Study of lightning channel through 3D reconstruction images: a case study

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ABSTRACT: Forty-three lightning flashes were observed, during the summers from 2010 to 2013, in the urban area of São Bernardo do Campo, São Paulo. The 10 thunderstorms were monitoring simultaneously by a stereo system, E-field measurement and BrasilDat network. Several images of tortuous flashes were observed to identify the real tortuosity of the channel. The positive cloud-to-ground lightning flashes presented longer horizontal and transversal displacements than the negative cloud-to-ground flashes. Cases of stepped leader and its respective return stroke were observed on stereo vision identifying the main channel used by return stroke. Long horizontal and transversal channels were observed on looping events. Most electromagnetic models and studies of stepped leader propagation do not consider the real lightning flashes tortuosity. So, the application of stereo vision on lightning flashes images can come up with details of the real lightning flashes tortuosity as well as clarify looping events.

INTRODUCTION

Many studies based on laboratory experiments, photographs and simulations have presented characteristics of lightning flashes tortuosity and their branching [Amarasingle et al. 2007, Bazelyne and Raise, 2000, Hill 1968, 1988, Idone and Orville 1988, Kochkin et al. 2014, Mansell et al. 2002, Vargas and Torres 2008a, 2008b]. The most of electromagnetic models and the studies of return stroke fields and stepped leader propagation have represented the lightning flashes as a vertical channel [Rakov and Uman 2003], ignoring their real tortuosity. Recent studies have described the effects of lightning channel tortuosity and branching on measurements of electromagnetic fields and induced voltages. These effects can interfere on electrical distribution networks and errors in lightning locating systems [Andreotti et al. 2011, Chia and Liew 2008, Guo and Zhou 2009, Juan et al. 2013, Lupo et al.2000, Meredith et al. 2010, Peer and Kendl 2010, Saito et al. 2011, Vargas and Torres 2008a, 2008b, Zhao and Zhang, 2009]. Thus, the current studies present the importance of inclusion the real geometry of the lightning channel on the flash propagation models [Kong et al. 2008, Qie and Kong 2007, Vargas and Torres 2008a, 2008b]. The application of stereo vision in lightning flashes images can come up more details of the real lightning flashes tortuosity as well as clarify looping events.

The lightning channel tortuosity is associated with characteristics of stepped leader propagation. The stepped leader progressions define the branching on lightning flashes and identify the charge structures in thunderstorms [Aleksandrov et al. 2005, Mazur and Ruhnke 1998, Nag and Rakov 2009, Qie et al. 2005a, 2005b, Williams 1989, Zheng et al. 2010]. There are two conceptual models of the leader channel for cloud-to-ground lightning flashes (CG). The first concept described by Schonland [1938], considers the unipolar and unidirectional leader channel, originated from the charge center of the cloud, moving toward ground and transferring electrical charges from the cloud to the leader channel. This concept has been dismissed by many authors because there is no study which proves the electrical charges transfer from the cloud to the leader channel. The second concept, and more accepted by authors, considers the bipolar and bidirectional leader moving to opposite directions, in which, the negative channel propagates toward ground while the positive channel moves into the cloud. The deposited charge on each leader channel has the same magnitude and opposite polarities, which means there is no charge transfer from the cloud to the leader because the charge net on the bipolar leader is zero [Bazelyan and Raizer 2000, Heckman and Williams 1989, Kasemir 1960, 1983, Kawasaki and Mazur 1992, Mazur 1989, Mazur and Ruhnke 1994, Ruhnke 1994].

In this paper, we present some lightning flashes observations by stereo vision. The use of stereo vision applied for lightning channels identifies the real tortuosity of the lightning channel. The observations of natural lightning flashes can be applied on electromagnetic model and on studies of stepped leader propagation to improve the protection systems.

INSTRUMENTATION

Stereo Vision is the process of extracting 3D information from two or more 2D images of the same object. It is a Computer Vision technique that has been widely used in robotics in the last 30 years [Moravec 1977]. It is theoretically well defined [Faugeras 1993], usually working with two images taken with parallel cameras that were separated by a previously known horizontal distance. The result of the stereo algorithm is a disparity map that presents how far each point in the physical scene is from the camera. The need steps to compute the disparity map are: first, rectify the images, that is, to project both images onto an image plane that will align their coordinate systems. Next, a basic block matching is made: for every pixel in the right image, a square, small region of the image is defined, and a similar region is searched, in the same row. When a block that matches the original one is found, the distance, in pixels, between them is computed: this is the disparity. This matching is made for every pixel in the right image, creating a disparity map of the stereo pair. With the disparity map and information from the geometry of the camera, it is possible to compute the distance of each point in the image to the camera, creating a range image of the scene [Forsyth and Ponce 2002].

The stereo vision system applied for lightning flashes images used in this paper consists of two parallel cameras, 10m apart from one another, installed at FEI, São Bernardo do Campo. For this study it was used the parallel camera system in order to widen the observation area of the flashes. The current stereo systems use transversal cameras which restrict the observation area [Heber 2008, Liu 2012]. The cameras used on this study record images on 30 frames per second and present resolution of 512x328 pixels. However, the stereo vision system can be used by any digital camera with better capture speed and better resolution. More details of development and implantation of stereo vision system can be obtained on Bianchi and Gin [2014] and Antolini et al. [2013].

In this paper, the tortuosity of the natural flashes will be presented on cardinal coordinates: the y-coordinate identifies the height or length channel, the x-coordinate identifies the horizontal displacement channel and the z-coordinate identifies the transversal displacement channel (or depth). The average inclination of the lightning channel will be obtained by an average line that connects the start point to the end point along the lightning channel. The alpha and beta angles define the average inclination of the lightning channel inferring horizontal and transversal displacements, respectively. Some cases will be illustrated below.

RESULTS AND DISCUSSION

During the summers from 2010 to 2013, 10 thunderstorms were recorded by stereo system that presents 43 tortuous channel flashes. All the thunderstorms presented recording of local E-field, obtained by an Electric field mill sensor, and presented polarity, location and peak current estimate of CG flashes, obtained by BrasilDat network. The thunderstorms presented intensity of E-field over 10 kV/m and the CG flashes were located from 5km to 15km from FEI. For CG flashes the predominant polarity was negative (except for flashes 13, 28 and 30) and the medium peak of current estimate for negative and positive CG flashes were 20kA and 37kA, respectively.

Table 1 shows the date, the time and the type of flashes recorded on this period. The flashes were classified as: return stroke of CG flash (CG), return stroke of CG looping channel (CG*), stepped leader (SL) and cloud-to-air (CA). The flashes which presented recording of stepped leader are identified by letter “a” followed to the return stroke by letter “b”.

All CG flashes analyzed presented tortuous channel. The horizontal and transversal displacements for the negative and positive CG flashes could be observed. The tortuosity on branched stepped leader and on looping channel was observed, as well. Below there are examples of lightning flashes tortuosity, branched stepped leader and looping channel cases recorded at 5km from FEI.

a) Negative CG flashes

From the CG flashes, the negative flashes are the most frequent in the nature. The negative leaders begin on the main negative charge center of the thunderstorm and propagate in steps towards to the ground, visually recorded like branches leader. In general the negative flashes present multiple strokes and a medium peak current estimate of about 25kA, for this region [Gin et al., 2007].

Figure 1 shows the original image of the flash (a, e), the 3D reconstruction of the channel (b, f) and the average inclination channel on the horizontal and transverse diretion of the Flashes-3 and 12, respectively. The 2D perspective on yx-plane (horizontal plane) and on yz-plane (transverse plane) is obtained by 3D reconstruction of the channel flashes, using the same arbitraries unit scale, in which is calibrated and obtained their horizontal and transversal displacements.

Table 1 Events of 3D channel lightning flashes

flash	Date	Time(UT)	Type
1	09 November 2010	23:49:29.976	CA
2	09 November 2010	23:52:30.155	CA
3	09 November 2010	23:55:39.360	CG
4	09 November 2010	23:57:28.746	CG*
5	09 November 2010	23:59:45.998	CG
6	10 November 2010	00:01:13.371	CG*
7	10 November 2010	00:01:38.725	CG
8	10 November 2010	00:02:27.262	CA
9	10 November 2010	00:04:52.482	CA
10a	10 November 2010	00:05:08.900	SL
10b	10 November 2010	00:05:09.105	CG*
11	10 November 2010	00:06:01.178	CG
12	10 November 2010	01:59:53.055	CG
13	13 December 2010	03:29:22.900	CG
14	08 January 2011	17:40:06.154	CG
15	15 December 2011	02:3519.234	CG
16	15 December 2011	02:38:16.953	CG
17	15 December 2011	02:40:53.390	CG+CA
18	15 December 2011	02:43:38.109	CA
19	15 December 2011	02:46:57.687	CG
20	16 December 2011	01:17:53.296	CA
21	17 January 2012	17:04:43.585	CG
22	10 March 2012	17:48:34.700	CG
23	10 March 2012	18:06:51.150	CG
24	10 March 2012	18:16:47.499	CG
25	10 March 2012	18:30:56.435	CG
26	10 March 2012	18:31:50.218	CG
27	10 March 2012	18:50:47.345	CG
28	10 March 2012	19:16:37.399	CG
29	10 March 2012	20:09:14.875	CG
30	10 March 2012	20:15:48.046	CG+CA
31	16 February 2013	23:00:27.712	CG
32	16 February 2013	23:01:23.040	CG
33	16 February 2013	23:03:57.430	CG
34	16 February 2013	23:08:41.587	CG
35	18 February 2013	20:18:35.436	CG
36a	25 February 2013	01:11:42.094	SL
36b	25 February 2013	01:11:42.297	CG
37a	25 February 2013	01:14:43.047	SL
37b	25 February 2013	01:14:43.344	CG
38a	25 February 2013	01:20:20.188	SL
38b	25 February 2013	01:20:20.250	CG
39a	25 February 2013	01:28:21.672	SL
39b	25 February 2013	01:28:21.719	CG
40a	25 February 2013	01:30:45.203	SL
40b	25 February 2013	01:30:45.203	CG
41	10 March 2013	00:54:15.865	CG
42	10 March 2013	01:31:46.725	CA
43	10 March 2013	01:36:35.483	CA

CG return stroke (CG); Looping channel of CG return stroke (CG*); stepped leader (SL), cloud-to-air (CA)

The stereo system recorded a branched stepped leader on Flash-3, followed by 2 return strokes, in which the visual recording of total flash lasts about 600ms. On the other hand, a single stroke was recorded on the Flash-12, by starting though a long horizontal flash into the cloud, lasting about 650ms. The second stroke of Flash-3 (Figure 1a), recorded the medium peak current of 19kA and had a visual recording duration of about 500ms. The 2D original image of the Flash-3 presents a little channel tortuosity, 500m above the ground, whereas the 2D original image of the Flash 12 (Figure 1d) presents no tortuosity of the channel but it presents a single inclination of about 45^0 since the top channel. These original image flashes present a clear horizontal displacement along the channel but do not infer a transverse displacement just observed by 3D reconstruction of channel flashes.

The 3D reconstruction of channel flashes transforms the horizontal and transverse displacement into 2D images. Figures 1b and 1f present the 3D reconstruction of channel flashes to the Flashes-3 and 12, respectively. These pictures show the horizontal and transverse displacements expanded into yx-plane and yz-plane, respectively. The horizontal plane presents a short displacement to the Flash-3 (Figure 1c), estimated of about 1 km, and a long displacement to the Flash-12 (Figure 1g), estimated of about 3km. Otherwise, the transverse plane of Flash-3 (Figure 1d), estimated of about 2km, seems to be longer than the transverse displacement of Flash-12, estimated of about 0.9 km. The 3D perspective of the channel tortuosity presents a different behaviour to the negative CG flashes and needs more studies.

Statistics analyses of the return stroke channel tortuosity, based on photograph, were reported by Hill [1968, 1988] and by Idone and Orville [1988]. Hill [1968], with a high speed camera, studied the main channel tortuosity characteristics on scale of meters to kilometers. Similar study will be presented in the future.

b) Positive CG Flashes

The positive CG flashes are less frequent than negative CG flashes. However, the average peak current on stroke of positive CG flashes is higher than the negative CG flashes. Otherwise, the stroke associated with long continuing current are more frequent on positive CG flashes than negative CG flashes. The positive CG flashes are commonly observed at the beginning and the end of thunderstorms. Generally, they are triggered by long horizontal discharges, and in the most of cases present a single return stroke.

Figure 2 presents the original image and the 3D reconstruction to the positive channel for the Flashes-28 and 13. The Flash-28 presented the non-branched stepped leader, lasting about 40ms, and also one return stroke lasting about 250ms (Figure 2a). The peak current estimated for this stroke is about 22kA. This thunderstorm was associated with the Convergence Zone of South Atlantic, formed by long stratiform thunderstorms, which produce long horizontal discharges. The same behavior is observed on the dissipation stage of thunderstorm that produced the Flash-13. The positive CG Flash presented a single return stroke, medium peak current of 40kA, lasting 300ms (Figure 2e). The 3D reconstruction of channel for the Flashes 28 and 13 (Figure 2b and 2f) present the horizontal displacement (Figure 2c and 2g) and the transverse displacement along the channel (Figure 2d and 2h), respectively.

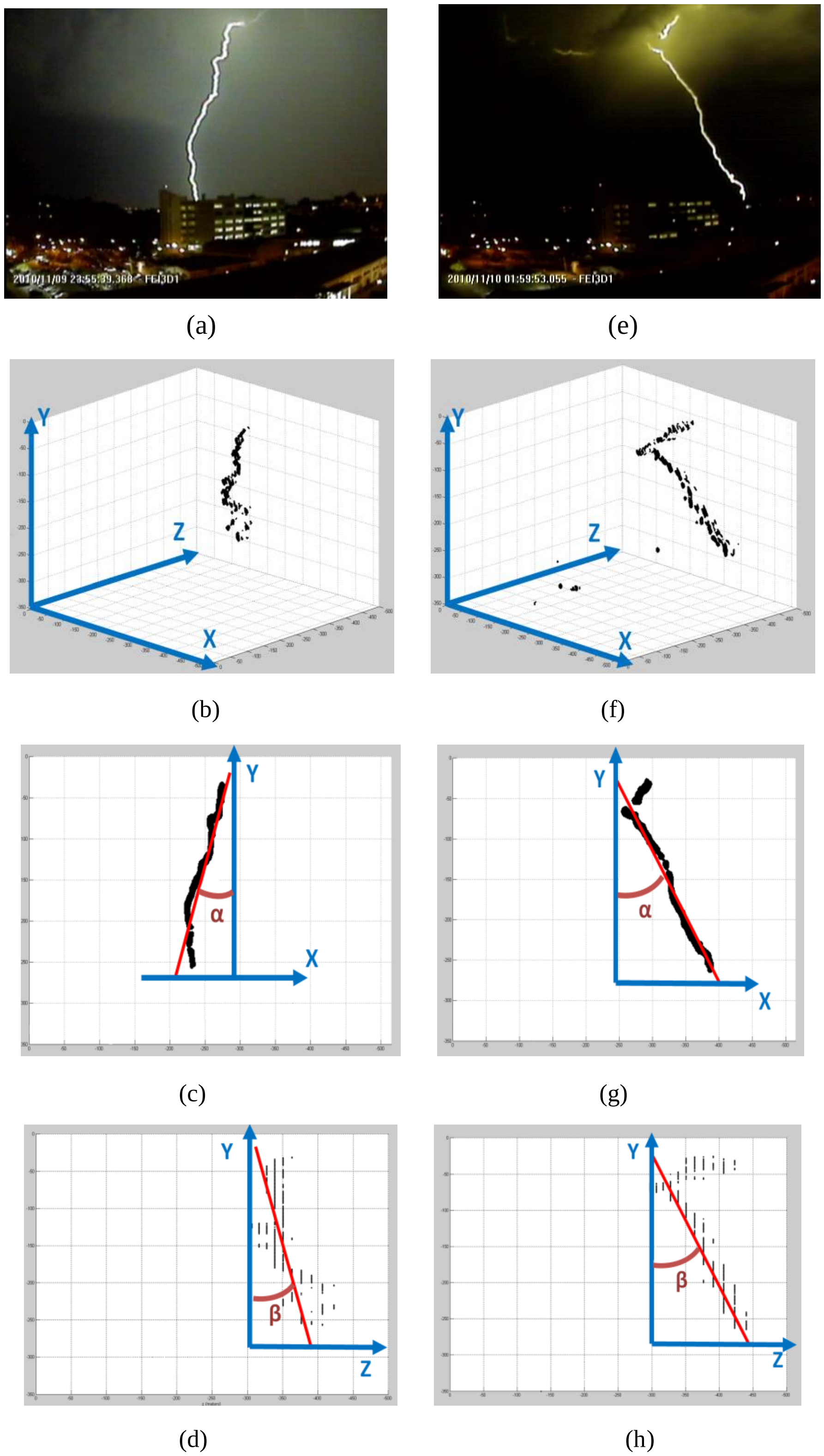

Figure 1. Original image of the channel flashes (a, e), 3D reconstruction of the channel (b,f) and 2D perspective channel to horizontal plane (c, g) and to transverse plane (d, h) for the Flashes-3 and 12, respectively.

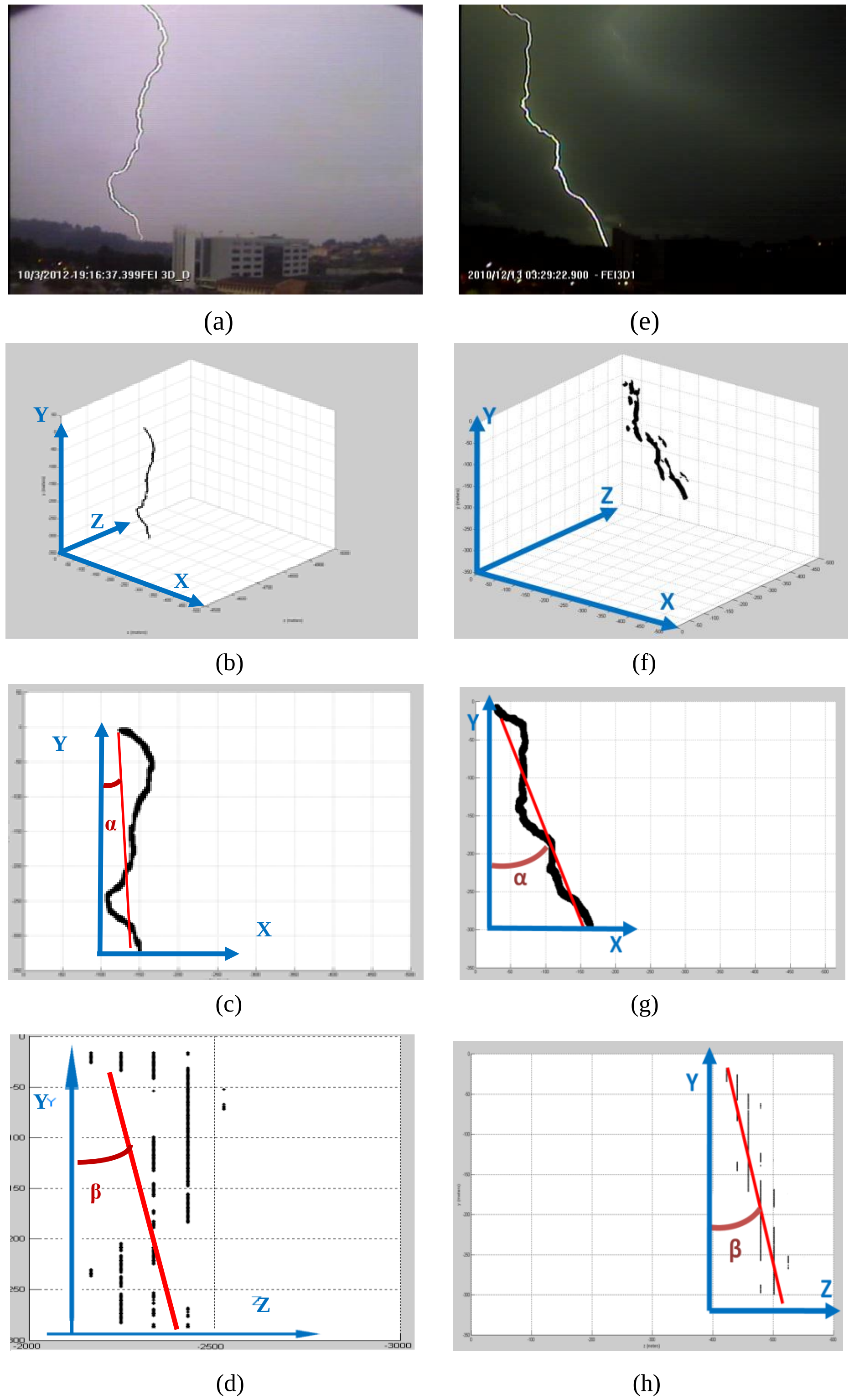

Figure 2. Original image of the channel flashes (a, e), 3D reconstruction of the channel (b,f) and 2D perspective channel to horizontal plane (c, g) and to transverse plane (d, h) for the Flashes 28 and 13, respectively.

On the horizontal plane, the channel of the Flash-28 presents a horizontal displacement of about 1km, in the altitude of 500m above the ground, whereas the channel of the Flash-13 presents a horizontal displacement of about 2.5km in two regions, one on the top of the channel and another one 1km below. On the transverse plane, the channel of the Flash-28 presents a short displacement of about 0.5km, whereas the channel of the Flash-13 presents the longest displacement observed on this study, about 6km. Long channel displacement has been attributed to positive CG flashes due to stepped leader propagation characteristics [Williams 2006, Yoshida et al. 2012]. It is important to clarify that the transverse displacements presented in this study can be overestimated due to the use of low resolution cameras. Therefore, this study presents a qualitative result in the transverse displacement of channel flashes.

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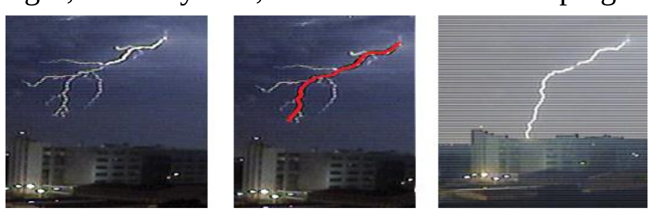
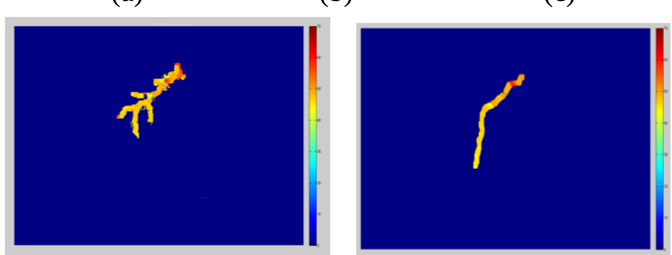
c) Branched Stepped leader

The bipolar and bidirectional stepped leader move in opposite directions. In the case of a negative CG flash, a stepped leader propagates towards the ground initiating the first return stroke. A negative single CG flash, Flash-39, was recorded by stereo system at 01:28UT on 25 February, 2013. The branched stepped leader (Figure 3a) lasted about 46ms, and the return stroke (Figure 3c) lasted 62ms. The Figure 3b presents the path taken by return stroke, highlighted by a red line, and the Figures 3d and 3e present the disparity map of the leader channel and of the stroke channel, respectively. The disparity map presents the horizontal displacement of the channel, yx-plane, and the transverse displacement, colour scale. This colour scale represents the transversal displacements in kilometres obtained after the events calibration. The Flash-39 presents longer horizontal displacement, about of 1.5km, than the transverse displacement, about 0.5km. However, some flashes present longer transverse displacements than horizontal displacements resulting in 2D picture as a looping channel. Thus, the application of disparity map in the lightning flashes images, stereo system, dismisses the false looping channels.



(a) (b) (c)



(d) (e)

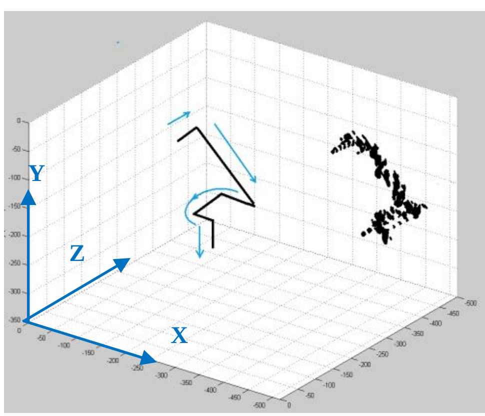
Figure 3. Original image and disparity map to Flash-39. Branched stepped leader original image (a), path taken by the return stroke (b), return stroke original image (c), disparity map for leader channel (d) and return stroke (e).

d) Looping Channel

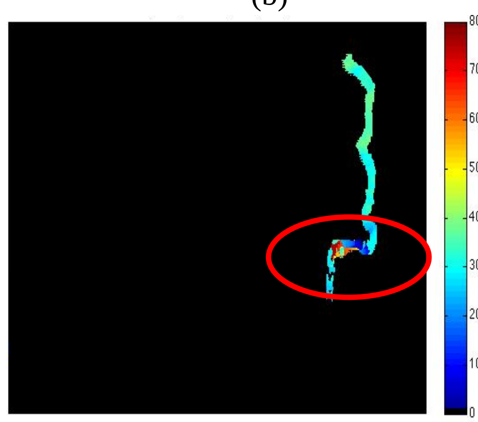
Long transversal displacement can be observed on lightning flashes. A negative looping CG flash was recorded by stereo system on Flash-10. A branched stepped leader (Figure 4a) was recorded about 32ms before the return stroke (Figure 4b), lasting 650ms. On 2D horizontal plane the lightning channel moves like a looping. However, when we use the 3D perspective (Figure 4c) and the disparity map (Figure 4d) we observe that there were simultaneous horizontal and transverse displacement in different paths. The horizontal and the transversal displacements of Flash-10 were estimated of 1.5km and 5km, respectively, in the looping channel altitude. The same result is observed on the Flash-4 (Figure 5). The 2D image of the Flash-4 (Figure 5a) presents a long horizontal looping on the top of the channel. However, when we use the disparity map (Figure 5b) we observe simultaneous horizontal and transverse displacements along of the channel, moving to different paths. The horizontal and transverse displacements of Flash-4 were estimated of 3.5km and 5km, respectively, in the looping channel altitude. So, the use of stereo system in 3D lightning channel visualization identifies the details of the stepped leader propagations and besides brings new information of the real tortuosity of the lightning channel.

(a)

(b)

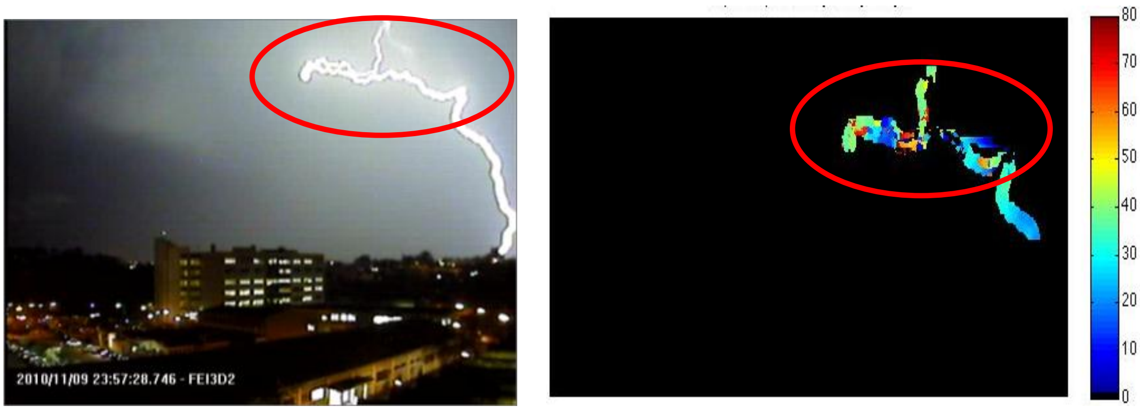


(c)



(d)

Figure 4. Original images of branched stepped leader (a) and return stroke (b), 3D reconstruction image of the channel (c) and disparity map of Flash-10 (d).



(a) (b)

Figure 5. Original image (a) and disparity map (b) of Flash-12 (b).

CONCLUSIONS

The stereo system applied to lightning flashes channel, identified the details of stepped leader propagation and presented the real tortuosity on CG lightning flashes. Negative and positive CG flashes were observed on three dimensions and presented horizontal and transversal displacement in kilometers. Two cases of looping channels were dismissed by disparity map, in which the horizontal and transverse displacements occur simultaneously though different paths. This information is very important to improve the electromagnetic models and the studies of stepped leader propagation.

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