

The optical characteristic of negative cloud-to-ground lightning flashes with multiple ground termination

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ABSTRACT: Thirty-two negative cloud-to-ground lightning flashes (CG) were observed in the urban area of São Bernardo do Campo, São Paulo, Brazil. The 10 thunderstorms were monitored simultaneously by a high-speed video camera (1000 frames/second and 1024x512 pixels resolution), electric field mill and Brazilian Lightning Detection Network (BrasilDat). The thunderstorms presented intensity of E-field over 10 kV/m, the peak current of CG flashes was estimated from 15kA to 40kA and the CG flashes recorded by camera were located from 3km to 30km from FEI. The optical characteristics of multiple ground termination flashes (MGT) were observed classifying them in branched stepped leader, continue luminosity of strokes, multiple channel flashes and stepped-to-dart leader observations. The MGT flashes presented the average and maximum number of about 3 - 9 ground termination per stroke, respectively. This result is higher than the others observed by the authors, 1.7 and 6, respectively. From the total of MGT flashes recorded, 94% presented branched stepped leader and 60% multiple strokes. From the multiple strokes recorded, the most common presented 2 (37%), 4 and 9 strokes (16%). The single flashes presented the stepped leader and the total flash average duration of 9ms and 20ms, respectively, while the multiple flashes presented the stepped leader and the total flash average duration of 12ms and 314ms, respectively. The single flashes recorded the longest duration, 40ms, of stepped leader and the first stroke. Three flashes presented multiple channel flashes (MCF). While the average inter-stroke time interval of MGT flashes is from 40ms to 50 ms, the inter-stroke time interval of MCF is from 90ms to 200ms. This paper presents: the maximum number of Multiple Ground Termination Stroke (MGTS), the longest inter-stroke distance of MCFs and the observation of stepped-to-dart leader (SD).

INTRODUCTION

The stepped leader of the cloud-to-ground lightning flashes progresses to ground on steps identifying high brightness on branches. Many studies show recording of the long leader branches by VHF/UHF interferometric technique, time of arrival technique, high speed cameras and E-field records (Rakov and Uman 1994; Shao et al. 1995; Krehbiel et al. 2000, Ballarotti et al. 2005; Kong et al. 2009; Ruhnke 2012). Some long leader branches can extend to the ground creating an additional stroke (Qie and Kong 2007, Kong et al. 2010). It occurs due to mechanism of current cutoff and of the reestablishment of current in the lightning flashes channel (Rakov et al. 2003; Mazur and Ruhnke 2012). According to Mazur and Ruhnke (2012) the branch leaders are not equal between the CG flashes. The negative CG flashes presents leader branches more extensive and top of leaders less luminous than the positive CG flashes. The difference between

the leader branches is due to the fast spreading of charges of negative CG flashes.

Stolzenburg et al. (2013) described no common flashes in which presented stepped-to-dart leaders. Three negative CG flashes were observed by high-speed video and electric field change data identifying the main characteristic of these flashes. The dart leader present characteristics of the stepped leader beginning a new channel into the cloud propagate to the same ground termination channel prior ionized. Stepped-to dart leader flashes were observed in this study and will be compared to Stolzenburg's observation.

In this paper, we present CG flashes recorded by a high speed camera during summers from 2011 to 2014, on Sao Bernardo do Campo, Sao Paulo-Brazil. The most of CG flashes presented long leader branches, some branches extending to the ground, negative polarity and multiple ground termination stroke (MGT). Cases of multiple channel flashes and stepped-to-dart leader flashes will be presented in this paper.

INSTRUMENTATION

The camera used in this study is a Nac Hi-DCam II which records the flashes on 1000 fps with the resolution of 1024x512 pixels. The thunderstorms are monitoring by Electric field mill and the Brazilian Lightning Detection Network (BrasilDat) was used to identify the polarity and estimated the peak of current of flashes. All sensors are GPS synchronized and are installed at FEI, on Sao Bernardo do Campo, Sao Paulo, Brazil.

In this paper, is presented the multiple ground termination flashes recorded by Hi-Dcam occurred from 3 to 30km from FEI. The flashes in which presented the maximum number of multiple ground termination stroke (MGTS), the higher inter-stroke distance for the multiple channel flashes (MCF) and observations of the stepped-to-dart leader (SD) will be presented below.

RESULTS AND DISCUSSION

During the summers from 2011 to 2014, 10 thunderstorms were recorded, by high speed video camera, presenting 32 negative cloud-to-ground lightning flashes with multiple-ground-termination (MGT). All the thunderstorms presented recording of local E-field, by an Electric field mill sensor, polarity, location and peak current estimate of CG flashes, by BrasilDat network. The thunderstorms presented an intensity of E-field over 10 kV/m, the peak current of CG flashes was estimated from 15kA to 40kA and the CG flashes recorded by camera were located from 3km to 30km from FEI. Table 1 presents and identifies the optical characteristics of MGT flashes, the date and the time of occurrence, stepped leader duration, multiplicity, the first stroke and total flash duration, the classification of the MGT (type) and the maximum number of ground terminations per stroke. The MGT flashes were classified according to its main optical characteristics as: stepped leader no recorded (0), branched stepped leader (1), continue luminosity of strokes (2), multiple channel flashes (3) and stepped-to-dart leader (4). In most cases the MGT in multiple flashes occur in only one stroke, which is always the first stroke. On the other hand, the stepped-to-dart leader (SD) observations presented more than one ground termination. These cases will be presented on the table below by following the strokes orders.

Table1. Optical characteristic of the cloud-to-ground flashes with multiple-ground-terminations

Flash	Date (dd/mm/yyyy)	Time (UT)	Stepped Leader Duration (ms)	Multiplicity	Stroke Duration (ms)	Total Duration (ms)	*Type	NGT
1	19/01/2011	18:21:21.748	8	1	12	20	1	2
2	21/01/2011	17:31:56.998	9	16	3	734	12	5
3	11/02/2011	18:46:25.627	2	1	4	6	1	3
4	11/02/2011	19:15:24.275	5	2	4	207	13	2
5	24/01/2012	19:22:45.425	8	1	14	15	1	3
6	24/01/2012	19:22:45.647	0	2	8	46	0	2
7	24/01/2012	19:31:43.407	0	1	3	3	0	2
8	19/12/2012	20:46:20.220	1	1	5	6	1	2
9	18/02/2013	22:32:14.345	3	1	4	7	1	2
10	19/02/2013	21:35:35.421	4	1	11	15	1	3
11	19/02/2013	21:41:23.471	1°.5 2°.1	2	1°.3 2°.4	8	14	1°.3 2°.4
12	19/02/2013	21:41:23.594	2	7	7	597	1	2
13	25/02/2013	22:45:25.382	6	1	12	18	1	2
14	25/02/2013	22:45:25.454	5	2	20	95	1	9
15	25/02/2013	23:05:32.488	7	4	10	410	12	3
16	25/02/2013	23:20:44.360	6	1	2	8	1	3
17	25/02/2013	23:23:14.347	19	4	10	263	13	3
18	25/02/2013	23:27:17.380	45	1	27	72	1	3
19	25/02/2013	23:29:36.547	22	2	7	101	12	2
20	25/02/2013	23:31:40.396	7	2	3	169	1	3
21	25/02/2013	23:33:28.353	17	5	3	279	12	2
22	25/02/2013	23:37:44.424	23	9	3	494	1	2
23	25/02/2013	23:47:45.188	26	19	1° 3 2° 1.	712	124	1° 5 2° 4
24	25/02/2013	23:49:51.122	15	4	2	202	1	4
25	25/02/2013	23:54:35.220	23	1	5	28	1	2
26	25/02/2013	23:54:35.315	16	4	5	280	12	2
27	25/02/2013	23:58:29.421	9	9	3	307	13	4
28	26/02/2013	00:08:06.423	4	10	5	837	1	4
29	06/03/2013	22:54:20.523	12	2	8	57	1	2
30	21/01/2014	20:24:32.529	8	9	18	653	12	2
31	21/01/2014	20:41:53.814	9	1	41	50	12	2
32	21/01/2014	20:48:56.448	9	8	7	492	1	2

*0. Stepped leader no observed 1.Branched Stepped Leader 2.Continue Current 3.Multiple Channel Flash
4. Stepped-to-dart leader

The MGT flashes presented the average and maximum number of about 3 - 9 ground termination per stroke, respectively. This result is higher than the others observed by the authors, 1.7 and 6, respectively (Valine and Krider 2002, Fleenor et al. 2009, Saraiva et al. 2010, Kong et al. 2009, Saba et al. 2010, Balarotti et al. 2005). From the total of MGT flashes recorded, 94% presented branched stepped leader and 60% multiple strokes. From the multiple strokes recorded, the most common presented 2 (37%), 4 and 9 strokes (16%). The single flashes presented the stepped leader and the total flash average duration of 9ms and 20ms, respectively, while the multiple flashes presented the stepped leader and the total flash average duration of 12ms and 314ms, respectively. The single flashes recorded the longest duration, 40 ms, of stepped leader and the first stroke. Three flashes presented multiple channel flashes (MCF). While the average inter-stroke time interval of MGT flashes is from 40ms to 50 ms, the inter-stroke time interval of MCF is from 90ms to 200ms. This paper presents: the maximum number of Multiple Ground Termination Stroke (MGTS), the longest inter-stroke distance of MCFs and the observation of stepped-to-dart leader (SD).

a) *The maximum number of multiple ground termination stroke (MGTS)*

Some long branched stepped leader can extend to the ground generating a multiple ground termination stroke. From all MGTS observed, the flash 14 presented the highest number of ground termination per stroke (9). Figure 1 presents the branched stepped leader of Flash 14, located 3.5 km from FEI, recorded by a high speed camera on February 25th, 2013 at 22:45:25UT. The blue arrows point to the stepped leader (SL) connection location along the channel (SL), the red arrows point to the ground termination of strokes and the number inside boxes indicate the frame number relative to the respective RS connection frame. The first SL recorded starts the count of the frames. The stepped leader subdivides into 3 long channels, lasting about 4ms (Figure 1 a-d), extending to the ground in 9 ground terminations (Figure 1e). An only one ground termination remains its luminosity during the flash (longer red arrow). The first stroke was recorded 5ms after the SL, while the second stroke was recorded 52ms after it. The luminosity of strokes remained for 2ms and 3 ms, respectively. The inter-stroke time interval was of 47ms and the dart leader was recorded 1ms before the second stroke. This flash presented total duration of 95ms, multiplicity 2 and average peak of current estimate of 19 kA.

b) *The longest inter-stroke distance in multiple channel flashes (MCF)*

A long leader can extend to the ground generating an additional stroke. Figure 2 shows the Flash 4, located 11km from FEI, recorded on February 11th, 2011 at 19:15:24UT. The blue arrows point to the stepped leaders connections location along the channel and the red and green arrows point to the multiple ground termination of the first and the second stroke, respectively. The number inside the boxes indicates the frame number relative to the respective RS connection frame. The first SL recorded starts the count of the frames. The stepped leader and strokes duration was observed 5ms and 4ms to the first stroke while the second stroke no recording was presented. The latest stroke duration was of 3ms. An inter-stroke time interval of 200ms was recorded to this flash generating a new ground termination with an inter-stroke distance of about

1 km. This observation is in accordance with Kitagawa et al. (1962) who found inter-stroke interval longer than 100ms for the new ground terminations. Krehbiel (1981) and Shao et al. (1995) showed that changes in the cloud's electric field could generating a new ground termination due to residual negative charge left by current cutoff. Mazur (2002) shows that the conductive channel branching and elongation contribute to the current cutoff, which is essential for the lightning flashes development process. Inter-stroke distance less than 2km is usually. The peak current estimated for the first stroke was 21kA.

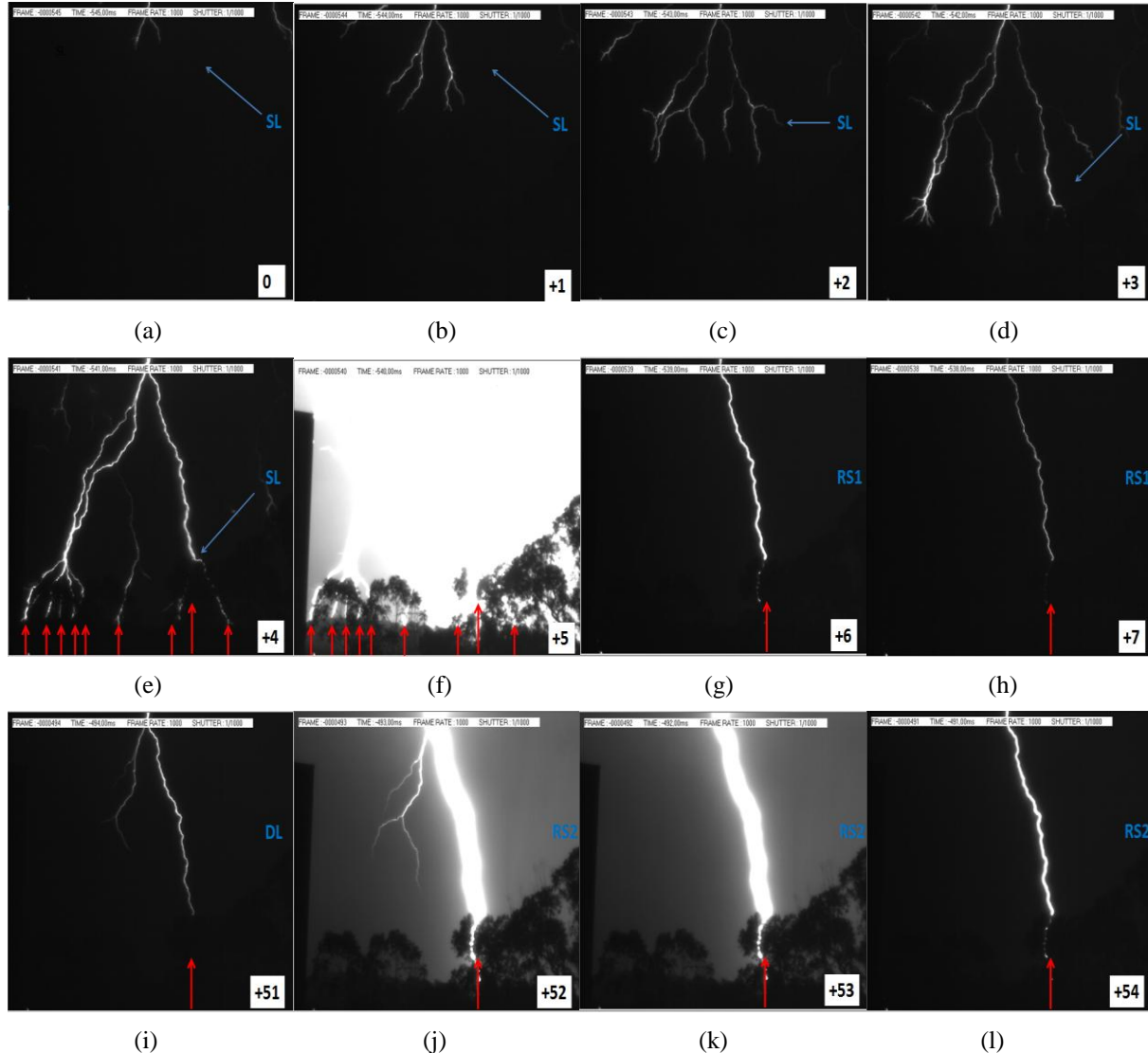


Figure 1. The maximum number of multiple ground termination stroke were recorded in the Flash 14. The blue arrows point to the connection location along the channel, the red arrows point to the ground termination of strokes and the number inside boxes indicate the frame number relative to the respective RS connection frame. The first SL recorded starts the count of the frames.

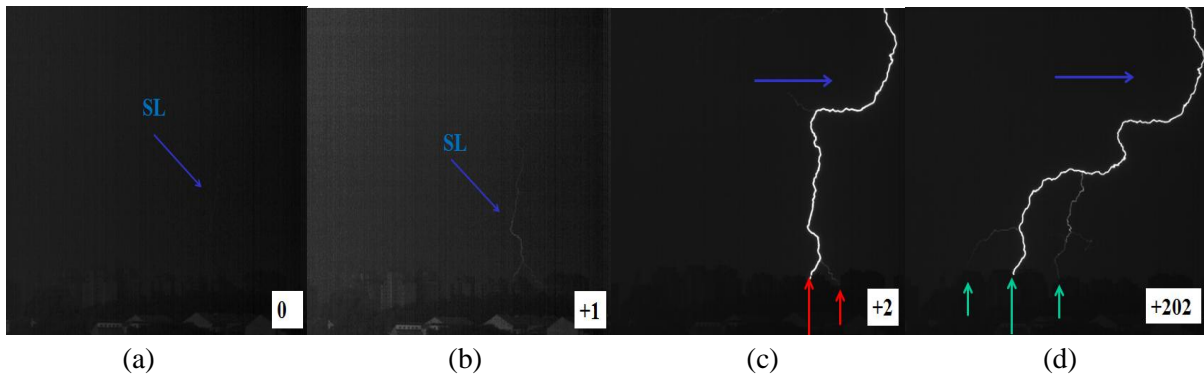


Figure 2. The longest inter-stroke distance in multiple channel flash recorded in Flash4. The blue arrows point to the leader connections location along the channel and the red and green arrows point to the multiple ground termination. The number inside the boxes indicates the frame number relative to the respective RS connection frame. The first SL recorded starts the count of the frames.

c) *Stepped-to-dart leader(SD)*

Stolzenburg et al. (2013) described the stepped-to-dart leaders as dart leaders which present optical characteristics of stepped leader in negative CG flashes, including average two-dimensional speeds of 10^5 m/s. Similar stepped-to-dart leader was observed on February 25th, 2013 at 23:47:45UT. Figure 3 shows the Flash 23, located 30km from FEI, recorded by the high speed camera. The blue arrows point to the leaders connections location along the channel (Figure 3a, e, i, l), the shortest red arrows point to the multiple ground termination of strokes (Figure 3b, d) and the longest red arrow shows the only ground termination that maintained the luminosity during the flash. Two different channels were started into the base of the cloud, point to A and B channel, following the same ground termination channel. The green arrows point to the channel used by different leaders and the number inside the boxes indicates the frame number relative to the respective RS connection frame. The first RS recorded starts the count of the frames. Eighteen subsequent strokes were observed, started by different leaders, using the same ground termination channel. The peak current of these strokes were estimate from 14 to 21 kA and the total duration of the flash was of about 700ms. The stroke duration and the inter-stroke interval duration were not higher than 10 and 100ms, respectively. The same result was recorded on Flash 11 and the details of the flash are described in the Table 1.

CONCLUSIONS

Thirty-two negative cloud-to-ground lightning flashes were observed by a high-speed video camera presenting multiple ground termination flashes, multiple channel flashes and stepped-to-dart leader observations. The MGT flashes presented long branched stepped leader, multiple strokes and average and maximum number of MGT higher than the observed by tother authors. More detail about long branched stepped leader and MGT flashes will be presented in the future.

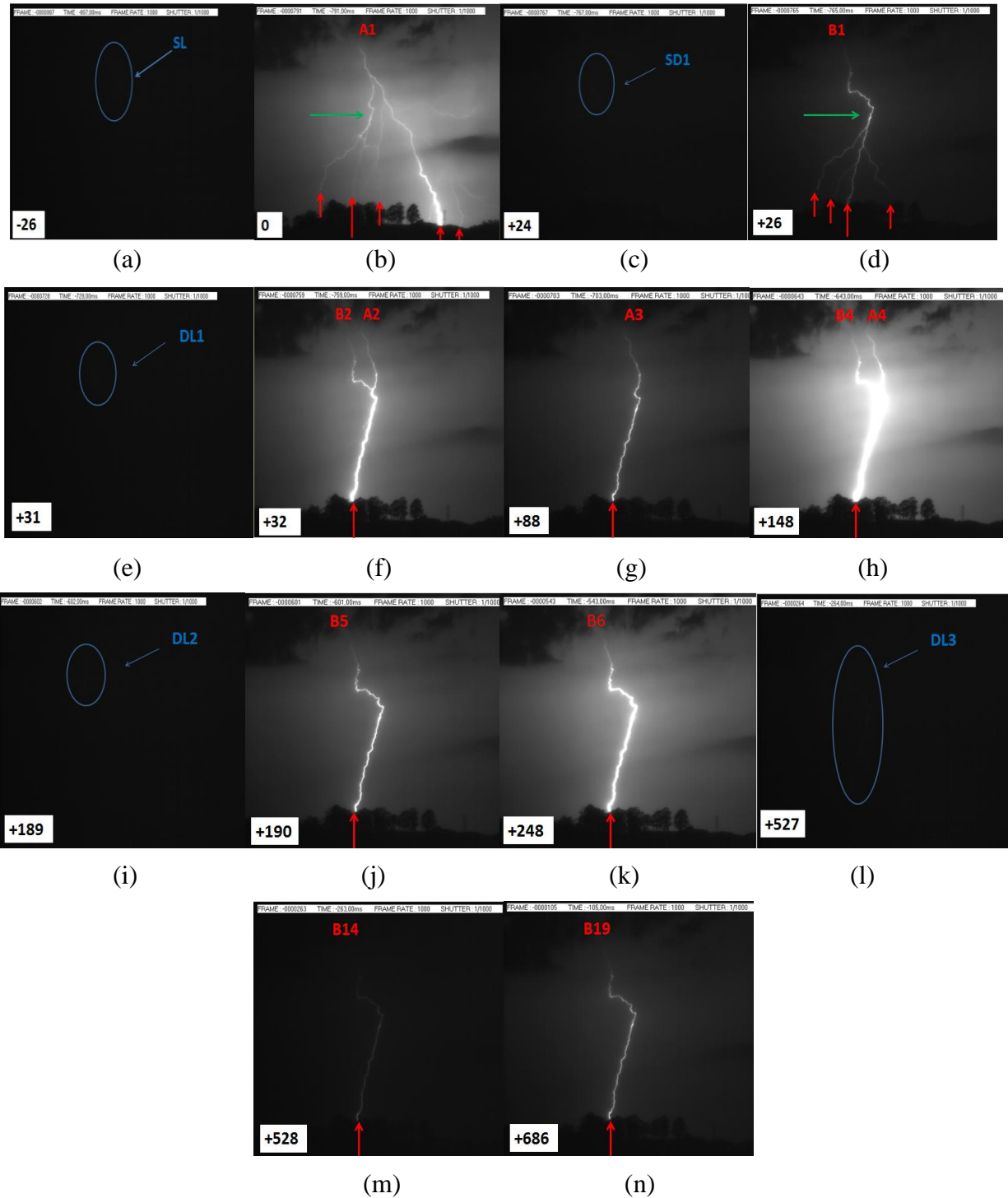


Figure 3. Stepped-to-dart leader recorded to the Flash 23. The blue arrows point to the leaders connections (a, e, i and l), the shortest and the longest red arrows point to the multiple ground termination of strokes (b, d) and the only ground termination that maintained the luminosity during the flash. Two different channels were started into the base of the cloud (A and B) and the green arrows point to the channel used. The number inside the boxes indicates the frame number relative to the respective RS connection frame and the first channel observed (A1) recorded starts the count of the frames.

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