Reply

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It is somewhat surprising that, in discussing my paper (Kinnell, 1976), Joss and Waldvogel considered the agreement between the standard calibration curve for their disdrometer,

$$U_c = 0.94D^{1.47}, \tag{1}$$

(where U_c is the peak height of the pulse produced by the processor and D is drop size) and the values of U_c measured for water drops traveling at terminal velocity to be a major result. Notwithstanding that this calibration curve was probably, or should have been, obtained from a similar experimental study, Joss and Waldvogel

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present equations which indicate that this calibration curve is inaccurate. They state that design considerations determined that the disdrometer should be a compromise between a device with a high-frequency broad bandwidth response where pulse height U_L is given by

$$U_L \propto MVt^{-1} \propto D^3V^2e_v^{-1}, \quad (2)$$

(where M is drop mass, V drop velocity, t impact time and e_v drop vertical extent) and a device with a low-frequency response where

$$U_L \propto MV. \quad (3)$$

As a consequence of this and the relationships between drop size, drop shape and terminal velocity, they state that the real output-pulse versus drop-diameter relationship can be expressed by

$$U_L \propto D^n, \quad (4)$$

where $4.3>n>3.1$ for $0.3<D<6$ mm. If, as would appear probable, the relationship obtained experimentally between U_c and U_L (Kinnell, 1976), i.e.,

$$U_c = 3.98U_L^{0.39}, \quad (5)$$

is valid for all drop sizes, then

$$U_c \propto D^k, \quad (6)$$

where $1.7>k>1.2$ for $0.3<D<6$ mm. The calibration curve [Eq. (1)], by maintaining k constant at a value of 1.47, can therefore be expected to exhibit its least accuracy over the drop sizes (<2 mm) most frequently observed in natural rainfall.

The main theme of the comments of Joss and Waldvogel centers around the discussion of errors generated in the measurement of raindrop size by variations in raindrop velocity and shape. Joss and Waldvogel object to the tentative conclusion that variations in raindrop velocity and shape might produce unacceptable errors under some rainfall conditions (Kinnell, 1976). The objection is based on the grounds that the instrument was tested under extreme and unrealistic conditions. There is no doubt that the test conditions were extreme. However, no attempt was made to extrapolate numerically the effects of drop shape and velocity observed for the low velocity conditions to the terminal velocity conditions expected to occur during natural rainfall.

Having established that both drop shape and velocity can influence pulse height at low drop velocities, it was considered necessary to establish the error in the measurement of drop size produced when drop shape and velocity deviate from the values which exist at terminal velocity. This second part of the exercise was, unfortunately, not backed by reliable experimental evidence or an accurately defined relationship between U_L and the factors M, V and t. However, it now can be seen from (2) and (3) that the worst case as regards the generation of errors in the measurement of drop size occurs for high-frequency devices. Here 1% variations in e_v and V would produce respective variations in drop size of 0.27 and 0.53% when $k=1.47$. If this worst case is applied to the deviations in drop shape (8% for e_v) and velocity (10%) quoted by Joss and Waldvogel, errors in the measurement of drop size of about 2 and 5%, respectively, could be anticipated to occur when $k=1.47$. Because of the design considerations, the errors attributable to the disdrometer should lie below these values. The error levels estimated by Joss and Waldvogel from the equation describing the relationship between U_L, D, V and t as

$$U_L \propto D^3Vt^{-0.5} \quad (7)$$

appear reasonable, at least in theory. There is, however, some conflict apparent between theory and practice. The simple power law described by (4) accounts for 100% of the variance in the U_L values calculated from Eqs. (2), (3) and (7) for $2.5<D<5.5$ mm when n has fixed (constant) values of 2.9, 3.2 and 3.0, respectively. On the other hand, (4) with n constant produces its best fit (accounting for 99.7% of the variance in U_L) to the U_L values obtained from the experimental study with water drops at terminal velocity when n has a value of 3.3. It might be concluded from this that the disdrometer behaves more like a high-frequency device than previously supposed.

Although the real levels of error in the measurement of drop size generated by variations in drop shape and velocity are unknown, it can be argued on theoretical grounds that the errors are within acceptable limits. The agreement, as quoted by Joss and Waldvogel, between rainfall amounts measured simultaneously by the disdrometer and an independent raingage tends to support this argument. However, the work of Kinnell (1976) and the comments of Joss and Waldvogel have shown that some inadequancies exist in the calibration curve [Eq. (1)] for the RD69 disdrometer. It is hoped that these inadequancies will be rectified some time in the future.

REFERENCE

Kinnell, P. I. A., 1976: Some observations of the Joss-Waldvogel rainfall disdrometer. *J. Appl. Meteor.*, **15**, 499–502.

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