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Estimates of recoil leader peak currents based on high-speed video observations

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***Abstract*— During the summer season of 2012, a network of high-speed cameras, called RAMMER network, recorded two bipolar flashes produced by a thunderstorm that occurred on March 13th. Data from BrasilDAT network provided location and peak current information for the events. Additional RAW data from the sensors, allowed more detailed analyses. Both bipolar flashes presented multiple negative return strokes, and there was intense recoil leader activity bellow cloud base. The objective of this work is the evaluation of the peak currents of those recoil leaders. The bipolar nature of these flashes allowed a unique way to calibrate the camera luminosity with the stroke peak currents estimated by the local lightning location system (LLS). Recoil leaders are commonly visible below cloud base during positive flashes development, but have not yet been observed during negative flashes in a similar fashion. The bipolar flashes observed had one positive return stroke and multiple negative return strokes that were used in the calibration process. In order to evaluate the recoil leaders peak current, the luminosity levels of each video were calibrated using the unsaturated pixel brightness levels during the negative return strokes and the data from the BrasilDAT LLS. The same high-speed camera used during the observation campaign was tested in laboratory to determine its CMOS sensor response curve. Through a scatter diagram of luminosity (estimated from the pixel intensity values) versus estimated peak current (provided by the BrasilDAT network), it was shown that both physical quantities are related. The calibrated pixel values were used to create equations to calculate the recoil leader peak currents. A total of 281 recoil leaders were identified, 191 in flash #1 and 90 in flash #2. Results show that recoil leader estimates are closely related to previous observations of cloud discharges by LLS. The geometric mean value was 1.06 kA, with a maximum of 7.7 kA. Less than 14% presented peak currents comparable to weak return strokes (> 2 kA).**

Keywords—recoil leaders; peak current estimates; high-speed videos; lightning location system; luminosity

I. INTRODUCTION

Recoil leaders, previously known in literature as K-changes or recoil streamers, were defined by Mazur [2002, p.1394] as “self-propagating discharges, moving along previously developed trails of the positively charged parts of bidirectional and zero-net charge leaders”. Originally observed in intracloud flashes through electric field sensors [e.g., Kitagawa and Kobayashi, 1959; Ogawa and Brook, 1964], it is a pivotal physical process in the current interpretation of the bipolar leader model of lightning initiation that was first proposed by Kasemir [1950, 1960]. Lightning observations in the VHF range [e.g., Shao et al., 1995; Rison et al., 1999] suggested that they are responsible for the initiation of subsequent strokes in negative lightning, and high-speed video records of downward positive leaders optically confirmed the definition of Mazur [2002] by showing that they propagate through branches previously ionized by the positive leader, moving towards the region where the leader originated [Saba et al., 2008]. When studying recoil leaders that occur in positive channels of upward lightning initiated in tall structures, Mazur and Ruhnke [2011] proposed that M components in negative cloud-to-ground flashes are initiated by in-cloud recoil leaders. From more recent optical observations by Mazur et al. [2013], evidence that recoil leaders develop bidirectionally were provided, suggesting that they are actually bipolar (with its negatively charged end propagating towards the main positive leader while its positively charged end progressed in the opposite direction) and not negative (as in the definition by Mazur [2002]). Additionally, Saraiva et al. [2014] presented high-speed video records in great detail of two bipolar cloud-to-ground flashes in which visible recoil leaders initiated the negative subsequent strokes.

In the present paper an attempt to estimate the peak current value of recoil leaders is made. The analysis is based on the relationship between the estimated peak currents of return strokes provided by BrasilDAT network and the pixel intensity of the associated frames recorded by a digital high-speed camera. The authors expect that this quantitative analysis will

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contribute to the current knowledge of the recoil leader process and characteristics.

II. Instrumentation and Data Description

During the summer of 2011/2012 the first lightning observation campaign of the RAMMER network (acronym in Portuguese for "Automatized multi-camera network to observe and study lighting" [Saraiva et al., 2011]) was conducted in São José dos Campos, SP, Brazil. The analysis presented in this paper will consist of data from one RAMMER station and the BrasilDAT network [Naccarato et al., 2012]. The next sections will present a brief description of the instruments used in this analysis.

A. RAMMER Network

The RAMMER network was developed at the Brazilian National Institute for Space Research, sponsored by FASPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo), beginning in late 2010. Each sensor consists of a high-speed camera, computer, GPS antenna, and some control circuitry. All equipment is stored in a weatherproof box, allowing it to be installed virtually anywhere.

The camera is a Phantom V9.1, manufactured by Vision Research, and was configured for video records of two-second duration at 2500 frames per second (fps) with a maximum exposure time of 390 µs (400 µs between frames). The spatial resolution of the videos was 1200 x 500 pixels, with 8-bit pixel depth (256 gray levels) and 60 dB of dynamic range. This set up generates a video file of about 3 GB, and requires about 2 minutes to be transferred from the camera to the computer. During these 2 minutes no other flash can be recorded. The lens used was an F-mount type, 18 – 56 mm (configure to 18 mm) and f3.5.

Two sensors were installed in São José dos Campos during that summer season and the operation began on November 30th, 2011, ending on March 30th, 2012.

B. Camera calibration

In order to obtain the desired correlation between pixel values from the camera frames and peak current values, the response curve of the camera sensor needed to be determined. A simple laboratory experiment was conducted, using a commercial dimmer, three 60 W lamps connected in parallel and a lux meter.

The camera and the lux meter were put in front of the set of lamps. The distance between them was determined by the ability of the camera in measuring minimum and maximum pixel values when the dimmer varies. As the dimmer is very imprecise, its variation was controlled by the luminous intensity values from the meter. Initially, the lux meter values were incremented by 10 lx and, at each increment, a video was recorded; using the same configuration when the flashes were recorded. Near the maximum, the dimmer became more imprecise, forcing higher increments, of 50 lx initially and, subsequently, 100 lx.

A total of 92 videos were recorded. The post-processing of those videos was done in IDL language. Several rectangular boxes were selected from the frames of the camera, selecting different areas. The mean values of the boxes over all frames of each video populated a table containing the video identification number, lux meter value and corresponding mean pixel values for each box. As expected, near saturation, each pixel value increment corresponds to a wider range of luminous flux per unit area. Figure 1 shows the calibration using one of the boxed areas, the abscissas correspond to pixel values and the ordinates to the luminosity provided by the lux meter. An exponential fit was applied to the data and the relationship between luminosity and pixel values for this test was:

$$L=32.268e^{0{,}0196P} \quad (1)$$

Where L is the luminosity in lux and P are pixel intensity values. The correlation coefficient R was calculated as 0.99.

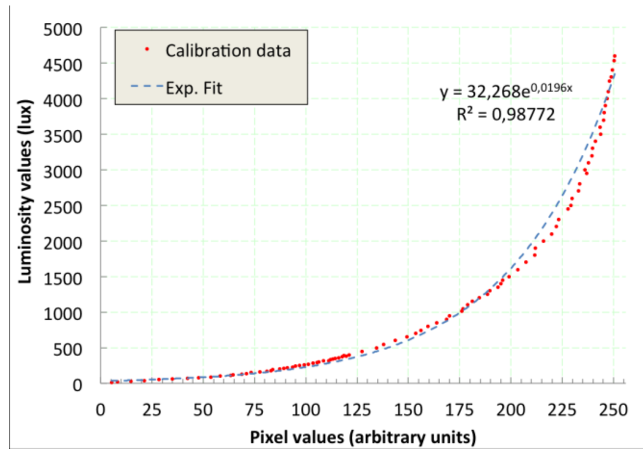

Fig. 1. Lab results from the camera calibration tests. Orange dots are the pixel values measured on the same rectangular area of the video frames. The dashed line is the exponential fit to the data.

C. BrasilDAT network

For the return strokes recorded by the high-speed cameras, some had their locations and peak currents estimated by the BrasilDAT network (EarthNetworks sensors) in operation during that summer. The LF-based networks provide estimates of location, time of occurrence and return stroke peak current. Waveforms of the sensor closest to the events were retrieved from EarthNetworks database, enabling us to recalculate peak currents more precisely and even estimate peak currents of strokes not detected operationally.

III. Data Analysis

During March 13th, 2012, several single and multicellular thunderstorms formed over the observation region (São Paulo metropolitan area and Vale do Paraíba), which led to the observation of unique events. Between 20:10 UT and 20:33 UT, the camera registered two bipolar cloud-to-ground (CG) flashes in a 3-minute interval, followed by 4 positive CG flashes. This behavior was never observed in that region during more than 10 years of high-speed camera observations. The camera observed no negative flash within this period, aside from the negative subsequent strokes in the bipolar CG flashes. All six flashes recorded presented intense recoil leader activity visible below cloud base with some of them also responsible for the formation of subsequent negative strokes in the bipolar CG cases.

This work aims to identify and estimate peak currents for recoil leaders, using a relationship between luminosity (recorded by the camera) and peak current. This relationship was already done by some authors (e.g., Wang et al. [2005], Zhou et al. [2013]) but its use is very limited to our dataset. First, there is no empirical equation that relates peak current and luminosity that could be used here, since each sensor has its own characteristics that must be taken into account when establishing the relationship. In our case, the relationship between luminosity and pixel values where done for one experiment only and are not valid for light sources far away from the camera. And finally, any rain shaft, humidity or anything that make the atmosphere opaque between the lightning and the camera would change that relationship, so a new ad hoc analysis is necessary for each event of interest.

The simpler solution to the problems discussed above would involve the direct comparison between peak current and pixel values, compensated by the calibration information. The peak current versus pixel values should be taken for the same event that produced the recoil leaders, to avoid weather and instrument variations that could compromise the validity of the relationship. There is, however, another issue. In order to find a good correlation between luminosity and pixel values for a single event, one should have several measurements of peak currents from that event. Recoils leaders below cloud base are observed in positive flashes, which have very low multiplicity, usually only one, thus making it almost impossible to have a reasonable amount of data. The solution came from the two unique events observed in March 13th; both were bipolar flashes presenting an intense recoil leader activity below cloud base and multiple strokes.

The first bipolar flash occurred at 20:10:50 (UT). The initial stroke had positive polarity, which was set up by a positive leader whose development was accompanied by a large number of recoil leaders clearly visible below cloud base. BrasilDAT provided a peak current estimate of +24 kA. It was followed by a continuing current of approximately 33 milliseconds and the estimated ground strike point was 44 km from the camera, as calculated by using the Lightning Location System (LLS) solutions and the GPS location of the observation site. After 168.4 ms, a sequence of recoil leaders generated the first subsequent stroke, of negative polarity, using the lower portion of the previous channel to ground. After that negative stroke, other three followed, totalizing 5 strokes in this flash. A combination of BrasilDAT locations and RAW data from its sensors allowed the proper identification of all strokes on that flash.

The second bipolar flash began at 20:13:46 (UT). It occurred approximately 3 minutes later than the first flash and, given the time taken to record, save and process the video file, the camera did not record any events in the period between the two events. Similar to the first bipolar flash, this one had a positive first stroke, with estimated ground contact (based on the camera records) at 20:13:45.905596 (UT) and was followed by fifteen subsequent negative strokes. Contrary to flash #1, the video record of the positive leader that produced the conductive path to ground showed very limited visible recoil activity below cloud base, possibly because of the larger distance from the camera. BrasilDAT estimated the striking point at approximately 47 km away from the camera. There was a persistence of the channel luminosity that lasted approximately 95 milliseconds, very close to the median value for the continuing current durations of positive strokes (97 ms, according to Saba et al. [2010]). The first negative stroke occurred 134.8 ms after the first stroke, with negative polarity, on a new location. The estimated ground contact was approximately 53 km away from the camera. A combination of BrasilDAT locations and RAW data from their sensors allowed the proper identification of 13 return strokes of that flash.

In order to maximize the information provided by the BrasilDAT sensors, the waveforms corresponding to both flashes were retrieved from the closest sensor to the flashes occurrence for a thorough evaluation. Most of the strokes that were not reported before by BrasilDAT were identified on the waveforms and had their E-field peak values used to estimate their corresponding peak currents. Figure 2 show the waveforms for all five strokes that compose flash #1; time t=0 represent the moment of the positive return stroke (20:10:50.943396 UT) and the subsequent time steps are presented in milliseconds. The waveforms also provide confirmation of the polarity change on the subsequent return strokes. Similar to the first flash, the waveforms related to the second were retrieved from a BrasilDAT sensor and waveforms for a selection of return strokes are displayed in Figure 3. Further details on this analysis are presented by Saraiva et al. [2014]. No recoil leader was identified during the RAW data analysis.

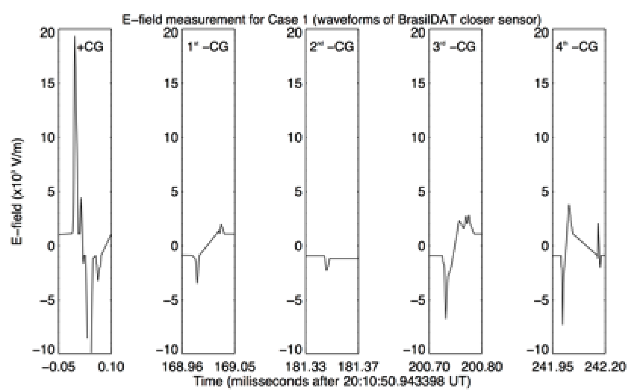

Fig. 2. Electric field waveforms extracted from the BrasilDAT sensor that was closest to Case 1 ground strike point. Each graph shows a few microseconds of data for each return stroke.

A. Photogrametric analysis of the videos

A photogrammetric analysis was conducted on the video data to extract pixel values corresponding to the return strokes luminous signature. It is well known that LF (low frequency) sensors measure the radiation from the lower portion of the lightning channel only, when it connects to the ground. To try emulating this feature, we analyzed also only the lower portion of the channel, close to ground, in the video records.

The pixel size, in meters, at the location of the strokes was estimated using some camera characteristics, such as: CMOS sensor size, focal distance, lens type, aperture size, etc. With the aperture angle of the camera and the distance to the return stroke estimated by the LLS, it was possible to evaluate the pixel size by using the same methodology applied in previous lightning leader studies [Saba et al., 2008; Campos et al., 2014]. A rectangular window box of 220 x 220 m was properly set close to the ground connection. The value of 220 m corresponds to the total width of the first stroke on flash #1 during its maximum intensity. The pixel values from within that box were extracted and averaged for each stroke of flash #1. This created a time series of pixel values. For flash #2, which produced two different ground contact points, two boxes were created over both regions, and two time series produced. The locations of the boxes on the video frames are shown in Figure 4. Finally, a table was created with stroke time information, pixel value and estimated peak current from BrasilDAT, for both flashes (Table I). It is important to notice that there is no reason to believe that negative or positive return strokes have different luminous signatures, and for that reason and for comparison purposes, any calculation from now on considers the absolute value of peak current only.

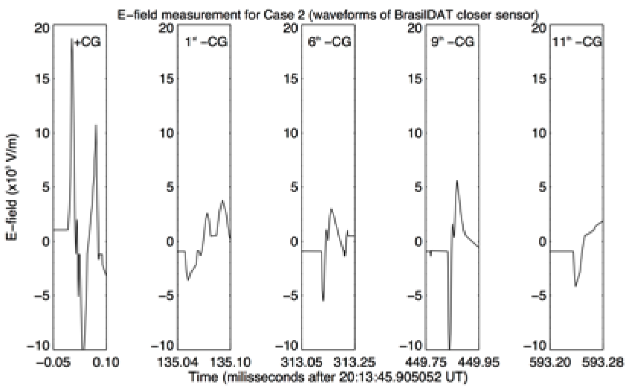

Fig. 3. Same as in Figure 2, but only some of the return stroke waveforms for Case 2 are shown. The positive stroke is the first graph, followed by the first negative CG, then the 6th, 9th and 11th –CGs.

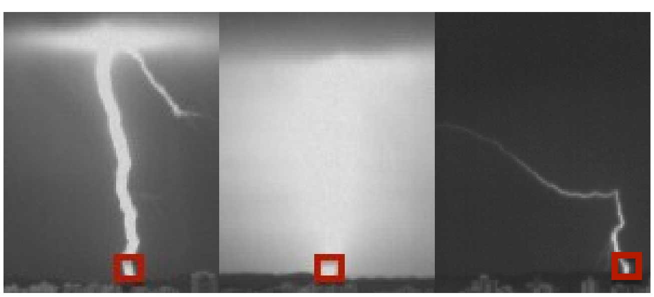

Fig. 4. Selected frames from all three ground contact points produced on the two bipolar CG flashes. The boxes in red are representations of the selected areas used to extract the pixel values.

B. *Luminosity vs peak current estimates*

Peak currents estimated by any LLS take into account the moment of maximum emitted radiation of the lightning stroke. From the high-speed videos, the frames considered in the analysis were the same that presented the maximum illumination from the return strokes. At the end, each stroke had a pair of pixel intensity values and peak current estimates. The result is shown in Figure 5, where the yellow triangles represent the data from flash #1, the orange square is the first stroke and the blue circles the subsequent strokes of flash #2. Peak currents from both flashes seem to follow a similar trend, but yellow triangles seem to have larger peak currents than the blue spheres when the average pixel intensity level increases. This effect is probably related to the striking point distance of those flashes from the camera. To properly relate pixel values with peak current, the data must be corrected by the response curve that was presented in Figure 1.

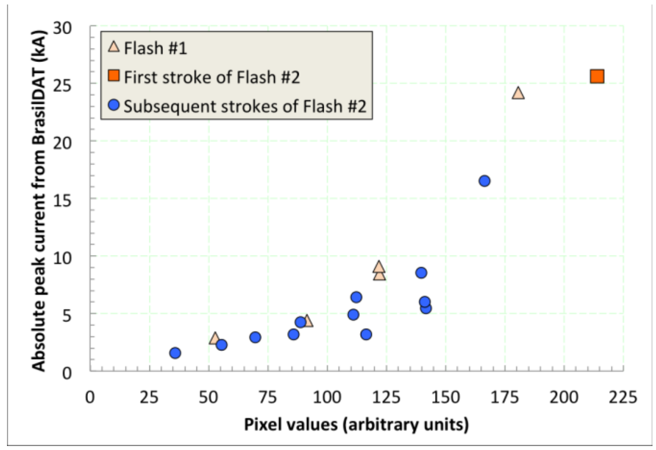

Fig. 5. Plot of pixel values *versus* the absolute of estimated peak current for both bipolar CG flashes. Yellow triangles represent flash #1, the square triangle is the first stroke (positive) on flash #2 and the blue dots are the subsequent strokes (negative) in flash #2.

The luminosity flux data was normalized with respect to its maximum value and plotted alongside the peak current estimates for both flashes. To match the normalized units, a factor was applied to the peak current estimates. If successfully done, the factor used in the peak current estimates could be used to find a proper relationship between pixel values and peak current valid for each event. The results are plotted in Figure 6. Using a scale factor of 0.011 to the peak current estimates in flash #1 and 0.017 in flash #2, it is possible to notice an agreement between the camera sensor response and the desired relationship between pixel values and peak current.

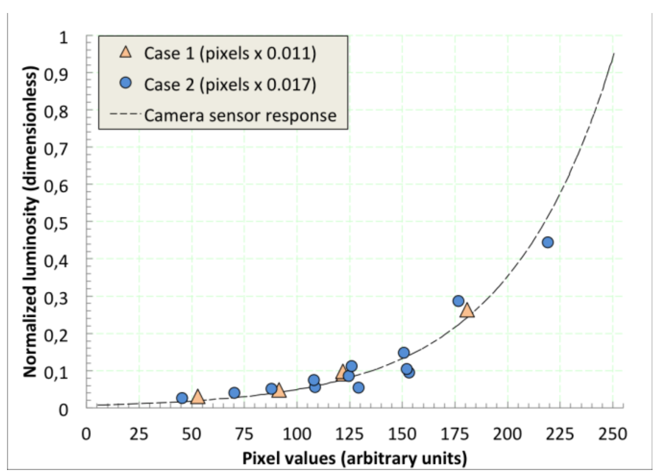

Fig. 6. Same as in Figure 5, but the peak currents were multiplied by a factor in order to fit the normalized luminosity from the calibration experiment.

Using the factors of Figure 6 in a modified Equation 1 (because the luminosity is now normalized), two new equations were established, relating peak currents and pixel intensity values for each bipolar CG flash. The equations are described below:

$$Ip_1= 0.64536e^{0,0196P_1} \quad (2)$$

$$Ip_2= 0.40335e^{0,0196P_2} \quad (3)$$

Where Ip_1 is the peak current for flash #1, Ip_2 is the peak current for the flash #2, and P_1 and P_2 are pixel values for flash #1 and flash #2, respectively.

To test the efficiency of the equations, all peak currents were recalculated and compared with the LLS estimates. The results are shown in Table I and plotted in Figure 7. A linear fit to the data showed that, in general, the calculated values mostly match the estimated ones by BrasilDAT. In Table I, the overall characteristics of both flashes are presented and, in the column called "Ip ratio", the ratio between the calculated and the estimated (BrasilDAT) values of peak current demonstrate the errors in the calculated peak currents are not greater than 40% and the average ratio is 0.78.

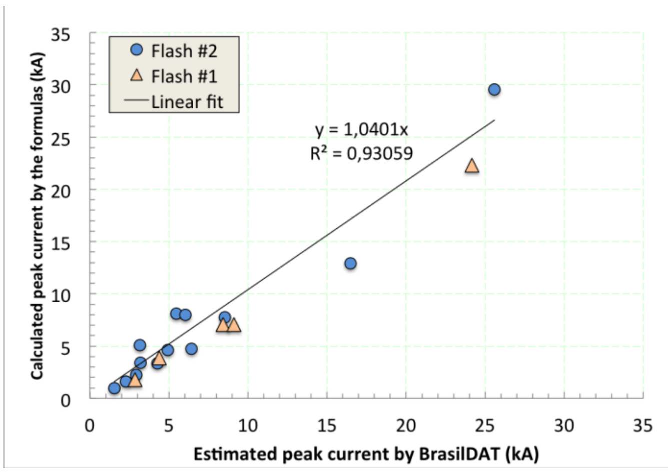

Fig. 7. Relationship between estimated peak currents by BrasilDAT and calculated peak currents using the Equations 2 and 3.

C. *Recoil leaders peak current estimates*

The main proposition of this paper is to obtain estimates of the peak currents of recoils leaders through the use of calibrated pixel values from the high-speed cameras. Figures 8 and 9 show integrated images of selected frames of flashes #1 and 2, respectively. In Figure 9, the frames were selected more carefully and the negative of their integration is shown to proper exhibit the weak recoil leader events. The calibration procedure was successfully done and two equations (one for each video) can be used to estimate the peak current of any lightning-related event during the duration of the videos. The recoil leaders whose peak current were estimated were assumed to be close to the return stroke in flash #1 and between the return strokes contact points in flash #2. Similarly to section III.B, a boxed area of 220 x 220 m around each recoil leader location was set and the pixels inside that box were averaged. Such configuration guarantees that the same total area was used to calculate the luminosity flux per unit area for all events.

A total of 281 recoil leaders were analyzed and their peak current estimated, 190 cases belonging to flash #1 and 91 to flash #2. There is no reason that justify the lower quantity of these events in flash #2, but it is probably related to the same unknown reason of why some positive leaders exhibit recoil leaders and others do not. The histogram of Figure 10 shows the distribution of peak currents for the events (bin size of 0.2 kA). It is clear that both distributions are similar, not only in shape, but also in terms of maximum and minimum values. This suggests that the less intense recoil leaders associated with flash #2 were not missed by the cameras, as the larger distance could have implied. The combined information of both flashes is displayed in Figure 11. The complete histogram has a log-normal shape similar to the distributions of return strokes peak currents.

As expected, the values of peak current of recoil leaders are very low, with some in the sub-kiloampère range. These values are also very similar to LLS estimates of intra-cloud peak currents detected in the USA by Cummins and Murphy [2009]. Only a few measurements (4) had peak currents comparable to weak return strokes (> 5kA). Values ranging from 2-5 kA are also not very common in the sample, only 34 cases, which represent 12% of the total. The geometric mean value of peak currents was 1.06 kA

Fig. 8. Integrated frames of flash #1. Several recoil leaders can be observed, but the weaker ones were also taken into account on the analysis.

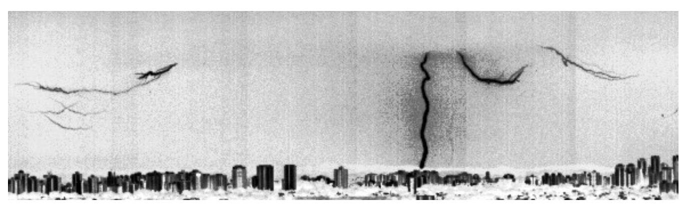

Fig. 9. Negative of the integraded frames of flash #2. To show the recoil leader activity, any bright frames were removed from the integration and the image was displayed in reverse colors.

IV. Concluding Remarks

In this paper, we estimated the peak current of recoil leaders occurred in two bipolar flashes from March 13th, 2012. These estimated values were only possible because the pixel intensity values were calibrated using the return strokes produced during the flash development. Due to the bipolar nature of the flashes and the relatively high stroke multiplicity on each video, there was a fair amount of pixel values/peak current pairs to establish a usable relationship. Those pairs were also adjusted to the CMOS sensor response to light in order to find a proper equation to calculate peak current from pixel values.

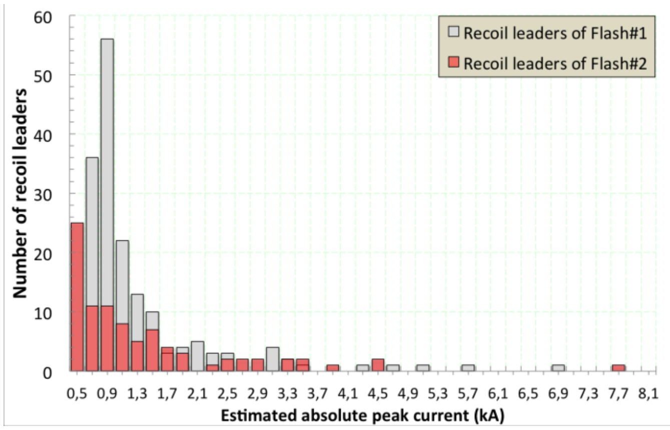

Fig. 10. Integrated frames of flash #1. Several recoil leaders can be observed, but the weaker ones were also taken into account on the analysis.

The calculation of peak currents for the return strokes showed that it is very reasonable to compare light emitted from the return stroke and peak current. The differences found between estimated (BrasilDAT) and calculated (from Equations 2 and 3) values are small, as seen in Table I, but they are probably related to the exposure time. If the return stroke happens within one frame only, the integrated luminosity will be different than the situation where the return stroke emission is split in two (or more) frames. Those small differences could be reduced with a higher frame rate. Also, the images are 8 bit (256 levels of gray) in a 60 dB dynamic range. Even with a very good dynamic range, a higher bit rate would improve the observations. However, in making those adjustments, one would lose the spatial resolution and increase in file size, consequently taking longer to transfer the data to the PC.

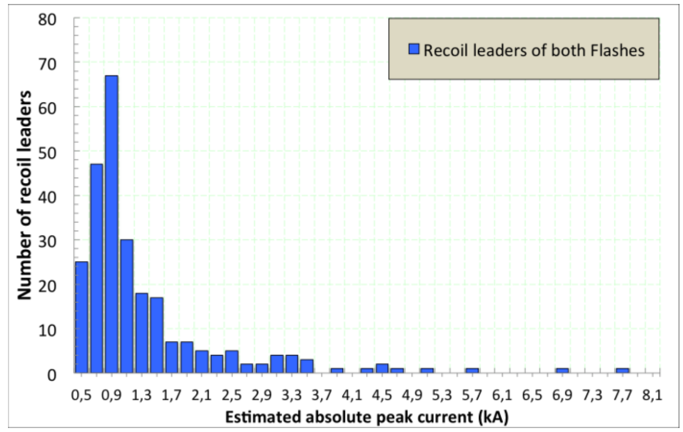

Fig. 11. Integrated frames of flash #1. Several recoil leaders can be observed, but the weaker ones were also taken into account on the analysis.

TABLE I. SUMMARY OF CHARACTERISTICS OF EACH RETURN STROKES PRESENTED IN FLASHES #1 AND #2. PIXEL VALUES WERE EXTRACTED FROM THE VIDEO CAMERAS AT THE TIME OF THE STROKE, IP (BRASILDAT) ARE THE ESTIMATED PEAK CURRENTS, IP (CALCULATED) ARE PEAK CURRENTS CALCULATED WITH THE RELATIONS PRESENTED IN THE TEXT. THE IP RATIO IS THE COMPARISON BETWEEN CALCULATED AND ESTIMATED PEAK CURRENTS.

Order	Time of occurrence (UT)	Pixel values	I_p (kA) *BrasilDAT*	I_p (kA)* *Calculated*	Ip Ratio *Calculated/BrasilDAT*
Flash #1					
Positive	20:10:50.944s (t = 0)	180.7	+24.2	22.28	0.92
1	51.113s (t = 168.4 ms)	91.52	–4.38	3.88	0.89
2	51.125s (t = 180.8 ms)	52.78	–2.87	1.82	0.63
3	51.144s (t = 200.0 ms)	122.2	–8.43	7.08	0.84
4	51.186s (t = 241.2 ms)	121.91	–9.11	7.04	0.77
Flash #2					
Positive	20:13:45.906s (t = 0)	213.85	+25.6	29.57	1.16
1	46.040s (t = 134.8 ms)	141.79	–5.47	8.11	1.48
2	46.059s (t = 153.6 ms)	116.44	–3.18	5.07	1.59
3	46.160s (t = 254.0 ms)	141.14	–6.03	7.97	1.32
4	46.170s (t = 264.8 ms)	24.27	-	0.74	-
5	46.184s (t = 278.0 ms)	69.59	–2.93	2.26	0.77
6	46.218s (t = 312.8 ms)	139.71	–8.55	7.75	0.91
7	46.244s (t = 338.4 ms)	85.92	–3.20	3.38	1.06
8	46.268s (t = 362.4 ms)	88.71	–4.27	3.35	0.79
9	46.355s (t = 449.6 ms)	166.52	–16.5	12.9	0.78
10	46.394s (t = 448.0 ms)	111.13	–4.92	4.62	0.94
11	46.498s (t = 592.8 ms)	112.35	–6.44	4.76	0.74
12	46.521s (t = 615.6 ms)	35.84	–1.55	0.98	0.63
13	46.553s (t = 647.6 ms)	55.41	–2.29	1.6	0.70
14	46.572s (t = 666.8 ms)	52.41	-	1.48	-
15	46.604s (t = 698.4 ms)	57.48	-	1.68	-

* Peak currents calculated from pixel values do not have polarity estimates.

The recoil leader peak current measurements displayed in Figures 10 and 11 show a similar behavior of, for example, negative CG stroke peak currents provided by any LLS. Histograms from both flashes agree in frequency, but it is too soon to assume that the behavior found here is common for the recoil leaders of all positive flashes, or only the positive flashes with visible recoil leaders below cloud base, or even if this is a typical behavior of recoil leaders that produce bipolar CG flashes. With these histograms agreeing well with peak currents from cloud discharges (e.g. Cummins and Murphy, 2009), it is natural to believe that a reasonable amount of cloud discharges reported by the LLS actually consists of intra-cloud recoil leaders. Even if cloud flashes dominate over CG flashes, it is natural to think that recoil leaders easily overcome the number of cloud flashes and are detectable by the LLS as they have detectable peak currents (as shown in this work). This assumption is also based on the amount of events registered in these two flashes. Only below cloud base, 281 recoil leaders were observed, produced in association with only two positive return strokes.

Equations 2 and 3 were responsible for the correlation between peak current and pixel values. In future works, data from luminosity decay rate with distance should be taken into account, as well as, parameters from the camera, in order to transform those two equations into an empirical formulae to calculate peak currents from high-speed video data.

The authors suggest that future observations should be tried with modern high-speed cameras, with higher frame rates without loosing spatial resolution. A CineMag system (very high speed hard drive) would aid in those recordings without missing temporally close events.

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