Location accuracy evaluation of lightning location systems using natural lightning flashes recorded by a network of high-speed cameras

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ABSTRACT: This work presents a preliminary method for the evaluation of location accuracy of all Lightning Location System (LLS) in operation in southeastern Brazil (e.g. BrasilDAT, RINDAT, StarNet, WWLLN, GLD360), using natural cloud-to-ground (CG) lightning flashes. This can be done through a multiple high-speed cameras network (RAMMER network) installed in the Paraiba Valley region – SP – Brazil. The RAMMER network (Automated Multi-camera Network for Monitoring and Study of Lightning) is composed by four high-speed cameras operating at 2,500 frames per second. Three stationary black-and-white (B&W) cameras were situated in the cities of São José dos Campos and Caçapava. A fourth color camera was mobile (installed in a car), but operated in a fixed location during the observation period, within the city of São José dos Campos. The average distance among cameras was 13 kilometers. Each RAMMER sensor position was determined so that the network can observe the same lightning flash from different angles and all recorded videos were GPS (Global Position System) time stamped, allowing comparisons of events between cameras and the LLS. The RAMMER sensor is basically composed by a computer, a Phantom high-speed camera version 9.1 and a GPS unit. The lightning cases analyzed in the present work were observed by at least two cameras, their position was visually triangulated and the results compared with BrasilDAT network, during the summer seasons of 2011/2012 and 2012/2013. The visual triangulation method is presented in details. The calibration procedure showed an accuracy of 9 meters between the accurate GPS position of the object triangulated and the result from the visual triangulation method. Lightning return stroke positions, estimated with the visual triangulation method, were compared with LLS locations. Differences between solutions were not greater than 1.8 km.

INTRODUCTION

Detection Efficiency (DE) and Location Accuracy (LA) are the main parameters to analyze the performance of a lightning location system [Cummins et al., 1998; Bouscheidt, 2012]. The detection efficiency of the local lightning location system for the region of the Paraíba Valley (city of São José dos Campos and neighboring cities) was studied by the Atmospheric Electricity Group at the National Institute for Space Research (ELAT/INPE – Grupo de Eletricidade Atmosférica do Instituto Nacional de Pesquisas Espaciais), [Naccarato, 2006; Naccarato et al., 2009; Bourscheidt et al., 2012; Bourscheidt, 2012],

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addressing one of the main factors in the performance evaluation for the local lightning detection network.

Only one unpublished work done by Solorzano [2003] verified the flash location accuracy at the same region using rocket-triggered lightning; this technique has been used to evaluate lightning location systems [Jerauld et al., 2005; Nag et al., 2011; Mallik et al., 2014]. Solorzano work verified the lightning location accuracy for the Lightning Location System (LLS) named RINDAT (Portuguese acronym for National Integrated Network of Atmospheric Discharges). RINDAT network is composed by Vaisala sensors.

After the implementation of the LLS named BrasilDAT (Brazilian Total Lightning Network, composed by 48 sensors developed and manufactured by EarthNetworks) at the Paraíba Valley Naccarato et al. [2012], showed that the average location error by the BrasilDAT network was 362 m through the evaluation of 14 upward lightning events in the Jaragua's Peak situated approximately 100 kilometers from the city of Sao Jose dos Campos.. No further study for location accuracy was conducted using either upward lightning or natural cloud-to-ground (CG) lightning. This work aims to fill a gap in the evaluation of location accuracy using natural CG lightning in the Paraiba Valley region.

Many studies were done by ELAT-INPE using high-speed cameras [Ballarotti et al., 2005, 2012; Campos and Saba, 2013; Campos et al., 2007, 2009, 2014a, 2014b; Ferro et al., 2009, 2012; Saba et al., 2006a, 2006b, 2008, 2009, 2010, 2013; Saraiva et al., 2013]. In 2011 it was installed the RAMMER network (Portuguese acronym to Automated Multi-camera Network for Monitoring and Study of Lightning) in the cities of São José dos Campos and Caçapava, both of them located in Paraiba Valley. The RAMMER network is composed of four high-speed and high-resolution cameras that enable the observation of thunderstorms from different angles, providing a better statistic characterization of the lightning flashes in the same thunderstorm.

The previous analysis of lightning location accuracy using standard camera images was done by Idone et al. [1998] for the NLDN (National Lightning Detection Network) in the vicinity of Albany, New York State – USA. In the Idone et al. (1998) study it was possible to obtain a mean location accuracy of 484 meters before the network upgrade in 1995 [Cummins et al., 1998].

Observing a same flash from different angles using the RAMMER network made possible the determination of the ground strike point of the lightning return strokes. The method proposed here presented very good location accuracy for a validation case (the error between the object location and the solution by the proposed method was 9 meters). The precision of the image method allowed an evaluation of precision the solutions provided by BrasilDAT. At the moment, no other LLS were evaluated.

The present work use images to determine the location of the ground strike point of natural cloud-to-ground lightning like Idone et al. [1998]. However, it presents a new methodology developed specifically for this study, described in greater details in the upcoming Methodology section.

INSTRUMENTATION

RAMMER Network

The RAMMER network is composed of one mobile color camera and three fixed cameras separated by distances of 13 kilometers in average. They were located in the Paraiba Valley (in the cities of São José dos Campos and Caçapava, centered in the former), SP, Brazil. This configuration allowed RAMMER to see the same thunderstorm from different angles and register the some lightning flashes simultaneously by multiple cameras.

Each RAMMER sensor is composed by a triggering system and a Phantom high-speed camera version 9.1, which is set to operate at a frame rate of 2,500 frames per second with a lens Nikkor (model AF-S DX 18-55 mm 1:3.5 – 5.6 G in the stationary sensors, and a lens model AF-S ED 24 mm – 1:1.4 in the mobile sensor). All videos were GPS (Global Positioning System) time stamped. The sensors R1, R2 and R3 are black and white cameras and the sensor RM is a colored camera. The camera lenses have about 37 degree to the field-of-view and have no distortion in the images formed by them. Figure 1 shows their relative positions.

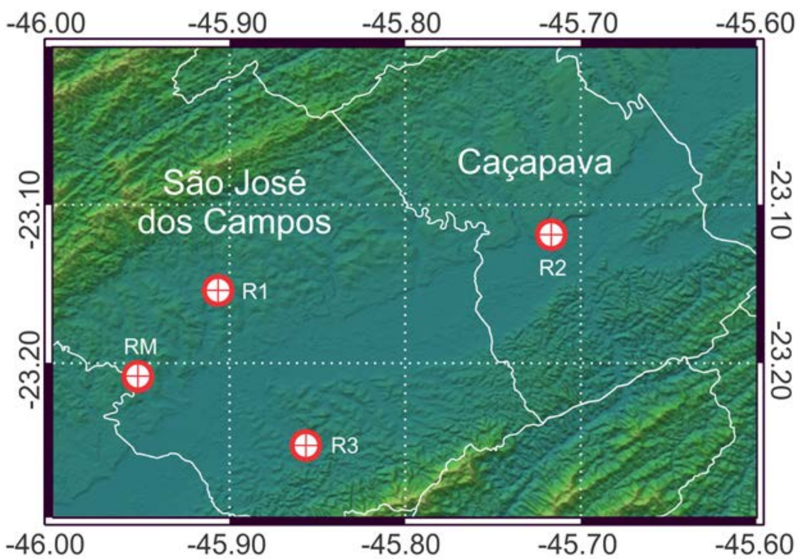

Figure 1 – Location of the RAMMER sensors in the cities of Sao Jose dos Campos and Caçapava and topography of the region. R1, R2 and R3 are fixed, black-and-white sensors. RM is a colored sensor installed in a car that operated in the marked spot.

BrasilDAT Lightning Location System

The lightning detection system called BrasilDAT started its operation on December of 2010. This network is composed by 56 EarthNetworks sensors (EarthNetworks Total Lightning System) distributed throughout Brazil, except in the Amazon region [Naccarato et al., 2012]. Figure 2 shows the distribution of the BrasilDAT sensors around the Paraiba Valley Region, the sensors in this region are completely installed and fully operational.

The each sensor that integrate the BrasilDAT network use the time-of-arrival (TOA) technique, synchronized by GPS timing operating in the frequency range between 1 Hz and 12 MHz, where it is possible to determine the location of an individual lightning discharges (return strokes). The verybroad operating frequency range of these sensors makes it possible to detect both of cloud-to-ground and intra-cloud discharges; the system differentiates these discharges through the waveforms registered by the sensors [Naccaratto et al., 2012].

Also according Naccarato et al. [2012], some theoretical calculations show that BrasilDAT has a detection efficiency of 50 - 60% for intra-cloud discharges and 85 - 90% for cloud-to-ground discharges, with an estimated location accuracy of about 500 meters to the Southeastern Brazil.

Figure 2 – Map of BrasilDAT sensors. The green diamonds represents sensors installed and operational and the red diamonds represents sensors that will be installed before the end of 2014.
Source: Naccarato et al. [2012]

METHODOLOGY

Lightning Location using multiple images

The methodology of cloud-to-ground flash location (the point that the lightning strikes the ground) is described in this section. This method uses data provided by two RAMMER sensor to obtain the location solution. The two sensors are called sensor 1 and sensor 2 without loss of generality.

In order to facilitate the understanding of the method, two domains were defined: spatial domain and image domain. In this work, always that is cited the image domain, we are referring to any proprieties or object in the image obtained by the camera sensor. Also, when in this text it is said that something is located in the spatial domain it means that it is geographically located. For example, point P (tip of the red arrow) in the Figure 3 has its geographic coordinate known and is in the spatial domain, but this point is represented in the image domain by the projection of the point P in the camera sensor resulting in the point P'.

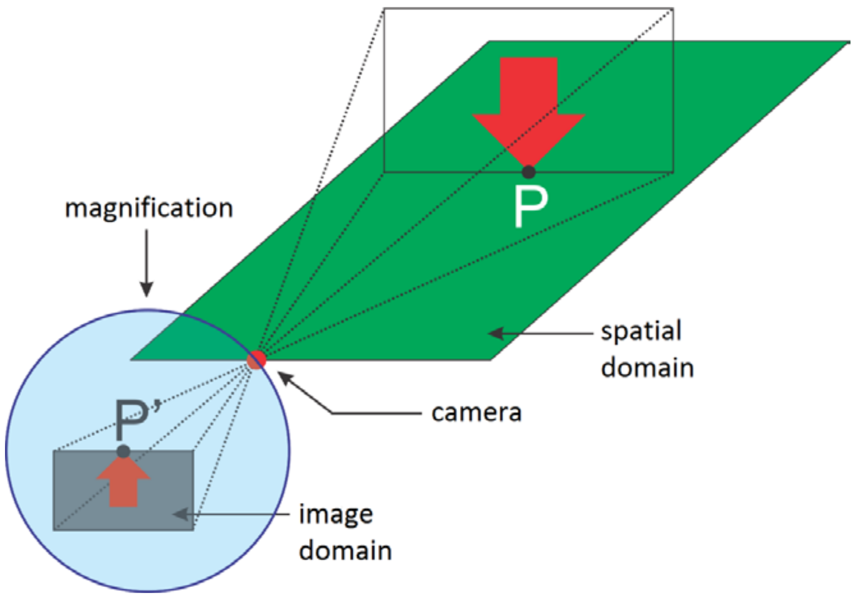

Figure 3 – Representation of the spatial and image domains for the observation of point P by the camera. The blue circle shows the magnification of the image formation by the camera and lens.

Without loss of generality, we may consider a rotation a 180-degree in the image domain, resulting in its alignment n the same orientation of the observed scenario, as shown in Figure 4. In the sequence of the text, every time that the image domain is mentioned we are referring to the "rotated image domain" (yellow surface in Figure 4).

In Figure 4, point P' is the projection of point P (spatial domain) in the camera sensor and, without loss of generality, we determine that point P'' is the 180-degree rotation around the point determined by the intersection of the beams of light from the object (point P). The blue circle in Figures 3 and 4 indicates that we have an exaggeration in the image dimensions in order to show the geometrical construction of the much smaller part of the camera in greater detail. In other words, all objects within the blue circle have much smaller dimensions than the distance between the camera and an object.

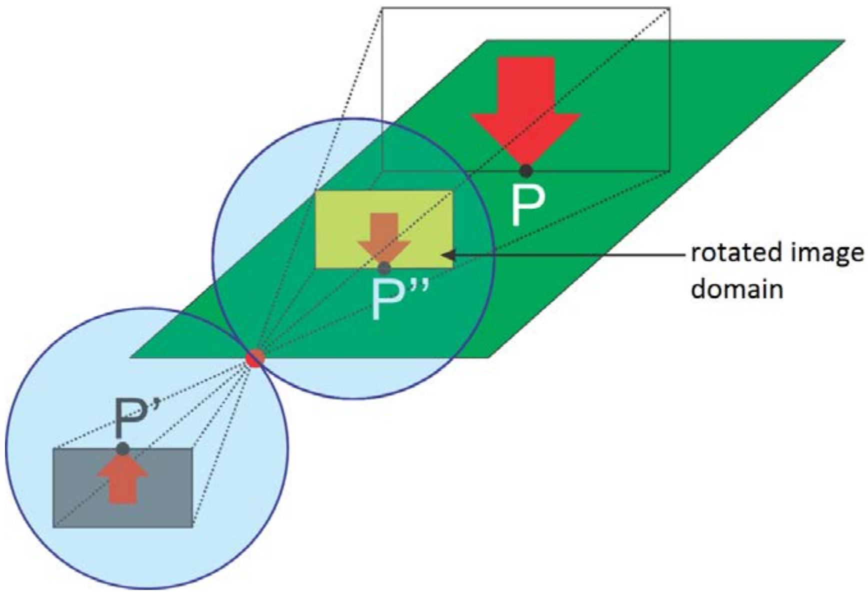

Figure 4 – Rotated image domain (yellow plane) with point P'' that resulted from a 180-degree rotation around the point determined by the intersection of the light beams from the object (point P). The blue circles represent a magnification as in Figure 3.

To each image (image domain) registered by a RAMMER network sensor we determine some points called control points. These control points can be buildings, towers or trees that were used to obtain their geographical coordinates (spatial domain). Next, it was possible to relate the horizontal location of a pixel in the image with the geographic coordinates of the control point, i.e., establish a relationship between the spatial and the image domains. For each control point the following information are determined: latitude and longitude related the spatial domain and horizontal pixel location of the center of the control point referring to the image domain, as shown in Figure 5. The solid red arrows indicate the control points observed from the R1 sensor (camera installed in the Vanguard TV tower in São José dos Campos) and the yellow arrow indicates the location of the discharge to be located.

For the control points (red arrows in Figure 5), the coordinates are known in both the spatial domain (latitude and longitude) and in the image domain (horizontal pixel position). However, for the lightning ground strike point (lightning location), indicated by the yellow narrow in Figure 5, initially only the location in image domain can be determined. This methodology aims to determine the lightning location in the spatial domain from that information.

Figure 5 – Selected frame of a lightning flash registered by the R1 RAMMER sensor. The red arrows indicates the control points that were used for this case and the yellow arrow indicates the lightning stroke location in the image domain.

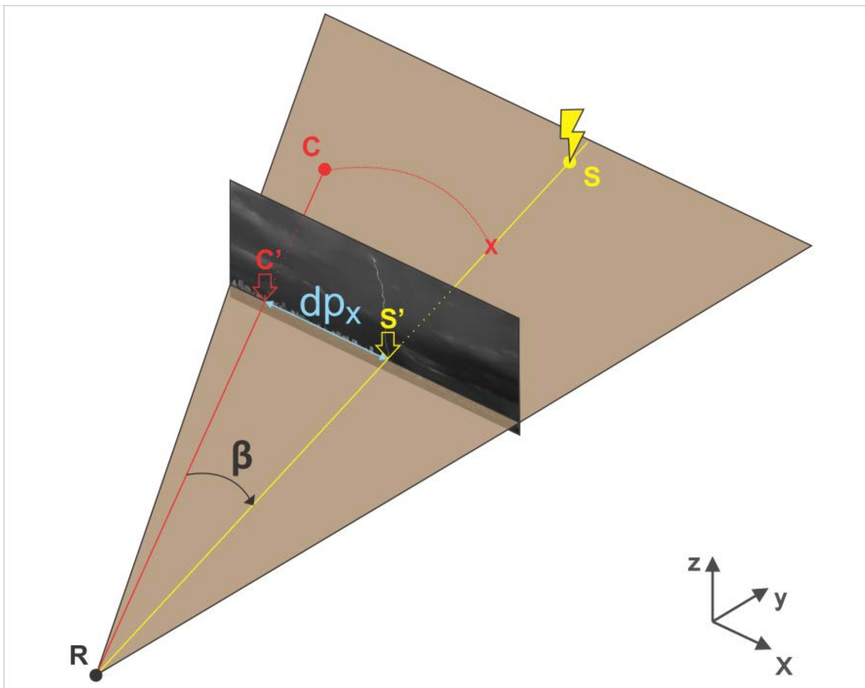

Figure 6 – The ralation between spatial and image domains representing the rotatation of the control point (C) by the angle β, where β is obtained by the pixel distance between the points C'and S, the control point and the discharge location in the image domain, respectivelly. The points X (rotated point) and R (camera location) determine the direction of the discharge S. Point S' in the image domain is the lightning location and the horizontal distance (in pixel) between the points C' amd S' is dp_x value.

Through laboratory calibration and confirmation with the use of control points in the analyzed dataset, it was possible to verify that the angle per pixel relation is approximately constant in all extension of the camera sensors and valid both in the camera black and white and color camera.

The calibration of the camera showed that the angle/pixel relation is constant and by knowing the location of the control points and flash location in the image domain it is possible to determine the angle (β) between the control point C' and point S', considering the camera location (represented by point R in Figure 6) as the vertex. Therefore, the straight line determined by the geographical coordinates of the control points and the camera (both in the spatial domain) can be rotated in β degrees around point R, establishing the yellow line that indicate the direction of the flash location in the spatial domain.

By appling a rotation in point C (spatial domain) around point R (camera) of angle β, point X can be obtained (as shown in the Figure 6). Then points R and X in the spatial domain determine the direction of the stroke for a camera. This algorithm is repeated to the other camera so that two lines that intersect in a point are determined. The intersection point of these two lines is the location solution for the discharge in the spatial domain and this value is compared with the solution provided by the LLS being evaluated in this study (BrasilDAT).

Until now, the algorithm was present considering just one control point for each camera, but the case studies presented here had more than one control points analyzed. In the analyses for each image domain (i. e. for each sensor) were considered the maximum numbers of control points as possible with the goal of introduce more accuracy in the location of the flash by this method. If one control point has an location error, the final result will be inacurated determined. This will not occur if several control points are used, since the error of one of them will be greatly diminished accordingly to the total point used.

Based on the method proposed above, three other methods were developed to find the best fit of the final location using multiple control points in each image domain these three methods are named: (i) location solution by image using the average, (ii) location solution by image using the median and (iii) location solution by image using the linear fit. The following describes each method:

(i) Location solution by image using the average

Figure 6 presents only one control point, but in practical cases we have as many control points as we can get to construct any rotated (as described previously) point for each sensor.

Assuming that one sensor (generally called of sensor 1) has *n* control points and that another (sensor 2) has *m* control points, we obtain *n* straight lines for the sensor 1 and *m* lines for the sensor 2, where each line is given by each control point in the sensor as previously described.

In the average method, a two-by-two combination is done, in other words, for each line in sensor 1, we obtain a point of intersection with a line in the sensor 2. In the text example where sensor 1 and sensor 2 have respectively *n* and *m* control points, we have *m*x*n* solutions by the two-by-two combination, this is called a solution set.

In order to determine the final solution in this method the averages for the latitude and longitude values are calculated.

(ii) Location solution by image using the median

The solution obtained through this method is similar to the previous one (i), except for the calculation of the final solution, which is done with the median of the latitude and longitude values in the solution set, instead of using a simple average.

(iii) Location solution by image using the linear fit

Analogously to method (i) we have the rotated control points for each sensor. A straight line is then defined by a linear fit using the Least Squares Method over the rotated points from each camera, where the boundary condition is that the straight line pass through the respective camera point (spatial domain). The intersection between these two lines determine the final solution for this method.

Figures 7 and 8 represent the solution by each method to the validation case.

Dataset

The dataset analyzed in the present work was obtained by two cameras and compared with BrasilDAT during three thunderstorm days in the summer of 2011/2012 and 2012/2013. Five different natural CG flashes were analyzed, one flash occurs on February 18th, 2013, two on February 19th, 2013, and two on March 13th, 2012. They are summarized in Table 1, which shows each stroke and the referred case name.

Table 1 – Reference to the dataset

Date	Flash Number	Stroke Number	Case Name
February 18th, 2013	Flash #1	Stroke #1	1
February 19th, 2013	Flash #2	Stroke #1	2
	Flash #3	Stroke #1	3.1
		Stroke #2	3.2
		Stroke #3	3.3
		Stroke #4	3.4
March 12th, 2012	Flash #4	Stroke #1	4.1
		Stroke #2	4.2
	Flash #5	Stroke #1	5

The five flashes allowed the analysis of nine strokes (five different return stroke channels). The lightning flash that occurred in February 19th, 2013 had three strokes detected by the location system and the one flash that occurred on March 12th, 2013 had two strokes detected, while the other ones have one stroke detected for each.

The analysis was done only for strokes that were detected by the local lightning location system, because of the comparison purpose of this work.

RESULTS

Validation Case

For the validation of the image based lightning location method proposed in this work, the image method was applied in a case of study where a building was in the field-of-view for two locally separated high-speed cameras. The image method was completely applied as if the building was a lightning discharge to be located.

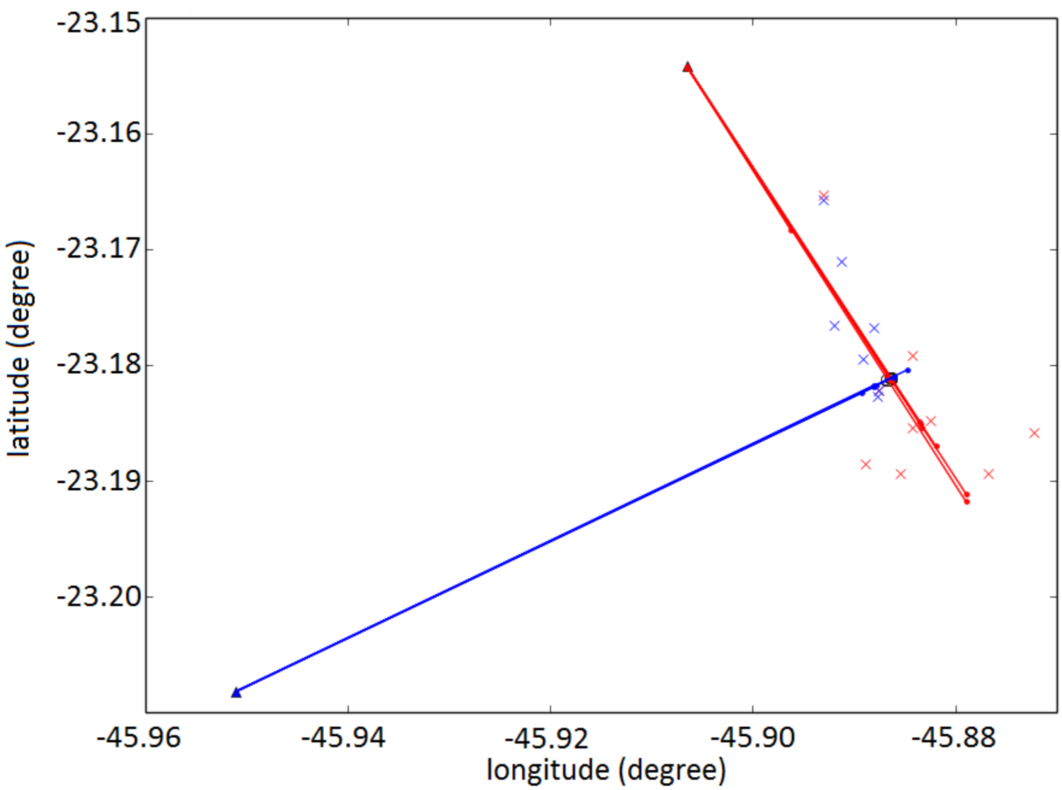

Figure 7 – Spatial domain for the validation case. The X points are the control points for each camera represented by the triangle with the same color. The blue line segment were determined by the RM camera and the rotated control points. Similarly, the red line segment is related with the R1 camera.

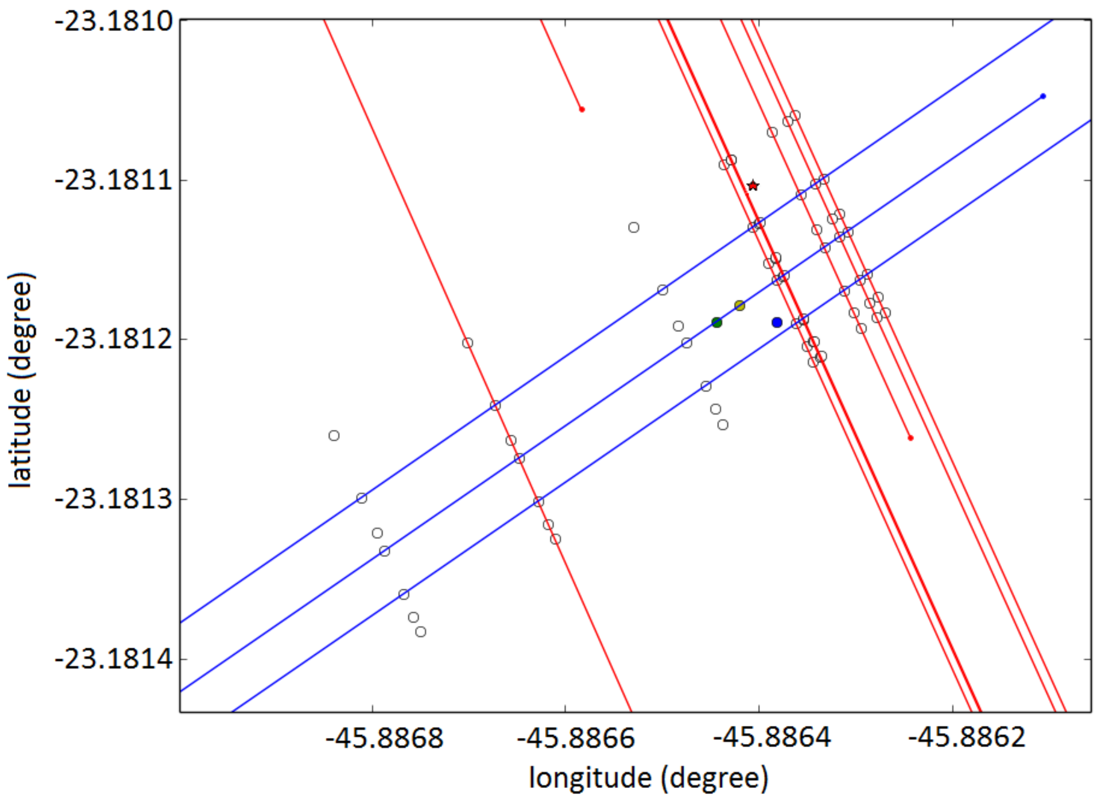

Figure 8 – Zoom into Figure 7. White circles represent the solution set. The red star is the object actual location, the green circle is the solution provided by the average method, the blue circle was estimated by the median method and the yellow circle was found by the linear fit method. The distance between the object actual position and each of the solutions are, respectively, 10, 9 and 8 meters.

The difference between the location obtained by the image method and the real building location (obtained by GPS) was 10, 9 and 8 meters, respectively, for the image method using the average, median and linear fit. Figure 7 shows the spatial domain of the validation case.

Therefore the location accuracy measured in this case study is of the order of magnitude of the object itself which shows the location of the image method is valid for application to real cases of natural discharges.

Lightning Cases

Nine strokes of natural CG lightning flashes (five distinct return strokes, i.e., in different positions) were analyzed and their ground strike locations were determined by the image method. In these nine cases it was possible strike point location because control points could be determined and the strokes were also located by BrasilDAT.

Table 2 shows the location provided by BrasilDAT and the difference (in meters) from the BrasilDAT solution to the image method location. The table also shows the peak current and the classification obtained by the system.

Table 2 – System solutions and location error for each method

Case Name	System solution				Error Distances (meters)		
	classification	latitude	longitude	Ip (kA)	average	median	linear fit
1	CG	-23.3441	-45.9347	-29	210	207	56
2	CG	-23.2730	-46.0062	-25	144	220	43
3.1	IC	-23.2195	-45.8507	-8	996	938	1044
3.2	IC	-23.2192	-45.8471	-50	1037	979	989
3.3	IC	-23.2161	-45.8647	-13	1545	1533	1798
3.4	CG	-23.2233	-45.8497	-16	1421	1363	1442
4.1	CG	-23.2652	-45.8287	-11	67	89	48
4.2	CG	-23.2697	-45.8340	-18	718	719	739
5	CG	-23.2399	-45.8154	-14	694	665	236

Considering a unique average error for each lightning flash we have the results presented in Table 3. Although some differences between methods is found, the overall analysis showed that all three methods share an average distance from BrasilDAT locations of the order of 500 meters, similar to the results of Naccarato et al. [2012].

Table 3 – Return stroke location error by each method

Case Name	Error Distances		
	average	median	linear fit
1	210	207	56
2	144	220	43
Average for 3	1249.75	1203.25	1318.25
Average for 4	392.5	404	393.5
5	694	665	236
Final average	538.05	539.85	409.35

CONCLUSIONS

The method was able to reproduce with good accuracy the location of natural CG lightning striking points by using two cameras located at different places. Assuming that the error of this method is in the order of tens of meters, the average location error of the BrasilDAT was about 500 meters, close to the values reported by Naccarato et al. [2012] obtained by theoretical calculations.

The method proposed in this paper presents some advantages in determining the location of the lightning discharge, such as the ability to determine the location independently of the peak current and the possibility of determine an unique location for strokes in the same channel, because in LLS based the use of the electromagnetic waves provides different solutions for those strokes, even if these solutions are close. Another advantage of the proposed method is the fact that it can distinguish strokes of a same flash, even if they occur closeby.

The disadvantage of the image method using data without the accurate inclination and azimuth of the camera, as in this case, is the necessity of identifying buildings, towers, trees, etc. (control points) in the image of each camera, that is not possible when recording in low light conditions. A possible alternative for that limitation is the total fixation of all cameras in their observation sites, allowing us to use precise fixed values of azimuth and inclination for all observed events.

This work is a preliminary analysis; in the future we will apply this method not only to other cases whose data have already been obtained but also for those that will be recorded in new data collection campaigns so that representative statistics of the location accuracy, detection efficiency and discharges classification (in either cloud-to-ground or intra-cloud) can be made.

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