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# Ice Crystal Number Densities and Size Distributions from HOLODEC

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## 1. Introduction

Satellite measurement validations, global climate models and cloud models in general depend on accurate measurements of the number density of ice particles, and in particular, small ice particles (< 100 µm extent). Indeed, modeling of important cloud processes such as radiative transfer, precipitation, and particle surface chemistry are particularly sensitive to these measurements because of the overwhelming populations of small ice particles relative to large ice particles (Baum et al. 2005b). Ironically, it is also in this size range that it is most difficult for common aircraft instruments to accurately measure ice particle size and density (Baum et al. 2005a, Heymsfield et al. 2002)

The limitations of the commonly used aircraft probes to measure small ice particles are explored by several authors including Korolev and Isaac (2005), Field et al. (2003), Baumgardner and Korolev (1997), Gayet et al. (1996), Gayet et al. (1991), and Korolev et al. (1991). The potential problems of these probes include ice particle break up due to mechanical impact on leading probe parts and due to wind shear near the probe tips. Other potential problems include the sensitivity of probe sample volumes to ice particle size and ice crystal habit. Corrections for these limitations have been proposed and perhaps are being used (Baumgardner and Korolev 1997, Smedley et al. 2003). However, new methods of measuring ice particle size, number density, and habit may be helpful. Holography is one such method.

## 2. HOLODEC

The HOLODEC (Holographic Detector for Clouds) probe that was flown during the IDEAS 3 (Instrument Development and Education in Airborne Science Phase 3) project during August and September 2003 over northeastern Colorado on NCAR's (National Center for Atmospheric Research) C130-Q Hercules aircraft along with other standard aircraft instruments (Fugal et al. 2004). The advantage holography offers includes a well defined sample volume as there is no depth of focus[1] as in imaging. Further, it is possible to detect shattered particles as an unusually high local concentration of ice particles. Figure 1, shows a hologram and its reconstruction of many smaller ice particles most likely from a shattered ice particle. Figure 2 also shows a particle in the process of breakup and a large pristine ice particle.

HOLODEC uses a camera that has 1024x768 4.65 µm square pixels and a 15 Hz frame rate. The ice particles fall between 30 to 80 mm from the camera. This yields a potential sample volume of 4.8 mm x 3.6 mm x 50 mm. In practice we use the inner 3.9 mm x 3.1 x 30 mm which gives us 0.52 cm$^{-3}$ sample volume per hologram.

HOLODEC is capable of reliably reconstructing particles as small as 15 µm which is determined by the diffraction limit of the CCD at the maximum reconstruction distance. We have reconstructed particles up to 1000 µm, although it is difficult to reconstruct particles larger than 100 µm using the straightforward intensity method (Fugal et al. 2004).

While HOLODEC has fewer uncertainties for measuring small ice particles than other probes, it does have the disadvantages of a lower volumetric sample rate due to the slow frame rate of the camera used, and requires longer post processing time to reconstruct the holograms. In the future, these weaknesses will likely be made up for by the ever increasing power of computers and cameras.

## 3. Preliminary Comparisons to Standard Probes

The aircraft instruments used to measure ice particle size distributions and number density include the PMS (Particle Measuring System) FSSP (Forward Scattering Spectrometer Probe) series probes, PMS 2DC (2 Dimensional Condensation) series probes, PMS 2DP (2 Dimensional Precipitation) series probes, and the SPEC (Straton Park Engineering Corporation) HVPS (High Volume Particle Spectrometer) probe. Table 1 summarizes some of the instruments' parameters.

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1 While some use the term "depth of focus" to describe a particle appearing in and out of "focus" in different hologram reconstruction planes, in imaging the term has a well defined meaning.

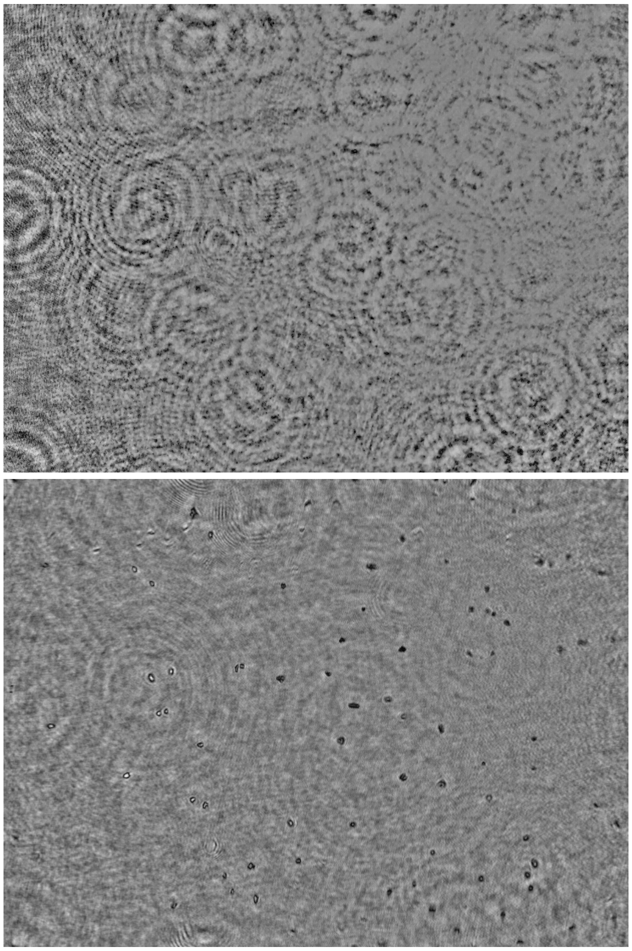
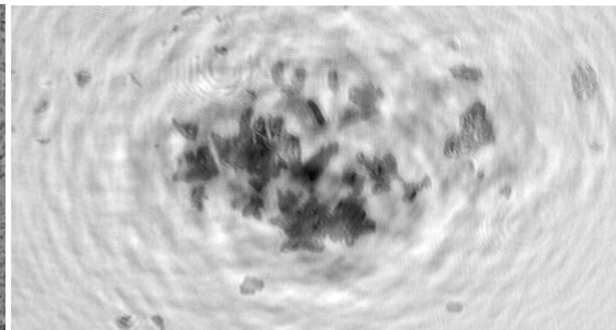


***Figure 1.*** *(top panel) A hologram taken with HOLODEC on Research Flight 9, on Sep. 17, 2003 over Northeastern Colorado. View area is 3.6 x 4.8 mm. The many rings are interference patterns from the incident laser beam and scattered beam of the small ice crystals reconstructed in the lower panel. (bottom panel) The smallest ice crystals are of order 10 µm in size. Note that nearly all the ice crystals are appear in one plane and that the usual number of small ice crystals per hologram is less than 10. This leads us to the conclusion that these are not undisturbed crystals, but are shards from a shattered crystal.*



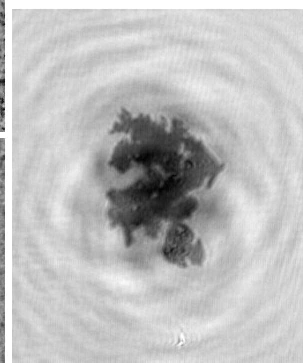


***Figure 2.*** *Two ice crystals are shown reconstructed from two different holograms. The crystal above is in the process of breaking up. The crystal on the left is approximately 600x400 micrometers. The waviness and blurs in both images are the particles' virtual image that increases in strength with particle size and nearness to the camera.*

Generally speaking, these aforementioned probes have the advantages of high sample rate, continuous operation, and nearly instantaneous results. They are also commonly used and have a long history in the cloud observational field. It would then be insightful to compare their ice particle number densities and size distributions to HOLODEC.

For the purposes of comparison, we have selected several segments from Research Flight 9 (Sep. 17, 2003) during the IDEAS 3 project. Figures 3 and 4 show the total and liquid water content, and cloud particle concentrations from standard cloud probes. The regions in which we have clear holograms of sufficient quality to allow for accurate digital reconstruction are marked with black diamonds. We have reconstructed holograms from these segments and have automated the process of identifying and counting ice crystals. Based on our analysis between approximately 20% and 60% of the particles counted by HOLODEC are shattered pieces of larger particles.

Identification of shattered crystals is based on the ability to find groups of closely-spaced particles in individual, three-dimensional reconstructed volumes. We apply a somewhat subjective criterion as to how many particles within how much distance depth wise before we reject that reconstructed hologram as tainted by shattered ice particles. It is useful to search for concentrations along the depth direction as particles that shatter on the probe tips will tend to appear in a thin sheet perpendicular to the optical axis of the camera (see Figure 1, lower panel). The ability to apply such a criterion is unique to the holographic method.

We note that so far, HOLODEC number densities have shown essentially the same profile (e.g. shape and slope) as the FSSP instrument, and therefore similar number densities might be expected.

Ongoing work includes determination of particle size from reconstructed 3-D images, which will allow for comparison of size distributions with other instruments. In particular, we note that HOLODEC has the advantage

| Instrument | Particle Size Range (µm) | Measurement Method |
|---|---|---|
| PMS FSSP series | 1-50 (typ.) | Scattering |
| PMS 2DC | 20-1500 (typ.) | Optical Array |
| PMS 2DP | 100-6000 (typ.) | Optical Array |
| SPEC HVPS | 200-50000 | Optical Array |
| HOLODEC | 15-2000 | Holography |

***Table 1.*** *Size range and measurement method of commonly used aircraft probes for ice crystal measurements.*

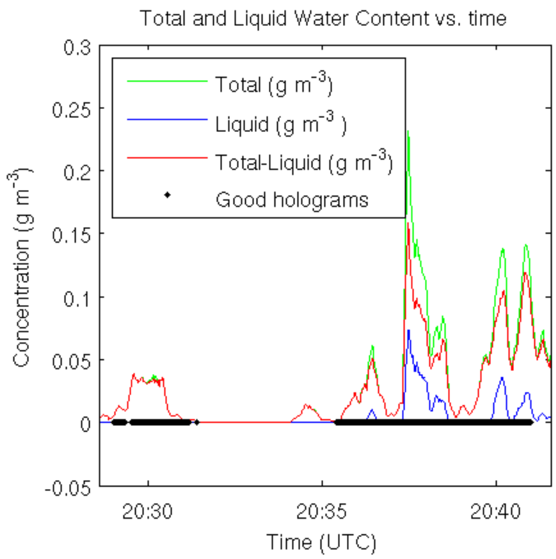



***Figure 3.*** *Total water and liquid water content on portion of IDEAS 3 Research Flight 9 in which HOLODEC holograms are processed.*

of measuring continuously over the size range 10 to 100 microns, which to date has been a long lived gap between the FSSP and 2DC probes. Preliminary results suggest reasonable agreement with the FSSP (d<50 µm), but significantly higher ice crystal concentrations than measured by the 2D-C for sizes less than 100 µm.

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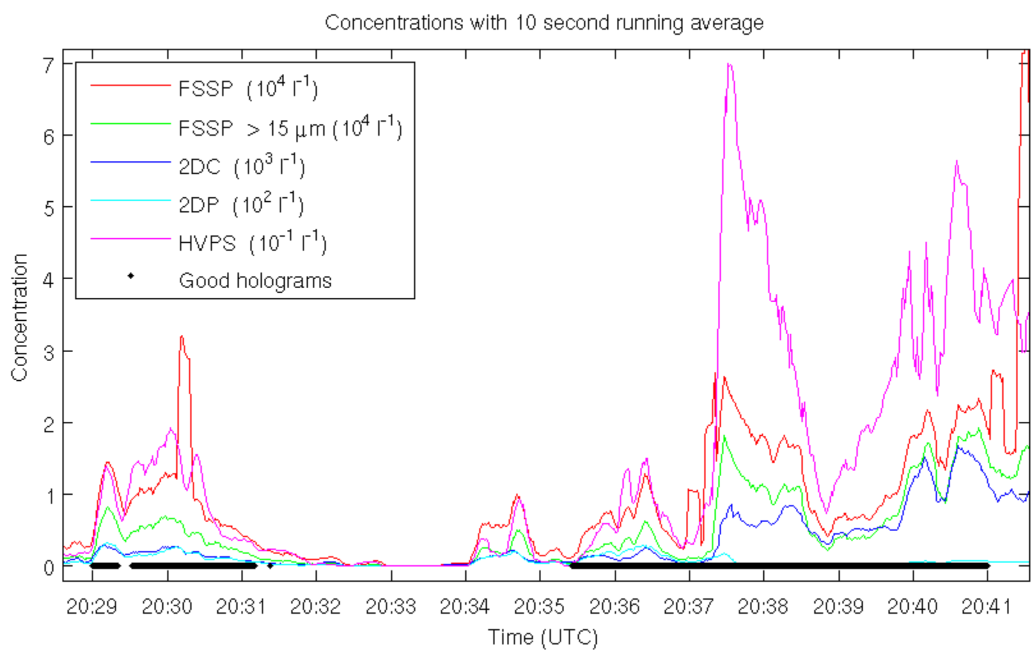


***Figure 4.*** *Concentrations from other probes on the portion of IDEAS 3 Research Flight 9 in which we process HOLODEC holograms.*

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## References

B. A. Baum, A. J. Heymsfield, P. Yang, and S. Bedka, 2005a, Bulk scattering properties for the remote sensing of ice clouds. Part I: Microphysical data and models, *J. of Applied Meteorology*, **44**, 1885-1895.

B. A. Baum, P. Yang, A. J. Heymsfield, S. Platnick, M. D. King, Y.-X. Hu, and S. Bedka, 2005b, Bulk scattering properties for the remote sensing of ice clouds. Part II: Narrowband models, *J. of Applied Meteorology*, **44**, 1896-1911.

D. Baumgardner, and A. J. Korolev, 1997, Airspeed Corrections for Optical Array Probe Sample Volumes, *J. of Atmos. and Oceanic Tech.*, **14**, 1224-1229.

P. R. Field, R. Wood, and P. R. A. Brown, 2003, Ice particle interarrival times measured with a Fast FSSP, *J. of Atmos. and Oceanic Tech.*, **20**, 249-261.

J. P. Fugal, R. A. Shaw, E. W. Saw, and A. V. Sergeyev, 2004, Airborne digital holographic system for cloud particle measurements, *Applied Optics*, **43**, 5987-5995.

J.-F. Gayet, G. Febvre, and H. Larsen, 1996, The reliability of the PMS FSSP in the presence of small ice crystals, *J. of Atmos. and Oceanic Tech.*, **13**, 1300-1310.

J.-F. Gayet, P. R. A. Brown, and F. Albers, 1991, A comparison of in-cloud measurements obtained with six PMS 2D-C probes, *J. of Atmos. and Oceanic Tech.*, **10**, 184-190.

A. J. Heymsfield, A. Bansemer, P. R. Field, S. L. Dueden, J. L. Stith, J. E. Dye, W. Hall, and C. A. Grainger, 2002, Observations and parameterizations of particle size distributions in deep tropical cirrus and stratiform precipitating clouds: Results from in situ observations in TRMM field campaigns, *J. of the Atmos. Sciences*, **59**, 3457-3491.

A. Korolev, and G. Isaac, 2005, Shattering during sampling by OAPs and HVPS. Part I: Snow particles, *J. of Atmos. and Oceanic Tech.*, **22**, 528-542.

A. Korolev, S. V. Kuznetsoz, Y. E. Makarov, and V. S. Novikov, 1991, Evaluation of measurements of particle size and sample area from optical array probes, *J. of Atmos. and Oceanic Tech.*, **8**, 514-522.

A. R. D. Smedley, C. P. R. Saunders, and A. R. Webb, 2003, Small-particle size determination by optical array probe oversampling, *J. of Atmos. and Oceanic Tech.*, **20**, 1568-1575.