AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2016JD025461

Key Points:

- Thirteen (3%) out of 427 flashes recorded at the Säntis Tower are classified as bipolar events of Categories I, II, and III
- That scenario belongs to Category I, which also includes polarity reversals due to in-cloud processes
- That scenario involves two upward leaders of opposite polarity initiated from the tower tens of milliseconds apart

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Citation:
Azadifar, M., F. Rachidi, M. Rubinstein, V. A. Rakov, M. Paolone, and D. Pavanello (2016), Bipolar lightning flashes observed at the Säntis Tower: Do we need to modify the traditional classification?, *J. Geophys. Res. Atmos.*, *121*, 14,117–14,126, doi:10.1002/2016JD025461.

Received 2 JUN 2016
Accepted 30 NOV 2016
Accepted article online 7 DEC 2016
Published online 14 DEC 2016

Bipolar lightning flashes observed at the Säntis Tower: Do we need to modify the traditional classification?

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Abstract We present and discuss current waveforms associated with 13 bipolar lightning flashes recorded at the Säntis Tower during the period from June 2010 to January 2015. During this period, a total of 427 flashes were recorded, of which 13 (3%) were classified as bipolar flashes. The majority of the recorded flashes (10 out of 13) exhibited a polarity reversal during the initial continuous current, therefore belonging to Category I according to the classification proposed by Rakov (2003). Of the three remaining flashes, two were characterized by different polarities of the initial stage current and the following return stroke or strokes (Category II), and one flash involved return strokes of opposite polarity within the same flash (Category III). In Category I bipolar flashes, the polarity reversal is usually assumed to be associated with in-cloud processes. However, two of our 10 Category I flashes appeared to be each a sequence of two upward discharges of opposite polarity, initiated from the tower within tens of milliseconds of each other. This is the first time that such a sequence has been observed from the same tower. We suggest that the traditional classification of bipolar flashes should be modified to distinguish between two types of Category I flashes: those in which the polarity reversal during the initial stage is associated with in-cloud processes (Category Ia) and those in which the polarity reversal is due to initiation of two opposite-polarity leaders from the tower (Category Ib).

1. Introduction

Bipolar lightning discharges transfer both negative and positive charges to ground. They are usually initiated by upward leaders from tall structures, but they can also be downward flashes. Current waveforms associated with bipolar flashes were first reported by *McEachron* [1939] from his studies at the Empire State Building. The overall percentage of bipolar lightning discharges is relatively low, but their probability of occurrence is believed to be about the same as that of positive lightning [*Rakov et al.*, 2014]. Table 1 gives a summary of studies reporting bipolar flashes observed at instrumented towers and in rocket-triggered lightning experiments.

The types of cloud structure and discharge processes involved in the formation of bipolar flashes are still not clearly understood, although some scenarios have been suggested in the literature [e.g., *Narita et al.*, 1989; *Saba et al.*, 2013; *Saraiva et al.*, 2014].

In this study, we present 13 bipolar lightning flashes recorded at the Säntis Tower in Switzerland during the period of June 2010 to January 2015. All the 13 bipolar flashes were upward discharges.

Our data represent a useful source of information for studying the physics of bipolar flashes, which are rare events, with only limited number of well-documented cases being found in the literature. Based on our observations and the existing literature, we suggest a modification to the traditional classification of bipolar flashes.

2. Experimental Observation

The data presented in this paper were obtained at the 124 m tall Säntis Tower, located in the northeast of Switzerland (47°14′57″N and 9°20′32″E). The Säntis Tower has been instrumented since May 2010 with a

Table 1. Summary of Observations of Bipolar Lightning

Reference	Country	Experiment	Number of Events	Percentage (%)
Hagenguth and Anderson [1952]	USA	Empire State Building	11 (10 years of observation)	-
Berger [1978]	Switzerland	Mount San Salvatore	68 (out of 1196)	5.7
Hubert and Mouget [1981]	France	Triggered lightning	1	-
Nakahori et al. [1982]	Japan	Fukui chimney	2 (out of 14)	14.3
Gorin and Shkilev [1984]	Russia	Ostankino Tower	6 (out of 90)	6.7
Akiyama et al. [1985]	Japan	Triggered lightning	2	-
Heidler et al. [2000]	Germany	Peissenberg Tower	2	-
Miki et al. [2004]	Japan	Fukui chimney	43 (out of 213)	20.2
Jerauld et al. [2004]	USA	Triggered lightning	1	-
Wang and Takagi [2008]	Japan	Windmill and lightning protection tower	3	-
Zhou et al. [2011]	Austria	Gaisberg Tower	21 (out of 652)	3.2
This Study	Switzerland	Säntis Tower	13 (out of 427)	3.0

current measurement system to record lightning currents with high sampling rates (50 and 100 MS/s) and relatively long record length of 1.2 s or 2.4 s. The lightning current and its time derivative are measured at two different heights, 24 m and 82 m above the base of the tower, using Rogowski coils and B-dot sensors. More details on the Säntis Tower lightning current measurement system and recent upgrades can be found in *Romero et al*. [2012] and *Azadifar et al*. [2014].

During the considered period (June 2010 to January 2015), 427 flashes were recorded at the Säntis Tower, out of which 58 (13.5%) were classified as positive flashes and 13 (3.0%) as bipolar flashes. In 2014, 7 from a total 100 recorded flashes were bipolar, a fraction that is considerably larger than in previous years (a total of six bipolar flashes were recorded in the time period from June 2010 to December 2013).

Rakov [2003] classified bipolar flashes into three categories: (1) polarity reversal during the initial continuous current with a possible no-current interval between the two polarities, (2) different polarities of the initial stage current and the following return stroke or strokes, and (3) return strokes of opposite polarity.

Each one of the 13 recorded bipolar flashes of this study could be assigned to one of the three categories introduced in *Rakov* [2003]. We found that the currents of two out of the 10 Category I flashes in our data set presented evidence of two distinct upward leader channels of opposite polarity, sequentially initiated from the tower within tens of milliseconds of each other. In the remaining eight Category I flashes, the polarity reversal was apparently associated with in-cloud processes. Based on our observations and the existing literature, we suggest a more detailed classification of bipolar flashes, which will be described in section 2.4. Table 2 summarizes the events examined in this study. It should be noted that in this paper, negative current polarity indicates negative charge transfer to ground, which is equivalent to positive charge transfer upward.

Table 2. Summary of Säntis Tower Bipolar Flashes; Categories I Through III

Date and Time	Category (According To *Rakov* [2003])	Current Waveform Example
2011-8-27 07:20:34	IIIa	Figure 7
2011-8-27 08:05:26	Ia	Figure 4
2011-8-27 08:42:42	II	Figure 5
2012-7-4 18:45:09	Ia	Figure 1
2012-8-24 01:28:22	Ia	-
2012-9-11 16:05:05	Ia	-
2014-5-7 20:42:26	Ib	Figure 9
2014-5-7 20:46:00	Ia	Figure 3
2014-6-23 16:07:45	II	Figure 6
2014-6-23 16:55:13	Ia	-
2014-9-21 15:14:09	Ia	Figure 2
2014-9-21 15:22:51	Ib	Figure 8
2014-10-20 23:47:00	Ia	-

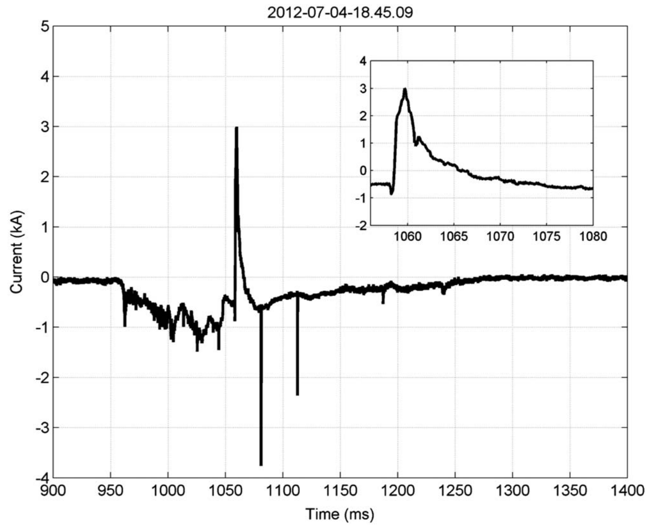

Figure 1. Bipolar flash of Category I that occurred on 4 July 2012, 18:45:09. An expanded view of the positive pulse is presented in the inset. This flash contained no return strokes.

2.1. Current Waveforms Belonging to Category I

This category of bipolar flashes is characterized by a change of polarity of the current during the initial stage [*Rakov*, 2003]. The majority of recorded bipolar flashes (10 out of 13) belong to this category. Figure 1 shows the current waveform of an upward flash of this category recorded on 4 July 2012. The waveform corresponds to an upward positive leader followed by an initial continuous current (ICC). This flash contained no return strokes. Several pulses are superimposed on the ICC, including one positive pulse which resulted in a polarity reversal of the current. An expanded view of the positive pulse is presented in the inset. The positive current pulse is characterized by a peak value of 3.6 kA and a risetime of 940 μs. The latter is much longer than that characteristic of return strokes.

Figure 2 presents another example of a Category I upward bipolar flash recorded on 21 September 2014. The waveform starts with an initial stage current with tens of ICC pulses, including one large positive pulse. An expanded view of the positive pulse is presented in the inset of the figure. The positive pulse is characterized by a peak value of 39.6 kA and a 10–90% risetime of 31 μs. Note that the ICC level (100 A) prior to the positive pulse is not discernible (not resolved on the tens of kiloamperes amplitude scale).

A similar example is presented in Figure 3. In this case, the positive current pulse is characterized by a peak value of 5.4 kA and an unusually fast risetime of 0.46 μs. The ICC level prior to this pulse was 150 A.

Note that the characteristics of positive pulses in the two bipolar flashes presented in Figures 2 and 3 are similar to those observed in positive flashes of type I [*Romero et al.*, 2013].

Figure 4 presents another example of a measured current waveform associated with a Category I bipolar flash. In this flash, the current exhibits first a positive excursion (corresponding to a positive charge transfer

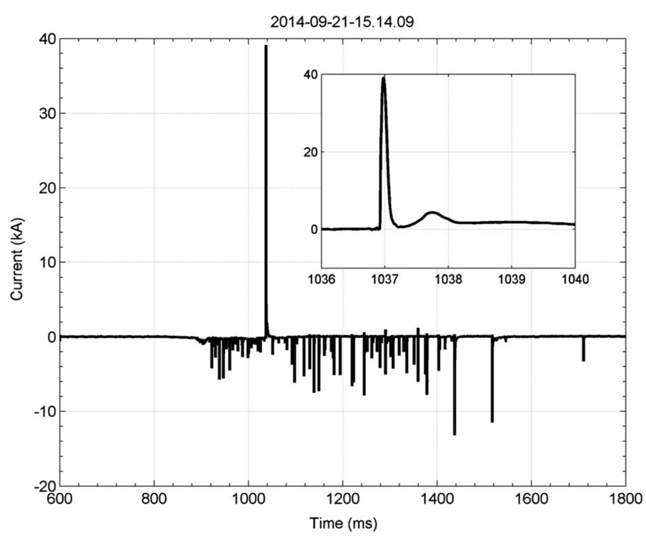

Figure 2. Bipolar flash of Category I that occurred on 21 September 2014, 15:14:09. An expanded view of the positive pulse is shown in the inset. The positive pulse is characterized by a peak value of 39.6 kA and a risetime of 31 μs.

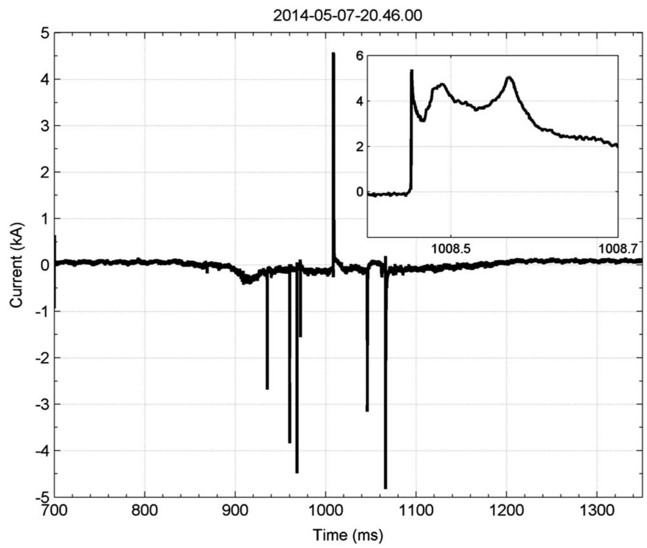

Figure 3. Bipolar flash of Category I that occurred on 7 May 2014, 20:46:00. An expanded view of the positive pulse is shown in the inset. The positive pulse is characterized by a peak value of 5.4 kA and a risetime of 0.46 μs. This flash contained no return strokes.

to ground) followed by a reversal of current polarity from positive to negative. Note that a negative 3 kA ICC pulse occurred after the ICC polarity reversal. An expanded view of this pulse is shown in the inset of the figure.

2.2. Current Waveforms Belonging to Category II

Category II is characterized by different polarities of the initial stage current and the following return strokes [*Rakov*, 2003]. Two out of 13 bipolar flashes of the present study belong to this category. In both cases, the initial stage current waveform corresponds to a type II positive flash [*Romero et al*., 2013]. Type II positive flashes are defined in *Romero et al*. [2013] as "classical" upward flashes characterized by millisecond-scale waveforms with large oscillatory pulse trains superimposed on their rising portion, which are inferred to be due to upward negative stepped leaders.

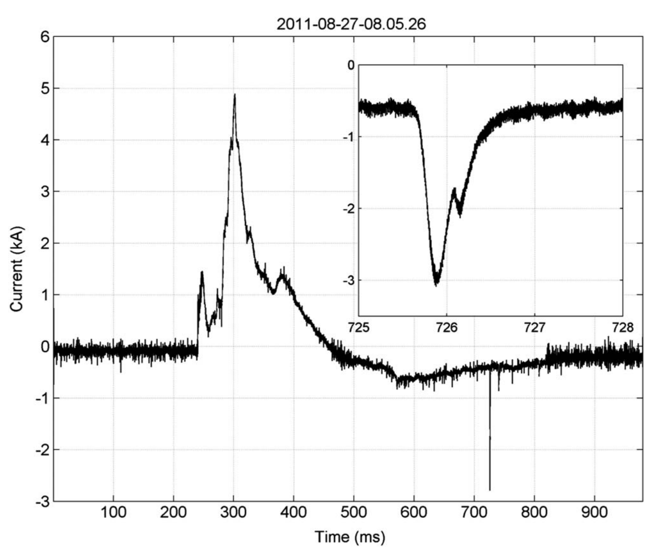

Figure 4. Bipolar flash of Category I that occurred on 27 August 2011, 8:05:26. An expanded view of the negative ICC pulse occurring during the late part of the bipolar ICC is presented in the inset. This flash contained no return strokes.

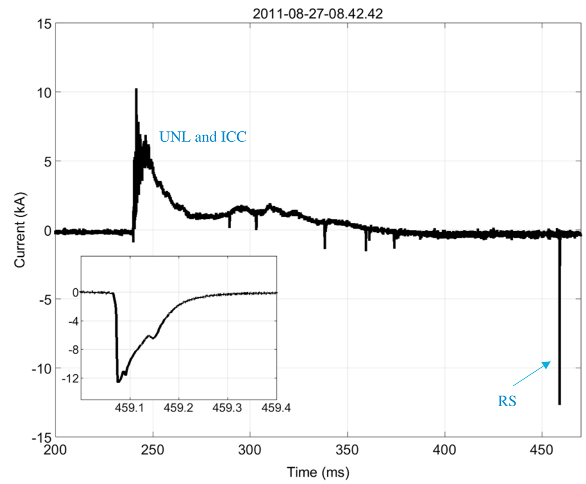

Figure 5. Bipolar flash of Category II that occurred on 27 August 2011, 8:42:42. An expanded view of the negative pulse associated with the only negative return stroke of this flash is presented in the inset. The negative return stroke current is characterized by a peak value of 12.6 kA and a risetime of 5.1 μs. UNL Stands of upward negative leader, ICC for initial continuous current, and RS for return stroke.

Figures 5 and 6 present two waveforms corresponding to this category recorded on 27 August 2011 and 23 June 2014, respectively.

For the first waveform (Figure 5), the peak of the initial positive pulse train is about 10 kA. The long steady current following the peak features several *M* component-like superimposed pulses of negative polarity. After the cessation of the steady current and a no-current interval of about 100 ms, a negative return stroke (12.6 kA peak and 5.1 μs risetime) occurred. For the second waveform (Figure 6), the largest positive pulse has a peak value of about 38 kA, followed by a no-current interval of nearly 300 ms and four negative return strokes.

2.3. Current Waveforms Belonging to Category III

This category involves return strokes of different polarities within the same flash. *Rakov* [2005] distinguished between upward or triggered lightning flashes (Category IIIa) and downward flashes (Category IIIb). Only 1 out of the 13 bipolar flashes in our data set could be classified as a Category IIIa bipolar flash. The current

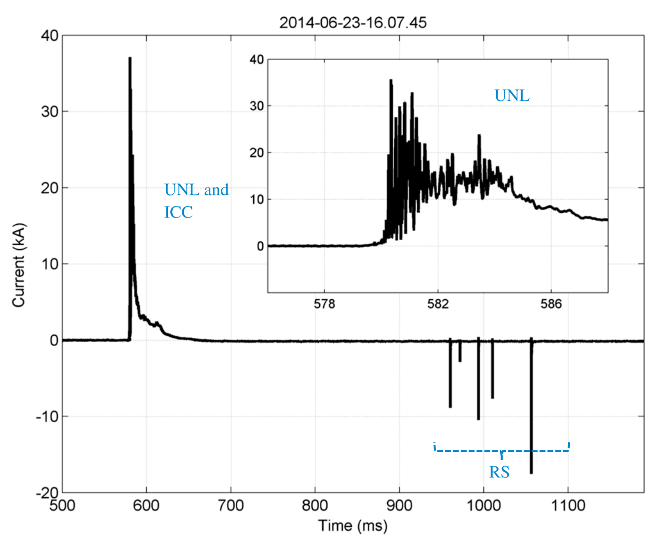

Figure 6. Bipolar flash of Category II that occurred on 23 June 2014, 16:07:45. An expanded view of the upward negative leader (UNL) is presented in the inset.

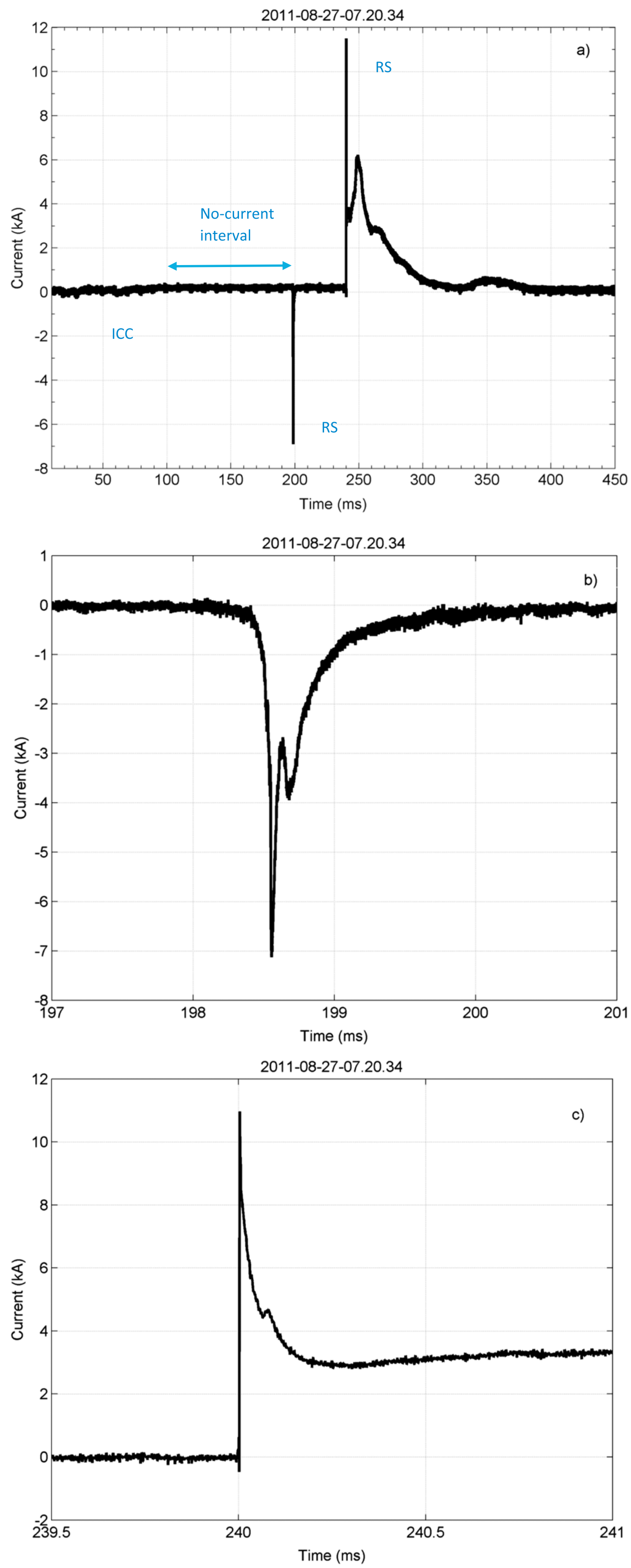

Figure 7. (a) Bipolar flash of category III that occurred on 27 August 2011. (b) Expanded view of the negative RS pulse (peak of 7.1 kA and a risetime of 75 μs). (c) Expanded view of the positive RS pulse (peak of 11 kA and a risetime of 0.88 μs).

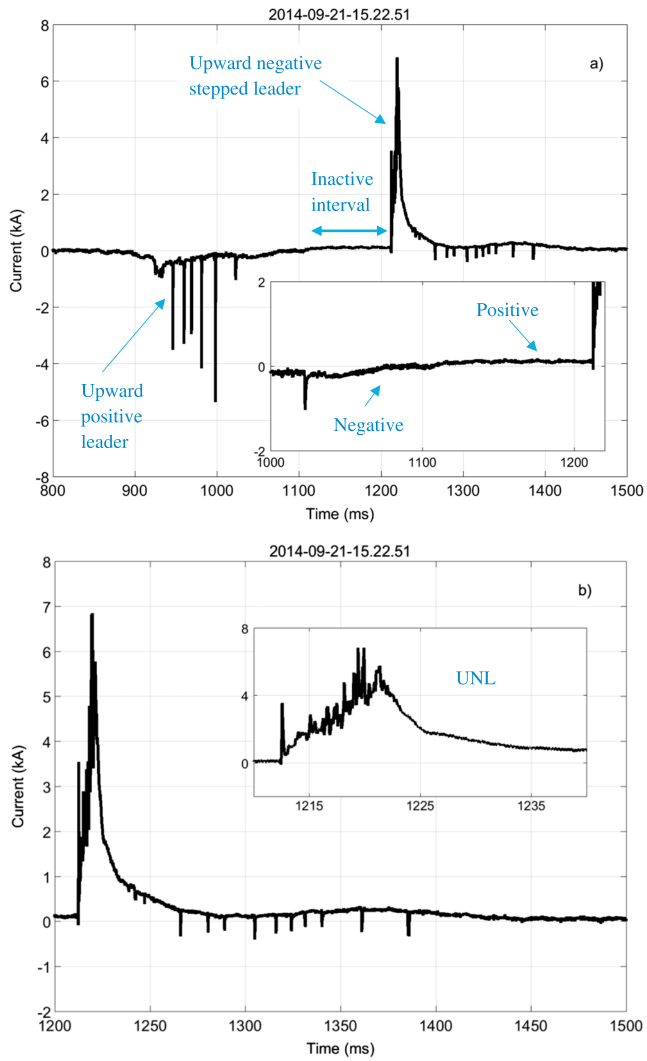

Figure 8. Bipolar flash that occurred on 21 September 2014. (a) Overall current waveform. An expanded view of the time interval including the reversal of current polarity is shown in the inset. (b) An expanded view of positive current pulse associated with upward negative leader. The pulse train in the initial rising portion of the current waveform is shown in the inset. This flash contained no return strokes.

waveform for this flash is presented in Figure 7a. Note that the pretrigger time of this record was not long enough to capture the whole initial stage process. We can see, however, the late part of the initial continuous current associated with an upward positive leader (negative charge transfer to ground), which ceased at about 100 ms, followed by two return stroke pulses of opposite polarity at 200 ms and 240 ms. Expanded views of the negative and positive return stroke (RS) pulses are presented in Figures 7b and 7c, respectively. The negative RS pulse has a peak of 7.1 kA and a risetime of 75 μs. This event would not be classified as an RS based on the current risetime (typical RS current risetimes are 1 to 2 orders of magnitude shorter). We treated it as a RS, because it was preceded by a 98 ms no-current interval. The positive RS pulse has a peak of 11 kA and a risetime of 0.88 μs. Similar current records showing return stroke pulses of opposite polarity have been reported in *Miki et al*. [2004], *Jerauld et al*. [2004], and *Schulz and Diendorfer* [2003].

2.4. Suggested Modification to the Traditional Classification of Bipolar Flashes

As mentioned earlier, two bipolar flashes without return strokes in this study were each characterized by a current waveform that could be formally assigned to Category I proposed in *Rakov* [2003] but showed evidence of two upward leaders of opposite polarity initiated from the tower. In Category I bipolar flashes, the polarity reversal is usually assumed to be associated with in-cloud processes. We suggest that the

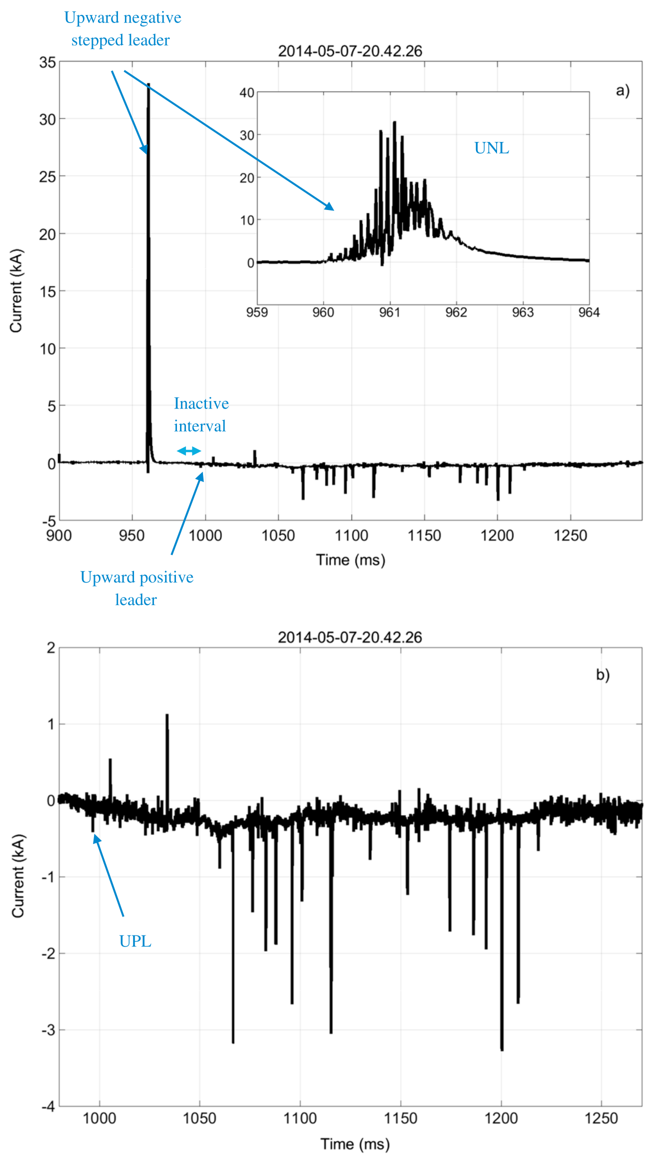

Figure 9. Bipolar flash that occurred on 7 May 2014. (a) Overall current waveform. An expanded view of the current waveform corresponding to the upward negative leader is presented in the inset. (b) Expanded view of the current waveform corresponding to the upward positive leader (UPL) and following ICC with superimposed pulses. This flash contained no return strokes.

traditional classification of bipolar flashes should be modified to distinguish between two types of Category I flashes: those in which the polarity reversal during the initial stage is associated with in-cloud processes (Category Ia) and those in which the polarity reversal is due to initiation of two opposite-polarity leaders from the tower (Category Ib).

Current waveforms of the two bipolar flashes of Category Ib are presented in Figures 8 and 9. In Figure 8, the current features an initial stage current associated with transporting the negative charge to ground with six superimposed ICC pulses, followed by a waveform characteristic of a type II upward positive flash initiated by an upward negative leader from the tower [*Romero et al.*, 2013]. The time interval between the end of the negative waveform and the start of the initial positive pulse (shown in the inset) is about 77 ms. During this time interval, the current reversed polarity from negative to positive. The steady positive current was about 150 A. This polarity change is indicative of Category I bipolar flash. However, the steady inactive positive current interval was abruptly ended by the upward negative leader developing in virgin air, as further discussed at the end of this section.

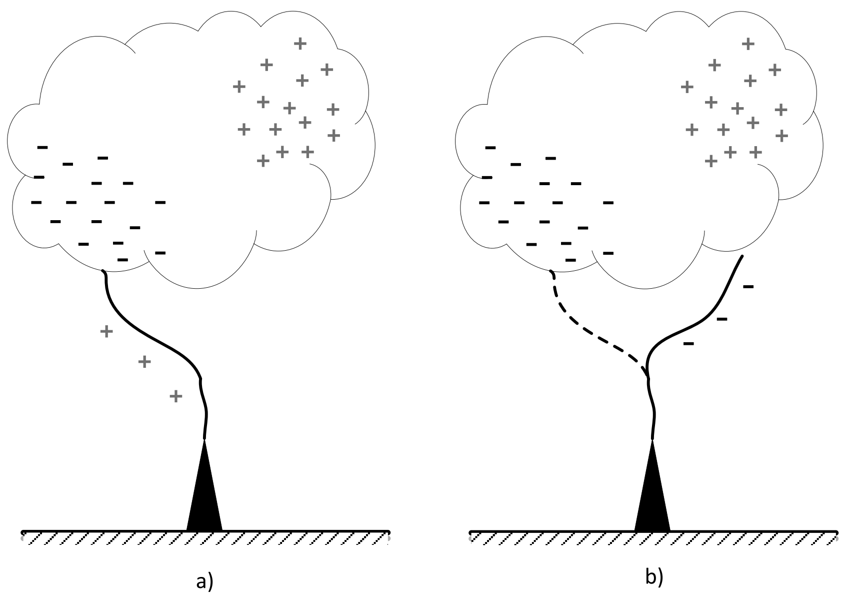

Figure 10. Schematic diagram illustrating the formation of the bipolar flash presented in Figure 8. It is essentially a sequence of two upward flashes separated by an unusually short time interval, (a) the first one initiated by an upward positive leader and (b) the second one by an upward negative leader.

Figure 9a presents the second case, which starts with a millisecond-scale waveform of positive polarity, superimposed on which are numerous large pulses, characteristic of a type II upward positive flash [*Romero et al*., 2013]. This waveform is followed by a slow-varying current waveform of negative polarity with superimposed pulses of both polarities. An expanded view of the negative waveform, which is indicative of negative charge transfer to ground and, hence, of an upward positive leader, is shown in Figure 9b. The inactive time interval between the end of the positive waveform and the start of the negative one is about 15 ms, during which a steady positive current of about 20 A was observed.

The initial stages of negative and positive upward flashes are associated with upward positive and upward negative leaders, respectively [*Miki et al*., 2005, 2014]. The two observed flashes of Figures 8 and 9 indicate that both positive and negative upward leaders can be initiated from the tower on the time scale of one flash. Further, based on video observations of upward positive flashes, it has been inferred [e.g., *Miki et al*., 2005] that the pulse trains in the initial rising portion of the initial stage current waveform are due to the stepping of an upward negative leader. The stepping-process signatures seen in the positive current waveforms in Figures 5, 8, and 9 are similar, although their durations differ by a factor of 5 or so. Since the upward negative leader shown in Figure 9 developed in virgin air, this similarity implies that the upward negative leader (shown in Figure 8) did not follow the same path as the preceding upward positive leader. Note, however, that it is conceivable that the negative stepped leader did not start from the tower tip but from the previously created channel carrying a 150 A steady current. To the best of our knowledge, this type of event has not been previously observed at an instrumented tower. Note, however, that a similar event was observed in triggered lightning experiments by *Horii* [1982, 1986]. That event is shown in Figure 8.9 of *Rakov and Uman* [2003], although no evidence of stepping is seen in the positive current waveform. Based on the above discussion, we hypothesize that two distinct upward leader channels of opposite polarity were involved in the development of the bipolar flash presented in Figure 8. Figure 10 shows a schematic diagram illustrating this hypothesis. The bipolar flash shown in Figure 9 might have followed a similar scenario, but in the reverse order.

The Category Ib bipolar flashes can be defined as a sequence of two, and possibly more, upward leaders of different polarities, initiated from the tower less than 100 ms or so apart (see Figure 10). It is worth noting that *Lu et al*. [2009] have reported on two associated upward flashes of opposite polarity within a time interval of 45 ms. However, those flashes initiated from two different towers separated by a distance of 375 m.

More data on upward leaders of opposite polarity initiated from the same tower within the same flash are required to improve our understanding of Category Ib bipolar lightning.

3. Conclusion

We presented and discussed current waveforms associated with 13 bipolar flashes recoded at the Säntis Tower during the period from June 2010 to January 2015. A total of 427 flashes were recorded, of which 58 (13.5%) were classified as positive flashes and 13 (3.0%) as bipolar flashes.

The majority of the recorded bipolar flashes (10 out of 13) showed a polarity reversal during the initial continuous current, therefore belonging to Category I, according to *Rakov* [2003]. Further, two flashes were characterized by different polarities of the initial stage current and the following return stroke or strokes (Category II) and one flash involved return strokes of different polarity (Category III).

Two of the 10 Category I bipolar flashes were each characterized by a sequence of two upward leaders of opposite polarity within the same flash, a scenario that has never been reported from previous observations at instrumented towers. The fact that two upward, opposite-polarity leaders can occur within tens of milliseconds of each other maybe of interest for lightning protection studies.

Further observations are needed to improve the traditional classification of bipolar flashes. Such observations should include the mapping of lightning channels inside the cloud to identify cloud charge structures and other conditions that can facilitate polarity changes in the course of the same flash.

Acknowledgments
This work was supported in part by the Swiss National Science Foundation (project 200021_147058) and by GRF grant 14.B25.31.0023. All the lightning current data presented in this paper are available upon request from the EMC Laboratory of EPFL (farhad.rachidi@epfl.ch).

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