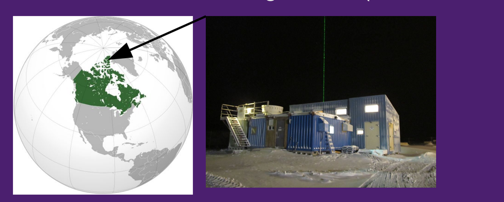
Calibrating the CRL for depolarization measurements

Emily McCullough[1], S. Gammage[1], C. Perro[2], J. Hopper[2], R. J. Sica[1], T. J. Duck[2], K. A. Walker[3], and J. R. Drummond[2]

CRL lidar at ØPAL (Zero-Altitude PEARL Auxilliary Lab) in Eureka, Nunavut in the Canadian High Arctic (80º N, 86º W).



This project is part of the larger CANDAC (Canadian Network for the Detection of Atmospheric Change) project at PEARL (Polar Environment Atmospheric Research Laboratory).

Introduction to Lidar Depolarization

Lidar Depolarization measurements allow liquid droplets to be discerned from frozen particles in clouds. Liquid droplets can exist well below 0 ºC, so this is an interesting quantity to examine in cold Arctic clouds.

- **Parallel Channel:** Admits light which has been backscattered with polarization "parallel" to the polarization of the transmitted beam (i.e. polarization unchanged by the scatterers in the atmosphere)

- **Perpendicular Channel:** Admits light whose plane of polarization is now perpendicular to that of the transmitted beam (i.e. from interaction with some non-spherical atmospheric scatterers)

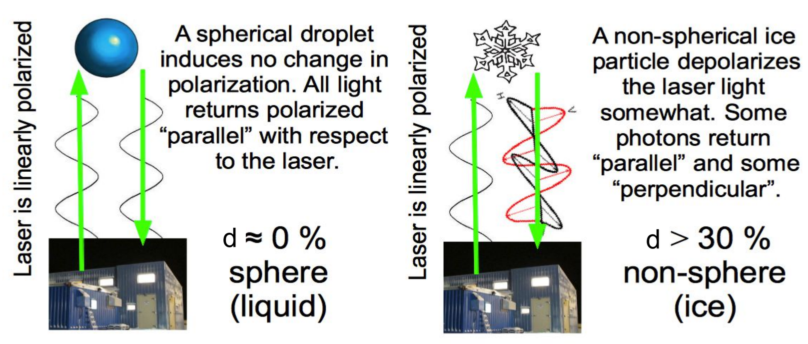


Figure 1: Lidar depolarization in the sky

Depolarization Factor (*d*) measurements are made using two polarization-dedicated measurement channels. In the CRL these are both measured using the same PMT, with a Licel Polarotor (a linear polarizer) rotating in front of the PMT on each laser shot.

Usually, the Depolarization Factor *d* and the related Depolarization Ratio (δ) is calculated assuming that the only instrument effect is a constant difference in total gains $G_{\|total}$ and $G_{\perp total}$ between the channels (see Ref. 1).

$$[1]\quad d = \frac{2S_\perp}{\frac{G_{\perp total}}{G_{\| total}} S_\| + S_\perp} \qquad [2]\quad \delta = \frac{G_{\| total}}{G_{\perp total}} \frac{S_\perp}{S_\|}$$

Note that these total channel gains include more than only the PMT gains $G_\|$ and $G_\perp$ later in the poster. For CRL, $G_\| = G_\perp$; $G_{\|total} \neq G_{\perp total}$. $S_\|$ and $S_\perp$ are the signals in each detection channel.

How can we ensure these equations are realistic for the CRL lidar?
A more complete matrix derivation of the depolarization parameter is developed. It accounts for more possible instrument contributions.

Effects of Calibration on Cloud Interpretation

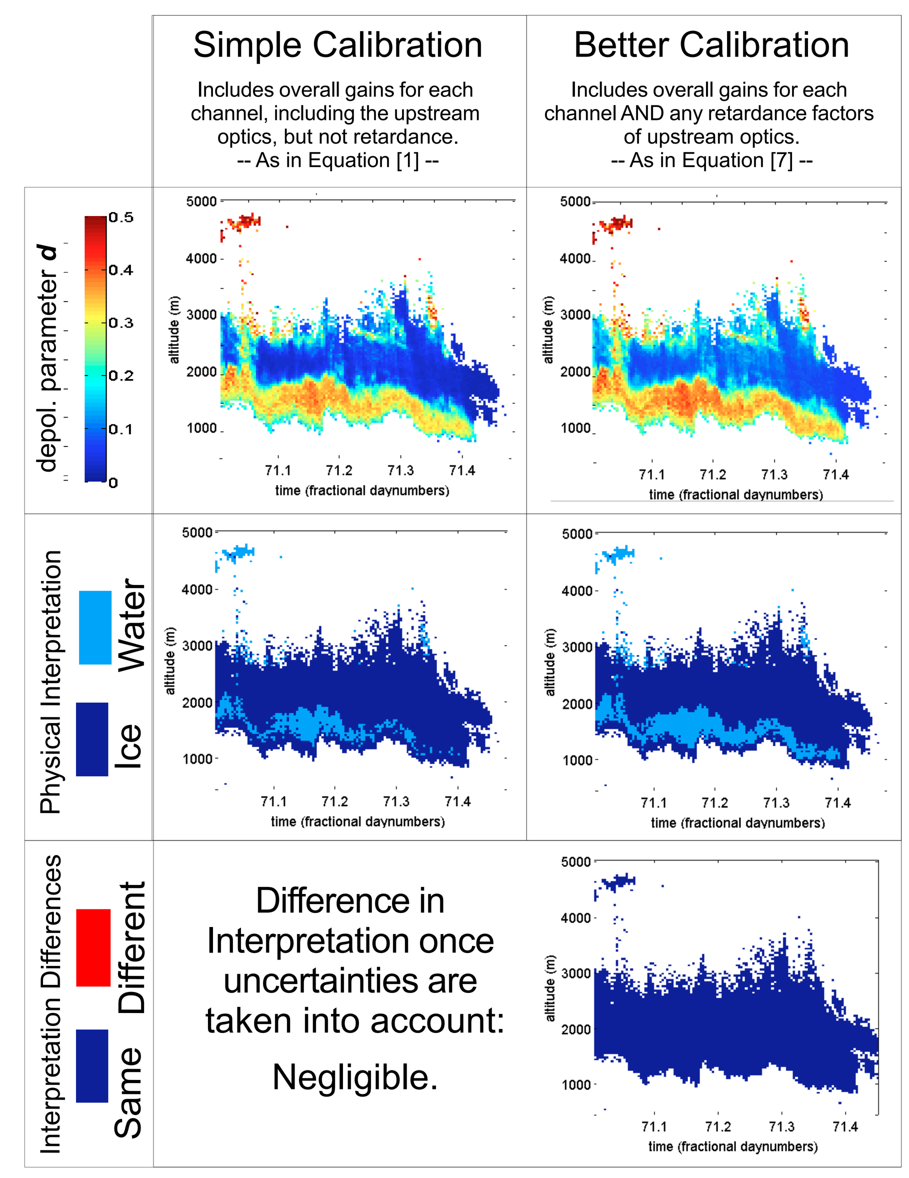


Figure 2 (at left): Depolarization measurements from 12 March 2013 are shown with 5-minute and 37.5-metre resolution. Depolarization parameters (top), and their interpretation as liquid or ice (bottom), are made using increasingly complex calibration methods (left to right).

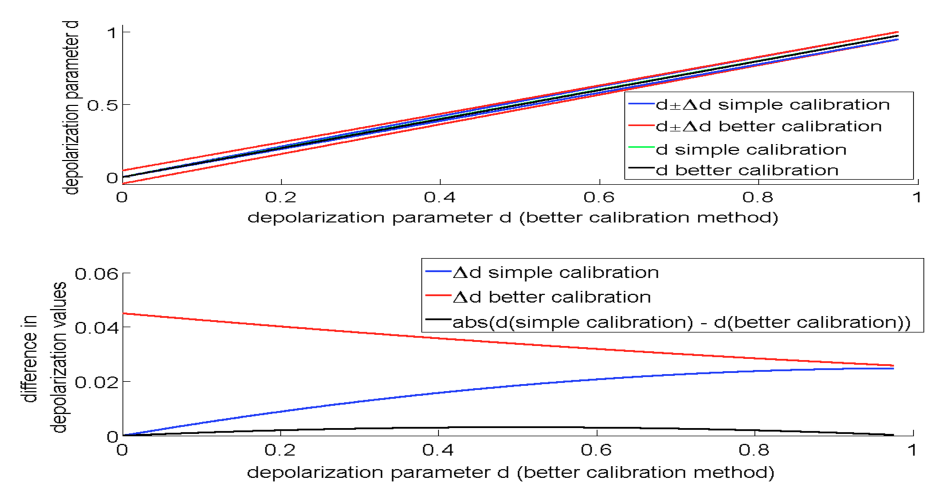


Figure 3 (above): The difference between depolarization parameters retrieved using the simple vs. the more accurate calibration constants is smaller than the uncertainty in the depolarization parameter itself.

New calibration constants show that:

1. Equation [1] is not quite accurate for the CRL (i.e. optics upstream of the polarotor are having effects in addition to constant gains)
2. Nevertheless, this has a negligible effect on the interpretation of cloud particle phase.

Derivation of the depolarization equations

We can describe light as a Stokes vector [1x4] and any optical components as [4x4] matrices.

$$\begin{bmatrix} S_{out0} \\ S_{out1} \\ S_{out2} \\ S_{out3} \end{bmatrix} = \begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} S_{in0} \\ S_{in1} \\ S_{in2} \\ S_{in3} \end{bmatrix}$$

Light at the end — Optical Component(s) which do something to the light — Light at the start

1. Start with a vector for light transmitted by the laser to sky
2. Include a matrix to describe how the atmosphere changes the properties of the laser light as it backscatters it (including depolarization parameter *d* which we want to find)
3. Choose instrument matrices to describe how this light is changed by the receiver optics before it hits the detectors
4. End with a new vector for the light received by the PMTs.

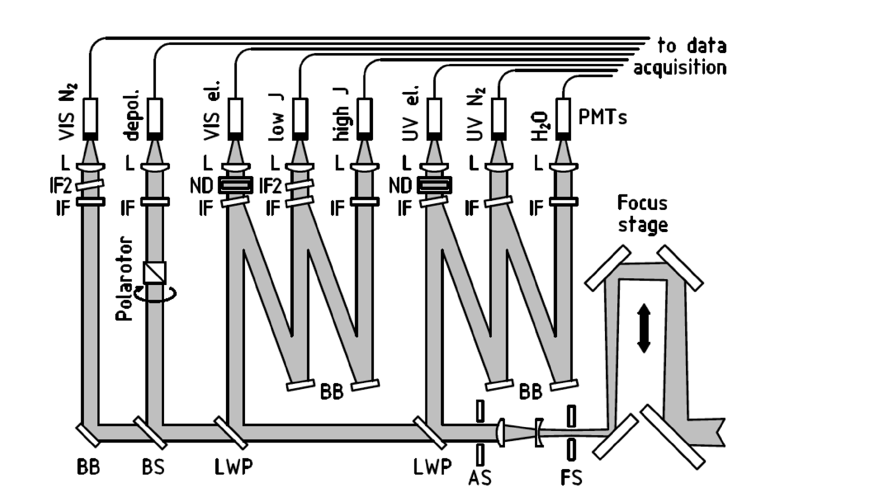


Figure 4: CRL lidar receiver showing all CRL lidar channels, including the depolarization channel with its rotating Licel Polarotor linear polarizer.

Transmitted light vector:

The CRL lidar emits linearly polarized light, with laser intensity I_{laser}:

$$I_{laser} \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix}$$

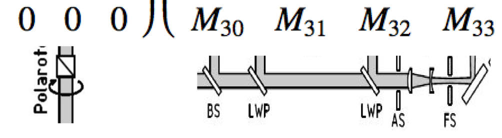
- Intensity (Measured by PMT)
- Linear Pol. in x and y (Not measured directly)
- Linear Pol. in +45° and -45° (Not meas. directly)
- Circular Pol. (Not measured directly)

Instrument Matrix (or matrices):

For the CRL receiver (Figure 4), we specify the polarotor and PMT(photomultiplier tube) optics as one Mueller matrix for each polarotor position, and the rest of the upstream optics as another Mueller matrix (beamsplitters, LWP filters, etc).

Here are the instrument matrices for the Parallel channel:

$$\frac{G_\|}{2} \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} M_{00} & M_{01} & M_{02} & M_{03} \\ M_{10} & M_{11} & M_{12} & M_{13} \\ M_{20} & M_{21} & M_{22} & M_{23} \\ M_{30} & M_{31} & M_{32} & M_{33} \end{pmatrix}$$



Gain of PMT (Same for Parallel and Perpendicular) — Polarotor in Parallel position — "Upstream Optics" in common for both depol channels

We find that equations [1] and [2] are precisely valid ONLY in the case where :

$$M_{00} = M_{11} \quad \text{and} \quad M_{01} = M_{10}$$

Calibrations assuming these conditions are called the "simple calibration method" in this poster.

Atmospheric Matrix:

Particles in the sky which backscatter the laser light are described by the following matrix:

$$[3]\quad M_{atm} = b \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1-d & 0 & 0 \\ 0 & 0 & d-1 & 0 \\ 0 & 0 & 0 & 2d-1 \end{pmatrix}$$

The value *d* is the depolarization factor, and describes the extent to which the transmitted light has been depolarized by the atmosphere. It varies between 0 (no depolarization) and 1 (complete depolarization). The value *b* is a constant.

Matrix equation for the entire system:

To find the value *d*, we can make several matrix equations using our parallel and perpendicular channels, such as:

$$[4]\quad I_\| = \frac{G_\|}{2} \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} M_{00} & M_{01} & M_{02} & M_{03} \\ M_{10} & M_{11} & M_{12} & M_{13} \\ M_{20} & M_{21} & M_{22} & M_{23} \\ M_{30} & M_{31} & M_{32} & M_{33} \end{pmatrix} b \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1-d & 0 & 0 \\ 0 & 0 & d-1 & 0 \\ 0 & 0 & 0 & 2d-1 \end{pmatrix} I_{laser} \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix}$$

We measure the first term of the resulting vector as the signal in a particular channel:

$$[5]\quad S_\| = \frac{G_\| b I_{laser}}{2}(M_{00} + M_{10} + (M_{01} + M_{11})(1-d)) \qquad [6]\quad S_\perp = \frac{G_\perp b I_{laser}}{2}(M_{00} - M_{10} + (M_{01} - M_{11})(1-d))$$

The value *d* can be calculated as follows:

$$[7]\quad d = 1 - \frac{\frac{M_{10}}{M_{00}}\left(1 + \frac{S_\perp}{S_\|}\right) - \left(1 - \frac{S_\perp}{S_\|}\right)}{\frac{M_{01}}{M_{00}}\left(1 - \frac{S_\perp}{S_\|}\right) - \frac{M_{11}}{M_{00}}\left(1 + \frac{S_\perp}{S_\|}\right)}$$

Because the CRL uses a single PMT for both channels the PMT gain in each is identical, and therefore, $G_\| = G_\perp$.

To calculate d, we need only to calibrate for three constants:

$$\frac{M_{01}}{M_{00}} \; ; \; \frac{M_{10}}{M_{00}} \; ; \; \frac{M_{11}}{M_{00}}$$

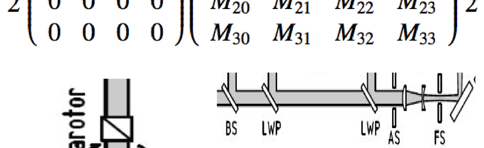
Determining the calibration constants M_{01}/M_{00}, M_{10}/M_{00} and M_{11}/M_{00}

We can get new equations for calibration by illuminating the receiver with light of a known polarization. We do this using a depolarizer and/or an extra linear polarizer as close to the beginning of the receiver as possible.

Using polarized calibration light

An extra linear polarizer is used after the lamp and depolarizing Glassine sheet. As it is rotated, light of various known polarizations is introduced into the lidar receiver. The Glassine ensures that the light entering the polarizer does not vary during the test (in case calibration lamp is itself polarized).

$$[12]\quad \begin{pmatrix} S_{out0} \\ S_{out1} \\ S_{out2} \\ S_{out3} \end{pmatrix}_\| = \frac{1}{2} \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} M_{00} & M_{01} & M_{02} & M_{03} \\ M_{10} & M_{11} & M_{12} & M_{13} \\ M_{20} & M_{21} & M_{22} & M_{23} \\ M_{30} & M_{31} & M_{32} & M_{33} \end{pmatrix} \frac{1}{2} \begin{pmatrix} 1 & cos2\theta & sin2\theta & 0 \\ cos2\theta & cos^2 2\theta & \frac{1}{2}sin4\theta & 0 \\ sin2\theta & \frac{1}{2}sin4\theta & sin^2 2\theta & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} I_{lamp}$$



Polarotor in Parallel position — "Upstream Optics" that are the same for both depol channels

Polarizer at angle ϴ

Lamp with Depolarizing Sheet

Measurements at many angles ϴ give two equations for signals:

$$[13]\quad S_{\|\theta} = \frac{I_{lamp}}{4}(M_{00} + M_{10} + (M_{01} + M_{11})cos2\theta + (M_{02} + M_{12})sin2\theta)$$

$$[14]\quad S_{\perp\theta} = \frac{I_{lamp}}{4}(M_{00} - M_{10} + (M_{01} - M_{11})cos2\theta + (M_{02} - M_{12})sin2\theta)$$

Simplification

An assessment of the measurements shown in Figure 11 (at right) shows that the terms $M_{02} = M_{12} = 0$ for the CRL lidar. This is demonstrated by the symmetry in the measurement (i.e. the values at ϴ = 0.25π equal those at ϴ = 0.75π for both the parallel and perpendicular channels).

Combine to find a single equation

Equations 13 and 14 both contain all three calibration constants, but they also include the GbI_{laser}, which we do not particularly want. If we combine the equations 13 and 14, and make the simplification from above, we can make a third equation which includes only constants that we seek:

$$[15]\quad \frac{S_{\|\theta} - S_{\perp\theta}}{S_{\|\theta} + S_{\perp\theta}} = \frac{\frac{M_{10}}{M_{00}} + \frac{M_{11}}{M_{00}} cos2\theta}{1 + \frac{M_{01}}{M_{00}} cos2\theta}$$

Fitting equation 15

Many combinations of M_{01}/M_{00}, M_{10}/M_{00} and M_{11}/M_{00} were used to find the weighted-least-squares best fit to [15].

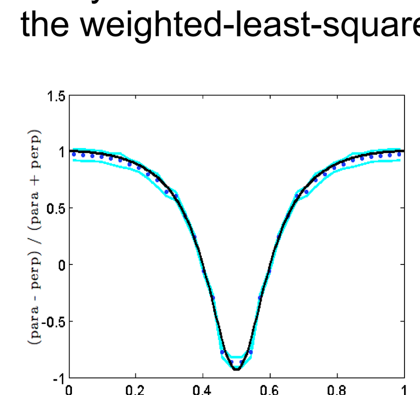


Figure 5: Polarized calibration measurements from equation 15 (blue points; LHS of equation) with the best fit line (black; RHS of equation) as a function of incident light polarization angle. Angle ϴ = 0π is completely parallel; ϴ = 0.5π is completely perpendicular. The best fit line falls entirely within ± 1σ of the measurement (cyan).

Checking with equations 13 & 14

These fit values were checked with [13] and [14]. Looping through various values of GbI_{laser} ensured that the original data could be reproduced using the parameters found in the fit to [15].

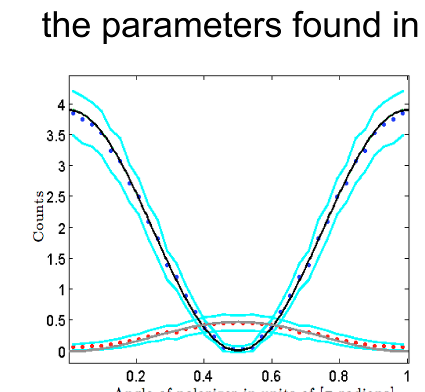


Figure 6: Polarized calibration measurements as a function of incident light polarization angle. Angle ϴ = 0π is completely parallel; ϴ = 0.5π is completely perpendicular. The best fits to parallel measurements (blue dots; black line) and perpendicular measurements (red dots; grey line) are shown. The best fit lines fall entirely within ± 1σ of the measurements (cyan).

Results of fitting

$$\frac{M_{01}}{M_{00}} = 0.756 \pm 0.01$$

$$\frac{M_{10}}{M_{00}} = 0.778 \pm 0.01$$

$M_{01} \neq M_{10}$ to within uncertainty

$$\frac{M_{11}}{M_{00}} = 0.978 \pm 0.01$$

$M_{11} \neq M_{00}$ to within uncertainty

Based on these calibration coefficients, we do not expect depolarization parameters calculated using equation [1] to be quite correct.

Equation [7] should give slightly more accurate depolarization parameter results.

Effects on depolarization ratio measurements

These effects are SMALL for the CRL lidar; smaller than uncertainty in d. A comparison for one night of lidar measurement at the CRL is given in the top-right panel of this poster to show the negligible effect of a more complete calibration versus a simple calibration.

Correspondence:

Emily McCullough
Department of Physics and Astronomy
The University of Western Ontario
London, ON N6A 2K7
519-661-2111 ext. 86554
emccull2@uwo.ca

References: [1] Gimmestad, G. G. Reexamination of depolarization in lidar measurements, Applied Optics, 2008. See references therein for development of the matrix in Equation 3.

Author Affiliations:
[1]Department of Physics and Astronomy, The University of Western Ontario, Canada.
[2]Department of Physics and Atmospheric Science, Dalhousie University, Canada.
[3]Department of Physics, University of Toronto, Canada.

Special thanks to: Dr. Pierre Fogal and the station staff at Eureka Weather Station.

We gratefully acknowledge the financial and logistical support provided by: