Impact of clouds on aerosol scattering as observed by lidar

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Cloud – aerosol interactions

As the global mean density of aerosols increases, their impact on the global energy budget becomes increasingly important. A significant and poorly understood component of this relates to the aerosol's interactions with clouds. [1] These interactions have been investigated using satellite observations, but it is not generally possible to retrieve cloud and aerosol properties from a single set of radiance measurements. Hence, it has become common practice to assume that aerosol properties vary over length scales much greater than that of a cloud, such that retrievals can be averaged over several days and tens of kilometers, e.g. [2, 3]. To investigate the validity of this assumption, a measurement of aerosol properties that is independent of cloud cover is required. Lidar can provide this.

Optimal estimation retrieval

Increasingly common in the analysis of satellite data, optimal estimation is a scheme to determine the state of the atmosphere that, while obeying prescribed physical constraints, is most likely, given a set of observations. [4] For a set of measurements, $\boldsymbol{y}$, this is the atmospheric state, $\boldsymbol{x}$, that satisfies the inverse problem,

$$\boldsymbol{y} = \boldsymbol{F}(\boldsymbol{x}) + \boldsymbol{\epsilon}, \quad (1)$$

where $\boldsymbol{F}(\boldsymbol{x})$ is a forward model describing the physics of the atmosphere and observing system and $\boldsymbol{\epsilon}$ summarises the noise of the measurement.

Application to lidar

The few studies to have applied optimal estimation to lidar data linearised their forward models, e.g. [5, 6]. For a non-linear forward model, the Levenberg-Marquardt method utilises an *a priori* estimate of the mean state of the atmosphere, $\boldsymbol{x}_a$, and iterates towards a solution,

$$\boldsymbol{x}_{i+1} = \boldsymbol{x}_i + [(1+\gamma_i)\boldsymbol{S}_a^{-1} + \boldsymbol{K}_i^T \boldsymbol{S}_\epsilon^{-1} \boldsymbol{K}_i]^{-1} \{\boldsymbol{K}_i^T \boldsymbol{S}_\epsilon^{-1}[\boldsymbol{y} - \boldsymbol{F}(\boldsymbol{x}_i)] - \boldsymbol{S}_a^{-1}(\boldsymbol{x}_i - \boldsymbol{x}_a)\}, \quad (2)$$

where $\boldsymbol{S}_{\epsilon|a}$ are the measurement and *a priori* covariance matrices; $\boldsymbol{K}_i = \boldsymbol{\nabla}_{\boldsymbol{x}} \boldsymbol{F}(\boldsymbol{x}_i)$, the weighting function matrix; and γ_i is a constant chosen with each iteration to minimise a cost function.

For a lidar, $\boldsymbol{y}$ incorporates the number of photons observed from each range bin. The state of the atmosphere is then summarised by the aerosol backscatter and extinction profiles, α_a and β_a, with the magnitude of Rayleigh scattering estimated from radiosonde measurements.

This work considers a selection of partly cloudy days observed with the resident UV Raman lidar system at the Chilbolton Observatory in southern England. At this preliminary stage, only the elastically and Raman (N_2) backscattered profiles, at 355 and 387 nm, are considered. The number of photons observed over background levels in a range bin, i, can then be expressed as,

$$n(\lambda_0, z_i) = v(\lambda_0, z_i)\mathcal{T}_a(\lambda_0, z_i)[\beta_m(z_i) + \beta_a(z_i)], \quad (3)$$

$$n(\lambda_{N_2}, z_i) = v(\lambda_{N_2}, z_i)\mathcal{T}_a(\lambda_{N_2}, z_i)\beta_{N_2}(z_i), \quad (4)$$

where v describes the known properties of the system, such as optical efficiency and overlap function, and $\mathcal{T}_a$ is the atmospheric transmission due to aerosols, which can be written in terms of aerosol extinction as,

$$\mathcal{T}_a(\lambda, z_i) = \exp\left\{-\zeta\left[\frac{\alpha_a(\lambda, z_i) + \alpha_a(\lambda, z_0)}{2} + \sum_{j=1}^{i-1} \alpha_a(\lambda, z_j)\right]\right\}, \quad (5)$$

where $\zeta = w(1 + \lambda/\lambda_0)$ and w is the length of a range bin.

A simple correction is then applied to account for the non-linearity of the photomultiplier tubes at high count rates in the photon-counting mode.

Validation

The STFC Chilbolton Observatory hosts an AERONET site. Aerosol optical thickness (AOT) measurements are compared to the retrieved AOT at 10 km in fig. 1, where a strong one-to-one relationship is found. The bias is related to a systematic error in the specification of the lidar. Favourable comparisons can also be made against retrievals using more standard methods [7], where the algorithm resolves significantly greater detail both in and above the boundary layer (fig. 2).

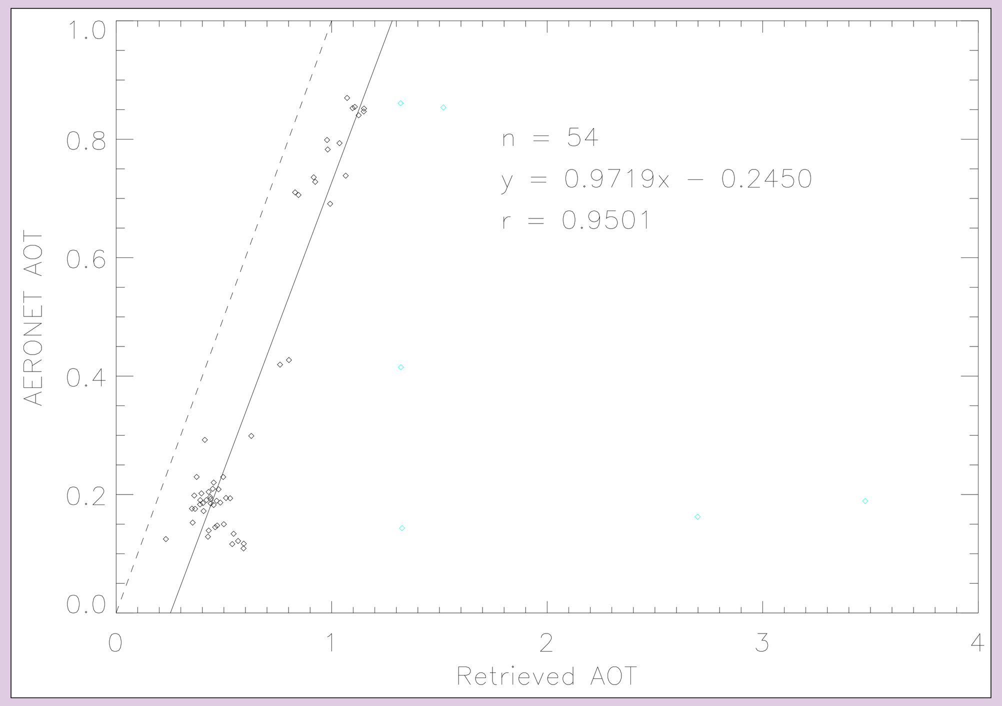

Figure 1: AOT at 355 nm retrieved by optimal estimation against simultaneous, co-located AERONET measurements at 340 nm. Outliers (blue) are related to the presence of a cloud in the lidar's field of view.

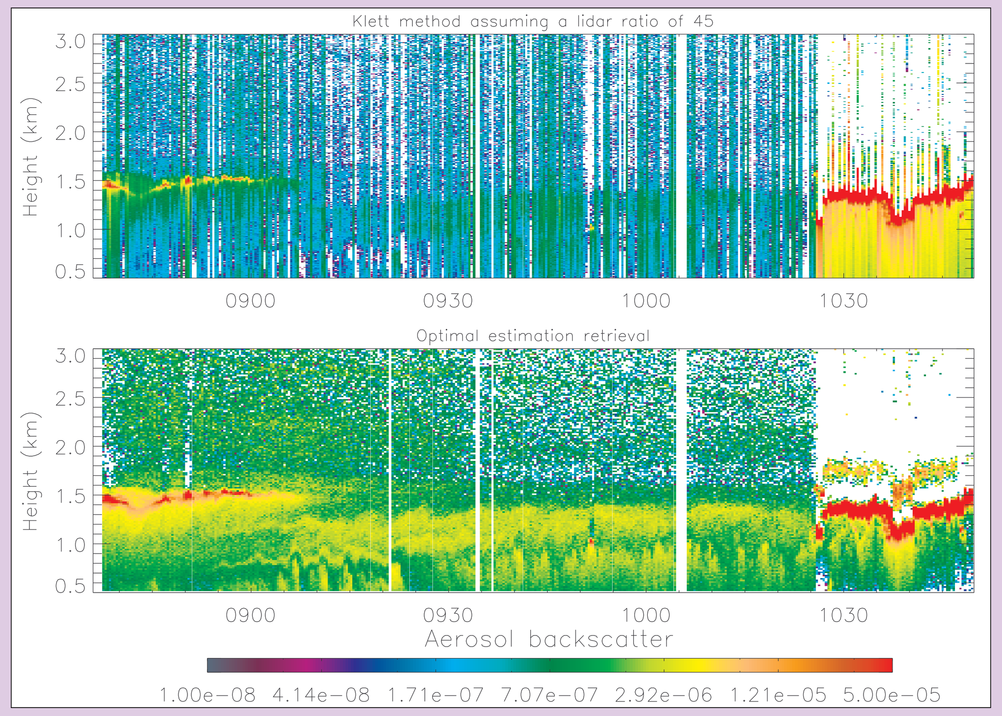

Figure 2: Aerosol backscatter on 29 Aug 2007 as derived by a standard elastic algorithm [7], assuming a clear atmosphere at 7 km and a constant lidar ratio of 45 (top), and by optimal estimation retrieval, at a resolution of 20 s and 17 m (bottom).

Interaction with clouds

As an initial investigation, the cloud base and boundary layer heights were determined for partly cloudy days using a simple gradient method. Fig. 3 shows the backscatter retrieved against height beneath these features for cloudy and clear profiles. The two plots show no significant difference beyond the presence of clouds and aerosol swelling immediately beneath them.

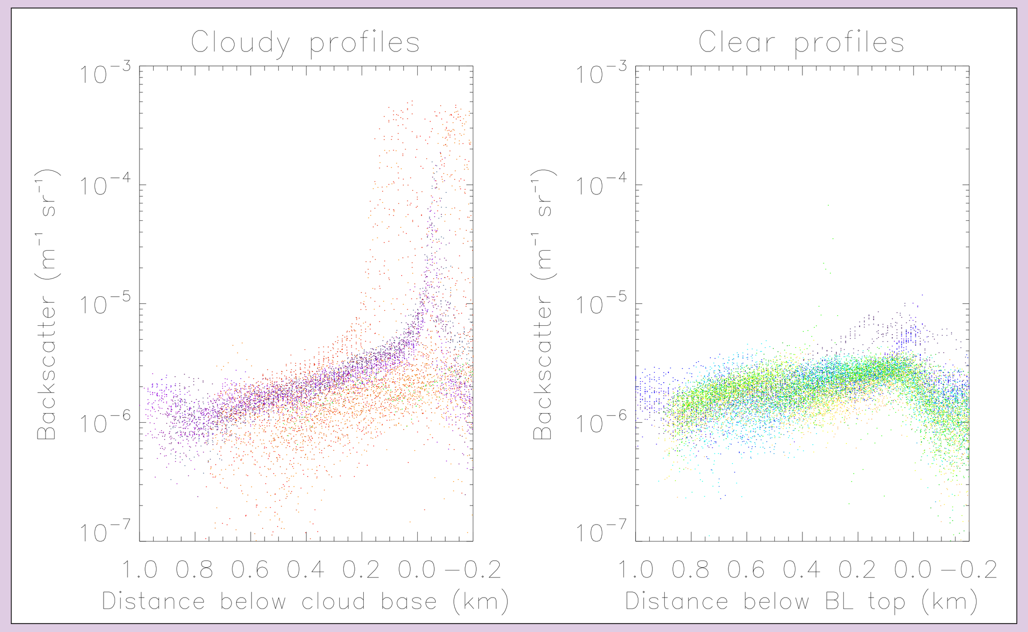

Figure 3: Aerosol backscatter as a function of height for 29 Aug 2007. Colour indicates time of day from 0830 – 1045 for 133 cloudy and 231 clear profiles. The presence of a cloud was flagged by a strong, positive gradient in the range-corrected lidar profile.

This indicates that the presence of a cloud above the boundary layer has no visible effect on the scattering properties of those aerosols. This lends itself to the hypothesis that aerosol properties change over greater length scales than clouds.

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