Airborne Instruments for Measuring Concentrations and Size Distributions of Hydrometeors

Airborne Instrumentation Talk #2

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ASP Colloquium June 2009

Outline

1. Uses and General Nature of Hydrometeor Measurements
   - Some Measurements Needed for Studies of Clouds
   - Examples of Measured Hydrometeor Size Distributions
2. Survey of Instruments
   - Cloud Droplets
   - Hydrometeor Spectrometers
   - Imaging Probes For Hydrometeors
   - Other Measurements (e.g., LWC/IWC)
3. Conclusion
   - Unmet Needs and Summary

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COMMON MEASUREMENTS OF INTEREST

Measurements Often Used In Research

- Determine concentrations of:
  - Cloud droplets
  - Rain and drizzle drops
  - Ice crystals
- Determine size distributions [n(d)]
- Determine ice concentrations, ice n(d), habits
- Determine moments of n(d): LWC, r_e, Z, etc..

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Types of Instruments

- Instruments that measure moments of the size distribution (LWC, effective radius)
- Instruments that measure portions of the size distribution
- Instruments that record images of the hydrometeors
- Instruments that distinguish water from ice
- "Special": e.g., holographic imaging, multiple-view imaging, instruments to measure the distance between particles, impactors, ...

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Sources of Information on Instruments for Airborne Research

Web Sites With More Information

- Facilities Assessment Database:
  - http://www.eol.ucar.edu/fai/
    NSF Facilities Assessment Final Report.pdf
- EUFAR Database:
  - http://www.eufar.net – see "instruments"

Challenges

Why These Measurements Are Difficult

Hydrometeors of Interest:

- Sizes range from 1-10000 μm
- Concentrations of 10^{-6} to 10^{3} cm^{-3}
- Complex range of ice shapes

Measurements from research aircraft must be made at speeds of 100–200 m/s

- High data rates: up to 100,000 hydrometeors/s
- Short times for detection: 10 μm at 200 m/s => 50 ns response for imaging probes

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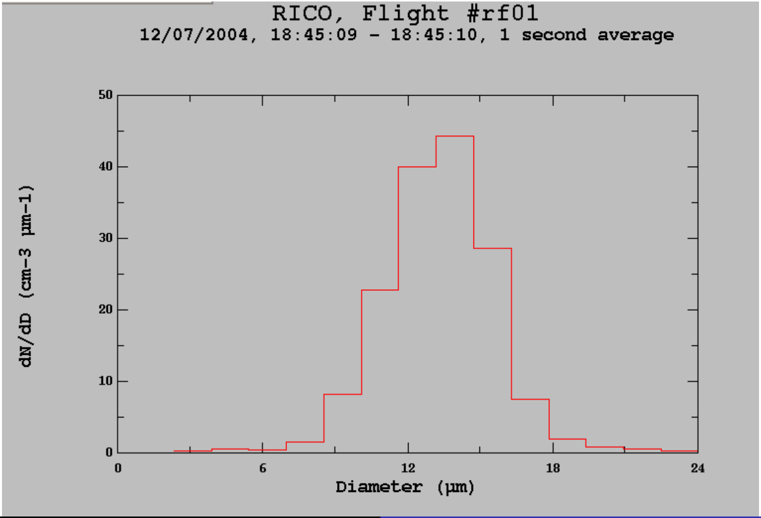
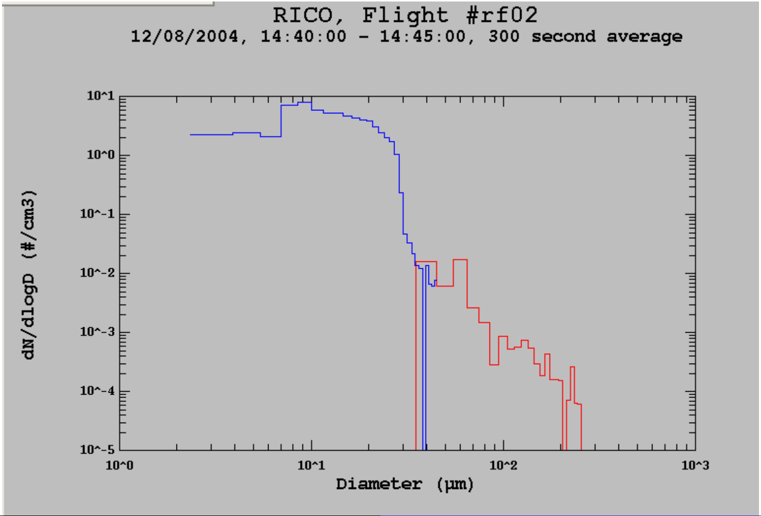
EXAMPLE CLOUD DROPLET SIZE DISTRIBUTION

FSSP Measurements



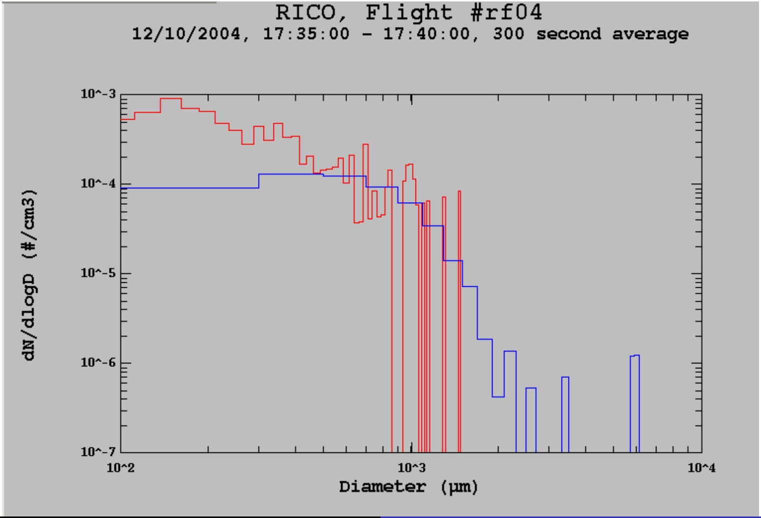
EXAMPLE DRIZZLE DROPLET SIZE DISTRIBUTION

260X+FSSP Measurements



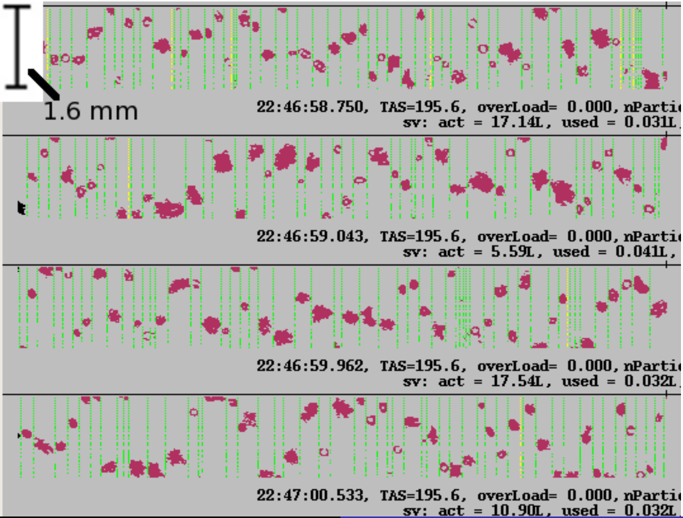
EXAMPLE RAIN SIZE DISTRIBUTION

2DC+2DP



EXAMPLE ICE IMAGES

2DC



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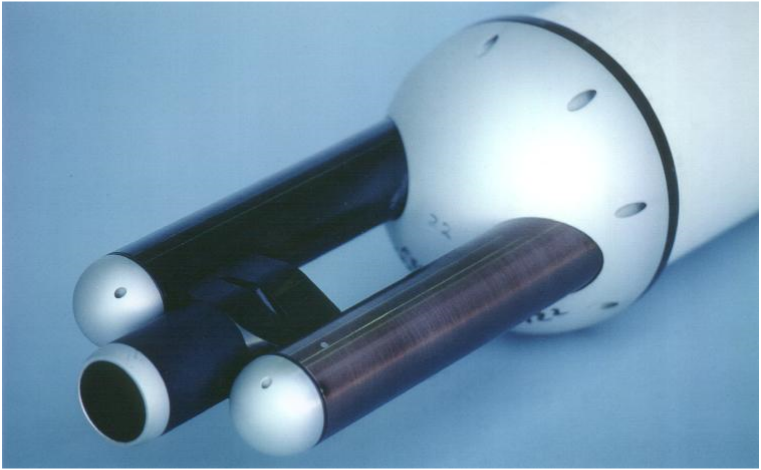
Really Old Techniques

- Impactors [Formvar, soot-coated slides]
  - issues: collection efficiency, need for short exposure, crater-to-size conversion
  - analysis laborious!
- Hot-wire sensors ["Johnson-Williams"] for LWC
- Icing detectors [Rosemount Icing Probe] for supercooled liquid water content

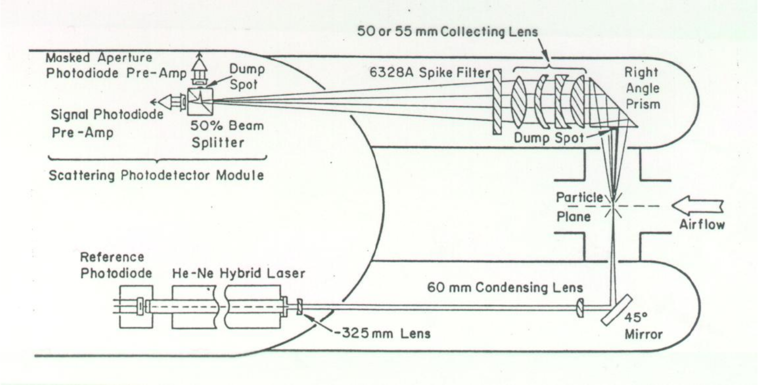
The Forward Scattering Spectrometer Probe
FSSP

- Entered use about 1976
- Detects light scattered from a laser beam as a droplet passes through
- Counts and sizes individual droplets, 15 channels, 2-47 μm
- The standard/conventional measurement for about 3 decades

The FSSP-100



FSSP SCHEMATIC DIAGRAM



DEFINITION OF THE SAMPLE VOLUME

FSSP Sample Volume

- The laser is focused to the center of the sampling aperture.
- The focal plane is focused again on a detector where the beam is split.
- One sensor is masked so that, in the focal plane, the scattered light is focused on the mask.
- Pulses are rejected if the light sensed by the masked detector exceeds a fixed fraction of that sensed by the unmasked detector.

ADVANTAGES OF THE FSSP

- Provides automated measurement of the droplet size distribution (15 channels)
- A routine and standard measurement that rapidly became the world-wide standard
- Contributed to many scientific studies

Some Problems with the FSSP

- Uneven laser illumination causes variations is measured sizes and degrades size resolution
- Coincidence effects on the measurements were serious at modest concentrations (700 cm^{-3})
- Slow electronics in older versions.
  - Pulses were undersized even at 125 m/s
  - Elongated pulses increased coincidence effects
- Particle shattering causes false counts
- False counts also obtained from ice particles

SOME MODIFICATIONS
FSSP

"Fast FSSP" – Brenguier et al., France

- Measures times between droplet arrival
- Modified optics to improve definition of the sample volume

Particle Spacing Monitor

- RAF instrument to measure the interarrival times

THE DMT CLOUD DROPLET PROBE

Droplet Measurement Technologies CDP

Similar to FSSP but with:

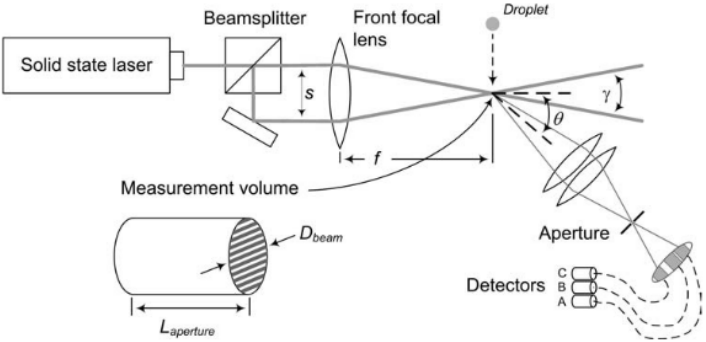
- fast electronics (200 m/s)
- more channels (20-40)
- Laser diode instead of He-Ne
- Positive optical mask
- No dead-time losses

Sample rate (25 cm^3/s at 100 m/s)

Phase Doppler Interferometer

A fundamentally different way of measuring droplet size:

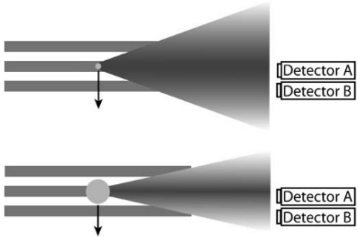
- PDI measures droplet size by reference to the wavelength of the light.
- Not subject to intensity fluctuations; high stability.
- Schematic from Chuang et al., 2006: AST, 42, 685-703.



PDI Sizing by Phase Shift

- Droplets pass through interference fringes
- Small droplets scatter light over a larger cone, so detectors see a small phase difference (top)
- Large droplets scatter light in a narrower beam, so detectors see a larger phase difference (bottom)
- Phase shift and the fringe pattern spacing => size and velocity.

Also from Chuang et al. (2008):



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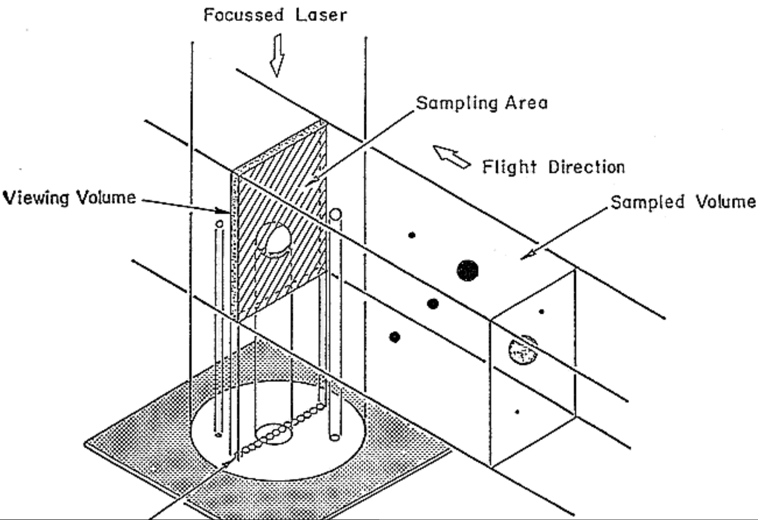
SIZE DISTRIBUTIONS FOR LARGER HYDROMETEORS

drizzle, ice graupel, rain

OPTICAL CONFIGURATION

OAPs



VARIETIES OF OAPs

- 200X (20 μm resolution)
- 200Y (300 μm resolution)
- 260X (10 or 12.5 μm resolution)
- DMT CIP=Cloud Imaging Probe (25 μm resolution) and PIP=Precip. Imaging Probe (100 μm resolution) – also 2D probes
- SPEC “HVPS” (200 μm resolution)

WEAKNESSES OF OAP SPECTROMETERS

- Depth-of-field uncertainty:
  - At small size, DOF is $<$ aperture
  - Away from the focal plane, diffraction distorts size, requiring correction to the measured size
- In common with almost all hydrometeor probes, shattering can contaminate the measurements
- Sample volumes are sometimes too small for statistically reliable measurement
- Some (probably small) errors may arise from coincidence of particles in the sample volume

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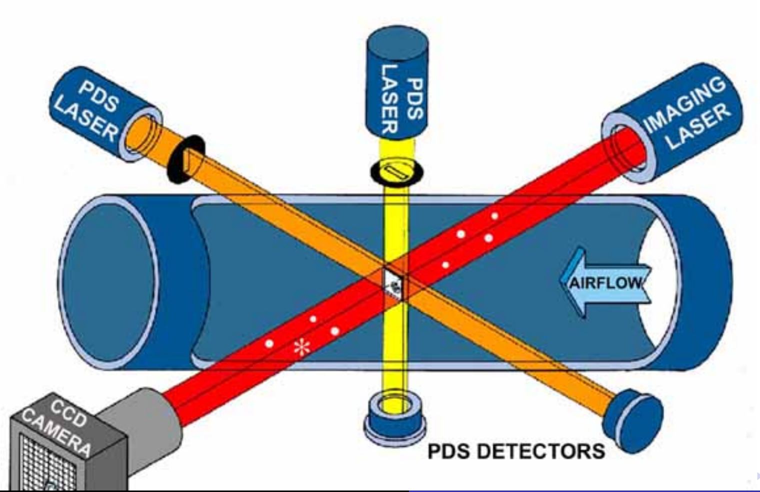
2D OPTICAL ARRAY PROBES

- Optically similar to 1D OAPs
- record images of particles:
  - record the status of the diode array at high frequency
  - as the hydrometeor shadow passes over it, the images is recorded
  - typically 25 μm or 200 μm resolution
  - new versions now available with higher resolution
- Weaknesses similar to 1-D OAPs
- Image information can help identify spurious images (e.g., "streaking" or fragments from shattering)
- Sophisticated processing algorithms are possible (circle fits to rain images, pattern recognition for crystal habits, etc.)

CLOUD PARTICLE IMAGER
SPEC CPI

From SPEC:

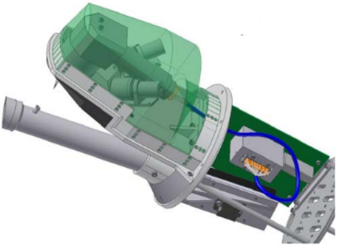


CPI Measurements

Small Ice Detector (SID)

University of Hertfordshire

- Uses multiple detectors to detect light scattered in various directions
- Discriminates ice from water on the basis of non-uniformity in the scattering pattern
- Counts and sizes small ice (few μm)



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Liquid Water Content

LWC/IWC

- Heated elements:
  - King LWC: constant-temperature element heated to evaporate water
  - Other collectors attempt to collect ice and measure ice water content
- Counterflow virtual impactor and other evaporators:
  - collect the cloud water (in the CVI, by virtual impaction),
  - evaporate the water
  - measure the LWC from the resulting water vapor density.
- Gerber PVM:
  - uses scattering from an ensemble of droplets at specific angles chosen to respond to the 3rd moment of the size distribution
  - can also measure the 2nd moment (effective radius)

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Weaknesses in Capabilities

- Need standardized calibration facilities and procedures!
- Inadequate size resolution for cloud droplets (but promising new approach in the PDI).
- Uncertainties in sample volume for many instruments.
- Inadequate sample volume for some hydrometeor sizes (esp. rain)
- Uncertain detection of small ice crystals and drizzle (e.g., 50-100 μm) with adequate sample rates.
- Uncertainties in how airflow affects the measurements.
- Contamination of measurements by shattering.

Conclusion

- An impressive array of automated airborne hydrometeor sensors is now available.
- There has been significant recent progress toward addressing key uncertainties.
- Further progress will probably require in-depth study of the nature of the instruments and the measurements, esp. regarding sample volumes, calibration, and data interpretation.