Correlation of USDA Forest Service Droplet Size Distributions Between PMS Optical Array Probe and Malvern Laser Diffraction

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Abstract
This paper considers the practical correlation between droplet spectra recovered in instruments. The resulting correlation is applied to the historical USDA Forest Service database (PMS), to provide data consistent with the Spray Drift Task Force database found in AgDRIFT® (Malvern).

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, correlating the data, and developing scaling laws for non-Newtonian fluids [4].

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 size resolution of 34 μm. Recently, the Spray Drift Task Force (SDTF) developed a large database of spray droplet size information [5], based on the Malvern laser diffraction analyzer, located at New Mexico State University (NMSU) and SpraySearch in Victoria, Australia. The resolution of this technique allowed measurements of droplet diameters down to 4 μm. The subsequent SDTF field and modeling studies established that 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 in [4]) confirmed the applicability and acceptance of the Malvern (or similar laser diffraction instrument) approach to data collection over and above the PMS approach.

To establish a consistent terminology with regard to droplet size categories (for all measurement systems), the American Society of Agricultural Engineers (ASAE) extended the nozzle classification scheme developed by the British Crop Protection Council [6] to the spray quality breadth anticipated in the United States. This standard, ASAE S-572 (1999), also addressed test procedures. Five nozzle classifications were identified, from Very Fine to Extremely Coarse.

The effective use of the FS database requires that its PMS measurements be rationalized within the five Malvern standard nozzle measurements. To that end, this paper takes PMS standard nozzle measurements from the UC-Davis wind tunnel and compares them with

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corresponding Malvern measurements of the same nozzles. This work is an extension of a previous effort [4] to convert PMS measurements, but applies the insights gained previously to complete the comparison, resolve instrument differences, and recover the desired small end of the droplet spectrum.

**Measurement Considerations**

Within the last 15 years several researchers have found differences in droplet size information measured with PMS and Malvern techniques. Large differences were occasionally observed in the data produced by the different instruments, and even by the same instrument type in different wind tunnels or with different researchers. The Malvern generally yields finer droplet diameter data than the PMS, which produces droplet diameter data generally more distributed toward larger droplet diameter size classes than the Malvern [7]. Differences appear to be sensitive to the combinations of nozzles and test substances used [8], or due to instrument limitations or differences in sampling techniques.

Laser diffraction techniques (Malvern) involve a “spatial” number-density-weighted sampling technique, whereas optical array probes (PMS) measure a “temporal” number-flux weighted sampling technique. Both techniques have been observed to produce different results if the nozzle spray does not contain droplets traveling at uniform speed at the point of sampling. However, at the typical sampling distances considered here, 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.

Operational differences depend on the nozzle, the test substance, the wind tunnel, and the researcher. The laser diffraction technique (Malvern) is used in a completely non-intrusive way for measuring agricultural sprays, whereas the PMS instrument is inserted into the spray, an action that would logically influence the droplet flow field encountered by the measuring device. A consistent representation by either technique would seem to require the use of a standardized nozzle set, a known test substance, the same wind tunnel, and the same researcher.

Standardized reference nozzles overcome the first problem [9, 10]; using tap water overcomes the second. The same wind tunnel and the same researcher are not so easily resolved, and although ASAE S-572 addresses measurement platforms and experimental approaches, these areas are probably responsible for most of the variation seen in the published literature.

Nonetheless, it would appear proper to compare PMS measurements to Malvern on a standardized nozzle set and, in doing so, correlate the small end of the droplet spectrum (below 34 μm), and extend the volume fraction across the droplet size distribution. Developing such an approach, and applying it to the historical FS database, form the basis of the work reported here.

The reference nozzles are: 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 Extremely Coarse).

**Problem Definition**

The specific problem may be easily identified by examining consistent droplet size distribution data sets taken with PMS and Malvern instruments. ASAE S-572 recognizes that the same instrument type and laboratory, and the same procedure, should be used to measure the reference nozzles and the nozzles of interest. While that approach is noble, it could not be followed here. Rather, our intent and purpose was to quantify a path between the UC-Davis wind tunnel (where the FS database was measured with PMS) to the NMSU wind tunnel (where the references nozzles were measured with Malvern).

To this end the reference nozzles were measured by the PMS in the UC-Davis wind tunnel by Norm Akesson and Abram Jones, to whom we acknowledge our gratitude. These data are plotted in Figure 1 against Malvern data supplied by the SDTF and measured by co-author Andrew Hewitt in the NMSU wind tunnel. It may be seen that the transition curves for both instruments have nearly the same volume median diameter (Dₙ₅ₐ) (except for Very Coarse to Extremely Coarse spray quality), and that the PMS curves exhibit a lower slope than the Malvern curves (except for Very Fine to Fine).

**Solution Approach**

The most straightforward way to rationalize the two sets of curves plotted in Figure 1 is through the use of an interpolation technique that gathers all of the data available in these droplet size distributions and represents them by a two-parameter mathematical model. The approach of choice here is the root-normal [11]. Based on past experience [4], the PMS data will be adjusted toward the Malvern data.

In the root-normal technique 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 $D_{0.5}$, a least squares fit through the droplet size distribution plotted in these coordinates yields a straight line of the form

$$\sqrt{\frac{D}{D_{0.5}}} = 1 + S Pr$$

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 $D_{0.5}$; when $CVF = 0.1$, $Pr = -1.2817$, and when $CVF = 0.9$, $Pr = 1.2817$.

The PMS data must first be corrected for volume missed by the instrument below 34 μm, by identifying that volume fraction in the Malven data. This approach recovers the expression $Vol_{\text{missed}} = 0.04336 - 0.00023728 D_{0.5} + 0.00000032294 D_{0.5}^2 \ (R^2 = 1.0)$ based on the uncorrected $D_{0.5}$. An additional droplet size category is constructed between 4 and 34 μm, and the PMS data are renormalized appropriately.

The transformed PMS data are plotted in Figure 2. When the $D_{0.5}$ and $S$ data are used to regenerate the original PMS droplet size distributions, the average accuracy is $R^2 = 0.9937$.

Evaluation of the two parameters $D_{0.5}$ and $S$ in each of the droplet size spectra, and least-squares curve-fitting of these relationships, recovers the correlation expressions $D_{0.5} = 55.136 + 0.81402 D_{0.5}$ ($R^2 = 0.9856$), where $D_{0.5}$ and $D_{0.5}$ are the volume median diameters for Malvern and PMS, respectively, and $S_m = 0.14293 + 0.30102 S_r - 0.24424 S_r^2 \ (R^2 = 0.9947)$, where $S_m$ and $S_r$ are the slopes for Malvern and PMS, respectively. The PMS droplet spectra may then be transformed into Malvern-like spectra, using these correlation factors, to recover the comparison curves shown in Figure 3.

Figure 1. Unmodified droplet size distributions from the Malvern (solid curves) and PMS (dashed curves), where the boundary curves separate, from left to right, Very Fine to Fine spray quality, Fine to Medium, Medium to Coarse, Coarse to Very Coarse, and Very Coarse to Extremely Coarse. Measurements of the same nozzles with both instruments in different tunnels with different researchers show important data differences. The cutoff at 34 μm for the PMS is clearly seen.

Figure 2. Root-normal transformation of the PMS data. Straight-line representation is evident from the data and consistent with the transformation, but not at the ends.

Figure 3. PMS droplet size distributions (dashed curves) converted by reconstructing a root-normal distribution with the transformed values of $D_{0.5}$ and $S$ correlated with Malvern measurements (solid curves), with average accuracy of $R^2 = 0.9961$, for, from left to right, Very Fine to Fine, Fine to Medium, Medium to Coarse, Coarse to Very Coarse, and Very Coarse to Extremely Coarse.

Off-target drift in aerial application is generally identified with the smaller droplets in the spectrum (drift also occurs with the larger droplets, but only those that evaporate to smaller sizes and travel downwind). Figure 3 shows that the transformed results recover a non-conservative prediction of all five droplet spectra, particularly below $CVF = 0.2$ (non-conservative in the sense that there is less volume in the transformed droplet spectra at the smaller droplet sizes). If a useable correlation is to be achieved, an alternate approach – one that matches the smaller droplets in the droplet spectra – must be developed.

The original DropKick analysis [12, 13] sought to develop a nozzle-independent model for predicting droplet size distributions, by developing regression models for $D_{0.5}$ and percent volumes less than 50 μm, 141 μm, and 220 μm (natural droplet size categories selected from Malvern output). One problem with this approach was the need for constitutive equations limiting the obvious relationships between percent
volumes as droplet diameter increases. This problem is obviated by using the root-normal slope, instead of the percent volumes, along with $D_{0.5}$, even though the accuracy of the fit may be less [14]. Kirk [15, 16] developed spreadsheets containing $D_{0.5}$, relative span $RS = (D_{0.95} - D_{0.5})/D_{0.5}$ (with $S = 0.1951$ RS), and percent volumes less than 100 µm and 200 µm. He found well-correlated results for $D_{0.5}$ and percent volumes, but rather poor correlation for $RS$.

A sensitivity study of these parameters suggests that $D_{0.5}$ strongly affects the placement of the droplet size distribution, while $S$ contributes to the shape of the final cumulative volume curve. It is the shape of these curves that need reassessment.

The approach proposed here is to extend the root-normal representation to higher order. It may be seen in Figure 2, for example, that between CVF = 0.1 and 0.9 (for $|Pr| < 1.2817$), the root-normal transformations are in fact nonlinear. The proposed representation becomes

$$\sqrt{D} = 1 + A Pr - B Pr^2$$

where least-squares curve-fitting of these relationships recovers the correlation expressions $A_d = 0.18983 + 0.01902 A_P$ ($R^2 = 0.6634$), where $A_d$ and $A_P$ are the first coefficients for Malvern and PMS, respectively, and $B_d = 0.032269 - 0.18353 B_P$ ($R^2 = 0.7873$), where $B_d$ and $B_P$ are the second coefficients for Malvern and PMS, respectively. While these coefficients are not as highly correlated as in the linear representation, the results (Figure 4) are far more acceptable for the purposes discussed here. The correlations between PMS and Malvern below CVF = 0.2 now recover a conservative representation of all of the droplet spectra examined.

**Results**

The correlations shown here were accomplished even though the two sets of data were collected in different wind tunnels, with different instruments, and by different researchers. Transformed by this approach, the PMS data provide a conservative estimate of the smaller droplets in the spectra, the ones most prone to drift in an aerial application.

Converting PMS droplet data to Malvern-equivalent droplet data requires a three-step process:

1. The PMS droplet size distribution must first be processed to recover the values of $D_{0.5}$, $A$, and $B$.
2. The transformed values of $D_{0.5}$, $A$, and $B$ are found from formulas similar to those shown here (which are specific to the data examined here).
3. The Malvern-equivalent droplet size distribution is constructed from the transformed values for $D_{0.5}$, $A$, and $B$.

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 dynamic size ranges, with 4 to 1504 µm being common for characterizing most agricultural sprays.

When this procedure is applied to the FS database, the level of volume fraction collected below 34 µm (and therefore “missed” by the PMS measurements) is shown in Figure 5. While a correction of several percentage may not seem important, it should be remembered that all of the missed volume will drift downwind. Thus, it may be seen that over half of the FS database is affected, especially the droplet spectra for which $D_{0.5}$ is less than 300 µm, including all droplet spectra generated from rotary atomizers.

**Figure 4.** PMS droplet size distributions (dashed curves) converted by reconstructing a root-normal distribution with the transformed values of $D_{0.5}$, $A$, and $B$ correlated with Malvern measurements (solid curves), with average accuracy of $R^2 = 0.9975$, for, from left to right, Very Fine to Fine, Fine to Medium, Medium to Coarse, Coarse to Very Coarse, and Very Coarse to Extremely Coarse.

**Figure 5.** Volume fraction recovered below 34 µm across the FS database. The number of droplet spectra (out of 250) that requires more than a 0.01 adjustment in volume is 164 (65.6%).
Conclusions

This paper has applied a simple technique for converting PMS droplet data into Malvern-equivalent data, 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 model [17] will undoubtedly result.

These results, and the collection of the PMS data, suggest five steps be taken to improve the process discussed here:

1. A previously published droplet spectrum, generated from PMS, should be measured in the UC-Davis wind tunnel, to benchmark the instrument and verify the consistency of the experimental approach used to collect the PMS data.
2. A nozzle classification smaller than Very Fine to Fine should be measured with both PMS and Malvern, to improve the Vol_{m\text{ed}} correlation.
3. A consistent wind tunnel study with both PMS and Malvern should be considered, as their raw data results (Figure 1) are so different, and should be re-examined.
4. To complement the FS database at the small D_{50} end, an extensive set of rotary atomizer data should be collected with a Malvern. To our knowledge neither the FS nor the SDTF is contemplating such a study at the present time.
5. While the ASTM is developing a standard for Malvern measurements, no such standard is anticipated for PMS, but should be as well.

References