DOE/SC-ARM-TR-246

Cloud, Aerosol, and Precipitation Spectrometer Instrument Handbook

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DISCLAIMER

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Acronyms and Abbreviations

2D	two-dimensional
2DS-AIR	two-dimensional stereo probe aboard aircraft
AAF	ARM Aerial Facility
ACAPEX	ARM Cloud Aerosol Precipitation Experiment
ACE-ENA	Aerosol and Cloud Experiments in the Eastern North Atlantic
ARM	Atmospheric Radiation Measurement
CACTI	Cloud, Aerosol, and Complex Terrain Interactions
CAPS	cloud, aerosol, and precipitation spectrometer
CAS	cloud and aerosol spectrometer
CIP	cloud imaging probe
DMT	Droplet Measurement Technologies
DPOL	dual polarization
DQ	data quality
ED	effective diameter
FCDP	fast cloud droplet probe
GUI	graphical user interface
HI-SCALE	Holistic Interactions of Shallow Clouds, Aerosols, and Ecosystems
HW	hotwire
ICARTT	International Consortium for Atmospheric Research on Transport and Transformation
IOP	intensive operational period
LWC	liquid water content
MVD	median volume diameter
netcdf	Network Common Data Form
PADS	personal automated design solutions
PBP	particle by particle
PSL	polystyrene latex
RTD	resistance temperature detector
TCAP	Two-Column Aerosol Project
UTC	Coordinated Universal Time
WCM	water content meter

Contents

Figures

1.0 Instrument Title

This manual covers the cloud, aerosol, and precipitation spectrometer (CAPS). CAPS comprises three separate instruments, as follows:

- Cloud and aerosol spectrometer (CAS)
  - Routine data name: aafcas*
  - Intensive operational period (IOP) data name: cas* or cas-air
- Cloud imaging probe (CIP)
  - Routine data name: aafcip*
  - IOP data name: cip or cip-air*
- Liquid water content (LWC) hotwire (HW)
  - IOP data name: lwc-air**

*These data sets contain the same information, differing only by name due to the method of submission. Data sets going forward will be considered "routine data" and use that naming convention.

**This data set was first submitted as part of a merged LWC product for ARM's Cloud, Aerosol, and Complex Terrain Interactions (CACTI) campaign in 2019 containing data also from the Gerber PVM-100a liquid water probe and the water content meter (WCM). If you are looking for a liquid water content measurement from previous campaigns, please use the WCM data set (https://adc.arm.gov/discovery/#v/results/s/finst::wcm).

2.0 Mentor Contact Information

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3.0 Vendor/Developer Contact Information

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Ph: +001-303-440-5576
customer-contact@dropletmeasdurement.com]

4.0 Instrument Description

The cloud, aerosol, and precipitation spectrometer is a multipurpose, research-grade cloud spectrometer that includes three Droplet Measurement Technologies instruments plus temperature and relative humidity sensors (Baumgardner 2001). The CAS portion of the instrument uses forward- and backscattering detection techniques to provide cloud droplet and aerosol sizes and optical properties. The CIP uses shadow images from a photo-detector array to provide shape and size information for larger aerosol and hydrometeors. The HW sensor uses a platinum resistance temperature detector (RTD) wire sensor to detect liquid water content.

Figure 1. The U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility Aerial Facility (AAF) pylon configuration with the CAPS instrument for the Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) campaign, 2018.

5.0 Measurements Taken

The CAS portion of the instrument provides aerosol particle and cloud hydrometeor size distributions from 0.51 to 50 µm, particle optical properties (refractive index), and particle shape assessments (discrimination between water and ice via depolarization). ARM currently reports size distribution measurements from the CAS. The CIP measures aerosol particle and cloud hydrometeor size distributions from 12.5 um–1.55 mm (standard) at 1 Hz time resolution. The HW sensor detects liquid water content.

6.0 Links to Definitions and Relevant Information

Vendor website: http://dropletmeasurement.com/cloud-aerosol-and-precipitation-spectrometer-caps

6.1 Data Object Description

Routine data is packaged as netcdf files. Older campaign data submitted as 'IOP' or ops data is in text file format.

CAS data present in International Consortium for Atmospheric Research on Transport and Transformation (ICARTT) format on ARM.gov:

Col 1:Mission time, UTC
Cols 2-30: Mean Bin Size, concentration per bin (#/CC)
Col 31: Number Concentration (#/CC)
Col 32: Area_Conc_(um^2/cm^3)
Col 33: Vol_Conc_(um^3/cm^3)
Col 34: Data_Flag
Col 35: Cloud_Flag

CIP data present in ICARTT format on ARM.gov:

Col 1: Mission time, UTC
Cols 2-62: Mean Bin Size, concentration per bin (#/CC)
Col 63: Number Concentration (#/CC)
Col 64: Area_Conc_(um^2/cm^3)
Col 65: Vol_Conc_(um^3/cm^3)
Col 66: Data Flag
Col 67: Cloud Flag

6.2 Data Ordering

These data sets can be downloaded online via the ARM Data Center (https://adc.arm.gov/discovery/).

6.3 Data Plots

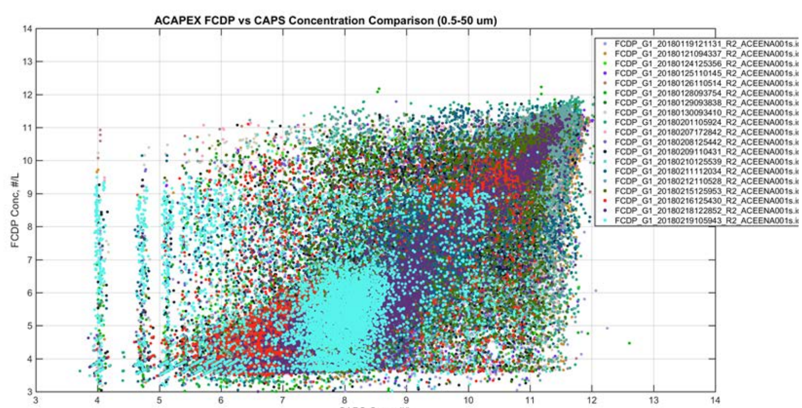

Figure 2. One-to-one comparison of total concentration of CAPS to fast cloud droplet probe (FCDP) during the ARM Cloud Aerosol Precipitation Experiment (ACAPEX). Data found and downloaded from ARM's Data Center via "Data Discovery".

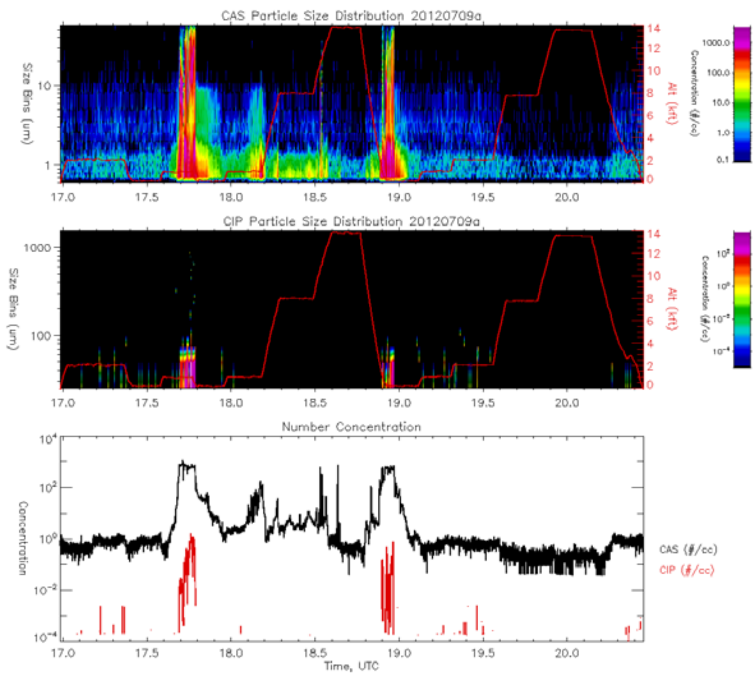

Figure 3. Example data plot taken from the data quality (DQ) plot browser. The data presented here is from ARM's Two-Column Aerosol Project (TCAP).

6.4 Data Quality

No links found to DQ page.

6.5 Instrument Mentor Monthly Summary

Last vendor calibration performed October 2019.

6.6 Calibration Data Base

The results of field and laboratory calibrations and vendor calibrations are currently tracked by AAF's director of engineering. Contact Jason Tomlinson directly for more information. AAF is currently working to incorporate its calibrations into ARM's databases.

7.0 Technical Specification

7.1 Units

7.1.1 CAS

Cols 2-30: Mean Bin Size, concentration per bin (#/CC)
Col 31: Number Concentration (#/CC)

Col 32: Area_Conc_(um^2/cm^3)
Col 33: Vol_Conc_(um^3/cm^3)

7.1.2 CIP

Cols 2-62: Mean Bin Size, concentration per bin (#/CC)
Col 63: Number Concentration (#/CC)
Col 64: Area_Conc_(um^2/cm^3)
Col 65: Vol_Conc_(um^3/cm^3)

7.2 Range

7.2.1 CAS

Aerosol particle and cloud hydrometeor size distributions from 0.51 to 50 µm are reported at 1 Hz time resolution. The possible sampling frequency is 0.1 to 10 Hz. The sample area for forward and back scattering is 1.1 mm x 120 µm. The airspeed range at which the measurements will be valid is 10−200 m/s. The range of refractive index for non-absorbing samples is 1.3−1.7. The wavelength of the laser used is 658 nm. The maximum concentration sample is 10,000 cm^3.

7.2.2 CIP

Aerosol particle, precipitation, and hydrometeor size distributions are reported from 25 to 1550 µm. The instrument has the ability to report 1d histogram data from 0.1 to 10 Hz but is reported at 1 Hz time resolution. The sample area for the diode array is 10 cm x 1.55 mm. The airspeed range at which the measurements will be valid is 10−300 m/s.

7.2.3 HW

The LWC range is from 0.01 to 3 g/m^3. The airspeed range at which the measurements will be valid is 10−300 m/s. The sampling frequency is 0.1 to 10 Hz. The auxiliary parameters required to make this measurement are ambient temperature, static pressure, dynamic pressure, and airspeed.

7.3 Accuracy

The CIP probe has Korolev tips installed with a 70mm beam opening. Large discrepancies were observed between the 2DS and CIP at size greater than 150 µm. It is recommended one uses the two-dimensional stereo probe aboard aircraft (2DS-AIR) data over the CIP data. Recent comparisons of the CAPS hot wire to the WCM 2000 show good agreement for LWC within uncertainty bounds.

7.4 Repeatability

Proper operating ranges:

Temperature: -50–50°C
Humidity: 0–100%, non-condensing
Altitude: 50,000 ft

7.5 Sensitivity

The CAS probe measures particle inter-arrival time, the time between two particles being detected. This information is output with the particle-by-particle (PBP) data. Along with inter-arrival time, the S&P data is used to make sure the particle detected is in focus. When the laser hits the particle, the amount of light bounced back to the detector is then related to the size of the particle. However, this is only accurate if the particle is perfectly in between the sapphire windows. Otherwise the particle will be out of focus, and the amount of light bounced back will not correspond to the true size of the particle. “S” and “P” are the names of the variables; they are unitless. However, their ratio shows if the particle is in focus or not. Therefore, if the S&P data are good, the size data are also considered to be good. This is explained in more detail in the measurement theory section. Overall, these measurements allow the CAS probe to limit coincidence errors, mask instances of ice shattering from the probe tips, and determine if the particles are in focus and sampled properly on a particle-by-particle basis.

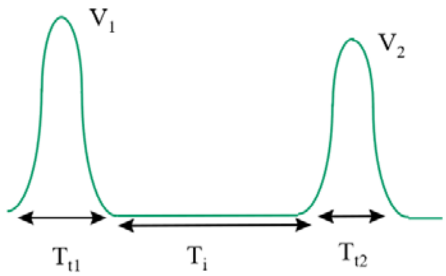

Figure 4. Imaging demonstrating particle inter-arrival time and the signal response from the detectors as seen on an oscilloscope taken from the DMT manual, Rev. F.

7.6 Uncertainty

7.6.1 CAS

There are uncertainties in the buffer and data collection at high concentrations. Baumgardner et al. 2001 suggest +- 15% in concentration.

7.6.2 CIP

Upper concentration range: Depends on particle size, but up to 500 particles/ cm^3 for a CIP with standard tips and arm width.

2D image data: variable interval, when buffer fills.

7.7 Input Voltage

CAS System data: RS-232 or RS-422, 56.6 kb/sec Baud rate

Maximum packet size: 8200 bits

2D CIP data: RS-422, High Speed, 4 Mb/sec Baud rate

CIP System data: RS-232 or RS-422, 56.6 kb/sec Baud rate

HW system: RS-232 or RS-422, 56.6 kb/sec Baud rate

7.8 Output Values

CAS: Time, inter-passage time, sizer low, sizer high, qualifier high, qualifier low, S high, S low, P high, P low

8.0 Instrument System Functional Diagram

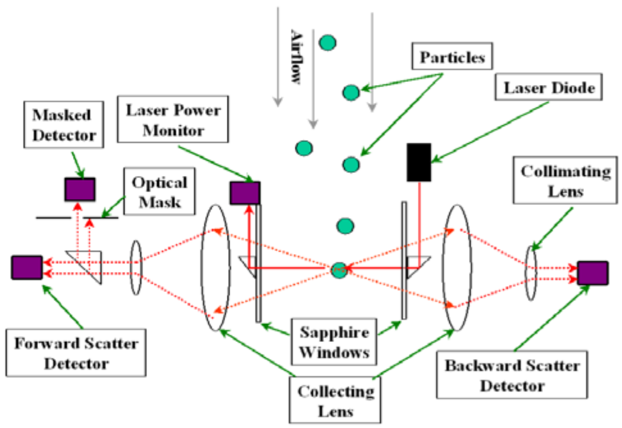

Figure 5. Schematic of forward and backscattering optical paths in the CAS from the DMT manual, Rev. F.

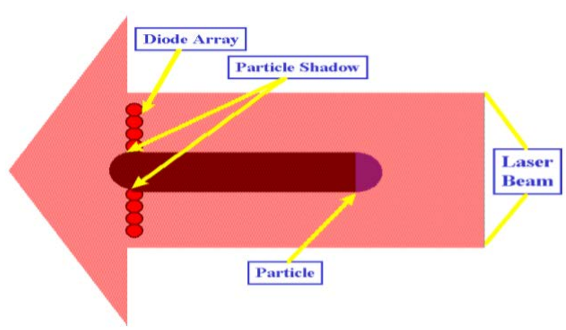

Figure 6. Representation of CIP theory of operation from the DMT manual, Rev. F.

CIP laser is 658 nm, 30 mW. DMT-manufactured laser with Arima Lasers Corporation diode.

9.0 Instrument/Measurement Theory

The CAS, which measures smaller particles, relies on light-scattering rather than imaging techniques. Particles scatter light from an incident laser, and collecting optics guide the light scattered in the 4 to 12 degree range into a forward-sizing photodetector. This light is measured and used to infer particle size.

Backscatter optics also measure light in the 168 to 176 degree range. The CAS polarization feature allows it to differentiate between water and ice particles for particles in the 0.5−50 μm range. The CAPS measures forward-scattered light and the S-state and P-state polarizations with two backscatter detectors. For spherical particles, typically droplets, the polarization of the incident light will be retained and the crossed polarization in the backscatter will not generate any signal. Depending on the asphericity of the particles, there will be increased signal in the backscatter detector with the crossed polarizer. The first deployment of the CAS with dual polarization (DPOL) was during ARM's Holistic Interactions of Shallow Clouds, Aerosols, and Ecosystems (HI-SCALE) campaign in 2016. The CAS was processed with a refractive index of 1.33 for liquid water. To use for aerosols, a correction will need to be made.

The CAS probe determines how to assign each sizer signal to a bin via a high and low gain stage. The roll-over value is 14336, the gain added value is 16384 (2^14), and there is a gain multiplier of 128. If the value in the lower gain stage is less than 150, it is ignored as noise. If the incoming signal is less than the roll-over value, the higher gain stage is used; if less, the values in the lower gain stage are used. The same gain stages are used to determine the qualifier used as rejection criteria. If 0.5*Sizer < Qualifier, the particle is rejected for not being in focus. Finally, the resulting size value will be placed in a bin in accordance with the threshold table of the corresponding index of refraction.

To determine the polarization data, the following calculation is done with the S&P values:

$$\frac{S-P}{S+P}$$

If the value is less than -0.5, the hydrometeor is water. If greater than 0, it is ice. The AAF CAS is always processed in the configuration for water.

The CIP, which measures larger particles, operates as follows. Shadow images of particles passing through a collimated laser beam are projected onto a linear array of 64 photodetectors. The presence of a particle is registered by a change in the light level on each diode. The CIP registers the change as either "On" or "Off," where "On" is when the light level decreases below 50%. The registered changes in the photodetectors are stored at a rate consistent with probe velocity and the instrument's size resolution. Particle images are reconstructed from individual "slices," where a slice is the state of the 64-element linear array at a given moment in time. A slice must be stored each time interval that the particle advances through the beam a distance equal to the resolution of the probe.

The laser produces an oval 50 mW beam illuminating the diode array. Whenever a particle passes through the laser beam, its shadow is optically magnified onto a 200-μm pitch, 64-element photo-diode array. The CIP determines the particle's size based on how many diodes in the array its shadow obscures. Particles shadowing an end diode (i.e., diode number one or sixty-four) are rejected from the sizing routine but will generate a 2D image. The size range for CIP-detected particles ranges from 12.5 to 1550 μm.

The probe has Korolev tips installed with a 70mm beam opening to prevent ice shattering (Korolev 2013).

10.0 Setup and Operation of Instrument

The CAPS instrument is installed in a wing pylon with access to power that is controlled from a switch inside the aircraft. Once power is applied, the probe itself is controlled via the vendor-provided graphical user interface (GUI). If temperatures reach 0 deg C, the anti-ice heaters need to be turned on manually.

11.0 Software

The software provided by vendor, called the Particle Analysis and Display System (PADS), provides a GUI that allows the user to do the following tasks (below taken verbatim from the developer website):

- Start data recording and sampling
- View real-time particle image data acquired by the CIP
- View particle volume and number concentrations, as well as median volume diameter (MVD) and effective diameter (ED)
- View LWC as measured or calculated by the hotwire LWC, CIP, and CAS
- Monitor instrument parameters like CIP laser current and various electronics voltages
- Play back data for post-flight viewing.

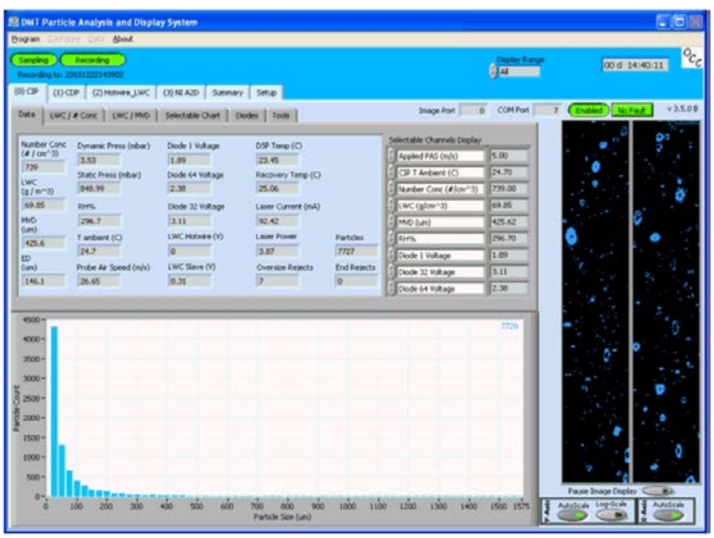

Figure 7. Image of software GUI from DMT's website.

Future campaign data sets from this probe will be collected on its own data acquisition workstation and processed using the PADS software. For campaigns before 2019, the data from the CAPS probe was collected by the M300 data acquisition station, post-processed using a code written by Jason Tomlinson, and verified using data from the FCDP probe. This process used the true airspeed recorded by the aircraft and not the true airspeed recorded by the pitot tube on the CAPS probe itself to develop the shadow images taken by the CIP. This had the potential to impact the timing of the imaging on the CIP and could distort the size of the image (elongating or squashing the images), leading to under-sizing the droplets.

This issue was more pronounced with larger sizes. In general, we recommend for droplets larger than 150 μm to use data from the 2DS-AIR probe for data sets from 2019 and earlier.

12.0 Calibration

12.1 Field and In-Laboratory Calibration Methods

12.1.1 Frequency

In the field, the CAPS is calibrated before and after the first and last research flights. One day a week is dedicated to calibrations; the CAPS is generally calibrated every other week.

Between campaigns the CAPS probe is shipped to the vendor for in-depth calibration. Once returned to AAF, staff calibrate the probe, as well as right before stowage and shipment for a campaign.

12.1.2 Methods

12.1.2.1 CAS

The setup is as follows: a guiding pipe is inserted into the CAS that directs the calibration source to the windows. Into the other end of the pipe is inserted a vial filled with calibration beads. AAF uses multiple sizes of PSL (polystyrene latex) beads from 5−50 μm. To send the beads to the detector, a puff of air is sent through the vial to push out the beads via a tank of compressed air. Through processing, the width and position of the resulting size distribution is recorded. Generally, this is a delta function with most of the signal corresponding to the size of the beads.

Figure 8. Glass bead calibration system for calibrations and tests. Image taken from 2010 vendor instrument manual uses a duster can instead of compressed air.

Note that for this calibration the threshold table is changed to match the density of the PSL; for operations we use the threshold table for water to match its Mie curve.

12.1.2.2 CIP

A spinning disk that attaches to the CAPS probe was provided by DMT for calibrations. Once attached, it recreates the images of perfectly spherical drops (four in total of different sizes). The operator aligns the spinning disk with the photo-detector array. Via the PADS software, the operator can see if the particles are aligned, and manually adjusts the airspeed until the drops appear spherical in the GUI window. Once properly aligned and viewing properly, the known diameter of the 'drops' are compared to the live histogram of sizes on the GUI. If they agree, the calibration is complete. If incorrect, the vendor is contacted to check the calibration values.

Figure 9. Spinning disk attachment provided by DMT.

12.1.2.3 HW

Test the signal when water is sprayed on the wire. In field measurements, we have compared to the WCM, which has operated reliably for years. Please consult that handbook for more detail.

12.2 Vendor Calibrations

12.2.1 CAS

- Heater checked
- Windows cleaned
- Detectors realigned and calibrated
- Gain stage ratio checked and voltage and resistance checked for detector components and their gain stages
- DPOL returned values checked with the following particulates:
  - 32.5 μm glass beads (pre and post cal as well)
  - 49.3 μm glass beads (pre and post cal as well)

- – fine dust (pre and post cal as well)
- – pine pollen (pre and post cal as well)
- – 0.707 µm PSL, 5.4 µm glass beads
- – 2.1 µm PSL
- – 8.1 µm glass beads
- – 14.4 µm glass beads
- – volcanic ash.

12.2.2 CIP

- Check heaters and probe tip conditions.
- Pitot tube calibrated by checking dynamic and static pressure versus counts detected at four different values. The pitot is necessary for determining the airspeed of incoming aerosol and hydrometeors.
- The spinning disk calibration technique is used to validate the CIP, the same as the in-field/laboratory procedure.
- Windows cleaned.
- Detectors realigned and calibrated.
- Gain stage ratio checked.
- Voltage and resistance checked for detector components and their gain stages.

12.2.3 HW

- Calibration.
- Post-calibration, the probe is placed in a wind tunnel and observes different concentrations of liquid water (0.15, 0.65, 1, 1.4, 1.65, 0, 1.65, 0 g/m^3) for 10-minute intervals.

12.2.4 Results

The vendor calibrations supply updated values for the calibration curves and constants used in the signal-to-output conversions.

The latest vendor calibration was in October 2019. The previous one was in August 2016.

13.0 Maintenance

Use acetone on Q-tips to clean the CIP window before every flight. The CAS windows are more protected and are cleaned only on calibration days (once per week). Clean any insects or residue from the surface of the probe if visible.

14.0 Safety

When not in use, two safety caps must always be on the end of the CIP's ice-shattering-prevention tips to prevent injury. Stow the probe in its approved crate. If installed in its pylon and the aircraft is grounded (e.g., before flight, on calibration days), place a bright orange traffic cone in front of the probe to prevent contact with the probe tips.

15.0 Citable References

Baumgardner, D, H Jonsson, W Dawson, D O'Connor, and R Newton. 2001. "The cloud, aerosol and precipitation spectrometer: a new instrument for cloud investigations." *Atmospheric Research* 59-60: 251−264, https://doi.org/10.1016/S0169-8095(01)00119-3

http://dropletmeasurement.com/cloud-aerosol-and-precipitation-spectrometer-caps

CAPS Manual: CAPS operator Manual 2010 w wiring schematics.pdf

Cloud Aerosol Spectrometer with Particle by Particle Manual

The Cloud Aerosol Spectrometer Depolarization Option

Korolev, Alexi. 2013. "Modification and Tests of Particle Probe Tips to Mitigate Effects of Ice Shattering." *Journal of Atmospheric and Oceanic Technology* 30(4): 690−708, https://doi.org/10.1175/JTECH-D-12-00142.1

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