Ice Particle Size Distributions Measured with an Airborne Digital In-line Holographic Instrument

Jacob P. Fugal and Raymond A. Shaw

1 National Center for Atmospheric Research, Boulder, CO 80027, USA
2 Department of Physics, Michigan Technological University, Houghton, MI 49931, USA

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1. ABSTRACT

Holographic data from the prototype airborne digital holographic probe, HOLODEC 1 (Holographic Detector for Clouds), taken during test flights are digitally reconstructed to obtain the size, three-dimensional position, and two-dimensional profile of ice particles and then ice particle size distributions and number densities are calculated using an automated algorithm with minimal user intervention. The holographic method offers the advantages of a well-defined sample volume size that is not dependent on particle size or airspeed, and offers a unique method of detecting shattered particles. The holographic method also allows the volume sample rate to be increased beyond that of the prototype HOLODEC 1 instrument, limited solely by camera technology.

HOLODEC 1 size distributions taken in mixed-phase regions of cloud compare well to size distributions from a PMS FSSP probe also onboard the aircraft during the test flights. In regions of cloud with nearly pure ice, the HOLODEC size distributions compare better to FSSP size distributions corrected for non-spherical ice particles. A straightforward algorithm for detecting shattered particles utilizing the particles’ three-dimensional positions eliminates the obvious ice particle shattering events from the data set. Resulting size distributions are reduced by approximately a factor of two for particles 25 to 70 µm in equivalent diameter, compared to size distributions of all particles. The comparison with the FSSP under cloud conditions free of large ice particles provides an estimate of the magnitude of shattering biases in the FSSP and a correction for the FSSP’s calibration for particle sizing.

2. HOLOGRAPHY VS. OTHER METHODS TO MEASURE CLOUD ICE PARTICLES
Accurate ice particle size distributions and number densities are necessary for understanding and modeling cloud processes such as precipitation formation and radiative transfer, and for validation of remote sensing and satellite measurements. Many methods and instruments have been devised to measure ice particles, yet there is still considerable uncertainty in measuring small (less than about 100 µm) ice particles (Baum et al., 2005; McFarquhar et al., 2007). Beyond the inherent uncertainty in counting statistics, the uncertainty in small ice size distributions results primarily from poorly defined sample volumes, instrument particle-size resolution limits, and instrument-induced ice particle breakup.

Remedies for some of these problems exist: for example, given certain assumptions FSSP size measurements can be corrected for ice, effective instrument resolution can be improved via post-processing (Korolev, 2007), and instrument housings can be modified to reduce shattering (Field et al., 2003b). Furthermore, new instruments are being developed to measure small ice particles without some of these problems, such as the Small Ice Detector (SID) (Field et al., 2003a) and the SPEC 2D-S (Stereo) probe (Lawson et al., 2006). The SID probe measures light scattered by ice particles at many angles, and can yield ice particle size and crystal habit within the size range of approximately 1 to 50 µm. The SPEC 2D-S (Stereo) optical array probe can measure cloud particle size and a two-dimensional (sometimes three-dimensional) profile in the size range of about 10 to 1000 um.

Digital holography is one of several approaches that allows for improvements in the measurement of ice size distributions. In this abstract, we briefly present some results from the Holographic Detector for Clouds (HOLODEC) 1, which is a prototype airborne digital holographic instrument. In relation to the existing uncertainties, holography has the benefit of providing a well-defined sample volume, a uniform and well-defined resolution, and three-dimensional spatial information that can assist in identifying shattered crystals. The difficulty of using digital holography is the added complexity in data processing, which includes digital reconstruction and particle detection.

In the rest of this abstract, we show size distributions taken during the 2003-09-17 Research Flight of the IDEAS 3 field campaign conducted in the Colorado area during August and September 2003 (Fugal et al., 2004). Holograms were reconstructed via commonly used methods (Fugal et al., 2004; Kim and Lee, 2007; Kreis et al., 1997) as further detailed in Fugal et al. (2008). The reconstruction of about 10,000 holograms was done in about 6 days on a 32 processor computer cluster using MATLAB cluster computing software running on a Ubuntu Linux operating system. The next section discusses the cloud environmental conditions in which these holograms were taken using measurements from other instrument aboard the aircraft. The final section shows several results from this single flight.

3. DATA SAMPLE

Here we show the cloud environmental conditions in which the HOLODEC 1 instrument aboard the U.S. National Center for Atmospheric Research C-130 Hercules Q aircraft obtained holograms during Research Flight 2003-09-17. Figure 1 shows the altitude, temperature, and dewpoint during the time period during which we show results from HOLODEC 1 holograms. The bars in the figure (also shown
in Figures 2 and 3) show times for which size distributions in Figure 4 are calculated. The black dots in this Figure show times during which we obtained good holograms (also in Figures 2 and 3). Figure 2 shows total and liquid water content as measured by the Nevzorov probe showing when we expect nearly all ice or mixed ice and liquid water cloud particles. While the King probe might be preferable to indicate ice or mixed-phase clouds, it’s data quality from this flight was too poor to use in data analysis. Finally, Figure 3 shows 2D-C and FSSP number densities for both data sets as well as times at which HOLODEC 1 recorded good holograms. These time periods are of interest as the low number densities of the 2D-C instrument indicate that there are few large ice particles to shatter on the leading probe parts, and the high number densities of the FSSP indicate we should have measurable number densities of ice particles to compare between the FSSP and HOLODEC probes.

4. RESULTS

After reconstructing the holograms of cloud particles, we have the three-dimensional position of each particle, its two-dimensional profile, and its size. The shattering detection algorithm utilizes the three-dimensional position information of the ice particles to search for extremely localized clusters of ice particles. These clusters are most probably shards of larger particles having impacted on leading probe housing and are swept along an aerodynamic surface that intersects the sample volume. Holograms with these clusters of ice particles are excluded from the size distributions and number densities shown as blue squares in Figures 4 and 5.

Also, we’ve attempted to correct reported FSSP size distributions which are calibrated for spherical water droplets to randomly oriented droxtal shaped (a type of faceted sphere) ice particles (Yang et al., 2003; Zhang et al., 2004). The correction is only approximate as ice particles appear in many habits and surface conditions. This approximate correction aids in estimating actual size distributions, and, in our case, comparing size distributions of ice particles (Field et al., 2003a).

Figure 4 compares HOLODEC 1 size distributions for all particles, and excluding shattered particles with FSSP size distributions for both uncorrected and ice-corrected size distributions. Note in row (a) that the ice-corrected distribution matches much better than the uncorrected. Row (b) has neither FSSP uncorrected or ice-corrected matching very well, but row (c) has the uncorrected distribution comparing the best. This is consistent with the Nevzorov probe measurements in Figure 2 with nearly pure ice appearing in time period (a) and mixed phase occurring in time periods (b) and (c). The temperatures in Figure 1 also shows time periods (b) and (c) being warmer and at lower altitudes than time period (a). Figure 5 shows the number density of all detected particles as a time series in comparison with the FSSP number densities with the approximate correction for ice particles. The corrected FSSP number densities compare well earlier in the time series where the particles are nearly pure ice, and worse in the time period when the cloud is warmer and mixed phase. Note that the rejected shattered particles (difference of green pentagrams and blue squares) are typically no more than approximately 50% of all particles in the time series.

Finally, Figure 6 shows some of the reconstructed ice particle images of various sizes as reconstructed by the automated particle finding algorithm. This figure shows the quality of reconstructed...
Figure 1: Altitude, temperature and dewpoint during times of which good holograms were taken and reconstructed for the 2003-09-17 Research Flight. The labels in brackets from (a) to (c) correspond to size distribution panels in Figure 4.

particle images in holograms. It also gives evidence than an automated particle finding algorithm can correctly find the particle position without user intervention even for large complex-shaped particles. This is critical for an instrument such as HOLODEC 1 to be useful for routine cloud particle measurements in the field.

5. CONCLUSION
We have shown that the HOLODEC 1 instrument and its associated automated hologram processing routines can produce size distributions of cloud ice particles in the size range of 25 µm to about 100 µm comparable to that of other commonly used instruments such as the FSSP. It can distinguish ice and water particles when they are large enough (∼ 100 µm) to distinguish by shape. It can detect shattered events based on the three-dimensional spatial distributions of cloud ice particles and searching for anomalously high local concentrations of these particles. Finally, we have shown that the automated hologram processing routine can find the position, shape and size of even the larger particles. Future versions of this instrument would be improved by including a camera with a much higher and/or larger image size and therefore have a larger volume sample rate which would yield better statistics in number densities of the larger particles.

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Figure 2: Total, liquid, and ice (total minus liquid) water content for the 2003-09-17 Research Flight. The labels in brackets from (a) to (c) correspond to size distribution panels in Figure 4.

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Figure 3: Particle number densities from the FSSP and the 2D-C probes from the 2003-09-17 Research Flight. Also shown are the times where HOLODEC recorded clear holograms. The labels in brackets from (a) to (c) correspond to size distribution panels in Figure 4.


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Figure 4: Size distributions for the time shown above each plot as is the number $N$ of particles used to figure the HOLODEC 1 total size distribution. The red circles show the FSSP size distributions, the green pentagrams and error bars show the HOLODEC 1 size distributions, and the blue squares show the HOLODEC 1 size distributions with the holograms with shattered particles excluded. The left column shows FSSP size distributions as calibrated for spherical water droplets. The right column shows FSSP sizes corrected for randomly oriented droxtal (a type of faceted sphere) shaped ice particles.
Figure 5: Number densities averaged over 10 second intervals from FSSP (corrected to droxtal-shaped ice particles) and HOLODEC.
Figure 6: A sample of ice particles taken during Research Flight 2003-09-17. All particles are shown as reconstructed by the automated particle finding algorithm (Fugal et al., 2008) and are only scaled to improve contrast for printing. The white scale bar in the upper left is 0.5 mm in length.