Calibration of Knollenberg FSSP Light-Scattering Counters for Measurement of Cloud Droplets

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ABSTRACT

Measurement of cloud drop size distributions with the Knollenberg model FSSP-100 light-scattering counter can lead to artificial bumps or knees in the distributions at ~0.6 μm and sometimes 2–4 μm radius if the manufacturer-supplied calibration is used. These artifacts are a consequence of the instrument having multivalued or slowly changing response in these regions of particle size. A modified calibration procedure is given that removes these artifacts so that the true droplet size distribution can be obtained. Measurement of slightly nonspherical particles with refractive indexes characteristic of those of atmospheric aerosols will generally lead to undersizing if the FSSP manufacturer-calibration is used, but likely by not more than a factor 2.

1. Introduction

A number of investigators have used (Stephens *et al.*, 1978; Heymsfield *et al.*, 1979) or are presently using (several papers in the *Proceedings of the 8th International Cloud Physics Conference*, Clermont-Ferrand, France, 15–19 July 1980) the Knollenberg Forward Scattering Spectrometer Probe (FSSP-100) to determine the drop size distribution or liquid water content in atmospheric cloud. This device[2] works on the principle that as droplets flow through an illuminated volume, laser-light scattered by a single drop into a particular near-forward solid angle is measured and used to determine droplet size by electronically classifying response pulses according to their magnitude. Determination of drop size from the response is indirect because of the dependence of the response on factors other than particle size, namely, the refractive index of the drop and the lens geometry of the counter optical system. In the previously reported studies the manufacturer-supplied calibration is used to determine the drop size (and by integrating the drop size, liquid water content) from the instrument response voltages.

We show in this paper that this procedure can lead to artificial peaks in the resulting drop size spectrum that are peculiar to the instrument and not real; and offer a calibration procedure (slightly different than that supplied by the manufacturer) that removes these instrumental artifacts. Our calibration procedure, which has been described for the similar Knollenberg CSASP-100 counter in an earlier paper (Pinnick and Auvermann, 1979), involves grouping size channels so that regions of multivalued responses are avoided. As a result the size resolution of the instrument is somewhat reduced (as compared to that inferred from the manufacturer-supplied calibration), particularly for droplets in the 0.5–4 μm radius range. For larger particles our calibration differs little from the manufacturer's, in agreement with the findings of Cannon and Grotewold (1980).

Our calibration is based on Mie calculations of the instrument's response (to water drops) which have in turn been experimentally verified for various kinds of uniform particles. Thus in Section 2 this verification is discussed. In Section 3 data collected with an FSSP in atmospheric fog is reduced to drop size distribution in two ways: using the manufacturer-calibration and using our Mie-calibration. Differences are greatest in the 0.5–2 μm radius range where particles are comparable in size to the wavelength of the FSSP (He-Ne) laser source. In Section 4 calibration of the FSSP instrument for measurement of spherical particles other than water droplets is discussed; in Section 5 some results and comments are offered on measurement of slightly irregular particles, and in Section 6 FSSP sampling losses are investigated.

2. FSSP response characteristics

Our conjecture is that the FSSP response can be calculated assuming plane wave scattering by a sphere; i.e., by assuming the well-known Mie theory.

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[2] Manufactured by Particle Measuring Systems, Inc. (PMS), Boulder, CO.

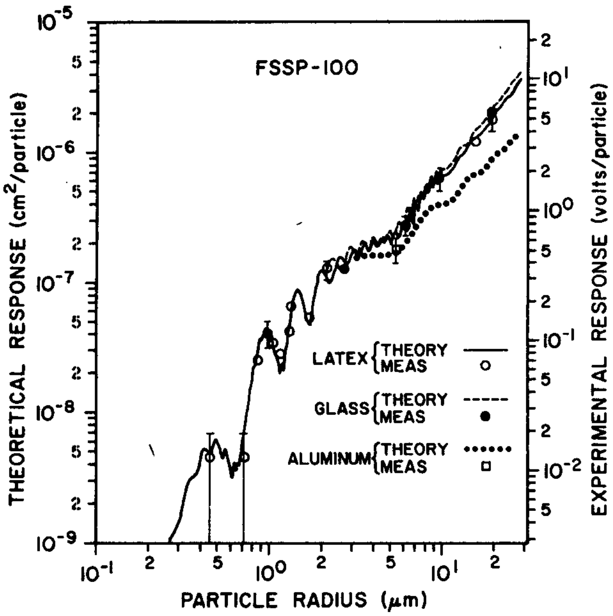

FIG. 1. Comparison of the Knollenberg FSSP response: measured for latex spheres with refractive index $m = 1.588-0i$ (open circles), glass beads with $m = 1.51-0i$ (closed circles), and aluminum spheres with $m = 1.44-3.69i$ (squares); and calculated using Mie scattering theory (smooth curves). The latex particles used include particle diameters 0.945, 1.48, 1.74, 32.2 and 40 μm polystyrene; 2.02, 2.154 and 2.35 μm polyvinyltoluene; and 2.70, 2.77, 3.44, and 4.33 μm styrene divinylbenzene. The theoretical curves for glass beads and aluminum extend only down to ~3 μm radius.

These calculations must of course take into account the particle size and refractive index, the wavelength of the FSSP laser source, and the geometry of the instrument optics. Although such calculations are straightforward and have been reported previously (Pinnick and Auvermann, 1979), there are some minor complications caused by focusing of the laser source (not considered before) that are addressed in Appendix A.

To check the validity of the response calculations, we measured the FSSP response to uniform particles of known size and refractive index: spherical particles of polystyrene, polyvinyltoluene and styrene divinylbenzene latex, glass beads, and aluminum were used. The results are summarized in Fig. 1 where the theoretical response is expressed in cross section per particle and the measured response in volts per particle. The experimental scale has been normalized to the theoretical scale to achieve best agreement between experiment and theory for the latex particles. The resulting normalization factor ($C = 2.8 \times 10^6$ V cm^{-2}) was used for the remaining experimental data.

It is clearly evident in Fig. 1 that the theoretical response for the FSSP is corroborated by measurements of uniform particles having three markedly different indexes of refraction and having radii 1–20 μm. In particular, note that the second latex resonance around 1 μm radius (where a number of latex particle sizes are available) is borne out well by the measurements. Further, similar measurements on uniform latex particles with a different FSSP instrument are in agreement with these results (S. G. Jennings, private communication, 1980). Thus, the theoretical response calculations adequately predict the FSSP response for spheres, regardless of effects that may be caused by multimode operation of the instrument laser source that might render the plane wave assumption in Mie theory invalid.

When making cloud or fog measurements with the FSSP, it follows we should rely on the theoretical response curve for water particles shown in Fig. 2, rather than the manufacturer-suggested calibration, which is also shown in the figure for comparison. (The details of how the manufacturer calibration is plotted in Fig. 2 appear in Appendix B.) A word of caution is in order concerning use of the theoretical curve to redefine size channels. Channels should be grouped with less size resolution than the response curve dictates because, in practice, spectra broadening effects result in some cross-channel sensitivity. Thus, channels set near regions of multivalued response and narrow size channels (in regions where the response curve is steep) should be avoided.

A comparison of the manufacturer's calibration for the FSSP and our calibration (which takes into

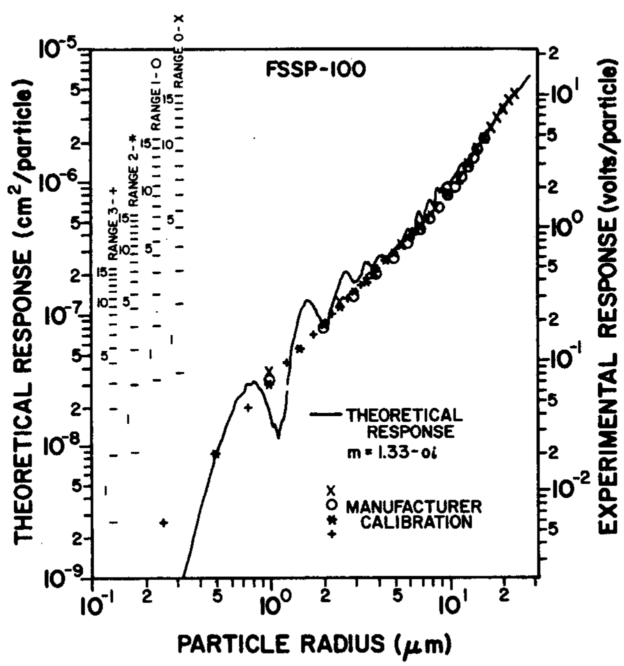

FIG. 2. Relation between the FSSP response and water drop size as predicted by theory (smooth curve), and as advertised by the manufacturer (points). The pulse height discriminator level settings (for ranges 0, 1, 2 and 3) utilized in this particular instrument are also shown.

TABLE 1. Particle size channel widths (radii in micrometers) for the Knollenberg FSSP light scattering aerosol counter: (a) as specified by PMS and (b) present work, under the assumption that particles are water droplets.

	Instrument range							
	0		1		2		3	
Channel	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
1	1.0–2.5	–	1.0–2.0	–	0.5–1.0	0.5–	0.25–0.5	–
2	2.5–4.0	–	2.0–3.0	1.4–	1.0–1.5	–1.4	0.50–0.75	0.5–
3	4.0–5.5	3.2–5.4	3.0–4.0	–3.1	1.5–2.0	1.4–	0.75–1.0	–
4	5.5–7.0	5.4–	4.0–5.0	3.1–	2.0–2.5	–	1.00–1.25	–
5	7.0–8.5	–7.6	5.0–6.0	–5.8	2.5–3.0	–	1.25–1.5	–
6	8.5–10	7.6–	6.0–7.0	5.8–	3.0–3.5	–	1.50–1.75	–1.4
7	10–11.5	–10.7	7.0–8.0	–7.1	3.5–4.0	–3.3	1.75–2.0	1.4–
8	11.5–13	10.7–	8.0–9.0	7.1–	4.0–4.5	3.3–	2.00–2.25	–
9	13–14.5	–14.2	9.0–10	–8.7	4.5–5.0	–5.1	2.25–2.5	–
10	14.5–16	14.2–	10–11	8.7–	5.0–5.5	5.1–	2.50–2.75	–
11	16–17.5	–18	11–12	–11.3	5.5–6.0	–	2.75–3.0	–
12	17.5–19	18–	12–13	11.3–	6.0–6.5	–6.4	3.00–3.25	–2.5
13	19–20.5	–21.4	13–14	–13.5	6.5–7.0	6.4–	3.25–3.5	2.5–
14	20.5–22	21.4–	14–15	13.5–	7.0–7.5	–	3.5–3.75	–
15	22–23.5	–24.6	15–16	–16.2	7.5–8.0	–7.5	3.75–4.0	–3.6

account the theoretical response curve for water and the spectra broadening considerations) is presented in Table 1. We caution the reader that our calibration shown in Table 1 can only be used for FSSP instruments with discriminator levels set as they are for our particular instrument. FSSP instruments with different discriminator level settings would of course require different channel groupings and size definitions (see Appendix B).

3. FSSP fog measurements

To demonstrate the difference between invoking the manufacturer-calibration and our Mie calibration for some real data, we chose some fog measurements made during April 1978 near Meppen, Germany. The measurements were made with an aspirated FSSP at 2 m above ground level operated in a range-cycling mode allowing maximum use of the dynamic range of the instrument. In this mode droplets in four overlapping size ranges are measured sequentially and we have combined the data for a 5 min time interval into a single size distribution. Actually the instrument cycled through a complete set of measurements in a shorter time (50 s) but because the fog was relatively stable we chose to integrate over a longer period to reduce statistical counting errors.

The drop size distributions obtained from these measurements are displayed in Fig. 3; the dashed curve derives from the manufacturer-calibration, and the solid curve from our Mie calibration. [In both distributions the data from the first channel (of range 3) has been ignored because it was suspect.] We note that the distribution derived from our calibration has fewer size channels, which results from the fact that we cannot use pulse height discriminator levels set in regions of multivalued response—such channels must be grouped together to avoid these regions. In fact, the peaks around 0.6 and 2 μm radius that appear in the distribution derived from the manufacturer-calibration we suggest are a consequence of particle pile up in channels where the response is multi-valued or slowly changing. Thus the overall shape of the manufacturer-

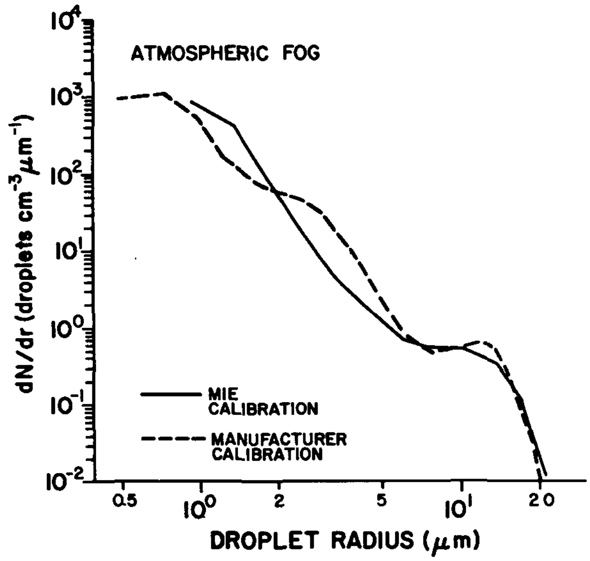

FIG. 3. Comparison of FSSP fog drop size distributions obtained in two ways: one using the manufacturer-supplied calibration (dashed curve) and the other using our suggested calibration based on the theoretical response curve of Fig. 2 (solid curve). The peaks that appear around 0.6 and 2 μm radius in the dashed-curve distribution are believed to be artifacts caused by multivalued response characteristics of the FSSP instrument.

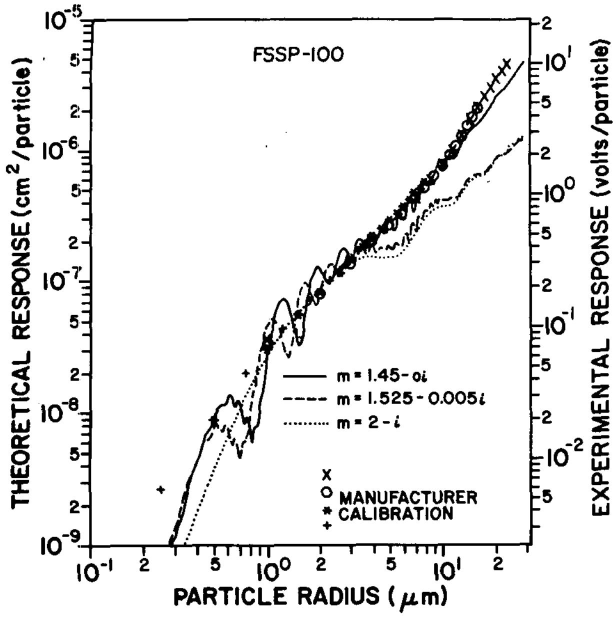

FIG. 4. FSSP response curves for particles with refractive indexes characteristic of those of atmospheric constituents: soil-derived aerosols with $m = 1.525-0.005i$ (Grams *et al.*, 1974), desert aerosols with $m = 1.45-0i$ (Reagan *et al.*, 1980), and carbonaceous aerosol with $m = 2-i$. The manufacturer-supplied calibration relating instrument response to particle size is shown for comparison.

calibration derived distribution is correct, but it contains artificial humps, knees and points of inflection near sizes where the Mie response function oscillates. These artifacts can only be expected to appear if the instrument is properly aligned and calibrated (otherwise the Mie resonances may not be resolvable). Another factor that can contribute to the washing out of these artifacts is the sampling of fog or cloud droplets for a period during which the droplet size distribution is continually changing. The artifacts may not appear for haze aerosol unless the particles are homogeneous and spherical.

The differences in the drop size distributions in the 10–15 μm region (where the manufacturer-calibration derived distribution shows a more pronounced peak) result from the slightly different character of the response curves in this region (see Fig. 2).

Finally, we note that the liquid water contents for the distributions in Fig. 3 differ by only 16% (the Mie calibration resulting in lower liquid content), suggesting the manufacturer calibration is adequate for liquid water content determinations in cloud and fog. It turns out the differences in extinction coefficients calculated from these distributions are also small; we found the extinction coefficient to be 28% lower for the Mie calibration at a wavelength $\lambda = 0.55$ μm, 26% lower at $\lambda = 4$ μm, and 16% lower at $\lambda = 10$ μm. Comparisons of liquid water content and extinction coefficients for a wide range of fog measurements gave similar (but usually smaller) differences.

4. FSSP measurements of other spherical particles

Measurement of particles other than fog or cloud with the FSSP requires a different calibration. If the particles are homogeneous spheres, then the calibration can be easily worked out from the response curves (by grouping channels together to avoid regions of multivalued response) much in the same way as for water. Examples of response curves for several refractive indexes characteristic of atmospheric aerosol constituents are shown in Fig. 4. As is evident from the figure the positions of the resonances are refractive index dependent. The manufacturer calibration very roughly approximates the general form of these response curves except for absorptive particles with radii > 3 μm.

To demonstrate our calibration procedure for homogeneous particles with refractive index $m = 1.45-0i$ we measured an aerosol of Dow Corning 200 fluid with this index in the laboratory. The resulting size

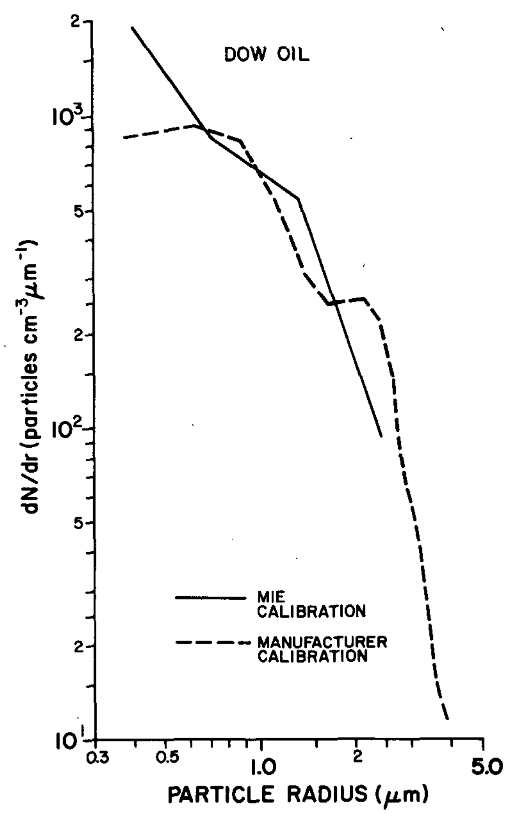

FIG. 5. As in Fig. 3 except in this case oil droplets (with $m = 1.45-0i$) were measured rather than fog. The bumps in the size distribution derived from the manufacturer-supplied calibration (dashed curve) again are believed to be artifacts caused by multivalued response characteristics of the FSSP. The bumps are shifted to slightly smaller sizes (as compared to fog) in accordance with the shift in the positions of the oscillations in the response curve.

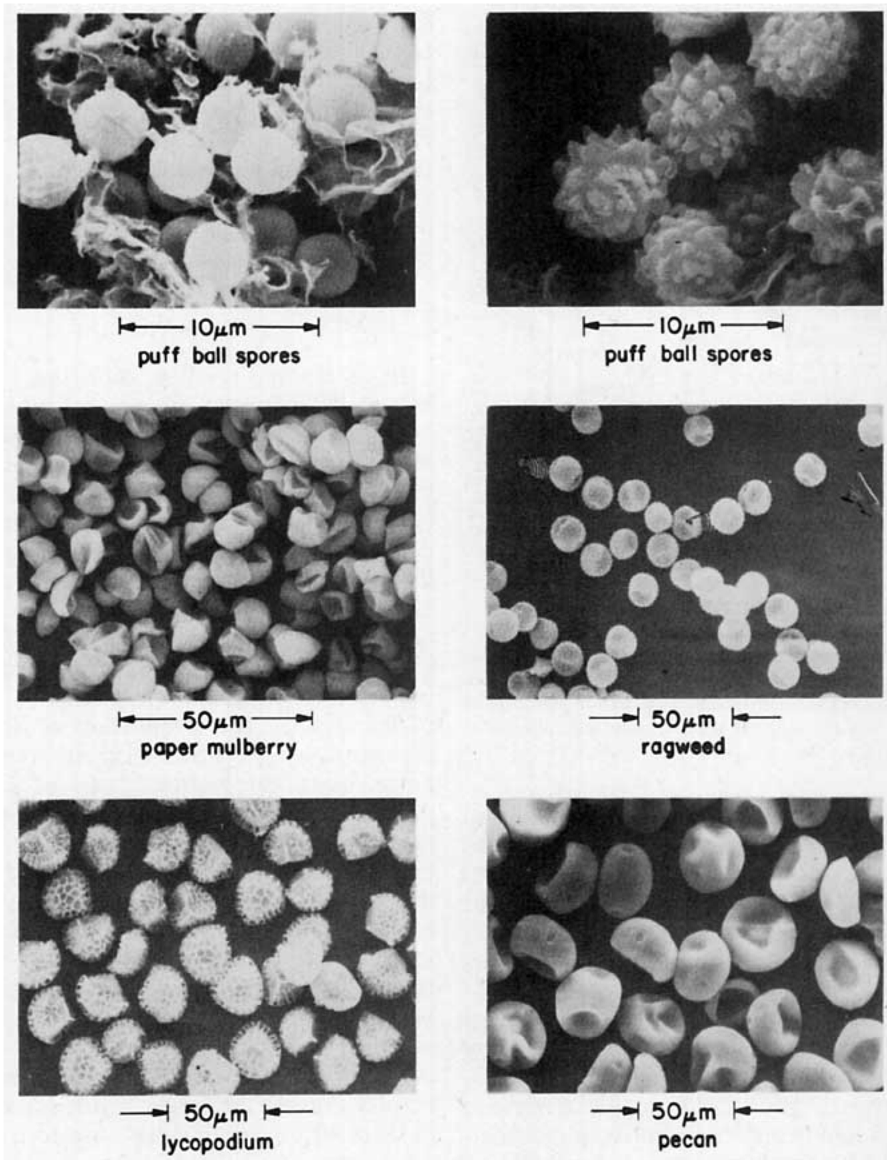

FIG. 6. Scanning electron microscope micrographs of slightly nonspherical pollens and spores used to measure the FSSP response characteristics.

distributions inferred from the data appear in Fig. 5. For this aerosol the artifacts in the manufacturer-calibration derived distribution move to slightly smaller particle sizes (as compared to fog, Fig. 3), since the oscillations in the response functions are shifted (compare the theoretical response curves for $m = 1.33-0i$ and $m = 1.45-0i$ in Figs. 2 and 4). We have not made independent measurements of the Dow oil drop size distribution so this figure by itself does not prove the validity of our calibration procedure over that supplied by the manufacturer. However, it is unlikely that our technique of aerosol generation (a nebulizer) would result in the bimodal distribution of droplets that results from invoking the manufacturer's calibration.

In the case where the FSSP is used to measure aerosol of unknown or mixed composition (and refractive index), we suggest that the manufacturer calibration simply be used with error in particle size determined by an envelope encompassing the possible response curves. Under the constraint that no large ($\geqslant 3$ μm radius) absorptive particles are present, these errors can be expected to be on the order of a factor 2 or less.

5. FSSP measurements of irregular particles

The FSSP calibration for irregular particles is not so clear-cut as it is for spheres. For one thing, since the intensity of light scattered by a nonspherical particle depends on its orientation with respect to the laser beam direction, even identical nonspherical

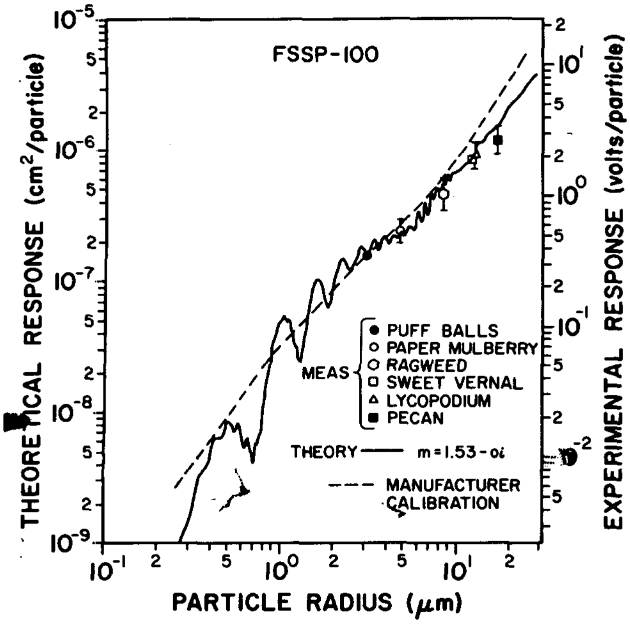

FIG. 7. Measurements of the FSSP response to slightly nonspherical pollen and spore particles (some of which are shown in Fig. 6). The measurements are compared to the theoretical response for spheres of equal cross section (smooth curve) and to the manufacturer-supplied calibration (dashed curve).

particles measured with the FSSP may result in markedly different response pulses. This will obviously degrade the size resolution of the instrument. There is also the complication of deciding what equivalent radius to assign to irregular particles that might have rather complex morphology—such particles commonly occur in the atmosphere.

We decided to make only a superficial investigation of the FSSP response to irregular particles by limiting our measurements to just slightly nonspherical pollens and spores. Micrographs of some of these particles, which include puff ball spores, paper mulberry, ragweed, lycopodium, sweet vernal, and pecan pollens are shown in Fig. 6. The measured response to these particles, shown compared to the calculated response for spheres of equal cross section, are presented in Fig. 7. Also shown for comparison is the FSSP manufacturer calibration. The comparison suggests that the FSSP responds to slightly nonspherical particles very nearly as it would to spheres of equal cross section and refractive index. We can also conclude that application of the manufacturer calibration to measurements of slightly nonspherical atmospheric aerosols (which generally have refractive indexes close to that of pollens and spores) will lead to undersizing of the particles, but probably by not more than a factor 2. (We realize of course that the manufacturer did not intend that his calibration be used for atmospheric aerosols.)

Our speculation regarding the FSSP response to ice particles (which have refractive index $1.30-0i$) is that *providing the particles are only slightly irregular* (like the pollen particles of Fig. 6) their response can be approximated by that of water spheres. However, it is doubtful that their response characteristics would evidence resonance structure and thus we cannot recommend our calibration procedure over that supplied by the manufacturer in this case.

6. FSSP sampling losses

In its normal configuration the FSSP is aircraft mounted. However, it can be purchased with an aspirator and horn for ground or laboratory use. Since the FSSP is capable of sensing particles that have appreciable fall speeds, the question of nonisokinetic sampling losses was investigated. To accomplish this, a mixture of relatively small (7 μm mean diameter) puff ball spores and rather large (40 μm mean diameter) glass beads was sprinkled into the ambient air within ~5 cm of the FSSP horn. [The aspirator fan draws air through the horn and FSSP inlet (which has minimum diameter 1.9 cm) at a rate of 0.5 L s^{-1}.] The proportion of spores to beads measured by the FSSP (for either vertical or horizontal horn orientations) was in good agreement (within 50%) with that determined by counting the number of spores and beads in the mixture sprinkled onto a microscope slide. It should be mentioned that there is considerable uncertainty in determining the proportion of spores to beads in both FSSP and microscope measurements because a significant fraction of the spores stick to the larger beads. In any case under the assumption that the 7 μm spores are sampled with 100% efficiency under calm air conditions (which is likely a good assumption), these results suggest the larger beads (and cloud droplets at least 40 μm in diameter) are too.

7. Conclusion

In summary, utilization of the FSSP manufacturer-supplied calibration will lead to fairly accurate values of cloud or fog liquid water content but the true cloud or fog drop size distributions will be distorted. These distortions are evident in the form of bumps or knees in the size distribution at ~0.6 μm and 2–4 μm radii and are a consequence of the instrument having multi-valued or slowly varying response in these regions of particle size. An alternative calibration procedure is offered that removes these artifacts in the drop size distribution. The calibration procedure can be applied with slight modification to FSSP measurements of polydispersions of particles other than water, providing they are spherical and uniform in composition. For measurement of slightly irregular particles or particles of mixed composition, the manufacturer-calibration will generally lead to undersizing of particles, but likely by not more than a factor 2.

Acknowledgments. The computer programming efforts of Chris Ham and Joanne Esparza are gratefully acknowledged. An expanded version of this paper is available from the authors in internal report form.

APPENDIX A

FSSP-100 Response for Various Collecting Angles

The solid angle over which scattered light is detected in the FSSP depends on the size of the dump spot located on the right angle prism and the dimension of the prism itself (see Fig. A1). According to the manufacturer the dump spot has a radius of 2 mm and light is collected out to a radius of 8.7 mm on the prism face. Since the prism face is 38 mm away from the particle plane, the limits of the solid angle over which light is detected are easily calculated: $\alpha = \arctan(2/38) \approx 3°$, $\beta = \arctan(8.7/38) \approx 13°$. These are the values used by Pinnick and Auvermann (1979).

Because it is likely that these dimensions are not identical on every instrument, and because it is possible that for some instruments the laser beam may not be accurately centered on the dump spot, sensitivity calculations were made to determine the effects of small changes in α and β on the calculated response. Thus response curves for water ($m = 1.33-0i$) were determined for the angle pairs $\alpha = 2.5°$, $\beta = 14°$; $\alpha = 3°$, $\beta = 14°$; and $\alpha = 3.5°$, $\beta = 14°$ (see Fig. A2). If was found that increasing β by 1° results in a negligible change in the calculated response curve but that changing α by 0.5° affects the response curve markedly. As α decreases from 3.5 to 2.5° the response of the instrument is significantly enhanced for particles with radii greater than ~2 μm and the "knee" in the response curve moves from ~3.5 μm to ~7 μm. These effects can be attributed to the forward "diffraction" lobe. For intermediate-sized particles the lobe becomes more sharply peaked in the forward direction so that an appreciable fraction of the scattered light will be found between 2.5 and 3.5°. For larger particles the lobe becomes even more sharply peaked and the fraction of scattered light between 2.5 and 3.5°, while still appreciable, is reduced.

An additional factor not taken into account in calculating the FSSP response curves is the focusing of the incident laser light. Using an analytical expression derived by Hodkinson and Greenfield (1965), Cooke and Kerker (1975) have considered this effect for various optical counters in which the light is highly focused. Their formulation is based on the assumption that the light is focused to a dimension large compared to the sizes of the particles but sufficiently small that a photon passing the particle plane is equally likely to have "originated" from any point on the focusing lens. In the FSSP the light is focused to a diameter of ~200 μm at the particle plane. The half-angle of the focusing cone can be calculated as follows: $\delta/2 = \arctan(1.5/60) \approx 1.4°$, where the diameter of the laser beam at the condensing lens is 3 mm and the focal length of the condensing lens is 60 mm. The FSSP response curve for water, calculated using the expressions of Cooke and Kerker and normalized to unit intensity at the particle plane, generally falls between the curves for $\alpha = 2.5°$, $\beta = 14°$ and $\alpha = 3°$, $\beta = 14°$ in Fig. A2 (it is closer to the latter curve). The effect of the

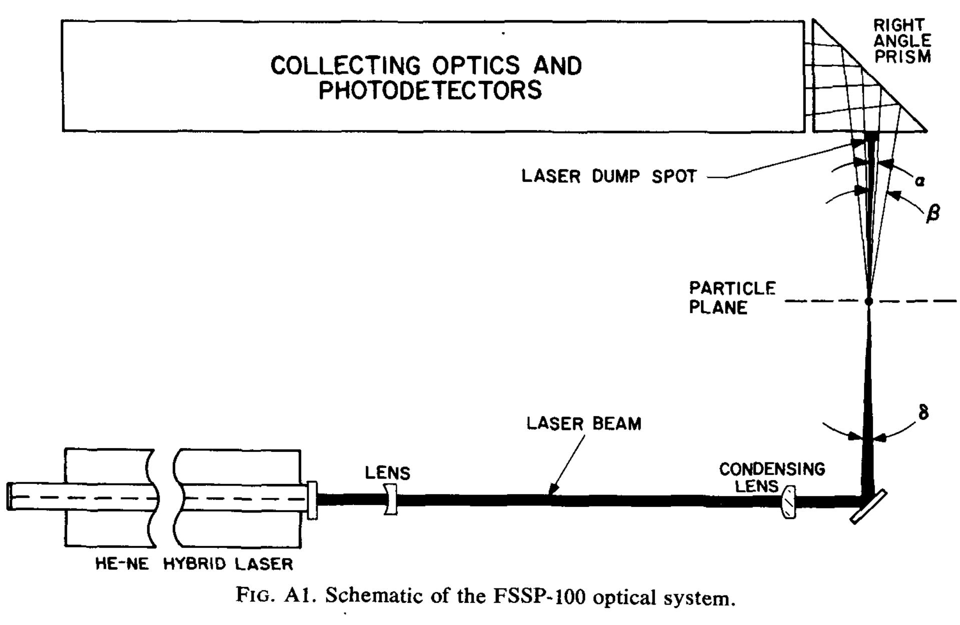

FIG. A1. Schematic of the FSSP-100 optical system.

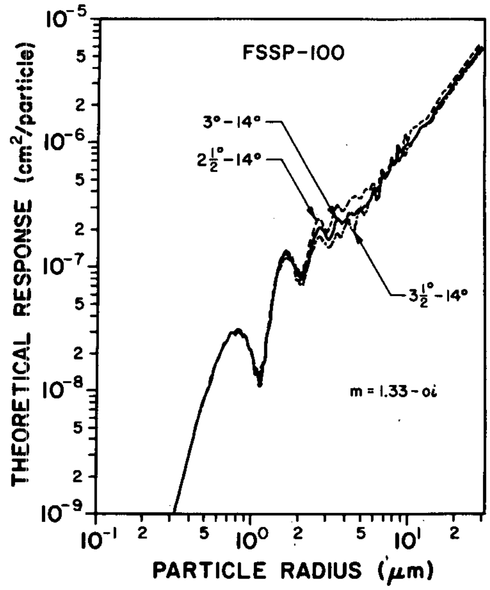

FIG. A2. FSSP response curves for water drops ($m = 1.33-0i$) for three slightly different solid angles subtended by the light-collecting optics. The solid angles are defined by the angle pairs α, β (see Fig. A1).

converging beam is thus to spread the detecting solid angle beyond the lower and upper limits of α and β.

The curve for $\alpha = 2.5°$ and $\beta = 14°$ probably places an upper bound on the actual response curve of the instrument. In this work the values $\alpha = 3°$ and $\beta = 14°$ have been used in calculating response curves for various refractive indices. The curves do not differ in any significant way from those presented by Pinnick and Auvermann (1979).

APPENDIX B

The Manufacturer's FSSP Calibration

In this appendix we show how the manufacturer's calibration for the FSSP is plotted relative to the theoretical response curve for water in Fig. 2. The problem is to determine the positions of the instrument discriminator level settings (which are given in the manual in terms of voltages) relative to the theoretical response (cm^2 $particle^{-1}$).

Our first step is to determine the values of the discriminator level voltages (DL) for the different ranges of the instrument relative to each other (and worry later about the normalization to theoretical results). For convenience we choose the top of channel 15, range 0 to be 10 V. The remaining discriminator levels in range 0 can then to first order be taken directly from the manual. To find the voltage levels for the remaining ranges (1, 2, and 3) the gain ratios (GR) for the corresponding preamplifiers must be deduced from the appropriate resistance values given in the manual. Once this gain ratio is found for a particular range the voltage level for the top of channel 15 for that range can be calculated relative to 10 volts (the top of channel 15, range 0). The remaining discriminator levels in that range can then again be determined from the corresponding voltages given in the manual.

A slight modification of this procedure is required because of the negative bias offset (BO) voltages employed in the processing of particle signals. Unfortunately, these bias offset voltages are different for different ranges and for different instruments, and may not be given in the manual (they can be easily measured, however). According to the manufacturer (private communication) the effective offset (EO) for each discriminator level is scaled according to

$$\mathrm{EO} = \frac{(10 - \mathrm{DL})}{10}\,\mathrm{BO}, \qquad \text{(B1)}$$

where all voltages are in volts.

In order for a signal to achieve a voltage level above a given discriminator level, the amplified pulse due to a particular particle must first overcome this effective bias offset. Thus the relative discriminator level settings (denoted MC for manufacturer calibration) can be calculated according to

$$\mathrm{MC} = \left[\mathrm{DL} + \frac{(10 - \mathrm{DL})}{10}\,\mathrm{BO}\right]\Big/\mathrm{GR}. \qquad \text{(B2)}$$

In this formula the value of MC is normalized to 10 volts at the top discriminator level of channel 15, range 0. These discriminator level settings (which depend on the preamplifier bias offsets for each range, the discriminator level voltages for each range, and the gain ratios) together with the particle size definitions given in the manual comprise the "manufacturer calibration" and are given in Table B1 for our particular FSSP instrument.

It is important to note that there may be differences in bias offsets, discriminator level voltages, and gain ratios for FSSP's of different vintage; calibration of other instruments must necessarily take these differences into account.

The plot of relative discriminator level settings MC (in volts) versus particle size R is fixed by the above procedure. It remains only to use the experimentally derived response voltages for spherical particles of known size and index of refraction to determine the normalization constant relating the experimental response (in volts) to the theoretically calculated scattering cross section (cm^2). Using this normalization the manufacturer's calibration can be plotted relative to the theoretical response curve for the aerosol to be measured.

The normalization constant for our FSSP instrument, providing it is "in calibration" according to the manual, is $C = 2.2 \times 10^6$ V cm^{-2}. As it turned out our particular FSSP was slightly out of calibration during this study (latex particles peaked in a

TABLE B1. FSSP-100 Manufacturer calibration.

Channel	Range 0 Radius (μm)	Range 0 MC (V)	Range 1 Radius (μm)	Range 1 MC (V)	Range 2 Radius (μm)	Range 2 MC (V)	Range 3 Radius (μm)	Range 3 MC (V)
	23.5	10.00	16.0	4.562	8.0	1.260	4.0	0.497
15	22.0	8.785	15.0	3.905	7.5	1.146	3.75	0.455
14	20.5	7.651	14.0	3.331	7.0	1.037	3.5	0.414
13	19.0	6.579	13.0	2.829	6.5	0.933	3.25	0.375
12	17.5	5.567	12.0	2.390	6.0	0.833	3.0	0.336
11	16.0	4.620	11.0	2.011	5.5	0.738	2.75	0.298
10	14.5	3.703	10.0	1.688	5.0	0.646	2.5	0.262
9	13.0	2.868	9.0	1.412	4.5	0.559	2.25	0.226
8	11.5	2.223	8.0	1.172	4.0	0.475	2.0	0.192
7	10.0	1.715	7.0	0.960	3.5	0.397	1.75	0.159
6	8.5	1.309	6.0	0.772	3.0	0.322	1.5	0.127
5	7.0	0.978	5.0	0.601	2.5	0.251	1.25	0.0973
4	5.5	0.692	4.0	0.446	2.0	0.184	1.0	0.0690
3	4.0	0.459	3.0	0.305	1.5	0.123	0.75	0.0445
2	2.5	0.263	2.0	0.178	1.0	0.0671	0.5	0.0198
1	1.0	0.0789	1.0	0.0697	0.5	0.0199	0.25	0.0059

MC denotes the relative discriminator level setting and was calculated according to Eq. (B2) using discriminator level voltages DL from the instrument manual: gain ratios GR of 1.00, 2.192, 7.935, 20.1 (for ranges 0, 1, 2, 3); and bias offsets BO of 20, 25, 30, 60 mV (for ranges 0, 1, 2, 3).

slightly higher channel than advertised in the manual) necessitating use of a slightly different normalization constant (we used 2.8×10^6 V cm^{-2}). In order to avoid confusion regarding the application of these results for a particular instrument at a particular time to the more general problem of using the PMS calibration for other FSSP's, the normalization constant $C = 2.2 \times 10^6$ V cm^{-2} has been used in Figs. 2, 4, and 7. The response of similar instruments which, in fact, are in calibration according to the PMS instrument manual can be compared with any of the theoretical response curves given in this paper by utilizing the value $C = 2.2 \times 10^6$ V cm^{-2}. (The experimental response measurements shown in Figs. 1 and 7 are plotted using the normalization constant peculiar to our instrument $C = 2.8 \times 10^6$ V cm^{-2}.)

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