Responses to reviewer #1

Authors are grateful to the reviewer for a careful reading of the work and valuable comments

Comments 1

Pg 2, Line 51

“Another effect caused by the horizontally oriented columns is the cornerreflection when the lidar is tilted at 30 deg...” The 30 deg corner reflection comesfrom plates, not columns. Columns also have a corner reflection but it is closer to 60degrees. This is noted in A. Borovoi, I. Grishin, E. Naats, and U. Oppel, “Backscatteringpeak of hexagonal ice columns and plates,” Opt. Lett. 25(18), 1388–1390 (2000).

Response

Yes you are right. Depolarization of backscattered radiation has a maximum at a lidar tilt of 30 degrees for oriented plates and about 60 degrees for columns (Borovoi et al., 2000). A more detailed simulations show that when angular reflection is taken into account, the element a_{44} of the BSPM is most informative in determining of the flutter (Konoshonkin, 2016). For the plates, an abrupt change in the a_{44} occurs at a tilt angle of 30 degrees, while for the columns this element begins to grow smoothly at 30 degrees and reaches a maximum at 60° (Konoshonkin et al., 2016).

Reference to add:

Borovoi, A., Grishin, I., Naats, E., and Oppel, U., “Backscattering peak of hexagonal ice columns and plates,” Opt. Lett., 25(18), 1388–1390 (2000).

Konoshonkin, A.V., "Simulation of the scanning lidar signals for a cloud of monodisperse quasi-horizontal oriented particle," Optika Atmosfery i Okeana, 29, No. 12, 1053–1060 (2016) [in Russian].)

Revised text

Another effect caused by the horizontally oriented plates and columns is the corner reflection. It appears when the lidar is tilted at a significant angle. Depolarization of backscattered radiation has a maximum at a lidar tilt of 30 degrees for oriented plates and about 60 degrees for columns (Borovoi et al., 2000). A more detailed simulations show that when angular reflection is taken into account, the element a_{44} of the light backscattering phase matrix (BSPM) is most informative in determining of the flutter (Konoshonkin, 2016). For the plates, an abrupt change in the a_{44} occurs at a tilt angle of 30 degrees, while for the columns this element begins to grow smoothly at 30 degrees and reaches a maximum at 60° (Konoshonkin et al., 2016). Some experiments with tilted lidars were carried out (Del Guasta et al., 2006; Hayman et al., 2012, 2014; Neely et al., 2013, Veselovskii et al., 2017) and showed a high probability of the presence of oriented particles.

Comments 2

Pg 2, Line 54.

In this paragraph the authors cite several works stating that these works observed both horizontal orientation and azimuthal orientation. This is not true. Most of the references make no mention of observing azimuthally oriented ice crystals which implicitly seems to suggest they didn't observe any. There are a few works (such as Kaul 2004 and Balin 2011) that do mention observing this effect. Beyond that I happen to know number of the researchers cited are very skeptical about the existence of of azimuthally oriented ice crystals outside of thunderstorms. I doubt they would appreciate being cited in support of this claim. The authors need to accurately represent the results of prior work and most of the citations used here do not support the statement or even contradict the statement.

Response

Indeed I put this phrase very incorrectly. Sorry, I mistakenly cited some authors who did not mention the azimuthal orientation.

I reason like this. If azimuthal orientation takes place, the parameters of the backscattered radiation depend on the orientation of the lidar reference plane relative to the direction of the preferential orientation of particles. *Direct measurements* of azimuthal orientation should be carried out as follows. We set lidar vertical and use linear polarized radiation. If the lidar reference plane coincides with the direction of the action of the orienting factor, the matrix of this cloud will have a block form

$$\mathbf{M} = \begin{vmatrix} m_{11} & m_{12} & 0 & 0 \\ m_{12} & m_{22} & 0 & 0 \\ 0 & 0 & m_{33} & m_{34} \\ 0 & 0 & -m_{34} & m_{44} \end{vmatrix}$$

, (Kaul, 2000). Then we rotate the lidar around a vertical axis. One can easily show (Kokhanenko et al., 2018) that signal energy $E^{lin} = m_{11} + m_{12}\cos 2\varphi$ depends on the angle of rotation of the lidar relative to the plane of preferential orientation of the particles in the cloud if $m_{12} \neq 0$. According to a large array of experimentally measured BSPM (Kaul et al., 2004), the average value of $m_{12} = -0.22$. The distributions of relative frequencies for m_{12} shows the probability that the value of m_{12} lies in the interval [-0.6, -0.3] is approximately equal to 30% (Kaul et al., 2004, Balin et al. 2009). Therefore we would have to observe the modulation of the signal very often.

The density of the cloud can change during the time of rotation. The signal from circular polarization serves as a reference for tracking changes in the signal that are not related to the rotation of the lidar. The function $F(\varphi) = \dfrac{E^{lin}(\varphi)}{E^{circ}(\varphi)} = 1 + \dfrac{m_{12}}{m_{11}}\cos 2\varphi$ varies with a period of 180° and one of the extremes of this dependence (max or min, this depends on the sign of the element m_{12}) coincides with the position of the plane of symmetry. However, authors are unaware of such direct measurements. Because our lidar (i) can scan around vertical axes, and (ii) measures both linear and circular polarization, we can make observations using this technique. It is unfortunate, but all the measurements we carried out to date, have not shown the presence of azimuthal orientation. We plan to continue such observations in the future.

Indirect evidence of the existence of a preferential azimuthal orientation can be obtained from the form of measured BSPM. Instead of lidar rotation we can transform the matrix using the rotation matrix R(φ) to the plane of symmetry. If the matrix may be represented in the block form, this suggests a high probability of the presence of a fraction of oriented particles (Kaul 2000, Kaul et al. 2004, Samokhvalov et al. 2014). In a similar manner Hayman et al., 2014 simulated the rotation of measured matrix and made a conclusion about the orientation of the particles based on the change of the calculated depolarization ratio.

References to add:

Kokhanenko, G.P., Balin Yu.S., Borovoi A.G., Klemasheva M.G., Nasonov S.V., Novoselov M.M., Penner I.E., Samoilova S.V. "Investigations of the crystalline particle orientation in high-level clouds with a scanning lidar," ", Proc. SPIE 10833, 24th International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics, 1083347 (13 December 2018); https://doi.org/10.1117/12.2504129

Samokhvalov, I.V., Nasonov, S.V., Stykon, A.P., Bryukhanov, I.D., Borovoi, A.G., Volkov, S.N., Kustova, N.V., and Konoshonkin, A. V., "Investigation of phase matrices of cirrus containing ensembles of oriented ice particles," Proc. SPIE 9292, 20th International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics, 92922M (25 November 2014); doi: 10.1117/12.2075562

Revised text

Particle orientations are promoted not only by aerodynamic forces, but also by forces of a different nature, such as wind shifts and electric fields. Kaul 2000 supposed that in such conditions, crystalline particles can have a preferential orientation in the horizontal plane (azimuthal orientation). It is obvious that the direction of preferential orientation is connected with the direction of action of these forces. The basis for such conclusion is the observed non-invariance of the BSPM with respect to rotation of the coordinate system (Kaul 2000, Kaul et al. 2004, Samokhvalov et al. 2014, Hayman et al., 2014). If we use linear polarized radiation and rotate the lidar around a vertical axis, signal energy depends on the angle of lidar rotation relative to the plane of preferential orientation of the particles if $m_{12} \neq 0$ (Kokhanenko et al., 2018). According to a large array of experimentally measured BSPM, the distribution of relative frequencies for m_{12} shows that the value of m_{12} lies in the interval [-0.6, -0.3] with the probability about 30% (Kaul et al., 2004, Balin et al. 2009). Therefore we would have to observe the modulation of the signal very often. However, authors are unaware of such direct measurements.

Discretionary Edits

Comment 3.

...The authors should be careful about overasserting what their observations definitively prove about the scattering volume. . (Pg. 8 starting on line 235)... In that context, the authors later assert that the depolarization values are indicators for the relative mass of oriented and randomly oriented ice (Pg. 10 line 284). .....

Response

Your comments are very useful, and I will try to take it into account when finalizing the text. As for line 284, I try to revise this text

Revised text

pg.10, Line 302

the ratio $\left(I_{\parallel}\left(0°\right)-I_{0}\right)/I_{0}$ may reflect the contribution of mirror particles to the lidar signal.

Comment 4.

Pg 11, Line 316 "... including exploring the azimuthal orientation of particles." I suggest being clear that this was not explored in the current work and that looking for azimuthal orientation of particles would be in future work.

Response

I slightly changed the text

Revised text

pg.11, Line 331

Since the circular polarization signal does not depend on the rotation of the lidar relative to the direction of particle orientation, this polarization can be used as a reference for investigation the azimuthal orientation of the particles.

Comment 5.

Pg 3, Line 62-64 It is not clear how the authors come to the conclusion that m12=-0.22 +/ -0.2 means that in 30% of the observational cases, the depolarization depends on the lidar reference plane. The value of m12 certainly does not dictate this. Is the assumption that PDF of m12 is Gaussian?

Pg 3, Line 64 "In other words: : :" This statement isn't totally clear. I think to clarify you want to say "...when the lidar's linear polarization rotates around: : :"

Response

See the response to comment 2

Comment 6.

With regard to the near range channel, I'm a little confused about what its purpose is. Doesn't the fiber scramble the polarization modes and therefore prevent measurement of the depolarization ratio with this channel? What is this channel being used for? What ranges are the near and far range channels used for?

Added text

pg.4, Line 124

The small receiver is closer to the transmitter, so the transition to range-square mode starts earlier (80-100 m) than for the large receiver (800-900 m). During data processing signals from near zone (50-1200 m) and far zone (400 m-15 km) fit together at a distance of 800-900 m when range-square mode for large receiver starts. Of course, the optic fiber destroys the polarization state of the signal, so near-zone data cannot be used for polarization analysis.

Comment 7.

Pg. 10 Line 278 The authors state that the signal variations with angle are smaller than the measurement errors. This really depends on what the authors mean by "measurement errors" because one can clearly see a trend in the data, so the limiting factor does not appear to be random error. If they mean this is less than the systematic error of the instrument, this is certainly a valid point. It would be good to clarify which type of errors they are referring to.

Also with regard to Figure 10 and the perpendicular measurements, I wonder if this angle dependence is the result of cross talk between the channels. Perhaps this is what the authors are referring to as "measurement error". If so it would be helpful to simply state that explicitly.

Response

Analysis of measurements errors is very difficult. As for "cross talk", I suspected that this is so, but I did not know how to express it.

Revised text

pg.10, Line 293

Cross-polarized signals $I_{\perp}$ have random variations from pulse to pulse comparable with the average value. In most cases the values of $I_{\perp}$ show a weak decline of intensity with the angle, but these variations do not exceed instrumental errors (about 1% for depolarization ratio). Figure 10a shows the variations even less the 0.5%. Moreover, a slightly noticeable maximum at α=0° looks like signal penetration from parallel to perpendicular channel. Therefore we think, than linear trend is not statistically reliable. We can conclude that $I_{\perp}$ is practically independent of the tilt angle.

Comment 8.

Pg. 10, Line 300 The authors describe that the depolarization measurements at 532 nm are only made for linear polarizations. This needs to be better explained in section 2 Lidar Description. I had assumed (incorrectly) that the authors were using a dual wavelength wave plate. Make it clear what wavelengths the polarization optics are designed for and please be clear throughout the manuscript that this instrument performs the two polarization measurements only at 1064.

Response

The measurements for linear polarization can be made simultaneously for two wavelength 532 and 1064 nm. As for circular polarization, it is depend on the installed quarter-wave plates. Experiments described in the article were made with the plate, designed for 1064 nm. We can use a quarter-wave plate for 532 nm if it is planned. Similar we change a half-wave plate (532 or 1064nm) for calibration.

Revised text

pg.4, Line 107

We have two sets of quarter-wave plates. One set is designed for 532 nm, another set for 1064 nm. For the wavelength of installed plates (below are the results only for installed 1064 nm plates) we can investigate both linear and circular polarizations. For the second wavelength (532 nm) polarization state when turning 45 degrees is not determined. However, in the position where the axis of the rotating phase plate coincides with the plane of polarization of the transmitter, the radiation remains linearly polarized for any wavelength. So the measurements for the wavelength of $\lambda = 532$ nm were carried out only for linear polarization of radiation. Of course, in our lidar we can use a quarter-wave plates for 532 nm if such experiments were planned.

Thanks again for the helpful comments.