NOTES AND CORRESPONDENCE

Evidence for an Oscillatory Rain Rate in a Midwestern Winter Rain

R. B. FRITZ, R. J. HILL AND J. T. PRIESTLEY

NOAA/ERL/Wave Propagation Laboratory, Boulder, Colorado

W. P. SCHOENFELD

Cooperative Institute for Research in the Environmental Sciences (CIRES), University of Colorado/NOAA, Boulder, Colorado

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ABSTRACT

Rain rate during light precipitation in winter was measured with high temporal resolution optical systems at a site in Illinois. In addition to quasi-periodic variations, a clearly sinusoidal oscillation in rain rate was found imbedded in the general precipitation. The phase shift in the occurrence of the oscillation at two sensors, with the simultaneous recording of sinusoidal fluctuations of the attenuation of a millimeter wave signal, allows simulation of this particular rain pattern by a simple model. The basic mechanism that can produce a rain event with such a sinusoidal pattern is not clearly understood.

1. Introduction

Between 1983 and 1985, an experiment was carried out to measure the propagation characteristics of millimeter waves over flat terrain in Illinois under a variety of meteorological conditions. The meteorological instrumentation included several weighing-bucket raingages and two optical rain-rate instruments. The optical instruments use the detection of the diffraction pattern of rain drops falling through a laser beam to measure rain rate averaged over a 50 m path (Wang et al., 1979). These devices have been tested with tipping bucket raingages and found to be accurate within a few percent between 1 and 100 mm h^{-1} rain rates. The rain-measuring instruments were deployed in a line parallel to and 90 m east of the 1374 m long millimeter wave propagation path, oriented north–south. The station 2 optical raingage was centered 520 m north of the millimeter-wave transmitter; the station 1 optical raingage was centered 400 m north of station 2; and the millimeter-wave receiver was 454 m north of station 1. Weighing-bucket raingages were used to calibrate the optical gages. The arrangement of the field site is shown in Fig. 1.

On 21 February 1985, a light rain began at approximately 0750 CST and continued through most of the day. Cloud base was between 600 and 900 m above ground. Synoptic weather maps show that precipitation extended over an area of several hundred square kilometers. Figure 2 illustrates the rain rate measured by the optical instruments during that morning, showing variation from 0 to 7 mm h^{-1}. These data were sampled every 2.56 s and telemetered to a single recording system by fiber optic cable. The two optical rain rates are well correlated, with the more northern optical rain rate lagging the southern one. This suggests movement from the south of the precipitation-producing features of the stratiform cloud cover. The wind at a height of 4 m was 5 to 7 m s^{-1} from the south-southeast, as measured by prop-vane anemometers within 100 m of each optical instrument. The location of these measurements was a flat and level agricultural field with no obstructions to wind flow other than instrument towers and shelters within 400 m in any direction.

Very high variability of rain rate has been recognized to occur during summer thunderstorms. For example, using a capacitive type raingage with a resolution of 1 s, Hogg et al. (personal communication) measured a standard deviation of rain rate of 26 mm h^{-1} during a rain storm with a mean rain rate of 54 mm h^{-1}. This variabilty is related to the evolution and motion of convective storm cells. However, midwestern winter rains possess little convective activity, and cloud height and thickness are relatively uniform over wide areas.

Henrion et al. (1978) studied the quasi-periodic nature of precipitation streamers from a similar stratiform cloud in February 1977. By flying an instrumented aircraft through the streamers, they found a correlation between fluctuations of temperature and hydrometeor number density, thus implying that precipitation growth is related to weak convection which in turn is caused by release of latent heat. They did not find the strong sinusoidal precipitation rate variation noted here, but rather the more usual variations shown in

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Corresponding author address: Richard B. Fritz, NOAA Wave Propagation Laboratory, 325 Broadway R/E/WP 7, Boulder CO 80303.

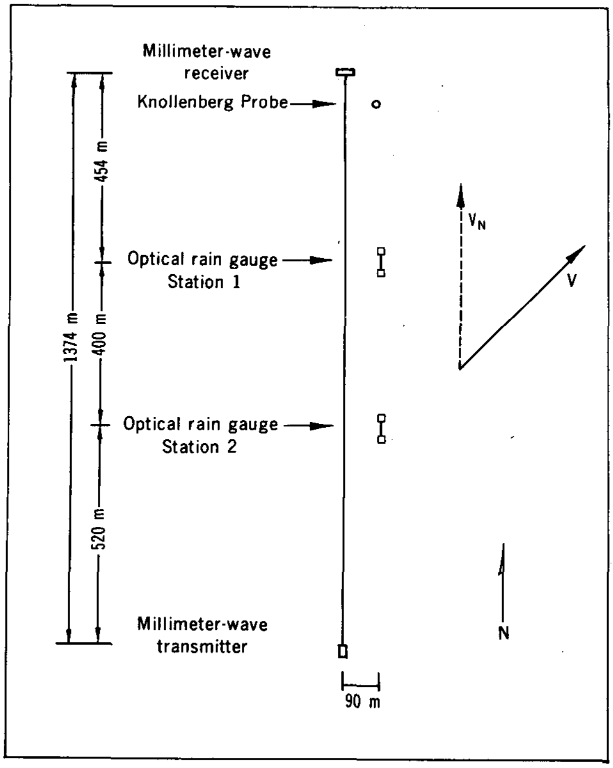

FIG. 1. Millimeter wave propagation field site configuration at Flatville, Illinois. Here V is the wind direction at cloud height and V_N is the phase velocity parallel to the millimeter and optical propagation paths.

Fig. 2. The persistence of regularly spaced weak convection in stratiform cloud cover is evidenced by the corrugated appearance of the top of such clouds, which suggests that the precipitation-generating system is aligned in horizontal rolls. Sauvageot (1974) showed that such a structure could explain the appearance of radar echoes.

2. The oscillatory rain event

At about 0836 CST, both optical instruments responded to an apparent wave-like oscillation in rain rate. This oscillation is shown in an expanded time scale in Fig. 3. The oscillation at station 1 (the more northern station) gives nearly a factor-of-2 change in rain rate. Except for the small temporal phase shift, there appears to be very high correlation between the two traces. The oscillation has a period of about 75 s, and the trace of the south instrument leads that of the north instrument by about 18 s.

Rishel (personal communication) of New Mexico State University has analyzed data from a Knollenberg probe which was located near the receiver end (north end) of the millimeter-wave propagation range. This instrument provided readings every 20 s, and the disturbance is evident in the data. However, there are insufficient data points for accurately determining a phase shift relative to the optical instruments. His estimates of drop size show no oscillation, and the mean drop size was about 0.85 mm.

The wave pattern appears in the amplitude of the 230 GHz millimeter wave signal. In Fig. 3 we show a curve for $-\ln(I/\langle I\rangle)$, where I is the measured millimeter-wave intensity and $\langle I\rangle$ is its average value. This quantity is the optical depth of the rain to within an additive constant. Olsen et al. (1978) showed that the specific attenuation (dB/km) of millimeter waves by rain can be expressed as $A \times R^b$, where R is the rain rate in millimeters per hour and the values of $A = 2.2$ and $b = 0.68$ are appropriate for the frequency of 230 gigahertz and light rain. Then the optical depth τ at time t is given by the following integral along the propagation path:

$$\tau(t) = A\int_{x_0}^{x_r} R(x,t)^b dx = 2.2\int_0^{1374\,\mathrm{m}} R(x,t)^{0.68} dx \qquad (1)$$

where x_0 is the transmitter location and x_r the receiver location. The raingages path average over 50 m, but the millimeter-wave amplitude represents an influence averaged over its 1374 m propagation path. The millimeter-wave trace in Fig. 3 leads station 2 (south) which in turn leads station 1 (north) rain rate.

If we assume that maxima and minima of the raingage traces are on the same phase front, with the south

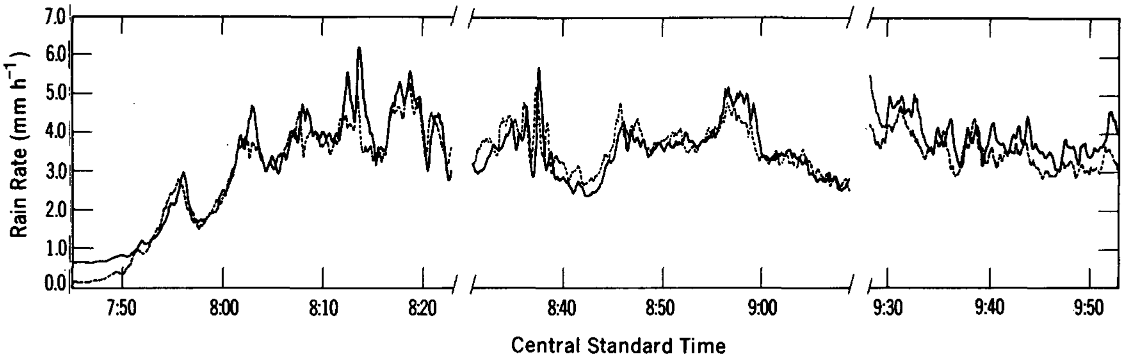

FIG. 2. Time series of rain rates measured by path-averaging optical raingages. Precipitation began at approximately 0750 CST; apparent rain rate below approximately 0.7 mm h^{-1} is actually system noise. Traces are discontinuous because of separated recording intervals. Note oscillatory feature at approximately 0837 CST.

trace leading the north trace by 18 s and a period of 75 s, then the spatial wavelength in the north–south direction is roughly 1700 m and the northward phase velocity is 22 m s^{-1}. Both the oscillatory feature in Fig. 2 near 0838 CST and nonoscillatory features at nearly the same time have about the same time lag between the two optical instruments. This implies that the oscillation might be stationary relative to the air at cloud height, or at least have a small propagation phase velocity relative to the air aloft.

The derived estimates of north–south wavelength (1700 m) and northward phase velocity (22 m s^{-1}) are representative of the situation, specifically at 0838:00 CST. The rain rates at the two optical gages were out of phase by 0839:00 CST, and the oscillation of the millimeter signal intensity disappeared.

We assume the following form for the distribution of rain rate along the millimeter wave propagation path:

$$R(x, t) = \langle R \rangle + R_A \cos(k_x x - \omega t + \phi). \qquad (2)$$

Substitution of (2) into (1) gives the bottom curve for optical depth in Fig. 3; the amplitude and phase of this curve is to be compared with the curve for $-\ln(I/\langle I \rangle)$ in Fig. 3. For the calculations we used the figures given in Table 1. The agreement is favorable between the calculated and measured optical depths. Many uncertainties contribute to the difference between calculated and measured optical depth. For instance, we have measured the rain rate at only two 50 m paths that show substantial evolution of the oscillatory feature during its northward movement, so (2) is a necessarily crude guess of the spatio–temporal distribution of rain rate.

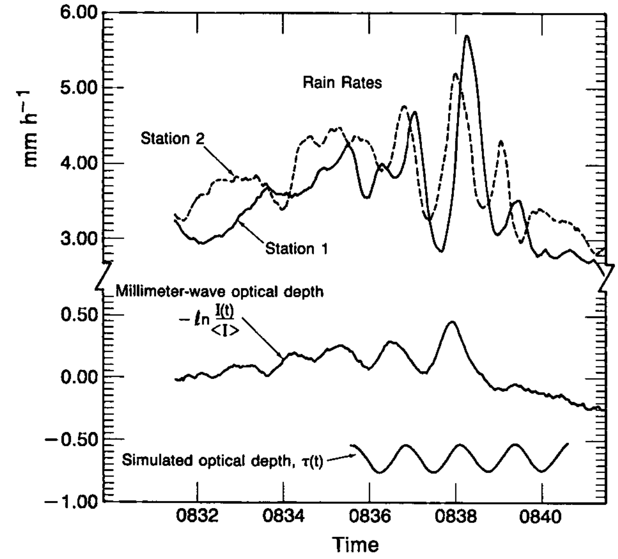

FIG. 3. Detail of rain rates and millimeter-wave attenuation, 0832–0841 CST. Bottom trace is the simulated millimeter-wave path optical depth calculated by Eq. (2).

TABLE 1. Parameters for simulated optical depth.

Parameter	Value
ω	$2\pi/75.4\ s^{-1}$
k_x	$2\pi/1755\ m^{-1}$
ϕ	5.7 rad
R_A	1.45 mm h^{-1}
$\langle R \rangle$	4.2 mm h^{-1}
t	0 corresponds to start of digital recording.

The phase shift between observed and simulated millimeter-wave attenuation is approximately 18 s. Since the optical raingages are east of the millimeter-wave propagation path, we might conclude that the wave front was propagating from west of due south. Although surface winds were from the south-southeast, rawinsonde data indicated that winds at cloud height were approximately 30 m s^{-1} from an azimuth of 190°.

The peak amplitude of the actual attenuation is larger than the simulated attenuation, but the rain rates from the two optical instruments also show difference in amplitude. The increasing amplitude of the individual rain rate and millimeter-wave attenuation traces suggests a resonance condition.

3. Conclusion

We have shown high temporal-resolution rain rates obtained from two optical raingages spaced 400 m apart, each averaging over a 50 m propagation path. A strongly oscillatory event is evident in the time series, and this event evolves rapidly with time. The optical depth of millimeter waves propagating through rain is calculated on the basis of an ad hoc model of the spatio-temporal distribution of rain rate along the 1374 m millimeter-wave propagation path. This calculation is in adequate agreement with the measured optical depth. The data are consistent with a convective instability in the clouds having a horizontal wavelength of roughly 1700 m in the north–south direction and probably moving with the wind at cloud height.

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