Size Calibration Corrections for the Forward Scattering Spectrometer Probe (FSSP) for Measurement of Atmospheric Aerosols of Different Refractive Indices

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ABSTRACT

The response of the Forward Scattering Spectrometer Probe (FSSP) is affected by the optical properties of measured particles. The manufacturer's size calibration data are specifically applicable to nonabsorbing water droplets. Response functions of the FSSP probe are calculated for different complex refractive indices corresponding to different types of atmospheric aerosols under various relative humidity conditions. Based on the results of these response calculations, new corrected size calibrations are determined for six relative humidity values (0%, 50%, 70%, 80%, 90% and 99%) and for three atmospheric aerosol types (Rural, Urban and Maritime). Sample calculations with these corrected size calibration data show that a significant underestimation of the aerosol size/volume distribution can result, especially for dry atmospheric aerosols, if the manufacturer's size calibration data are used.

1. Introduction

The Forward Scattering Spectrometer Probe (FSSP), manufactured by Particle Measuring Systems, Inc. (PMS), has been widely used by many investigators to measure the size distribution and liquid water content within clouds. Since its development (Knollenberg 1976), many workers have reported measurement errors associated with the FSSP which can cause undersizing of droplet diameter at high sampling speed and undercounting of droplets due to optical coincidence and electronic dead-time losses (Pinnick et al. 1981; Cerni 1983; Dye and Baumgardner 1984; Baumgardner et al. 1985; Baumgardner 1987; Cooper 1988). The FSSP probe determines the particle size by measuring the light intensity scattered by individual particles passing through the scattering volume of its receiving optics. The probe's response depends not only on particle size but also on particle shape and complex refractive index. Thus, the accuracy of particle sizing with the FSSP is degraded, unless the optical properties of the measured particles are known. The size calibration data supplied by the manufacturer are specifically applicable to nonabsorbing water droplets.

The FSSP probe has also been used to measure the size distribution of atmospheric aerosols other than cloud droplets (Patterson et al. 1980; Isaac et al. 1986; Kim et al. 1988). Pinnick et al. (1981) calculated the theoretical response function of the FSSP probe for different complex refractive index values. They concluded that measurement of atmospheric aerosols with the FSSP probe would lead to undersizing if the manufacturer's calibration were used.

An active scattering aerosol spectrometer probe (ASASP) and an FSSP mounted on the NOAA King Air research aircraft were used by the Air Quality Group of the National Oceanic and Atmospheric Administration, Environmental Research Laboratories to measure the size distribution of background atmospheric aerosols under cloud free conditions during the CURTAIN measurement program (Kim et al. 1988; Boatman et al. 1989).

This paper discusses the size calibration corrections for the FSSP probe based on Mie scattering calculations for different complex refractive indices. Response functions of the FSSP probe were calculated for three atmospheric aerosol types and for six relative humidity conditions. Based on the response functions, corrected size calibration data were suggested for two measurement ranges of the FSSP probe. These corrected size calibration data were used to determine the aerosol volume distributions by applying a log-normal fit routine (Horvath et al. 1990) to aerosol data collected during the CURTAIN program.

2. FSSP response calculations

The response function of the FSSP probe, defined as the scattered power by a single particle normalized by the irradiance of the incident laser beam, is given

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TABLE 1. Refractive index of atmospheric aerosol particles at a wavelength of 0.6328 μm for three aerosol models.

	Aerosol model		
Relative humidity	Rural	Urban	Maritime
0%	$1.530-6.60 \times 10^{-3}i$	$1.574-9.13 \times 10^{-2}i$	$1.490-2.00 \times 10^{-8}i$
50%	$1.520-6.26 \times 10^{-3}i$	$1.555-8.40 \times 10^{-2}i$	$1.461-1.90 \times 10^{-8}i$
70%	$1.497-5.49 \times 10^{-3}i$	$1.474-5.36 \times 10^{-2}i$	$1.408-1.72 \times 10^{-8}i$
80%	$1.428-3.19 \times 10^{-3}i$	$1.411-2.99 \times 10^{-2}i$	$1.352-1.53 \times 10^{-8}i$
90%	$1.390-1.94 \times 10^{-3}i$	$1.376-1.66 \times 10^{-2}i$	$1.344-1.50 \times 10^{-8}i$
99%	$1.342-3.23 \times 10^{-4}i$	$1.337-1.78 \times 10^{-3}i$	$1.334-1.47 \times 10^{-8}i$

as (Pinnick and Auvermann 1979; Barnard and Harrison 1988):

$$R = \frac{\lambda^2}{2\pi}\int_{\theta_1}^{\theta_2}\frac{1}{2}\left(|S_1(x, m, \theta)|^2 + |S_2(x, m, \theta)|^2\right)\sin\theta d\theta \quad (1)$$

where λ is the wavelength of the laser beam, θ_1 is the forward truncation scattering angle, θ_2 is the rear truncation scattering angle, $S_1(x, m, \theta)$ and $S_2(x, m, \theta)$ are the Mie scattering amplitude functions (van de Hulst 1957) and m is the particle complex refractive index. x is the size parameter defined by $\pi d_p/\lambda$, where d_p is the particle diameter. The response function, R, depends on x, m, θ_1 and θ_2. For our FSSP, θ_1 and θ_2 were measured to be 3.0° and 12.7°, respectively.

Response functions were calculated as a function of particle diameter in the range 0.5–50 μm for different refractive indices. The computer code developed by Bohren and Huffman (1983) was used to calculate the Mie scattering amplitude functions. The response function, R, was determined by integrating the Mie scattering amplitude functions over the scattering angle range (3.0°–12.7°) with an increment of 0.1°.

The optical properties of particles must be known in order to size them correctly with an optical particle counter such as the FSSP probe. However, the refractive index of atmospheric aerosols varies greatly depending on their composition, which is determined by source signatures, atmospheric transport/transformation processes, and relative humidity conditions. At high relative humidity conditions, water vapor condenses on the atmospheric core particles. Thus, size and effective refractive index of atmospheric aerosols also vary with relative humidity (Hänel 1976; Shettle and Fenn 1979).

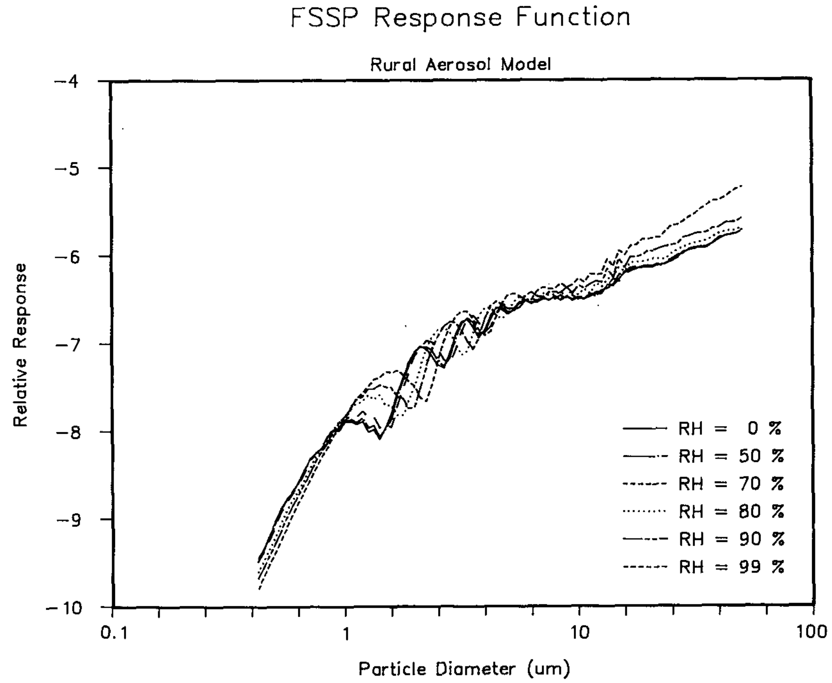

FIG. 1. Theoretical response function of the FSSP probe for the Rural aerosol model under different relative humidity conditions.

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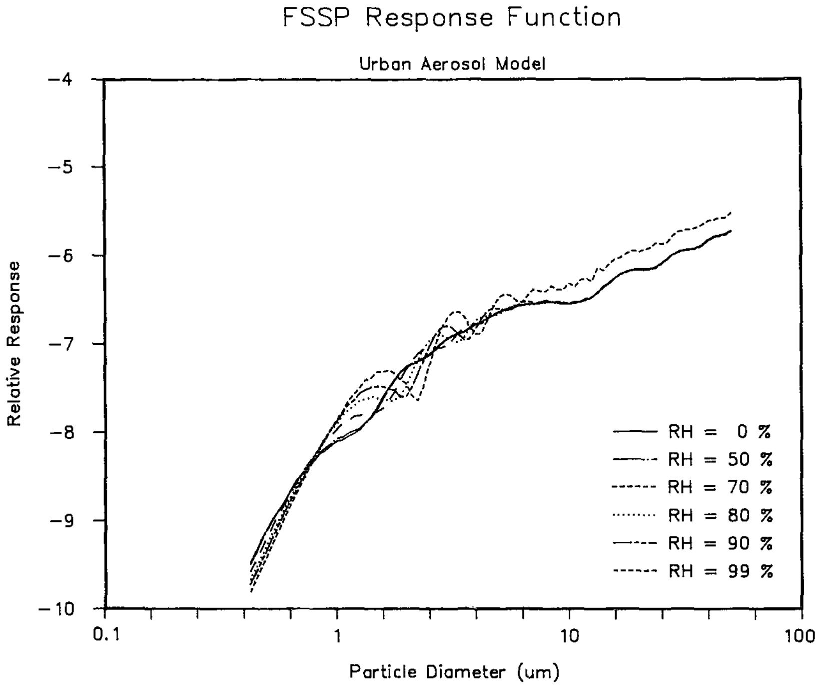

FIG. 2. Theoretical response function of the FSSP probe for the Urban aerosol model under different relative humidity conditions.

In this paper, aerosol models by Shettle and Fenn (1979) were used to estimate the refractive indices of three atmospheric aerosol types; Rural, Urban, and Maritime, in the lower troposphere. The refractive indices of coarse particles ($d_p > 1.0$ μm) for the three aerosol models are given for six relative humidity values in Table 1 (Shettle and Fenn 1979). The total aerosols of the rural model aerosols are assumed to be composed of a mixture of 70% water soluble ($m = 1.53 - 0.006i$) and 30% dust-like aerosols ($m = 1.53 - 0.008i$). Urban model aerosols are taken to be a mixture of the rural aerosols with carbonaceous aerosols ($m = 1.75 - 0.43i$). Maritime model aerosols are composed of sea-salt particles ($m = 1.49 - 2.0 \times 10^{-8}i$) and rural aerosols. It is seen that, as relative humidity rises above 90%, the refractive index of atmospheric aerosols approaches that of water ($m = 1.33 - 0.0i$).

Response functions of the FSSP probe were calculated for each of the refractive indices shown in Table 1. The resulting response functions are plotted in Figs. 1–3. Figure 1 shows the response functions of the FSSP for the Rural model aerosols at different relative humidities. The response function curves exhibit resonance in the size range 1–6 μm, resulting in sizing imprecision.

Response functions for the Urban model aerosols are shown in Fig. 2. As relative humidity increases, the response function curve shows more distinct resonant characteristics. Higher values in the imaginary part of the refractive index smooth out the resonance of the response function curves at low relative humidity conditions. The amplitude of the response function was decreased for the Urban model. This could result in severe undersizing of particles, if the manufacturer's calibration based on water droplets were used.

Figure 3 shows the response functions for the Maritime model aerosols for different relative humidity conditions. The trend in the response functions with particle size is similar to that of the Rural aerosol model. As relative humidity increases, the response function curves in Fig. 3 become closer to that of water, which is discussed in the following section.

3. Size calibration corrections

Calibration of the FSSP is usually done in a laboratory by drawing latex particles or glass beads through its scattering volume with a vacuum pump. It is known that measurements of particle size and concentration with the FSSP also depend on air speed due to the electronic response time limitation of the probe (Cerni 1983; Dye and Baumgardner 1984). During CURTAIN flights, aircraft speed was kept relatively constant around 70 m/sec. Sizing error at that air speed is believed to be minimal (Cerni 1983).

The response function was calculated for the refractive index value representing water droplets ($m = 1.33 - 0.0i$). The pulse height analyzer (PHA) threshold voltage set by the manufacturer was measured for each of fifteen size channels of the FSSP probe. Figure 4

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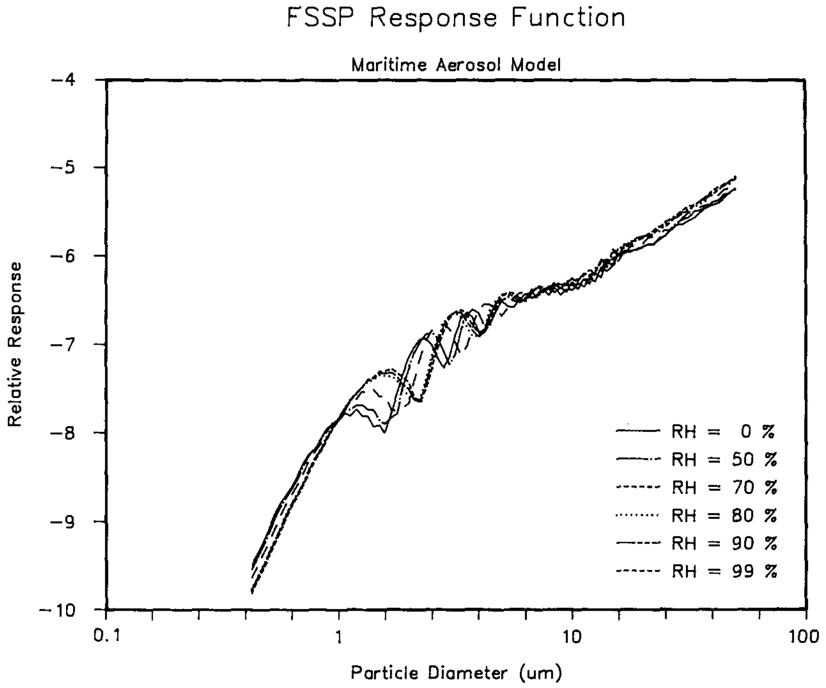

FIG. 3. Theoretical response function of the FSSP probe for the Maritime aerosol model under different relative humidity conditions.

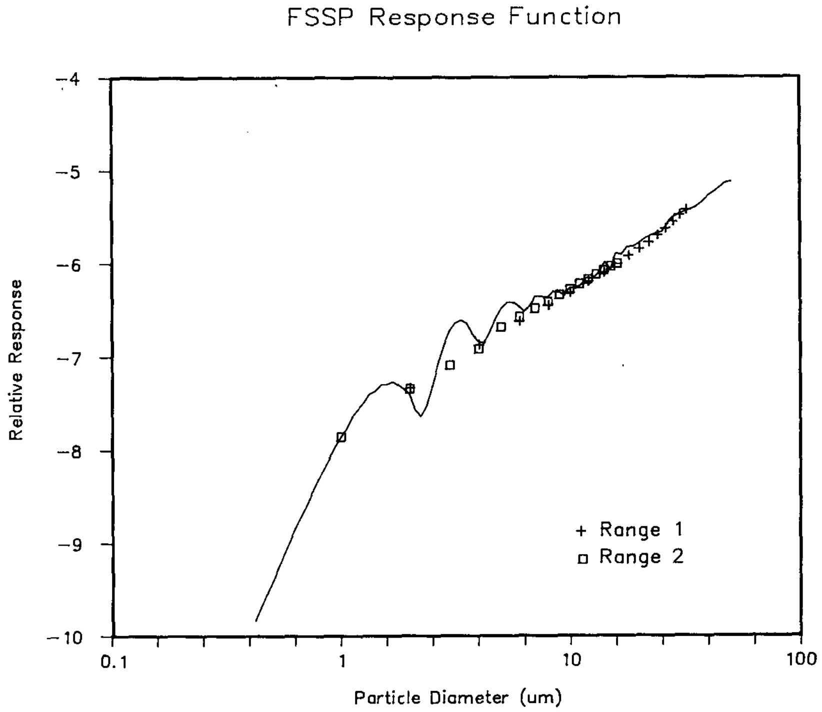

FIG. 4. Theoretical response function and the pulse height analyzer (PHA) settings of the FSSP probe.

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TABLE 2. Size calibration data for water droplets.

Size channel	Range 1* diameter (μm)	Range 2* diameter (μm)
0	1.8	1.0
1	—	—
2	4.7	2.7
3	—	—
4	9.7	—
5	11.5	4.8
6	13.4	—
7	14.3	6.8
8	—	—
9	17.5	9.9
10	20.2	—
11	22.8	11.7
12	25.7	—
13	27.0	13.5
14	29.3	—
15	33.0	15.3

* All values are the upper limit particle sizes except for size channel 0, which is the lower limit particle size of size channel 1.

shows the theoretical response function curve for water droplets along with the response function values corresponding to PHA threshold settings for comparison. Only measurement ranges 1 (2–32 μm) and 2 (1–16 μm) are presented in Fig. 4, because they were the ones used for atmospheric aerosol measurements during the CURTAIN program. Corrected size calibration data were determined by grouping size channels in the regions of multivalued responses as proposed by Pinnick et al. (1981) and Cerni (1983). Although the size resolution is reduced by the size channels grouping, overall measurement accuracy can be improved by avoiding defining calibration sizes near regions of multivalued response. Artificial peaks in the size spectrum due to narrow size channels can also be avoided (Pinnick et al. 1981). The results of the size calibration correction for water droplets are tabulated in Table 2.

Each of the response function curves in Figs. 1–3 was compared with the PHA threshold values in Fig. 4 in order to determine the corrected size calibration data. Then corrected particle sizes were determined by combining size channels in the regions of multivalued responses for three atmospheric aerosol models. Tables 3–5 delineate the corrected size classes for the two measurement ranges at six different relative humidities (0%, 50%, 70%, 80%, 90% and 99%) for the Rural, Urban and Maritime aerosol models. Response function curves in Figs. 1–4 are based on the Mie scattering calculations for spherical particles. In real measurement conditions, other factors such as particle shape and nonuniform laser beam intensity profile of the probe will further increase the uncertainties associated with the size calibration values shown in Table 3–5. Tables 3 and 4 reveal that severe underestimation of particle size would result for Rural and Urban aerosols, especially under low relative humidity conditions, if either the manufacturer's calibration or calibration based on the water droplets were used. If a corrected new calibration size was calculated to be larger than 50 μm, which is considered to be the upper size limit of the atmospheric aerosols of interest, it was discarded and marked as 'not available (NA)' in Tables 3 and 4. Table 5 shows that the corrected calibration sizes for Maritime model aerosols are comparable to those for water droplets (Table 2).

These results strongly suggest that the preceding new particle size classes should be used, after choosing the appropriate aerosol model and relative humidity, to

TABLE 3. Size calibration data for the Rural model aerosols.

Size channel	Range 1* diameter (μm) Relative humidity						Range 2* diameter (μm) Relative humidity					
	0%	50%	70%	80%	90%	99%	0%	50%	70%	80%	90%	99%
0	1.8	1.8	1.9	2.1	2.2	2.4	1.6	1.2	1.0	1.0	1.0	1.0
1	—	—	—	—	—	—	—	—	—	—	—	—
2	5.3	5.3	4.6	5.1	4.1	4.6	2.8	2.9	3.0	3.4	2.4	2.6
3	11.7	12.1	11.5	—	7.3	—	—	—	—	—	—	—
4	—	—	—	13.0	—	10.6	4.2	4.3	4.4	4.9	4.0	4.5
5	15.9	16.6	16.0	—	14.4	12.7	5.4	5.5	5.7	—	—	—
6	24.2	24.0	22.7	16.7	—	—	—	—	—	6.8	5.9	6.4
7	27.3	27.0	26.6	24.7	18.6	—	12.8	12.5	12.6	—	—	—
8	35.4	33.8	31.2	28.1	22.9	16.6	14.4	14.1	13.5	—	11.1	9.5
9	38.7	38.8	38.4	34.8	27.2	18.5	—	—	—	13.3	—	—
10	44.1	44.1	43.3	39.0	30.6	22.9	15.6	15.3	15.7	—	14.3	12.3
11	NA	NA	NA	49.0	37.5	24.4	16.7	17.4	—	—	—	—
12	NA	NA	NA	NA	46.6	27.9	22.2	22.9	21.4	16.5	16.1	14.2
13	NA	NA	NA	NA	NA	30.7	25.3	24.8	24.1	19.2	—	—
14	NA	NA	NA	NA	NA	33.5	26.8	26.1	25.7	—	—	—
15	NA	NA	NA	NA	NA	36.0	27.4	27.3	26.8	24.8	18.8	15.9

* All values are the upper limit particle sizes except for size channel 0, which is the lower-limit particle size of size channel 1.

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TABLE 4. Size calibration data for the Urban model aerosols.

Size channel	Range 1* diameter (μm) Relative humidity						Range 2* diameter (μm) Relative humidity					
	0%	50%	70%	80%	90%	99%	0%	50%	70%	80%	90%	99%
0	1.9	1.9	2.0	2.1	2.3	2.5	1.4	1.4	1.1	1.0	1.0	1.0
1	—	—	—	—	—	—	—	—	—	—	—	—
2	5.2	5.2	5.2	5.3	5.5	4.6	2.6	2.6	2.3	2.3	2.5	2.6
3	12.9	12.9	12.9	12.9	12.9	6.7	—	—	—	—	—	—
4	14.9	14.9	14.9	15.0	15.1	11.0	4.7	4.7	4.7	4.7	4.3	4.5
5	17.3	17.3	17.4	17.5	17.5	13.1	—	—	—	—	—	—
6	24.9	24.9	25.0	25.1	25.1	15.0	12.3	12.3	12.4	12.4	12.2	6.5
7	27.6	27.6	27.6	27.7	27.7	17.1	13.4	13.4	13.4	13.5	13.5	8.0
8	35.3	35.4	35.6	35.7	35.8	22.0	14.4	14.4	14.5	14.5	14.4	10.8
9	38.8	38.8	38.9	39.1	39.1	26.7	15.4	15.5	15.5	15.5	15.5	12.7
10	44.2	44.3	44.7	45.4	45.9	28.2	16.5	16.5	16.6	16.6	16.6	—
11	NA	NA	NA	NA	NA	34.8	18.4	18.4	18.5	18.6	18.5	14.2
12	NA	NA	NA	NA	NA	38.8	24.1	24.1	24.2	24.3	24.4	—
13	NA	NA	NA	NA	NA	48.4	25.6	25.6	25.7	25.8	25.8	15.3
14	NA	NA	NA	NA	NA	NA	26.9	26.9	26.9	27.0	27.0	16.3
15	NA	NA	NA	NA	NA	NA	27.7	27.7	27.8	27.8	27.9	17.2

* All values are the upper limit particle sizes except for size channel 0, which is the lower limit particle size of size channel 1.

better analyze the atmospheric aerosol data measured with the FSSP probe.

4. Applications

New size calibration data obtained in the preceding section were applied to aerosol data measured during the CURTAIN program in order to show their effects on final data analysis. The data measured, on 21 April 1988 over rural area near Little Rock, Arkansas are used in the example.

A log-normal fit was applied to the FSSP aerosol data averaged over a flight path around 1450 m above sea level (asl), using the computer fitting routine developed by Horvath et al. (1990). First, the manufacturer's calibration was used to calculate the volume geometric median diameter (VGMD), geometric standard deviation (σ_g), and total particle number and volume concentration (N_{cal} and V_{cal}) under the fitted log-normal distribution. Then, the corrected calibration sizes for water droplets and three aerosol models were used to perform the same calculations.

The results of these analyses are summarized in Table 6. Table 6 shows that log-normal aerosol volume distributions, based on the corrected size calibration for the Rural aerosol model, were significantly different

TABLE 5. Size calibration data for Maritime model aerosols.

Size channel	Range 1* diameter (μm) Relative humidity						Range 2* diameter (μm) Relative humidity					
	0%	50%	70%	80%	90%	99%	0%	50%	70%	80%	90%	99%
0	1.9	2.0	2.1	2.4	2.4	2.5	1.6	1.7	1.0	1.0	1.0	1.0
1	—	—	—	—	—	—	—	—	—	—	—	—
2	4.6	4.7	5.2	4.4	4.6	4.7	3.0	3.2	3.4	2.5	2.6	2.6
3	8.0	7.2	7.0	6.4	—	—	—	—	—	—	—	—
4	—	—	—	9.3	9.5	9.6	4.5	4.6	5.0	—	—	—
5	13.0	13.6	12.4	12.2	12.5	11.5	—	—	—	4.5	4.6	4.7
6	—	—	—	—	—	—	—	—	—	—	—	—
7	15.7	16.2	15.5	14.7	15.9	15.2	9.2	9.5	8.0	7.5	6.6	6.8
8	19.0	19.3	17.5	16.5	—	—	11.4	10.8	10.6	—	—	—
9	23.1	22.9	20.4	18.5	18.1	17.7	—	—	—	10.5	10.7	10.6
10	25.0	25.1	22.3	20.2	21.1	20.6	12.9	13.5	12.2	—	—	—
11	26.8	26.6	26.9	24.3	23.8	22.9	—	—	13.4	12.4	12.7	12.7
12	30.4	28.3	28.5	25.4	24.9	26.2	14.9	—	—	—	—	—
13	34.1	31.8	30.3	27.6	28.6	27.8	—	15.5	15.1	14.4	14.4	13.3
14	36.4	35.7	34.2	30.8	31.7	29.7	—	—	—	—	—	—
15	39.9	38.2	37.8	34.7	33.5	33.4	15.7	16.3	15.5	14.7	15.9	15.2

* All values are the upper limit particle sizes except for size channel 0, which is the lower limit particle size of size channel 1.

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TABLE 6. Aerosol volume distribution based on different calibration data at different relative humidities for different types of atmospheric aerosol particles.

Calibration data/aerosol model	RH (%)	VGMD (μm)	σ_g	N_{cal} (cm^{-3})	V_{cal} (μm^3 cm^{-3})
MC*		7.29	1.96	0.36	13.09
Water droplet		6.49	2.10	0.55	10.58
Rural	0	14.51	2.24	0.66	27.34
	50	14.08	2.16	0.66	26.59
	70	17.00	2.63	0.91	29.44
	80	12.21	2.70	0.74	26.41
	90	9.47	2.67	1.41	15.31
	99	6.43	2.11	1.11	15.26
Urban	0	17.82	2.54	0.76	40.70
	50	17.85	2.54	0.76	40.76
	70	17.75	2.54	0.81	41.14
	80	17.57	2.57	0.83	41.80
	90	16.82	2.59	0.85	42.91
	99	7.22	3.19	1.14	19.94
Maritime	0	7.89	2.21	0.73	11.84
	50	7.70	2.35	0.82	12.89
	70	6.34	2.26	0.60	13.53
	80	6.73	2.40	1.17	13.14
	90	6.13	2.35	1.06	13.57
	99	6.61	2.21	0.96	15.82

* MC: manufacturer's calibration; RH: relative humidity; VGMD: volume geometric diameter; σ_g: geometric standard deviation; N_{cal}: aerosol number concentration; V_{cal}: aerosol volume concentration.

from that obtained using the manufacturer's calibration. The difference between the volume distributions increased as relative humidity decreased. Under dry conditions (RH = 0%) VGMD and V_{cal} were 14.51 μm and 27.34 μm^3 cm^{-3} versus. 7.29 μm and 13.09 μm^3 cm^{-3}, for the manufacturer's calibration. As relative humidity increases, the resulting aerosol volume distribution for the Rural aerosol model converges to that based on the manufacturer's calibration. It is concluded that use of the manufacturer's size calibration severely underestimates the particle size and volume concentration of atmospheric aerosols, especially under dry conditions.

Similar results were obtained for the Urban aerosol model particles. Log-normal aerosol volume distribution, based on the manufacturer's calibration, would underestimate VGMD and V_{cal} significantly for all relative humidity conditions except RH = 99%. The aerosol volume distributions in Table 6, obtained using the corrected size calibration data, may be unrealistic because these FSSP data were measured not in an urban (absorbing) aerosol but in a continental background aerosol. Nevertheless, they support the conclusion that the manufacturer's calibration results in an underestimation of the aerosol size/volume distribution for Urban aerosol model particles.

For the Maritime aerosol model, unlike the Rural or Urban aerosol models the resulting log-normal aerosol volume distributions, based on the corrected size calibration data, were comparable to those based on the manufacturer's calibration and water droplet calibration. This is because the imaginary part of the refractive index of the Maritime aerosol model is close to zero. Thus, the size calibration data of the Maritime aerosol mode converge to those of the water droplet calibration.

5. Discussion and conclusions

New size calibration data were obtained for the Forward Scattering Spectrometer Probe (FSSP) in order to improve its measurement accuracy in determining the size distribution of atmospheric aerosols. Although it has been known that the response of the FSSP is affected by the optical properties of measured particles, no quantified size correction data are available that are useful for atmospheric aerosol measurement applications. New calibration size data are determined in this paper for six relative humidity values (0%, 50%, 70%, 80%, 90% and 99%) and for three typical aerosol types (Rural, Urban, and Maritime). Sample calculations with these corrected size calibration data show that a significant underestimation of the aerosol volume distribution can result for atmospheric aerosols if uncorrected manufacturer's calibration data are used, especially for low relative humidity conditions. This justifies the necessity of new size calibration data applicable to measurement of atmospheric aerosols with an FSSP.

The primary impetus of this paper was to suggest new size calibration data which an user of the FSSP instrument could use as an appropriate reference for atmospheric aerosol measurements, even when information on optical properties of measured particles were not available. Validation of these size calibration correction data would require extensive laboratory and/or field experiments, that becomes in itself a challenging project and are beyond the scope of this paper. Mass size distribution data measured with a collocated cascade impactor can be compared to those inferred from FSSP measurements. Spectral transmittance measured with a transmissometer can also be a candidate for validating FSSP size calibration data. However, there is no absolute instrument for in situ measurement of aerosol size distribution. Other types of comparable instruments, whether they measure deposited particle mass or spectral transmittance, have their own inherent problems in absolute calibration. Although without experimental validation, the size calibration correction data, reported in this paper, are a step forward toward an accurate measurement of atmospheric-aerosol size distribution with an FSSP, which is an extension of its original purposed usage.

Prior knowledge of optical properties of atmospheric aerosol particles is essential for an accurate measurement of particle size with an FSSP. In real cases, refractive index of particles would be somewhat different

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depending on their actual chemical composition from the values assumed in the aerosol models in Table 1. Atmospheric aerosol particles might also be nonspherical in their shape, especially for dry particles. However, size calibration correction data presented in this paper would provide users of FSSP instruments with quantified information useful for analyzing measured FSSP data, provided that appropriate aerosol type and relative humidity value are chosen. The size calibration correction data presented in this paper are based on the Mie scattering calculations for aerosol models for the lower atmosphere. However, these models represent only a simple, generalized version of typical conditions. Physiochemical and optical properties of individual atmospheric aerosols can be different from those of the aerosol models. If the average refractive index values of the particles of measurement is known, the measurement accuracy can be improved by using the size calibration data based on that value. Variations in the refractive index and nonspherical shape of atmospheric particles further degrade the size resolution of the FSSP.

APPENDIX

Size Calibration Corrections for an FSSP Having Different PHA Levels

The corrected calibration data presented in this paper are based on the pulse height analyzer (PHA) levels of the FSSP used by the authors. The PHA levels are not the same for all FSSP instruments. Pinnick et al. (1981) reported an algorithm that can calculate the relative PHA levels from the measured PHA levels, bias offset voltage, and the gain ratios for the corresponding preamplifiers of the FSSP. The relative PHA levels are summarized in Table A1 for the FSSP described in this paper. Size calibration corrections for an FSSP having different PHA levels can be made through interpolation between its measured relative PHA levels and those listed in Table A1, assuming a linear response curve in each size interval.

TABLE A1. Relative pulse height analyzer levels.

Size channel	Range 1 (mV)	Range 2 (mV)
0	133	132
1	375	438
2	667	793
3	998	1184
4	1342	2039
5	1750	2618
6	2170	3250
7	2670	3855
8	3263	4523
9	3842	5250
10	4513	6000
11	5408	6750
12	6368	7580
13	7500	8460
14	8790	9342
15	10000	10000

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