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Observations of the spectral dependence of particle depolarization ratio of aerosols using NASA Langley airborne High Spectral Resolution Lidar

by S. P. Burton, et al.

The paper is well written, well suited for ACP. The measurement cases are well described and put into relation with other measurements and model results.

Although the title of the paper emphasizes the three reported measurement cases of the linear depolarization ratio of aerosols, the part describing the instrument, its errors and the error calculation seems to be the more important of this paper, because it will serve as the reference for future papers about the depolarisation measurements with this instrument.

I propose to publish the paper under consideration of following remarks concerning the description of the system set-up and the error calculations.

Chap. 2 Instrument description and measurement methodology

Because measurements of the linear depolarization ratio with the HSRL-1 and HSRL-2 are directly compared, the set-up differences between both instruments, in case they exist, should be explicitly mentioned, which could be relevant for the measurement of the linear depolarization ratio.

Page 24757 Line 2

The polarization axis of the outgoing light is matched to that of the receiver with an approach similar to that outlined by Alvarez et al. (2006) using seven fixed polarization angles between ±45°, using the half-wave calibration wave plates indicated in Fig. 1.

How accurate can the offset angle between the outgoing polarization and the receiver be determined?

This should be determinable from the uncertainty of the fit of the Alvarez-calibration with the seven polarization angles. It is conjecturable that the offset angle changes during a flight and between different flights due to thermal and pressure influences e.g. on the birefringence of the exit window, wherefore I would not average between different calibrations, especially not for a conservative error estimate (further discussion about the systematic error below).

Page 24757 Line 5

Following the alignment, the gain ratio between the cross-polarized and co-polarized channels is routinely determined in flight by rotating the transmitted polarization 45° relative to the receiver, ...

How accurate can the 45° angle be adjusted with respect to the receiver?

I guess that the precision is high by means of position encoders or similar. But what about the absolute accuracy? As shown by Freudenthaler et al. (2009), the high precision of the angular positioning can be used to achieve a high accuracy for the polarization calibration by means of the +-45° calibration regardless of the polarization offset angle. This could easily be done with the two of the seven calibration positions which are exactly 90° apart.

As an example, Fig.1 below shows the calibration factor (with Ic / Ip = I cross / I parallel) with assumed electronic gain ratio = 1, calculated with Eqs. (1), (A1), and (A2) of this paper for δ_{tot} = 0.1, a polarization ellipticity angle θ = 5°, and a polarization offset angle ψoffset = -2°. The red marks show the seven measurements at nominal positions ψ as used by the authors of this paper, and the large error of the calibration factor at +45° or -45° positions. The green line shows the calibration factors calculated with the square root of the geometric mean of measurement pairs of the blue line which are 90° apart (e.g. -60° and +30°).

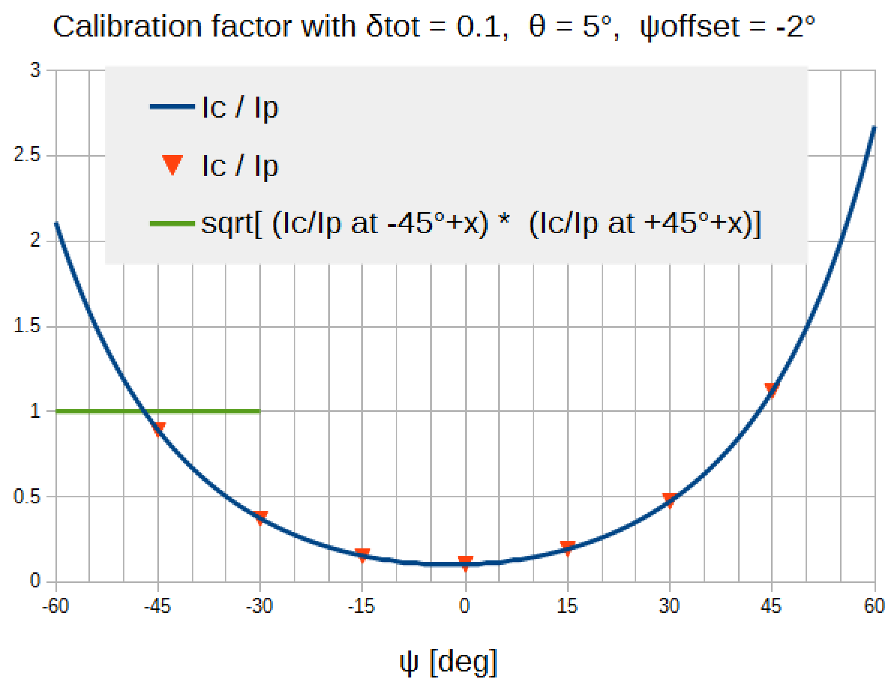

Fig. 1 (see text)

It would be very helpful for the readers if such a calibration measurement (with statistical and systematic error bars) could be shown in the paper.

Page 24757 Line 28

The polarization extinction ratio measured in the system is 300 : 1 ….

The extinction ratio is the ratio of the transmission of the unwanted component to the wanted component. It is defined like that, e.g., by Tompkins and Irene (2005), by Bennett (2009) in OSA's Handbook of Optics, and Goldstein (2003) writes in Chap. 26.2.1: "The extinction ratio should be a small number and the transmittance ratio a large number; if this is not the case, the term at hand is being misused." Unfortunately, searching the literature, I find "misuse" by the larger part.

Page 24757 Line 28

The co-polarized signal and cross-polarized signal are used to determine total depolarization.

Although for an insider it is clear from the instrument description what is meant with total depolarization, the correct naming for the measured quantities are linear depolarization ratio and volume (or total) linear depolarization ratio, etc.. This is important, because some lidar systems measure the circular depolarization ratio, and it should be at least mentioned once at the begin of the paper before proceeding with the short-cuts.

Page 24758 Line 12

The separation of the aerosol and molecular signals is the basis of the HSRL technique for extinction and backscatter retrieval. Since it is also relevant to the systematic error in particle depolarization ratio, it will be discussed again in Sect. 2.2, below.

The discussion of the errors of the backscatter ratio and its influence on the error of the linear depolarization ratio are described not sufficiently. Page 24758 Line 15 refers to Sect. 2.2, which refers to the appendix, but there just a value for the error is given and little explained.

In Hair et al. (2008) Chap. 7 a detailed error analysis was promised in a following paper: *An analysis of the systematic errors for all data products from the airborne HSRL is beyond the scope of this paper. A manuscript focused on a complete error analysis and validation of extinction measurements is currently in preparation.*

I couldn't find this paper.

Page 24759 Line 21

Different names are used for the same thing, e.g. volume depolarization, total depolarization, volume depolarization ratio, which is confusing. Please decide for only one short-cut (see comment above Page 24757 Line 28) throughout the paper.

Similar: there are several calibrations: polarization angle calibration, backscatter gain ratio calibration, depolarization gain ratio calibration, etc.. Please use unique names and only one for the same in the whole paper, and always use the full unique name.

Similar: fractional error = relative error?

Page 24760 Line 2

... we estimate a reasonable upper bound on the systematic error in the volume depolarization ratio measurement to be 4.7 % (fractional error) in the 355 nm channel, the larger of 5 % fractional error or 0.007 absolute error in the 532 nm channel, and the larger of 2.6 % fractional error or 0.007 absolute error in the 1064 nm channel.

Why is there no absolute error (offset) at 355 nm?

Page 24760 Line 13

... the molecular depolarization arises only from the central Cabannes line and is very well characterized, with a value of 0.0036...

The molecular (air) linear depolarization ratio is wavelength dependent and actually 0.003946 at 355 nm, 0.003656 at 532 nm, and 0.003524 at 1064 nm. (Own calculations for air with 385 ppmv CO_2 and 0% RH).

Page 24760 Line 14

More critically important is ***a*** *potential systematic error in the total scattering* ***gain(?)*** *ratio. We estimate the effective upper bound of this error to be 4.1 % in the 532 nm channel from an analysis of the stability of the* ***gain (?)*** *ratio;...*

Stability (precision) is not accuracy. Furthermore, how is the error of the of the total scattering ratio determined?

Page 24760 Line 21

The estimates given above are intended to be a conservative upper bound on the systematic errors. The systematic errors on the three quantities, δ mol, δ tot, and R, are combined in quadrature using standard propagation of errors for independent variables, as described in the Appendix.

I do not agree, that this "standard" propagation of errors is the right one for the systematic errors mentioned here (see discussion Systematic errors below).

Page 24762 Line 8

For that case, the particle depolarization ratios at 532 and 1064 nm are 0.33 ± 0.02 (standard deviation) ...

What does "standard deviation" mean here? Probably the propagated error due to (random) signal noise is meant (see discussion Systematic errors below).

Figure 14

The x-scales could be adjusted for each wavelength to make the data better visible.

Page 24776 Line 20

The calibration procedure has been carefully designed and used successfully on both the HSRL-1 and HSRL-2 systems since 2006, and the stability of the offset angle is high. Changes indicated during calibrations are at most 0.4◦ of polarization (0.2◦ rotation of the half-wave plate) for all channels (assessed, as before, using the mean plus two standard deviations for all flights having multiple calibrations during the latest field mission).

This tells us only something about the stability (or precision) of the 45° angle adjustment, but nothing about the accuracy, which is the basic important value.

What does "*Changes indicated* " mean?

Page 24777 Line 12

Change:

This effect on the measured gain will be reflected in the ~~stability~~ ***error*** *of the gain ratio, ...*

Page 24777 Line 18

The stability of this gain ratio was assessed in a similar manner to the offset angle and polarization gain ratios given above.

Again: precision (stability) is not accuracy. Please explain.

Systematic errors

A well-founded error calculation for lidar products is a really laborious task. The effort done in this paper is ambitious. Nevertheless, I would like to make a general remark and some comments in the following:

Error bars are essential in several respects, e.g. for the retrieval of micro-physical aerosol parameters with model calculations, for the comparison of results from different instruments, or for aerosol classification. The two scenarios A and B in Fig. 2 show their importance: in scenario A the two values 1 and 2 cannot be measurements of the same object, because the error bars don't overlap. At least if we take the error bars seriously. In scenario B we cannot exclude that value 1 and 2 are measurements of the same object. They are not distinguishable considering the accuracy of the measurements.

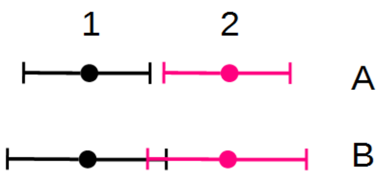

Fig. 2 (see text)

Furthermore, if we know from other measurements that object 1 and 2 are actually the same, as it is sometimes the case from simultaneous measurements in multi-sensor field campaigns, we must conclude from scenario A that there are unaccounted instrumental errors, and from scenario B that the true value of the object is in the small overlap region of the two measurements.

This shows first, that error bars are very valuable and powerful information, and second, that we must be careful because other scientist will take our error bars and interpret them in their context if we don't specify them sufficiently.

Models need the experimental error bars as constraints. They often produce results with statistical probabilities from many trials. Often Gaussian like distributions arise due to the central limit theorem, even if the original parameters are evenly distributed. But for that more than about ten different input values for each parameter are required.

But an instrument like a lidar system has only one set of system parameters at the time of a certain measurement, which usually shouldn't change during the measurement. Therefore the application of the statistical error propagation for independent parameters (sum of squares), which assumes a Gaussian distribution of the "erroneous" parameters, is not appropriate for the error propagation of fixed systematic errors. Should a system parameter nevertheless change during a measurement, its behaviour should be determined and an appropriate error propagation developed. This would be the preferred method, but it is often too complex to accomplish. Also in this case an error calculation using the extreme bounds is the conservative way.

Furthermore, if the lidar error bars are too large, a too large variety of model results fall within the error bars, and if the lidar error bars are too small, the model solutions which would come close to the reality might be excluded. If lidar error bars are getting smaller and reliable, the lidar measurements can be really helpful to improve the model developments.

Detailed comments:

1. The details of the error calculation should not fall back behind the one presented by Freudenthaler et al. (2009). The equations for the F_x-values should be presented as well as the ones for the calculation of the error of the backscatter ratio due to the HSRL technique.

As already mentioned, the "manuscript focused on a complete error analysis and validation of extinction measurements" promised by Hair et al. (2008) is missing.

2. The absolute error (offset) of the volume linear depolarization ratio can only be positive. The only way to decrease the depolarization is a polarization filter, which is the case if the receiver optics has diattenuation. But this effect is in principle fully corrected with the polarization calibration. (I propose to use "polarization calibration" instead of "*de*polarization calibration".) Therefore, this error would have a one-sided distribution if many different instrument adjustments were done, which is clearly not a Gaussian distribution.

3. Eq. (1) of this paper corrects only for different electronic gain and optical transmission after the polarizing beam splitter, but not for the cross talk of the polarizing beam splitter as shown by Freudenthaler et al. (2009) Eqs. (15) and (16). Although the extinction ratios of the polarizing beam splitter assemblies used in the HSRL-2 receiver are quite good, the error from neglecting their cross talk is maximal for low depolarization and amounts for the molecular linear depolarization ratios to +0.0023 at 355 nm and +0.0010 at 532 and 1064 nm using the transmission ratios in page 24757 line 29. The linear depolarization ratio values presented in the paper could be easily corrected for that effect.

However, this calculation also shows, that the effect is not sufficient to explain the assumed-molecular linear depolarization ratios of 0.0085 to 0.0135 measured since 2006 (Page 24775 Line 14).

The molecular linear depolarization ratio is the only calibration standard we have for depolarization measurements. Deviations from that can be due to an offset, due to a calibration factor, and due to a combination of both. Assuming that the error of the calibration factor can be reduced to a few percent, the offset can be determined and all measurements can be corrected for that error with the appropriate equations. The remaining error is then the unexplained spread of the assumed-molecular linear depolarization ratios of 0.0085 to 0.0135.

4. Elliptically polarized output light can be separated in the Stokes vector in a pure linearly polarized and a pure circularly polarized part. The circularly polarized part is detected by the linear polarization analyser, i.e. the polarizing beam splitter in the lidar receiver, as depolarization and gives a more or less constant offset contribution to the linear depolarization ratio (decreasing

slightly with increasing atmospheric depolarization). It doesn't influence the polarization calibration factor.

In contrast, if there is a rotation of the plane of polarization of the emitted light with respect to the receiver, it is probably also there for the polarization calibration, which results in a relative error of the gain and therefore in a relative error of the linear depolarization ratio (see above comment to Page 24757 Line 5).

Therefore, the two systematic errors, i.e. elliptical polarization and angle of the plane of polarization, cannot be treated identically as cross-talk (Page 24776 Line 8).

Page 24776 Line 17

Taking this into account, we include a factor of 0.007 (absolute) due to cross-talk in the estimated volume depolarization error.

The value 0.007 is not a factor, but an absolute offset. The cross-talk error should be a relative error. See discussions above.

Table 2

Instead of somehow arbitrary value combinations the real values for Table 1 should be used, and maybe some extreme values to show certain aspects. Furthermore, the equations used to calculate the factors and errors should be shown, which would be valuable for the readers to improve their own error calculation.

The uncertainty for R is only +-5%, but for 1064 nm +-20% are mentioned in the paper.

Summary

The offset errors and the errors of the calibration factors should be separated as much as possible.

The polarization calibration error can be decreased and separated from the measurements error of the polarization angle by using the +-45° calibration.

The error of the polarization angle should be determined for each calibration separately and propagated to the corresponding measurements.

The cross talk error from the polarizing beam splitters should be corrected.

The determination of the backscatter ratio error should be described more detailed and its influence on the error of the linear depolarization ratio should be made more clear.

With a small error of the calibration factor, the more or less constant offset error can be accurately determined, and the values of the linear depolarization ratio can be corrected for that.

1.1 References

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