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Observations of VHF Source Powers Radiated by Lightning

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Abstract. Three-dimensional lightning mapping observations have been used to estimate the peak source powers radiated by individual VHF events of lightning discharges. The peak powers vary from minimum locatable values of about 1 W typically up to 10-30 kW or more in the 60-66 MHz passband of the receivers. An energetic positive bipolar event radiated in excess of 300 kW peak power. The strongest radiation sources tended to be observed in the upper part of storms, corresponding to the upper positive charge region, where the breakdown is of negative polarity. The results illustrate the bidirectional nature of intracloud discharges, with the largest source powers being along the negative portion of the discharge and an order of magnitude greater than the source powers along the positive portion. Overall, the source powers follow an approximate P^{-1} distribution for powers above about 100 W. The radiation sources indicate the location of the main charge regions in a storm; sample comparisons with radar data show that the main negative charge coincided with the precipitation core passed through the core. The intracloud discharge occurred between the middle and upper levels of the storm, which from other studies correspond respectively to the main negative and upper positive charge regions [*e.g., Williams*, 1989; *Bateman et al.*, 1999; *Shao and Krehbiel,* 1996]. The cloud-to-ground discharge occurred between the main negative charge region and ground. Its radiation sources overlapped those of the intracloud discharge in the negative charge region. The radar comparisons show that the negative charge coincided with the precipitation core at 7-8 km altitude msl ($\simeq -15$ to -20 °C), in good agreement with other studies [*e.g., Krehbiel* 1986; *Dye et al.,* 1988]. The radiation sources between 3 and 5 km altitude indicate the presence of lower positive charge in the storm, and are in the vicinity of the the 0 °C level (at 4-4.5 km MSL).

Figures 2 and 3 show estimated peak source powers for the two discharges. The upper panel of each figure shows the source altitudes vs. time; the other panels show the sources in vertical and plan views and the distribution of source powers. The intracloud discharge had a typical bilevel structure and, as usual for such discharges, began just above the main negative charge region and developed upward in the storm [*Shao and Krehbiel*, 1996]. The upward breakdown was of negative polarity, i.e., it transported negative charge in its direction of propagation. The onset of significant radiation in the main negative charge region was delayed from that of the upward breakdown. Positive polarity breakdown into the negative charge region tends not to radiate strongly at VHF, and is followed after a delay by negative polarity events back along the inferred positive channels [*Shao and Krehbiel,* 1996; *Shao et al.*, 1996].

With the exception of the initial radiation event, discussed below, the intracloud discharge radiated most strongly in the upper positive charge region. The overall source powers ranged from the minimum locatable value of about 1 W (0 dBW) up to about 10 kW (40 dBW) in the 60-66 MHz passband of the measurements (VHF channel 3). The source powers were determined by assuming that each event radiated isotropically and by averaging the linear source power estimates from each station. Individual estimates that differed by more than a factor of 10 from the median source power were eliminated from the average, as being affected by attenuation or interference effects or to occasional incorporation of local corona noise into the solution. No attempt was made to account for the antenna pattern of the dipole receiving antennas, whose gain was assumed to be 0 dB.

The intracloud discharge differed from other discharges in the storm (both intracloud and cloud-to-ground) in that its initial radiation source had a very high peak power. The source power was greater than 300 kW (55 dBW) and the event is indicated by the red diamond. From other mea-

1. Introduction

A deployable, GPS-based system has recently been developed that locates the sources of lightning radiation in three spatial dimensions and time [*Rison et al.,* 1999a; *Krehbiel et al.,* 2000]. The system, called the Lightning Mapping Array (LMA), accurately measures the arrival time of impulsive radiation events in an unused VHF television channel at nine to ten measurement locations over a countywide area. Each station records the peak radiation event in successive 100 μs time intervals; from this, several hundred to over a thousand radiation sources are typically located per lightning discharge.

In addition to measuring the arrival times, each station records the peak received power of the events. Since the source locations are known, the total peak power radiated by the sources can be estimated. The purpose of this paper is to report sample results obtained from the study of New Mexico storms on a number of active days during the summers of 1999 and 1998.

2. Results.

Figure 1 shows vertical cross-sections of the radiation sources for an intracloud and cloud-to-ground discharge, overlaid on the radar echo from the storm. The discharges were located in the core of the storm, and the radar scan

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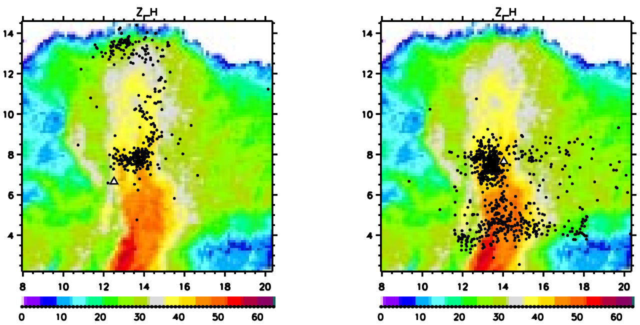

Figure 1. VHF radiation sources for an intracloud discharge (left) and a cloud-to-ground discharge (right), overlaid on a vertical radar scan through the discharges for a storm on August 2, 1999. Distances are in km above mean sea level and away from the radar, respectively. The intracloud discharge occurred at 21:06:20, 16 seconds before the radar scan. The cloud-to-ground discharge occurred at 21:08:10. The triangles denote the initial radiation event for each flash.

surements, the event produced an energetic fast electric field change known as a narrow positive bipolar pulse [e.g., *Willett et al.,* 1988]. The radiation was therefore produced by energetic breakdown that raised negative charge in the cloud [*Smith et al.,* 1999]. The radiation slightly saturated the receivers at several of the mapping stations, which would cause the source power to be somewhat underestimated and the source location to be in error. Indeed, from Figure 2, the source location was below the inferred negative charge region, inconsistent with the raising of negative charge. Observations of other positive bipolar events have indicated they occur above the negative charge region [*Smith et al.,* 1999; *Rison et al.,* 1999b], and it is likely that was the case here.

The breakdown was otherwise typical of intracloud discharges, both in terms of its temporal and spatial development and the nature of the source powers. Radiation in the negative charge region had typical source powers at or below 10-100 W. Source powers in the upper positive charge region and in the upward channel ranged from the minimum locatable values up to about 10 kW.

The source powers of the cloud-to-ground (CG) discharge (Figure 3) were primarily ≤100-200 W. Radiation from CG discharges is typically observed to be somewhat stronger in the inferred lower positive charge region than in the main negative region, but below about 500 W. Breakdown in the lower positive charge region therefore does not radiate as strongly as in the upper positive charge region. The discharge of Figure 3 was somewhat different from most CG discharges in that there was a brief phase of relatively strong (30 to 300 W) radiation in the negative charge region following the second stroke to ground. The ground strike information is from the National Lightning Detection Network and is indicated by the triangles in the figure.

Figure 4 shows a composite of ten minutes of lightning activity around the time of the above discharges. Nineteen discharges occurred during this time; most were negative polarity cloud-to-ground flashes that radiated extensively in the lower positive charge region. With the exception of the positive bipolar event, the source powers tended to be

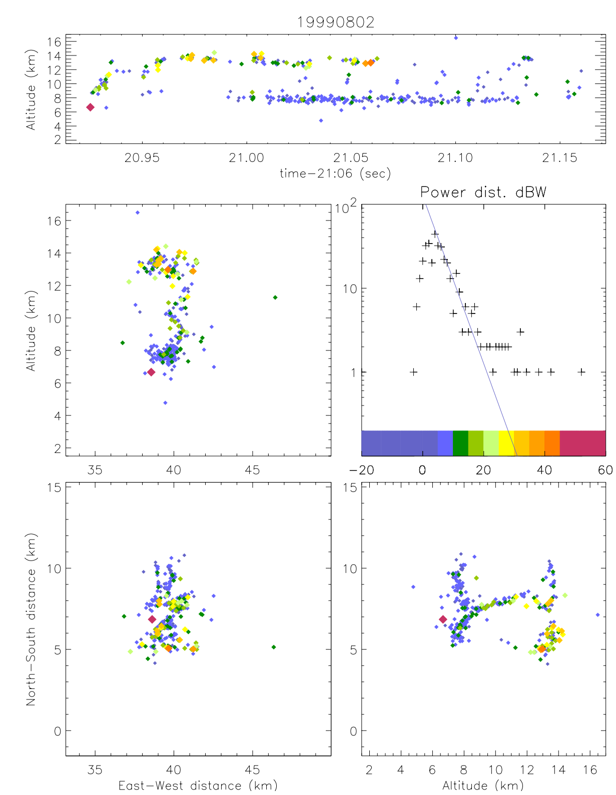

Figure 2. Source powers and temporal development of the intracloud lightning discharge of Figure 1. The source powers are in dBW units as indicated by the color bar.

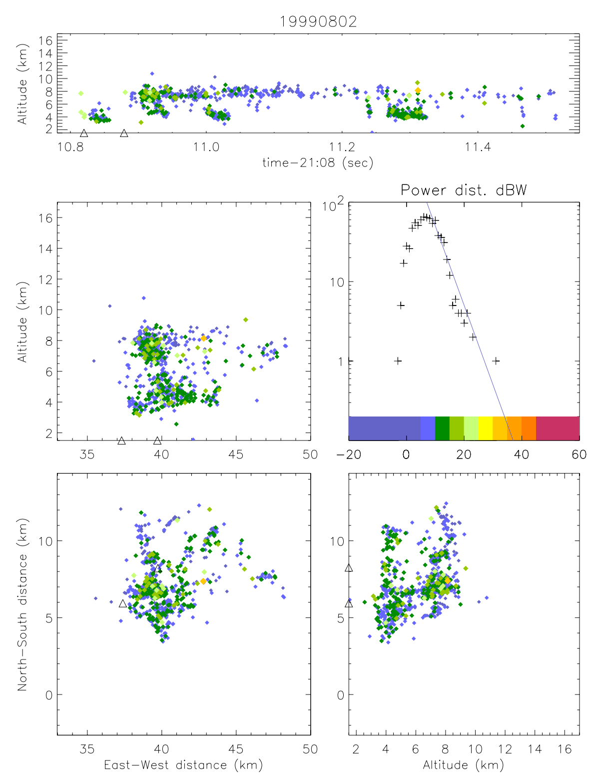

Figure 3. Same as Figure 2, but for the cloud-to-ground discharge of Figure 1. The straight line in the power distribution panel corresponds to a P^{-1} distribution.

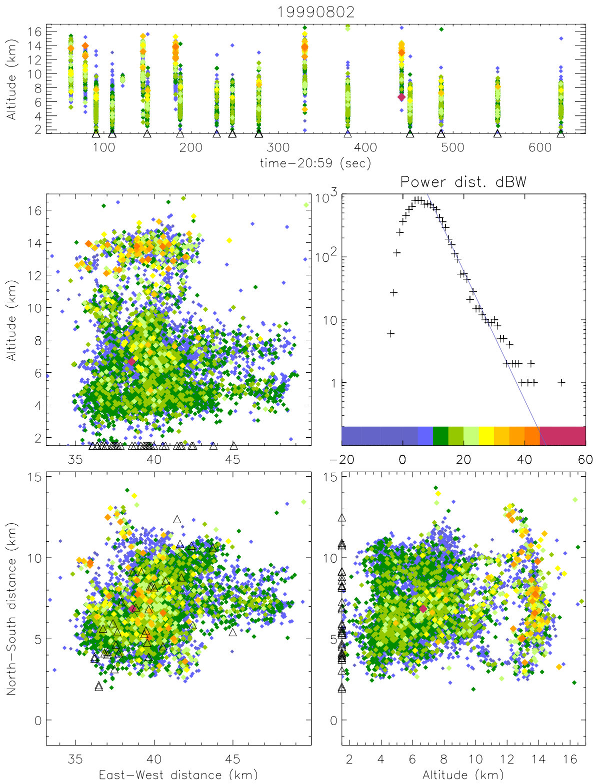

Figure 4. Source powers during 10 minutes of lightning activity in the storm of Figure 1.

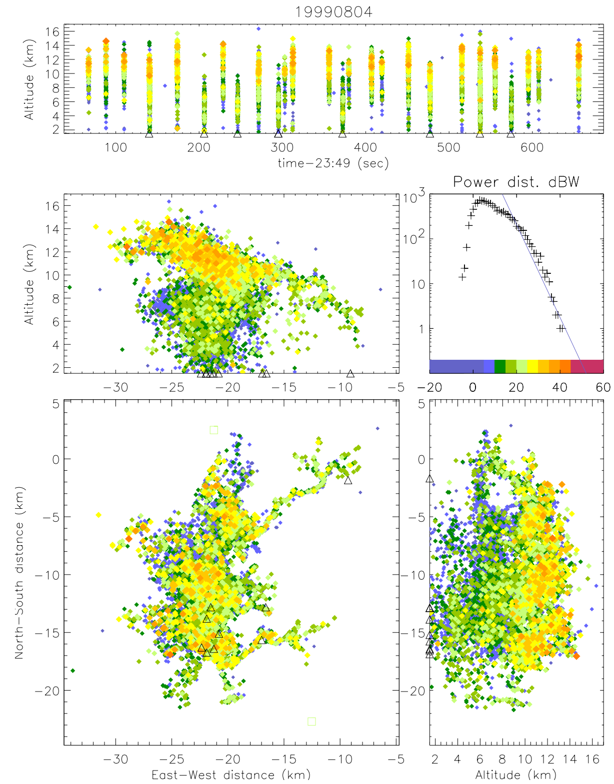

Figure 5. Same as Figure 4, except for a storm on August 4, 1999.

strongest in the upper positive charge region. Overall, the radiated powers tended to follow a P^{-1} distribution, as indicated by the line in the histogram, with the positive bipolar event being an exception.

The above storm occurred on August 2, 1999 and was situated 40 km ENE of Tech's Langmuir Laboratory for Atmospheric Research, located at the center of the measurement network. Figure 5 shows ten minutes of lightning activity in a storm on August 4, 1999, 25 km WSW of Langmuir Laboratory. The radiation sources were again strongest in the upper positive charge region, which sloped upward to the west. The strongest sources had peak powers of about 10 kW. The distribution of source powers was slightly 'rounded' relative to a P^{-1} distribution for values below about 100 W. This is often observed in storms.

Figure 6 shows the discharge that extended northeastward from the storm in Figure 5. This is an example of a newly identified type of cloud-to-ground discharge, namely one that goes indirectly to ground via the upper positive charge region rather than directly to ground through lower positive (or no) charge. A similar flash has been described by *Rison et al.* [1999a]; such flashes are often observed by the mapping system in New Mexico storms. They begin as a normal intracloud discharge with negative polarity breakdown into the upper positive charge region which, instead of stopping there, continues horizontally away from the cloud and then to ground. Although the channel to ground emanates from the upper positive charge region, the discharges are of normal, negative polarity. For the discharge of Figure 6, the ground strike location was 10 km away from the other activity in the storm. Another discharge of the same

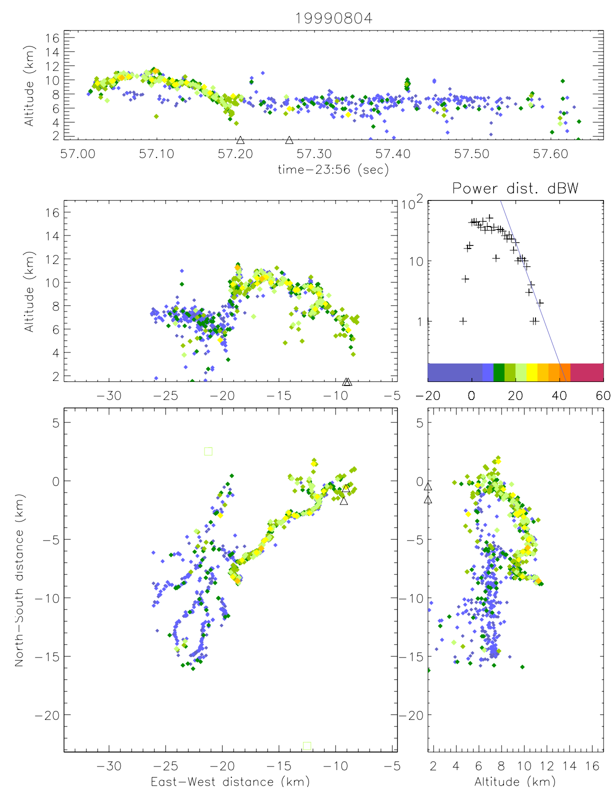

Figure 6. A cloud-to-ground discharge that went to ground via the upper positive charge region, outside the main part of the storm of Figure 5, showing the difference in peak power values between negative and positive portions of the discharge.

type occurred on the southeastern part of the storm in Figure 5.

The Figure 6 results illustrate the difference in maximum power values radiated by the positive and negative ends of a discharge. The negative polarity breakdown had numerous source powers between 30 W and 1 kW, while sources along the positive breakdown channels radiated typically below 30 W. One is able to readily discern the bidirectional nature of the breakdown from this difference. It is not known if the positive breakdown sources were associated with the breakdown itself, or with subsequent negative-polarity activity back along the positive channels.

3. Summary and Discussion.

The results of this study indicate that the peak VHF source powers radiated by normal lightning processes range from minimum locatable values of about 1 W up to 10-30 kW at 60-66 MHz. In most of the storms observed, the strongest radiation events tended to occur in the upper positive charge region. Less convective storms which had more complex lightning, including positive CG discharges, have been found to radiate strongly throughout the full depth of the storm above the 0°C level. The source powers clearly illustrate the bidirectional nature of intracloud discharges, with the strongest powers being along the negative portion of the discharge and an order of magnitude stronger than those along the positive portion. The overall source powers tend to follow an approximate P^{-1} distribution above 100 W, with a lesser slope at lower powers.

The energetic positive bipolar breakdown event observed in this study radiated an estimated peak power greater than 300 kW. As discussed by *Smith et al.* [1999], such bipolar events are the likely source of energetic trans-ionospheric pulse pairs (TIPPs) detected from the earth by satellites. *Jacobson et al.* [2000] report lightning source powers detected by the FORTE satellite and find the powers to have an approximate Gaussian distribution with mean values between about 10^4 to 10^5 W. The detected events were biased toward higher powers by the event triggering. However, events associated with inferred intracloud discharges were observed to have greater mean power than for cloud-to-ground discharges, consistent with the results presented here. Assuming an f^{-2} spectral variation between the 38 and 63 MHz center frequencies of the two systems, and accounting for the 22 MHz bandwidth of the FORTE system, the FORTE-determined powers are a factor of 10 higher than would be measured by the mapping system. The 300 kW positive bipolar event would therefore have been observed by FORTE as a 3 MW event, placing it among the strongest natural VHF events emanating from the earth.

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