NOTES AND CORRESPONDENCE

Field Observations of Multimode Raindrop Oscillations by High-Speed Imaging

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ABSTRACT

Periodic oscillations of raindrops falling at terminal velocity in natural rain are visualized for the first time by high-speed imaging. These images show the existence of an oscillation mode with the same frequency as the fundamental harmonic, but with shape different than that predicted by linear theory. These oscillations cause a lateral drift with a speed of approximately 20%–30% of the drop terminal velocity and without a preferred direction. These experimental observations serve as an insightful illustration of the potential benefit of applying high-speed imaging technology to investigate the dynamical microstructure of rainfall at the raindrop scale.

1. Introduction

Accurate characterization of raindrop shape has long been an important research subject due to its immediate applications in radar meteorology (Atlas and Ulbrich 1990; Bringi and Chandrasekar 2001, among others). Since raindrops are not exactly spherical, reflectivities of the dual-polarization weather radars from horizontally and vertically polarized waves will differ depending on the ratios of vertical (υ) and horizontal (h) chords of raindrops, $\alpha = \upsilon/h$. This dependency between radar measurables and raindrop chord ratios allows remote sensing of various rain characteristics (e.g., rainfall rate).

Laboratory and field observations have shown that a raindrop falling at terminal velocity (U_t) may exhibit either an equilibrium (steady state) shape or an instantaneous shape induced by oscillations (Jones 1959; Pruppacher and Beard 1970; Chandrasekar et al. 1988; Beard et al. 1991; Tokay et al. 2000; and many others). The equilibrium shape of a raindrop is characterized by various competing physical factors including, external (aerodynamic) and internal (hydrostatic) pressure distributions, surface tension forces, and others (McDonald 1954; Beard and Chuang 1987). For smaller raindrops ($d_0 < 1$ mm, d_0 is the equivalent diameter of a sphere having the same volume as the drop) surface tension forces dominate over other factors keeping the drop spherical or slightly deformed as an oblate spheroid. On the other hand, for larger raindrops ($d_0 \geq 1$ mm) effects of both external and internal pressures become more pronounced and lead to an increased drop deformation. Equilibrium shapes of these larger drops display a marked flattening on the lower surface and smoothly rounded curvature on the upper surface (see Fig. 1).

The steady state of a raindrop may be perturbed by different forcing mechanisms such as vortex shedding in the drop wake (Beard et al. 1989; Saylor and Jones 2005), collisions with drizzle drops (Johnson and Beard 1984; Beard and Johnson 1984), and wind shear and turbulence (Tokay and Beard 1996). As a response, raindrops oscillate and try to dissipate excessive energy induced by those perturbations through viscous dissi-

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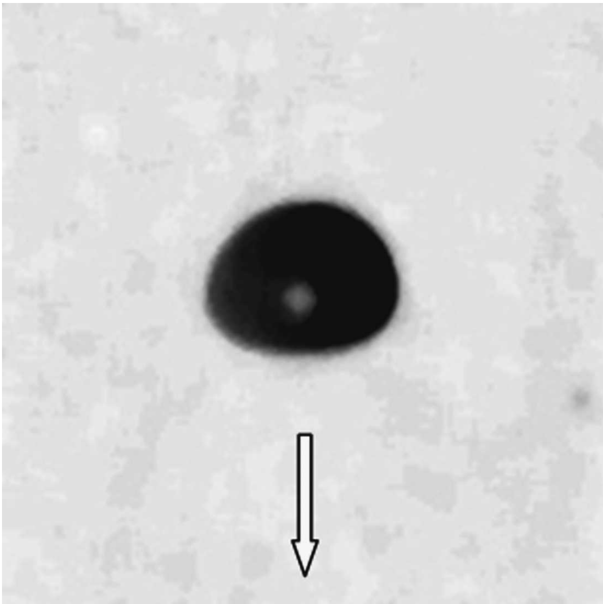

FIG. 1. Image of a raindrop (d_0 = 4.5 mm) falling at terminal velocity (U_t = 8.8 m s^{-1}). White arrow indicates the direction of gravity vector and size of the image frame (12.5 mm × 12.5 mm) gives the scale. This photograph is taken by a high-speed camera at the bottom end of the raintower (NASA WFF Rain–Sea Interaction Laboratory) after a 14-m fall of the drop. In Figs. 1, 4, and 5, drops are illuminated from behind. The result is an image having a bright background, a dark drop silhouette, and a bright region in the center of the drop that is an image of the illumination source obtained through the drop.

pation. Small-amplitude raindrop oscillations can be described by spherical harmonic perturbations with frequencies given by

$$f_n = \left[\frac{2n(n-1)(n+2)\sigma}{\pi^2 \rho d_0^3}\right]^{1/2}, \tag{1}$$

where n is the order of spherical harmonic perturbation, σ and ρ are the surface tension and the density of water, respectively (Rayleigh 1879; Lamb 1932). For each harmonic n ($n \geq 2$), there are $m = n + 1$ "degenerate" modes having unique spatial orientations. Because of faster damping of higher harmonics [see the parameterization for the decay time scale of oscillations in Beard et al. (1991)], instantaneous raindrop shapes are considered to be mainly determined by the fundamental (n = 2) and the first (n = 3) harmonics with little contribution from higher harmonics. This fact has been supported by previous laboratory and field observations using the photographs of backscattered light from the primary rainbow (Beard and Tokay 1991; Beard et al. 1991; Kubesh and Beard 1993). However, previously recorded signatures of the raindrops did not permit extraction of information on the shape modes.

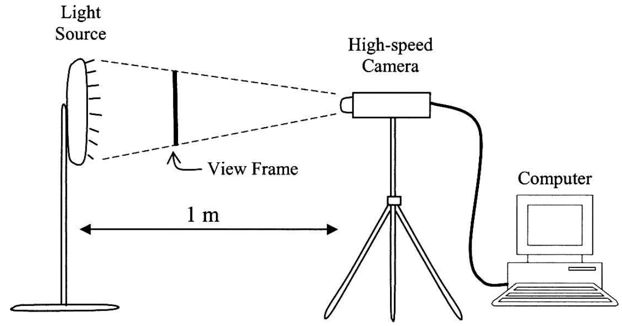

FIG. 2. Schematic of the experimental setup. Light source and Redlake high-speed camera are shielded and placed 1 m apart under rain. Images with a resolution of 432 (horizontal) pixels × 768 (vertical) pixels (corresponding to a view frame of approximately 43 mm × 77 mm) are captured at a rate of 1000 frames per second and transferred to the computer via a frame grabber.

Therefore, the presence of particular shape modes has been interpreted only by means of indirect methods such as by comparing the mean chord ratios of the observed drops and equilibrium drops (see Beard and Kubesh 1991; Andsager et al. 1999; Thurai and Bringi 2005).

4. Summary

Periodic raindrop oscillations in natural rain visualized for the first time by high-speed imaging were presented. Analysis of the images revealed the existence of an oscillation mode that cannot be characterized by linear theory. The authors propose that the identified oscillation mode is the result of interacting modes due to the nonlinear effects associated with large amplitude oscillations. These oscillations induced significant transverse drifts with constant speeds (≈0.2–0.3 U_t) and no preferred direction.

Further studies aiming at the quantitative characterization of raindrop oscillations, their causes and consequences are of great interest for radar rainfall studies. The technique presented in this note enables such detailed investigations based on direct observations [e.g., modal analysis (Prosperetti 1980; Becker et al. 1991)]. In this regard, a field experimental campaign aiming a comprehensive dataset is underway.