Polar nephelometer for light-scattering measurements of ice crystals

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We report on a small, lightweight polar nephelometer for the measurement of the light-scattering properties of cloud particles, specifically designed for use on a balloonborne platform in cirrus cloud conditions. The instrument consists of 33 fiber-optic light guides positioned in a two-dimensional plane from 5° to 175° that direct the scattered light to photodiode detectors–amplifier units. The system uses an onboard computer and data acquisition card to collect and store the measured signals. The instrument’s calibration is tested by measurement of light scattered into a two-dimensional plane from small water droplets generated by an ultrasonic humidifier. Excellent comparisons between the measured water-droplet scattering properties and expectations generated by Mie calculation are shown. The measured scattering properties of ice crystals generated in a cold chamber also compare reasonably well with the theoretical results based on calculations from a unified theory of light scattering by ice crystals that use the particle size distribution measured in the chamber. © 2001 Optical Society of America

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Cirrus clouds are composed of ice crystals that generally have hexagonal shapes that vary in both time and space from simple plates and columns to complex hexagonal shapes, such as aggregates and bullet rosettes. The manner in which sunlight interacts with ice crystals is dependent on the crystals’ size, shape, and orientation with respect to the incident light direction. In recent years, through theoretical and numerical efforts, it has become possible to determine the scattering-phase function of these nonspherical ice particles,1–3 which describes the three-dimensional single-scattering intensity distribution. The scattering-phase functions are highly dependent on the crystal habit and orientation. For remote-sensing applications, it is imperative to have proper phase-function information to develop reliable methods for the retrieval of the optical and microphysical properties of ice clouds, based on bidirectional reflectance measurements from space.1 We have designed an instrument for the purpose of measuring the scattering properties in a two-dimensional plane of ice crystals that occur in the atmosphere.

Polar nephelometers have been used to measure the scattering properties of ice-cloud particles in a laboratory setting.5,6 Successful use of nephelometers in aircraft has been limited.7,8 It is our intent to develop an instrument that one can use on a balloonborne platform to prevent the uncertainties inherent in the scattering measurements of aircraft-based instruments, which are caused by the high speed of the aircraft. Also, since the instrument measures the scattering properties of freely falling particles, information caused by any preferred crystal orientation could be preserved.

As shown in Fig. 1, there are 33 fiber-optic light guides positioned to sense the light that is scattered from particles in a two-dimensional plane from 5° to 175°. The angular displacement of the fiber optics is reduced between 20° to 25° and between 120° and 170°. The fiber light guides have a diameter of 1 mm, and, given the array diameter of 15 cm, each fiber light guide collects a solid angle of approximately $1.4 \times 10^{-4}$ sr. A 3-mm-diameter collimated and unpolarized spherical beam from a small diode laser with a wavelength of 670 nm and a power of 0.95 mW illuminates the scattering sample, which is allowed to fall freely into the center of the fiber-optic sensor array through a small black aluminum tube with an inside diameter of 3 mm. A larger black aluminum tube (5-mm inside diameter) directs the falling crystals out of the bottom of the instrument. The amount of unwanted scattered light in the scattering volume is minimal because of a beam dump that prevents the laser beam from backscattering into the detector array and two three-dimensional light absorbers that are positioned above and below the scattering plane to absorb light that is scattered...
anywhere other than the detector array. The fiber
light guides direct the scattered light to 33 large-area
silicon photodiode detectors with linear amplifiers
that convert the scattered intensities to proportional
voltage signals. A data acquisition card and a PC
with a solid-state hard drive are mounted in the
instrument, allowing one to control, collect, and store
the resulting signals. As the instrument uses only 10 W
of power, it can be operated with batteries. With the
acquisition and averaging of multiple measurements
of each channel to reduce electronic noise, the system
is capable of linearly measuring over 3 decades of
light intensity at 100 full angular measurements per
second. The system determines the presence of water
or ice particles at the scattering center by monitoring
the scattered intensity at the near-forward angles.
It automatically stores the measured voltages when
this signal increases above an experimentally prede-
termined level and the signal level measured at the
side-scattering angles is above the minimum signal
level, as determined by the calibration described
below.

The system is calibrated with a 670-nm laser beam
directed by a fiber light guide to a small, diffuse Teflon
light source, 1.3 cm in diameter, which we constructed
to fit at the scattering center and pivot in a manner
that allows the source to sweep across the fiber-optic
array. When this light source is rotated across the
detector array, it simulates an isotropic light source
when the strongest detected signal is recovered, and
this signal is used to calibrate the detector array via
software-implemented multiplicative adjustments in a
manner similar to that described in Ref. 9. The rela-
tive response between the channels differs by less
than 1% at the upper level of the detector sensitivity,
and a 10% difference in response is designated as
the lower limit of acceptable signal, which provides
over 3 decades of response, well within the expected
dynamic range of scattering from ice particles and
water droplets between the angular detection limits of
the instrument. The amount of light scattered into
the near-forward detectors from the incident laser
beam is minimal and is subtracted from the final
scattering results of all experiments.

The system accuracy is verified by measurement of
the scattering properties of water droplets generated
by a common household ultrasonic humidifier at room
temperature (21 °C), as shown in Fig. 2. The water
droplets falling through the upper sample tube (which
is removed from the instrument and shielded from air
currents) are seen as a collimated and continuous white
stream of particles. As there are no direct measure-
ments of the droplet-size distribution, several mean
effective sizes and variances are generated by Mie cal-
culations and compared with the experimental results.
The experimental results are adjusted to fit the nor-
malized theoretical results by use of a multiplicative
constant in which a log-normal size distribution with
a mean effective radius of 3.75 μm and a variance of
0.1 produces the best match. The error bar of 10% in
Fig. 2 represents the system error at the low intensity
limit of the instrument’s response, whereas the 1% er-ror at the upper end of the instrument’s response is not
shown. Overall, the measurement matches the expec-
tation and accurately reproduces the rainbow feature
at 140°. The small differences are attributed to er-
rors that are not corrected for by the calibration at the
low-intensity range of the instrument response.

The cloud chamber consists of a dry-ice-cooled
stainless-steel box with a volume of 0.288 m³ placed
within a larger Styrofoam-insulated plywood box, and
an ice cloud is formed by injection of small water drops
generated by an ultrasonic humidifier into the cold
chamber. Because the chamber walls are directly
cooled by the dry ice, there is always a large nucleating
surface to produce ice crystals. More information
on the ice-cloud properties and the cloud chamber is
given in Ref. 10. Placing the nephelometer inside this
cloud chamber produces the scattering measurement
shown in Fig. 3. The ice crystals falling through the
sample tube also appear visually as a collimated and
continuous white stream of particles. The ice-crystal
habit is determined from photomicrographs of replicas
such as that shown at the bottom of Fig. 3, which are
formed by the vapor method.11 Because of the cold
temperature of the chamber (≈−30 °C), small irregular
ice crystals with an average mean maximum dimen-
sion of −7.5 μm are observed, with a size distribution
similar to that described in Ref. 10. The theoretical
curve is for randomly oriented irregular bullet rosette
and plate crystals with rough surfaces calculated from
the unified theory of light scattering by ice crystals3
using the measured size distribution. The experimen-
tal results are matched to the expectations with a
multiplicative constant, and the error bar (10%) is
determined as described above. As expected for
nonspherical particles, there is no indication of a
rainbow feature in the reverse direction. The absence
of halo phenomena commonly seen at 22° and 46° is
an indication of the irregular crystal types generated
in the cold chamber. Efforts are under way in the
laboratory to generate ice crystals that are more
representative of those found in nature.

Fig. 2. Experimentally measured two-dimensional scat-
tering properties and the theoretically derived phase
function of water droplets with unpolarized incident light.
We have shown that the measured two-dimensional scattering properties of both laboratory-generated water droplets and ice particles compare well with theoretically derived expectations. We are developing methods to produce scattering measurements of different ice-crystal sizes and shapes in the laboratory for further comparison with theoretical results. The instrument reported here is well suited for in situ measurements on a balloonborne platform, as it is lightweight and can operate autonomously with batteries. We expect to place this instrument aloft in the near future.

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