sun
→ intensity decreases within shadow

leaking: photons may exit cloud edge towards shadow
→ intensity decreases at cloud edges

cloud side brightening: sun illuminates facing cloud edge
→ intensity increases

The air-mass factor (AMF) concept is used to illustrate and quantify the different effects below. The 3D discrete boxAMF measures the photon path length in a certain grid-cell (or box):

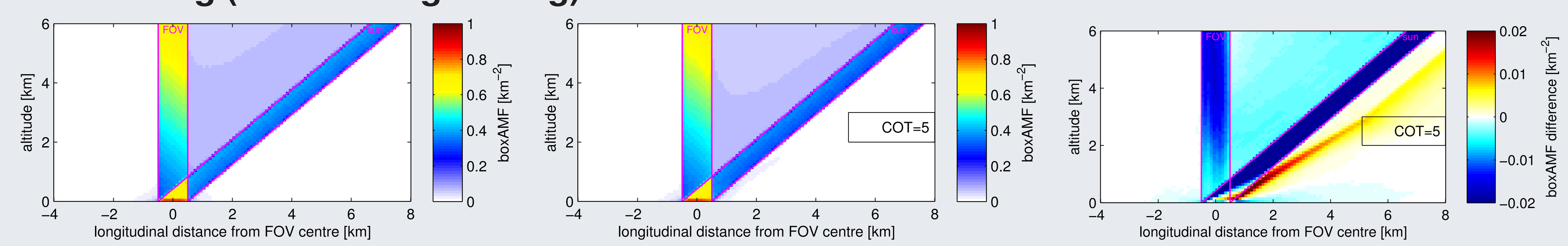
$$\text{boxAMF} = \frac{1}{hA}\frac{d\log(I)}{d\beta} = \frac{1}{hAI}\frac{dI}{d\beta}$$

where I is intensity, h is layer/box height, A is the unit area in [km^2], and β is absorption coefficient in [km^{-1}].

Influence of 3D cloud effects on spatial sensitivity (λ = 440 nm)

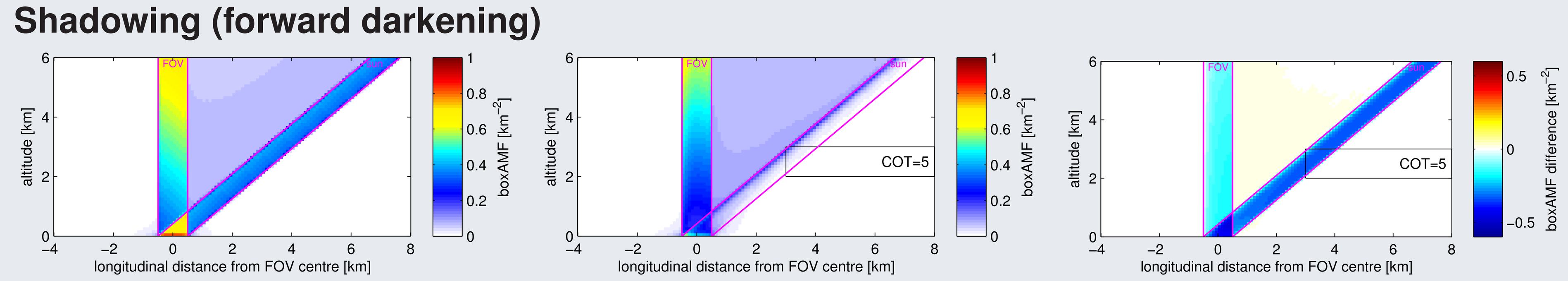
1D reference boxAMF | *3D effect boxAMF* | *boxAMF difference*

Channelling (forward brightening)



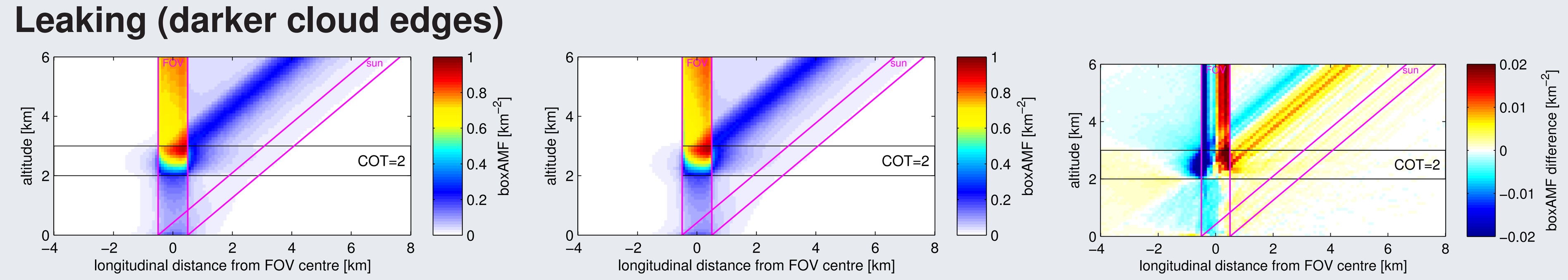
The clear-sky boxAMFs reveals that the maximum measurement sensitivity follows the geometric light path (left). If a cloud is placed in the direction of the sun whose geometric shadow is outside the FOV (middle), the difference reveals that photons from the sun are forward-scattered by the cloud into the FOV (right). Consequently, the boxAMFs within the geometric light path decrease (cold colors). Warm colors indicate enhanced boxAMFs i. e. an enhanced sensitivity of the measurement compared to the undisturbed case.

Shadowing (forward darkening)



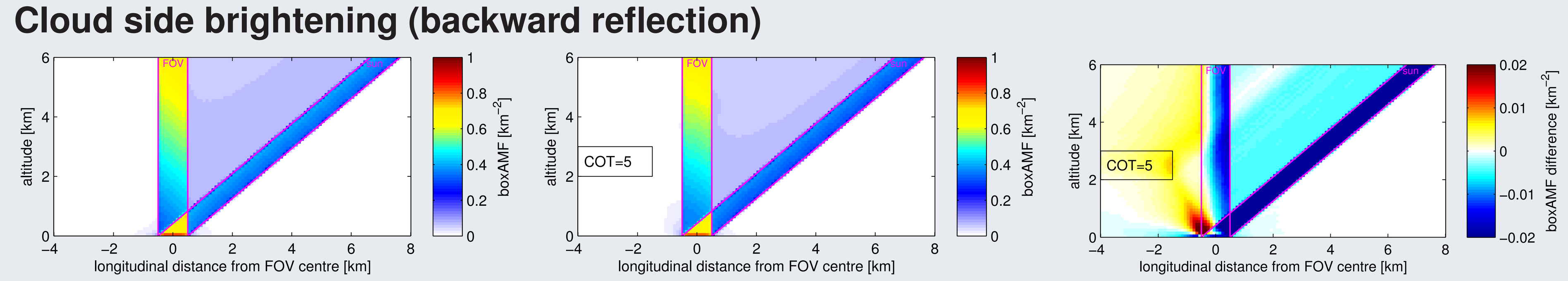
The FOV is within the shadow of a cloud with a medium optical thickness of 5(middle). This strongly decreases the measurement sensitivity at the surface and along the geometric light path (right). Note the expanded colorbar in the difference image (right).

Leaking (darker cloud edges)



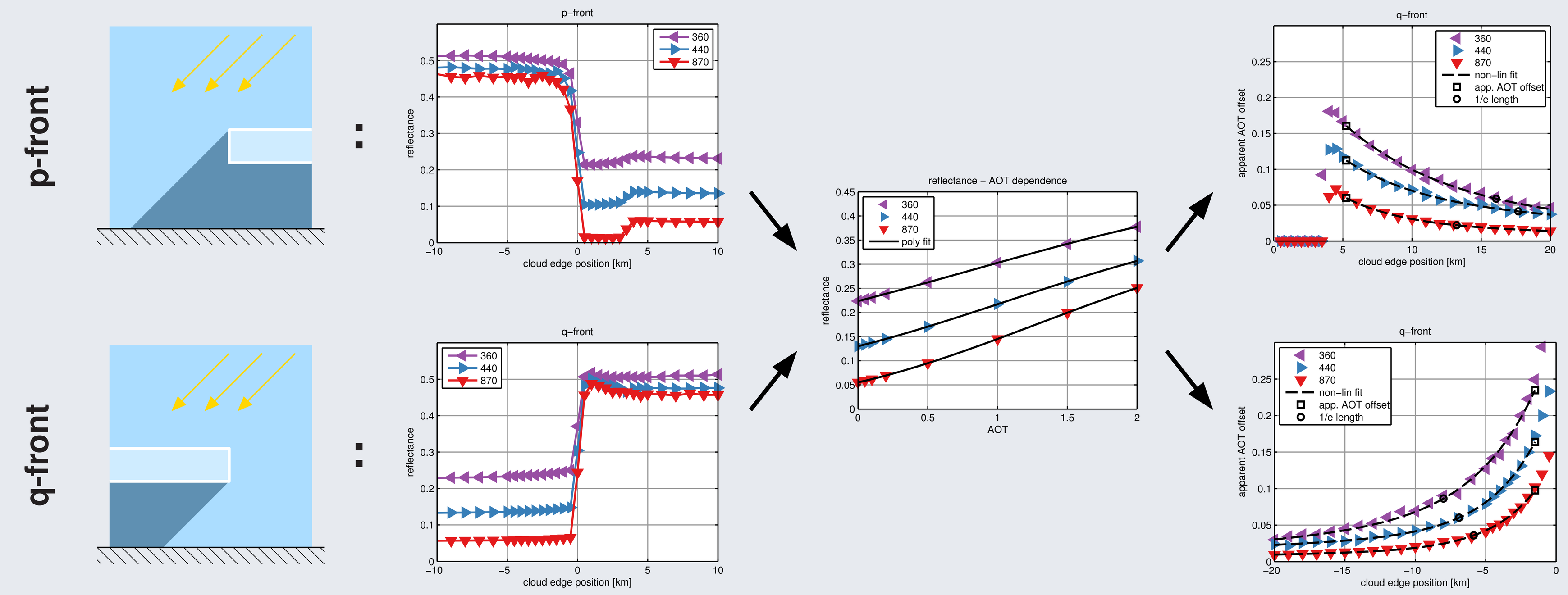
Here, a constant cloud is used as a reference (right). When removing the sun-averted cloud part outside the FOV (middle), a darkening of the cloud edge is observed (right). The sensitivity closer to the edge is decreased (cold colors) which is partially compensated by a higher sensitivity further away from the cloud edge (warmer colors).

Cloud side brightening (backward reflection)



In order to illustrate the effects of cloud side illumination, a cloud is placed into the half-space opposing the sun relative to the FOV (middle). This leads to an intensity increase (not displayed) and an increased measurement sensitivity in the troposphere also left of the FOV.

From modelled reflectance to apparent AOT offset – base-case



derivation of maximum apparent AOT offset:

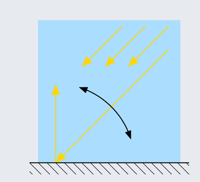
- model reflectance at different cloud edge positions
- translate modelled reflectance in clear-sky sector into AOT using a 3rd order polynomial fitted to clear-sky results
- non-linear fit to data neither affected by clouds nor cloud-shadow using

$$f(x) = ae^{bx} + cx + d$$

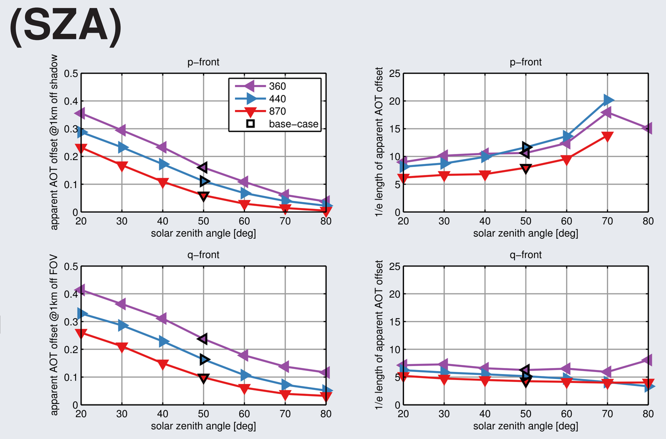
- output maximum AOT offset outside shadow/FOV and corresponding 1/e length for both geometries, respectively

Results – apparent AOT offset by clouds outside satellite FOV

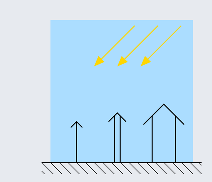
1) Solar zenith angle (SZA)



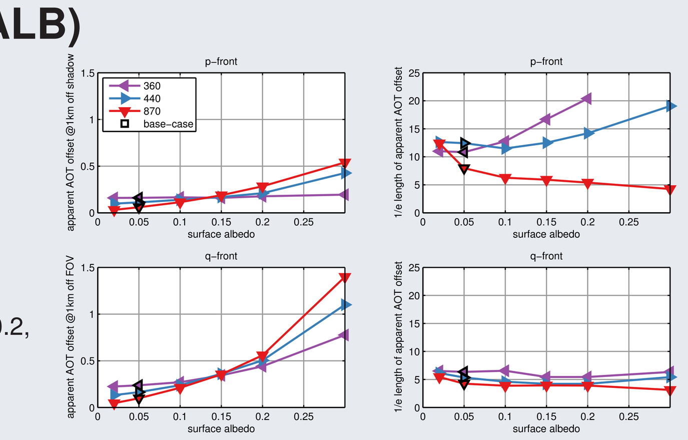
- SZA = 20, 30, 40, 50, 60, 70, and 80°



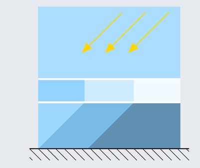
2) Surface albedo (ALB)



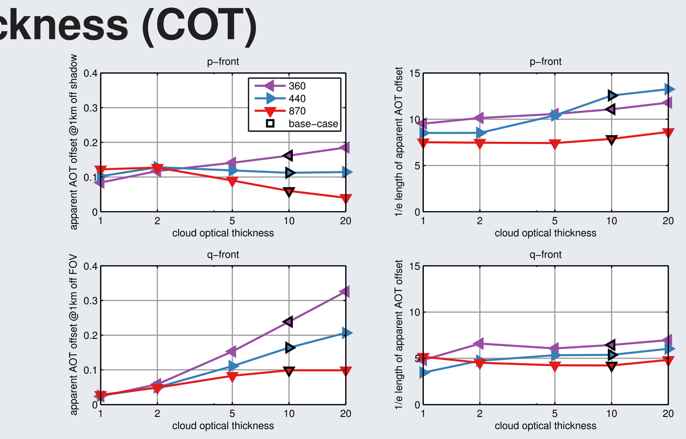
- albedo = 0.02, 0.05, 0.1, 0.15, 0.2, and 0.3



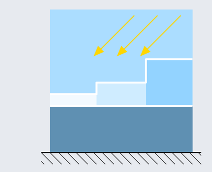
3) Cloud optical thickness (COT)



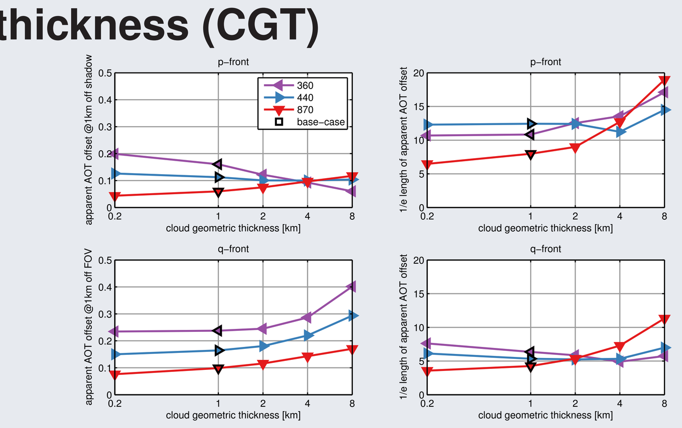
- COT = 1, 2, 5, 10, and 20



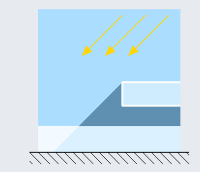
4) Cloud geometric thickness (CGT)



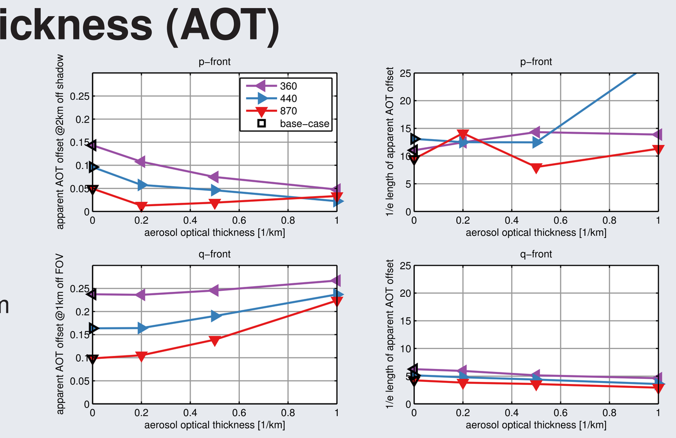
- CGT = 0.2, 1, 2, 4, and 8 km
- cloud base is fixed at 2 km
- COT is constant



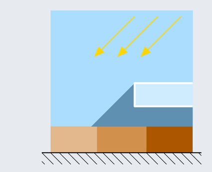
5) Aerosol optical thickness (AOT)



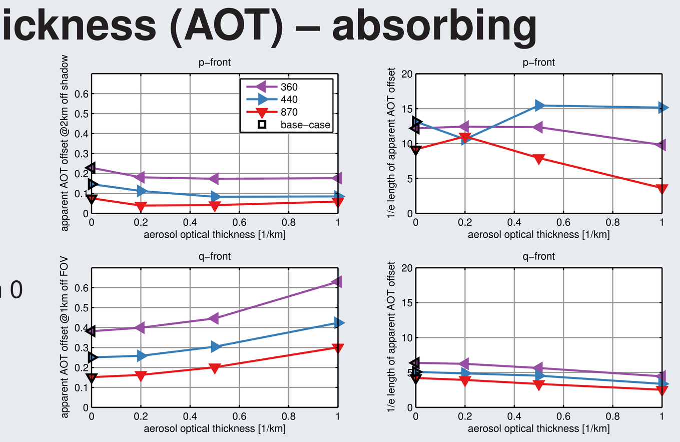
- aerosol layer between 0 and 1 km
- AOT = 0, 0.2, 0.5, and 1
- SSA = 1



6) Aerosol optical thickness (AOT) – absorbing



- absorbing aerosol layer between 0 and 1 km
- SSA = 0.9 (also as reference)
- AOT = 0, 0.2, 0.5, and 1



Conclusions

- for satellite measurements on spatial scales similar or smaller than clouds, 3D effects need to be considered
- 3D effects interfere with aerosol/cloud and trace gas retrieval by changing the radiance and AMF, respectively
- all satellite observations close to clouds and their shadows are systematically biased
- retrievals of albedo background maps (minimum reflectance, cloud-free composites etc.) are potentially biased
- effects for aerosol retrievals based on radiance measurements at a single wavelength
  - the introduced **apparent AOT offset** depends mostly on **wavelength**(+/−), **SZA** (−), and **albedo**(+)
  - outside cloud-shadow boundary: between +0.1 to +0.2 on average
  - over bright surfaces ≥+.5 possible
  - effect declines to 1/e between 5 and 15 km

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- O. V. Nikolaeva, L.P. Bass, T.A. Germogenova, A. A. Kokhanovsky, V. S. Kuznetsov, B. Mayer, The influence of neighbouring clouds on the clear sky reflectance studied with the 3-D transport code RADUGA, *J. Quant. Spectrosc. Ra.*, 2005.