Determination of the Size and Concentration of Cloud Drops with an FSSP

TODD A. CERNI

Department of Atmospheric Science, University of Wyoming, Laramie, WY 82071

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ABSTRACT

A detailed size calibration of the Forward Scattering Spectrometer Probe (FSSP) over the size ranges of interest to cloud physics (2–47 μm), is presented. The calibration includes laboratory tests with glass spheres, Mie scattering calculations and airborne cloud measurements. Each size bin of the FSSP was found to have errors of 0–5 μm in diameter. The magnitude and sign of the errors were dependent on airspeed for airspeeds greater than 55 m s^{-1}. This sizing error can lead to errors of 70% or more in derived cloud liquid water content. In addition, a concentration algorithm was derived from laboratory tests with pseudo-random pulse generators which properly corrects for probe dead time. After application of both calibration algorithms the instrument is capable of yielding mean diameters that agree with predicted mean diameters to within a few tenths of a micron and liquid water contents which are in good agreement with an independent liquid water measurement. Even after corrections, the instrument still produces significant artifical broadening of a cloud drop spectrum.

1. Introduction

The Forward Scattering Spectrometer Probe (FSSP-100), manufactured by Particle Measuring Systems, has come into wide use in cloud physics research and has replaced impactor slides as the preferred means of measuring cloud drop concentrations and spectra. Although the latter technique has received considerable scrutiny with respect to calibration and measurement accuracy, the former had received virtually none until the recent treatments by Pinnick *et al.* (1981), Personne *et al.* (1982). The Axially Scattering Spectrometer Probe (ASSP), predecessor to the FSSP, has been scrutinized by Jeck (1979) and Baumgardner (1983). This article contains a detailed analysis of the sizing errors present in an FSSP, an examination of the dependency of sizing on airspeed, an investigation of the dead time error, and develops conclusions which differ somewhat from those of Pinnick *et al.* (1981).

The following analysis is composed of four parts. First, an instrument calibration is developed by determining the instrument's response to glass beads of known size and refractive index, and employing Mie scattering calculations to transfer those results to water drops. Second, the dependence of sizing on airspeed is determined with the use of glass beads and an algorithm developed to correct for the effect. Third, pseudo-random pulse generators are used to simulate a stream of randomly spaced particles such that the probe's dead time correction for the calculation of concentration, can be empirically determined. Last, the effects of sizing errors on cloud drop spectra from continental cumulus are presented and a comparison is made between the FSSP derived liquid water contents and those measured with a calibrated Johnson–Williams hot wire device. This work concentrates on FSSP ranges 0 and 1 (nominally 2–47 μm and 2–32 μm respectively), or those of primary interest in cloud physics work.

The FSSP detects light pulses produced by scattering from individual cloud drops as they pass through a sample area of about 0.5 mm^2, which is illuminated by a focused laser beam. Each light pulse within the sample area is counted and sized by a 15 channel pulse height analyzer (PHA). If the laser wavelength, the drop's refractive index and the geometry of the collecting optics are known, then the scattered power is solely a function of the drop diameter. A more complete description of the FSSP can be found in Knollenberg (1976), Pinnick *et al.* (1981), Baumgardner and Dye (1982). The third reference gives a complete set of definitions of various terms and performance factors for the FSSP, and those definitions are common to this paper. For the FSSP owned and operated by the University of Wyoming, the total sample area has been determined to be 0.498 mm^2, the velocity acceptance fraction averages 0.46 at 100 m s^{-1}, and the fast and slow delay times have been measured at 3.0 and 6.5 μs respectively. It has a separate PHA for each of its four ranges.

2. Size calibration

Size distributions for the two glass bead samples used are shown in Fig. 1. These homogeneous glass spheres were photographed through a microscope and

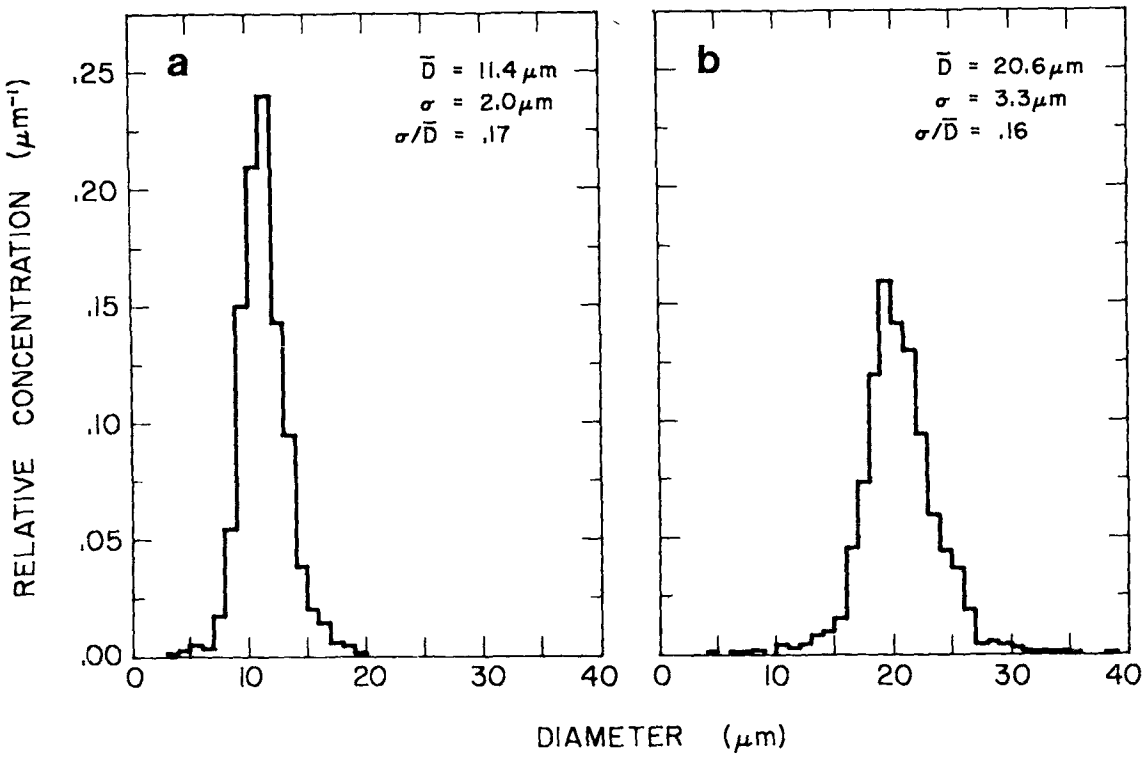

FIG. 1. Measured size distributions for the two glass bead samples. They represent the results of sizing a minimum of 1000 beads, and are presented without smoothing. The mean of the distribution is represented by $\bar{D}$, the standard deviation by σ, and the dispersion by $\sigma/\bar{D}$. The distribution is normalized to yield a total concentration of 1.0, (a) glass bead sample 1 and (b) sample 2.

the photographic images sized with a Zeiss TGZ3 particle size analyzer. The mean sizes and dispersions are similar to those observed for continental cumulus clouds and two bead samples were found to be adequate for the present calibration procedure. Glass bead calibrations are preferred over direct water drop calibrations because the former are non-volatile, easier to size and better represent a portable, reproduceable sample.

Calibration of the FSSP is based on the comparison of measured and predicted glass bead spectra. The former is obtained simply by passing the glass beads through the FSSP. The latter is calculated from Mie scattering theory, using the microscopically determined glass bead size distributions. The applicability of Mie theory to the FSSP has been demonstrated by Pinnick *et al.* (1981). Figure 2 shows the calculated results of signal versus diameter for glass and water spheres, for the scattering geometry measured for the Wyoming probe (collects scattered light over 4.6–12.8° in scattering angle). The code used to generate these results is that of Wiscombe (1979) and has been checked against the work of Wickramasinghe (1973) and Pinnick *et al.* (1981).

A properly calibrated FSSP would size a glass bead as if it were that diameter of water drop which produced the same scattered power into the instrument. The relative scattered power levels which correspond to each of the 16 PHA levels are fixed and different for each FSSP range (Appendix A). Results displayed

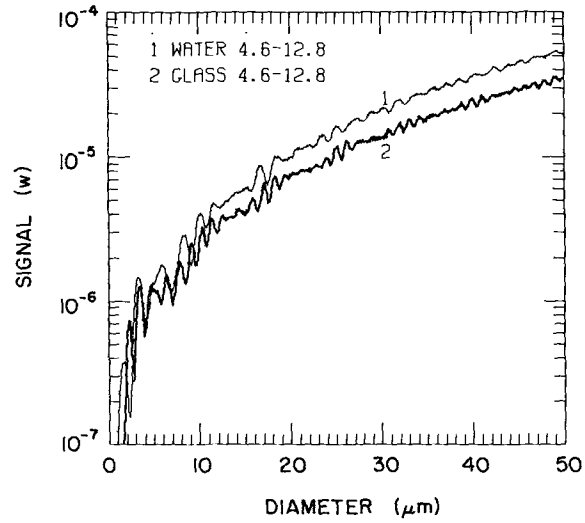

FIG. 2. FSSP signal versus diameter for water and glass spheres. The results were obtained using refractive indicies of 1.33-0.0i for water and 1.51-0.0i for glass. The laser wavelength was 0.6328 μm and the scattered light collected over 4.6–12.8° in scattering angle.

in Figs. 1 and 2, in conjunction with the measured relative PHA levels, can be employed to produce a predicted FSSP spectrum for a glass bead sample. Each relative PHA level was multiplied by a single (for each range) scaling factor to obtain a best fit of measured to predicted spectra mean diameters. The power level which then corresponds to each PHA level allows the 16 levels to be calibrated in terms of the diameter of a water sphere. Figure 3 displays the results which allow for this calibration. Figure 4 shows the resulting best fit of measured to predicted spectra, using the new size bin definitions. The criteria used to determine best fit was a match of measured and predicted spectra mean diameters. The mean was chosen over the mode because the average behavior of a polydispersion which passes through the sample area was judged to be more important and more precisely defined than the mode.

Table 1 shows two possible size bin definitions which result from this calibration procedure. The columns of Table 1 labeled smoothed Mie are the result of replacing the multiple valued Mie scattering curve for water with a fitted cubic polynomial (4). The columns of Table 1 labeled Mie are the result of using the multiple valued Mie scattering curve for water, in which case some PHA levels fall in a distinctly multiple valued portion of the water curve and must be dropped. The latter of these two size calibrations is the more physically correct and has a large impact on measured aerosol and fog size distributions (Pinnick *et al.*, 1981). The former is offered because it is consistent with the work which follows (Section 3) and does not make a large difference when applied to cloud drop distributions, where the vast majority of particles are larger than the region of greatest multiple valued behavior.

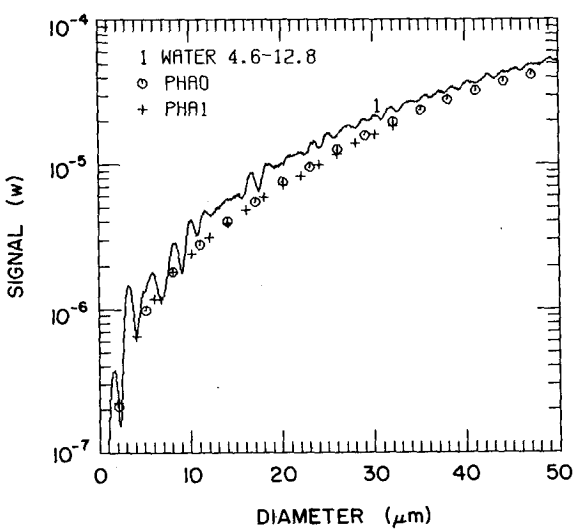

FIG. 3. FSSP signal versus diameter for water spheres, in addition to PHA levels for ranges 0 and 1. The water curve is the same as shown in Fig. 2. Each PHA level is plotted according to its original size definition and that signal level which resulted in the best fit of measured to predicted glass bead spectra (Fig. 4).

The original size calibration was performed periodically by the manufacturer and the instrument maintained to an accuracy of ± 1 μm with respect to that calibration. In Fig. 3, the horizontal distances between the water curve and the points representing each PHA level are the error in the original factory calibration for each level. Each bin of the FSSP was found to have errors of 0–5 μm, with the largest errors in the region $D \geqslant 20$ μm. Also of note from Fig. 3 is the fact that no scaling factor would be capable of forcing the 16 PHA levels, for either range, to coincide with a smoothed version of the water curve as they should (Knollenberg, 1976). This suggests that there were errors in the original (manufacturer's) scattering calculations.

Although measured and predicted glass bead mean diameters agree to within 0.2 μm (Fig. 4), measured standard deviations and liquid water contents are noticeably larger than predicted. This represents artificial broadening by the instrument. Using the data displayed in Figs. 4a–c for comparison, the broadening results in a 1.1 to 1.3 μm increase in standard deviation and a 10 to 21% increase in liquid water (when mismatch in mean diameters is accounted for). If one assumes that the instrumental broadening can be described according to

$$\sigma^2_{\text{measured}} = \sigma^2_{\text{predicted}} + \sigma^2_{\text{instrument}}, \qquad (1)$$

then $\sigma_{\text{instrument}}$ must be 2–3 μm. Causes for this spectra broadening have not been investigated, but one can speculate that it could be due to nonuniformity of the laser beam within the sample area.

3. Dependence of sizing on airspeed

The measured glass bead FSSP spectra presented in the preceding section were obtained at an airspeed of 45 m s^{-1} by pulling the beads through the sample area with a low pressure source. While this is the procedure most convenient for field operations and that suggested by the manufacturer, it does not simulate realistic cloud penetration speeds of 75–135 m s^{-1} achieved by the Wyoming King Air research aircraft. When glass beads were pushed through the sample area with a high pressure source, a substantial dependence of sizing on airspeed was discovered (Fig. 5). The airspeed was calculated from the transit time measurement contained within the FSSP. Although this airspeed determination is subject to any errors which may be inherent to the FSSP transit time circuitry, it is probably the best means of determining airspeed for the glass bead tests. The relationship between output of the FSSP transit time circuitry and the pulse width of simulated optical pulses was determined from laboratory tests. With knowledge of

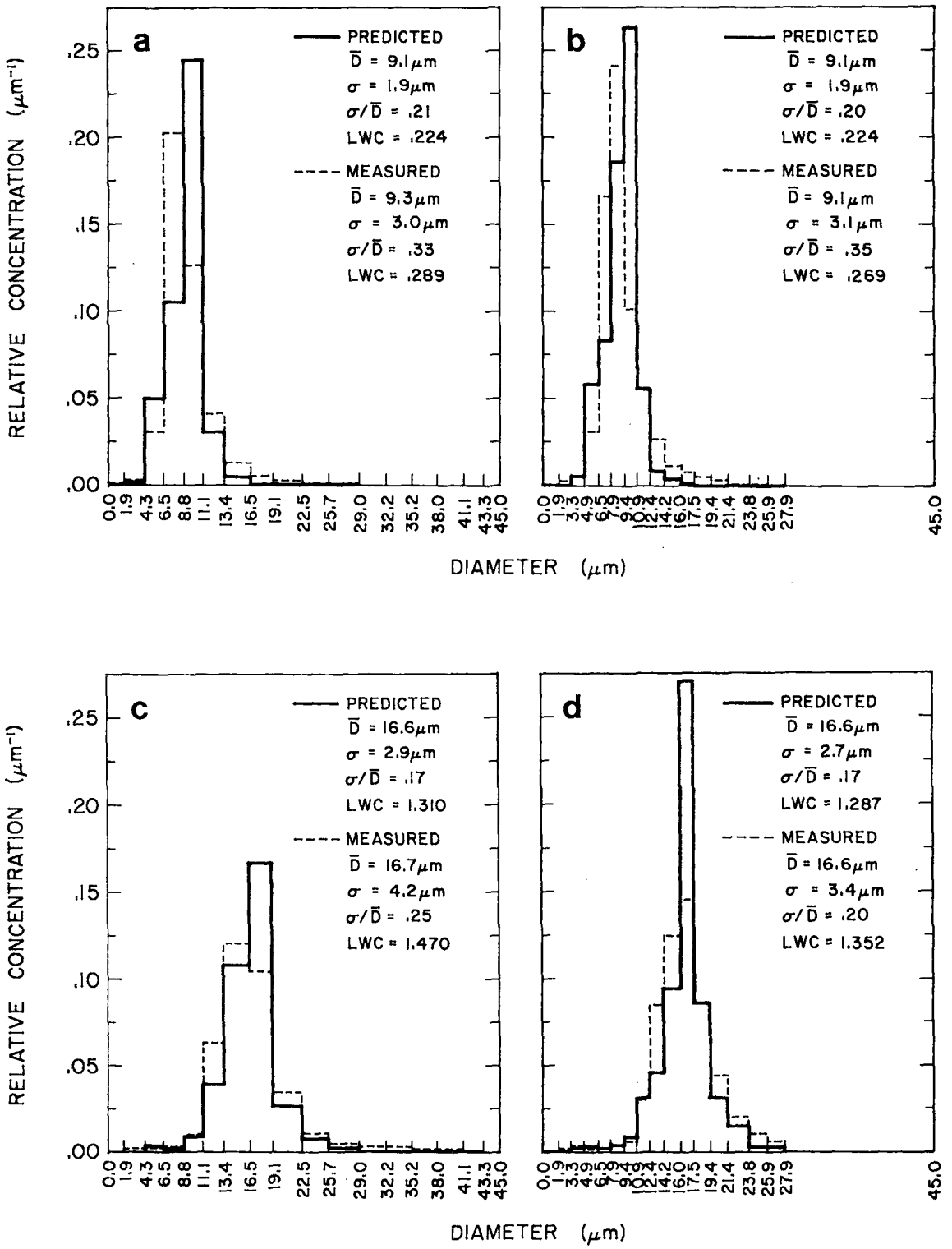

FIG. 4. Measured and predicted FSSP spectra for the two glass bead samples and the two FSSP ranges of interest. FSSP size bins represent a redefinition to produce a best fit between measured and predicted spectra. Glass bead sample 1 for (a) range 0 and (b) range 1. Sample 2, for (c) range 0 and (d) range 1. Mean diameter, standard deviation, dispersion, and relative concentration are the same as for Fig. 1. The liquid water content (LWC) represents the third moment of the distribution multiplied by a constant.

TABLE 1. FSSP size calibration. The columns labeled PMS refer to the manufacturer's calibration, the columns labeled Mie refer to the present work employing the exact Mie scattering curve for water and the columns labeled Smoothed Mie refer to the present work employing a single-valued approximation to the Mie scattering curve for water. All numbers refer to the calibration of a PHA level in terms of the diameter of a water sphere in μm.

	Range 0			Range 1		
PHA level	PMS	Smoothed Mie	Mie	PMS	Smoothed Mie	Mie
1	2.0	1.9	—	2.0	1.9	—
2	5.0	4.3	—	4.0	3.3	2.7
3	8.0	6.5	7.6	6.0	4.9	—
4	11.0	8.8	9.6	8.0	6.5	7.6
5	14.0	11.1	11.2	10.0	7.9	—
6	17.0	13.4	13.6	12.0	9.4	9.6
7	20.0	16.5	—	14.0	10.9	11.1
8	23.0	19.1	18.2	16.0	12.4	12.8
9	26.0	22.5	23.0	18.0	14.2	15.3
10	29.0	25.7	25.5	20.0	16.0	—
11	32.0	29.0	28.6	22.0	17.5	—
12	35.0	32.2	31.5	24.0	19.4	19.8
13	38.0	35.2	35.1	26.0	21.4	21.5
14	41.0	38.0	38.1	28.0	23.8	24.5
15	44.0	41.1	41.6	30.0	25.9	26.2
16	47.0	43.3	43.5	32.0	27.9	28.3

the laser beam width, this pulse width was then translated into airspeed. The test results of Fig. 5 can be fit with the curve

$$\left.\begin{aligned} \bar{D}_G &= 20.7, && TAS < 55 \\ \bar{D}_G &= 20.7 - a_2(TAS - 55)^{b_2}, && TAS \geqslant 55 \end{aligned}\right\}, \quad (2)$$

where $\bar{D}_G$ is the measured mean diameter of the glass bead spectra in μm, TAS is the (true) airspeed in m s^{-1}, a_2 equals 1.976×10^{-3}, and b_2 equals 1.751. Tests performed using simulated optical pulses indicate that high frequency roll off of the analogue electronics is responsible for this behavior.

The problem remains to find a means by which to incorporate this airspeed dependency into the calibration scheme. One approach to the problem is to use a different scaling factor for each airspeed, when calibrating the PHA levels as described in the preceding section. A plot of scaling factor versus predicted $\bar{D}_G$ was made and it was found that the data can be represented by the expression

$$\text{scale factor} = \frac{S_L}{(R_L S_{32})} = a_1 \bar{D}_G{}^{b_1}, \quad (3)$$

where S_L is the signal level in Watts corresponding to each PHA level, R_L is the relative value for a PHA level (normalized to level 16), S_{32} is the signal in Watts for a 32 μm diameter water sphere, a_1 equals 125.5 and b_1 equals -1.696, for FSSP range 1. It is not possible to proceed with an airspeed dependent calibration unless the actual Mie scattering curve for water can be replaced by a single-valued expression. The polynomial

$$S = C_0 + C_1 D_w + C_2 D_w{}^2 + C_3 D_w{}^3 \quad (4)$$

represents a good, smooth curve fit to the Mie scattering curve for water over the range of 2 to 50 μm. In (4), S is the signal in watts, D_w the diameter of a water sphere in μm, C_0 equals -2.641×10^{-7}, C_1 equals 2.260×10^{-7}, C_2 equals 1.361×10^{-8} and C_3 equals 7.462×10^{-11}. Finally S can be set equal to S_L, measured $\bar{D}_G$ can be set equal to predicted $\bar{D}_G$ and (2), (3), (4) combined to solve for D_w as a function of TAS. The resultant expression is very cumbersome, but can be represented to within 1% accuracy by the simple, second-order polynomial

$$D_{w,L} = A_L + B_L TAS + C_L TAS^2, \quad TAS \geqslant 55, \quad (5)$$

where $D_{w,L}$ is the water sphere diameter in μm corresponding to PHA level L, TAS is the true airspeed in m s^{-1} and A_L, B_L, C_L are different for each level L.

This procedure can be repeated for FSSP range 0. Table 2 gives the values for all required constants such that (5) can be used to calculate each PHA level as a function of airspeed.

4. Calculation of FSSP concentration

Calculation of particle concentration from measured particle rates is not a simple task. The calculation requires accurate knowledge of the true airspeed, the FSSP sample area and the FSSP dead time;

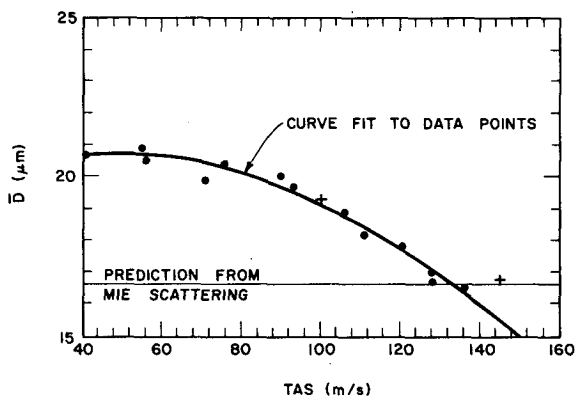

FIG. 5. Mean diameter for the glass bead FSSP spectra, obtained with glass bead sample 2 and FSSP range 1, versus (true) airspeed. The mean diameters were computed using the original bin size definitions. The dots represent the laboratory measurements (data). The crosses represent the manufacturer's nominal design goals (R. G. Knollenberg, private communication, 1982) for 1 dB and 3 dB high frequency roll-off of the analogue electronics.

the fraction of time during which the instrument cannot measure particles because it is busy processing pulses corresponding to preceding particles. A means of calculating concentration (CONC) is

$$\text{CONC} = \frac{P_1}{TAS \times S \times VA \times (1 - F)}, \quad (6)$$

where P_1 is the particle rate as accepted by the velocity acceptance circuitry, TAS is the true airspeed, S the sample area (the product of laser beam width and depth-of-field), VA is the velocity acceptance fraction and F the dead time fraction. Data have shown that VA is not a constant, as it should be. Therefore, better accuracy in concentration should be obtained by replacing P_1/VA with P_2, the particle rate through the sample area (the total strobe rate).

The greatest difficulty lies in estimating the factor F. Most of the FSSP's currently in use contain an activity counter which was intended to directly measure F. However, the manufacturer suggests that

$$F = K \times ACT, \quad (7)$$

where ACT is the output of the activity counter and K is a constant between zero and one, whose value is probe dependent. Laboratory tests have verified that the activity counter overestimates dead time.

A means has been devised by which the dead time fraction can be determined from laboratory tests. A stream of randomly spaced particles was simulated by a pseudo-random pulse generator which consisted of four unsynchronized multivibrators whose outputs were combined through an OR gate. The output of one pseudo-random pulse generator was applied to the cathode of the signal photodiode to simulate particles within the depth-of-field and the output of a second such generator was applied to the cathode of the annulus photodiode to simulate particles outside the depth-of-field. Both laboratory and field data are plotted in Fig. 6. The ratio of simulated particles within to out of the depth-of-field was that which gave the best match of laboratory to field data, for particle repetition rate versus activity. A least squares fit of (7) to the laboratory data yielded a value of 0.54 for K.

Hence, the concentration algorithm used for all field data presented in this paper is

$$\text{CONC} = \frac{P_2}{TAS \times S \times (1 - 0.54\,ACT)}. \quad (8)$$

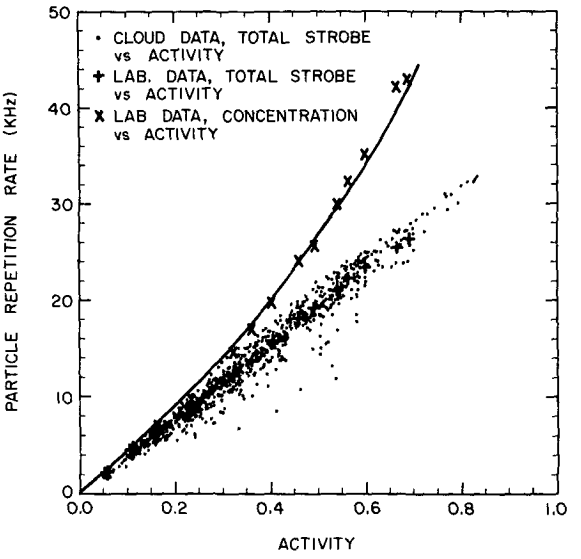

FIG. 6. A comparison of cloud data with the results of the laboratory tests using two pseudo-random pulse generators. The cloud data represent over 800 five second averages from the 1980 HIPLEX field season. The laboratory data are partially obscured by and immersed within the cloud data. The solid line represents the least squares fit: CONC = $P_2/(1 - 0.54\,ACT)$. At an airspeed of 100 m s^{-1}, a particle repetition rate of 20 KHz would correspond to a drop concentration of 402 cm^{-3}.

TABLE 2. Calibration coefficients.

	Range 0			Range 1		
Level	A_L	B_L	$C_L \times 10^4$	A_L	B_L	$C_L \times 10^4$
1	2.035	−0.005578	0.5033	2.155	−0.007686	0.6536
2	4.903	−0.02026	1.824	3.796	−0.01765	1.569
3	7.169	−0.02618	2.549	5.511	−0.02333	2.222
4	10.01	−0.04270	3.758	7.492	−0.03529	3.137
5	12.43	−0.04838	4.412	9.273	−0.04725	4.052
6	14.84	−0.05407	5.065	10.99	−0.05466	4.673
7	18.22	−0.06431	6.013	12.71	−0.06206	5.294
8	20.77	−0.06544	6.373	14.17	−0.06319	5.654
9	24.45	−0.07569	7.320	16.18	−0.07059	6.275
10	27.93	−0.08593	8.268	18.37	−0.08255	7.190
11	31.50	−0.09618	9.216	19.92	−0.08539	7.516
12	35.08	−0.1081	10.13	21.78	−0.08652	7.876
13	38.36	−0.1184	11.08	23.73	−0.08765	8.235
14	41.11	−0.1195	11.44	26.94	−0.1104	9.706
15	44.59	−0.1315	12.35	28.99	−0.1116	10.07
16	46.59	−0.1280	12.42	31.21	−0.1190	10.69

5. Cloud measurements

An examination of actual cloud measurements obtained with the FSSP serves two purposes. First, it provides a verification of laboratory calibrations through comparison with an independent measurement of liquid water content, and second, it demonstrates the effect of sizing errors on cloud drop spectra.

The Wyoming King Air research aircraft is equipped with a Johnson–Williams (JW) hot wire

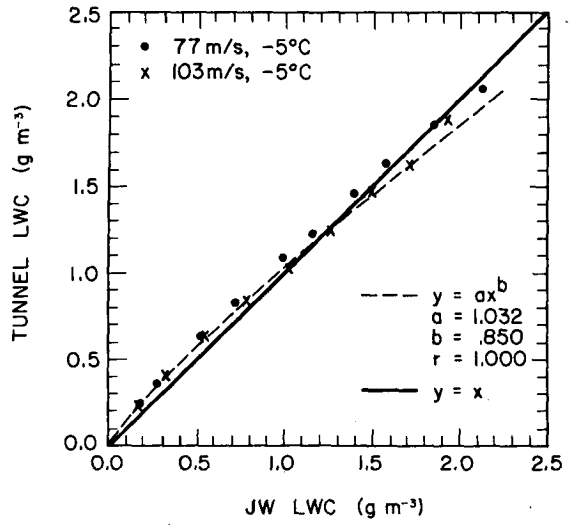

FIG. 7. November 1980 wind tunnel calibration of Wyoming JW head Number 227. Head 227 was used for all the 1980 HIPLEX data represented in this report. The dashed line represents a least squares fit to all the 103 m s^{-1} data points.

device as a second measurement of liquid water content. Calibration in a high speed, wet wind tunnel (Strapp and Schemenauer, 1982) has shown it to have errors of ≤ 0.1 g m^{-3} over the range of 0–2.0 g m^{-3} and very little airspeed dependence (see Fig. 7). In addition, Boatman (1981) has found the instrument to yield adiabatic liquid water contents in cloud regimes suspected of being adiabatic. There have been criticisms raised regarding the stability of the JW in certain airborne applications. The data presented in this paper has been carefully selected to avoid such periods of uncertainty. Comparisons of FSSP liquid water content to an independent measure of same provides a test of mean sizing accuracy, since liquid water is proportional to the third moment of a spectrum. The data set used for this spectrum consists of 670, 5 sec (~500 m) averages of penetrations by the Wyoming King Air through CuCg and one small Cb on 21 June, 2 July, 15 July, 19 July and 26 July 1980 as part of the 1980 HIPLEX[1] field season. Some characteristics of these continental cumuli are described in Cerni (1982). Figure 8 shows the substantial improvement in FSSP liquid water content brought about by the new size calibration (5). The original size calibration gave a liquid water content which was 72% larger than the JW. The new calibration gives a liquid water content which is 15% larger than the JW; consistent with the predictions from laboratory results that a properly calibrated FSSP would yield liquid water contents an average of 10–20% too large due to artificial spectra broadening.

Additional support for the calibration proposed in (4) can be found from an examination of the ratio of FSSP to JW liquid water contents versus certain other variables, such as airspeed, drop concentration and spectra mean drop diameter. Ideally, there should be no dependence of the liquid water ratio on these

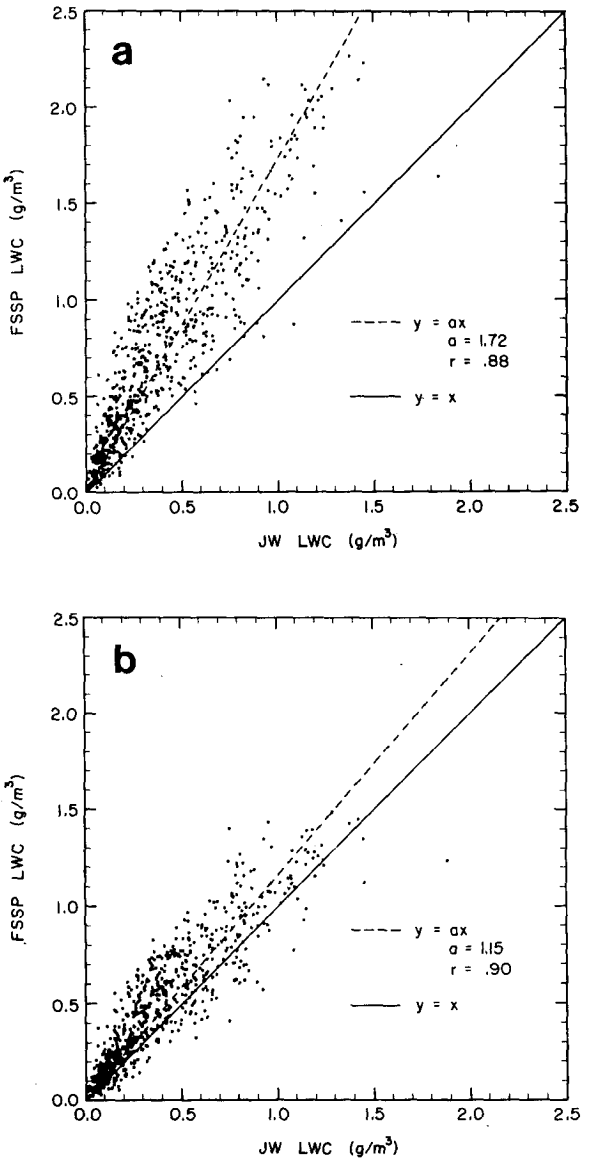

FIG. 8. Scatter plots of FSSP liquid water content versus JW liquid water content for 670 five second averages (~0.5 km) from the 1980 HIPLEX season. FSSP liquid water calculated using (a) the original FSSP size bin definitions and (b) the corrected [Eq. (5)] FSSP size bin definitions. For both figures, the JW liquid water was corrected using the wind tunnel results at 103 m s^{-1} and −5°C (Fig. 7). Dashed lines represent least squares fits to all the data points.

[1] HIPLEX is the High Plains Cooperative Experiment and is sponsored by the Bureau of Reclamation, Department of the Interior. The HIPLEX data reported here were collected at the Miles City, Montana, field site.

variables. For the same HIPLEX data set described earlier, the calibration (4) reduced the correlation coefficient between the liquid water ratio and airspeed to a mere 0.04. It had been 0.31 using the manufacturer's size calibration. The dependence of the liquid water ratio on concentration and mean diameter was also reduced to insignificant levels by the use of (4) as the correlation coefficients become 0.02 and 0.16, respectively.

Examples of the effect of sizing error on individual cloud drop spectra are shown in Figs. 9 and 10. The new calibration approximately reduces to the original around 130 m s^{-1}. At slower speeds the effects on mean diameter, standard deviation and liquid water content can be significant.

6. Comparison with other work

The issue of FSSP size calibration has been briefly dealt with by Cannon and Grotewold (1980) and in considerable detail by Pinnick *et al.* (1981). Both reports concluded that sizing errors were small and not consistently of one sign. The basic conclusions of Pinnick *et al.* (1981) were that FSSP sizing errors could significantly distort the shape of a fog, cloud or aerosol distribution, especially for diameters less than about 4 μm, but that liquid water content should be fairly accurate. Conversely, the present work has shown that a factory calibrated FSSP can consistently oversize cloud drops, with errors of up to 5 μm in diameter, and can lead to liquid water contents which are 70% too large.

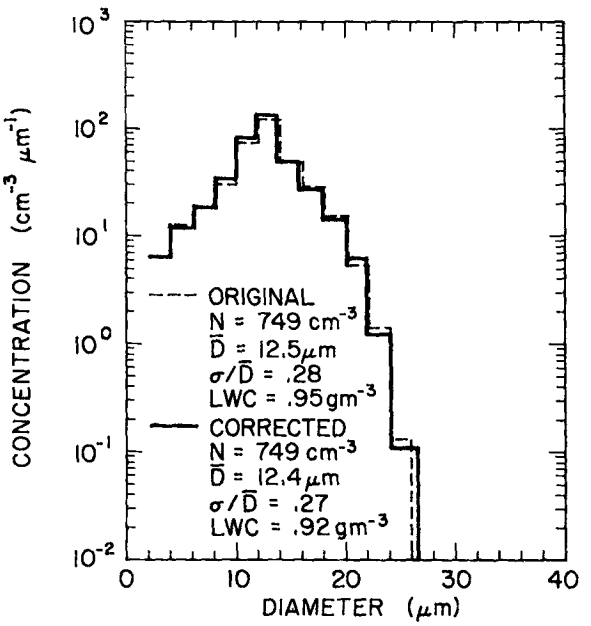

FIG. 9. A 1 s averaged FSSP cloud drop spectrum from a CuCg penetrated on 19 June 1980 as part of the 1980 HIPLEX field season. The spectrum is shown with both the original and corrected size bin definitions. The airspeed was 132 m s^{-1} and the FSSP range was 1.

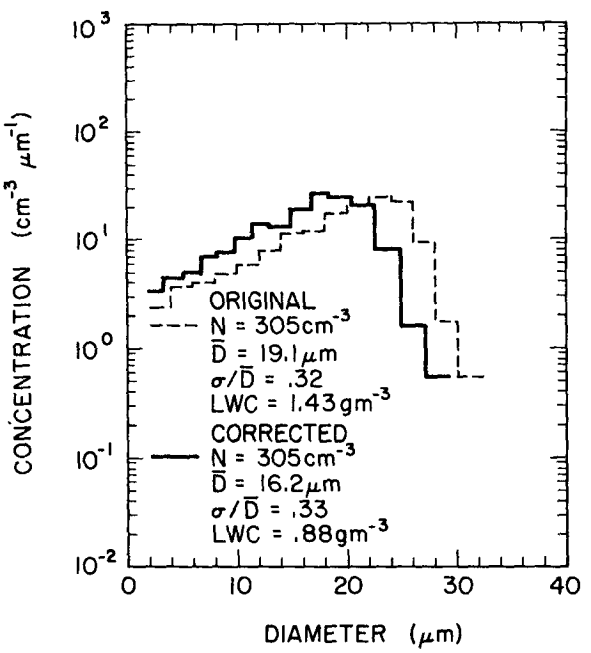

FIG. 10. A 1 s averaged FSSP cloud drop spectrum from a Cb penetrated on 10 June 1980 as part of the 1980 HIPLEX field season. The spectrum is shown with both the original and corrected size bin definitions. The airspeed was 90 m s^{-1} and the FSSP range was 1.

The difference between this and the two earlier reports is likely due to two reasons: differences between water drop spectra examined and differences between instruments. Although the size calibration procedure employed by Pinnick *et al.* (1981) and that described in this paper would seem on the surface to be very different, they are similar in principle and should be considered equally valid. The work of Pinnick *et al.* (1981) showed each bin of the FSSP to have sizing errors of 0–2.6 μm diameter, with consistent oversizing at 3 μm to 27 μm diameter, for range 1. When applied to a sample fog drop distribution, these sizing errors only lead to a 16% overestimate of the fog liquid water content. However, there are enormous differences between the fog drop distribution shown by Pinnick *et al.* (1981) and typical cloud drop distributions. The former has most of the drops and most of the liquid water content at sizes less than 5–10 μm in diameter, whereas the reverse is true for the latter. If one would apply their calibration results for FSSP range 1 to a cloud drop distribution, with mean volume diameters[2] of 11.6–17.4 μm, an overestimate

[2] If a spectrum were replaced with an equivalent monodisperse spectrum with the same drop concentration and same liquid water content, the drops of the monodisperse spectrum would have a diameter equal to the mean volume diameter of the original spectrum. Mean volume diameters of 10–20 μm are common for continental cumulus clouds. Those of Figs. 9 and 10, for instance, are 13.3 and 17.7 μm respectively for the corrected size bin definitions.

of 11–52% in liquid water content could result. Hence when their size calibration is applied to cloud drop spectra, the resulting errors in size and liquid water content can be significant and of the same sign, though smaller magnitude, as those presented in this paper. The second cause for disagreement is the fact that there can be significant differences between instruments of the same species (FSSP-100). Baumgardner and Dye (1982), reporting the results of a recent NCAR (National Center for Atmospheric Research) instrumentation workshop, noted large differences in the digital electronics used to compute drop concentration, the relative PHA levels, the geometry of the collecting optics and the sizing of a given glass bead sample. The instrument described by Pinnick *et al.* (1981) had approximately the same PHA levels as the instrument described here, but collected scattered light over significantly different angles; see Pinnick *et al.* for a discussion of the effects of such differences. No description was given for the instrument used by Cannon and Grotewald (1980).

Personne *et al.* (1982), in a comparative study of FSSP and JW liquid water measurements, did not discover any FSSP sizing errors. Their FSSP and JW calibrations were based on a statistical procedure which forced agreement between the two liquid water contents. The present work has demonstrated good agreement between these two liquid water measurements through independent calibration of each instrument.

Jeck (1979) performed a size calibration on an ASSP using methods similar to those described in Section 2 of this paper. He found that the ASSP had significant sizing errors, typically on the order of 2–4 μm for the 2–32 μm range, and artificially broadened a spectrum by a considerable amount. The results reported by Jeck (1979) are in good agreement with those reported in Section 2 of this paper.

None of the aforementioned authors have dealt with the problems of airspeed dependent sizing or a means for determining the proper dead time correction for the concentration algorithm.

7. Conclusions

The conclusions which follow pertain primarily to FSSP ranges 0 and 1, or those most pertinent to cloud physics work. Results of a recent NCAR workshop (Baumgardner and Dye, 1982) suggest that the FSSP-100 has been manufactured in different configurations over the years. Modification of the calibration coefficients presented in Table 2 will be required for instruments which were originally calibrated or configured differently than the one described here.

- Each bin of the FSSP was found to have errors of 0–5 μm in diameter, for airspeeds less than 55 m s^{-1}, with the largest errors occurring at diameters greater than 20 μm. The magnitude and sign of this error was dependent upon airspeed for airspeeds greater than 55 m s^{-1}. This sizing error can lead to errors of 70% or greater in cloud liquid water content.
- A calibration procedure is described whereby the FSSP sizing errors can be corrected to yield mean diameters which agree with predicted mean diameters to within a few tenths of a micron. These corrections can be made entirely with software and require no hardware adjustments. These corrections have little effect on the dispersion of a spectrum, but have a significant effect on the mean diameter, standard deviation and liquid water content. The corrected liquid water content was shown to yield good agreement with an independent measurement of liquid water.
- The FSSP artificially broadens a cloud drop spectrum. This produces a significant increase in dispersion and a liquid water content which is an average of 10–20% too large, for typical continental cumulus spectra. The minimum spectra standard deviation which can be resolved by the instrument appears to be 2–3 μm.
- A laboratory procedure was developed whereby the probe's dead time can be accurately determined. The output of the activity counter provides an overestimate of dead time.

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APPENDIX

Pulse Height Analyzer Levels

The relative PHA levels of the FSSP must be incorporated into any calibration scheme proposed for the instrument. Those levels are not the same for all FSSP-100's which have been sold by PMS. The relative PHA levels were measured for the instrument described in this paper and the measured values incorporated into the calibration scheme described in the text. The measured values differed from those listed in the instrument operating manual by an average of less than 3%; both are listed in Table A1.

TABLE A1. Relative Pulse Height Analyzer levels.

Level	Range 0		Range 1	
	Instrument manual	Measured	Instrument manual	Measured
16	1.0000	1.000	1.0000	1.000
15	0.8789	0.902	0.8560	0.876
14	0.7658	0.780	0.7298	0.756
13	0.6591	0.677	0.6195	0.634
12	0.5583	0.573	0.5230	0.537
11	0.4640	0.476	0.4398	0.451
10	0.3765	0.384	0.3733	0.380
9	0.2976	0.305	0.3163	0.323
8	0.2299	0.232	0.2595	0.262
7	0.1760	0.183	0.2092	0.213
6	0.1328	0.132	0.1679	0.171
5	0.0970	0.0976	0.1301	0.132
4	0.0679	0.0683	0.0955	0.0988
3	0.0442	0.0439	0.0645	0.0646
2	0.0244	0.0238	0.0366	0.0354
1	0.0059	0.0051	0.0128	0.0122

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