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# Exact and near backscattering measurements of the linear depolarisation ratio of various ice crystal habits generated in a laboratory cloud chamber

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ABSTRACT

Ice clouds were generated in the Manchester Ice Cloud Chamber (MICC), and the backscattering linear depolarisation ratio, $\delta$, was measured for a variety of habits. To create an assortment of particle morphologies, the humidity in the chamber was varied throughout each experiment, resulting in a range of habits from the pristine to the complex. This technique was repeated at three temperatures: $-7\,°\mathrm{C}$, $-15\,°\mathrm{C}$ and $-30\,°\mathrm{C}$, in order to produce both solid and hollow columns, plates, sectored plates and dendrites. A linearly polarised 532 nm continuous wave diode laser was directed through a section of the cloud using a non-polarising 50:50 beam splitter. Measurements of the scattered light were taken at 178°, 179° and 180°, using a Glan–Taylor prism to separate the co- and cross-polarised components. The intensities of these components were measured using two amplified photodetectors and the ratio of the cross- to co-polarised intensities was measured to find the linear depolarisation ratio. In general, it was found that Ray Tracing over-predicts the linear depolarisation ratio. However, by creating more accurate particle models which better represent the internal structure of ice particles, discrepancies between measured and modelled results (based on Ray Tracing) were reduced.

## 1. Introduction

The recent meeting of the Intergovernmental Panel on Climate Change highlighted the role of clouds in the Earth's atmosphere as one of the biggest uncertainties in predicting climate change today [1]. One such cloud type that adds to the uncertainty in predicting climate change is cirrus. This is because the net radiative effect of cirrus can be positive or negative, and the direction and the magnitude of this forcing is highly sensitive to the microphysical properties of the constituent ice particles [2–4]. Such particle properties are typically investigated with the use of Optical Array Probes (OAPs), which use optical arrays to capture 2 dimensional particle images. OAPs include the Stratton Park Engineering Company's Cloud Particle Imager (CPI) [5], the 2 Dimensional Stereo probe (2D-S) [6], the Cloud Imaging Probe (CIP) and the Precipitation Imaging Probe (PIP) by Droplet Measurement Technologies (DMT) [7]. These probes have been used both in situ and in laboratory experiments for the counting, sizing and habit classification of ice particles [8–11]. Although successful in characterising larger particles, the discrete pixel size of the array limits the image resolution, meaning that smaller particles (below 80 μm) cannot be accurately categorised. Small ice crystals in cirrus can be influential on the bulk optical properties of the cloud and therefore the accurate counting and sizing of these smaller particles is crucial [11]. Furthermore, the measurement of other atmospheric

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particulates is necessary, not only for determining their optical properties but also due to their role in cloud formation and evolution [12–14]. These small particles cannot be measured using OAPs and therefore other techniques must be employed.

In addition to imaging probes, there currently exists a range of in situ instrumentation, which use singly-scattered light to determine information about the scattering particle. Forward scattering probes, such as the Forward Scattering Spectrometer Probe (FSSP) by Particle Measurement Systems (PMS) [15,16], and the Cloud Droplet Probe (CDP) by DMT [17], measure scattered intensities in a given angular range in the forward direction. These measurements are used to count and size particles based on a Mie approximation for homogeneous spheres. Ice and aerosol particles are generally nonspherical and may also be inhomogeneous, thus limiting the accuracy of forward scattering probes for the sizing of nonspherical particles. The ability to determine particle asphericity is a useful tool, not only for particle sizing but for the determination of thermodynamic phase (by discriminating droplets from small ice). One probe which can differentiate between spherical and nonspherical particles is the Small Ice Detector 3 (SID-3). While this instrument also gathers forward scattered light in the 6–25° range, the optical array is used to capture the 2 dimensional scattering pattern. This pattern can be used not only to size the particle, but also to estimate the particle habit and the surface roughness [18,19]. Near backscattered light is also measured by certain in situ instrumentation such as DMT's CAS-DPOL [20], and Cloud Particle Spectrometer with Polarization Detection (CPSPD) [21] instruments, which measure the linear depolarisation ratio of the scattered light [22,23]. Ice particles depolarise the incident light by internal reflection, effectively rotating the vibration plane of the incident beam. Therefore faceted particles such as ice are more strongly depolarising than water droplets, with measurements of linear depolarisation ratio typically an order of magnitude higher for ice clouds compared with water clouds [24,25]. Measurements from the CAS-DPOL and CPSPD can therefore be used for determining particle asphericity, and in the discrimination of liquid water from ice. Further to in situ instrumentation, ground and space based remote sensing relies on scattered signals to determine particle properties [26–30]. The backscattering linear depolarisation ratio has long been used by LIDAR instruments/analysis to determine the thermodynamic phase, size, orientation and habit of cloud particles.

Each of the instruments discussed so far uses measurements of scattered light to determine microphysical properties based on comparisons to current theoretical or observational data. However, discrepancies between measured and modelled results exist. LIDAR measurements of linear depolarisation ratio in cirrus are typically lower than those predicted by theory [31]. These observations have previously been attributed to preferential crystal orientation and the presence of liquid water [31]. However, interpretations of these data usually rely on simulations from Ray Tracing, where highly idealised particles are assumed [27]. Particle complexities such as inclusions, cavities and surface roughness are known to affect the single scattering properties of ice particles [32–36]. Theoretical studies have shown that indentations on the basal facets (frequently seen in laboratory, in situ and ground based studies in the form of 'hollow' columns) act to significantly reduce the linear depolarisation ratio [37,38]. Similar results were shown during laboratory experiments in the Aerosol Interaction and Dynamics in the Atmosphere (AIDA) chamber where low depolarisation ratios of 0.1–0.15 were recorded using the Scattering Intensity Measurement for the Optical detectioN of icE (SIMONE) instrument for a cloud comprised predominantly of hollow columns [39]. By comparison, a cloud composed of solid crystals was measured to have significantly higher depolarisation ratios of 0.3 [39]. By incorporating these particle cavities (along with further complexities such as inclusions and particle roughness) geometric particle models may be improved, thus yielding more realistic values of linear depolarisation ratio from Ray Tracing simulations.

From the current literature, we see that different scattering angles, and different elements of the scattering phase matrix can hold information about particular microphysical properties. Therefore the development and use of scattering instrumentation (both in situ and remote) may contribute a plethora of useful information to supplement data gathered from 2D imaging probes. Of interest here is the linear depolarisation ratio which is typically measured at near back-scattering angles to determine particle sphericity (and thus discriminate between ice and liquid water). Further controlled measurements are therefore useful in examining the sensitivity of linear depolarisation ratio on various microphysical characteristics, and also to test the ability of scattering models to recreate these results. In the work presented here, the linear depolarisation ratios were measured experimentally for a variety of ice crystal habits at scattering angles of 178°, 179° and 180° at temperatures between $-7\,^{\circ}\mathrm{C}$ and $-30\,^{\circ}\mathrm{C}$. Measured depolarisation ratios are presented for several habits including solid and hollow columns, plates, sectored plates and dendrites. These results are compared with modelled results from Ray Tracing [40], and the applicability of this scattering model is discussed.

## 2. Methods

### 2.1. Experimental methods

#### 2.1.1. Production of the cloud

This work was conducted in the Manchester Ice Cloud Chamber (MICC) as described in previous papers [32,10]. The cloud chamber is a 10 m tall by 1 m diameter cylindrical fall tube which is housed over three floors, in three stacked cold rooms. The chamber can maintain temperatures down to $-50\,^{\circ}\mathrm{C}$, and the temperature is monitored via 10 equidistant thermocouples which are placed along the length of the chamber.

For this particular experiment, the chamber is humidified using a water boiler, which introduces water vapour near the centre of the chamber as shown in Fig. 1. After the chamber has been humidified, the boiler is switched off; ice is then nucleated at the top of the chamber using the 'air popper' technique [32,10,41]. The air popper utilises a