FINAL REPORT
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ACCURACY OF THE CLOUD INTEGRATING NEPHELOMETER

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(December 1, 2004)

ABSTRACT

Potential error sources for measurements with the Cloud Integrating Nephelometer (CIN) are discussed and analyzed, including systematic errors of the measurement approach, flow and particle-trajectory deviations at flight velocity, ice-crystal breakup on probe surfaces, and errors in calibration and developing scaling constants. It is concluded that errors are minimal, and that the accuracy of the CIN should be close to the systematic behavior of the CIN derived in Gerber et al (2000). Absolute calibration of the CIN with a transmissometer operating co-located in a mountain-top cloud shows that the earlier scaling constant for the optical extinction coefficient obtained by other means is within 5% of the absolute calibration value, and that the CIN measurements on the Citation aircraft flights during the CRYSTAL-FACE study are accurate.

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1. Introduction

The Cloud Integrating Nephelometer (CIN) is an aircraft probe that was developed under a NASA Langley research grant and has been used for incloud measurements in several NASA-sponsored aircraft studies including FIRE-ACE and CRYSTAL-FACE (C-F). This probe has the unique capability of measuring in-situ the cloud-particle optical extinction coefficient in the visible spectrum, the asymmetry parameter, and the back-scatter ratio. It has served as a tool for validating remote-sensing of cloud optical thickness (Platnick, 2001), and has produced new information on the optical properties of ice crystals and ice clouds (Garrett, 2001, 2003, 2004; Gerber, 2000, 2004)

The purpose of this report is to present our current knowledge on the accuracy of the measurements made by the CIN. Errors for the CIN can have four sources: 1) systematic errors due to the operating principle, 2) deviations due to the probe of air-flow streamlines and of particle trajectories, 3) breakup of ice-crystals on the leading edges of the probe, and 4) errors from incorrect calibration and scaling of the probe. The first two items will be summarized given that their effect on the CIN has been researched earlier, the third item has new information that will be presented, and item 4) will be dealt with in detail.

The present grant's effort focused on the calibration of the CIN (item 4), because of results stemming from probe intercomparisons during the C-F study on Florida thunderstorms and anvils. We found that the CIN extinction coefficient on the U. N. Dakota Citation aircraft was about a factor of 2 larger than this coefficient calculated from the particle spectra measured with the NCAR 2-DC and FSSP-100 spectrometers co-located on the same aircraft. This factor was consistent in all flights of the Citation, including in all ice clouds and clouds with liquid drops. This large difference motivated a thorough look at the previous calibration techniques used with the CIN, and provided the basis for the work done under the present grant. This work entailed comparing the CIN extinction measurements to a ground-based transmissometer that directly measures the extinction coefficient. Since such a transmissometer, suitable for accurate incloud measurements, was not found to be available commercially, this work included designing and constructing such a transmissometer, and conducting a co-located comparison of the CIN with the transmissometer incloud to discover whether the difference in extinction measurements were a result of errors in the CIN's calibration.

2. Extinction Coefficient Measurements during Crystal-Face on the Citation

The following pages present four examples of the extinction coefficients measured by the CIN vs that measured by the spectrometers (FSSP-100 and 2-DC) during flights of the N.D. Citation aircraft. The first three figures show results in ice clouds, while the fourth is a segment of the flight on July 9 when only large liquid drops were present. These examples all show the CIN extinction larger than the spectrometer extinction by a factor of about 2. It is important to note that the liquid water case (Fig. 4) also showed a similar difference. This difference in extinctions was found in all flights of the Citation during C-F. It was not possible for Drs. Heymfield and Bensamer of NCAR to find an error in their spectrometer measurements, nor was it possible for this P.I. to discover the reason why the CIN may have caused this approximately constant factor difference.

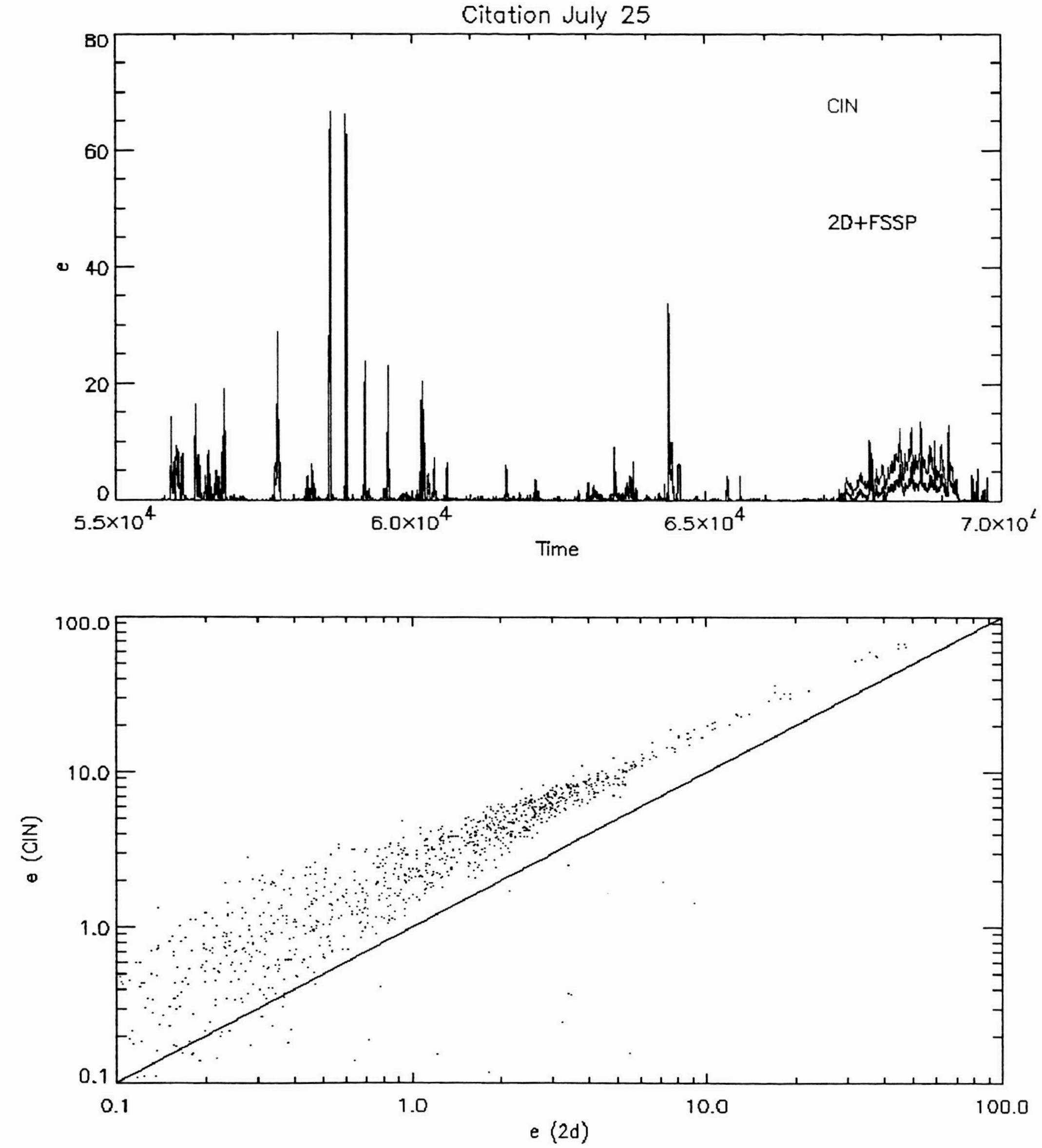


Fig. 1 - Comparison of optical extinction measurements in the visible spectrum measured in ice clouds on 25 July by the CIN and calculated by integrating particle size spectra from the 2-DC and FSSP-100 spectrometers. (Courtesy of Drs. Heymsfield and Bansemer, NCAR)

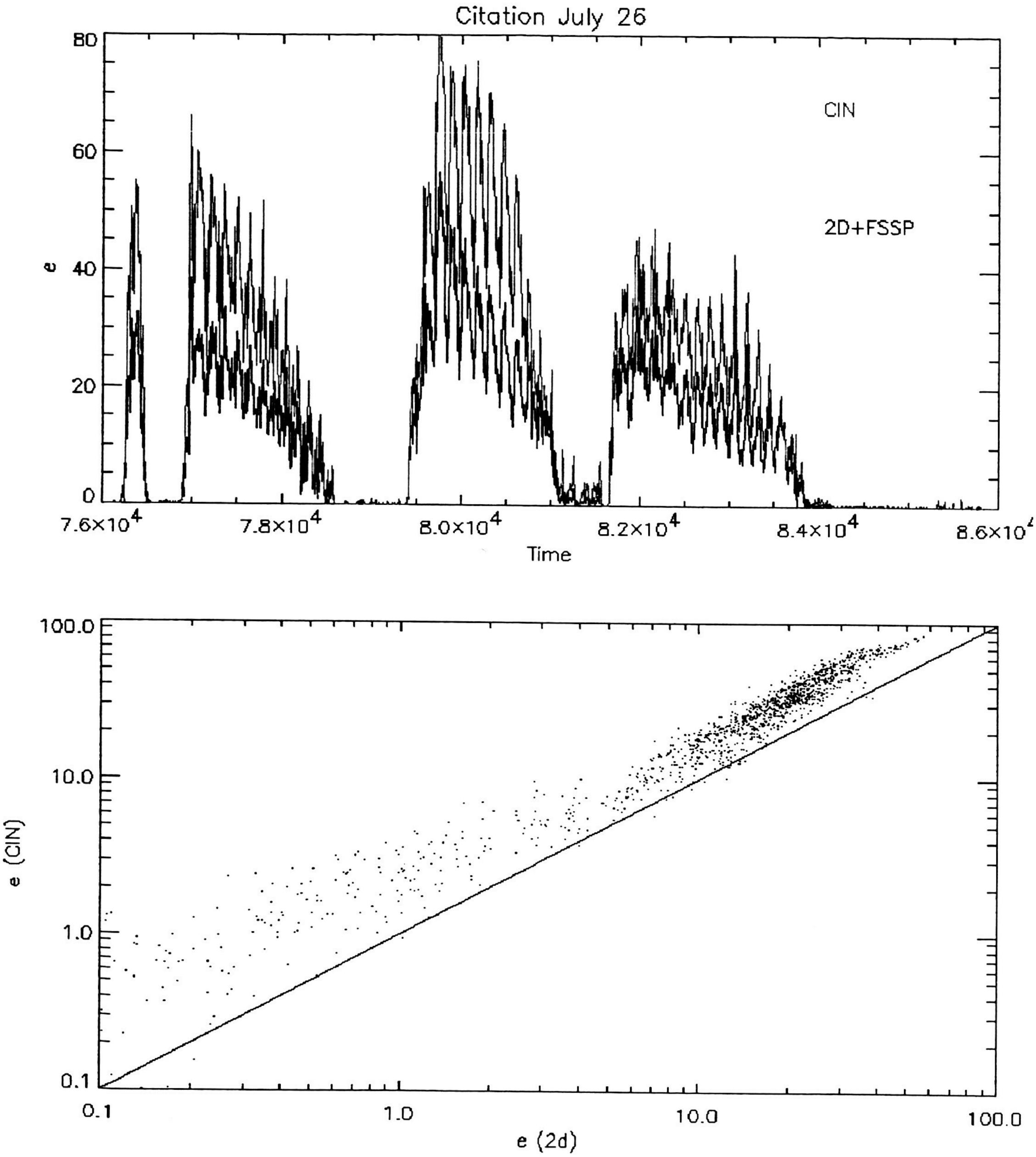


Fig. 2 - Same as Fig. 1, but for 26 July.

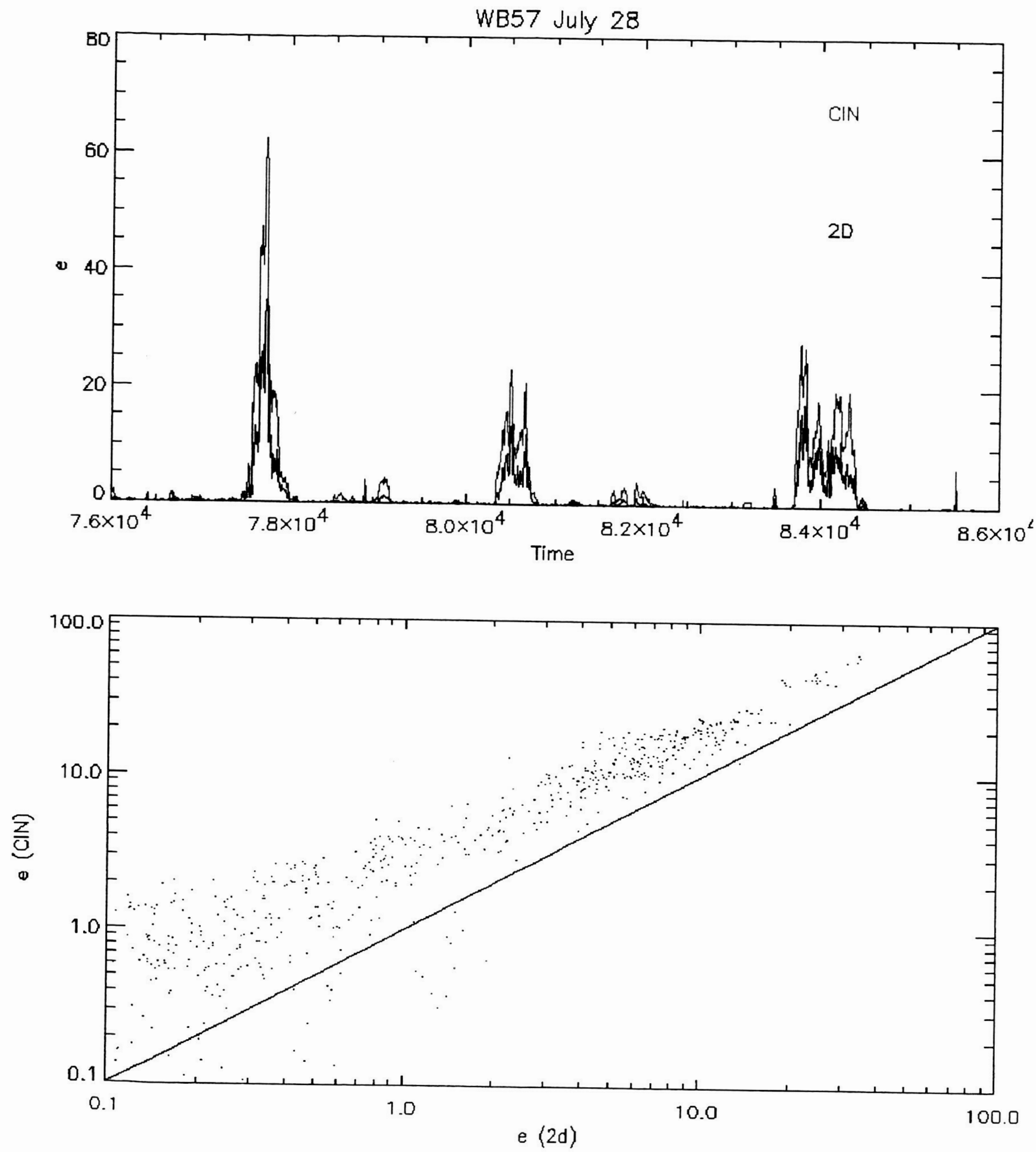


Fig. 3 - Same as Fig. 1, but for 28 July.

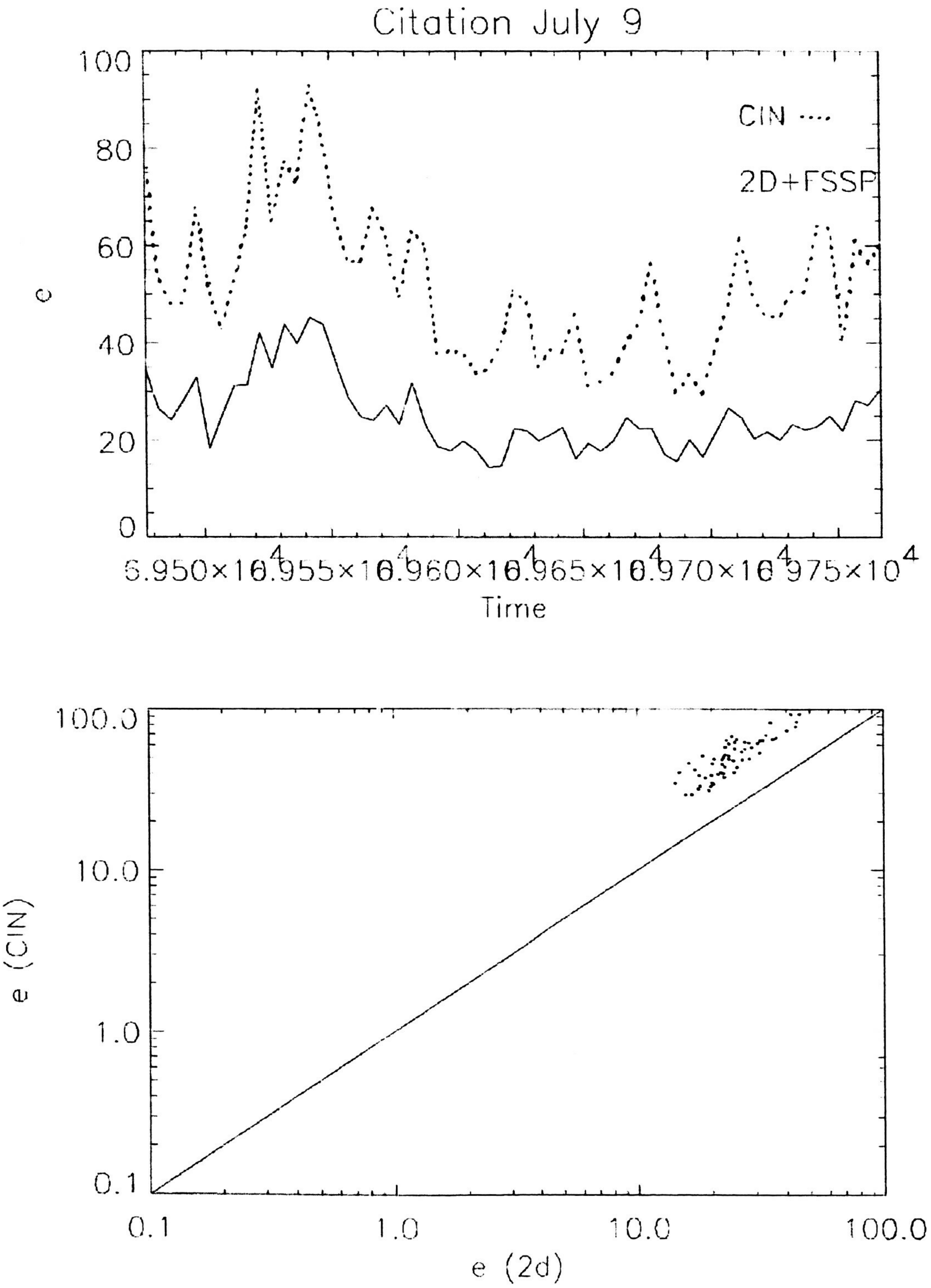


Fig. 4 - Same as Fig. 1, except for a segment of the cloud on 9 July consisting of large liquid water drops.

3. Calibration of the CIN

3.1 CIN Scaling Constants

The four channels of the CIN produce voltages and have the following names (see Gerber et al., 2000):

F = forward scatter
B = back scatter
cF = cosine weighted forward scatter
cB = cosine weighted back scatter

The voltage outputs of the four channels are combined to provide the extinction coefficient (extc.), the asymmetry parameter (g), and the backscatter coefficient (bscat.) as follows:

$$\text{extc.}(\text{km}^{-1}) = C5\ [(F \times C1) + (B \times C2)]/(1-f) \qquad (1)$$

$$g = \{f[(F \times C1)+(B \times C2)] + (1-f)\ [(cF \times C3) -(cB \times C4)]\}/\ [(F \times C1) + (B \times C2)] \qquad (2)$$

$$\text{bscat.}(\text{km}^{-1}) = [(B \times C2)\ (1-f)]/[(F \times C1) + (B \times C2)] \qquad (3)$$

where C1, C2, C3, C4 are constants that scale the relative sensitivity of the four photomultipliers and the electronics to produce the same outputs for the same amount of scattered light incident on each sensor. The most recent intercomparison of the four channel sensitivities is illustrated in Fig. 5.

In order to produce the outputs in Fig. 5 a light diffusing bar is inserted into the CIN laser beam at specific locations marked on the inside surface of the CIN wings. This procedure must be done with the wings unattached from the CIN electronic box, and the baffles near the Lambertian diffusers removed. For the 3-Nov. case shown in Fig. 5 the average voltages for each channel are F = 1.286V, B = 6.364V, cF = 0.828V, and cB = 5.787. Given that backscatter from cloud particles is much smaller and forward scatter, the two B channels are amplified electronically by a factor of about 5 greater than the two F channels. When the B channel is taken as the reference, then C for the channels are calculated as follows:

C1(F) = 6.364V/1.286V = 4.949

C2(B) = 6.363V/6.364V = 1.000

C3(cF) = 6.364V/0.828V = 7.686

C4(cB) = 6.364V/5.787V = 1.100

The value of f in Eqs. (1)-(3) is a constant related to the ratio of forward-scattered light to the total light scattered by the particles. The value ranges from about 0.52 to 0.57 depending on the liquid- or ice-nature of the cloud particles. For a detailed discussion of the derivation of f see Gerber et al. (2000).

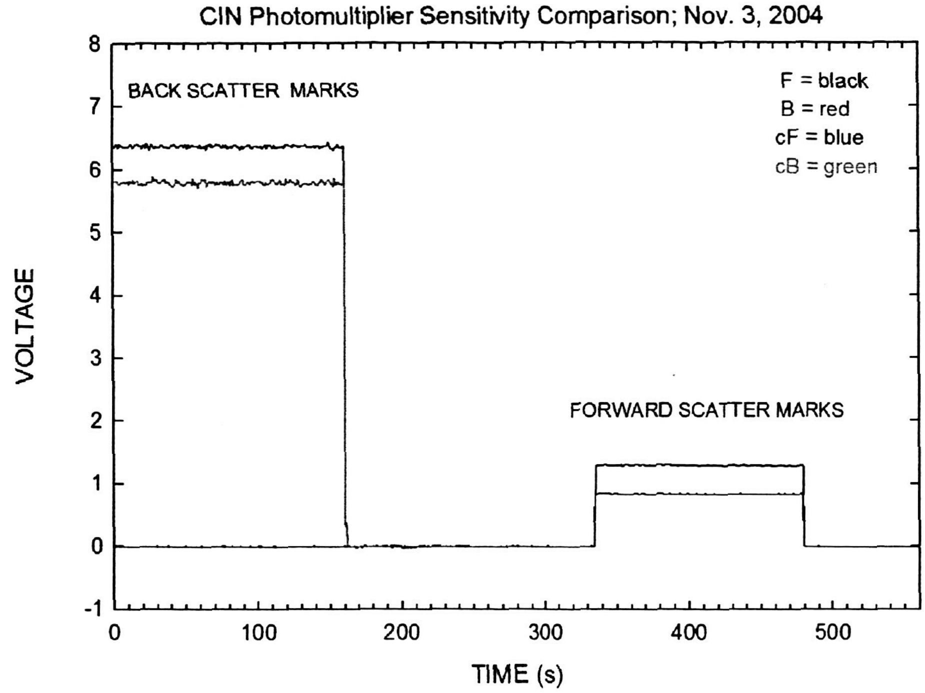


Fig. 5 - Comparison of the sensitivity of the four channels of the CIN in order to determine the scaling constant C1, C2, C3, C4. The marks relate to the location where the light-diffusing bar is positioned.

3.2 Original Determination of the Scaling Constant C5

Given that the extc. is proportional to the integrated surface area for large-enough cloud droplets according to Mie theory, it is possible to determine the CIN scaling constant C5 by relating PSA (particle Surface Area) measured by the PVM Particle Volume Monitor (Gerber et al, 1994) to the CIN output measured in the same cloud. The relationship between PSA and CIN measuremtns is given by

$$C5 = [0.05\ (1-f)\ PSA]/[(F \times C1) + (B \times C2)] \quad (\mathrm{volt}^{-1}\ \mathrm{km}^{-1}) \tag{4}$$

This method was used to scale the CIN in the FIRE/ACE and C-F studies. C5 = 9.25 (V km^{-1}) for C-F. For The accuracy of C5 determined in this fashion depends, of course, on the reliability of the PSA measured by the PVM. The PSA measurement is traceable to the original PVM calibrations done in the Petten, The Netherlands continuous flow chamber (Gerber et al., 1994) where FSSP-100 measurements corrected with absolute measurements of liquid water content provided the basis for calibrating PSA.

While this published calibration description appears reliable, it nevertheless depends in part on the FSSP-100, which is not known for accurate measurements. This was a main motivation to doing the present work with the transmissometer which through its ability to measure extc. directly incloud can be considered an absolute means for calibration of the CIN.

3.3 Transmissometer Design

The basic design of a transmissometer suitable for incloud measurements is shown in Fig. 6.

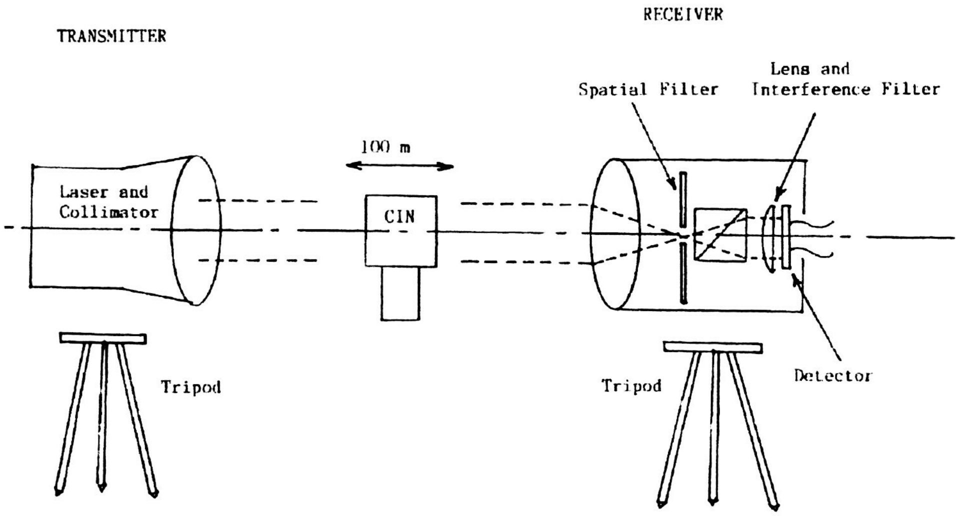


Fig. 6 - Sketch of the transmissometer components and the CIN location.

The transmissometer projects a beam of light over a sufficient distance so that a measurable part of the beam is lost by scattering on irradiated cloud particles. The receiver measures the direct beam during and after cloud episodes so that the extinction forms a ratio that can be used with Beer's law to calculate the extinction coefficient in the cloud. It is crucial for the proper performance of the transmissometer that both the transmitter and receiver for the laser beam are highly collimated so that a minimal amount of light is forward scattered into the receiver optics. The divergence of the beam at the transmitter end can be controlled readily, because a laser beam (HeNe) is used which already has a small amount of divergence. By adding a beam expander to the laser, a very small amount of beam divergence can be achieved; 0.02 deg. for the HeNe laser used here.

To achieve a narrow field of view at the receiver end of the transmissometer is somewhat more complex, given that a spatial filter consisting of a small pinhole must be used at the focal plane of the collecting lens of the receiver. "It is sufficient in practice if the angle subtended by the diameter of the pinhole at its lens is not more than one-tenth of the angle of the first angular minimum in the Fraunhofer diffraction pattern of a disc equal to the particle in projected area, i.e. not more than one-tenth of 3.84/alpha radians" (Davies, C.N., 1966); where alpha is the Mie parameter (3.1416 x drop diameter/ wavelength). Given this constraint and the desire to measure accurately the extinction due to drops in the laser beam up to a diameter of 20-um, it is possible to calculate the required pinhole diameter given the focal length of the collecting lens (~10cm). The pinhole required is ~400-um in diameter, which leads to a divergence of the receiver optics of 0.220 deg. Clearly, pointing accuracy of both transmitter and receiver of the transmissometer are critical given these small divergences.

The choice of 20-um diameter as the upper size limit that the transmissometer can measure accurately without requiring any corrections is not arbitrary. Given that the transmissometer comparison with the CIN was planned for a mountain top in a continental area suggests that clouds without precipitation will have droplet size spectra that are within this size limit.

The response of the transmissometer was tested in the laboratory. Filters with a known ND (neutral density) were placed between the transmitter and receiver to reduce the laser beam intensity by a known amount. The transmittance measured by the receiver was then compared to the transmittance expected from placing the filters in the path of the laser beam. Figure 7 shows the results of this test which illustrate that the transmissometer will provide a linear output with transmittance of the laser beam over at least two orders of magnitude of transmittance.

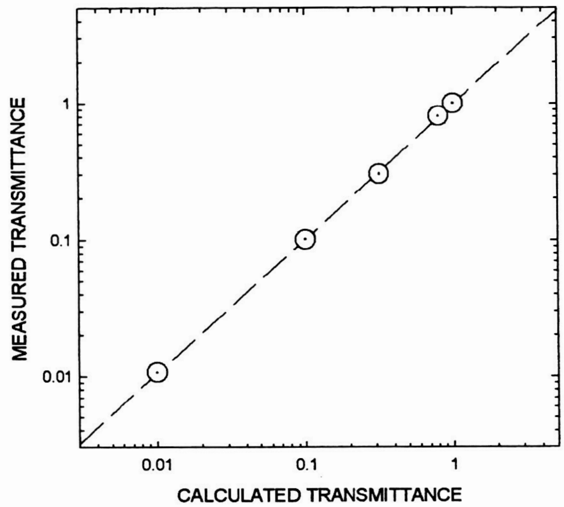
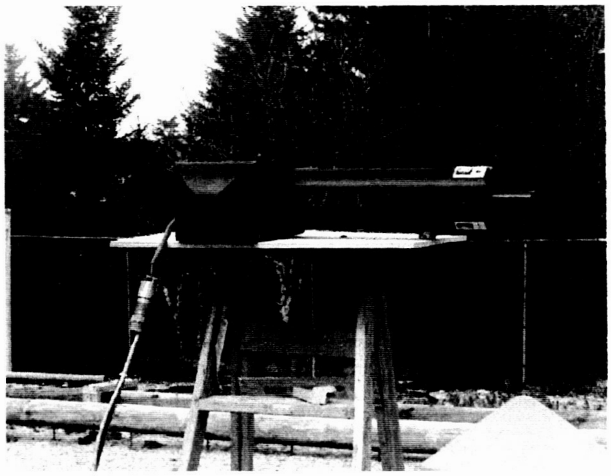


Fig. 7 - Laboratory test of the linearity of transmittance measured by the transmissometer

3.4 CIN and Transmissometer Comparison

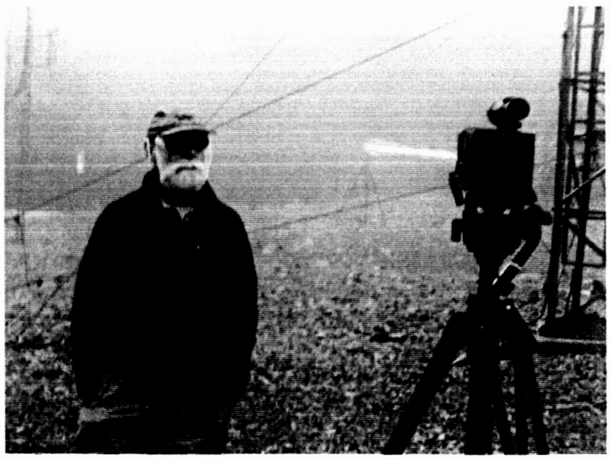
A field experiment was planned to expose simultaneously the transmissometer and the CIN to a cloudy atmosphere. A mountain top site was sought to improve the probability of experiencing cloud. Additional requirements were a site that gave limited access to the public, and where electrical power was available. On 30 June, 2004 a visit was paid to the U.S. Forest Service office at Mt. Rogers National Recreational Area in SW Virginia to further explore the possibility of using their site on the summit of 5,520 ft. Whitetop Mt. for our experiment. The Area Ranger, Elisabeth Merz, provided a tour of their facility on the mountain. The fenced in area on the summit of Whitetop Mt. is about 300 ft. square, has a gravel surface, some smaller buildings, and no vegetation. Small fir trees surround the outside of the fence; see Fig. 8. The people at the Forest Service proved to be exceptionally helpful, and promised to make power available for our effort.

The field experiment on Whitetop Mt. occurred on 22-26 Oct., 2004. The transmissometer was set up in the middle of the fenced-in area, with the transmitter and receiver separated by 100 ft. Figure 8 shows the transmissometer in operation during a cloudy period where scattered light from the laser beam is visible; the laser beam is about 6 ft. above the ground. The CIN was placed on top of a step ladder (Fig. 8) at a 6-ft. height above the ground and half way between the transmitter and receiver of the transmissometer. A small portable shelter was constructed to house data logger, computer, and power supplies.



a

b



c

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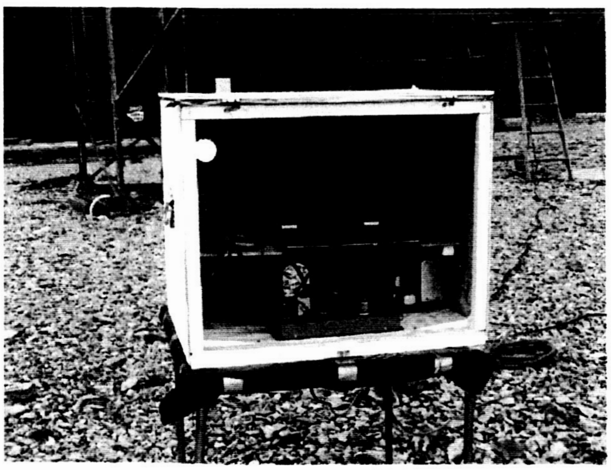

e

Fig. 8 - **a**. 5,520- ft. Whitetop Mt. with the summit covered in cloud. **b**. CIN in the position for measurements in the summit fenced enclosure. **c**. transmitter with laser beam scattering light in a cloud. **d**. receiver measuring laser beam intensity. **e**. portable shelter housing data logging components.

A suitable cloud episode occurred on the summit of Whitetop Mt. on 25 Oct. for comparing optical extinction measured by the transmissometer and the CIN. The cloud appeared just before sunrise and lasted for about 2 hrs. during which time continuous measurements were made at a rate of 10 hz. Figure 9 shows a

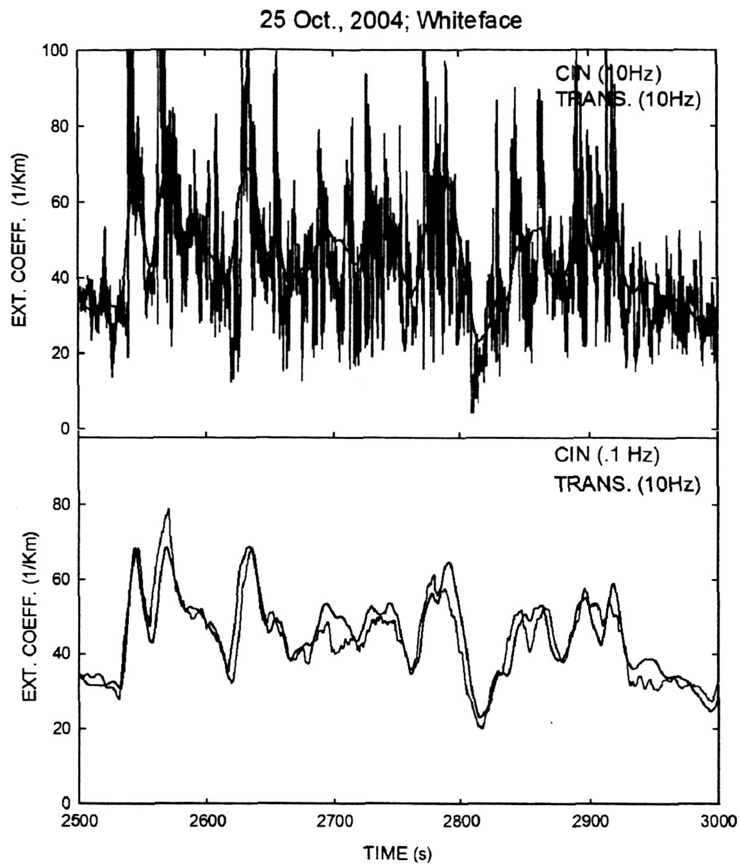

Fig. 9 - The optical extinction coefficient in a 500-s time segment measured by the transmissometer and the CIN on the summit of Whitetop Mt. On 25 Oct., 2004. The upper panel shows the data at 10 hz (rate of logger), and the lower panel shows the same data, but with the CIN data given a running average of 10 s.

a time segment of the 2-hr. data record for the transmissometer and the CIN. The upper panel in Fig. 9 shows much more variability in the CIN record than in the transmissometer record. The reason for this difference is the large difference in baselines for each instrument, with the transmissometer having a 100-ft. baseline, and the CIN only about 1ft. The CIN thus sees more clearly the fine structure of the cloud, whereas, the transmissometer's long baseline averages out the fine structures. In the lower panel the 10-hz CIN data has been averaged to an equivalent sampling rate of 0.1 hz which now causes the CIN data to correlate much better with the transmissometer data. The cloud was highly variable over the 2-hr. period with visibility (calculated from Koschmieder's equation) ranging between 36m to 592m.

The entire data set of extinction coefficients, calculated from about 70,000 measurements for each instrument, is shown in the scatter plot of Fig. 10.

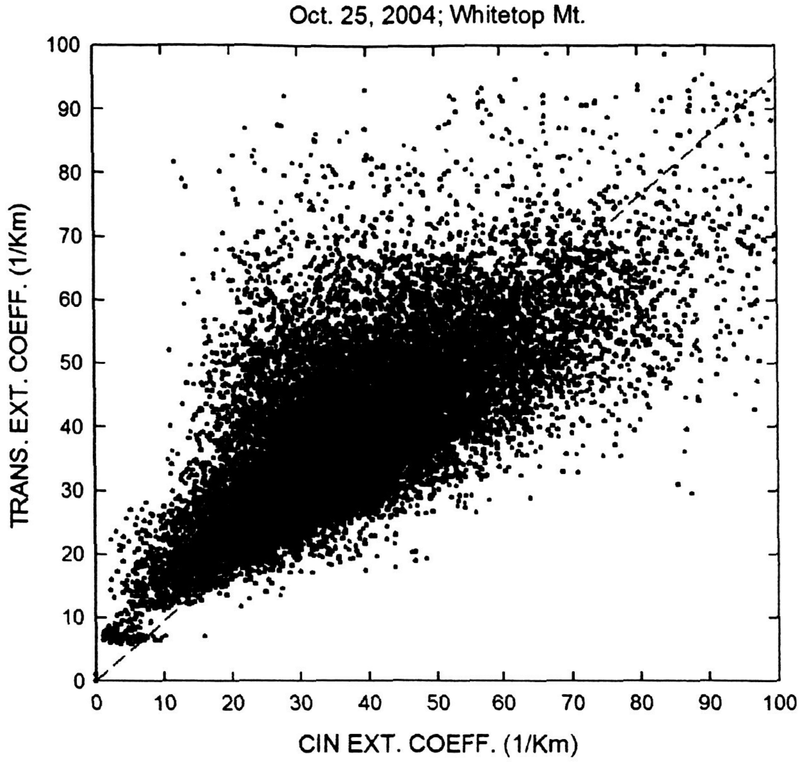

Fig. 10 - Two-hr. record of extinction coefficients measurements made during the cloud episode on the summit of Whiteface Mt. on 25 Oct., 2004. The red dashed line is the linear least-squares best fit to the data.

The linear regression line in Fig. 10 results in a ratio of exctc.(CIN)/exctc.(trans.) = 0.950; and the mean ratio of extc.(CIN)/extc.(trans.) = 0.988. Given these results it is possible to conclude that the earlier calibrations of the CIN that depended on using the the PSA channel of the PVM were done in an acceptable fashion. The value of C5 calculated from this transmissometer/CIN comparison and using Eq. (1) is 9.80 V km^{-1}.

4. Ice-Crystal Breakup on the CIN

A potential problem for aircraft cloud probes is that they cause breakup of ice crystals that impact probe surfaces. If the shards from this breakup enter the sensitive volume of the probes incorrect measurements will result. In the CIN such breakup would affect the measurement of the extinction coefficient, since the shards would present a larger surface area to the laser beam than would the original single ice crystal. This is a difficult problem with cloud probes to deal with quantitatively. However, there are several indirect indications that the breakup on the CIN does not play a significant role. They are as follow:

1. The approximately constant factor of 2 offset between the spectrometer extinction measurements and the CIN extinction measurements during all flights of the Citation in the C-F

study suggests that breakup is not important for those probes. Given that the clouds from C-F contained ice crystals of many shapes and sizes, and that some clouds contained only large liquid water drops (as on 9 July; see Fig. 4), it would be highly unlikely that these probes, differing greatly in geometry, would have the same measurement results from the breakup of ice crystals. Thus breakup likely was insignificant.

2. Alexi Korolev conducted a wind tunnel experiment (personal communication) where he attempted to quantify the ice-crystal breakup as a function of ice-crystal size. He found that only crystals with a diameter larger than about 500-um diameter had the propensity to generate breakup shards given impaction on surfaces of typical cloud probes. This may explain the lack of breakup evidence in the C-F measurements where the vast majority of ice crystal as observed using CPI (Cloud Particle Imager; Spec. Inc.) were significantly smaller than 500-um in diameter.

3. The present P.I. has looked at a large number of CPI images collected on the Citation flights during C-F. Shards closely associated with larger images of ice crystals, or unusual clusters of shards were not in evidence.

5. Streamline and Particle-Trajectory Analysis

Another potential source of incorrect measurements by the CIN is the possibility that the probe distorts the airflow during use on an aircraft in such a fashion as to affect the trajectory as well as composition (evaporation due to dynamic heating) of the cloud particles. These possibilities were investigated by Dr. Cynthia Twohy (Oregon State University) who applied computational-fluid-dynamics-software to the geometry of the CIN. Figure 11 shows

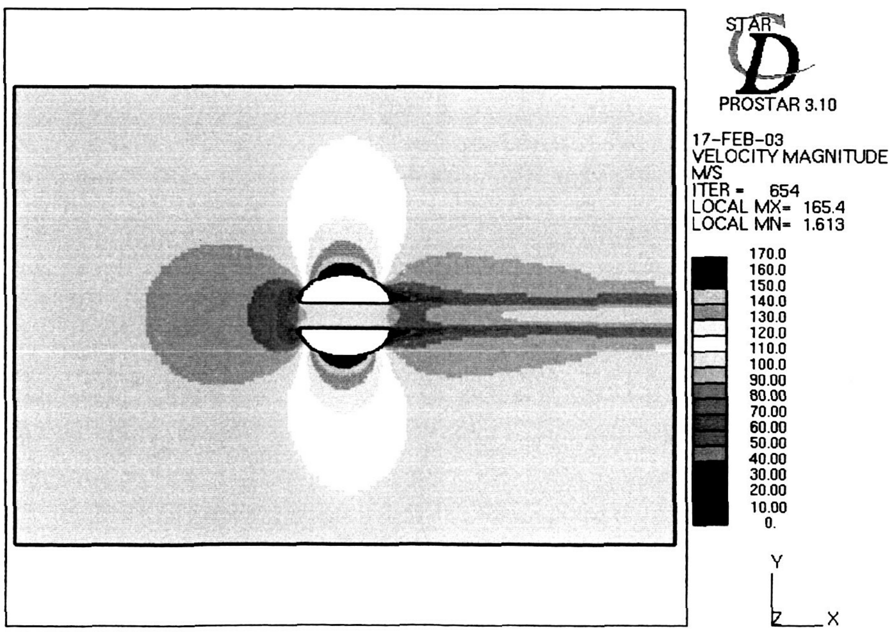

Fig. 11 - Velocity calculation around the wings of the CIN during simulated aircraft flight at 100 m/s. Air flow from the left.

the velocity pattern around the cross section of the wings of the CIN calculated by the fluid-dynamics software. The wings are a lengthy split elliptical strut down the center of which the laser beam irradiates the cloud particles; the detectors are located in the wings. The geometry of the two wings with respect to the flow constitutes two opposing airfoils for which the greatest velocity deviation from ambient flow occurs along the outside surfaces. There is some decelleration of the air as it approaches the probe causing some warming of the air; however, the flow between the wings relaxes and is again close to the ambient velocity. The design of the wings is the best tradeoff between disturbing the flow the least and shielding the detectors on the inside surface of the wings from excessive ambient light.

Figure 12 shows a closeup of the calculated velocities around the wings and arrows indicating the magnitude and direction of the streamlines.

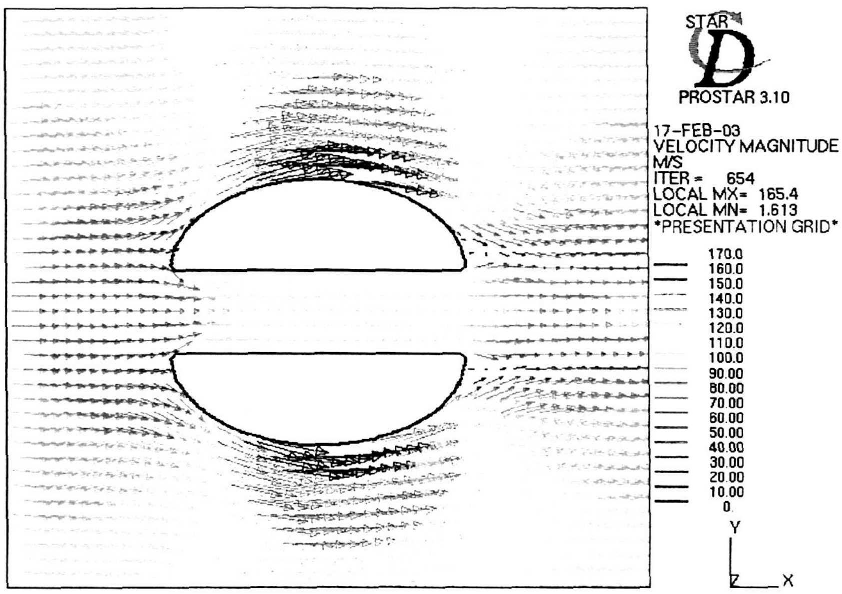

Fig. 12 - Velocities and streamlines of flow around the wings of the CIN. Flow is from the left and at 100 m/s. The wings are separated by 3.5 cm, and the cross section of the laser beam would appear as a 1-cm diameter circle centered in between the wings.

There is some distortion in the flow as it approaches the front of the wings, with flow deviating around the wings, and some flow being forced into the gap between the wings. However, along the centerline of the flow and coincident with the position of the laser, the deviation of the streamlines is minimal. These results suggest that during aircraft flight the CIN needs to be accurately pointed into the direction of the flow.

Figure 13 shows particle trajectory calculation that correspond to the flows shown in Figs. 11 and 12. The droplets size for these calculations were 10-um diameter. The separation between the trajectories in the oncoming flow is 1 cm. Some deviation is seen in the trajectories as they approach the CIN; however, by the time they have reached the location of the laser beam between the wings their separation is nearly identical to the ambient separation. This result indicates that the concentration of drops seen by the CIN should not deviate to a significant degree from the unaffected ambient concentration of the drops. The calculations were repeated for drop with a diameter of 100 um; less deviations were seen than for the smaller droplets given the greater inertia of the larger drops.

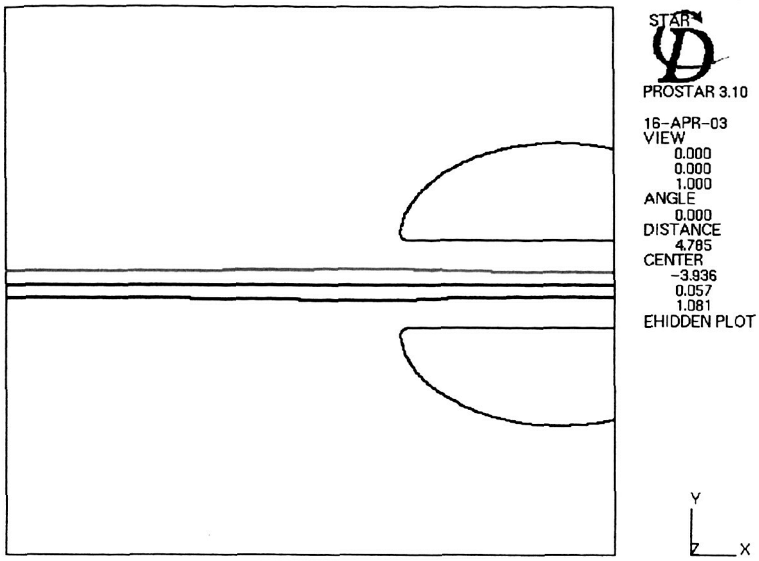

Fig. 13 - Trajectory calculations of drops 10-um in diameter embedded in flow from the left at 100 m/s. The center trajectory is on the central axis of the flow and of the location of the laser, and the other two are initially +/- 0.5 cm on either side of this axis

6. Accuracy of the CIN

The accuracy of CIN measurements depends on several factors which have been discussed here. The systematic errors of this measurement approach are described and estimated in Gerber et al (2000). These errors can range from a few percent to +/- 15% for optical extinction measurements, with the larger estimate corresponding to cases where the nothing is known about the composition of the cloud. If the cloud can be identified as either consisting of ice or liquid water the estimated systematic error significantly decreases.

The issue of ice-crystal breakup affecting the CIN measurements does not appear to be significant given evidence related to the ice-cloud measurements made co-located with other probes on the Citation aircraft during CRYSTAL-FACE study.

The calibration constant for the CIN are obtained from ground-based measurements, such as the transmissometer comparison described here. One could argue that these are not done at aircraft speed and thus could lead to errors in the aircraft measurements. The support for the validity of the calibration constants for aircraft use comes from two aspects: 1) the CIN response is independent of air speed, and 2) the fluid-dynamic flow and trajectory calculation done for the CIN indicate that neither the flow nor drop trajectories deviate significantly from ideal conditions.

The transmissometer measurements described here resulted in a scaling constant for the extinction coefficient measured by the CIN that agreed within about 5% of this constant obtained earlier by other means and utilized in the CRYSTAL-FACE CIN measurements. *This permits us to conclude that the factor of about 2 difference found between the CIN optical extinctions and those derived from the co-located NCAR particle size spectrometers on the Citation aircraft is not a result of mis-scaling the CIN.*

7. References

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8. Acknowlegments

Dr. Cynthia Twohy of Oregon State University is thanked for applying computation fluid dynamics calculations to flow and trajectory analyses of the CIN. The present work was supported by NASA Goddard, Grant No. NNG04GN436.

October 29, 2004

Elizabeth Merz, Area Ranger
USDA, U.S. Forest Service
Mt. Rogers National Recreation Area
George Washington and Jefferson National Forests
3714 Hwy. 16
Marion, VA 24354

Dear Ms. Merz,

I want to express my appreciation for you permitting our utilization of the Forest Service fenced enclosure on the summit of 5,500+ft. heigh Whitetop Mt. to calibrate a Cloud Integrating Nephelometer as required by a NASA research effort. This instrument is used by NASA for aircraft cloud measurements that are related to estimating the solar radiation balance in our atmosphere, and thus are also related to the broader issue of climate change. We found your facility at the summit to be ideal for these in-cloud calibration measurements which were essential for accurate application of the Nephelometer in ongoing and future aircraft studies. The weather on Whitetop may not have been ideal for most, but for us it was, given the high frequency cloud presence; we succeeded in getting excellent results for this important calibration.

I also wish to give special thanks to Bruce Cross from the Raleigh U.S. Forest Service office for coming a long way to make the modifications on the summit that gave us the needed electrical power.

With best regards,

Hermann E. Gerber
President, GERBER SCIENTIFIC INC.

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