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COMPARISON OF LIGHTNING LOCATION DATA AND POLARISATION RADAR OBSERVATIONS OF CLOUDS

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ABSTRACT

Simultaneous observations of both the precipitation and the lightning associated with thunderstorms show that the lightning is within 3km of the maximum precipitation echo. The intensity and type of the precipitation is observed with 500m spatial accuracy using an S-band polarisation radar and the position of lighting is inferred from a low frequency magnetic direction finding location system. Empirical adjustments to the angles using the redundancy of the lightning data reduce this error. Radar echoes above 45dBZ may be caused by soft hail or hailstones, but similarly intense echoes may result from melting snow. Our data show that a new polarisation radar parameter, the linear depolarisation ratio, can distinguish between soft hail and melting snow, and that the intense radar echoes associated with melting snow pose no threat of lightning. A lightning risk only exists when the radar indicates that the clouds contain soft hail or hailstones.

1. INTRODUCTION

In this paper we examine the accuracy of a lightning location system by comparison with radar data, and examine how a new polarisation radar parameter can identify those clouds which contain soft hail or hailstones and pose a risk of lightning before natural lightning has occurred. In Section 2 we describe the Chilbolton polarisation radar. A brief description of the lightning location system is provided in Section 3. The lightning location system operates 24 hours a day, and aims to record every flash to ground over England, but the radar is a research instrument which can scan only slowly and is not operated continuously. In Section 4 we present the results from case studies on different days and discuss the results in Section 5.

2. CHILBOLTON RADAR

The Chilbolton radar (1) situated in Hampshire, operates at S-band (10cm) and, with a 25m dish, has a beamwidth of only a quarter of a degree. The conventional radar reflectivity, Z, is proportional to ND^6, where N is the concentration of particles of diameter D, summed over all sizes. Z is usually expressed in units of dB relative to the signal from a 1mm raindrop per cubic meter. The reflectivity of a raindrop is 7dB higher than the equivalent mass of ice, but from Z alone it is not possible to distinguish rain from ice. Neither can Z be used to differentiate between the various forms of frozen hydrometeors (snow, soft hail, hailstones etc).

The linear depolarisation ratio, LDR, is a new parameter which is a measure of the fall mode of the precipitation particles. It appears to be an excellent indicator of wet ice and can identify regions of cloud containing soft hail. LDR is defined as:

$$LDR = 10 \log(ZVH/ZH) \tag{1}$$

where ZVH is the (horizontal) cross-polar return from a vertically polarised transmitted pulse, and ZH is the conventional reflectivity (the co-polar, horizontal, return for horizontally polarised transmission).

A cross-polar return occurs only when oblate hydrometeors fall with their major or minor axis at an angle to the vertical. The highest values of LDR are found at the melting level and are associated with particles which are wet, oblate and tumbling (2). Simultaneous in-situ aircraft measurements of particle shapes and LDR measurements have confirmed (3) two distinct regimes for LDR:

i) An LDR of about -15dB indicates melting snowflakes (low density aggregates of crystals with a mean axial ratio of about 0.5).

ii) LDR values of about -24dB are associated with melting soft hail, which is much more spherical than melting snow.

Radar data taken when the aircraft was struck by lightning as it penetrated a cloud confirmed the above description (4). The lightning occurred when the LDR indicated soft hail and not in the regions where the radar suggested the presence of snow. An LDR of -20dB seems a reasonable criterion to separate the two types of precipitation particles.

3. THE ERDC LIGHTNING LOCATION SYSTEM

The lightning location system operated by the Electricity Research and Development Centre is described in more detail by Scott (5) and Lees (6). It is a magnetic direction finding system operating at 1kHz with a bandwidth of 350Hz. Five stations are available with a typical separation of 300km, but for most of the data in this paper three stations were used, each being about 200km from the radar. The error of the fix was estimated from the scatter of the three intersections of the three direction vectors. In 1988 the accuracy of the directions angles was limited by the precision of the coil alignments. In 1990 the redundancy of the data was used to make empirical adjustments to the direction angles so that the fixes were more consistent (6). These improved bearings are used for the locations reported in this paper.

4. CASE STUDIES

We shall consider data gathered on five different days. On 15 May 1988 a small isolated shower was observed for three hours; during this time it gave 24 flashes, the only ones detected over the UK on this day. On 10 May 90 a rather larger sheared cloud gave four flashes. This contrasts with 11 June 1990 where a much more intense echo gave no lightning, the radar indicating that the high Z was caused by melting snow. Four flashes were observed on 24 September, one from a very small isolated storm of low Z. Finally, on 15 October 150 discharges were observed in 40 minutes; the discharges were associated with a high Z region containing soft hail, whereas no lightning was observed from an intense echo 40km away which did not contain soft hail.

4.1 15 May 1988

An isolated shower was observed for three hours during which time it steadily moved 100km in a westerly direction. There were three periods of electrical activity: 1251-1309 (ten flashes); 1334-1356 (six flashes); and 1551-1557 (eight flashes). All times are GMT. Figure 1 shows part of a radar PPI (scan in azimuth at low and constant elevation) taken at 1309. The scales indicate North-South and East-West distance from the radar and the superposed numbers are the minute of the flash, starting at 1253 and finishing at 1307. For simplicity three Z contours are shown; 10dBZ to outline the extent of the precipitation, 30dB, and 45dBZ. Using an empirical relationship of the form $Z = 284R^{1.47}$, these Z values are equivalent to a rain rate (R) of about 0.1, 2.5 and 25mm/hr respectively. Melting snow has a very high radar reflectivity ('the bright band'), in which case rain rates calculated from Z may be overestimated by up to a factor of six.

The errors quoted for the lightning fixes in Figure 1 are about 1km; the actual locations of these flashes seem to be about 3km N of the very localised 45dBZ echo (extent only 2km by 2km). If we consider that the echo was probably 8km further west at 1253, then the locations are within 3km of the 30dBZ echo. The PPI at 1251 confirms this. A similar proximity to the echo maximum is apparent for the 1334-1356 period.

Figure 2 is a radar scan at 1556 during the third period of lightning which lasted from 1551-1557. The 45dBZ echo is still 15km N of Chilbolton, but in the two hours since Figure 1 has moved 100km to be between 20 and 25km west of Chilbolton. During the period of the lightning it would have moved westwards by less than 3km. The computed errors for these eight flashes are typically 2km, and the Figure shows that the fixes are within 3km of the 45dBZ maximum echo. The two flashes which are rather further distant (1556) have a quoted error of 2.8km. These results indicate that the accuracy of these lightning fixes is approaching 3km.

Implicit in the above argument is the assumption that the lightning strike to ground must be coincident with the regions of highest reflectivity. It is known, for example, that lightning can occur from anvils, and there is some evidence that lightning rates are lower in regions of the very highest reflectivity which probably contain large hail. Figure 3 displays an RHI (vertical section) of Z and LDR through maximum echo in Figure 2. It is typical for the data on this day. There is no anvil, and the LDR at the melting layer (2km altitude) is about -24dB. This indicates that the clouds contained soft hail, but not large hail which would have taken a longer time to melt and given these values of LDR all the way to the ground. Note that the cross-polar power is less that the co-polar, and so when Z is low the cross-polar power falls below the radar sensitivity and is not plotted in the Figure. The value of LDR in the rain and the dry ice in Figure 3 is -32dB (the antenna limit). The low altitude echo from 10 to 20km range is ground clutter.

4.2 10 May 1990

Four flashes were observed with coincident radar data. On this day the clouds were sheared with anvils and LDR indicated regions of both snow and soft hail. The best coincident data is shown in the RHI in Figure 4 taken at 1220.41 and an azimuth of 223°. The lightning at 1221.24 was located at an azimuth of 222.3° and a range of 34.1km (error 300m). Although the maximum

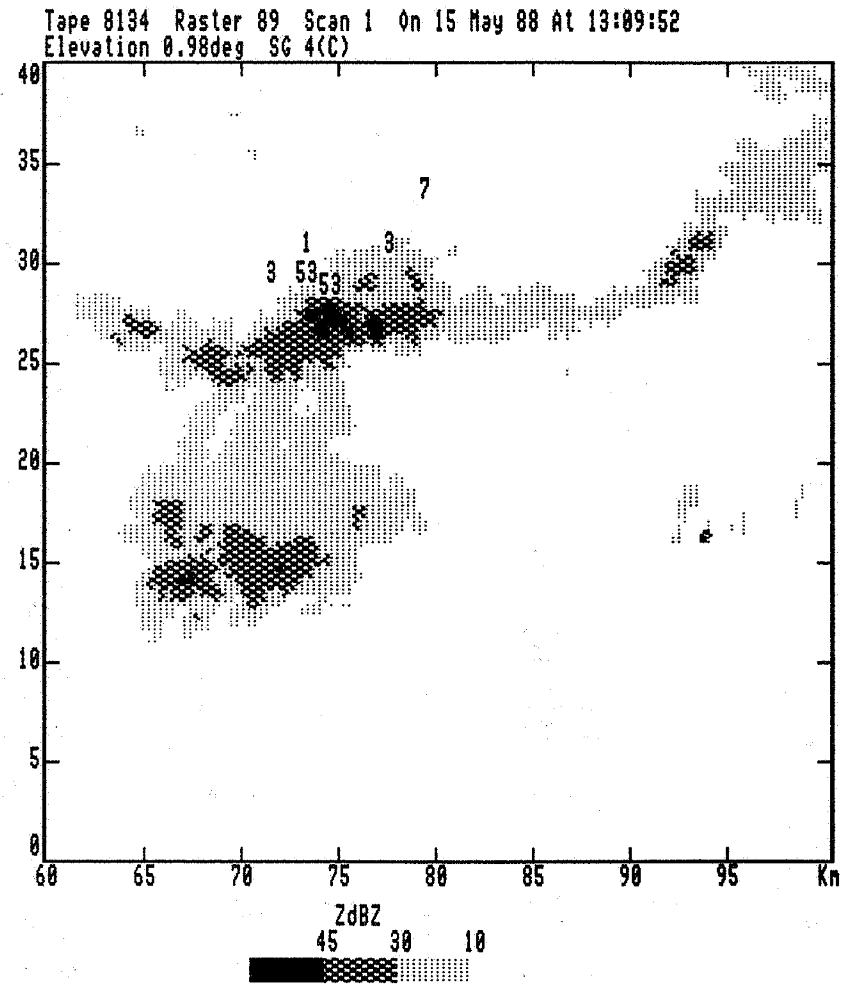

Figure 1. A PPI of the radar reflectivity on 15 May 1988 at 1309. The axes mark the distances in km from the radar (E-W and N-S). The position of the lightning flashes is indicated by the superimposed digits, with the number indicating the time in minutes.

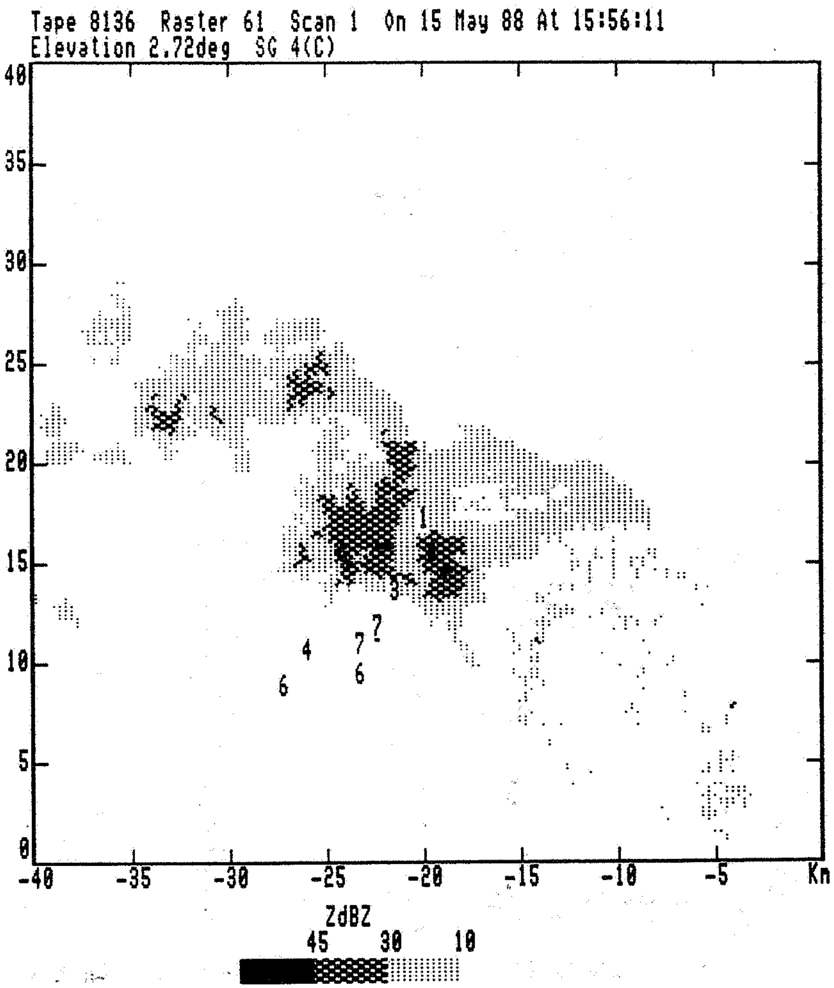

Figure 2. As for Figure 1 but at 1556, with the superimposed digits indicating the lightning position and time in minutes between 1551 and 1557. Computed errors 2km, but 2.8km for the 1556 fixes.

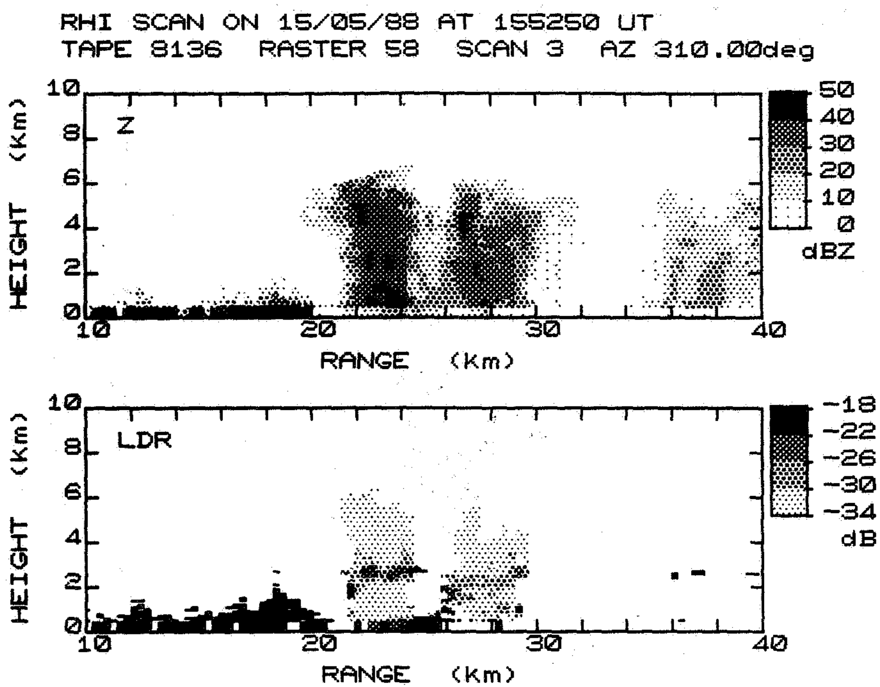

Figure 3. An RHI of the reflectivity, Z, and the linear depolarisation ratio, LDR, taken through the cloud in Figure 2. LDR of -24dB at the melting level indicates melting soft hail. The low level echo from 10 to 20km is ground clutter.

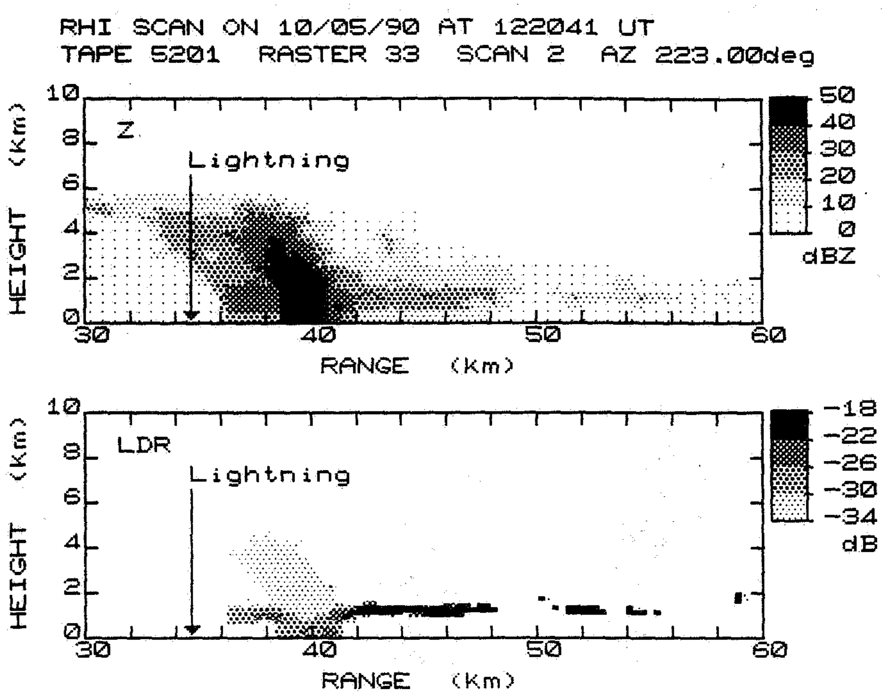

Figure 4. An RHI in Z and LDR obtained on 10 May 1990. The position of the lighting is shown by an arrow; there are indications that this was a positive discharge LDR indicates the presence of graupel at ranges 36 to 41km range.

echo is at 39km range, at 34km range there is an anvil type echo at 4km height with a Z above 30dBZ. The lightning fix waveforms indicate that this discharge had positive polarity.

The LDR data in Figure 4 provide additional information. Note the melting layer at 1km altitude signifies graupel from 36km to 41km range but snow at greater ranges. Other RHIs show that the bright band values due to melting snow exceeded 45dBZ. The sloping region of LDR -32dB (the antenna limit) at altitudes from 1 to 4km is due to dry graupel; because the Z value is so high the cross-polar return is still detectable even though it is 32dB down.

4.3 11 June 1990

The PPI shown in Figure 5 shows a much larger region of high Z than on any of the cases discussed so far, yet on this day the closest lightning was 100km due south of the radar, about 140km distant from the echo in the Figure. The echo in Figure 5 appears to be that of a vigorous shower, Z exceeds 30dBZ over an area about 20km by 20km, with a central region 10km by 3km where Z is above 45dBZ; 40km away from the central region the echo is below the 10dBZ limit. However the LDR data in Figure 6 reveal that the LDR values are above -20dB and that the precipitation is thus in the form of low density half melted snowflakes. An RHI through this cloud confirms the existence of a distinct bright band. Actual rain rates at the ground are much lower than these values of Z would suggest.

It is often thought that stratiform rain is uniform, and that the bright bands can be recognised as concentric rings of enhanced reflectivity whose range depends on the elevation of the PPI. Such rings are occasionally visible in very light widespread rain, but this is unusual, rainfall fields are usually vary variable in space. It is our experience in the UK that most areas with Z above 45dBZ are in fact melting snow.

4.4 24 September 1990

Four coincident radar and lightning fixes were achieved on this day. On the first two occasions the fixes occurred where the echo structure was ill defined with no definite localised maximum and for the third flash the radar and lightning data were separated by eight minutes. The location of the fourth flash is shown in Figure 7; it is an isolated echo contains only a few range gates where Z exceeds 30dBZ. During its lifetime this cell produced only one flash; it occurred one minute after the radar scan with a quoted error of 1.6km and was within 1km of the maximum echo. This cell was never very intense, but 10 minutes earlier the 30dBZ echo had an area of about $1km^2$. The LDR data showed that this small echo contained soft hail.

4.5 15 October 1990

Over 150 coincident lighting locations and fixes were achieved on this day within the space of just 40 minutes. An example is given in Figure 8 which displays the nine fixes within one period of 700msec. LDR shows that the high Z is due to soft hail. It appears that this was a complex flash with strokes to ground at different positions. It is encouraging to note how seven of the fixes are centred on a Z region above 45dBZ and fall within the 30dBZ contour. This day was of particular interest because the lightning producing echo was embedded in a large area of high Z as shown in Figure 9 which displays the Z and LDR data and superimposed lighting data over a 50^{o} PPI sector to a range of 150km. The lightning is associated with the high Z

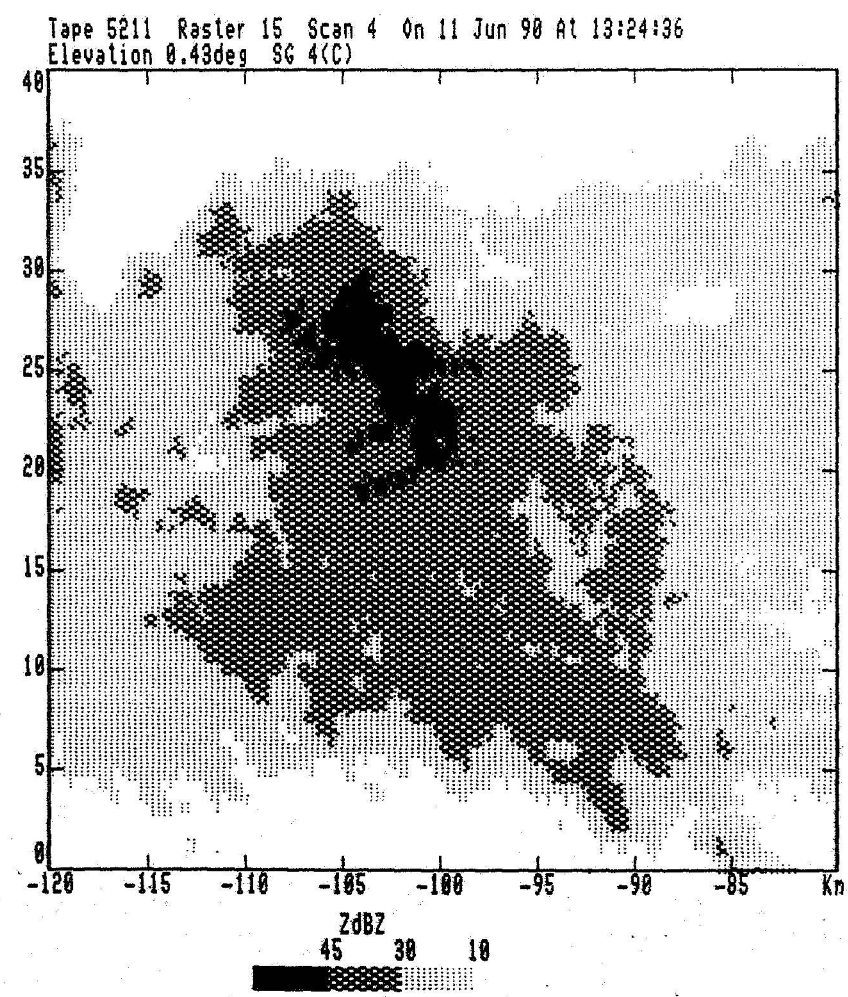

Figure 5. A PPI of the reflectivity on 11 June 1990. No lightning was observed.

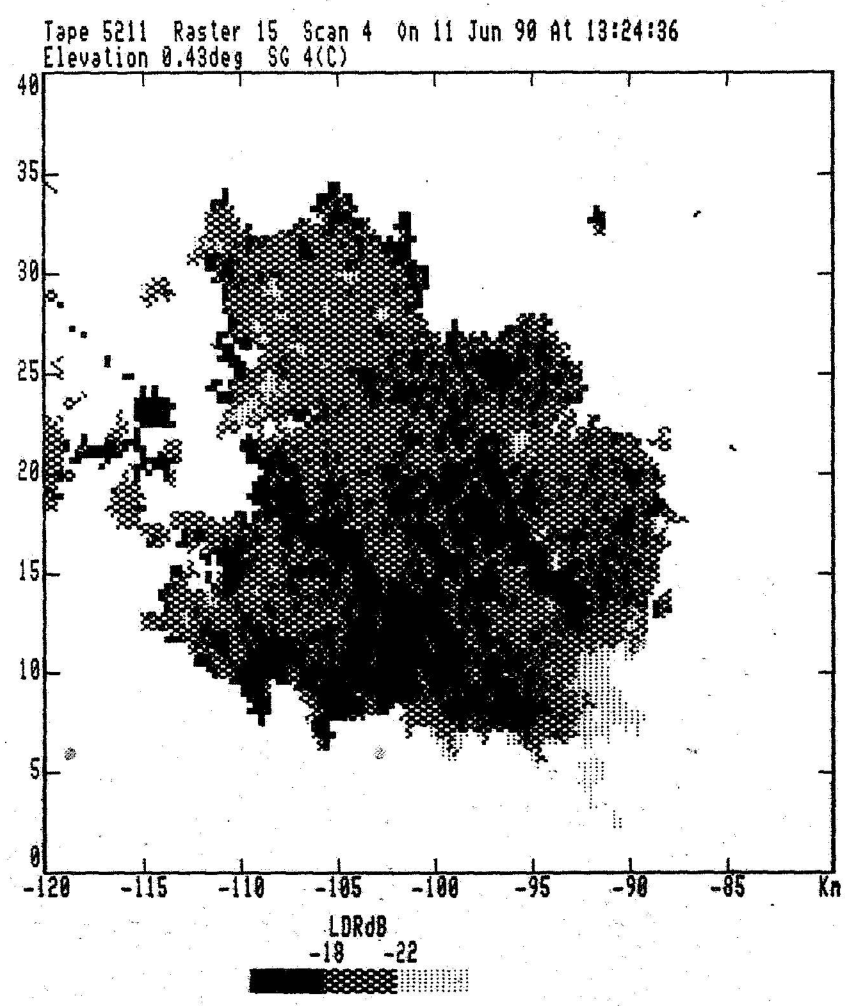

Figure 6. Values of LDR indicating melting snow for the PPI in Figure 4.

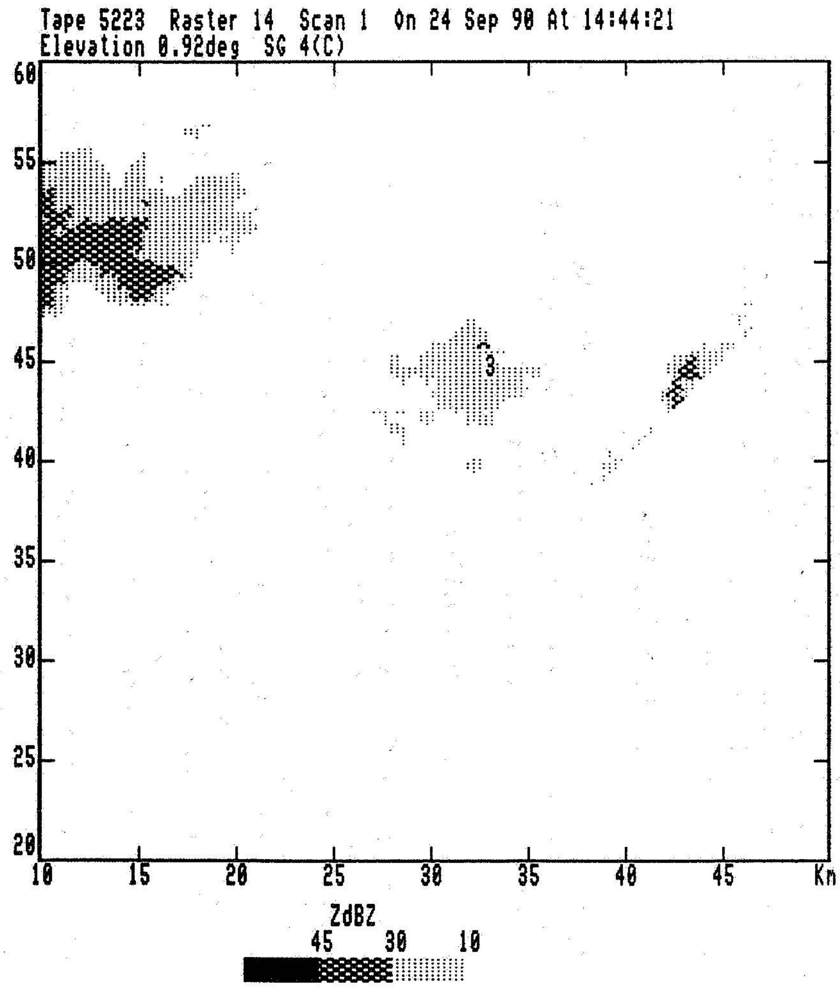

Figure 7. 24 September 1990. Radar echo which produced a single lightning flash at 1443.

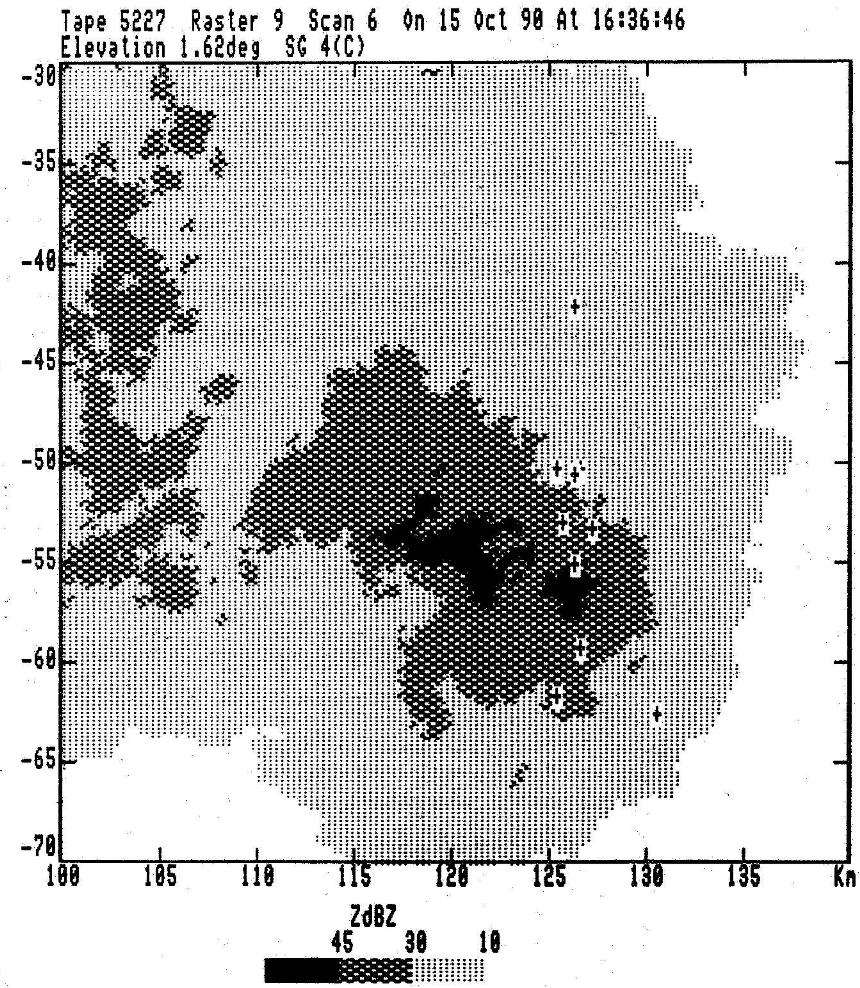

Figure 8. 15 October 1991. Radar reflectivity and nine lightning fixes (+) during a 700ms period; probably individual strokes of a single flash.

regions at ranges of 90 to 140km which contain soft hail, but there is no lightning in the high Z region at about 60km range where there is melting snow.

5. DISCUSSIONS AND CONCLUSIONS

The exact mechanism by which thunderstorms become electrified is still a matter of some debate (7). The findings presented here demonstrate that the lightning is associated with the presence of soft hail and lend support to the theory that charge separation occurs when ice crystals collide with and separate from small hail pellets. The absolute value of reflectivity is not crucial, occasional lighting being observed with maximum values below 45dBZ, whereas much more intense and extensive echoes which are not associated with hail pellets produce no lightning at all.

The presence of soft hail as revealed by the LDR radar signature appears to be a necessary condition for lightning, but small showers with soft hail are observed which fail to give lightning. However, we can assume that some charge separation is occurring in such clouds, and though the field is not sufficient for natural lightning, the presence of an aircraft may be sufficient to enhance the field to trigger a discharge. In the UK a much more common occurrence is to have more intense echoes but no soft hail present, and on these occasions there would not appear to be any risk of triggered lightning.

Comparisons of the lighting fixes with the coincident reflectivity patterns suggest that a very high accuracy is being achieved. For such comparison the ideal echoes should be of very limited spatial extent, moving slowly and with no shear. In such circumstances the data are unambiguous and it appears that, although the locating stations are 200km distant, the locations are correct to better than 3km. Agreement of 1km has been observed from data taken under these circumstances in 1990.

6. ACKNOWLEDGEMENTS

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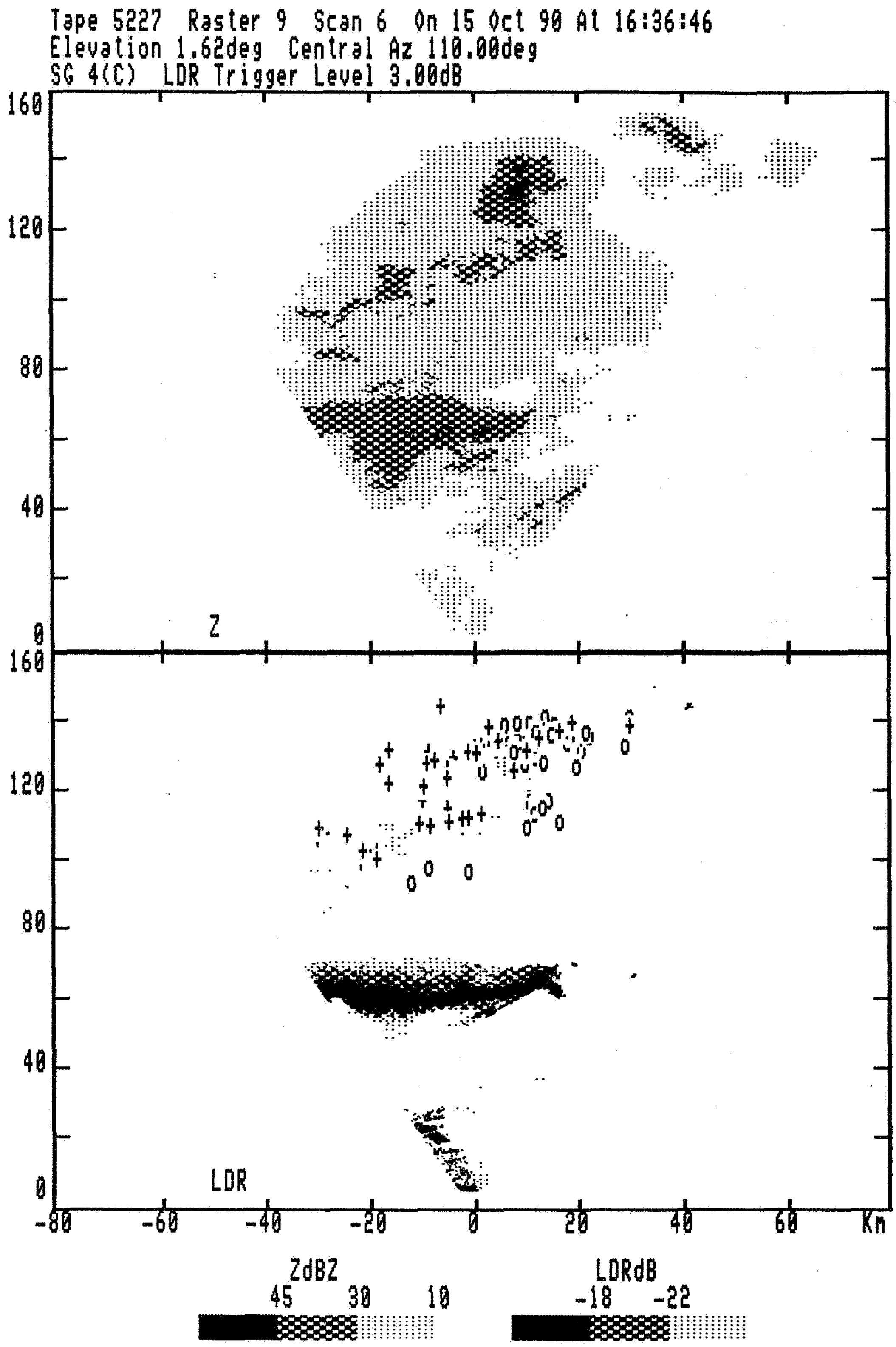

Figure 9. 15 October 1991. PPI of Z and LDR over a 50° sector. Lightning is restricted to areas where LDR indicates soft hail.
Lightning fixes: O, 1630-1639; +, 1640-1649.