

A light scattering instrument for investigating cloud ice microcrystal morphology

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Abstract

We describe an optical scattering instrument designed to assess the shapes and sizes of microscopic atmospheric cloud particles, especially the smallest ice crystals that can profoundly affect cloud processes and radiative properties yet cannot be seen clearly using in situ cloud particle imaging probes. The new instrument captures high-resolution spatial light scattering patterns from individual particles down to $\sim 1 \mu\text{m}$ in size passing through a laser beam. Its significance lies in the ability of these patterns to provide morphological data for particle sizes well below the optical resolution limits of current probes.

1 Introduction

Clouds influence climate through radiative (scattering and absorption of solar and thermal radiation) and other physical processes that impact on the Earth's radiation budget and alter the magnitude of the climate change. Such cloud feedbacks are a source of significant uncertainty in climate models. Indeed, the Intergovernmental Panel on Climate Change (IPCC 2007) reiterated their view that 'cloud feedbacks remain the largest source of uncertainty' [1]. These uncertainties are especially acute for ice or mixed-phase clouds (the latter comprising both ice crystals and super-cooled droplets) since the radiative properties of such clouds are radically dependent upon the relative abundance of crystals and droplets, their size spectra and, in particular, the diverse crystal shapes present [2]. To be able to understand the radiative transfer properties of ice and mixed phase clouds, therefore, a detailed knowledge of the particles' shapes and sizes is required [3]. This is especially true for the smallest ice crystals (sub- $20 \mu\text{m}$) for which there is evidence of widespread abundance in cirrus clouds [4,5]. Detailed knowledge of these crystals is also crucial to space-borne remote sensing for the retrieval of cirrus properties [5].

A currently used instrument for capturing in-situ cloud ice crystal morphological data is the Cloud Particle Imager, CPI [6]. This uses pulsed laser illumination to capture real images of cloud particles on a CCD (charge coupled device) camera. It provides extremely valuable data for particles larger than $\sim 25 \mu\text{m}$, but below this, diffraction, optical aberrations, and constrained depth-of-field make detailed assessment of particle shape impractical. To gain insight into the shapes and structures of cloud particles smaller than this, an alternative approach must therefore be employed.

2 Spatial light scattering

Any discrete particle will scatter light spatially in a pattern dependent on its size, shape, orientation and internal structure (and on the wavelength and polarization of the incident light). These patterns are not bound by depth-of-field and optical resolution constraints common to imaging systems and can therefore yield data on particle shapes for much smaller particles (\sim wavelength of the incident light). We have previously employed this approach in the Small Ice Detector (SID1) [8], a wing-mounted probe that employs six discrete optical detectors arranged around a laser beam to capture the azimuthal distribution of light scattered by individual cloud particles passing through the beam. Since spherical droplets scattered equally to all detectors whilst non-spherical ice crystals produced unequal responses, discrimination between these particle classes can be readily achieved. However, with such limited spatial resolution, the light scattering data can reveal little about each crystal's actual shape and structure.

3 Particle Phase Discriminator, PPD1

In contrast, the new Particle Phase Discriminator instrument (PPD1) is capable of capturing high-resolution spatial light scattering patterns from individual atmospheric ice crystals down to $\sim 1 \mu\text{m}$ in size. The instrument has been designed for use in either an atmospheric research aircraft, drawing ambient atmospheric air through specially designed fuselage ports, or with laboratory-based cloud simulation chambers. A wing-mounted variant of the instrument has also been developed.

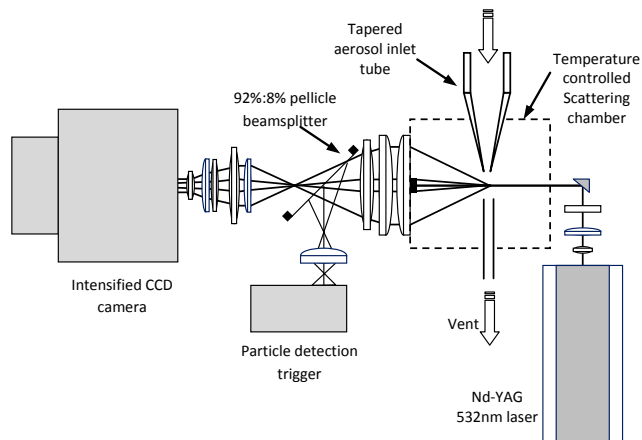


Figure 1. Schematic of PPD1 ice crystal scattering instrument

The instrument, shown schematically in Fig. 1, employs a gated intensified charge coupled device camera (ICCD) to record particle light scattering patterns with single photon sensitivity across 582×582 pixels. In operation, particle-laden sample air flows through a tapered thermally-controlled nozzle at typically 15 l min^{-1} ($\sim 80 \text{ ms}^{-1}$), although a much wider range of flow rates can be accommodated. The sample flow has a diameter of $\sim 2.5 \text{ mm}$ when it exits the nozzle and crosses the beam from a 150 mW 532 nm Nd-YAG laser (Crystalaser Inc., Reno, NV). The beam has an elliptical cross-section of 4.5 mm width and $120 \mu\text{m}$ depth and is circularly polarized to minimize polarization-dependent variations in the captured particle scattering patterns.

Receiving optics collect the scattered light over scattering angles from 6° to 25° , sufficient to encompass the classic 22° halo scattering from hexagonal ice particles. This light is then split 92:8 by a pellicle beamsplitter, the smaller proportion being directed to a photomultiplier module (Hamamatsu H6779) to allow both estimation of the particle size and to trigger the scattering pattern capture on the ICCD camera (Photek Ltd., East Sussex, UK). The estimated particle size is expressed, as with many conventional optical particle counters (OPCs), as the size of a spherical particle of known refractive index that would produce the same signal as the particle in question. For particles of regular geometric form, such as spherical droplets, ice columns, or platelets, a more accurate determination of particle size may be achieved from theoretical inversion of the captured scattering pattern images (see below).

The scattering pattern acquisition rate is $\sim 20 \text{ s}^{-1}$ (50 s^{-1} in burst mode). All other particles passing through the scattering volume are counted and sized (as described above) with the data transmitted at user-defined intervals (typically 100 ms) to a host computer in the form of 16-channel size histograms. Fig. 2 illustrates some of the numerous classes of scattering pattern captured in preliminary experiments at the University of Manchester Icing Cloud Chamber, a 10m fall tube in which ice cloud properties and crystal growth can be studied over temperatures down to -50°C .

The top row shows scattering images from water droplets of increasing size from $3.5 \mu\text{m}$ to $22 \mu\text{m}$ (determined by comparison with Mie Theory); row 2 illustrates classical scattering from hexagonal ice columns, exhibiting the bright 22° halo spot; row 3 may originate from freezing droplets exhibiting one or more ice facets, as observed experimentally for larger droplets up to $\sim 100 \mu\text{m}$ by Takahashi and Mori [9]; row 4 corresponds to hexagonal ice platelets; row 5 images exhibit features that they may result from

partially sublimated platelets in which the sharp crystal apices have become rounded.

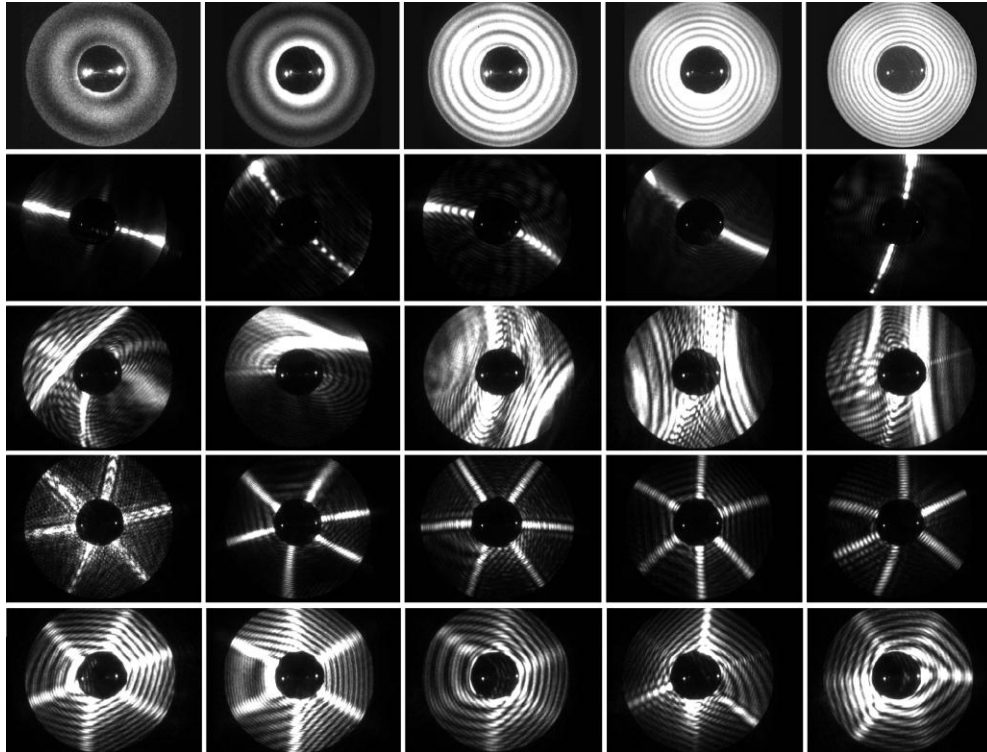


Figure 2. Droplet (top row) and ice crystal scattering patterns.

The scattering pattern images offer unique insights into the diverse habits of cloud ice crystals too small to be resolved by current cloud probes. However, whilst conventional pattern recognition methods may be readily used to group recorded images into broad ice habit classes such as those indicated in Fig. 2, more detailed theoretical inversion of the patterns is required to yield quantitative morphological data. This challenge is currently being addressed by the authors and others through both advancements in modeling [10,11] and by reference to scattering from known particles such as ice analogs [12,13]. Fig. 3 illustrates this modeling approach, showing two experimental patterns from Fig.2, each with its best-fit theoretical interpretation derived using Ray Tracing and Diffraction on Facets (RTDF) theory [10,11], and the corresponding particle shape and orientation (assuming beam direction into paper). The first corresponds to a hexagonal ice column 16 μm length and 7 μm across flats; the second, to a hexagonal ice platelet, 10 μm height and 43 μm across flats. The RTDF theory is still under development but already allows good assessment of size as well as shape for both pristine and complex ice crystals such as rosettes, despite not yet replicating some finer interference features of the experimental patterns.

4 Conclusion

We anticipate that advancement of theoretical scattering models will ultimately allow inversion of patterns for even imperfect (but realistic) ice crystals having rounded facets and/or rough surfaces. Until this is achieved, we are undertaking the parameterization of patterns from such morphologies by comparison with scattering patterns from ice crystal analogs of accurately known shape and structure [13]. With the ongoing improvement in inversion and interpretation of the scattering patterns, we hope that the resulting, previously unattainable, data on microscopic cloud particle shape, size and relative abundance will aid understanding of these particles' roles in cloud microphysical and radiative processes, and ultimately their effect on climate.

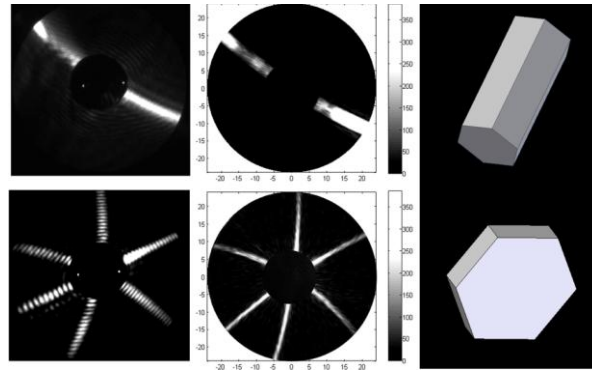


Figure 3. Experimental scattering pattern (left) with matching RTDF theory and corresponding crystal shape for ice column and ice platelet.

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