

STROKE MULTIPLICITY VERSUS HORIZONTAL SCALE OF NEGATIVE CHARGE REGIONS IN THUNDERCLOUDS

Earle Williams, Parsons Laboratory, MIT, Cambridge, MA, USA

Enrique Mattos and Luiz Machado, INPE, Cachoeira Paulista, Sao Paulo, Brazil

Abstract- An X-band polarimetric radar and multiple lightning detection systems are used to document the initial intracloud and cloud-to-ground lightning flashes in a large number (>100) of incipient thunderstorms, as part of the CHUVA-Vale field campaign. The results show an exceptionally low stroke multiplicity in the initial ground flashes, a finding consistent with the limited space available for positive leader extension into new regions of negative space charge in compact cells. The results here are contrasted with the behavior of ground flashes in mesoscale storms in previous studies.

1-INTRODUCTION

This study is concerned with an effort to shed further light on a problem in lightning physics that is still not well understood—the physical mechanism for multiple strokes in a flash to ground. Nor is it well known why some lightning flashes can transfer most of their charge by continuing current, following the initial stroke. Discussions on mechanisms for discrete strokes in lightning can be found in Heckman (1992), Mazur and Ruhnke (1993) and Williams and Heckman (2012). Fortunately, the sequence of events that make up a lightning flash is well documented on the basis of time-resolved measurements with field change antennae and VHF lightning mapping arrays. A cloud-to-ground flash is initiated by a bidirectional leader that itself is initiated in the strong field region between the main negative charge and the lower positive charge. The weakly radiating positive leader invades the negative charge region, while the opposite negatively charged and strongly radiating negative leader forges its way toward

ground. When the negative leader with large negative potential nears ground, streamers are launched from points on the ground and their thermalization constitutes the ‘final jump’, initiating the return stroke current that proceeds at near light speed back up the pre-ionized channel. Within a few milliseconds of the return stroke onset, the current in the channel to ground cuts off near the ground (Krehbiel, 1981) and the return stroke channel there becomes optically dark. All the while, the positive leader continues its extension into negative space charge aloft at a typical speed of 5×10^4 m/s, giving rise to the quasi-steady change in electric field at the ground in the interstroke interval known as the ‘J-process’ (Schonland, 1938; Malan, 1964). This action continues for typically 60-70 milliseconds until a dart leader is initiated aloft to activate another leader-return stroke sequence toward the second stroke. This process can repeat several times (the ‘stroke multiplicity’ of the flash) until the flash terminates. The field change antenna measurements (Krehbiel et al., 1979; Krehbiel, 1981) have shown systematic stroke-to-stroke horizontal displacements of the negative charge centers as the flash proceeds. These horizontal displacements are of the order of kilometers, and are generally consistent with the invasion distances possible during typical interstroke intervals by positive leaders at speeds of order 5×10^4 m/s. This general picture is also supported by the evidence that flash duration increases systematically with the number of strokes in a flash. For example, Saba et al. (2006) have measured flash durations with high-speed video and have constructed an empirical ‘best’ relationship between duration D and multiplicity M

$$D = 72 M - 100 \text{ msec} \quad (1)$$

with the implication that the mean duration of the interstroke interval is 72 msec.

The main goal in the present study is to find isolated thunderstorms on radar as they first appear, and whose lightning activity is well documented with special detection systems. In this way it is possible to study initial cloud-to-ground lightning flashes with a minimum in horizontal extent of the main negative charge region. The working hypothesis is that if the horizontal extent of the negative charge region is sufficiently small, then multiple stroke flashes will not be possible.

2-RADAR AND LIGHTNING OBSERVATIONS DURING CHUVA

The portable X-band polarimetric radar (Xpol) acquired for the CHUVA field experiment in Brazil was used in this study to identify and characterize a large number (>100) of incipient thunderstorms. The location of the radar on the UNIVAP campus in Sao Jose dos Campos with respect to the SPLMA and BrasilDat lightning sensors used in this field program is shown in Figure 1. Full radar volume scans were undertaken continuously every 4 minutes. Movies of the archived data were used to find initial radar echoes that evolved to thunderstorm stage as isolated convective cells.

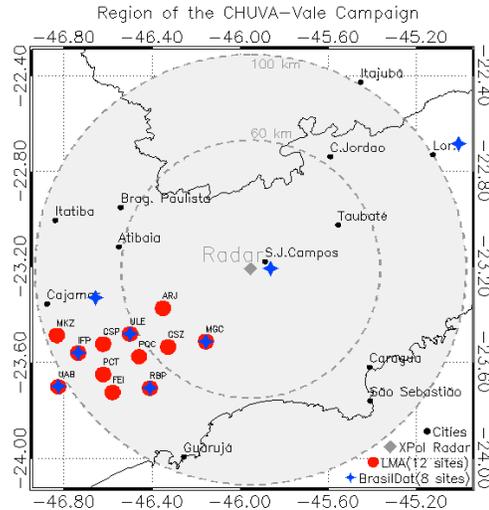


Figure 1 - Location of the XPOL radar in Sao Jose dos Campos, Brazil, together with the lightning sensor locations for SPLMA and BrasilDat networks used to characterize IC and CG lightning in incipient thunderstorms.

Two independent lightning detection networks were utilized to locate and characterize the initial intracloud and cloud-to-ground lightning flashes in these incipient thunderstorms during the CHUVA-Vale campaign. The SPLMA (Sao Paulo Lightning Mapping Array, set up and operated by NASA Marshall Space Flight Center, as discussed by Bailey et al., 2011, and shown in Figure 1) is a multi-station VHF time-of-arrival system whose station cluster is concentrated to the west south west of the X-band radar. VHF radiation sources associated with impulsive events, probably dominated by the negative leaders in both intracloud and cloud-to-ground lightning, are located three-dimensionally. The BrasilDat network for CHUVA-Vale (see also Figure 1), set up and operated by Earth Networks, is based on detections with a network of wideband flat plate electric field sensors. With this system, the times of lightning strokes (in both CG and IC flashes) can be determined accurately in time. The most typical behavior for the initial flashes in these specially selected storms is for the SPLMA sources to precede the BrasilDat stroke times for individual lightning flashes, consistent with the notion that bidirectional leader activity

precedes the return stroke in CG lightning flashes, as discussed in the Introduction.

3-RESULTS

Radar first echoes associated with developing moist convection were identified and followed in volume scan observations to the times of first intracloud flash and first cloud-to-ground flash for 74 incipient thunderstorms. In all cases, the initial lightning of the storm was intracloud, and was followed (with a mean time interval of 5 minutes) by the first cloud-to-ground flash. The XPOL radar data were examined in the PPI scan that most closely coincided with the 6 km MSL altitude at the time of the first ground flash, and the area covered by radar samples with 20 dBZ and greater in that scan was used as a proxy measure for the size of the negative charge region at that time. Those areas were equated with a circular area of radius R and the distribution of those storm radii are shown in histogram form in Figure 2. The mean radius is close to 5 km. Some radii are as small as 3 km.

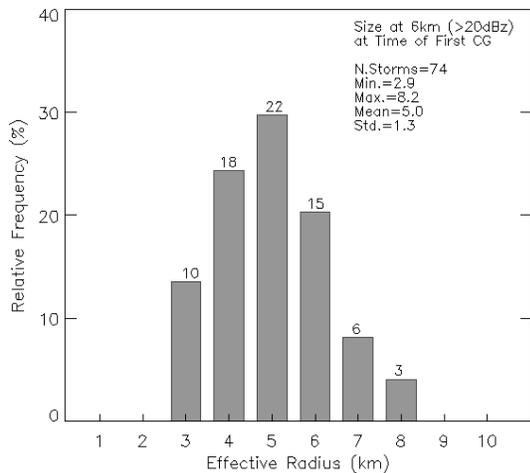


Figure 2 - Distribution of effective radii (km) associated with the >20 dBZ cell areas at 6 km altitude at the times of first cloud-to-ground lightning for 74 incipient thunderstorms. The XPOL radar observations were used for these estimates.

BrasilDat lightning data were used to determine the stroke multiplicity for all initial cloud-to-ground flashes in these developing storms. That

distribution of multiplicity is shown in Figure 3. No multiplicity greater than two was found, and the great majority (75%) of flashes showed single stroke behavior. To investigate the effects of increasing size on stroke multiplicity, the distribution of values was examined for the second cloud-to-ground lightning flash in the storms. Some flashes with multiplicities up to 5 were encountered (not shown). Further trends with time were not clear, maybe because the size of these storms did not increase a great deal following the initial lightning flashes.

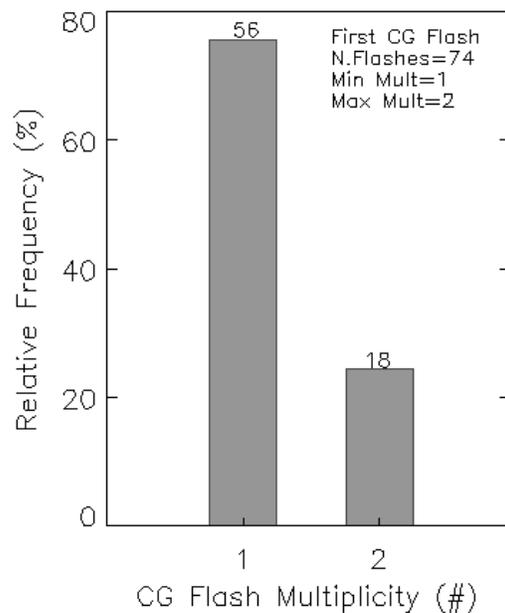


Figure 3 - Distribution of stroke multiplicities for all initial cloud-to-ground lightning flashes in the 74 incipient thunderstorms. BrasilDat observations were used for these determinations.

BrasilDat observations were also used to determine the distribution of interstroke intervals in the initial cloud-to-ground flashes in the incipient thunderstorms. That distribution of time intervals is shown in Figure 4. The mean interstroke time interval is 68 msec, similar to other results in storms that are less compact.

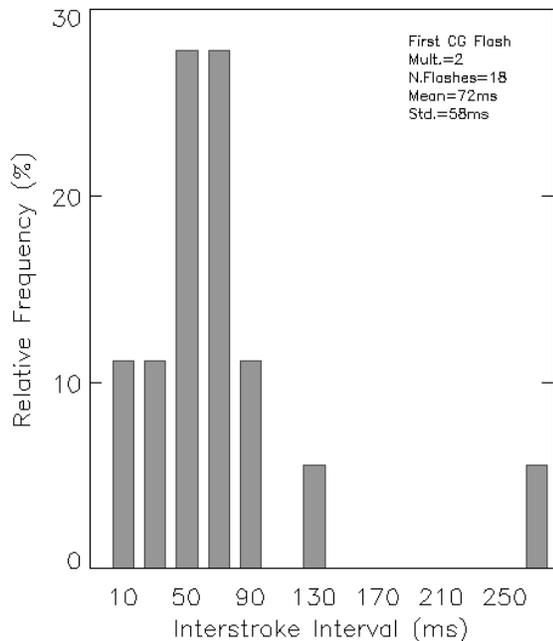


Figure 4 - Distribution of interstroke time intervals for initial multistroke cloud-to-ground lightning flashes in the set of 74 incipient thunderstorms. BrasilDat observations were used for these determinations.

4-DISCUSSION

The stroke multiplicities of lightning flashes in this special set of cloud-to-ground events in incipient thunderstorms differ markedly from those in earlier studies in which the storm size and horizontal extent of the main negative charge center were not controlled. Figure 5 summarizes results on a subset of results on stroke multiplicity in Florida (Rakov and Uman, 1990); in New Mexico (Kitagawa et al. 1962), in Kansas (Kitterman, 1980), and in Brazil (Saraiva, 2010), all of which involved multicellular thunderstorms and mesoscale activity. In the case of Kitterman (1980), multicellular squall lines were specifically targeted. In the case of Saraiva (2010) radar data were also used, but the character of the convection was mostly mesoscale and not isolated thunderstorms. Figure 5 shows that only in the case of the compact storms studied here is single-stroke lightning predominant.

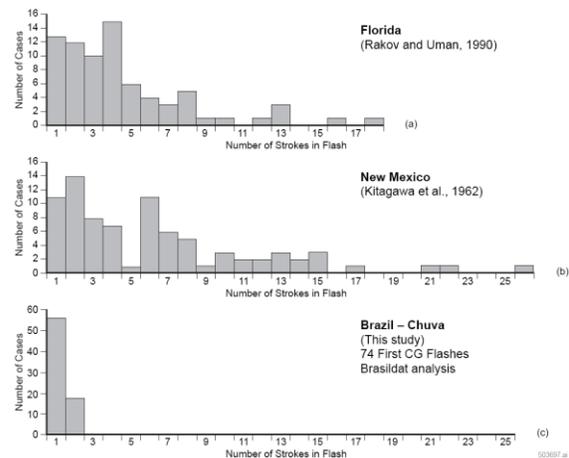


Figure 5 - Comparison of distributions of stroke multiplicity for cloud-to-ground lightning flashes in this and other previous studies. The predominance of stroke multiplicity =1 is unique to the present study.

In contrast with stroke multiplicity, the distribution of interstroke intervals for these compact storms is not markedly different than in the other studies, including Saba et al. (2006) already mentioned. If the horizontal extension speed of the positive leader is 5×10^4 m/s, then in a typical interstroke interval of 70 msec (consistent with the findings in Figure 4 for compact storms and with equation (1) from Saba et al. (2006) for storms with large stroke multiplicity), the leader will extend by 3.5 km. That distance is already an appreciable fraction of the estimated radius of the main negative charge region, based on the radar measurements in Figure 2. On that basis, compact cells may not be capable of supporting flashes to ground with multiplicities larger than 1 or 2. Based on the results of Saba et al. (2006) and Saraiva (2010), it is logical that one can measure the maximum horizontal extent of the negative charge region by counting the largest multiplicity exhibited by lightning in that system.

Schonland (1938) had suggested similar ideas in the context of his 'charge-pocket' explanation for multiple strokes in lightning, in writing: "The association of multiple strokes with large and extensive cloud masses is in accord with this suggestion, for the larger thunderclouds may be expected to possess several generating centers." The observations shown here support

the role for horizontal size in promoting multiplicity, but do not support the idea for distinct and separate charge centers, given the evidence for multiple strokes within the same contiguous radar echo at 6 km altitude in these incipient thunderstorms. It should also be noted that Schonland's original "junction streamer" idea to link the original channel with the charge pockets is unlikely to be occurring. The contemporary evidence for that assertion is that the main negative charge region is often devoid of the strong VHF radiation known to accompany the negative leaders which are fundamental players in his 1938 picture of multi-stroke flashes.

5-CONCLUSION

In incipient thunderstorms of minimum possible size (<10 km diameter), the time scale for leader progression in a typical interstroke interval is already comparable to or greater than the size of the main negative charge region, making multistroke flashes unlikely, consistent with observations noted here. Findings for incipient thunderstorms show marked contrast with findings for mesoscale convective systems with large horizontal extents (Kitterman, 1980; Saba et al., 2006; Saraiva, 2010) in which multiplicities of 10 and greater are exhibited. The finding here for compact storms is also consistent with the notion that the maximum number of strokes per flash can serve as a measure of the horizontal extent of the negative charge region in non-compact (i.e., mesoscale) thunderstorms (Saba et al., 2006; Saraiva, 2010).

6- ACKNOWLEDGEMENTS

This study was supported by a grant from Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) (2011/13673-8) that enabled the participation of the first author in CHUVA-Vale. The second author's work at MIT in this study was supported by FAPESP grant 2013/04292-6. We would also like to thank the CHUVA project, also supported by FAPESP with the grant 2009/15235-8. Discussions with NASA MSFC (Jeff Bailey, Richard Blakeslee and Steve Goodman) on SPLMA and Earth Networks (Stan Heckman) on BrasilDat results

are much appreciated. Discussions with Antonio Saraiva on a radar experiment in his doctoral thesis with a similar conceptual goal were also of great benefit to this study.

7- REFERENCES

Bailey, J. C., L. D. Carey, R. J. Blakeslee, S. J. Goodman, R. Albrecht, C. A. Morales, and O. Pinto Jr.,: São Paulo Lightning Mapping Array (SP-LMA): Deployment and plans. Proceedings, *XIV International Conference on Atmospheric Electricity*, Rio de Janeiro, RJ, ICAE, 1-4, 2011.

Brook, M., N. Kitagawa and E.J. Workman, Quantitative study of strokes and continuing currents in lightning discharges to ground, *J. Geophys. Res.*, 67, 649-659, 1962.

Heckman, S., Why does a lightning flash have multiple strokes? PhD thesis, Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, June, 1992, 134 pp.

Kitagawa, N., M. Brook, and E. J. Workman, Continuing currents in cloud-to-ground lightning discharges, *J. Geophys. Res.*, 67, 637-647, 1962.

Kitterman, C.G., Characteristics of lightning from frontal system thunderstorms, *J. Geophys. Res.*, 85, 5503-5505, doi:10.1029/JC085iC10p05503 , 1980.

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., An analysis of the electric field change produced by lightning, Vol. I and II, Report No. T-11, New Mexico Mining and Technology, Socorro, New Mexico, 1981.

Malan, D.J., *Physics of Lightning*, The English Universities Press, London, 1963.

Mazur, V. and L.H. Ruhnke, Common physical processes in natural and artificially triggered lightning, *J. Geophys. Res.*, 98, 12913-12930, 1993.

Rakov, V.A. and M.A. Uman, Some properties of negative cloud-to-ground lightning flashes versus stroke order, J. Geophys. Res., 95, 5447-5453, 1990.

Saba, M.M.F., M.G. Ballarotti and O. Pinto, Jr., Negative cloud-to-ground lightning properties from high-speed video observations, J. Geophys. Res., 111, 2006.

Saraiva, A.C.V., Study of the determinant aspects of the negative cloud-to-ground lightning parameters, Ph. D. Dissertation, INPE, Sao Jose dos Campos, Brazil, 2010.

Schonland, B.F.J., Progressive lightning IV—The discharge mechanism, Proc. Roy. Soc. London, Ser. A, A164, 132-150, 1938.

Williams, E. and S. Heckman, Polarity asymmetry in lightning leaders: The evolution of ideas on lightning behavior from strikes to aircraft, in *Lightning Hazards to Aircraft and Launchers*, Ed. P. Laroche, 2012.

Main author

Earle Williams

Parsons Laboratory

MIT

Cambridge, MA 02139 USA

Fax: 781-981-0732 Phone: 781-981-3744

Email: earlew@ll.mit.edu