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A GPS-based Three-Dimensional Lightning Mapping System: Initial Observations in Central New Mexico

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Abstract. A GPS-based system has been developed that accurately locates the sources of VHF radiation from lightning discharges in three spatial dimensions and time. The observations are found to reflect the basic charge structure of electrified storms. Observations have also been obtained of a distinct type of energetic discharge referred to as positive bipolar breakdown, recently identified as the source of trans-ionospheric pulse pairs (TIPPs) observed by satellites from space. The bipolar breakdown has been confirmed to occur between the main negative and upper positive charge regions of a storm and found to be the initial event of otherwise normal intracloud discharges. The latter is contrary to previous findings that the breakdown appeared to be temporally isolated from other lightning in a storm. Peak VHF radiation from the energetic discharges is observed to be typically 30 dB stronger than that from other lightning processes and to correspond to source power in excess of 100 kW over a 6 MHz bandwidth centered at 63 MHz.

1. Introduction

This paper describes initial results from a deployable system that locates lightning radiation sources in three spatial dimensions and time. The instrument, called the Lightning Mapping Array (LMA), is based on the Lightning Detection and Ranging (LDAR) system developed for use at the NASA Kennedy Space Center [*Maier et al.*, 1995]. The system measures the arrival time of impulsive VHF radiation at six or more stations and uses the arrival times to locate the sources of the radiation [*Proctor*, 1971]. Rather than telemetering high-speed video data to a central site for time-correlated digitizing, the deployable system takes advantage of GPS technology to measure the arrival times independently at each of the receiving sites. The relatively low speed time-of-arrival data can then be communicated via wireless communication links to a central site for processing. The system was initially operated in central Oklahoma during June of 1998 [*Krehbiel et al.*, 1998; *Thomas et al.*, 1999] and then in central New Mexico during August and September.

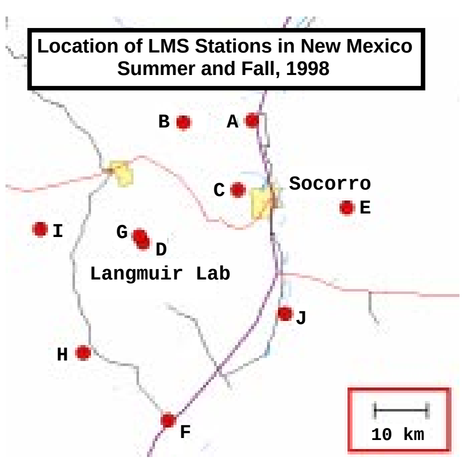

Figure 1. Map of the measurement stations.

2. System Operation and Results.

Ten measurement stations were deployed over an area about 60 km in diameter around Tech's Langmuir Laboratory for Atmospheric Research in the Magdalena Mountains west of Socorro (Figure 1). Each station detects the peak intensity of VHF radiation in the 6 MHz bandwidth of an unused television channel (channel 3, centered at 63 MHz). The time and magnitude of the peak radiation is recorded during every 100 μs time interval that the RF power exceeds a noise threshold. The peak signal times are recorded with 50 ns time resolution using a 20 MHz digitizer accurately phase locked to the 1 pulse per second output of a GPS receiver (Motorola Oncore). Well-defined events strong enough to be detected at six or more stations are located in three spatial dimensions and time.

Figure 2 shows peak power values versus time for an energetic narrow positive bipolar lightning event observed by the LMA. (The term 'narrow bipolar' derives from the shape of the associated sferic, which is bipolar and impulsive in nature, lasting only 10-15 μs [*Willett et al.*, 1989; *Smith et al.*, 1999]. A positive bipolar event transports negative charge upward in the cloud.) The horizontal scale is divided into the 100 μs time windows of the measurements and the vertical scale shows the peak power values in dBm. Strong radiation arrived at the nine operational LMA stations during the three-window interval between 995.9 ms and 996.2 ms. The calculated source time is indicated by the dashed vertical line. The signal strength tended to decrease with distance from the source but varied about this trend due to systematic differences in station sensitivities. Whereas the arrival times of normal lightning radiation were consistent with emission from a localized or point source, the positive bipolar (+BP) data were less consistent with a localized source. The statistical distribution of reduced χ^2 values indicates overall timing uncertainties of 40-50 ns rms for the LMA system. (Assuming RF radiation from a point source, the timing errors correspond to 50 m rms horizontal errors and 100 m rms vertical errors over the network, with larger

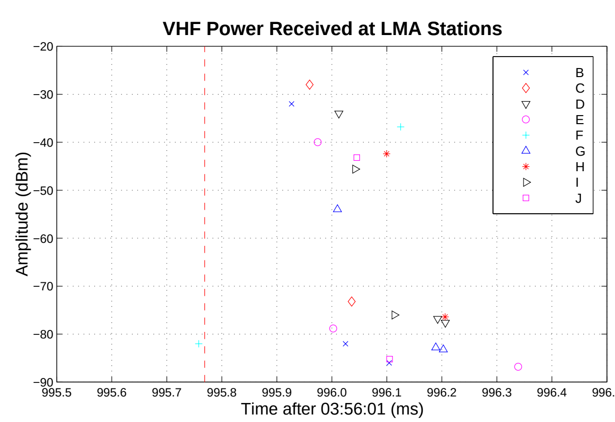

Figure 2. Observations of a positive bipolar event.

errors outside the network.) The timing uncertainties for +BP events were significantly greater, being about 750 ns rms for the event shown. The +BP radiation therefore appears to be from a spatially and temporally extensive source and is not dominated by a single peak. This is consistent with the inference by *Smith et al.* [1999] that the breakdown is about 0.5 to 1 km in length.

Figure 3 shows observations of an intracloud (IC) lightning discharge. The □ symbols in the plan view (lower left panel) indicate the locations of LMA stations. The origin of the coordinate system is Station D, located at Langmuir Laboratory (Figure 1). The solid line in the vertical cross-section panels indicates the local topography above mean sea level. The discharge had a bilevel structure typical of many IC flashes; the lower and upper levels correspond to the main negative and upper positive charge regions of the storm, respectively [*Shao and Krehbiel*, 1996]. Of 318 radiation events located during the flash, most were in the upper positive charge region and relatively few were in the lower, negative charge region (see the altitude histogram panel). This asymmetry is typical of observations by VHF location systems. Positive charge regions are penetrated by negative polarity breakdown, which is inherently noisier at RF than positive breakdown into negative charge regions [e.g., *Mazur and Ruhnke*, 1993; *Shao and Krehbiel*, 1996]. The difference is sufficiently pronounced that one can usually determine the polarity of the breakdown and the sign of a charge region from the relative number of located sources.

The upper panel of Figure 3 shows the temporal development of the flash. The breakdown began between the two charge levels and progressed upward with time, then outward along the upper level channels. Significant radiation was not detected in the lower level until after a time delay, about 50 ms in this case. This sequence of events is typical of IC flashes observed at VHF [*Shao and Krehbiel*, 1996] Radiation events detected in the lower level are probably associated with negative polarity breakdown back along the path of undetected positive leaders in the negative charge region.

Figure 4 shows an example of an unusual type of cloud-to-ground (CG) discharge. Instead of going directly from the main negative charge region to ground, as usually happens, the leader to ground was an extension of the upper level breakdown of an otherwise normal intracloud discharge. Such discharges are observed visually to emanate from the upper part of a cloud but their polarity or mechanism have not previously been understood. In this and other cases the cloud-to-ground discharge was of normal polarity, namely it transferred negative charge to ground. This is indicated by data from the National Lightning Detection Network (△) and is consistent with the fact that the breakdown into the upper cloud level would have been of negative polarity. Instead of dying out within the positive charge region, the upper level channel continued to progress away from the main part of the storm, eventually going to ground about 15 km west and south. The breakdown was in effect a long stepped leader that went to ground indirectly via the upper positive charge region. It required 150 ms to reach ground and was $\simeq 20 - 25$ km in length, corresponding to a speed of about 1.5×10^5 m s^{-1}, typical of initial leaders.

For comparison, Figure 5 shows a vertical cross-section and altitude histogram of a CG discharge that went directly to ground. In the process it appeared to discharge a region of lower positive charge. The latter is indicated by the large number of sources between 3 and 5 km altitude msl and is typical of CG observations with the mapping system. The negative charge region was at 6 km altitude and, as in the Figure 4 example, exhibited relatively few radiation sources even though it was the primary charge source for the flash [*Krehbiel et al.*, 1979]. Channels in the negative charge region are well-delineated by interferometer observations of dart-type leaders [*Shao et al.*, 1995], but such leaders are

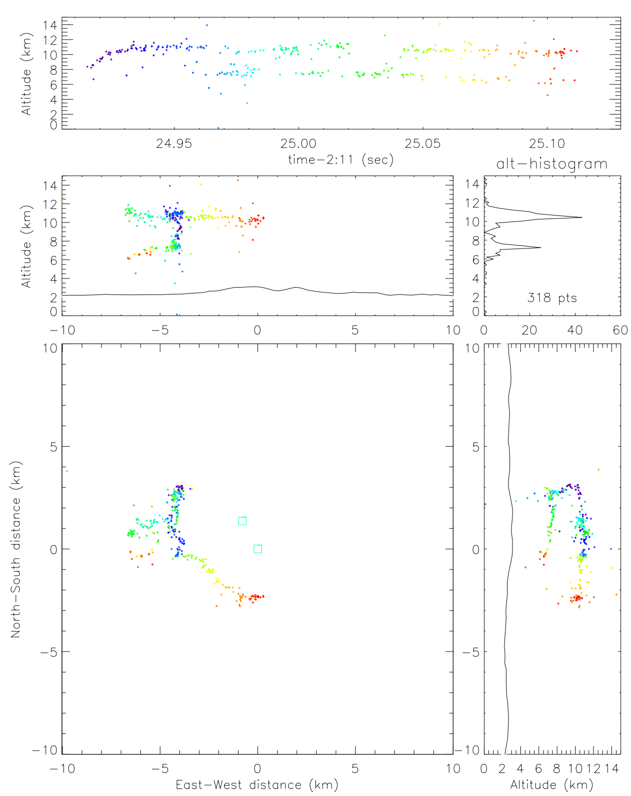

Figure 3. Observations of a bilevel intracloud flash.

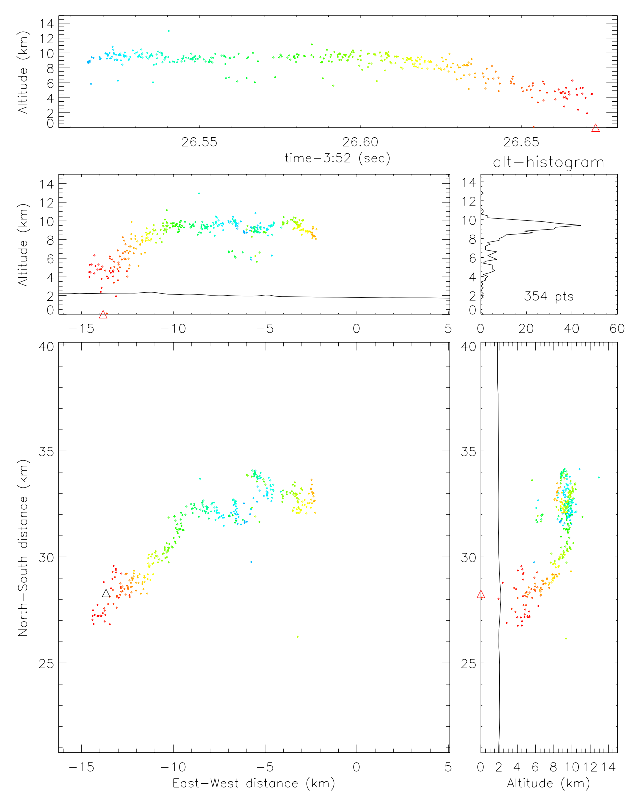

Figure 4. An unusual cloud-to-ground discharge.

not well located by time-of-arrival techniques because of their continuous nature and high speed.

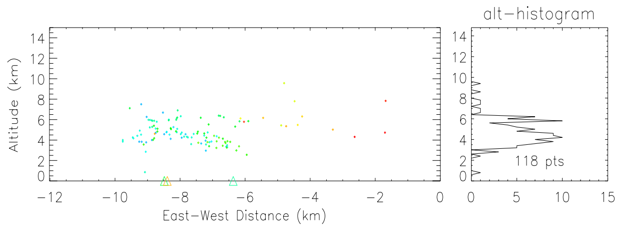

Figure 5. Observations of a CG flash involving lower positive charge.

One of the most interesting features of the New Mexico measurements has been the observations of narrow positive bipolar breakdown events. Figure 6 shows 15 ms of activity around the time of the energetic +BP event of Figure 2. Of particular interest is the lower amplitude radiation that followed the bipolar event. This radiation was produced by an intracloud discharge initiated by the bipolar breakdown. As seen in Figure 7, the bipolar event (identified by the $\diamond$ symbol) occurred at 8.6 km altitude and was followed during the next 10 ms by a succession of radiation events that progressed upward to 12 km altitude. The initial sources of the upward activity were between 8 and 9 km altitude and were within 1 km of the plan location of the +BP event. (The event shown in Figure 7 is outside the network. At this distance from the network the horizontal errors are about 150 m and the vertical errors are about 300 m.) The large reduced chi-square value of the +BP event ($\chi^2_\nu = 93$) makes its exact location uncertain in comparison with that of the subsequent radiation, which were located with $0.5 < \chi^2_\nu < 5$. Subsequent to the initial activity the intracloud flash spread horizontally through the storm.

The crosses ($\times$) in Figure 7 indicate the plan location of the +BP event as determined by an array of four sferics stations operated by Los Alamos National Laboratory [*Wiens et al.*, 1998]. The set of event times and locations from the Los Alamos array were used by us to find +BP events in the large amount of data from the lightning mapping system. During an active 2 hour interval on September 30, thirteen +BP events occurred within 160 km of the LMA center. In each instance the LMA data showed that the +BP event initiated an intracloud discharge.

3. Discussion.

The results of this study confirm the findings of *Smith et al.* [1999] that energetic bipolar breakdown occurs between the main negative and upper positive charge regions of a storm, in the same location where intracloud discharges are initiated, and that it transports negative charge upward in the storm. A surprising result was the finding that the bipolar events were in all cases the initial breakdown of an intracloud discharge. Previous studies had indicated that bipolar events were temporally isolated from other lightning discharges in the storm [*Willett et al.*, 1989; *Smith et al.*, 1999]. The discrepancy probably stems from the fact that the previous measurements primarily involved sferics measurements at relatively large distances (100 km or more). At these distances the sferics tend to be dominated by high-current processes such as return strokes in CG flashes and large-amplitude K-changes of intracloud discharges. The latter tend to occur in the late stages of intracloud flashes and would have been missed with short digitizing windows. Observations by *Medelius et al.* [1991] showed accompanying intracloud activity in about one-third of the cases.

Positive bipolar sferics are comparable in amplitude to return stroke sferics in CG discharges, which attests to the energetic nature of the bipolar breakdown. This is particularly significant when it is considered that +BP breakdown occurs in virgin air, while return strokes occur as the result of a long conducting leader contacting ground.

The best potential explanation of the energetic bipolar breakdown events is that they result from an electron avalanche process initiated by cosmic rays in regions of strong electric fields [*Roussel-Dupré*, 1998]. An important question is whether bipolar breakdown can have a range of strengths and be responsible for initiating all intracloud (and possibly CG) discharges. Observational evidence in support of this idea has come from a re-examination of intracloud sferics at relatively close range (M. Brook, private communication), and from a recent study by *Ishii et al.* [1999]. Additional questions concern a) the nature of negative narrow bipolar

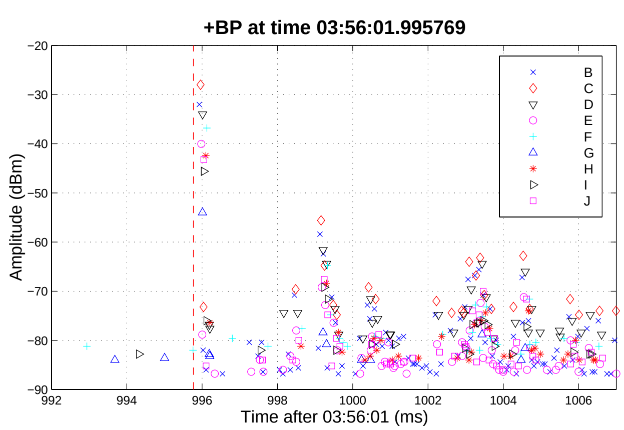

Figure 6. 15 ms of observations around the time of the narrow bipolar event of Figure 2.

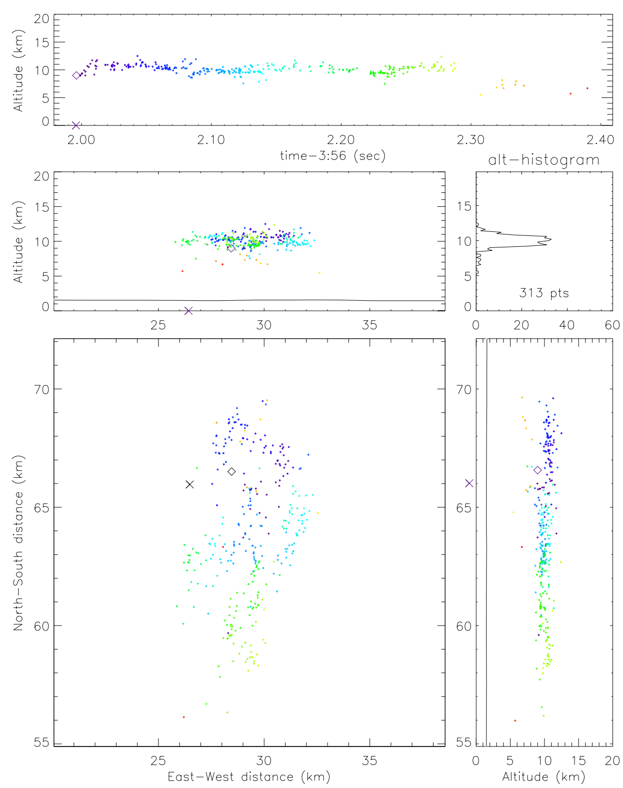

Figure 7. The intracloud discharge initiated by the energetic bipolar breakdown event ($\diamond$).

events [*Medelius et al.*, 1991; *Shao et al.*, 1998], and b) the extent to which bipolar breakdown events occur in isolation from other discharges.

The energetic nature of +BP breakdown is illustrated by the strength of its VHF radiation. Data such as that in Figure 6 show that the peak VHF radiation of energetic +BP events is typically 30 dB greater than that of normal intracloud and CG processes. From the distance to the source and the antenna gain one is able to estimate the total power radiated by +BP events. Assuming the radiation to be isotropic, normal lightning processes radiate peak powers up to 100 to 1000 W within the LMA receiver passband (6 MHz bandwidth centered at 63 MHz). By contrast the positive bipolar events of this study radiated in excess of 100 kW peak power.

As shown by *Smith et al.* [1999], +BP events are undoubtedly the source of trans-ionospheric pulse pairs (TIPPs) observed by satellites from space [e.g., *Massey et al.,* 1998]. The satellite observations have shown TIPPs to be the strongest source of naturally occurring terrestrial RF radiation. The latter agrees with the initial observations of the +BP radiation by *Le Vine* [1980] and is further confirmed by the present results. The peak source powers of satellite-detected TIPP events has been found to range between 10^3 to 10^6 in a 22 MHz bandwidth centered at 38 MHz, with the tail of the distribution extending to 10^7 W [*Jacobson et al.*, 1999]. Converting to the same center frequency and bandwidth, the +BP events of this study would have produced TIPPs with peak powers of 1×10^6 W or more, in the upper range of the satellite-observed powers.

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5. References

Ishii, M., J. Hojo, K. Shimizu, K. Sato, and K. Shinjo, Height of radiation sources associated with lightning discharges, in *11th Intern'l Conf. on Atmospheric Electricity, NASA Conf. Publ. 1999-209261*, pp. 10-13, 1999.

Jacobson, A.R., K.L. Cummins, M. Carter, P. Klingner, D. Roussel-Dupré, and S.O. Knox, FORTE observations of lightning radio-frequency signatures: Prompt coincidence with strokes detected by the National Lightning Detection Network, submitted to *J. Geophys. Res.*, 1999.

Krehbiel, P.R., M. Brook, and R.A. McCrory, An analysis of the charge structure of lightning discharges to ground, *J. Geophys. Res., 84*, 2432-2456, 1979.

Krehbiel, P., R. Thomas, W. Rison, T. Hamlin, J. Harlin, and M. Davis, Lightning mapping observations during MEaPRS in central Oklahoma, Abstract A22A-12, Fall Ann. Mtg., Amer. Geophys. Union, EOS, 79, p. F127, 1998.

Le Vine, D.M., Sources of the strongest RF radiation from lightning, *J. Geophys. Res., 85*, 4091-4095, 1980.

Maier, L., C. Lennon, T. Britt and S. Schaefer, LDAR system performance and analysis, in *Proceedings of the International Conference on Cloud Physics*, Am. Meteorol. Soc., Boston, Mass., Dallas, Tex., Jan 1995.

Massey, R.S., D.N. Holden, and X.M. Shao, Phenomenology of trans-ionospheric pulse pairs: Further observations, *Radio Sci., 33*, 1755-1761, 1998.

Medelius, P.J., E.M. Thomson, and J.S. Pierce, E and dE/dt waveshapes for narrow bipolar pulses in intracloud lightning, in *Proc. of Intn'l. Aerospace and Ground Conf. on Lightning and Static Electricity, NASA Conf. Publ. 3106*, pp. 12-1 to 12-10, 1991.

Mazur, V., and L. Ruhnke, Common physical processes of in natural and artificially triggered lightning, *J. Geophys. Res., 98*, 12,913-12,930, 1993.

Proctor, D. E., A Hyperbolic System for Obtaining VHF Radio Pictures of Lightning, *J. Geophys. Res., 76,* 1478-1489, 1971.

Roussel-Dupré, R., E. Symbalisti, and V. Yukhimuk, Inititation of Intra-Cloud Discharges by Runaway Air Breakdown, Abstract A31A-23, Fall Ann. Mtg., Amer. Geophys. Union, EOS, 79, p. F137, 1998.

Shao, X.M., and P.R. Krehbiel, The spatial and temporal development of intracloud lightning, *J. Geophys. Res., 101*, 26,641-26,668, 1996.

Shao, X.M., P.R. Krehbiel, R.J. Thomas, and W. Rison, Radio interferometric observations of cloud-to-ground lightning phenomena in Florida, *J. Geophys. Res., 100*, 2749-2783, 1995.

Shao, X.M., D.A. Smith, K. Eack, R. Massey, and K. Wiens, Observations of compact intracloud discharges (CIDs), Abstract A31D-05, Fall Ann. Mtg., Amer. Geophys. Union, EOS, 79, p. F143, 1998.

Smith, D., X.M. Shao, D.N. Holden, C.T. Rhodes, M. Brook, P.R. Krehbiel, M. Stanley, W. Rison, and R.J. Thomas, A distinct class of isolated intracloud lightning discharges and their associated radio emissions, *J. Geophys. Res., 104*, 4189-4212, 1999.

Thomas, R.J., P.R. Krehbiel, W. Rison, T. Hamlin, D.J. Boccippio, S.J. Goodman, H.J. Christian, Comparison of ground-based 3-dimensional lightning mapping observations with satellite-based LIS observations in Oklahoma, submitted to *Geophys. Res. Letts.*, May, 1999.

Wiens, K., R.S. Massey, X.M. Shao, M. Eberle, and K.B. Eack, The Los Alamos electric field change sensor array, Abstract A31D-04, Fall Ann. Mtg., Amer. Geophys. Union, EOS, 79, p. F142, 1998.

Willett, J.C., J.C. Bailey, and E.P. Krider, A class of unusual lightning electric field waveforms with very strong high-frequency radiation, *J. Geophys. Res., 101*, 26,641-26,668, 1989.