Conversion of Droplet Size Distributions from PMS Optical Array Probe to Malvern Laser Diffraction

M. E. Teske*, H. W. Thistle, A. J. Hewitt, and I. W. Kirk
Continuum Dynamics, Inc., 34 Lexington Avenue, Ewing, NJ 08618 USA
USDA Forest Service, 180 Canfield Street, Morgantown, WV 26505 USA
Stewart Agricultural Research Services, P. O. Box 509, Macon, MO 63552 USA
USDA Agricultural Research Service, 2771 F&B Road, College Station, TX 77845 USA

Abstract

This paper considers the practical conversion of droplet size spectra data from PMS optical array probe (temporal, or number-flux-weighted, sampling) to Malvern laser diffraction (spatial, or number-density-weighted, sampling). The transformation is applied to the historical United States Department of Agriculture Forest Service database.

Introduction

The droplet size distribution of agricultural spray material atomized by nozzles influences the magnitude of evaporation, spray deposition, drift, and application effectiveness. Droplet size information, in particular the volume fraction in the smaller droplet sizes (which tend to be more prone to drift) and the larger droplet sizes (which fall largely within the spray block), are critical to forest and agricultural applications, where specific levels of spray material must be deposited to achieve success and avoid excessive environmental contamination.

In an effort to build a database of typical formulations and aerial application conditions, the United States Department of Agriculture (USDA) Forest Service (FS), and other agencies and companies, conducted wind tunnel tests to determine droplet size distributions of pesticides and simulant spray material when applied through hydraulic and rotary atomizers. These studies, from the 1970s to the 1990s, were intended to provide data to determine the effects on the atomization of agricultural sprays of application and tank mix variables. These factors include the spray pressure, liquid flow rate, air velocity and shear across the atomizer, physical chemistry (viscosity, specific gravity, and surface tension), and atmospheric conditions. The FS database was summarized in [1], and subsequently assembled as a library within the aerial spray prediction models AGDISP [2] and FSCBG [3]. A preliminary examination of this database produced techniques for collapsing the data [4], correlating the data [5], and developing scaling laws for non-Newtonian fluids [6].

These data were measured exclusively with the PMS (Particle Measurement Systems) optical array probe, located at the University of California – Davis, with a minimum droplet resolution of 34 μm. Recently, the Spray Drift Task Force (SDTF) developed a large database of spray droplet size information [7], based on the Malvern laser diffraction analyzer, located at New Mexico State University and SpraySearch in Victoria, Australia. The resolution of this technique allowed measurements of droplet diameters down to 4 μm. The SDTF field and modeling studies established that knowledge of the droplet spectrum at its smaller droplet sizes is important for drift assessment, and that the Malvern instrument range is essential to recover that detail. A further review of the available literature (summarized below) confirms the applicability and acceptance of the Malvern approach to data collection over and above the PMS approach.

The effective use of the FS database in conjunction with the SDTF Malvern data, which includes more information on smaller droplet size classes, is desirable. Any adjustment approach should be mindful of previous efforts to examine the output difference in the two instruments, and of previous attempts made to reconcile their data differences. This paper considers these previous attempts and suggests a practical conversion technique of the PMS data to Malvern equivalence data, resolving instrument differences and recovering the small end of the droplet size spectrum.

Previous Spatial-Temporal Data Studies

Within the last 15 years several researchers have found differences in droplet size information measured with PMS and Malvern techniques. An early inter-

*Corresponding author

laboratory study conducted by the British Crop Protection Council [8] involved different particle measurement techniques, including the PMS and Malvern instruments. This study showed that, with the exception of the Malvern, the other analyzers examined showed no consistent agreement with each other [9]. Large differences were observed in the data produced by the different instruments, and even by the same instrument type, with the Malvern generally yielding finer droplet diameter data than the PMS. Trends in decreasing average droplet diameters with higher spray pressures were similar, although the absolute droplet parameter values differed considerably [10].

A similar comprehensive study in the United States compared Malvern, PMS, hot wire, Phase Doppler Particle Analysis (PDPA), and video imaging analyses [11]. Large variations were observed in mean droplet diameters measured by these different instrument types, with the results for the Malvern, PDPA, and video imaging instruments similar enough to be grouped together. The PMS instrument produced larger mean droplet diameter data, while the hot-wire approach produced different trends with different test substances. The agreement between the several Malvern instruments examined was superior to the agreement between the PDPA instruments.

Malvern and PMS droplet spectra have been examined in still air, with the PMS spectra generally more distributed toward the larger droplet diameter size classes than the Malvern [12].

Malvern, PMS, and PDPA particle size analyzers have been used by other researchers to simultaneously measure particle size spectra for freely falling glass beads and droplet sprays [10]. The glass bead samples produced very similar results with all three systems, while the liquid spray samples produced different data among the particle size analyzers, with the Malvern producing significantly smaller droplet size spectra than the PMS and PDPA, which both produced similar data. Differences were attributed mainly to differences in the temporal and spatial sampling techniques used by the instruments. By using published spatial/temporal conversion methods [13], these authors [10] converted the PMS temporal data to a spatial equivalent, and found that this approach produced a much closer agreement with the Malvern spatial data.

Other authors also found substantial differences in the droplet size data generated with the PMS and Malvern instruments [14]. These differences appeared to be sensitive to the combinations of nozzles and test substances tested: unfortunately, axial placement of the PMS and Malvern at different distances in the nozzle wake would appear conducive to large spatial/temporal differences not mentioned in their paper.

Still other authors [15] attributed differences in the droplet spectra to spatial sampling errors associated with the Malvern instrument, reaching this conclusion in spite of calculations conducted by the authors showing that spatial and temporal data should have been similar under the sampling conditions used. Independent calculations using the TESS model [16] showed that differences in spatial and temporal sampling under the assumed test conditions would cause a spatial sample increase of only 2%, where the study [15] showed a spatial sample decrease of 87% (L. G. Dodge, personal communication). It is therefore more likely that the large differences observed were due to sampling differences in the ways the instruments were used and to limitations of the instruments themselves, rather than spatial/temporal anomalies.

Other techniques [17] produced droplet size spectra with a Malvern-like instrument that skewed toward the larger droplet diameter size classes, but with a larger portion of the spray volume contained in size classes below approximately 15 μm.

Number-Density vs. Number-Flux

What then is accountable for the data differences observed between the PMS and Malvern instruments? The laser diffraction technique (Malvern) involves a "spatial" number-density-weighted sampling technique, whereas the optical array probe (PMS) measures a "temporal" number-flux weighted sampling technique [18, 19]. Both techniques have been observed to produce different results if the nozzle spray does not contain droplets traveling at uniform velocity at the point of sampling.

In the past, complex models have been developed to convert between number-density and number-weighted sampling data sets (for example [16]). It is evident, however, that at the typical sampling distances considered, air stream and axial droplet velocities represent differences between "spatial" and "temporal" sampling of only several percent. Thus, it may be argued that the larger differences observed in droplet size data collected between the PMS and Malvern instruments must be due more to sampling and operational differences than to differences between spatial and temporal sampling.

The laser diffraction technique (Malvern) is usually used in a completely non-intrusive way for measuring agricultural sprays, whereas the PMS instrument is usually inserted into the spray, which will logically have an effect on the droplet flow field encountered by the measuring device. Other points to be aware of when recording data are the following: (1) a representative cross-section average sample should be measured by using an appropriate traverse of either the spray or the

laser; (2) replication is normal practice to obtain statistically valid data; (3) care should be used to avoid spray contamination of lenses and other equipment; (4) sampling should avoid multiple scattering (caused by obscuration levels above approximately 0.6), or apply corrections if it is suspected with data collected using techniques like laser diffraction; (5) an adequate sample size should be taken, and processed using an appropriate mathematical model (the data processing routines can differ between instruments, and even for configurations of a given instrument); (6) depth of field limitations and spray density may affect measurements, particularly with the optical array probe technique (if the spray is very dense, particles may overlap, causing potential errors if not accounted for [20]); and (7) "dead time", when the optical array probe electronics are occupied in sizing and counting, can also introduce errors [15].

Further: the issue of dynamic size range effects on data is often more an issue of whether the instrument is configured to measure the appropriate size range of the spray being sampled. Truncation has been observed in some data sets where particles were contained in size classes above or below the dynamic size range.

Not withstanding the above-mentioned caveats on either instrument, it would appear proper to adjust the PMS measurements to be Malvern-like and, in doing so, not only recover the small end of the droplet spectrum (below 34 μm) but also extend the volume fraction down to smaller droplets across the droplet size spectrum. Developing such an approach, and applying it to the historical FS database, forms the basis of the work reported here.

Problem Definition

The specific problem may be easily identified by examining the two droplet size distribution data sets to be considered here: those recovered from the PMS instrument (measured in the USDA ARS wind tunnel, College Station, TX, and supplied by co-author IWK) and from the Malvern instrument (measured in the NMSU wind tunnel and supplied by co-author AJH and the SDTF) for the five ASAE standard nozzles (Standard No. 572: Spray Nozzle Classification by Droplet Spectra): 11001 (recovering the transition distribution between sprays classified as Very Fine to Fine), 11003 (Fine to Medium), 11006 (Medium to Coarse), 8008 (Coarse to Very Coarse), and 6510 (Very Coarse to Extra Coarse). These data are plotted in Figure 1. It may be seen that the transition curves tend to separate more as increasingly coarse sprays are involved.

The PMS droplet size data were recovered from a PMS instrument with a minimum droplet size resolution of 19.5 μm. To be consistent with the FS database, volume fraction below 34 μm must be removed (because in the UC-Davis setup these data were not measured) and the resulting distributions re-normalized, recovering results that are very similar to those plotted in Figure 1. The incremental volume fraction below 34 μm may then be curve fit for later use, as shown in Figure 2.

The FS database was collected with PMS measurements in the UC-Davis wind tunnel. Should comparable data become available, it would not be surprising to find the PMS droplet size spectra different from those used in this paper. The two PMS instruments are different, the two wind tunnel setups are different, results depend on the way the instrument is traversed, its setup (the slice rate and other sampling issues), resolution, whether the probe is 1-D or 2-D, and many other factors (similar factors may, of course, influence Malvern measurements). It is therefore important to develop an assessment technique that works with any two sets of PMS and Malvern data, whether obtained from one tunnel, two, or averaged across several. Such a solution approach follows.

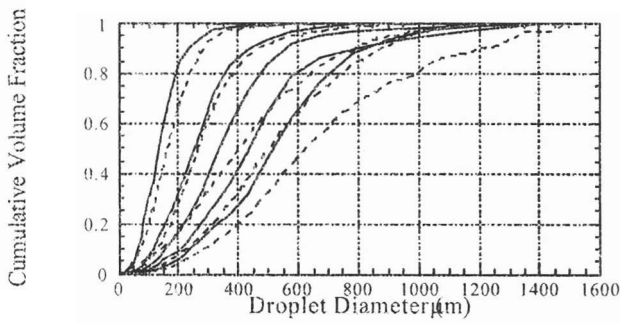

Figure 1. Unmodified droplet size distributions from the Malvern (solid curves) and PMS (dashed curves) instruments, where the ASAE spray quality reference boundary curves separate, from left to right, Very Fine to Fine, Fine to Medium, Medium to Coarse, Coarse to Very Coarse, and Very Coarse to Extra Coarse. Droplet diameter is volume-averaged within a droplet size category. Measurements with the PMS and Malvern instruments show significant differences, and can, in some cases, shift the spray quality a full category.

Solution Approach

The most straightforward way to rationalize the two sets of curves plotted in Figure 1 is through the use of interpolation techniques that gather all of the data available in these droplet size distributions and represent them by two-parameter mathematical models. The two more popular approaches to be applied here are the Root-Normal and Rosin-Rammler. Based on past experience and the literature reviewed above, the PMS data will be adjusted toward the Malvern data.

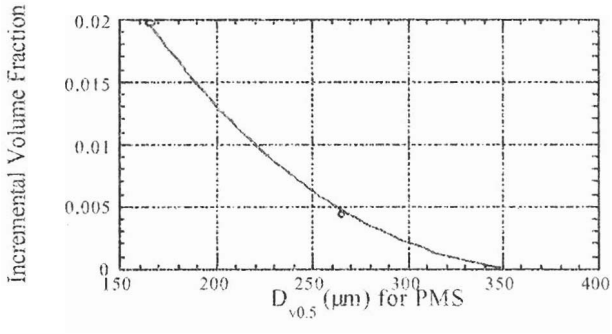

Figure 2. Incremental volume fraction removed below 34 μm in the Malvern measurements to recover the same minimum droplet size category as the PMS measurements summarized in [1]. Curve-fit is $\Delta V = 0.078506 - 0.00051845\ D_{v0.5P} + 1.1106E\text{-}06\ D_{v0.5P}^2 - 7.7194E\text{-}10\ D_{v0.5P}^3$ ($R = 0.9985$) below $D_{v0.5P} = 350$ μm, and $\Delta V = 0.0$ above, where ΔV is the incremental volume fraction removed and $D_{v0.5P}$ is the volume median diameter recovered from the PMS data.

In the Root-Normal technique [21] the cumulative volume fraction (CVF) is plotted on a normal probability distribution scale Pr as a function of the square root of the droplet diameter D. If droplet diameters are further normalized by volume median diameter ($D_{v0.5}$), a least squares fit through the droplet size distribution plotted in these coordinates yields a straight line of the form

$$\sqrt{\frac{D}{D_{v0.5}}} = S\,Pr(CVF) \qquad (1)$$

where S is the slope of the line in Root-Normal space. At its midpoint CVF = 0.5, Pr = 0.0, and droplet diameter D equals $D_{v0.5}$. Evaluation of the two parameters $D_{v0.5}$ and S determines the droplet size distribution. The transformed PMS data are plotted in Figure 3.

In the Rosin-Rammler approach [22] the droplet size distribution is represented by a logarithmic normal relationship

$$1 - CVF = \exp[-(D/X)^q] \qquad (2)$$

where X and q are the curvefitting parameters. If a natural logarithm were taken of this expression, multiplying both sides of the equation by -1, and then a second logarithm taken, there results

$$\log[-\log(1 - CVF)] = q\log(D/X) \qquad (3)$$

which represents the equation for a straight line in logarithmic space, of slope q and intercept (- q log X). Evaluation of the two parameters X and q determines the droplet size distribution. The transformed PMS data are plotted in Figure 4.

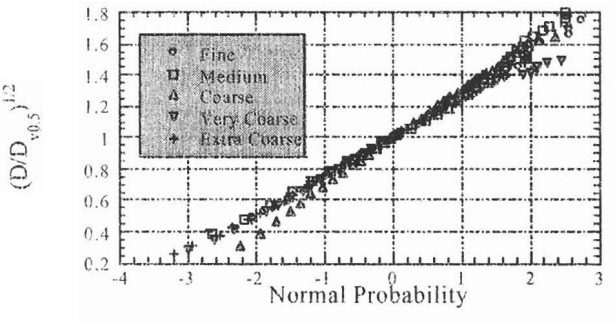

Figure 3. Root-Normal transformation of the PMS data. Representation by a straight line is evident from the plotted data.

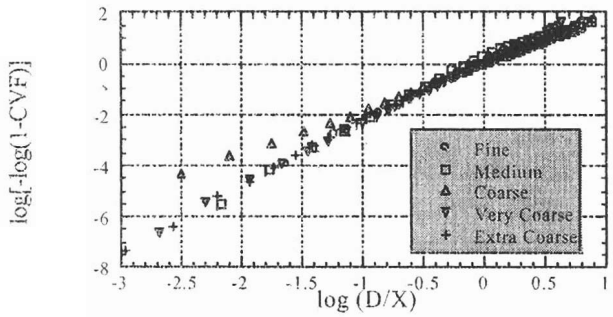

Figure 4. Rosin-Rammler transformation of the PMS data. Representation by a straight line is evident from the plotted data.

When both techniques are applied to the two data sets, the four curve-fitting relationships found in Figures 5 to 8 recover the least-squares relationships between $D_{v0.5}$, S, X, and q for PMS and Malvern. Clearly, the assumption of a straight-line representation, in the appropriate transform space, is warranted.

The most interesting aspect of the transformations is their strong correlation in droplet diameter $D_{v0.5}$ and X, and their (essentially) weak correlation with slope S and exponent q. A sensitivity study of these parameters shows that $D_{v0.5}$ and X strongly affect the placement of the droplet size distribution, while S and q more weakly contribute to the shape of the final cumulative volume fraction. The accuracy of S and q may therefore be not as critical to the success of the proposed approach as the droplet diameters $D_{v0.5}$ and X. Effects similar to these were observed in a companion analysis involving the same transformations [23].

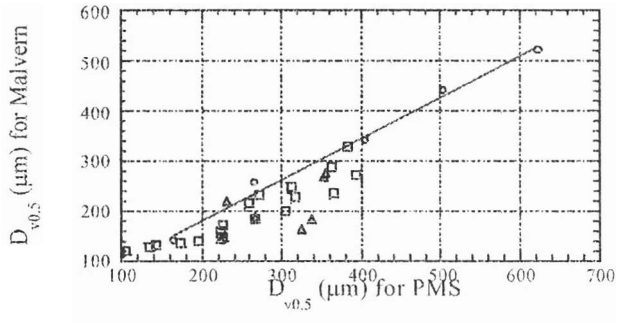

Figure 5. Comparison of $D_{v0.5}$ between PMS and Malvern for the five ASAE standard nozzles (open circles); other non-ASAE standard nozzle data [12] (squares) and [10] (triangles). The equation for the straight line through the present data is $D_{v0.5M} = 15.775 + 0.82122\ D_{v0.5P}$ (with R = 0.9952), where $D_{0.5M}$ is the volume median diameter for the Malvern data.

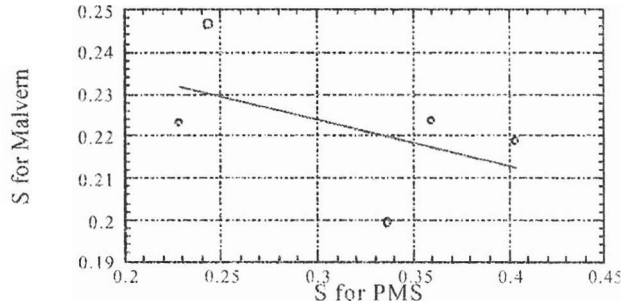

Figure 6. Comparison of Root-Normal slope between PMS and Malvern for the five ASAE standard nozzles. The equation for the straight line is $S_M = 0.25761 - 0.11238\ S_P$ (with R = 0.5034), where S_M and S_P are the slopes for the Malvern and PMS data, respectively.

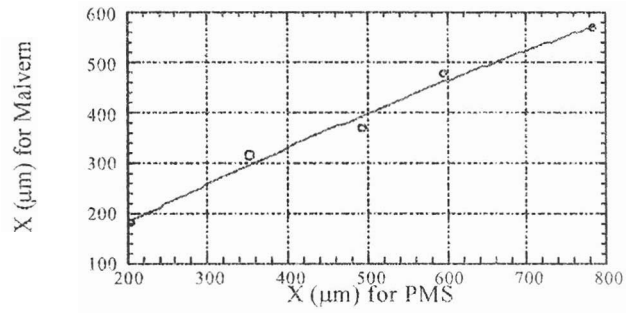

Figure 7. Comparison of X between PMS and Malvern for the five ASAE standard nozzles. The equation for the quadratic fit is $X_M = 14.816 + 0.86974\ X_P - 0.00020313\ X_P^2$ (with R = 0.9932), where X_M and X_P are the Rosin-Rammler diameters for Malvern and PMS, respectively.

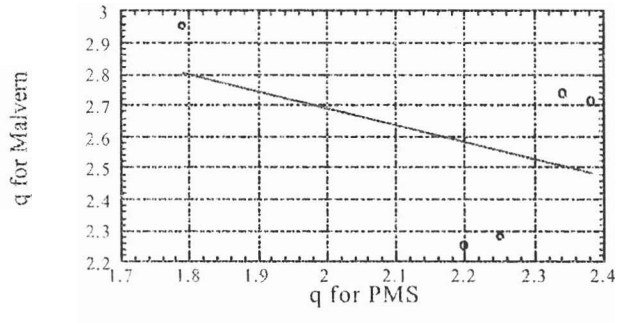

Figure 8. Comparison of exponential between PMS and Malvern for the five ASAE standard nozzles. The equation for the straight line is $q_M = 3.764 - 0.53726\ q_P$ (with R = 0.4127), where q_M and q_P are the Rosin-Rammler exponents for Malvern and PMS, respectively.

Results

The PMS droplet spectra may then be transformed into Malvern-like spectra, using the conversion factors determined above, and recovering the two sets of plots shown in Figures 9 and 10. The strong correlation shown here was accomplished even though the two sets of original data were collected in substantially different wind tunnels. Here it may be seen that the Rosin-Rammler approach recovers slightly better (more conservative) results at the smaller droplet sizes, and that, overall, the two data sets, when transformed, replicate each other.

In general, then, converting a PMS droplet size distribution with a minimum droplet size of 34 μm to Malvern-equivalent droplet size distribution requires a three-step process:

1. The PMS droplet size distribution must first be processed through the Root-Normal algorithm to recover the least-squares values of $D_{v0.5}$ and S, or through the Rosin-Rammler algorithm to recover the least-squares values of X and q.
2. The transformed values of $D_{v0.5}$ and S, or X and q, may then be found from the formulas provided in the captions to Figures 5 to 8.
3. The Malvern-equivalent droplet size distribution may then be constructed from the transformed values for $D_{v0.5}$ and S, or X and q.

The procedure detailed here may be generalized to include whatever lower limit (not necessarily 34 μm) exists for the PMS instrument. It should be noted that Malvern instruments can also be configured with various different dynamic size ranges, with the 4 μm to 1504 μm range used by the SDTF being common for characterizing agricultural sprays.

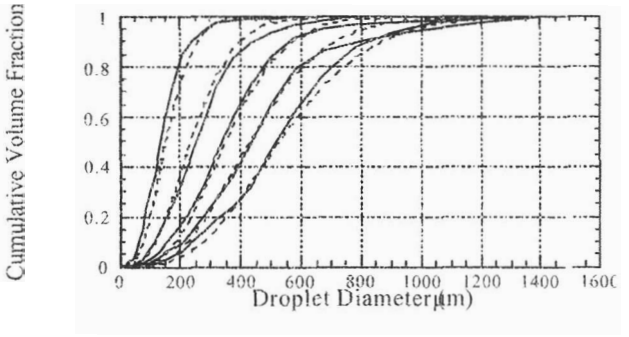

Figure 9. PMS droplet size distributions corrected by reconstructing a Root-Normal distribution with the transformed values of $D_{v0.5}$ and S correlated with Malvern measurements in Figures 5 and 6. Curve identification given in Figure 1.

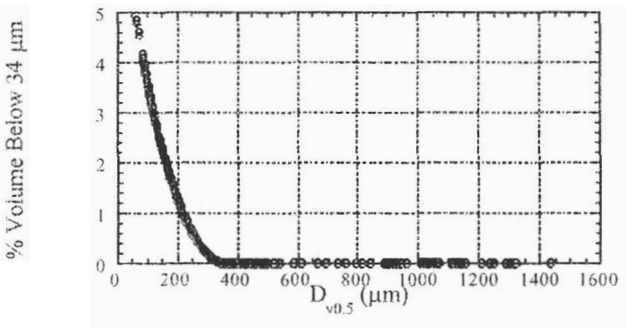

Figure 11. Conversion below 34 μm applied to the FS database. The number of droplet size distributions (total of 250) that recover between 0-1% volume is 58, 1-2% is 42, 2-3% is 34, 3-4% is 31, and 4-5% is 7. All droplet spectra are affected by the transformation.

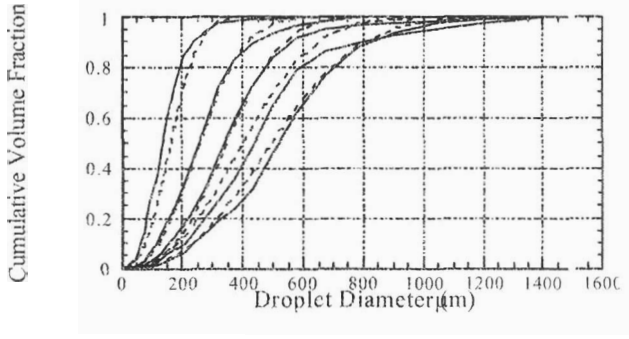

Figure 10. PMS droplet size distributions corrected by reconstructing a Rosin-Rammler distribution with the transformed values of X and q correlated with Malvern measurements in Figures 7 and 8. Curve identification given in Figure 1.

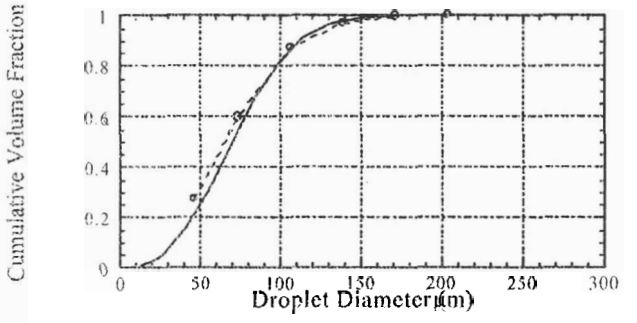

Figure 12. Droplet size distribution example for the largest ΔV recovered in the FS database: PMS original (dashed curve and open circles); Malvern equivalent (solid curve) using Rosin-Rammler.

When this procedure is applied to the FS database, the level of volume fraction recollected below 34 μm is shown in Figure 11. Such a level would be of consequence to off-target drift and eventual deposit on, along with the fact that the entire droplet spectrum shifts to lower droplet sizes with the transformations detailed here. This effect may be most easily seen by comparing the FS database entry most strongly affected, namely Micronair AU5000 operating at 10850 RPM with an airspeed of 58 m/s [1], with an application of the aerial spray model AgDRIFT/FS [24] for both the original PMS droplet spectra and the converted Malvern-like spectra. The original and transformed droplet size distributions are given in Figure 12, and the aerial spray model results are shown in Figure 13. This result clearly illustrates the power of, and the need for, the PMS to Malvern conversion on the historical FS database.

PMS Comparisons

An indication of tunnel-to-tunnel variability may be seen by comparing 18 droplet size distributions (various nozzle types, air speeds, and spray material) measured in the UC-Davis wind tunnel [25-27] with USDA ARS wind tunnel data [28-30 and unpublished, collected by co-author IWK] in Figures 14 and 15. In the absence of ASAE standard nozzle results in the UC-Davis wind tunnel (pending), the correlations shown here may be used when converting FS data from PMS measurements at UC-Davis to PMS measurements at USDA ARS.

Conclusions

This paper has developed a simple, yet practical technique for converting PMS droplet size distributions into Malvern-equivalent distributions and adjusting the historical FS database to reflect these changes. The proposed adjustment approach will allow PMS data to be more effectively used in conjunction with Malvern

data for present and future spray transport and deposition modeling. Improved model predictions with the AgDRIFT/FS code will undoubtedly result.

It would be advantageous to repeat this exercise with PMS data for the ASAE standard nozzles from within the UC-Davis wind tunnel, and to generalize the approach for the several lower droplet diameter limits available in the PMS and Malvern instruments.

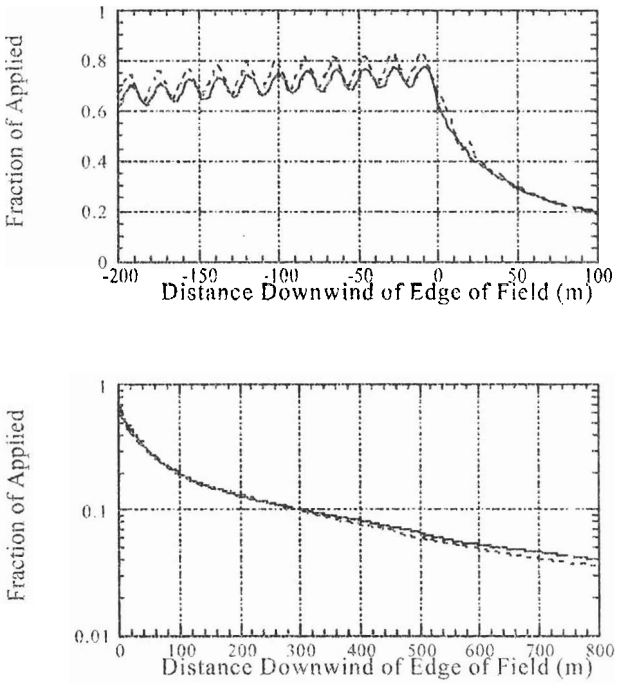

Figure 13. Resulting deposition patterns predicted by AgDRIFT/FS: PMS original droplet spectrum (dashed curve), Malvern equivalent spectrum using Rosin-Rammler (solid curve). The Malvern-like droplet size distribution tends to decrease the deposition within the spray block (for distances less than 0 m), top figure, and increase the deposition beyond 300 m downwind of the edge of the field, bottom figure.

References

1. Skyler, P. J. and Barry, J. W., "Compendium of Drop Size Spectra Compiled from Wind Tunnel Tests," USDA Forest Service Report No. FPM 90-9 (1991).
2. Bilanin, A. J., Teske, M. E., Barry, J. W. and Ekblad, R. B., "AGDISP: The Aircraft Spray Dispersion Model, Code Development and Experimental Validation," *Transactions of the ASAE* 32:327-334 (1989).
3. Teske, M. E., Bowers, J. F., Rafferty, J. E. and Barry, J. W., "FSCBG: An Aerial Spray Dispersion Model for Predicting the Fate of Released Material behind Aircraft," *Environmental Toxicology and Chemistry* 12:453-464 (1993).
4. Teske, M. E., Skyler, P. J. and Barry, J. W., "A Drop Size Distribution Data Base for Forest and Agricultural Spraying: Potential for Extended Application," ICLASS Fifth International Conference, NIST Special Publication No. 813, pp. 325-332 (1991).
5. Teske, M. E. and J. W. Barry, J. W., "Correlation of the USDA Forest Service Drop Size Distribution Data Base," ILASS-Americas Fifth Annual Conference, San Ramon, CA, pp. 157-161 (1992).
6. Teske, M. E. and Bilanin, A. J., "Drop Size Scaling Analysis of Non-Newtonian Fluids. *Atomization and Sprays* 4:473-483 (1994).

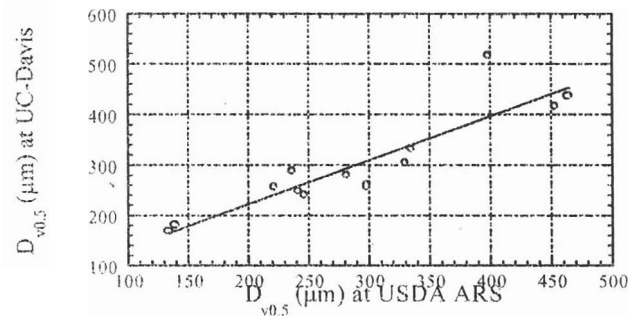

Figure 14. Comparison between $D_{0.5}$ for PMS in the USDA ARS and UC-Davis wind tunnels. The equation for the straight line is $D_{v0.5D} = 49.984 + 0.87247\ D_{0.5A}$ (with R = 0.9062), where $D_{v0.5A}$ is USDA ARS data and $D_{v0.5D}$ is UC-Davis data.

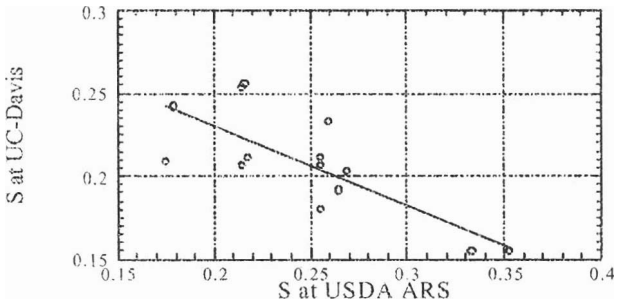

Figure 15. Comparison between slope S for PMS in the USDA ARS and UC-Davis wind tunnels. The equation for the straight line is $S_D = 0.32642 - 0.47941\ S_A$ (with R = 0.7685), where S_A is USDA ARS data and S_D is UC-Davis data.

7. Hewitt, A. J., Valcore, D. L. and Bryant, J. E., "Spray Drift Task Force Atomization Droplet Size Spectra Measurements," ILASS-Americas Ninth Annual Conference, San Francisco, CA, pp. 230-233 (1996).
8. Doble, S. J., Matthews, G. A., Rutherford, I. and Southcombe, E. S. E., "A System for Classifying Hydraulic Nozzles and Other Atomizers into Categories of Spray Quality," Proceedings of the 1985 British Crop Protection Conference: Weeds, vol. 9A-5, pp. 1125-1133 (1985).
9. Arnold, A. C., "A Comparative Study of Drop Sizing Equipment for Agricultural Fan-Spray Atomizers," *Aeronautical Science and Technology* 12:431-445 (1990).
10. Young, B. W. and Bachalo, W. D., "The Direct Comparison of Three 'In-Flight' Droplet Sizing Techniques for Pesticide Spray Research," International Symposium on Optical Particle Sizing: Theory and Practice, Rouen, France (1987).
11. Dodge, L. G., "Comparison of Performance of Drop-Sizing Instruments," *Applied Optics* 27:1328-1341 (1987).
12. Arnold, A. C., "The Dropsize of the Spray From Agricultural Fan Spray Atomizers as Determined by a Malvern and the Particle Measuring System (PMS) Instrument," *Atomization and Spray Technology* 3:155-167 (1987).
13. Bachalo, W. D., Houser, M. J. and Smith, J. N., "Evolutionary Behavior of Sprays Produced by Pressure Atomizers," Paper No. 86-0296, AIAA 24th Aerospace Science Meeting, Reno, NV (1986).
14. Reeves, K. C. and Womac, A. R., "Reduced Drift Characteristics of Pre-Orifice, Flat Spray RF Raindrop Nozzles," ASAE Paper No. 921612, Charlotte, NC (1992).
15. Picot, J. J. C., Goguen, R. and Murray, D., "Wind Tunnel Atomization Characterizations with the Malvern Spectrometer: The Spatial Sampling Error," ILASS-Americas Sixth Annual Conference, Worcester, MA, pp. 157-161 (1993).
16. Dodge, L. G., "TESS: Tool for Spray Studies," *Technology Today* (1992).
17. Schafer, M., Schegk, C. D. and Umhauer, H., "Comparison of the Measurement Results of Three Optical Measuring Techniques in the Determination of the Size Distributions of Droplets," Proceedings of the Third European Symposium on Particle Size Characterization, Nurnberg, Germany, pp. 241-261 (1984).
18. Dietrich, V. E., "Dropsize Distributions For Various Types of Nozzles," ICLASS Second International Conference, Tokyo, pp. 69-77 (1978).
19. Tishkoff, J. M., "Spray Characterization: Practices and Requirements," *Optical Engineering* 23(5):557-560 (1984).
20. Baumgardner, D., Strapp, W. and Dye, J. E., "Evaluation of the Forward Scattering Spectrometer Probe, Part II: Corrections for Coincidence and Dead-Time Losses," *Journal of Atmospheric and Oceanic Technology* 2(12):626-632 (1985).
21. Simmons, H. C., "The Correlation of Drop-Size Distributions in Fuel Nozzle Sprays," *Transactions of the ASME Journal of Engineering for Power* 99:309-314 (1977).
22. Rosin, P. and Rammler, E., "The Laws Governing the Fineness of Powdered Coal," *Journal of the Institute of Fuel* 7(31):29-36 (1933).
23. Teske, M. E. and Thistle, H. W., "Droplet Size Scaling of Agricultural Spray Material by Dimensional Analysis," *Atomization and Sprays* 10, to appear (2000).
24. Teske, M. E., "FSCBG 5.0: The Inclusion of the USDA Forest Service Aerial Application Model into AgDRIFT 3.0," Report No. 99-05, Continuum Dynamics, Inc., Princeton, NJ (2000).
25. Yates, W. E., Cowden, R. E. and Akesson, N. B., "Nozzle Design Influence on Uniformity of Droplet Size Spectrums from Agricultural Aircraft," *Transactions of the ASAE* 26(6):1633-1637, 1643 (1983).
26. Yates, W. E., Cowden, R. E. and Akesson, N. B., "Nozzle Orientation, Air Speed and Spray Formulation Effects on Drop Size Spectrums," *Transactions of the ASAE* 26(6):1638-1643 (1983).
27. Yates, W. E., Cowden, R. E. and Akesson, N. B., "Drop Size Spectra from Nozzles in High-Speed Airstreams," *Transactions of the ASAE* 28(2):405-410, 414 (1985).
28. Kirk, I. W., "Application Parameters for CP Nozzles," ASAE Paper No. AA97-006, Las Vegas, NV (1997).
29. Kirk, I. W., "Spray Quality from CP Straight Stream Nozzles," ASAE Paper No. AA98-002, Las Vegas, NV (1998).
30. Kirk, I. W., "Spray Quality Options with Aerial Straight Stream Nozzles," ASAE Paper No. AA99-006, Reno, NV (1999).