Statistical Distributions of Lightning Currents Associated With Upward Negative Flashes Based on the Data Collected at the Säntis (EMC) Tower in 2010 and 2011

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***Abstract*—This paper presents statistical distributions of lightning current parameters based on the lightning current and current-derivative waveforms measured at the Säntis Tower site in 2010 and 2011. The total number of flashes analyzed in this study was 167, which includes nearly 2000 pulses. The statistical distributions refer to upward negative flashes. It is shown that negative flashes are mainly concentrated in the summer months during the convective season. Statistical data on the salient lightning current parameters, namely, peak current, peak current derivative, risetime, pulse charge, pulse duration, interpulse interval, and flash multiplicity are presented and discussed. The obtained data that constitute the largest dataset available to this date for upward negative flashes are also compared with other available statistical distributions.**

***Index Terms*—Instrumented tower, lightning current, statistical distributions, upward flashes.**

I. Introduction

THE KNOWLEDGE of the lightning channel-base current waveforms is of primary importance for the analysis of lightning interaction with electrical power and electronic systems as well as for the design of relevant protections.

Lightning channel-base current waveforms are obtained either by direct measurements using instrumented towers (e.g., [1]–[5]) or from artificially-initiated lightning (e.g., [6]–[8]). Estimates of various lightning current parameters can also be obtained from the measurements of lightning electromagnetic fields assuming one or more empirical [9] or theoretical [10], [11] relations between the lightning current and associated electromagnetic fields.

In this paper, we present statistical data on lightning current parameters associated with upward negative flashes obtained using directly-measured current and current derivative waveforms in 2010 and 2011 at the Säntis Tower in Switzerland. The tower was instrumented in 2010 [12], [13]. The period of analysis extends from May 2010 to January 2012. Out of a total of 200 successfully recorded flashes, 167 were of negative upward type. The analysis presented in this paper concerns upward negative flashes. Data on positive and bipolar flashes will be presented in a subsequent publication. Reference is also made to available statistical distributions.

Upward flashes are of interest for lightning protection of tall structures such as telecommunications towers. Additionally, upward flashes are considered to be a major threat for modern wind turbines that are characterized by very long blades and tall masts with overall heights that usually exceed a 100 m. As a result, the majority of the strikes to modern turbines are expected to be upward lightning [14].

The paper is organized as follows: Section II describes the Säntis tower and the installed instrumentation. Section III describes the methods used to characterize lightning current parameters, as well as the algorithms used to post-process the measured lightning current waveforms to infer their relevant characteristics. Section IV presents the statistical analysis of the lightning current parameters. Finally, a summary and conclusions are presented in Section V.

II. Säntis Tower and its Instrumentation

The Säntis Tower (Fig. 1) is a 124-m-tall tower sitting on the top of the 2502-m-tall Mount Säntis located at 47° 14’57”N and 9° 20’32”E in the Appenzell region in the northeast of Switzerland. The grounding resistivity in the Säntis Mountain area (rocky soil) is in the order of 10 kΩm. The tower has a hollow, metallic inner conical structure of 2 m radius at the base and 1 m at its top. An outer Plexiglas structure has a radius of 3 m at the base and 1.5 m at the top. The structure serves mainly as a telecommunications tower and as a weather station. A decade-long analysis on the lightning incidence to several towers at various locations in Switzerland resulted in the choice of the Säntis tower, which is struck by lightning about 100 times a year [13].

The Säntis station has been instrumented using advanced and modern equipment including remote monitoring and control capabilities for an accurate measurement of lightning current parameters [13], [15]. The lightning current is measured at two

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Fig. 1. Säntis tower.

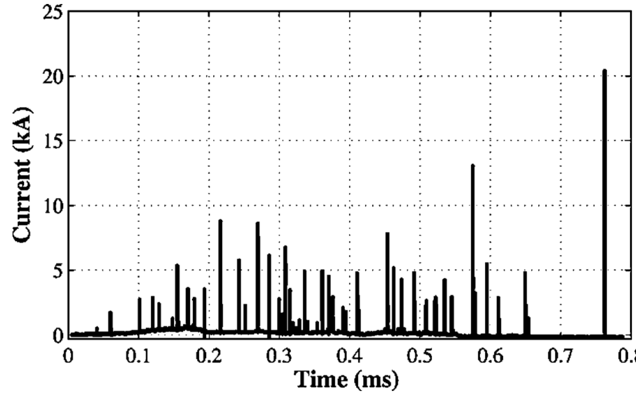

Fig. 2. Typical current waveform measured at the Säntis Tower using the Rogowski coil 82 m above ground level. The flash occurred on October 12, 2010, at 19h52.

different heights, 24 m and 82 m. At the lower height, we installed two Rogowski coils with different sensitivities, each one with its analog integrator used to obtain the current waveform. These Rogowski sensors were manufactured, respectively, by PEM Inc. and ROCOIL. Two further sensors were installed at 82 m. The first one is a Rogowski coil (PEM Inc.) coupled with its analog integrator. The second sensor placed at that height is a specially-designed multi-gap magnetic loop (B-Dot) sensor. It has been specifically developed to measure the lightning current derivative [16]. The analog outputs of the sensors are relayed to a digitizing system by means of analog-to-digital–digital-to-analog 12-bit optical links characterized by an overall bandwidth from dc to 25 MHz. The maximum measurable current level with the PEM Rogowski coils is 120 kA and the maximum measurable current derivative with the B-Dot sensor is 400 kA/is. The PEM Rogowski coil located at 82 m is characterized by a frequency response ranging from 50 mHz to 2.4 MHz, while the upper frequency limit of the B-Dot sensor is about 20 MHz (for more details, see [16]). The measurement window for each flash is 1.2 s with a pre-trigger delay of 0.25 s and a sampling frequency of 100 MHz. Each flash is triggered by the B-dot sensor and the trigger level is 2 kA/μs.

The status and settings of each pair of sensors can be monitored and changed by means of a control system designed and built using National Instruments Compact-RIO modules linked via fiber optics using 100Base-FX Ethernet. A local server running monitoring and storage tasks is housed in a shielded control room several tens of meters from the base of the tower. The server and the front-end station are connected to the Internet over a router and a standard DSL link, allowing remote maintenance, monitoring, and control of the overall measurement chain. More details on the installed measurement system can be found in [13], [16].

III. Lightning Current Parameters Considered in This Study

A. Current Waveform Associated With a Typical Upward Negative Flash

Fig. 2 shows an example of a flash current record measured by one of the Rogowski coils located at the top measuring location (82 m). The current waveform is typical of upward negative flashes with an initial continuous current (ICC) of about 500 ms duration, and superimposed ICC pulses. The number of recorded ICC pulses is in excess of 30, with peak amplitudes ranging from about 1 kA to 14 kA. After the extinction of the ICC, a return stroke with a peak current of about 22 kA can be distinguished. The maximum time derivative of the return stroke is about 56 kA/μs and the total transferred charge of this flash is 21 C.

For the statistical analysis of the parameters associated with current pulses, we considered together: 1) return stroke pulses, namely, pulses occurring after the extinction of the initial continuous current and 2) pulses superimposed on the initial continuous current fulfilling two conditions: a rise time lower than 8 μs and an amplitude greater than 2 kA. These pulses are believed to be associated with the leader/return stroke mode of charge transfer, as opposed to slower pulses which are associated with the M-component charge transfer mode [17].

B. Procedure for the Estimation of Lightning Current Parameters

Measured lightning currents are characterized by a frequency spectrum extending from dc to a few megahertz [18]. Broadband resistive shunts (e.g., [5]) represent an ideal solution for the measurement of lightning currents as their output is a faithful reproduction of the current associated with various processes of a lightning discharge including, in the case of upward discharges, the initial continuous current, superimposed pulses, and return strokes. However, such a solution was not possible in the case of the Säntis Tower. Another solution often adopted for the measurement of lightning currents on instrumented towers is the use of Rogowski coils (e.g., on the CN Tower in Canada [19]). Rogowski coils can, in principle, have a frequency response down to the Hz or even mHz regions and they should be able to record initial continuing currents associated with upward flashes (i.e., [20]). However, their high frequency response is limited by the size of the sensor and by its resonance frequency, which might be as low as some hundreds of kilohertz [15]. As a result, the current rise time and time-derivative might be affected by the high frequency shortcomings of Rogowski coils.

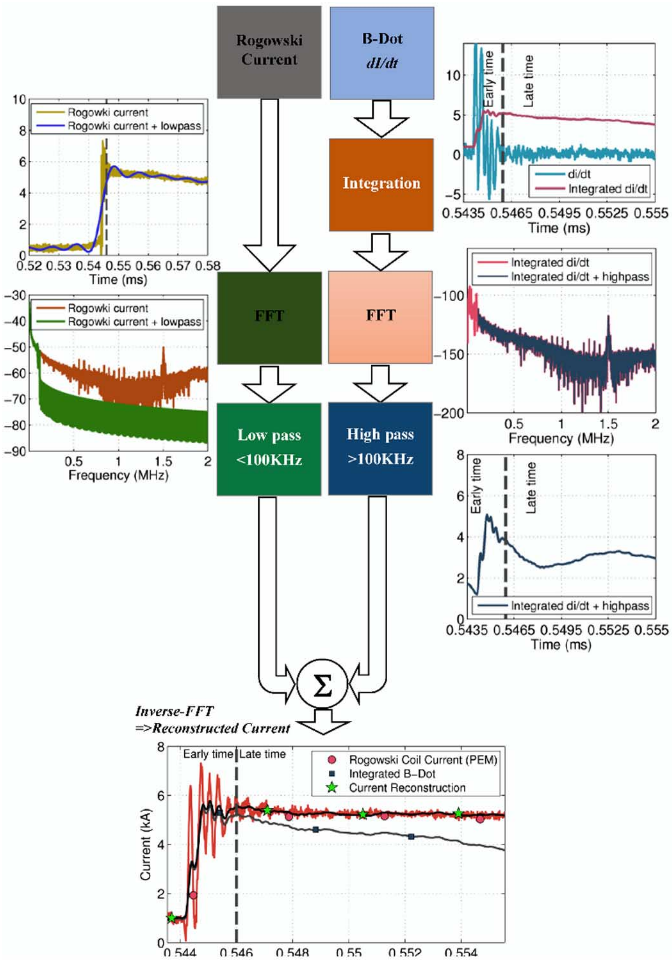

Fig. 3. Block diagram of the current reconstruction algorithm from the Rogowski coil and the B-dot sensor.

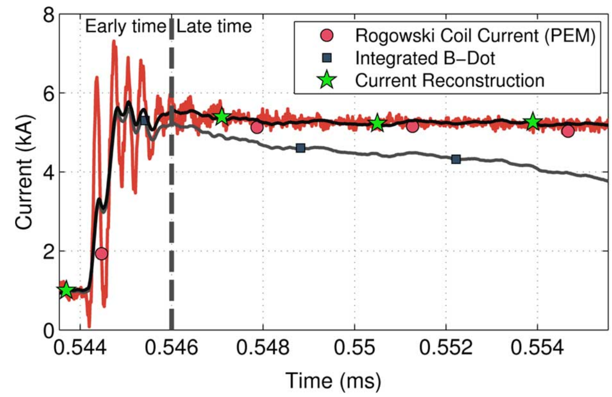

Fig. 4. Measured and reconstructed waveforms associated with a return stroke of an upward flash measured at Säntis. Dot markers: Current waveform measured by the Rogowski coil. Square markers: Current waveform obtained by numerical integration of the B-dot sensor. Star markers: Reconstructed waveform according to the procedure described in Fig. 3.

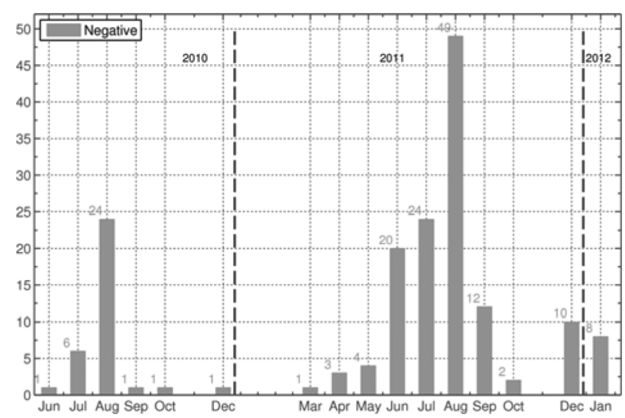

Fig. 5. Negative flash count to the Säntis tower. June 2010 to January 2012.

In order to overcome the limited high frequency response of the Rogowski coils, we used a multi-gap B-dot sensor which has been shown to be very accurate for the measurement of the early-time response of the current derivative [16]. Assuming proportionality between magnetic field and current, the current is obtained by numerical integration of the B-Dot sensor output. The effectiveness of the simultaneous use of Rogowski coils and B-dot sensors for the measurement of lightning currents was demonstrated through laboratory tests carried out in the high voltage laboratory of the Swiss Federal Institute of Technology, Lausanne (EPFL) [16].

An algorithm was developed and used for the reconstruction of the impulse current signal from the B-Dot and Rogowski signals (see the block diagram shown in Fig. 3).

One of the advantages of the developed measurement system is that all the signals are sampled in parallel as the adopted digitizers share the same trigger signal and have locked oscillators. As a consequence, we can apply subsequent filtering and superposition to signals coming from different sensors. In particular, the Rogowski coil signal is transformed into the frequency domain by applying an FFT and it is filtered using a 100 kHz low-pass equal-ripple FIR filter. This low-pass filter removes the measured resonance frequency of the Rogowski coils (1.2 MHz [16]). The B-dot sensor signal is integrated before being transformed into the frequency domain and filtered using a 100 kHz high-pass filter. The two signals are then added and converted back into the time domain. This approach was tested using different waveforms measured simultaneously by the two systems and found to be very reliable. Fig. 4 shows an example of waveforms recorded by the Rogowski coil and the integrated B-dot sensor output associated with a return stroke in an upward negative flash on the Säntis Tower where it can be seen that the early-time response of the reconstructed current is essentially determined by the B-dot sensor as it does not show the oscillatory behaviour of the Rogowski coil which is presumably due to the coil resonance [15]. On the other hand, the late time behaviour of the reconstructed signal follows that of the Rogowski coil.

IV. Statistical Analysis

A. Measured Data

The presented statistical analysis concerns data recorded at the Säntis Tower from May 2010 until January 2012. Over this period, a total of 200 flashes were recorded, including 33 positive and bipolar flashes. Although for many of the flashes, the continuous current was not high enough to be discernible above the noise, we assumed all flashes to be of the upward type as it

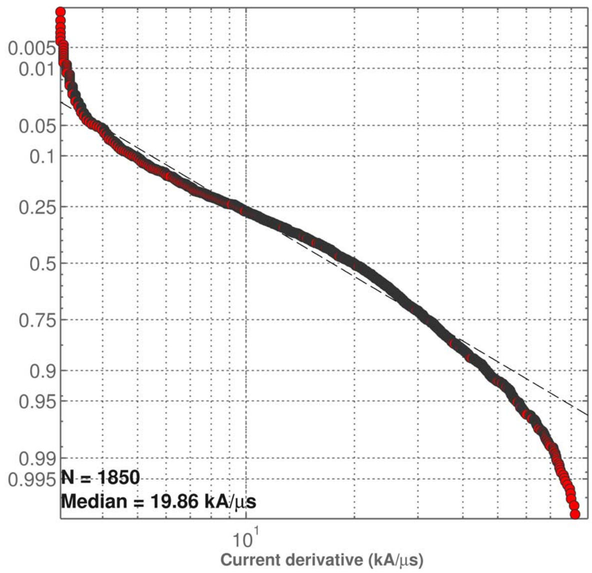

Fig. 6. Maximum current derivative probability plot.

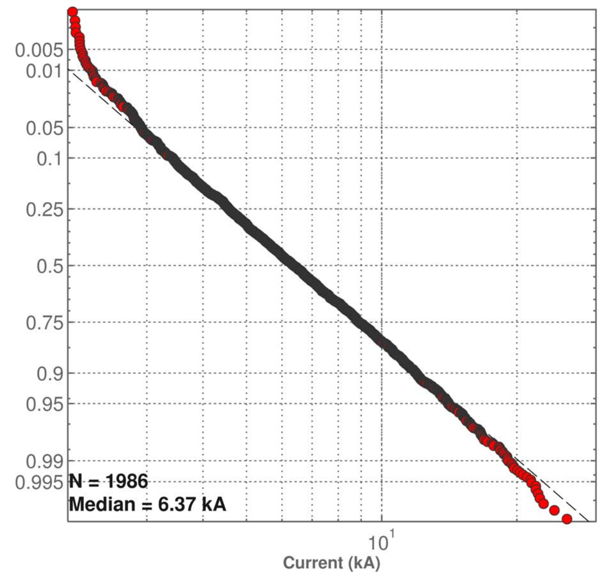

Fig. 7. Peak current probability plot.

TABLE I
STATISTICAL PARAMETERS OF PEAK CURRENT DERIVATIVE

Peak current derivative (kA/μs)

Tower	Sample size	Percentage Exceeding Tabulated Value 95%	90%	50%	10%	5%
Empire State Building [21]	71	1.2	2.5	13.0	33	38
San Salvatore [22]	710	-	5.6	26	123	-
Peissenberg [23]*	125	-	-	11	-	87
CN Tower [19]	387	3.8	-	18.8	-	37
Säntis (This study)	1850	3.9	4.8	19.9	46.5	56.3

* for ICC pulses and return-stroke pulses

TABLE II
STATISTICAL PARAMETERS OF PEAK CURRENT

Peak current (kA)

Tower	Sample size	Percentage Exceeding Tabulated Value 95%	90%	50%	10%	5%
Empire State Building [21]	82	-	4	5	10	-
San Salvatore [22]	176	-	4.2	10	25	-
Moscow Ostankino Tower [24]◊	58	-	4	9	19	-
Peissenberg [23]*	125	-	-	8.5	-	20
CN Tower [19]◊	387	1.3	-	5.1	-	16
Gaisberg Tower [5] #	476	3.5	4.2	9.2	18	22
Säntis (This study)	1986	2.9	3.4	6.4	11.9	14.1

◊ Measurements at 533 m above ground
* for ICC pulses and return-stroke pulses
\# Current pulses underwent a 250-kHz low pass filtering

is expected that a structure with the characteristics of the Säntis Tower be struck by upward lightning most or all of the time.

B. Seasonal Occurrence of Flashes to the Säntis Tower

Fig. 5 presents the monthly flash count spanned, and accumulated over the whole measurement period.

It can be seen from Fig. 5 that negative flashes are mainly concentrated in the summer months during the convective season, August being the month during which most of the negative flashes occurred (24 events in 2010 and 49 events in 2011). This distribution contrasts with the Gaisberg Tower measurements for which lightning strikes are quasiuniformly distributed over the year [5]. Note also the significant increase of the lightning activity in 2011 with respect to 2010. We believe that the increase is essentially due to year-to-year weather variations. Indeed, MeteoSuisse measured a mean temperature of 8 °C on the Säntis for the month of August 2011, which is about 60% higher than the 4.8 °C mean temperature for the same month in 2010. Also, more than 50 flashes (positive and negative) were measured during one single storm occurred in the morning of August 27, 2011. Finally, some flashes might have been missed by our system during the first months of operation.

C. Maximum Current Derivative

As indicated in [15], the scaled B-dot sensor is directly used for the evaluation of the maximum current derivative statistical values. Fig. 6 presents the probability plot and histogram of

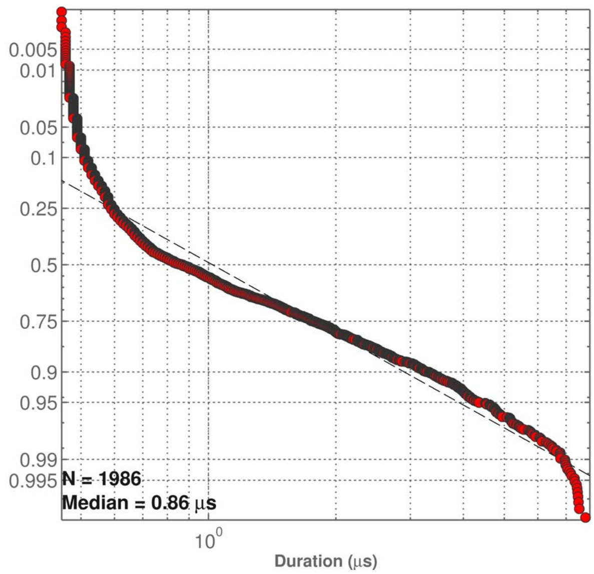

Fig. 8. Probability plot for the t_{10-90} current risetime.

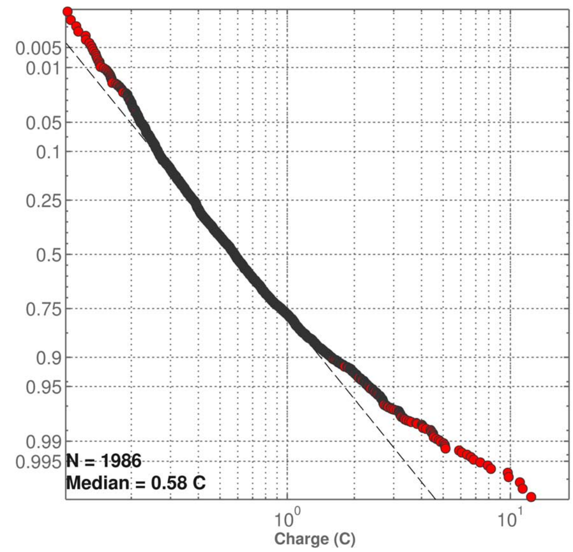

Fig. 9. Pulse charge probability plot.

TABLE III
STATISTICAL PARAMETERS OF CURRENT RISETIME

$t_{10-90\%}$ (μs)						
Tower	Sample size	Percentage Exceeding Tabulated Value 95%	90%	50%	10%	5%
Empire State Building [21]	82	-	0.3	1	5	-
San Salvatore [22]	696	-	0.3	1	4	-
Säntis (This study)	1986	0.49	0.51	0.86	3.29	4.36

*) Zero-to-peak
• Front duration: time interval between the 2 kA point and the peak

TABLE IV
STATISTICAL PARAMETERS OF PULSE CHARGE

Pulse Charge (C)						
Tower	Sample size	Percentage Exceeding Tabulated Value 95%	90%	50%	10%	5%
Empire State Building [21]	81	-	-	0.15	1.3	-
San Salvatore [22]	579	-	0.14	0.77	4.1	-
Gaisberg Tower [5]	615	0.15	0.2	0.51	1.2	1.7
Säntis (This study)	1986	0.2	0.3	0.6	1.6	2.3

the maximum current derivative for a total number of $N = 1850$ events. Note that this number is smaller than the total number of measured pulses, which is 1986. This is because the B-dot sensor cannot measure steepnesses lower than 2 kA/μs. The highest measured value for the maximum current derivative during the period of observation is 88.9 kA/μs. The straight line in Fig. 6 corresponds to the equivalent lognormal distribution. The median is found to be 19.9 kA/μs.

Table I summarizes the statistical data for the maximum current derivative, in comparison with existing available data. It can be seen that the Säntis data are very similar to the data associated with the CN Tower, with the exception of the 5% value, for which a larger difference can be observed.

D. Peak Pulse Current

Fig. 7 presents the probability plot of the peak current for a total number of $N = 1986$ events. The maximum measured value for the peak current during the period of observation is 26.5 kA and the median is 6.4 kA. Again, it can be seen from Table II that the obtained data at Säntis seem to be closest to the data associated with the CN Tower and to those obtained at the Empire State Building.

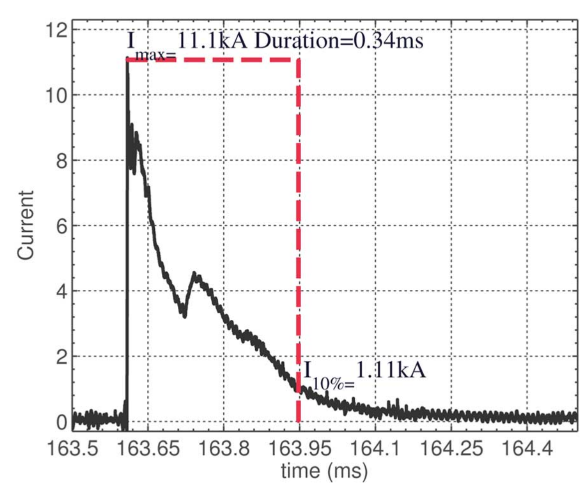

Fig. 10. Definition of the pulse duration.

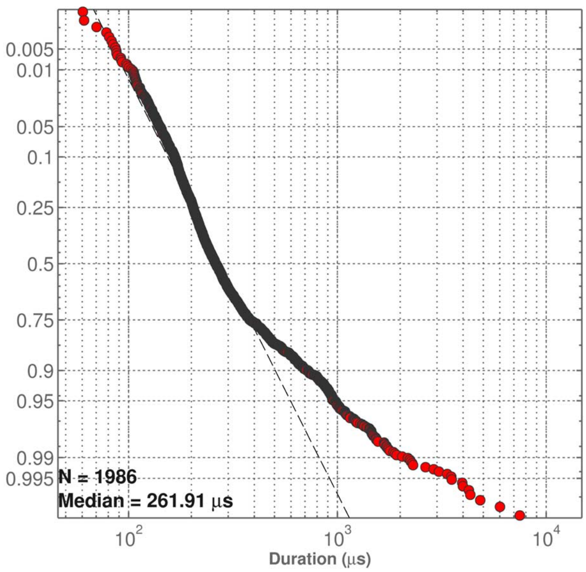

Fig. 11. Pulse duration probability plot.

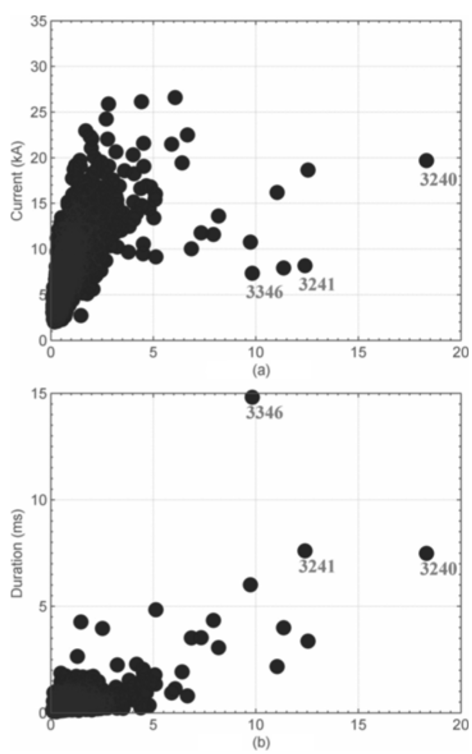

Fig. 12. Plots of (a) the current peak and (b) pulse duration versus transferred pulse charge.

E. Current Risetime

Estimates of the risetime of the measured lightning current pulses are useful in the determination of idealized lightning current waveforms that can be used in many applications such as testing, electromagnetic simulations, power system protection planning [25], bandwidth estimation, and sensor design (e.g., [26]).

Fig. 8 presents the probability plot of t_{10-90} for a total of $N = 1986$ events. Note that for the calculation of t_{10-90}, we

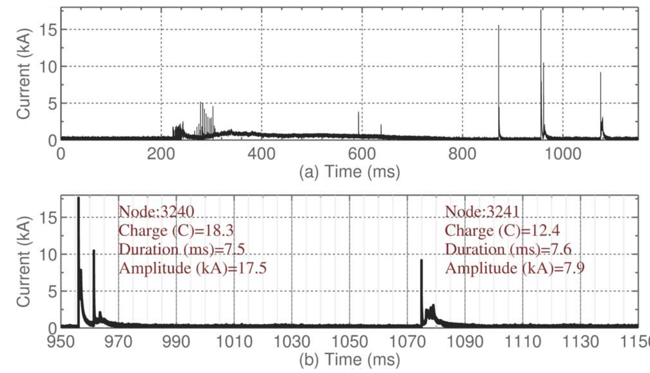

Fig. 13. Example of a current waveform associated with an upward negative flash occurred on 2011-07-13 at 17:36.26. (a) Overall flash current. (b) Details of the last two pulses (return strokes).

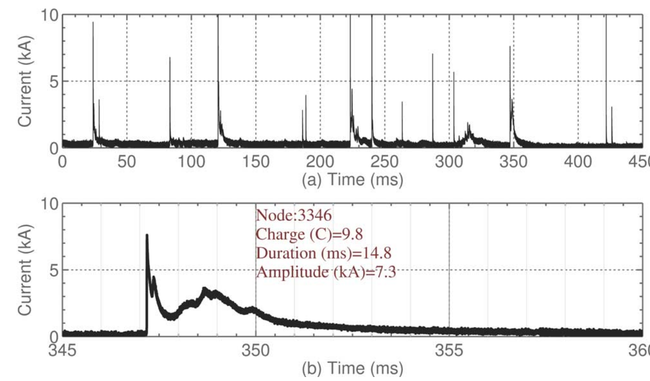

Fig. 14. Flash occurred on 2011-07-23 at 17:40.57. (a) Current for the overall flash. (b) Detail of the pulse occurred at about 350 ms, with the longest pulse duration (labeled as 3346 in Fig. 12).

considered the overall peak and the instants when the 10% and 90% amplitudes are reached for the first time.

Table III summarizes the statistical results associated with the current risetime. In the same table, we have presented available data associated with the Monte San Salvatore Tower and the Empire State Building. Note that in these studies, different definitions were used for the risetime, as mentioned in the table.

F. Pulse Charge

Fig. 9 presents the probability plot of the transferred charge associated with each pulse for a total of $N = 1986$ events. The median charge is 0.58 C.

Table IV presents a comparison of the obtained statistical data with available data in the literature. It can be seen that the obtained statistical data are very similar to those obtained recently at the Gaisberg Tower.

G. Pulse Duration

The pulse duration is defined as the time from the point in time at which the current reaches its peak to the point where the current decays to 10% of this value. This definition is illustrated in Fig. 10.

Fig. 11 presents the probability plot of the pulse duration. A total of $N = 1986$ events is analyzed.

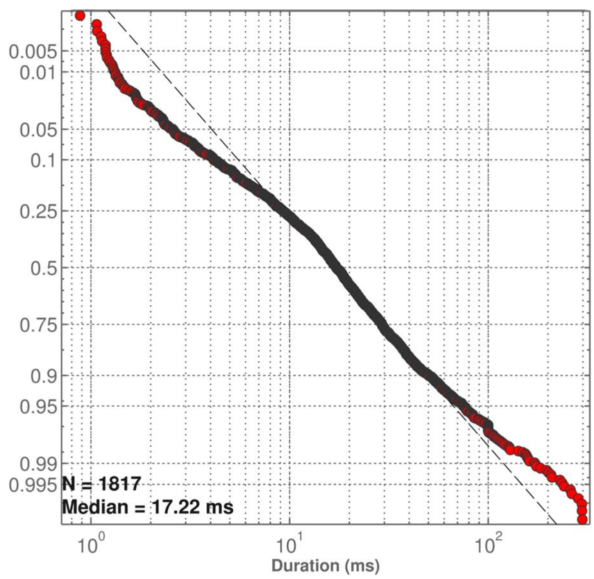

Fig. 15. Interpulse interval probability plot.

TABLE V
SUMMARY OF ESTIMATED PARAMETERS FOR THE TOTAL FLASH CHARGE IN FOUR EVENTS

Flash	Total Charge (C)	Total Duration (ms)	ICC current duration (ms)
Flash # 8 2010-07-26 at 17:42	101	1100*	400
Flash # 70 2011-06-22 at 17:21	92	800	700
Flash # 90 2011-07-13 at 16:20	60	550	300
Flash # 92 2011-07-13 at 17:38	181	1100*	800

* The maximum measurement window of the digitizers was insufficient to cover the whole flash duration

Fig. 12(a) and (b) presents scatter plots comparing the values of current peak and pulse duration as a function of transferred pulse charge. The data present a positive correlation for both figures.

Note that two pulses (labeled 3240, 3241 in the Säntis database, and visible in Fig. 12(a) and (b) labels) associated with high charges correspond to a single flash occurring on 2011-07-13 at 17:36.36 CET. The overall current measurement for this flash is presented in Fig. 13(a), and the detail of the aforementioned points in the scatter plots is depicted in Fig. 13(b). This flash is characterized by a long initial continuous current of about 400 ms, followed by four return strokes. The overall charge transferred to ground for this flash is close to 200 C.

The event corresponding to the longest pulse, labeled 3346 in the scatter plots in Fig. 12, is presented in Fig. 14. It is characterized by a measured pulse duration of 14.8 ms. Note that the long pulse duration is due to the presence of a continuous current following the main pulse.

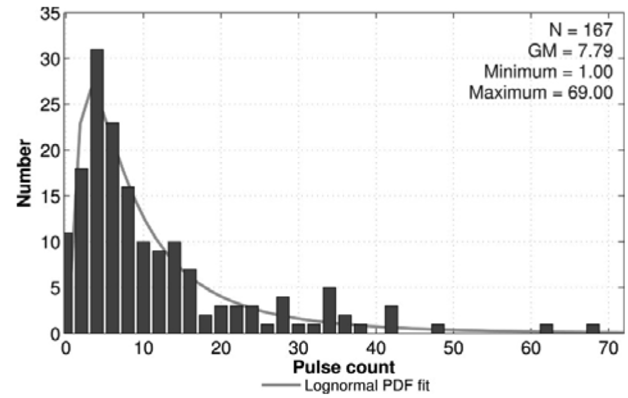

Fig. 16. Flash multiplicity histogram.

TABLE VI
SUMMARY OF STATISTICAL PARAMETERS OF LIGHTNING CURRENTS ASSOCIATED WITH UPWARD NEGATIVE FLASHES MEASURED AT THE SÄNTIS TOWER

Parameter	Sample size	Percentage Exceeding Tabulated Value 95%	90%	50%	10%	5%
Peak current derivative kA/µs	1850	3.9	4.8	19.9	46.5	56.3
Peak current kA	1986	2.9	3.4	6.4	11.9	14.1
$t_{10\text{-}90}$ µs	1986	0.49	0.51	0.86	3.29	4.36
Pulse Charge C	1986	0.2	0.3	0.6	1.6	2.3
Inter-pulse Interval ms	1817	2.57	4.15	17.2	50.1	75.1
Flash Multiplicity Count	167	1	2.2	8	29	37
Stroke Duration µs	1978	141	166	262	724	978

H. Interpulse Interval

Fig. 15 presents the probability plot and histogram of the interpulse interval for a total number of 1817 intervals. The obtained value for the median (17.2 ms) is consistent with the value reported for the Gaisberg Tower (17.3 ms) [8].

I. Total Flash Charge

The noise level associated with the measurement system does not allow us to accurately characterize flashes with a relatively low initial continuous current. As a result, no statistical data will be presented for the total transferred charge associated with the flashes. Table V presents the data for the total transferred charge, total flash duration, and the ICC duration for four flashes characterized by a relatively large continuous current. It is interesting to observe that, at least in some cases, large charge transfer amounts (in excess of 50 C) can be associated with upward negative flashes.

All four flashes in Table V were measured during the convective season (July 2011 and June 2012). The main charge transfer is due to the long initial continuous current, while the individual strokes contribute marginally to the total charge.

J. Flash Multiplicity

The histogram of the flash multiplicity (or the number of pulses per flash) is presented in Fig. 16. It presents a lognormal distribution with a median of eight pulses per flash. It is worth noting that the flash multiplicity is determined considering all the pulses of each flash satisfying the same two conditions that we used in our statistical analyses, already mentioned in Section III-A, that make them indicative of the leader/return-stroke mode of charge transfer [17], namely a risetime lower than 8 μs and an amplitude superior to 2 kA.

V. Summary and Conclusions

In this paper, we presented statistical distributions of the lightning current parameters based on the lightning current and current-derivative waveforms measured at the Säntis Tower site in 2010 and 2011. The total number of flashes analyzed in this study was 167, which include nearly 2000 pulses. The statistical distributions are associated with upward negative flashes.

In the collected measurement dataset, negative flashes were mainly concentrated in the summer months during the convective season. This distribution contrasts with the Gaisberg Tower measurements for which lightning strikes are essentially uniformly distributed over the year.

Table VI summarizes the obtained statistical data on lightning current parameters.

The obtained data were compared to and found, in general, to be consistent with published data associated with measurements obtained at other sites, the statistical values being closest to those at the CN Tower and the Empire State Building.

It is worth noting that the obtained data constitute the largest dataset on lightning current and currents derivatives associated with upward negative flashes available to this date.

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