ICLP2006 KANAZAWA
28th International Conference on Lightning Protection

Characteristics of positive upward lightning measured on an instrumented tower

Gerhard Diendorfer, *Austrian Electrotechnical Association (OVE-ALDIS*), H. Pichler, *Vienna University of Technology,* M. Mair, *Vienna University of Technology*

***Abstract*-- Lightning to elevated towers is mainly upward initiated. We have recorded 9 flashes to an instrumented tower that lowered positive charge to ground and have therefore been initiated by upward negative leaders from the tower top. All these 9 positive flashes occurred during the cold season or winter time (September – March). The observed overall current waveforms typically exhibit a front section with significant pulsing structure lasting for about 2.2 ms (mean). The total flash duration is in the range from 5 to 200 ms (mean 62 ms) and total charge transfer is in the range from 20 to 356 C (mean 128 C). Mean values of the peak current of these leader pulses are in the range of 1.6 to 13.7 kA. For each of the 9 flashes we have determined for the distinct pulses a mean charge transfer of 0.013 C to 0.321 C per pulse. The similarity of negative downward and upward stepped leaders is discussed.**

***Index Terms*— current, leader, positive lightning, tower measurements, upward initiated lightning, stepped leader**

I. INTRODUCTION

Positive lightning flashes are defined as those effectively transporting positive charge from the cloud to ground. Although only about 5-10% of all cloud-to-ground discharges is positive, these type of discharge is of considerable interest for several reasons [6] as:

- the highest recorded lightning current and charge transfer are thought to be associated with positive lightning
- in winter positive lightning discharges are more dominant
- Sprites are preferentially related to positive lightning

Contact Address:
Gerhard DIENDORFER
OVE-ALDIS
Kahlenberger Str. 2A, 1190, Vienna, Austria
E-mail: g.diendorfer@ove.at

Lightning to an instrumented tower (height 100 m) on Gaisberg, near to the city of Salzburg (Austria), is measured since 1998. From 2000-2003 we have recorded a total of 242 flashes to the instrumented tower. Lightning current is measured by digitizing (20 MS/s) the output signal of a 0.25 mΩ current viewing resistor over a sampling time of 800 ms. Details of the experimental setup are described in [2]. The fast majority (236 out of 242) of the recorded flashes were upward initiated, as typical for elevated objects.

In case of positive upward initiated lightning the discharge is initiated by an upward propagating negative leader from top of the instrumented tower [6]. Optical characteristics of upward negative leaders have been determined at the Monte San Salvatore. The upward propagation speed typically ranged from $8\text{x}10^4$ to $4.5\text{x}10^5$ m/s, the step length from 3 to 20 m and the interstep interval from 30 to 50 µs [1].

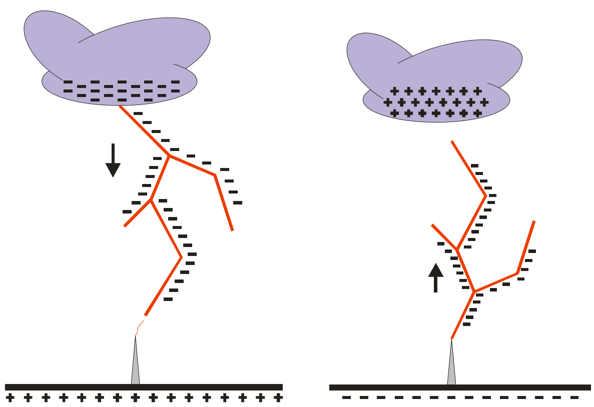

Figure 1: Leader direction and polarity of negative downward (left) and positive upward (right) lightning discharges

II. DATA

We analyze the current waveform of 9 upward initiated positive flashes recorded in the period 2000 - 2002. Figure 2 to Figure 4 show the typical waveform of a positive discharge to the tower (negative leader) in different time scales. Total current flow lasted for about 80 ms with a peak of about 10 kA (Figure 2). During the first 2.5 ms we observe a steadily increasing current ramp with superimposed current pulses in the microsecond time scale (Figure 3). Peaks of these current pulses shown in Figure 4 are in the range of up to 3 kA with a pulse width and a time between pulses in the range of some 10 µs. As obvious from Figure 4 in many cases there is not a clear structure that allows an unambiguous classification of individual pulses that is necessary for any statistical analysis of the time intervals between pulses and the pulse width.

To our best knowledge Yoda et al (1997) [7] observed high frequency pulses very similar to what we measure at the Gaisberg tower. At this time they attributed this waveform feature to measuring interferences, which we can exclude. All negative upward leaders at the Gaisberg tower show this distinct pulsing whereas it is not observed on any other recorded waveforms at the tower with current amplitudes and current risetimes being in the same order of magnitude.

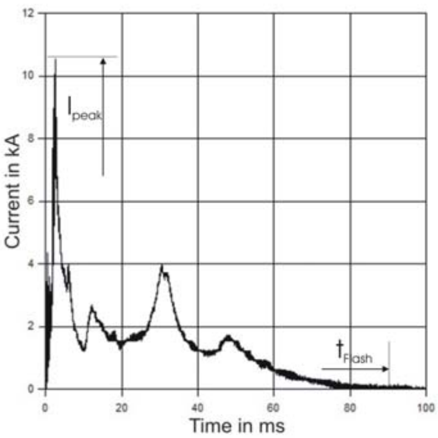

Figure 2: Example of total current waveform of a positive upward initiated lightning discharge (Flash #98, 21-01-2000, 16:17:55.457)

For a computer based evaluation of the numerous pulses that are present in the 9 waveforms one has to determine the starting and ending point of individual pulses. To do this we have applied three runs of a moving average calculation (8µs time window), which is to some extent arbitrary but provided acceptable results to find the time for the "most relevant" relative minima and maxima along the pulsing section of the current waveform.

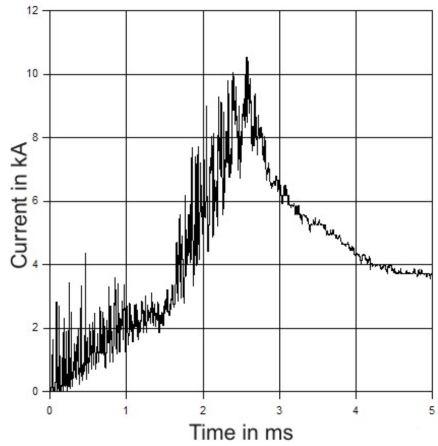

Figure 3: First 5 ms of the flash current shown in Figure 1 with pronounced pulses during the raising part of the waveshape

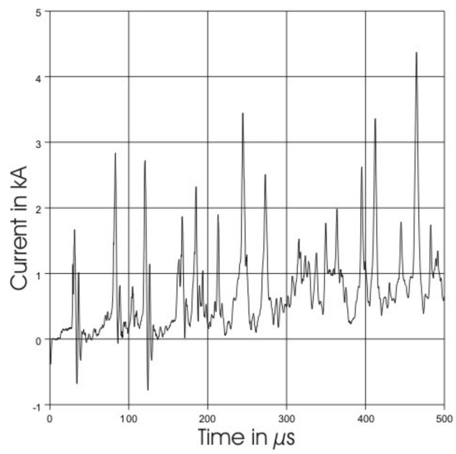

Figure 4: 500 µs sequence of the raising current front showing individual leader current pulses

Once when we have determined these time marks (shown as • in Figure 5), we return to the originally measured current waveform for the further analysis. A distinct pulse is then given by two consecutive relative minima and the relative maximum in between. The pulse peak current $I_{max,rel}$ is measured with reference to the connecting baseline of the pulse waveforms minima (see Figure 5).

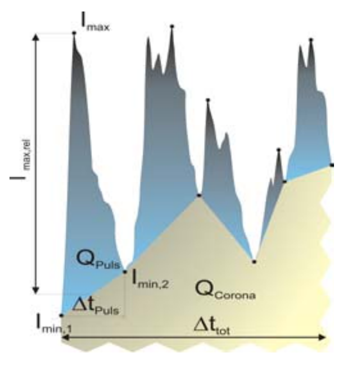

Figure 5: Definitions used in the data analysis in Table 1

Hence we have been able to determine the following parameters for each of the 9 positive flashes (see Table 1):

- N — Number of pulses of the flash
- Δt_{tot} — Total time duration of pulsing section
- $I_{max,rel}$ — Mean peak current of pulses of the flash
- Δt_{Pulse} — Mean pulse duration
- Q_{Pulse} — Mean charge of all pulses within the flash
- $Q_{Pulse,tot}$ — Accumulated pulse charge from 0 to Δt_{tot}
- Q_{Corona} — Total charge transfer by the underlying "continuous" current (see Figure 5)
- Q_{tot} — Sum of $Q_{Pulse,tot}$ and Q_{Corona}
- Q_{Flash} — Charge transfer by the entire flash
- I_{peak} — Peak current of the flash
- t_{Flash} — Total time of current flow in the lightning channel

TABLE 1: PARAMETERS OF PULSES AND OVERALL CURRENT OF POSITIVE UPWARD INITIATED LIGHTNING TO THE GAISBERG TOWER

Date	Time	Flash #	N Number Pulses	Δt_{tot} [ms]	$I_{max,rel}$ [kA]	Δt_{Puls} [µs]	Q_{Puls} [As]	$Q_{Puls,tot}$ [As]	Q_{Corona} [As]	Q_{tot} [As]	Q_{Flash} [As]	I_{peak} [kA]	t_{Flash} [ms]
21.01.2000	16:17:55	98	89	2.8	1.6	28.1	0.017	1.5	9.0	10.5	125	10.6	100
21.01.2000	16:25:28	112	68	2.5	5.0	35.7	0.069	4.7	19.7	24.3	356	18.0	70
04.03.2000	23:00:15	139	88	3.8	5.0	40	0.082	7.2	45.9	53.1	162	25.0	45
12.04.2000	10:42:19	161	63	2.4	3.0	34.6	0.036	2.3	11.4	13.8	220	11.9	200
08.11.2000	02:48:24	209	41	1.9	13.7	44.5	0.321	13.2	22.8	35.9	62	39.3	5
08.11.2000	02:50:03	210	48	1.9	13.1	37.7	0.238	11.4	19.0	30.4	55	39.3	16
23.02.2001	10:22:54	214	72	2.2	3.0	30.6	0.036	2.6	9.3	11.9	63	13.9	32
06.12.2001	07:05:25	270	25	0.9	1.8	27.2	0.013	0.4	0.7	1.1	20	2.0	12
23.03.2002	14:46:08	298	48	1.6	2.8	31.5	0.030	1.4	4.9	6.3	90	7.0	75
		Min	25	0.9	1.6	27.2	0.013	0.4	0.7	1.1	20	2.0	5
		Mean	**60**	**2.2**	**5.5**	**34.4**	**0.093**	**5.0**	**15.8**	**20.8**	**128**	**18.5**	**62**
		Max	89	3.8	13.7	44.5	0.321	13.2	45.9	53.1	356	39.9	200

Note: Q_{tot} is the charge transfer measured during the pulsing section (time period from 0 to Δt_{tot}) whereas Q_{Flash} is the transferred charge by the entire flash.

III. DISCUSSION

It is worth noting that all the positive flashes to the tower occurred during the cold season or even during winter time. Positive upward lightning is initiated by a negative leader, the same type of leader that initiates negative downward lightning, which is the most common type of lightning discharge to ground. We can speculate that the leader propagate upward until it reaches regions of positive charge in the cloud above the tower site. Thus the measured current at the tower provides some insight into the current characteristics and hence into the total charge that is deposited along the leader. It is commonly assumed, that there are two basic processes involved in the leader formation. The leader is vertically extended by each of the leader steps causing the observed short current pulses and at the same time charge is continuously deposited along the leader channel in a corona sheath surrounding the highly ionized leader core.

Total leader length and leader step length:

Assuming a typical stepped leader propagation speed of 300 m/ms (values measured by Berger and Vogelsanger (1969) [1] ranged from 80 to 450 m/ms) and the mean of measured time duration Δt_{tot} of 2.2 ms for the pulsing section (see Table 1) one can estimate a total channel length of 660 m. This somewhat short channel length seems reasonable for winter lightning to a 100 m tower located at a mountain top at 1280 m above sea level. One can also calculate an average length of the leader steps of 11 m when we divide the total estimated leader length of 660 m by the observed mean of 60 pulses during the stepping section. This is in acceptable agreement with measured step length from optical observations of 6.2 to 23 meter (mean 8.2 meter) at the Empire State Building [4] and 4 to 40 meter at the Mont San Salvatore [1].

The duration of the pulsing section of the current with a mean of 2.2 ms is significantly shorter than the mean leader duration of negative downward stepped leaders. A possible reason for this difference could be the proximity of the cloud charge to the ground in winter thunderstorms. Rakov and Uman (1990) [5] reported a geometric-mean leader duration of 35 ms for stepped leaders for strokes of various orders in Florida. Assuming an average stepped leader speed of 2×10^5 m/s they estimated a channel length of 7 km, a reasonable estimate for Florida lightning [6].

The observed mean of 34.4 µs for Δt_{Pulse} is well within the inter-step interval of 30 – 50 µs reported in [1] and is in the same range as measured intervals between stepped leader electric field pulses within a millisecond or so of the return stroke pulse (see Table 4.3 in [6]).

Leader steps current:

From measurements of the electric field pulses radiated by leader steps, peak step current was inferred to be at least 2-8 kA close to the ground [3]. For the upward negative leaders from the tower we have determined leader step peak currents ($I_{max,rel}$ in Table 1) in the range from 1.6 to 13.7 kA (mean 5.5 kA).

Leader charge:

All current waveforms of upward propagating negative leaders exhibit a similar basic structure. Current pulses are superimposed on a more or less steadily raising current slope (see Figure 2 and Figure 6) and pulsing vanishes at the time when the overall current reaches its first maximum. This is probably the time, when the upward propagating negative leader reaches positively charged regions in the cloud above and the compensation of leader charge is initiated. Compared to negative cloud-to-ground lightning there is not a striking point clearly defining the end of leader progression and the beginning of the return stroke phase, respectively.

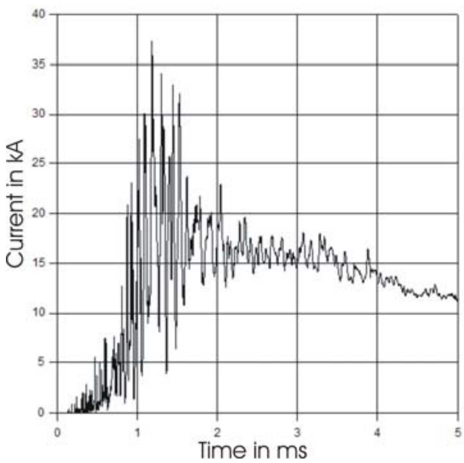

Figure 6: Overall current of upward negative leader current (Flash #139)

One can assume that the current component responsible for the establishment of the corona sheath along the leader channel is represented by the steadily raising current I_{Corona} and Q_{Corona}, respectively. A mean charge of 15.8 C is injected into the leader corresponding to a line charge density of 15.8 mC/m, when we assume a length of 1 km for the leader channel. By lack of optical information about the geometrical structure of the analyzed leaders we can only speculate about the effect of significant branching of the leader channel. Concurrent development of several leader channels at the same time most likely results in an increased total charge transfer from the tower top into the leader. Typically a line charge density of 1 mC/m is estimated for negative downward stepped leaders, being significantly smaller than the mean value of 15.8 mC/m. Different number of branches in the 9 flashes could also explain the wide range of Q_{Corona} from 0.7 C to 45.9 C.

It is worth noting that all the mean values of pulse current characteristics (current, duration, charge) to some extend are affected by the procedure that we have applied to classify individual leader current pulses.

IV. Conclusion

Direct measurement of the current of upward propagation leaders from a high tower allows comparison of the current parameters with published features of negative upward and downward propagating stepped leaders. These published leader current characteristics have been inferred either from optical measurements or from electric and/or magnetic field measurements. Many of the characteristics observed at the Gaisberg tower are in good agreement with published characteristics of negative stepped leaders and support the assumption of a strong similarity of the physical processes, independent of the direction of leader propagation.

V. References

[1] Berger, K., and Vogelsanger, E. 1969. New results of lightning observations. In Planetary Electrodynamics, eds. S.C. Coroniti and J. Hughes, pp. 489-510, New York: Gordon and Breach.

[2] Diendorfer, G., M. Mair, W. Schulz, W. Hadrian. 2002. Lightning current measurements in Austria – Experimental setup and first results. Proc. 25th International Conference on Lightning Protection (ICLP), Rhodos, Sept. 2000, pp. 44-47

[3] Krider, E.P., C. D. Weidman, R.C. Noggle. 1977. The Electric Fields Produced by Lightning Stepped Leaders. Journ. Geophys. Res. Vol.82, No 6

[4] McEachron, K. B. 1939. Lightning to the Empire State Building. J. Franklin Inst. 227: 149-217.

[5] Rakov, V. A. and M. A. Uman 1990. Waveforms of first and subsequent leaders in negative lightning flashes. Journ. Geophys. Res.Vol.95, N. D10, 16561-16577

[6] Rakov, V. A. and M. A. Uman 2003. Lightning : Physics and Effects. Cambridge Press

[7] Yoda, M., T. Nakajima, I. Miyachi, M. Ieda, K. Nakamura. 1997. Measurement of Lightning Current and Emission in Winter. Proc. 10th Intern. Symposium on High Voltage Engineering, Montreal, Canada