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Precipitation and Lightning Measurements by Polarization Diversity Radar

JAMES I. METCALF

7 September 1988

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Observations of severe convective storms in June 1987 by an 11-cm polarization diversity Doppler radar are described. Specific features include heavy rain, large hail, melting ice particles, lightning, and signal propagation effects. Of particular interest are the first measurements of the polarization differential reflectivity of lightning channels, which reveal the predominant orientations of the channels. Successive radar pulses were transmitted with alternating horizontal and vertical polarization by means of a high-power microwave switch to permit derivation of the differential reflectivity with a small standard error of estimate.

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Preface

I am indebted to the engineers and technicians of the Branch for their efforts in the modification and operation of the Doppler radar and the associated data system. Mr. Alexander Bishop has led the radar engineering work, assisted by TSgt Richard Chanley and Mr. Ruben Novack. Capt. Paul Sadoski and Mr. Graham Armstrong have been responsible for the data processing system, with the assistance of A1C Gregory Potter and Mr. William Smith. I particularly appreciate the efforts of Mr. Armstrong and Mr. Pio Petrocchi, who volunteered their time on a Saturday evening to acquire what turned out to be a significant set of radar data.

I am indebted to Mr. Paul Desrochers of ST Systems Corp. for providing the computer program that generates B-scan (range-azimuth) displays of radar data.

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1. INTRODUCTION

AFGL is developing a variety of techniques for characterizing the microphysical parameters of hydrometeors on the basis of remote measurements. A key element of this program is the acquisition of polarimetric data with the 11-cm (2.7-GHz) Doppler radar at Sudbury, Mass. This radar was modified to enable the measurement of the polarization differential reflectivity (Z_{DR}) and is undergoing further modification to enable the measurement of other polarimetric parameters. The measurements presented in this report represent our first use of the high-power microwave switch built by Raytheon Co., which enables pulse-to-pulse switching of the transmitted signal between horizontal and vertical polarizations. This transmission mode permits the derivation of the differential reflectivity between horizontal and vertical polarizations with a theoretical standard error of estimate about 0.1–0.2 dB.

(Received for publication 1 September 1988)

The radar is described in Section 2. Section 3 presents some observations of severe storms with emphasis on backscatter characteristics of hail and lightning. These observations are of general interest because of the variety of meteorological phenomena they depict. The observations of lightning provided the first measurements of the differential reflectivity of lightning.

2. THE RADAR SYSTEM

The 11-cm (2.7-GHz) Doppler radar operated by AFGL at Sudbury, Mass., has been described in a series of reports.[1,2] The original antenna was modified to a Cassegrain design for optimum dual polarization operations.[3] A data processor was designed and constructed in this laboratory for real-time computation of absolute reflectivity, polarization differential reflectivity, Doppler mean velocity, and Doppler spectrum variance.[4] A microwave switch, which is a network of three switchable circulators incorporating ferrite phase shifters, was installed in the late winter and spring of 1987 to enable the switching of transmitted polarization from pulse to pulse. Specifications of the switch were included in a previous report.[5] This switch replaced the microwave diplexer that was described in a previous report.[6] The diplexer permitted the nearly simultaneous transmission of two frequencies (2.71 and 2.76 GHz) with orthogonal polarizations. That configuration of the radar yielded simultaneous uncorrelated samples of reflectivity from the two orthogonal polarizations, from which we derived rather noisy estimates of differential reflectivity. The successive samples of reflectivity obtained with horizontal and vertical polarizations by means of the new microwave switch are highly correlated and permit the computation of the polarization differential reflectivity with standard error of estimate about 0.1 to 0.2 dB.

(Due to the large number of references cited above, they are not listed here. See References, page 19)

3. MEASUREMENTS

3.1. Hailstorm Observations

A severe thunderstorm that passed southwest of Boston, Mass. on Saturday, 13 June 1987, was among the first precipitation events observed after installation of the high power microwave switch. This storm is of particular interest because of a report of ¾-inch diameter hail coincident with some of the radar observations. The radar observations discussed below illustrate several features that are typical of deep convective storms. These features include (1) large positive values of differential reflectivity above the height of the 0° C isotherm in the updraft, indicative of large water drops; (2) differential reflectivity near 0 dB coincident with high absolute reflectivity below the 0° C isotherm, indicative of hail; (3) locally increased values of differential reflectivity near the height of the 0° C isotherm, indicative of melting aggregated crystals; and (4) slightly negative values of differential reflectivity on the far side of a core of heavy precipitation, indicative of differential attenuation in the heavy precipitation.

The storm of interest was one of several embedded in a line of convection that passed the radar site about 1830 EST. At the radar site, the passage was marked by a rainfall of 3 mm, including a brief shower at a rate of 25 mm hr^{-1}, and a temperature drop from 25° C to 20° C between 1830 and 1900 EST. (The maximum temperature of the day, 30° C, had occurred about 1600 EST.) The sequence of radar scans in azimuth and elevation is listed in Table 1. The general situation is illustrated in Figure 1, which depicts an azimuthal scan at 1.5° elevation angle (1950 EST). During the observations listed in Table 1 the center of the storm passed over Dover, Dedham, and Milton, Mass., 23–34 km distant from the radar, moving eastward at 36 km hr^{-1}. Hail of ¾-inch diameter, which is unusually large for New England, was observed in Dedham between 1951 and 1956 EST by Mr. John Conover, a retired meteorologist formerly employed at AFGL. The site of this observation is at a range of 33.7 km on an azimuth of 126° from the radar.

Maximum reflectivity in excess of 50 dBZ was measured at all elevation

Table 1. Radar Observations of Severe Storms, 13 June 1987.

Time (EST)	Elevation Angle (deg)	Azimuth Angle (deg)
1937-1942	0.5, 1.5, 3, 5, 7, 9	0-360
1943-1948	0.5, 1.5, 3, 5, 7, 9	0-360
1949-1951	0.5, 1.5, 3	0-360
1957-2009	0-15	121, 122, 123, 124
2010-2012	0.5	0-360

Figure 1. Reflectivity of Convective Storms, 13 June 1987. Azimuthal scan at an elevation angle of 3° was made at 1951 EST. Cell of particular interest was near 30 km range at an azimuth of 126°.

angles up to 9°. Neither the maximum reflectivity nor the area of reflectivity in excess of 50 dBZ changed significantly during the 40 minutes of observation. However, the differential reflectivity exhibited significant changes which appear to be associated with the development of hail in the storm. These changes are illustrated in Figures 2, 3, and 4, which depict the successive azimuthal scans at 1.5° elevation angle. The scan at 1938 (Figure 2) reveals no differential reflectivity less than 2.1 dB within the area of reflectivity greater than 50 dBZ. While this value of differential reflectivity is less than what one would expect in intense rain, it nevertheless indicates a predominance of melting or melted hydrometeors. The scan at 1944 (Figure 3) shows a significant area of differential reflectivity less than 1 dB coincident with the area of highest reflectivity. The minimum value is 0.6 dB. The scan at 1950 (Figure 4) shows a larger area of small values of differential reflectivity, with values as small as −0.2 dB, coincident with reflectivity in excess of 50 dBZ. The ranges at which the minima of differential reflectivity are observed correspond to altitudes of 560, 660, and 850 m in the successive scans. The decrease of differential reflectivity from scan to scan is consistent with the downward movement of large hail.

Azimuthal scans at 3° and 5° elevation angles, which are generally below the melting level (about 3 km altitude) at ranges of 30 km or less, show minimum values of differential reflectivity between 0.1 and −1.0 dB, with no obvious trend among successive scans. These suggest that randomly oriented ice particles, i.e., hail or graupel, were continuously present at altitudes of 1−2 km. Azimuthal scans at 0.5° elevation angle are more difficult to interpret, because of backscatter from topographic features and transmission towers. Values of differential reflectivity near 1.0 dB in the 0.5° scans at 1943 and 1949, directly below the minima observed at 1.5° at 1944 and 1950 (Figures 3 and 4), suggest that ice particles were reaching the surface at these times.

All the azimuthal scans show a region of large positive values of differential reflectivity at the far side of the storm, where the absolute reflectivity is about 20−30 dBZ. This feature is evident in Figures 2, 3, and 4 at ranges of 30, 32, and 36 km, respectively. Similar features have been observed elsewhere in association with the main updrafts of convective storms.

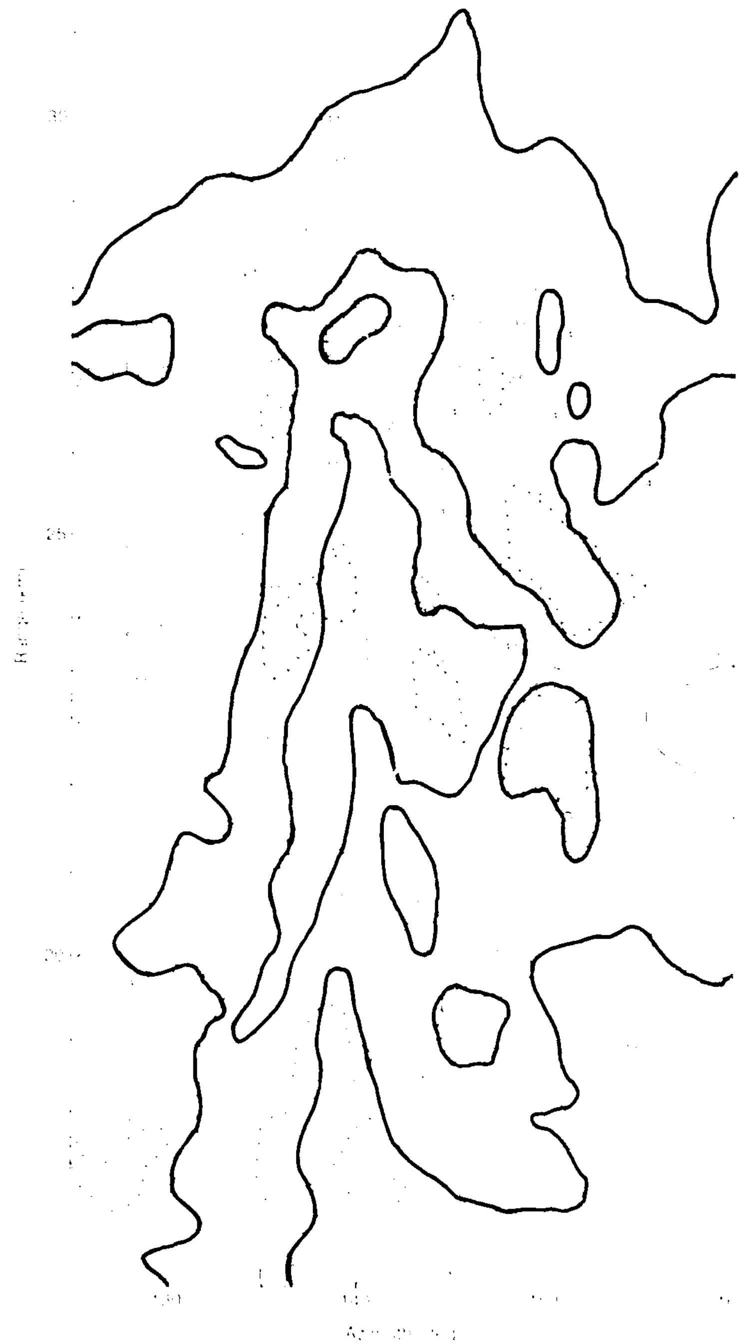

Figure 2. Absolute and Differential Reflectivity at 1.5° Elevation, 1938 EST. Thin lines denote differential reflectivity and thick lines denote absolute reflectivity of 20, 40, and 50 dBZ.

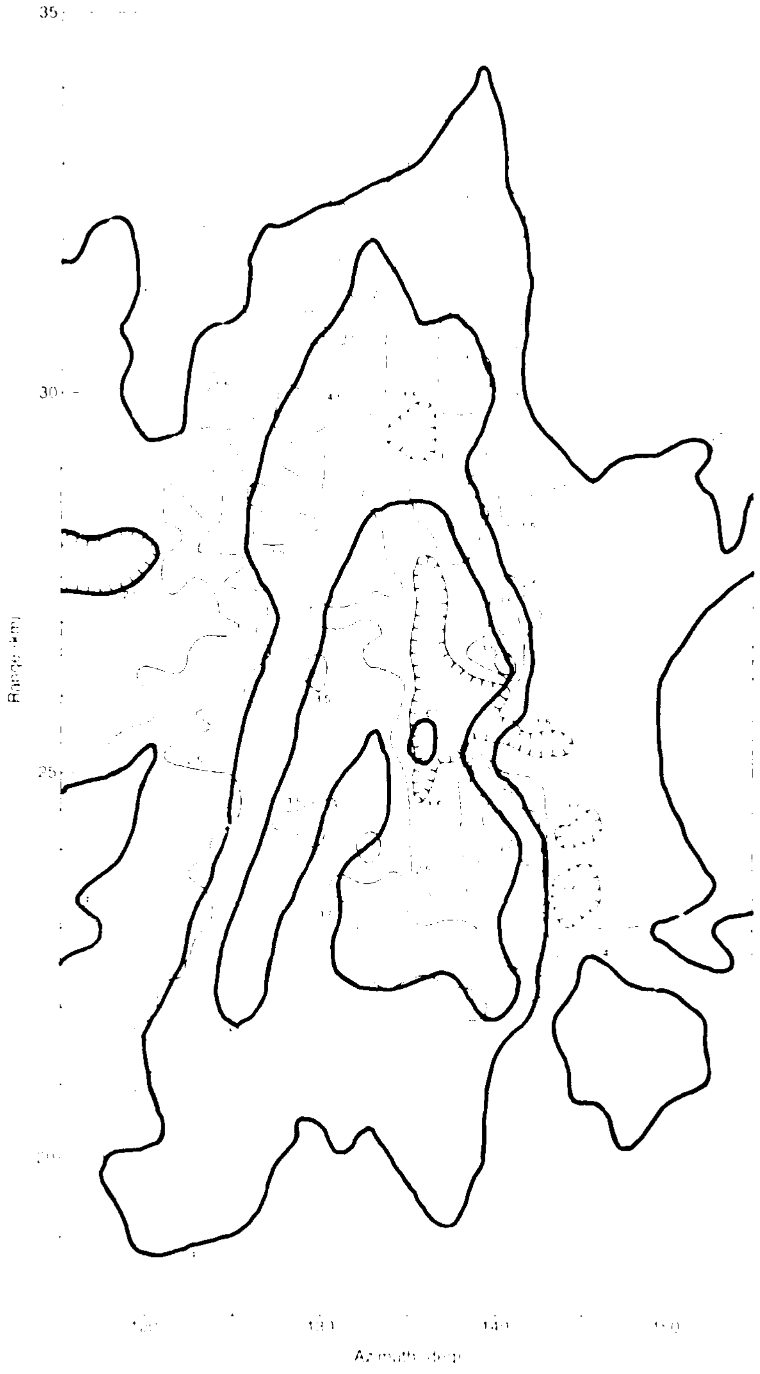

Figure 3. Absolute and Differential Reflectivity at 1.5° Elevation, 1944 EST. Notation is identical to that of Figure 2. Area of differential reflectivity less than +1.5 dB, coincident with maximum absolute reflectivity, was not evident in earlier scan.

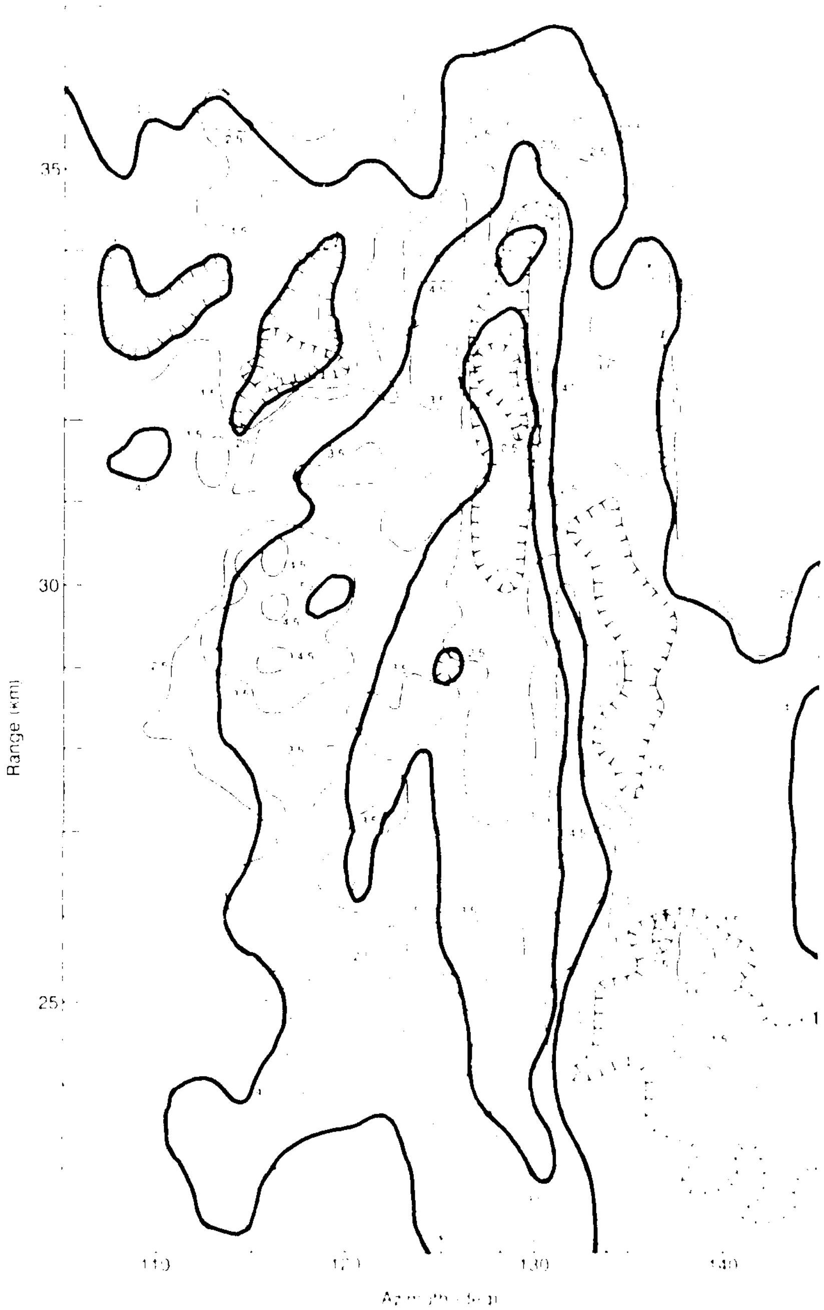

Figure 4. Absolute and Differential Reflectivity at 1.5° Elevation, 1950 EST. Notation is identical to that of Figure 2. Minimum differential reflectivity coincident with maximum absolute reflectivity has decreased to less than +0.5 dB.

One of the series of elevation scans through the storm is shown in Figure 5, in which key features are indicated for convenience. The scan was made at 1957 EST on an azimuth of 121°. This vertical cross-section of the storm indicates two distinct cores of intense precipitation. Within both, values of logarithmic differential reflectivity near zero extend well below the height of the 0° C isotherm. Within the cell centered at 29 km range, differential reflectivity above +4 dB, typical of heavy rain, indicates that melting was essentially complete about 1.5 km above the surface. Within the cell centered at 33 km range, the differential reflectivity increases only to about +2 dB at the bottom of the scan, indicating the likely occurrence of hail at the surface. On this azimuth, this feature is centered about 3 km northeast of the point at which hail was reported. It is likely that the center of this cell passed about 2 km north of Mr Conover's house during the time of the observed hailfall, just before the time of the radar observation.

The vertical cross-section also indicates the presence of large water drops at altitudes of 2–4 km near 38 km range, as noted above in relation to the azimuthal scans. This feature has been reported elsewhere in association with updrafts in convective storms. In the present case, the large drops are probably not supercooled. The surface temperatures of 25–30° C in advance of the convective line implies that the height of the 0° C isotherm in the updraft is about 4–4.5 km.

On the far side of the storm, where one might expect to find differential reflectivity near zero dB, characteristic of small water drops or small ice particles, there is a region of slightly negative differential reflectivity extending from near the surface to about 6 km altitude. This suggests a difference of attenuation of the horizontally and vertically polarized signals within the intervening regions of large, oriented water drops. Although radar wavelengths of 10 cm or longer are generally considered "non-attenuating," they do experience a small but measurable attenuation in heavy precipitation. Rain of 100 mm hr^{-1} with a Marshall-Palmer exponential drop size distribution, for example, yields a two-way specific attenuation of about 0.08 dB km^{-1} and a two-way differential specific attenuation of 0.024 dB km^{-1} between horizontally and vertically polarized signals of 11 cm wavelength. The observed differential attenuation of about 1 dB in the present case would require a propagation path of about 45 km through rain of 100 mm hr^{-1}. Because the path length through heavy or

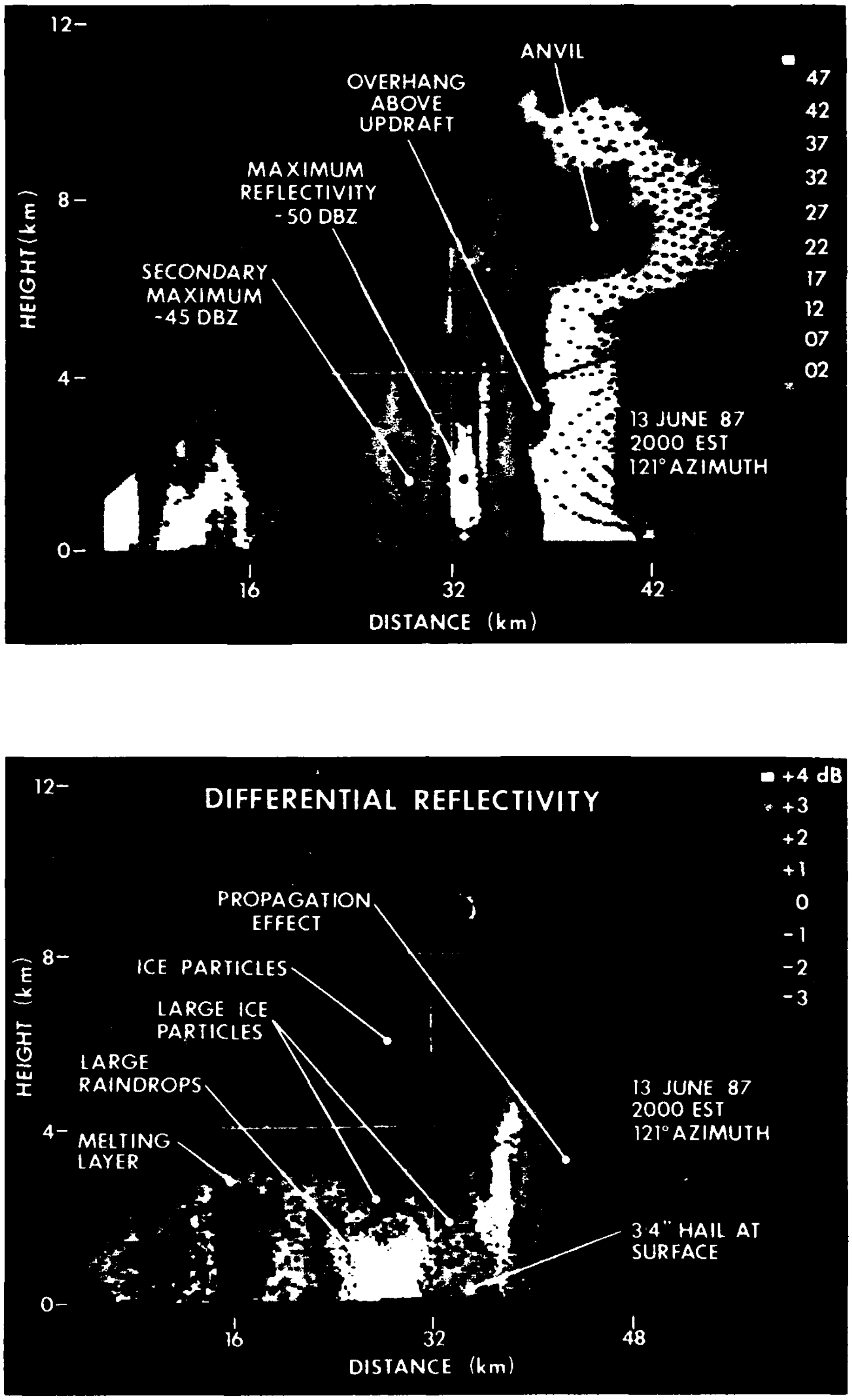

Figure 5. Vertical Section of Absolute Reflectivity *(upper panel)* and Differential Reflectivity *(lower panel)* at 121° Azimuth, 1957 EST. Key features of storm are highlighted in the figure and discussed in the text.

greater precipitation is only about 10 - 12 km in the present situation, it is likely that there is a larger proportion of large, highly oblate raindrops within the cells of highest precipitation than would occur in a Marshall-Palmer distribution. This is possible if residual ice cores are stabilizing the large drops against breakup.

This remarkable observation of a convective storm illustrates several features of the precipitation microphysics that have been observed elsewhere. These include large water drops in the region of the main updraft, small ice particles that aggregate and melt near the 0° C isotherm, larger ice particles that melt to heavy rain about 1 km below the 0° C isotherm, and very large ice particles that survive to the surface. Observations elsewhere have also shown the effects of differential attenuation on measurements of differential reflectivity, but not in combination with all the other features of this case.

3.2. Lightning Observations

There are numerous published reports of the detection of lightning by radar, dating back to the 1950's. In the past few years, efforts have been made to investigate the spatial and temporal structure and the physical attributes of lightning by means of radars. These include comparative observations of backscatter from lightning at wavelengths of 5.4 and 11 cm[7] and observations of the spatial distribution of lightning in a convective storm with a 70.5 cm radar.[8] At a wavelength of 11 cm the backscatter from raindrops is sufficiently strong that backscatter from lightning channels cannot be detected within the cores of convective storms. At longer wavelengths, the decreasing Rayleigh backscatter from raindrops, proportional to the inverse fourth power of wavelength, permits detection of lightning channels throughout a storm. The usual mode of observation is to point the antenna toward an electrically active cell for several minutes. The beam of an 11-cm radar must be elevated to illuminate a region where the reflectivity factor due to hydrometeors is less than about 30 dBZ. After several minutes, typically, the beam must be adjusted to compensate for movement of the cell.

The observations discussed here were made on 30 June 1987, when several convective storms were within range of the radar. A storm exhibiting maximum reflectivity of about 50 dBZ at a range of about 90 km was selected for detection of backscatter from lightning. During two periods of 7 and 2 min we observed 20 and 6 lightning events, respectively, which are summarized in Table 2. The radar operated at a pulse repetition rate of 971 Hz, transmitting alternate pulses with horizontal and vertical polarization. The absolute and differential reflectivities were computed from averages of 0.5 sec duration, comprising 256 pulses of each polarization, sampled each 0.25 sec. Typical lightning echoes are shown in Figures 6, 7, and 8. The lightning events were characterized by an enhancement of the equivalent reflectivity factor to 30–40 dBZ, usually within one sample interval, but occasionally spanning 3 or 4 intervals. Some long-lasting events exhibited a tendency to propagate in range. The rangewise extent of these lightning echoes varied from 150 m (the range resolution of the radar) to 6.8 km. The maximum reflectivity factor due to hydrometeors was about 34 dBZ during the first series of measurements and about 42 dBZ during the second, which was at a lower altitude. The relatively infrequent occurrence of lightning during the second observational period may have been due either to less than optimum pointing of the beam or to decreasing electrical activity in the storm.

These data show some of the complicated characteristics of lightning channels. For example, the extreme value of differential reflectivity does not generally coincide with the maximum reflectivity of a given event. Prior to these observations, it had been speculated that the differential reflectivity of lightning channels could have a magnitude up to 10 or 12 dB, either negative or positive, if the channels were predominantly of vertical or horizontal orientation. We observed differential reflectivity entirely within the range ±2 dB. However, the distribution of values is not random. Particular events usually exhibited either predominantly positive or predominantly negative values, and some events had distinct subregions of positive and negative differential reflectivity. It should be emphasized that these results are not conclusive with regard to the orientation of lightning channels. Observations of backscatter from lightning recorded with higher time resolution at Massachusetts Institute of Technology show that each lightning event having a duration of a few tenths of a second actually

Table 2. Radar Observations of Lightning, 30 June 1987. Time is given in minutes and seconds after 1700 EST. Maximum ΔZ refers to the greatest increase of reflectivity at any range cell, relative to the reflectivity due to precipitation. Successive time samples represent intervals of approximately 0.25 sec. Events 7a and 17a denote lightning echoes coincident in time but separated in range from Events 7 and 17.

Event No.	Time (m:s)	Max.Z (dBZ)	Max.ΔZ (dB)	Range cells	Samples (0.25 s)	Z_{DR} at max. Z	Range of Z_{DR}
First series (222° azimuth, 6.0° elevation, 9.5–11.0 km altitude)							
1	08:37	35	1	3	2	−0.2, +0.2	−0.9, +0.5
2	08:46	37	9	3	4	0.3	−0.7, +1.1
3	08:50	37	4	45	3	−1.2	−1.2, +2.0
4	08:53	34	3	9	1	−1.3, +1.9	−1.3, +1.9
5	09:00	36	19	26	4	1.2	−1.3, +2.0
6	09:18	36	12	7	2	0.4, 1.8	−0.5, +1.8
7	09:35	40	7	10	4	−0.2	−1.0, +1.5
7a	09:35	37	7	3	1	−1.4	−1.4, −0.3
8	09:44	34	7	6	2	0.4	−0.5, +1.3
9	09:54	35	2	1	1	−1.6	
10	10:03	41	14	16	4	0.1	−0.8, +1.8
11	10:16	32	6	10	2	1.6, 1.7	−1.3, +1.9
12	10:38	36	4	15	2	−0.6	−1.6, +0.5
13	11:03	35	6	8	3	−0.8	−0.9, +0.8
14	11:21	32	1	2	2	−1.3, −0.7	−2.2, −0.7
15	11:33	38	6	12	2	−0.3	−1.3, +0.4
16	11:49	35	6	5	2	−1.5	−1.6, +0.3
17	12:08	41	15	6	3	1.9	−0.8, +1.9
17a	12:08	31	2	5	3	−1.1	−1.1, 0
18	13:27	37	10	7	3	1.6, 2.3	−0.1, +2.3
19	14:00	28	2	8	2	−1.0	−1.2, +0.5
20	14:16	29	3	5	2	−1.9	−2.1, −0.4
Second series (211° azimuth, 3.8° elevation, 5.3–6.6 km altitude)							
1	20:37	41	4	4	4	1.8	−0.6, +1.8
2	20:53	36	4	8	3	0.3, 0.4	−0.6, +0.6
3	20:58	41	6	5	3	0.8	−1.1, +0.8
4	21:00	44	3	5	3	−0.3	−1.0, +0.1
5	21:18	33	10	20	4	0.2, 0.3, 1.0	−2.3, +2.6
6	21:33	37	3	5	1	1.3	−0.4, +1.3

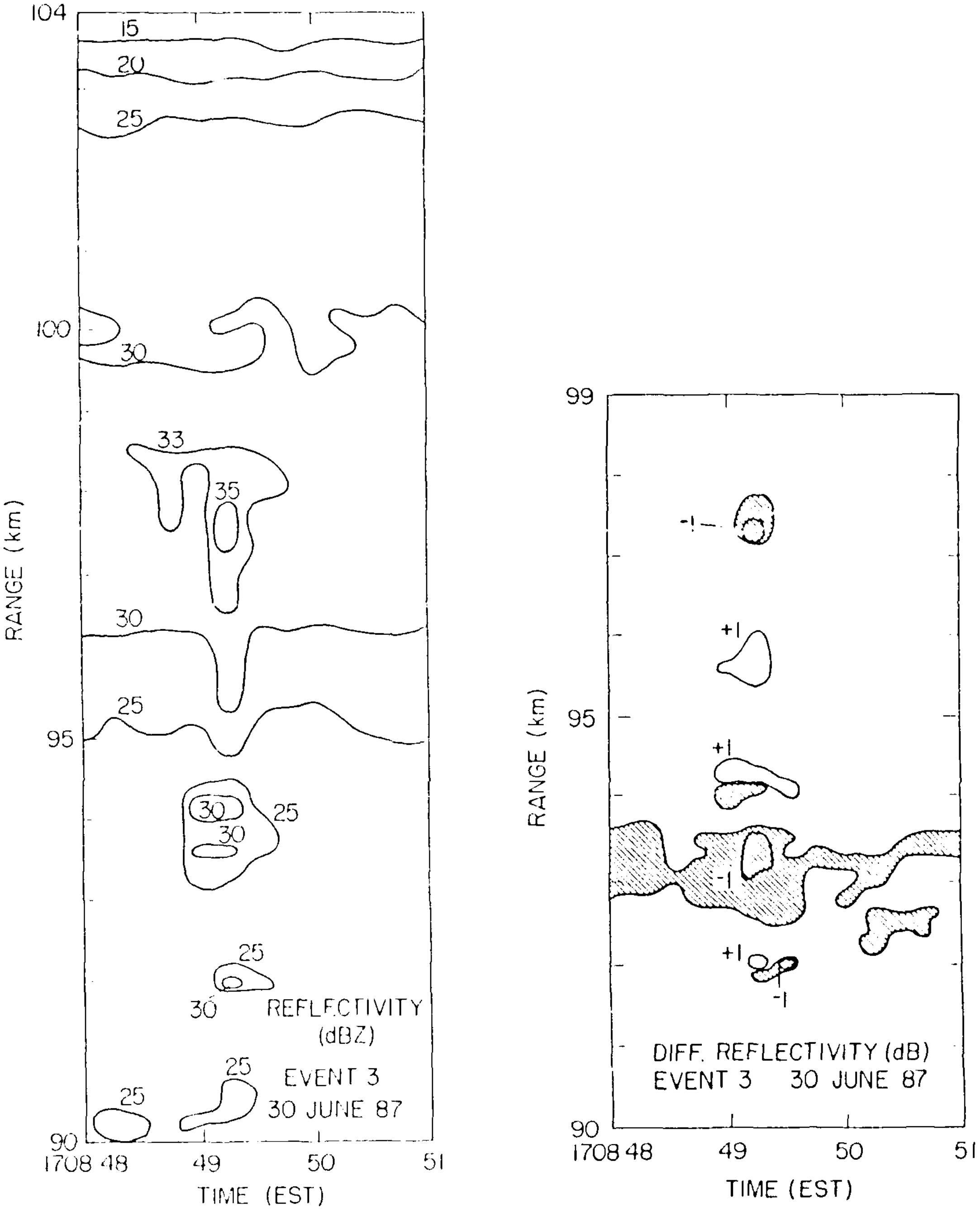

Figure 6. Absolute and Differential Reflectivity of Lightning Event 3, 30 June 1987. Enhancement of equivalent reflectivity factor *(left)* by echo from lightning varies from negligible to about 4 dB. Differential reflectivity *(right)* is mostly in the range −1 to +2 dB.

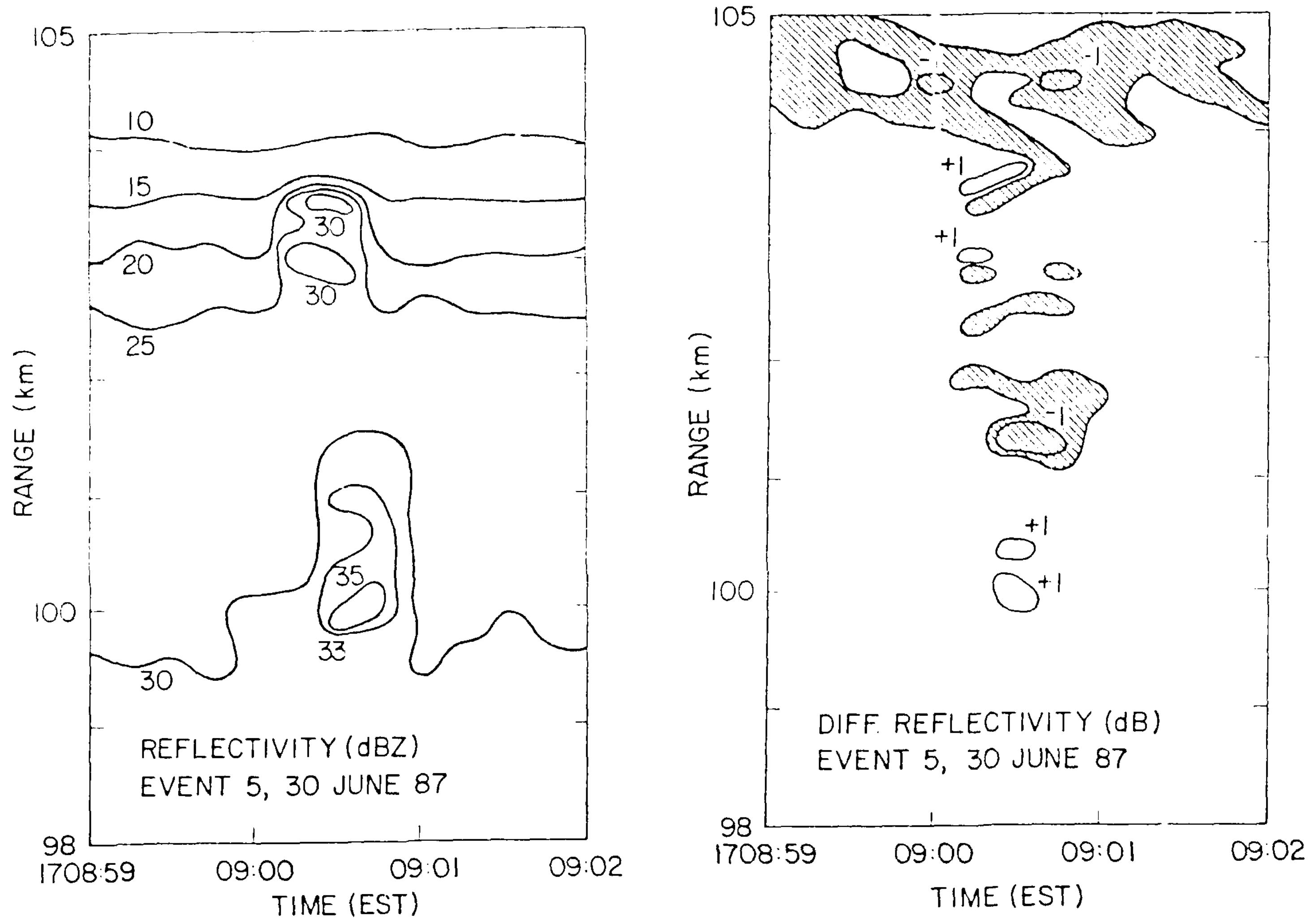

Figure 7. Absolute and Differential Reflectivity of Lightning Event 5, 30 June 1987. Echo due to lightning was detected on the far side of maximum reflectivity due to hydrometeors, with enhancement of more than 15 dB at some ranges.

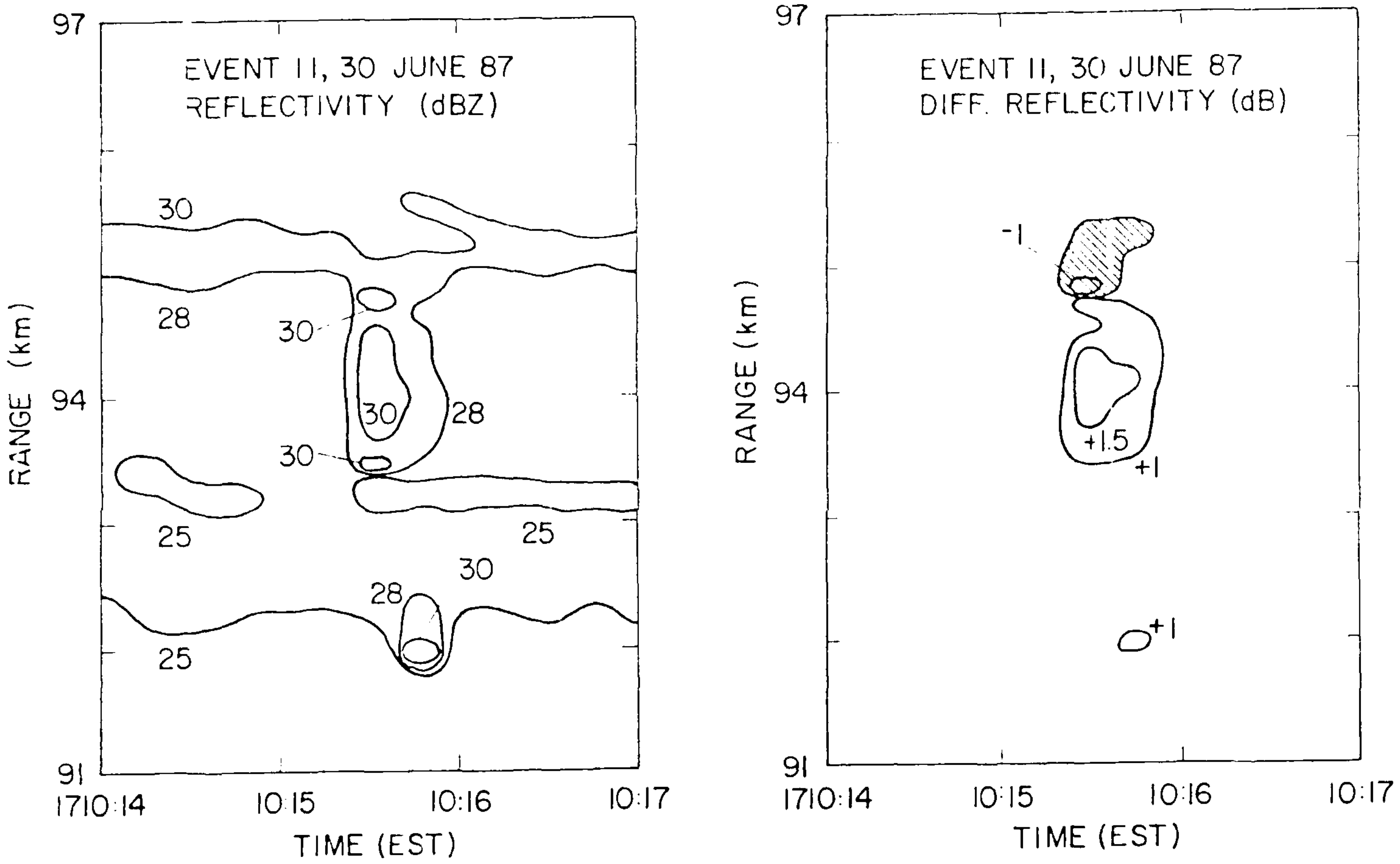

Figure 8. Absolute and Differential Reflectivity of Lightning Event 11, 30 June 1987. Echo due to lightning was detected on the near side of the maximum reflectivity due to hydrometeors. Event comprises two distinct segments within time interval of 0.5 sec.

comprises several events, each of which has a duration of a few tens of milliseconds. These short-time events may occur sequentially within different range intervals or simultaneously within noncontiguous range intervals. Hence, the observation of differential reflectivity at higher temporal resolution is an important goal for future research. A new data acquisition system to be installed later this year will enable us to acquire data for this more detailed analysis.

4. SUMMARY

The polarization differential reflectivity has been measured with standard error of estimate about 0.2 dB with the 11-cm Doppler radar operated by AFGL at Sudbury, Mass. The alternating polarization of successive transmitted pulses, required for these measurements, is accomplished by means of a network of switchable circulators that constitutes a high-power microwave switch. Radar observations have revealed a variety of meteorological and electromagnetic phenomena associated with severe convective storms. Of particular significance are the first observations of the differential reflectivity of lightning. The observations reported here emphasize the need for measurements at higher time resolution to discover characteristics of individual lightning discharges.

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