LITE ON ADM-AEOLUS PERFORMANCE

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ABSTRACT

ESA will fly a Doppler Wind Lidar (DWL) for the Atmospheric Dynamics Mission (ADM-Aeolus). Atmospheric heterogeneities in backscatter and clouds and wind variability will complicate the interpretation of the measurements. The Lidar-In-Space Technology Experiment, LITE, is used to shed some light onto these effects for ADM winds. Various effects leading to error correlation of wind vectors are identified and their potential impact on mission products is qualitatively summarised. Subsequently, a methodology is presented and used to perform an assessment of the quantitative impact of error correlation in the ADM wind profiles on the geophysical products. Using this basis, mission requirements were reviewed and recommendations formulated for updating and refining the initial requirements with the aim to limit the observation error correlation to acceptable levels.

On the basis of MERCI results it is strongly recommended

- To provide a stable instrument such that systematic error effects can be filtered against reference data sets, such as NWP model data;
- To oversample the vertical with the aerosol channel in the full troposphere in order to limit effects of reduced vertical representativeness in case of aerosol and cloud stratification;
- To reduce location errors in the vertical below 50 m RMS;
- To avoid higher-order receiver gain errors as much as possible as these put the mission at risk;
- To start building capabilities for ADM DWL data processing using available lidar data (e.g., LITE);
- To consider the assimilation of shear observations, rather than wind components directly.

1. Introduction

Here we will focus on the systematic error effects caused by the interaction of the ADM instrument with the atmosphere. Paul Ingmann (this issue; ESA, 1999) reviewed the status of ADM-Aeolus and presented the measurement principle. Instrument specifications and uncertainties are well identified at this stage of the programme, but atmospheric data to study the total end-to-end system are more difficult to obtain. We use LITE data to provide a measure of aerosol (Mie) and molecular backscatter (Raleigh) in the atmosphere and collocate it with meteorological data from the ECMWF model, which set is subsequently used to simulate ADM performance. We here describe the procedure of simulation, and focus on errors that may cause spatially or temporally correlated error in the ADM observations due to atmospheric backscatter heterogeneities and wind variability. A set of conclusions and recommendations to improve the ADM system is provided in the end.

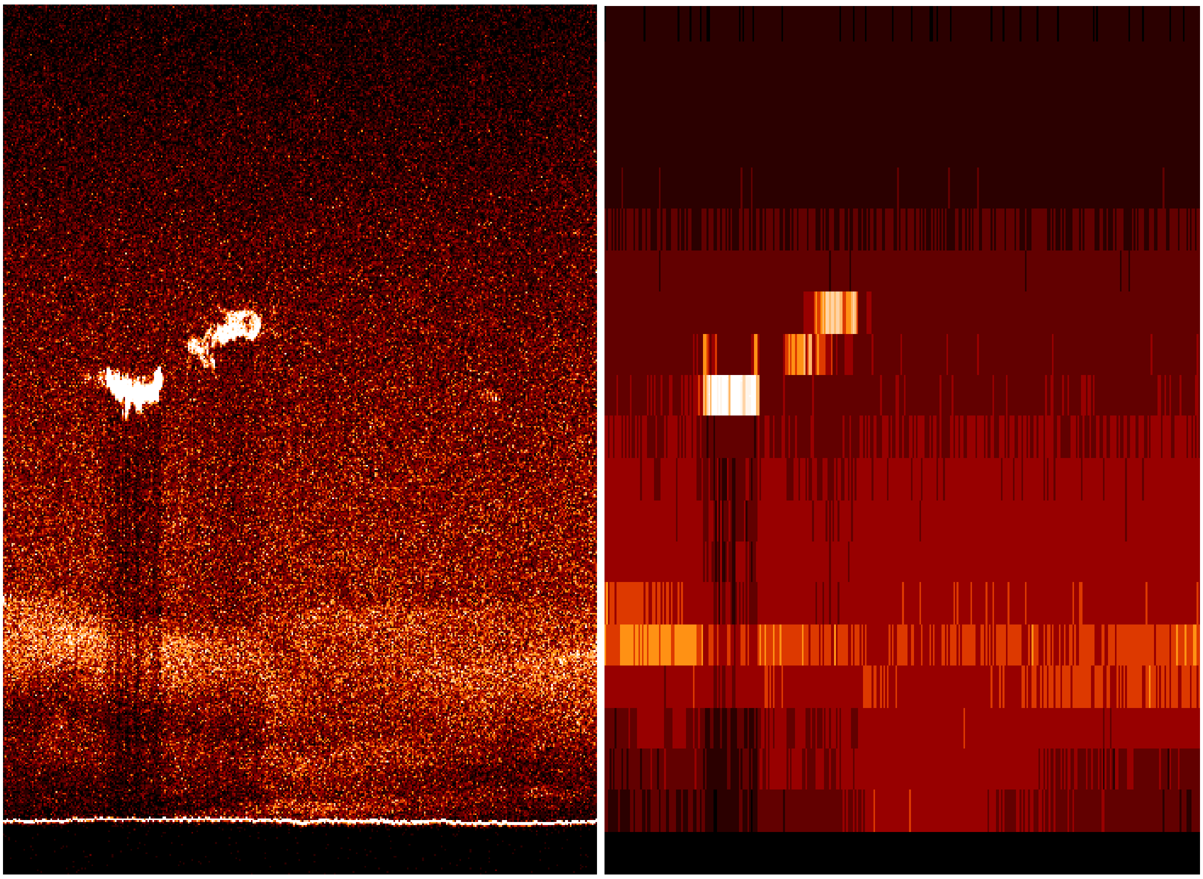

Figure 1: LITE UV 355 nm backscatter measurements over a period of about 10 s at full 15 m resolution (left) and at 1000 m resolution compatible with the ADM measurements (right). Cloud and aerosol structure that modulate the ADM signal are clearly lost by the ADM sampling giving rise to uncertainty in the interpretation, e.g., signal height assignment.

2. Potential Errors

Much experience exists with respect to correlated observations in meteorological analysis, and in particular errors on the synoptic scale in the horizontal and km-scale in the vertical are known to be detrimental; these detrimental effects of correlated data are supported by theoretical computations (MERCI, 2002). If the nature of the bias is known, bias correction or data thinning prior to data assimilation are known effective means to limit detrimental effects (see, e.g., Butterworth, this issue). So-called randomly correlated observation errors are most damaging; theoretical evidence shows that due to such errors information on atmospheric spatial structures is lost (MERCI, 2002). The loss of potentially important structures is most detrimental in cases that usually present air masses with strong space and time variations, and where the model forecasts are very sensitive to the initial state (analysis).

ADM errors that depend on the atmospheric state and/or the instrument were simulated to assess their potential detriment by computing the spatial covariance structure over a given data set. It is noted that for 10 independent random wind difference samples of NWP model minus DWL per profile, and if assuming independent random errors on different profiles, then for an expected wind difference <NWP-DWL> = 3 m/s, 40 profiles (400 data) can provide a bias correction with the acceptable accuracy of about 0.15 m/s. Clearly, the NWP model provides a reference that is useful for bias correction or quality monitoring, as is common practise for satellite data these days. Note

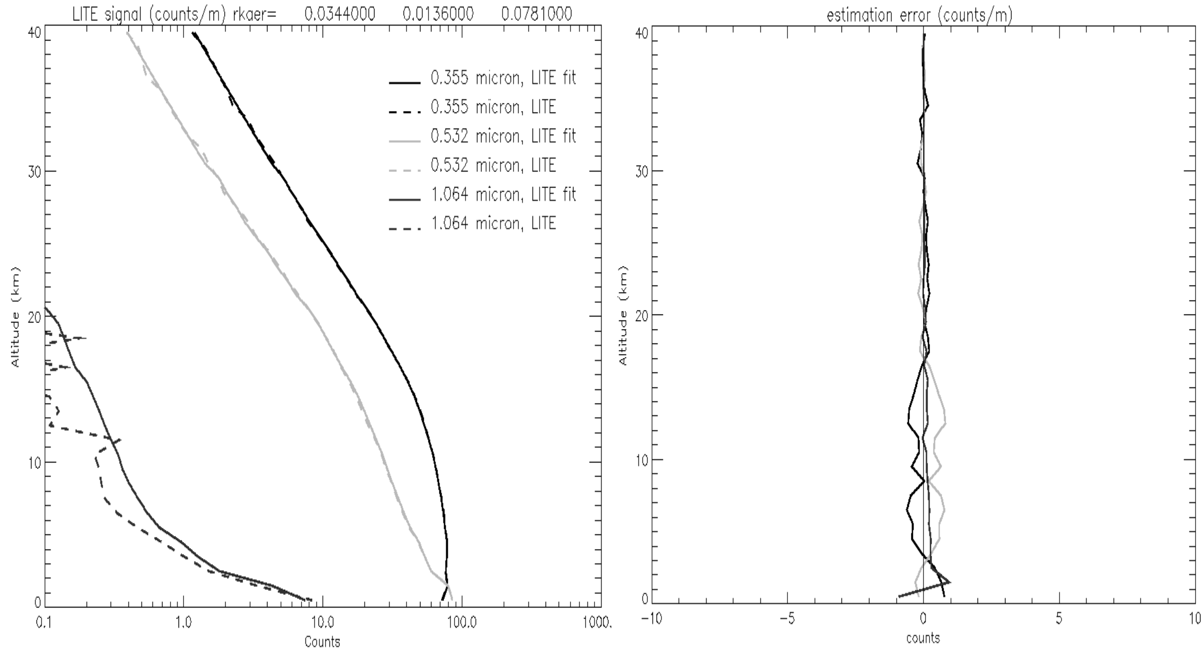

Figure 2: Average LITE signal in photon counts at 355 nm, 532 nm, and 1064 nm, and their fits by the estimation algorithm (left). The same, but fit minus measurement (right). The fitting procedure results in a close compromise of the measurements at the three wavelengths.

however that on the synoptic scales no correction of systematic biases will be possible due to the limited number of samples available, since 40 ADM profiles correspond to 8,000 km. As such, the capability for bias correction on those scales is limited.

We note that the average wind **shear per km** in the troposphere is **4 m/s**, thus presenting serious errors in case of a wrong vertical representation. Cloud and aerosol structure that modulate the ADM signal are lost by the ADM sampling giving rise to uncertainty in the interpretation, e.g., signal height assignment as illustrated in figure 1. In this respect, we studied relevant errors resulting from aerosol backscatter and clouds heterogeneities with LITE and collocated ECMWF data (KNMI). Moreover, vertical shifts Δz = 100 m and Δz = -100m due to range gate localisation errors were also investigated. Receiver gain biases of 1-5% were studies in order to detect implicit flow dependency of such errors. Bias inconsistencies between the Mie and Rayleigh channels could also potentially cause serious wind shear observation errors. Moreover, a combination of such errors, in particular height and gain errors could be particularly detrimental. Gain bias effects of higher order are particularly relevant at extreme wind speeds. As such, quadratic error terms, in addition to linear ones, were studied.

2. Molecular and Aerosol Scattering from LITE

LITE provided measurements at three wavelengths, including the ADM 355 nm. The lidar equation incorporates a molecular backscatter coefficient, an aerosol backscatter coefficient and a backscatter-to-extinction ratio as unknowns. Having just one measurement at each level, the set of unknowns is obviously larger than the set of knowns (measurements). We have improved the situation by incorporating knowledge on temperature and pressure to define the molecular scattering, and by assuming a well-mixed atmosphere, where the backscatter-to-extinction ratio is fixed in a vertical profile. To fully close the problem, we use the measurements at the three wavelengths

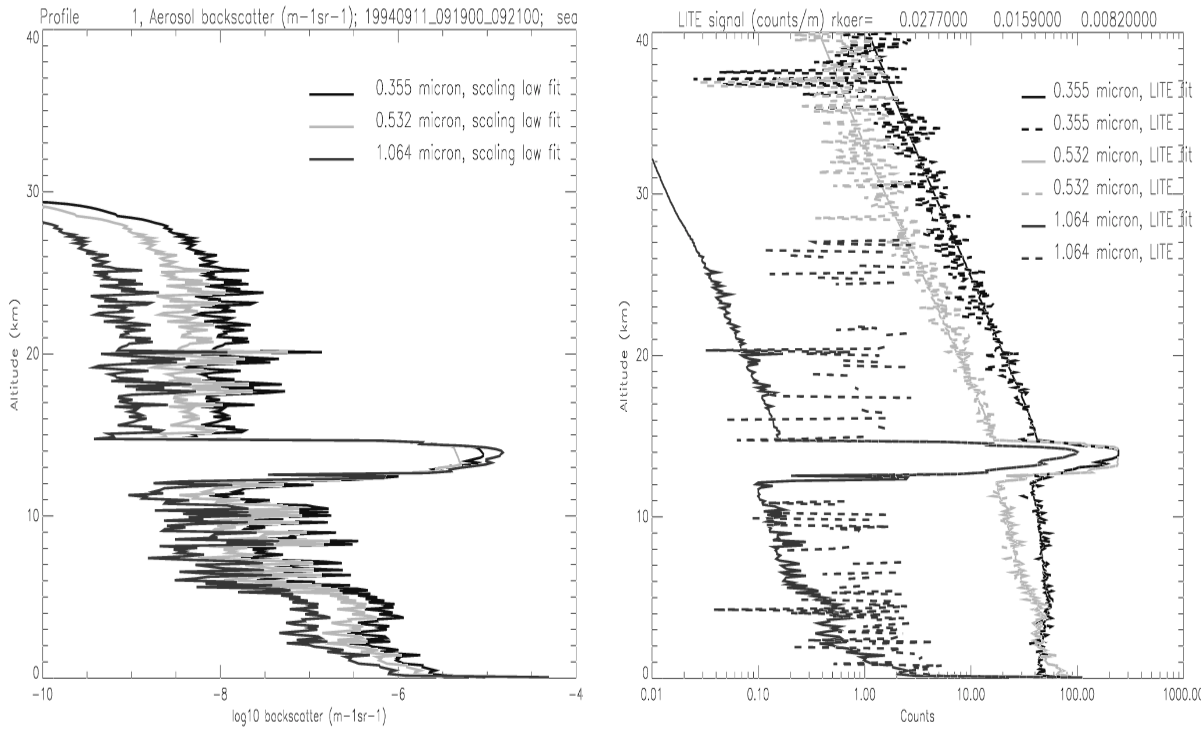

Figure 3: 105-m resolution LITE aerosol backscatter measurements at 355 nm, 532 nm, and 1064 nm averaged over 0.5 s (left). LITE signal in counts at those wavelengths together with the algorithm fit (right). We discriminate cloud levels and cloud extinction.

simultaneously, and use the wavelength scaling law for aerosol scattering from Vaughan et al. (1998) in order to make the problem overdetermined. A minimum variance estimation technique is then used to determine the physical scattering properties in each vertical profile.

The minimization of the mismatch in detected photon counts is generally quite successful as illustrated in figure 2. Figure 3 shows an example of a 105-m resolution LITE signal, averaged over a period of 0.5 s, and its fit. In this profile, the occurrence of cloud is obvious. As such, LITE data can be used to simulate the ADM processing capabilities in cloudy scenes. The 105-m resolution data were used to look at effects of spatial representation due to sub-sample variability. This was studied both for the vertical and the horizontal, but due to the overampling of the ADM in the horizontal, only the vertical errors are substantial and are shown first.

3. Spatial Representation

Figure 1 demonstrates the effect of averaging in the spatial domain. Certain sharp features are lost and smeared out. The Doppler shift measured in an ADM range gate can be written as the convolution of the returned signal and the wind. Subsample signal variability may thus result in assigning the wrong mean height to the sample, as set out in the caption of figure 4. Figure 5 displays this vertical height assignment error as a function of height. Since the Rayleigh signal merely depends on temperature and pressure, exposing relatively low vertical variability, the errors for this channel are limited. On the other hand for the Mie (aerosol) channel errors are generally around 100 m RMS in case of cloud scattering, but still substantial in the absence of clouds.

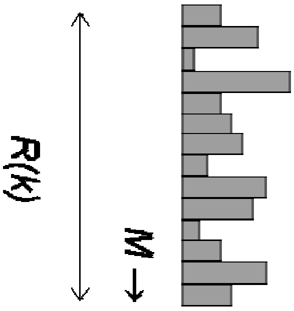

Figure 4: Illustration of vertical representation for range gate k with length R(k). We used the backscatter amplitude (bars) as a weight to determine the average location of backscatter with respect to the middle of the range gate. This is defined as the representativeness error. Moreover, we computed the backscatter variability within a range gate in order obtain a measure of uniformity.

Including clouds

Cloud-free

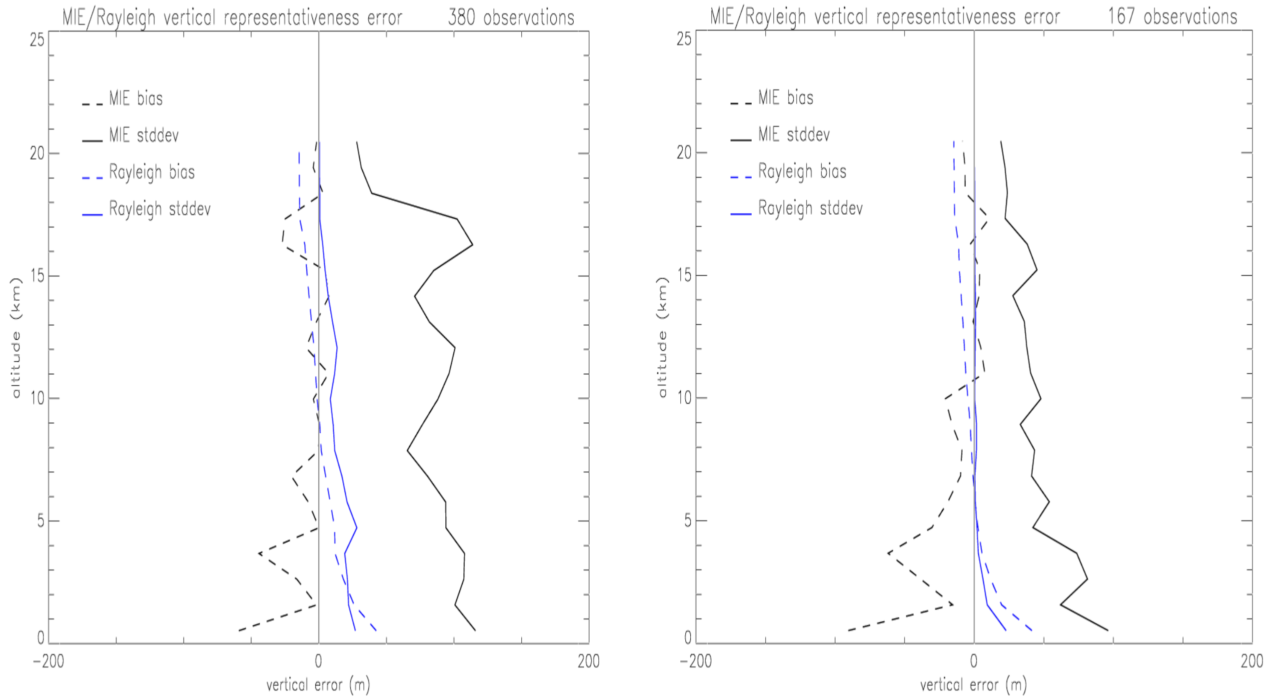

Figure 5: Height error bias and standard deviations due to vertical representation for the Mie and Rayleigh channels as a function of height including (left) and not including (right) cloudy scenes. The Mie channel represents serious height assignment errors due to aerosol signal variability.

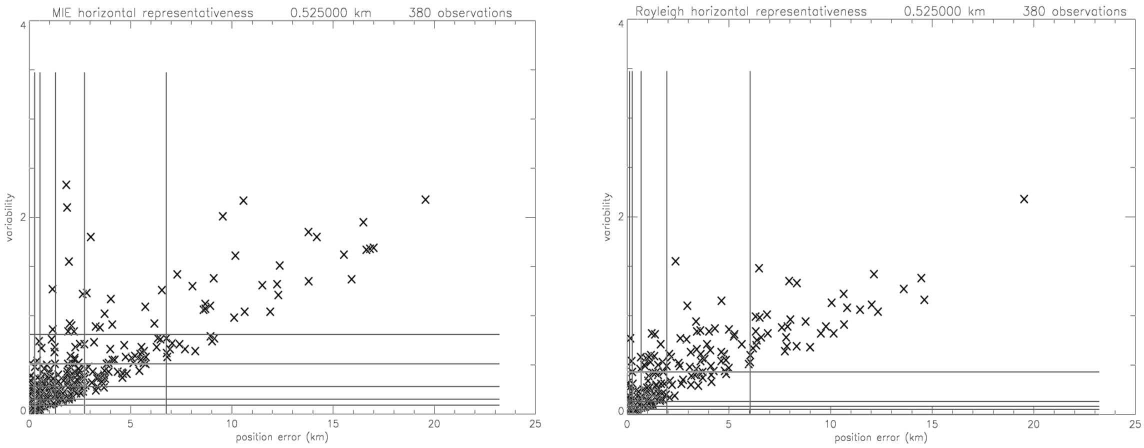

Figure 6. Horizontal location error for the Mie (left) and Rayleigh (right) channel for 380 HLOS wind observations in the range gate closest to the surface, using high-resolution LITE retrieved aerosol backscatter profiles. Each cross corresponds to a single HLOS wind observation. The horizontal axis denotes the error in km with respect to the center of the 50-km observation length. The vertical axis is a measure of variability of the number of detected photons over the 14 accumulations that are measured by ADM. Straight lines denote lower decile, lower quartile, median higher quartile and higher decile. Controlling photon count variability can reduce position errors. Horizontal representativeness is generally good for ADM.

We verified that the height assignment error scales with the range gate length, such that oversampling the vertical domain may reduce errors.

Height assignment errors are also induced by poor satellite platform attitude knowledge, in particular roll. Since ADM is side looking at 35 degrees, relatively small uncertainties in attitude angle can result in 50 m height errors. Given the average shear of 4 m/s per km in the atmosphere, RMS height errors of 50 or 100 m imply a serious wind error.

4. Quality Control

Spatial representation can be improved by subsampling. Figure 6 shows the photon count variability versus the location errors over a stretch of 50 km that is divided in 14 subsamples. In both x and y directions, the data distribution is indicated by lines depicting lower decile, lower quartile, median higher quartile and higher decile. In about 10% of cases the error exceeds 10 km, but in these cases the photon count variability is very high. As such, one could obviously correct the position error by providing a photon-count weighted mean location. In this case the spatial representation of the observation becomes poorer, since the average is not representative of a true 50-km mean. To prevent an unrepresentative observation to affect meteorological analysis, one could reject the observation with great success, based on the signal variations in the subsamples. Besides photon-count variability, one may also be able to exploit Doppler shift variability for QC, but this has not yet been tested. The feasibility of QC for ADM may be present, actual QC schemes will be developed in the years to come. LITE data will be useful for this purpose.

5. Concluding

ADM is designed to provide high quality observations that beneficially impact atmospheric analyses in line with WMO (2001) requirements. A detailed understanding of its functioning in heterogeneous atmospheric conditions is now opportune, since these conditions are often associated with extreme weather development. If ADM provides quality in this type of situation, its impact will most likely be beneficial.

LITE data was decomposed into molecular and aerosol and cloud scattering contributions, and was collocated with ECMWF meteorological data. As such, effects of ADM sampling a heterogeneous atmosphere could be realistically simulated. Errors in the ADM instrumentation interact with errors due to interaction of ADM with a variable atmosphere and were simulated adapting a KNMI simulation tool (Veldman, 1999). In particular errors on the synoptic scales and in the vertical were addressed, since these are difficult to correct by using background NWP model information prior to assimilating the ADM winds into the analysis. Effects of subsample wind variability were not addressed by using real data, but by using a climatological spectrum (following Lorenc et al, 1992).

Assimilating wind shear information can eliminate profile biases that are constant in height. In this case the errors disappear when taking differences, but this can only be done provided variable biases in the vertical are absent. Errors that are repetitive can be estimated (calibrated) by comparison to a reference data set, e.g., a NWP model (see, e.g., Stoffelen, 1998). Repetition should occur over an orbit, or as a function of other well-known parameters. We show that oversampling helps in the assignment of the backscatter volume, or in QC of extremely variable scenes. For ADM this will be exploited in the horizontal to allow segregation by cloud.

However, aerosol and cloud stratification cause serious problems with vertical height assignment of the aerosol signal. A vertical height assignment error of 50 m RMS creates large biases, particularly in cases of strong vertical wind shear. This type of error may further interact with variable instrument gain errors. For example, we found that in many cases the combination of the information from the Mie and Rayleigh channels in a simple way, lead to increased spatial error correlations. Moreover, higher order errors, e.g., quadratic in the wind speed, may cause large spatial error correlations in case of extreme winds and shear.

From our study into spatially correlated errors, the first recommendation would be to aim for a stable instrument such that systematic error effects can be filtered against reference data sets, such as NWP model data. Secondly, oversampling of the vertical with the aerosol channel will substantially reduce the height assignment error. In order to avoid substantial biases, height assignment errors in the vertical should be below 50 m RMS. Although not elaborated in this paper, relative gain errors and higher order errors also cause spatially correlated errors on the synoptic scales and in the vertical. In fact, this type of error depends on the atmospheric state (MERCI, 2002).

Collocated lidar and atmospheric model data sets were used successfully to simulate ADM. These datasets may be further exploited to build capabilities for ADM DWL data processing, e.g., to optimally combine Rayleigh and Mie measurements, or to prepare QC. Moreover, these can be used to consider and trade off more advanced vertical sampling modes.

In order to minimise the detrimental effect of vertical errors that are constant in height, we recommend furthermore to more fundamentally consider the assimilation of ADM shear observations, rather than HLOS winds.

We are confident that when our recommendations are fulfilled ADM will more substantially contribute to better atmospheric analyses. On the longer term, the experience with and beneficial use of good quality ADM data will result in the design of effective follow-on operational Doppler wind lidar missions, providing a larger quantity of observations.

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