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3.2.4 OBSERVATIONS OF THUNDER WITH THE ARECIBO VHF RADAR

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ABSTRACT

An experiment was carried out at the Arecibo Observatory in Puerto Rico in August 1985 to study Doppler velocities in a thunderstorm environment with a beam pointed 2.5° off-vertical. We have detected two types of echoes associated with lightning. The first is associated with scattering from the lightning channel itself and has characteristics similar to those observed previously with meteorological radars. The second appears to be due to scattering from the turbulence organized by phase fronts of an acoustic wave generated by lightning. The observation described here is consistent with a wave traveling at a velocity near the speed of sound and having a vertical phase velocity component of 40 m/s.

INTRODUCTION

A number of investigators, including LIGDA (1950), ATLAS (1958), HOLMES et al. (1980) and MAZUR et al. (1984), have observed transient echoes associated with lightning at shorter wavelengths typical of meteorological radars (e.g., S band). These transient echoes are generally attributed to scattering from the plasma in the lightning channel itself, as described by DAWSON (1972). The plasma is expected to move with the surrounding air, and, indeed, the transient echoes at S band (MAZUR et al., 1984) and our observations at UHF have mean Doppler shifts typical of the air motions inside a cloud and the spectral widths are in agreement with the broadening expected due to the effects of atmospheric turbulence.

ROTTGER (1981), GAGE et al. (1978), and FUKAO et al. (1985) have already shown that both the precipitation echoes and the "clear air" echoes due to scattering by turbulent variations in the refractive index can be detected at wavelengths near 6 m. The relative contributions of the two scattering mechanisms depend on the radar wavelength, the intensity of the turbulence, and the intensity of the precipitation, but usually it is not difficult to separate the effects since the precipitation and air motions will be different, except for the smallest droplets.

There have been very few observations of Doppler velocities in a thunderstorm environment at wavelengths longer than a few tens of centimeters. Exceptions include the experiments of LARSEN et al. (1982) at UHF and those of ROTTGER (1981), GAGE et al. (1978), and FUKAO et al. (1985) at VHF. In most of the experiments, the coherent integration has been sufficiently long to exclude the observation of effects on a time scale comparable to the scale of lightning or acoustic waves. In August 1985, we carried out an experiment with the new VHF radar located at the Arecibo Observatory in Puerto Rico in which the raw pulse-to-pulse data were recorded for later analysis. The observations show what we believe is the first detection of acoustic waves generated by lightning.

DESCRIPTION OF THE DATA

The VHF radar with a frequency of 46.8 MHz and UHF radar with a frequency of 430 MHz were operated on five separate afternoons in August 1985. We will focus on the VHF radar data for the afternoons of August 4th and August 7th.

The VHF transmitter operates at 50 kW peak power. The system uses the 300-m diameter dish, of which the Yagi feed at the focus illuminates 200 m for an effective beamwidth of less than 2°. The beam was pointed at 2.5° zenith angle in this experiment and operated in one of two data-taking modes. The first used a 1-μsec pulse length and coherent integration online to give an effective sampling time of 92 msec. The second mode used a 2-μsec pulse length and an interpulse period of 750 μsec. The raw data were then recorded on magnetic tape in this mode, so that the IPP and sampling interval were the same, or we could coherently integrate off line to produce a smaller Nyquist frequency if desired.

An electric field change meter and two tipping-bucket rain gauges were also installed at the site and operated in conjunction with the radar measurements. The field change meter was used to determine the time of occurrence of lightning, as well as a qualitative estimate of the distance of the discharge from the radar.

DOPPLER SPECTRA

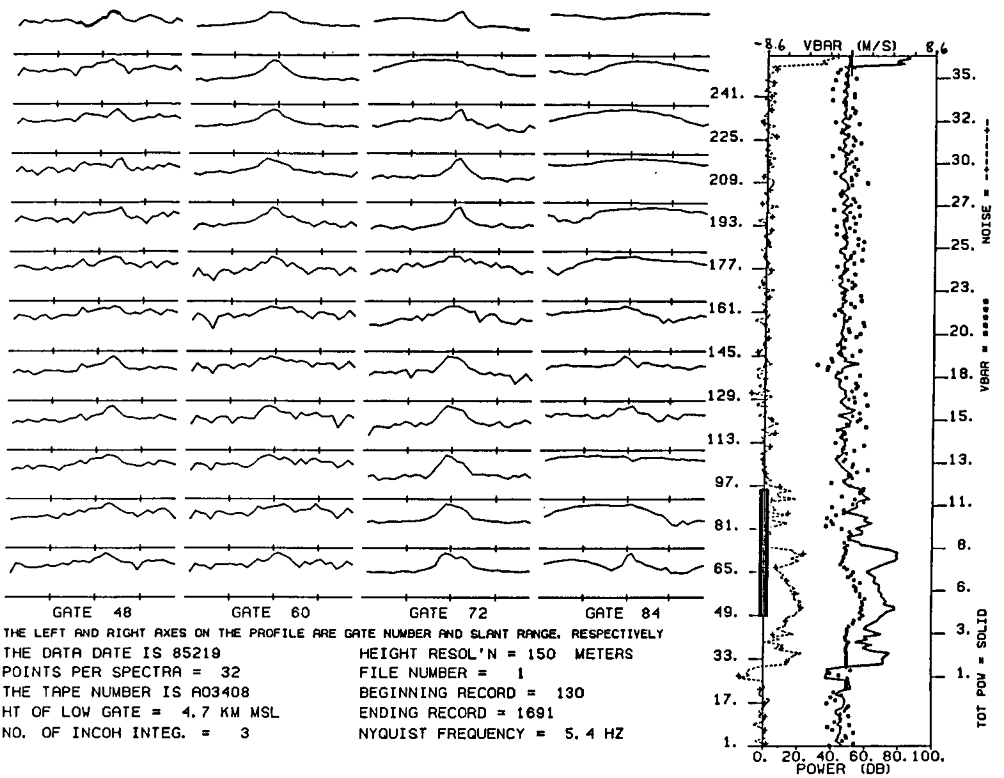
Figure 1 shows an example of Doppler spectra over a range of heights obtained with Mode I when a thunderstorm was overhead. The heights in range gates 48 through 81 show a contribution primarily from the "clear air" scatter. These spectra are wider than the spectra observed in a nonconvective environment. The upper heights, e.g., gates 82 to 95, show spectra that are broadened to such an extent that it is difficult to discern a peak. The power profile at the right of Figure 1 shows that these heights are characterized by high rather than low power levels.

The maximum unambiguous velocity using Mode I was ±8.7 m/s. The lightning-associated spectra have widths which are of the order of the spectral window since the power is essentially constant across the window. A possible explanation is that the mean Doppler velocity is much greater than the maximum resolvable velocity. We expect that the spectral width would scale in some way with the mean velocity and would account for these observations. Although a large velocity would cause aliasing, the aliasing itself would not account for the increase in the width of the spectra. We infer that lightning was present in the beam when only some of the range gates show the broad spectra, as in Figure 1.

An example of the spectra obtained using Mode II is shown in Figure 2. The increased time resolution made it possible to attain much larger unambiguous velocity determinations. We found no evidence of lightning in the beam on the days when data were taken with Mode II. However, the electric field change data did show evidence of more distant lightning discharges. Figure 2 shows such spectra recorded at the same time as a more distant discharge. Of particular interest are the features with velocities near ±30 m/s in gates 19 to 23 which appear only for the time required to produce the spectra (less than 4 sec). The change in sign of the vertical Doppler shift between gates 20 and 21 could be attributable to vertical phase variation in the wave or to the geometrical relation between the observing angle of the radar and the location of the source, as we will show in the next section.

INTERPRETATION OF MEASURED VELOCITIES

The signals measured at VHF will have a component due to the scattering from the lightning channel itself, a component due to the backscatter from refractive index variations, and a component due to the scatter from liquid or frozen droplets. The first does not appear to affect the observations on August 4th, based both on the characteristics of the spectra and the electric field change records which did not indicate any lightning nearby. It is



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THE LEFT AND RIGHT AXES ON THE PROFILE ARE GATE NUMBER AND SLANT RANGE, RESPECTIVELY
THE DATA DATE IS 85219              HEIGHT RESOL'N = 150  METERS
POINTS PER SPECTRA =  32            FILE NUMBER =   1
THE TAPE NUMBER IS A03408           BEGINNING RECORD =  130
HT OF LOW GATE =  4.7 KM MSL        ENDING RECORD = 1691
NO. OF INCOH INTEG. =   3           NYQUIST FREQUENCY =  5.4 HZ
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Figure 1. VHF Doppler spectra integrated for nine seconds, with spectra plotted for gates 44 through 91 and a height profile of mean velocity, total power, and noise level for 256 gates. Positive Doppler velocity (toward the radar) is to the right of center, each spectra is scaled to its own peak. Note the large variance in the upper gates (above 90) as compared with the lower ones.

unreasonable to expect that either solid or liquid precipitation will travel at velocities close to 40 m/s since terminal velocities, even for hail, are less than 20 m/s (PRUPPACHER and KLETT, 1980) and would be only downward directed; further, no precipitation was recorded by the rain gauges.

Vertical motions of 40 m/s inside the cloud cannot be excluded absolutely but appear unlikely. It would be easier to explain the observed velocities as being due to the vertical projection of a near-horizontal acoustic phase velocity. However, it cannot be that we are scattering from 3-m acoustic waves, because in that case only waves propagating parallel to the radar beam contribute to the backscatter. Also, a wavelength of 3 m is not consistent with the wave properties derived below. A possible explanation is that 3-m irregularities are acting as a tracer of the motion of the acoustic front.

The observations can be interpreted in terms of the dispersion relation for acoustic-gravity waves (YEH and LIU, 1974).

$$k_h^2 (1 - \omega_b^2/\omega) + k_z^2 = k_o^2 (1 - \omega_a^2/\omega^2).$$

The behavior will be complicated by the background temperature gradients and

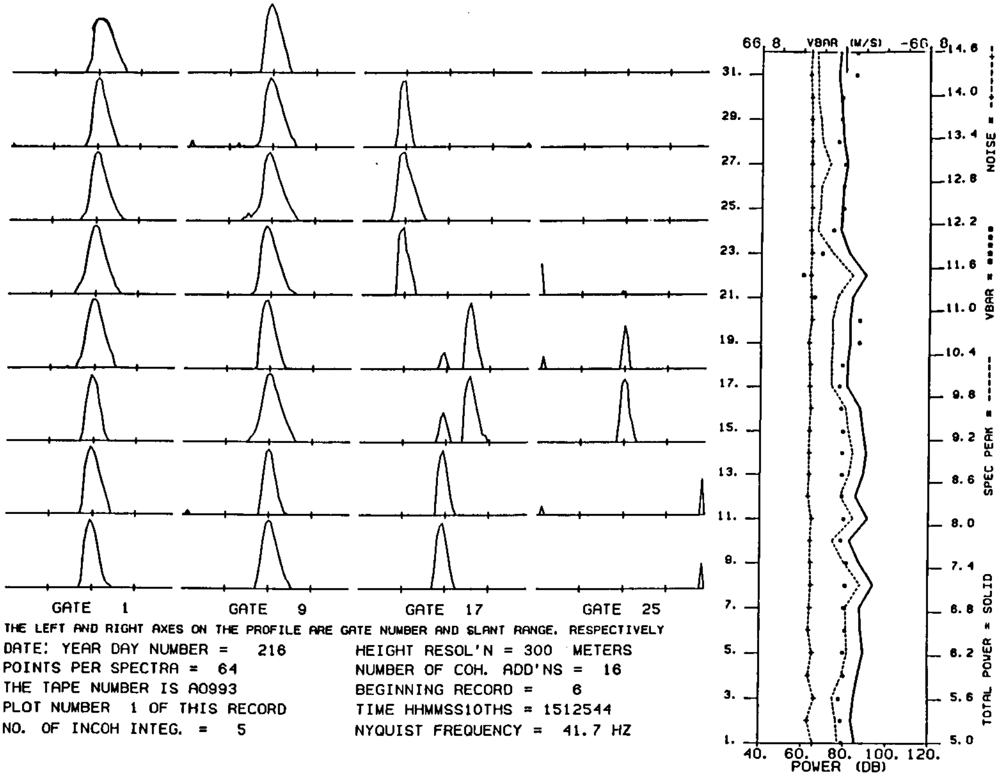

Figure 2. VHF Doppler spectra taken in mode II (see text). Note the large Doppler shift in gates 19 through 23. The spectra are integrated for 3.8 seconds, the anomalous echoes did not appear in the previous spectra nor in the next. The time of these spectra is coincident with a lightning discharge as indicated by an electric field change meter.

other effects not accounted for in this simple form of the dispersion relation. Here, $k_o = \omega/c_o$, $\omega_a = c_o/2H$ is the acoustic cut-off frequency, and ω_b is the Brunt-Vaisala frequency. The local speed of sound is c_o, the scale height is H, and k_h and k_z are the horizontal and vertical wave number components, respectively. The background parameters were calculated from the San Juan radiosonde data closest to the time of the observations.

We can only look at the behavior of the wave solutions in certain limits since we do not know the horizontal wave number. The first limit corresponds to a horizontal wave number that is much smaller than the vertical wave number which we calculate from the power profile to be $k_z = 2\pi/2400$ m. The solution for the wave period then gives a value of $\tau = 7.9$ s, which is on the acoustic branch of the dispersion relation. The total phase velocity is close to the speed of sound as determined from the sounding and has a large horizontal component.

If we assume that the horizontal and vertical wave numbers are comparable in magnitude, one solution corresponds to a period of 7.3 min which is in the gravity regime, the other solution corresponds to a period of 5.6 s which is also on the acoustic branch. However, the phase velocity of the gravity wave is much less than the observed velocity, and the observation could only be explained if the mean air motion over the pulse volume was of the order of 30-40 m/s.

A point source at some distance laterally will produce an acoustic wave that is propagating more or less horizontally above the vertically pointing radar. A wave traveling at the speed of sound (∿300 m/s) can produce a vertical component of the phase velocity of ∿30-40 m/s if it enters the pulse volume at a large zenith angle, say 85°. Also, there would be upward and downward velocity components above and below the height corresponding to the height of the source. Figure 3 shows the geometry of a single source, displaced horizontally 6 km and downward 0.2 km. The downward displacement accounts for the larger upward velocities observed in the upper range gates. The temperature profile to the right indicates an inversion at an altitude of around 11 km. The inversion may have provided some ducting of the acoustic wave which would explain the appearance of the anomalous echoes in only a few gates.

CONCLUSION

Experiments carried out with the 46.8-MHz Arecibo radar during August 1985, have shown that there is a component in backscattered signals produced in connection with lightning events that are not observed at shorter wavelengths, e.g., S band. There are many unknowns in the analysis of these new echoes, as detailed above, but is plausible that the echoes are due to scattering from refractive index variations associated with acoustic waves generated by

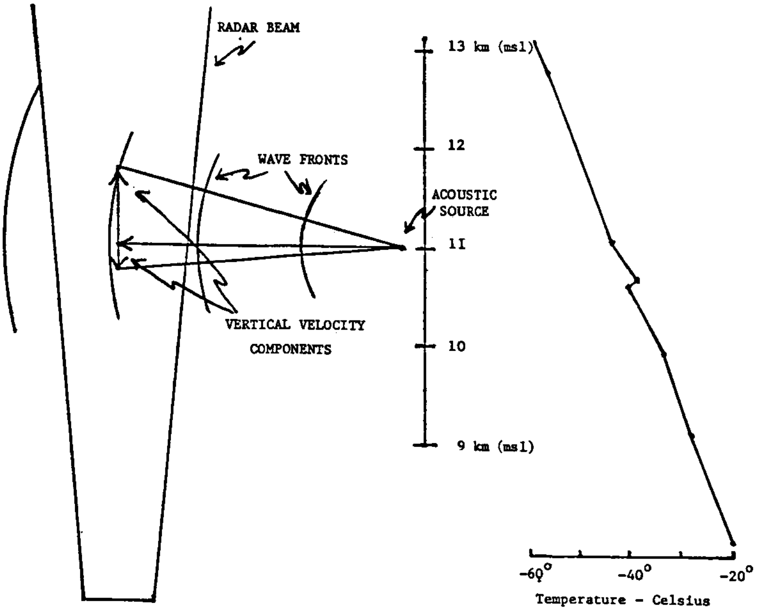

Figure 3. Schematic representation of lightning produced acoustic wave as measured by vertically pointing VHF Doppler radar. The distance from the source is estimated to be 6 kilometers, horizontally, where the angles have been enlarged for the sake of clarity. The temperature profile on the right is taken from the San Juan radiosonde. Note the inversion that occurs at approximately 11 km msl.

lightning. The data taken when lightning was some distance from the radar shows a pattern of positive and negative velocities with amplitudes on the order of 20-40 m/s. The observations can be explained if the velocity is the line-of-sight component of the acoustic phase velocity traced by 3-m irregularities and the source was some 6 km away. The data taken when lightning is in the beam are more difficult to interpret, partly because in that particular data-taking mode, a smaller value for the maximum unambiguous velocity resulted in aliasing of the Doppler spectra. We cannot rule out that acoustic waves were responsible for these echoes, as well.

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