Summary of the processing of the aerosol data from the ARM Raman lidar for the 2003 ARM Aerosol IOP

Dave Turner, Rich Ferrare, and Marian Clayton

23 December 2003

In May 2003, the ARM program sponsored an IOP (Intensive Operations Period) at the SGP site to focus on aerosols. The ARM Raman lidar (RL) was considered a critical component of this IOP, and significant efforts were undertaken to ensure that the laser was functioning normally during the entire experiment and that no significant downtime periods occurred. Indeed the RL was operational over 90% of the time during the IOP.

However, unbeknown to the experiment coordinators or the IOP participants, the sensitivity of the RL has been significantly declining since the end of 2001. The loss of sensitivity was not discovered until Aug 2003 while processing the aerosol data from the RL. Depending on the point of view, the sensitivity of the lidar is down by a factor of 2 to 4. The cause of the loss of sensitivity is currently unknown, and a problem identification form (PIF P031120.1) has been filed. However, this loss of sensitivity has greatly impacted the quality of the aerosol backscattering and extinction profiles derived from the RL during the aerosol IOP.

The loss of sensitivity impacts the RL aerosol VAPs (Value Added Procedures) in various ways. These impacts include: 1) significantly higher random noise component in the retrieved profiles, 2) reduction in the maximum altitude to which the aerosol profiles can be retrieved, and 3) occasional large systematic errors in the retrieved profiles due to errors in how the automated algorithms determine the overlap corrections that need to be applied to the high channel data. [The narrow field-of-view channels are often referred to as the high channels, since the data they collect are used higher in the atmosphere then the wide field-of-view, or low, channels.] Turner et al. (2002) describe how these automated algorithms are used to retrieve aerosol and water profiles.

The final point requires some explanation. The RL was designed primarily to measure water vapor in the boundary layer throughout the diurnal cycle and throughout the entire troposphere during the nighttime. Therefore, in order to optimize the water vapor retrievals, design choices were made that have made the automated retrieval of aerosol profiles from the RL data less than optimal. For example, the high elastic channel, which is needed for computing the aerosol scattering ratio (from which the aerosol backscatter coefficient is derived), was initially oriented normal to the optical bench while the other channels where placed parallel to each other on the optical bench. This resulted in the high elastic channel being much more susceptible to mechanical vibrations and possibly temperature fluctuations as compared to the other channels. The end result was that the near-field overlap correction needed for this channel often changed when the RL automatically attempted to optimize the location of the outgoing laser beam into the telescope's field-of-view (as seen by the high nitrogen channel). This procedure is called an "alignment tweak" and they typically occur every three hours if the RL determines that the sky is clear (which is done using a simple threshold test). If unaccounted for, this change in the near-field overlap correction would produce very obvious artifacts in the RL's backscatter coefficient data. Therefore, the VAP "ASR" (which processes the aerosol scattering ratio and backscatter coefficient profiles) attempts to use the low channel data to determine the overlap correction needed for the high channel for each period that is associated with the RL's automated alignment tweaks.

The alignment tweaks are required to compensate for small temperature fluctuations or drifts inside the lidar enclosure that can greatly impact the data quality in the RL's narrow (0.3 mrad) field-of-view channels (e.g. high altitude channels). However, during the aerosol IOP, the signal strengths were so low due to the loss of sensitivity that the system was erroneously concluding that it was cloudy every time it attempted to perform an alignment tweak, and thus no automated alignment tweaks were performed. This has resulted in many periods during the IOP where the alignment apparently drifted away from optimal which has impacted the quality of the aerosol products. Occasionally during the IOP, the system was recognized to be out of alignment and a manual alignment tweak was performed, but these occur too infrequently to greatly improve the data quality.

It should be recognized that there are two RL aerosol VAPs (ASR=aerosol scattering ratio and EXT=aerosol extinction) and both attempt to use the low channel to determine an overlap correction for the high channel. However, these are two different problems. The ASR VAP is attempting to determine the overlap correction for the high channel aerosol scattering ratio from the low channel aerosol scattering ratio. Intuitively, one might think that the overlap in the aerosol scattering ratio should be negligible because the near-field overlap in the elastic and nitrogen channels should cancel when the ratio is computed. If the two channels were perfectly aligned with each other, this would indeed be the case; however, as already stated, the high elastic channel's orientation causes it to often not be in good alignment with the other channels (and in particular the high nitrogen channel) which results in a difference of single-channel overlaps that does not cancel in the ratio. However, even after the mentor modified the system (using additional mirrors, etc.) so that all of the photomultipliers were parallel to each other on the optical bench, the high elastic channel is still much more susceptible to alignment difference than the other channels for some unknown reason. In summary, the ASR VAP then processes the low and high aerosol scattering ratios and then attempts to determine an overlap correction for the high channel ratio for each alignment period.

Unlike the ASR VAP, the EXT VAP, which computes the aerosol extinction and extinction-to-backscatter profiles, needs to automatically determine a single channel overlap for the high nitrogen channel. Aerosol extinction is calculated from the RL returns by taking the derivative of the log of the nitrogen signal. Therefore, any instrument-induced features must be accounted for before the extinction profile can be retrieved. The main instrument feature to account for is the overlap in the nitrogen channels. The low channel achieves full overlap (i.e., no longer needs an overlap correction) by approximately 800 m, while the high channel achieves full overlap around 5 km. Therefore, one might compute the extinction profile from the low channel from

800 m to 5 km and use the high channel above 5 km. However, above approximately 1500 m, the signal-to-noise in the low channel is too low to adequately (i.e., with random errors less than 20%) retrieve aerosol extinction. Therefore, the high channel data must be used well below the region of full overlap, which implies that an overlap correction must be determined and subsequently applied to the high channel data. The RL VAPs attempt to account for the drifting overlap corrections. However, the region where the low and high channels were merged was very noisy due to the lower maximum range of the low channel data, and there were obvious problems with some periods where we suspected poor alignment.

Another change was implemented to account for an error introduced in the initial run performed at the ARM Data Management Facility. As described by Turner et al. (2002), the RL aerosol extinction profiles are derived by multiplying the aerosol backscattering profiles by the aerosol extinction/backscatter ratio. The RL measurements of aerosol scattering ratio are use to derive aerosol backscattering profiles which are then used along with the RL measurements of aerosol extinction to derive the aerosol extinction/backscatter ratio (S_a). S_a will vary with changes in the size distribution, composition, and/or shape of the aerosols (Ferrare et al., 2001). However, the run that produced the results distributed during and shortly after the IOP, and which are also currently distributed by the ARM Archive, was discovered to have a bug in it which resulted in the extinction-to-backscatter ratio (S_a) to default to the background value of 60 sr for all times and heights. We expect that this bug was introduced into the code when the code was upgraded in 2002 to run in the new ARM 64-bit environment.

The following sections describe briefly how we have attempted to address these issues.

1) Changes/experiments with the ASR VAP:

The first change made to the ASR VAP was to change the altitude range over which the low and high aerosol scattering ratios are merged from 1.5-1.9 km to 1.0-1.5 km. This significantly reduced the noise in the merged product as the low channel data is much noisier above 1.5 km since the instrument has been degrading.

The second change is that the near-field overlap correction for the low aerosol scattering ratio data was determined from data collected during the IOP. The correction used for the initial processing was determined from data in 1999 and thus was several years out of date.

A new routine was written to identify when the raw data appear to show changes in alignment. Previously, the ASR code determined when the alignment changed by looking for the messages created by the instrument and stored in its log file when an automated alignment tweak occurred. However, manual alignment tweaks performed by site operations are not recorded in the log file (this is being addressed through an ARM Engineering Request Order). Since no automated alignment tweaks occurred during the Aerosol IOP, the original processing assumed that the alignment was constant when there were actually multiple realignments by site operations. These alignment tweaks are accounted for in this reprocessing.

However, even with these two changes, there are still periods during the IOP when the lidar's alignment obviously drifted, yet these periods were not associated with a particular alignment tweak. Consequently, the operational algorithms were unable to accommodate for these drifts. In January 2000, a new "calibration" mode was implemented in the lidar (called "mode8 data") and the system has collected 1-min of this mode8 data every hour. In mode8, a 355 nm (aerosol) filter is inserted into the high water vapor channel allowing the aerosol scattering ratio to be computed using either the water vapor channel or the elastic channel when the system is in this mode. The motivation behind the mode8 implementation is that the high water vapor channel appeared to be much more stable with respect to the high nitrogen channel (alignment-wise) and thus the mode8 data should be able to be used to essentially remove any changes in alignment in the high elastic channel. For the first time, we implemented a routine to utilize the mode8 data to do just that. While it showed some success accounting for alignment issues in the boundary layer, this routine introduced high biases in the middle troposphere, and these biases had a strong diurnal character to them. At this time, we have been unable to identify the source of this bias when the mode8 data are utilized, and have thus decided against its implementation in the operational code.

2) Changes/experiments with the EXT VAP:

The first change made to the EXT VAP was to change the vertical resolution (by about a factor of 2) of the low channel extinction data to improve the signal-to-noise ratio in the extinction profile.

The second change was to determine a near-field overlap correction for the low nitrogen channel so that aerosol extinction could be determined directly from this channel below the altitude of full overlap. This extends the extinction calculations from 800 m to less than 400 m.

Computing aerosol extinction from Raman nitrogen signals is difficult when the aerosol loading is low (e.g., for regions where the extinction coefficient is less than 0.03 km^{-1}), yet we desire to have aerosol extinction values for all times/heights in the lower to mid troposphere. Thus, the EXT code computes the extinction-to-backscatter ratio (S_a) whenever the aerosol extinction values are above 0.03 km^{-1} and the random error in these measurements is less than a threshold (typically 50%). This results in a relatively sparse set of S_a observations in time and space. The EXT code filters these S_a values, and interpolates/extrapolates them to cover all times and altitudes. The EXT code uses the filtered/interpolated/extrapolated S_a values along with the aerosol backscatter coefficient to compute aerosol extinction.

The third change to the EXT VAP was a significant improvement in the logic that filters/interpolates/extrapolates S_a. This algorithm begins by only computing S_a values where the random error in the extinction and backscatter are less than 50%, and where the extinction is larger than 0.03 km^{-1}. Additionally, any S_a values outside of a predefined range are also removed. Initially, this range was [5,130] sr, but it was modified to [10,100] after the Aerosol Working Group meeting in Sonoma.

These filtered values were then processed to fill in the gaps in time and height in the S_a record. The initial version of this algorithm used equal weights for both the vertical and temporal dimensions regardless of altitude of the "pixel" being computed. Furthermore, there was no limitation on the "distance" for the extrapolation; for example, if a day had only a single S_a point (after filtering), the initial algorithm used this S_a value for all times/heights for that day. The new algorithm that was recently implemented addresses both of these issues. First, the vertical and temporal weights change as a function of altitude; in the boundary layer where convection is more likely, the weights are higher in the vertical then in the temporal dimension, but in the free troposphere, the opposite is the case. Second, an extrapolation limit is set (based upon the weights) and if a point is beyond the limit then it inherits the background default value of 60 sr (which was determined from a 2-year analysis of SGP Raman lidar from 1998-1999).

As indicated in the introduction, the data from the high nitrogen channel are used to compute aerosol extinction well below its full overlap altitude because the signal-to-noise in the low nitrogen channel limits it to altitudes well below this height. Therefore, the EXT code needs to determine an overlap correction to apply to the high nitrogen channel. Therefore, the EXT code also needs to identify when alignment tweaks occur, as it is possible for the high channel overlap correction to change as a result of these tweaks. The EXT code was modified to use the same new logic that determines the alignment tweaks directly from the raw data.

Finally, we experimented with new routines to automatically determine the high channel overlap correction. The original routine averages the low and high nitrogen signals during the alignment tweak period and computes the ratio of the two to determine an overlap correction for the high channel. However, this ratio is often noisy (especially from 3-5 km when the signal-to-noise in the low channel gets low) and thus there was a quality-control "envelop" that was used to identify periods when the determined overlap correction was outside of reality and should not be used. Our new logic also made use of the fact that the overlap correction should be smooth, and thus it attempted to fit a polynomial to the ratio of the low to high nitrogen signals. However, computing aerosol extinction from nitrogen backscatter data is analogous to identifying changes in slope in the nitrogen data with altitude. Therefore, if the fitted polynomial (or any function) is not of the right form to describe the true overlap correction, then using this function as the overlap introduces biases into the extinction profile. While we experimented with many different polynomials of different orders, they all appeared to add (sometimes significant) biases to the extinction profiles and thus we have elected to continue using the original overlap correction logic in the EXT code.

3) Changes to the MR VAP:

A new set of overlap corrections were determined for the low and high channel water vapor mixing ratio data for this IOP, and the data have been reprocessed. Also, previous analysis from the 2000 WVIOP has suggested that calibration of the Raman lidar is actually very stable, and thus the small uncertainties in the daily calibration coefficient fits introduces more uncertainty in the mixing ratio data's calibration than if a constant calibration factor was assumed. Therefore, a single calibration coefficient has been determined for May 2003 and applied to all of the mixing ratio data for this month.

References:

Ferrare, R. A., D. D. Turner, L. A. Heilman, W. Feltz, O. Dubovik, and T. Tooman: Raman Lidar Measurements of the Aerosol Extinction-to-Backscatter Ratio Over the Southern Great Plains, *J. Geophys. Res.*, 106, 20333-20347, 2001.

Turner, D. D., R.A. Ferrare, L.A. Heilman, W.F. Feltz, and T. Tooman: Automated Retrievals of Aerosol Extinction and Backscatter Coefficient Profiles From a Raman Lidar, *J. Atmos. Oceanic Tech.*, 19, No. 1, p. 37-50, 2002.