Performance of the European Lightning Detection Network EUCLID in Case of Various Types of Current Pulses From Upward Lightning Measured at the Peissenberg Tower

Christian Paul, Fridolin H. Heidler, *Senior Member, IEEE*, and Wolfgang Schulz

***Abstract*—In this paper, we present current pulses from upward lightning, which have been measured since 2011 at the new top structure of the Peissenberg Tower, Germany. The study comprises 38 negative and two positive flashes, which contained 199 current pulses. About 49 of them were return stroke current pulses, 133 of them were current pulses, which superimposed the initial continuous current (ICC-pulses), and 17 of them were M-component current pulses, which superimposed the continuing current of a preceding return stroke. The current pulses are used to evaluate the performance of the European lightning location system EUCLID. Fifty one (25.6%) out of the 199 current pulses were detected by EUCLID, 40 (81.6%) return stroke current pulses, and 11 (8.5%) ICC-pulses or M-component current pulses. The peak currents ranged from 0.1 to 40.8 kA. Two groups of current pulses could be identified. The first group is related to branches of nearby downward lightning which got in contact with the tower. Therefore, EUCLID reported much higher peak currents (more than 100%) compared to the peak currents measured at the Peissenberg Tower. The first group comprises the total of nine current pulses (six ICC-pulses, three return stroke current pulses). The second group of current pulses is related to upward lightning initiated from the top of the tower. The peak current inferred from EUCLID deviates much less from peak current measured at the Peissenberg Tower. The peak current was overestimated by about 20% by EUCLID. The second group comprises the total of 42 current pulses (4 ICC-pulses, 1 M-component current pulses, and 37 return stroke current pulses). The peak currents ranged from 3.1 to 40.8 kA, the geometric mean (GM) was 9.4 kA. About 30% of these events were misclassified as intra-cloud pulses by EUCLID. The GM of the location error was 161 m for all events, and 132 m considering only the return stroke current pulses.**

***Index Terms*—Current pulses, electric field pulses, initial continuous current (ICC)-pulses, lightning, lightning electric field, lightning location performance, lightning location system (LLS), M-component, Peissenberg Tower, return stroke (RS).**

Manuscript received August 6, 2018; revised October 1, 2018 and November 16, 2018; accepted January 4, 2019. Date of publication January 22, 2019; date of current version February 13, 2020. *(Corresponding author: Christian Paul.)*

C. Paul and F. H. Heidler are with the Institute of High Voltage Technology and Lightning Research (EIT 7.1), University of the Federal Armed Forces-Munich, Neubiberg D-85577, Germany (e-mail: christian.paul@unibw.de; fridolin.heidler@unibw.de).

W. Schulz is with the Austrian Lightning Detection and Information System, OVE Service GmbH, Vienna 1190, Austria (e-mail: w.schulz@ove.at).

Digital Object Identifier 10.1109/TEMC.2019.2891898

I. Introduction

TALL STRUCTURES, with typical heights of more than 100 m, are often struck by upward lightning. In this case, the building itself initiates the lightning strike [1]–[7]. The leader moving upward from the top of the structure is associated with a slow-varying initial continuous current (ICC). The ICC is characterized by a typical magnitude of some tens to some thousands of amperes and a duration of some tens to some hundreds of milliseconds. It may be superimposed by impulsive currents, called ICC-pulses, and followed by one or more return stroke (RS) current pulses [8], [9]. On the contrary, if the upward lightning contains an ICC without significant ICC-pulse and without subsequent RS current pulses, it is classified as $\mathrm{ICC_{only}}$ flash [10]. Each RS may be followed by a continuing current, which has a typical magnitude of some tens to some hundreds of amperes and a duration of some tens to some hundreds of milliseconds. The continuing current can also be superimposed by impulsive currents, called M-component current pulses [11]. Paul and Heidler assumed that ICC-pulses and M-component currents were produced by similar processes [12]. Based on the current waveform, they categorized them into three groups and four sub-groups depending on whether they consist of single current pulses or combinations of at least two single current pulses [12], [13].

A lightning location system (LLS) consists of several stations, which record the electric or magnetic field of the lightning flashes. The striking point is derived either from the time-of-arrival of the field at the individual stations (TOA-method) or from the direction of the magnetic field vector measured at the stations (magnetic finding method), or from both. Additionally, the peak current (called inferred peak current) is evaluated from the received electric or magnetic fields [14]–[16].

The performance of LLSs can be determined comparing the data with those obtained at tall towers. In Europe, three instrumented towers, the Gaisberg Tower in Austria, the Peissenberg Tower in Germany, and the Saentis Tower in Switzerland, are used as ground truth data for such analyses. Azadifar *et al*. analyzed the performance of the European lightning location system called EUCLID (EUropean Cooperation for LIghtning Detection) based on lightning measurements at the Saentis Tower [17]. They reported a median location error of 186 m. Diendorfer *et al*. reported that ICC_{only} flashes cannot be detected by the LLS [10]. They further found out that 20% of the ICC-pulses and 31% of the RSs were misclassified as cloud pulses [18].

In some studies, inferred peak currents of LLSs were compared with lightning currents measured at instrumented towers. The analysis revealed a field enhancement due to the presence of the tower [19]–[21]. The analysis of Heidler and Schulz showed that the enhancement depends on the tower height and the rise time of the lightning current [22].

In this paper, we analyze the performance of EUCLID comparing the LLS-data with the data of the lightning currents measured at the Peissenberg Tower.

II. EUCLID Network

The EUCLID LLS is one of the most validated networks in the world. The EUCLID cooperation started in 2001 and since this time its performance was investigated in several campaigns in Europe, e.g., in Slovenia, where LLS data were compared to data from GPS synchronized flash counters installed on mobile phone towers [23], [24]. In France, video surveys were used to determine the actual network performance of the French lightning location system [25]. In Austria, an electric field and video recording system was developed to evaluate the network performance [26], the same system was used in Belgium [27]. More details about the evolution of the network and the used technology can be found in [28] and [29].

To be able to calculate with all the sensor data the position of a lightning strike, all the partners in this cooperation employ the similar sensor technology from a single manufacturer. As of January 2018, the EUCLID network employs 165 sensors, 34 IMPACT ES/ESP (mainly analog sensor with a dead time in the range of 1–3 ms), and 131 LS700X (sensor with digital signal processing of the field waveform and no dead time) sensors. Fig. 1 shows the EUCLID network configuration as of January 2018 together with the location of the Peissenberg Tower, which is basically in the center of the network. There are four EUCLID sensors within a distance of 150 km from the Peissenberg Tower.

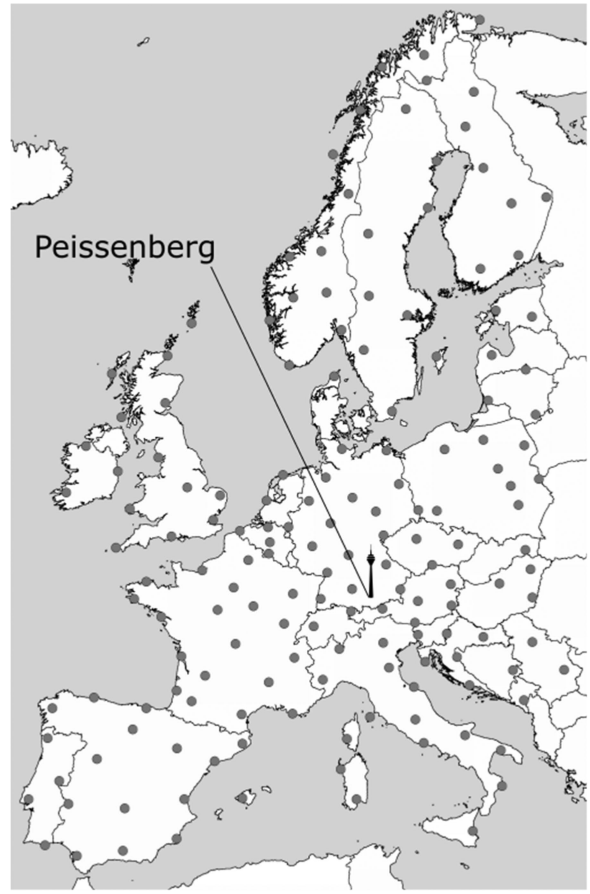

Fig. 1. EUCLID network configuration as of January 2018 with the location of the Peissenberg Tower. Sensor locations are shown as dots.

III. Experiment and Data Overview

The Peissenberg Tower is a 150 m high television broadcasting tower, located 60 km far from Munich (Germany) on the mountain "Hoher Peissenberg," about 940 m above mean sea level. We instrumented the top of the tower with a current probe and a *di/dt*-probe for the measurement of the lightning current and its time-derivative. Furthermore, a field measuring station was installed in the distance of about 180 m from the tower. There, the electric field, the magnetic field, and their time-derivatives were measured.

The measuring devices (NI PXI 5122, PXI 5124) recorded the lightning current and the electric field with 14 bit or 12 bit resolution. The sampling rate was 100 MS/s and the recording period was 2.56 s. The upper cut-off frequency was 30 MHz for the current measuring system and 12 MHz for the field measuring system. Both measuring systems were GPS time synchronized (NI PXI 6682). Between the current and electric field records, a time synchronization accuracy better than 0.1 μs could be achieved (for more details see [5], [6], [12], [13], [22]).

The current records were numerically filtered with a 350 kHz low-pass filter (second-order butterworth) to reduce the noise. Then, the steady components (ICC, continuing current) were subtracted. After that, the waveform of the impulsive current remained.

We classified impulsive currents as RSs, as soon as their 10%–90% rise time $(t_{10-90\%})$ was lower than 4 μs and their peak current (I_p) was higher than 2 kA [12], [13]. The peak current limit of 2 kA is chosen, because Cooray and Rakov estimated that the smallest peak current of a RS that can exist in nature is around to 2 kA [30].

Table I gives an overview of the analyzed impulse currents, measured between May 2011 and September 2017. In total, we analyzed 199 impulse currents, 133 of them were ICC-pulses, 17 of them were M-component currents, and 49 of them were currents of subsequent RSs. The peak current (I_p) ranged from 0.1 to 40.8 kA and the charge (Q) ranged from 2.2 mC to 10.6 C. The 10%–90% rise time $(t_{10\%-90\%})$ varied between 1.0 and 954.2 μs. The current duration is characterized by the full width at half maximum (FWHM), which varied between 5.2 μs and 3.3 ms.

TABLE I
OVERALL VALUES FOR THE ANALYZED 199 IMPULSIVE CURRENTS (133 ICC-PULSES, 17 M-COMPONENT CURRENTS, AND 49 RETURN STROKE CURRENTS)

	Peak current (absolute value) I_p (kA)	10%-to-90% rise time $t_{10\text{-}90\%}$ (µs)	FWHM (µs)	Charge Q (mC)
Minimum	0.1	1.0[a)]	5.2	2.2
Maximum	40.8	954.2	3337.6	$10.6\cdot10^3$
AM	3.5	37.8	182.7	363.0
GM	1.2	11.2	93.8	133.5

[a)]: The minimum value of the rise time may be increased due to the numerical filtering with 350 kHz, i.e. the real minimum rise time may be shorter.
AM: Arithmetic mean GM: Geometric mean

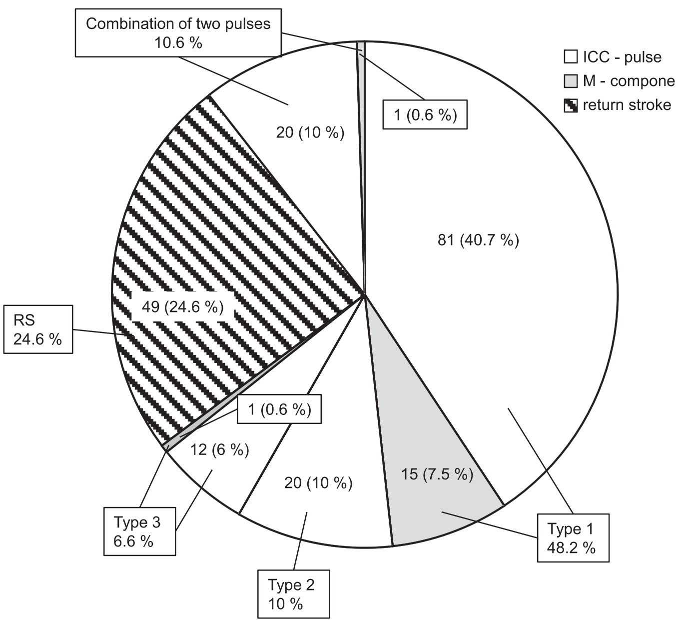

Fig. 2. Frequency distribution of the different types of current pulses.

We classified the ICC-pulses and M-components based on their waveforms, in accordance to the waveform criterion introduced by Paul and Heidler [12].

1) Type 1: Current pulse with almost symmetrical waveform.
2) Type 2: Current pulse with bipolar waveform.
3) Type 3: Current pulse with fast rise and longer decay time.

Four different combinations of current pulses were found.

1) Type A: Double symmetrical current pulse (Type 1 & Type 1).
2) Type B: Double bipolar current pulse (Type 2 & Type 2).
3) Type C: Fast rise and long decay current pulse, superimposed by a symmetrical current pulse (Type 3 & Type 1).
4) Type D: Fast rise and long decay current pulse, superimposed by a bipolar current pulse (Type 3 & Type 2).

Fig. 2 shows the frequency distribution of the 199 current pulses measured at Peissenberg Tower, classified according to the three single types and four combined types of current pulses

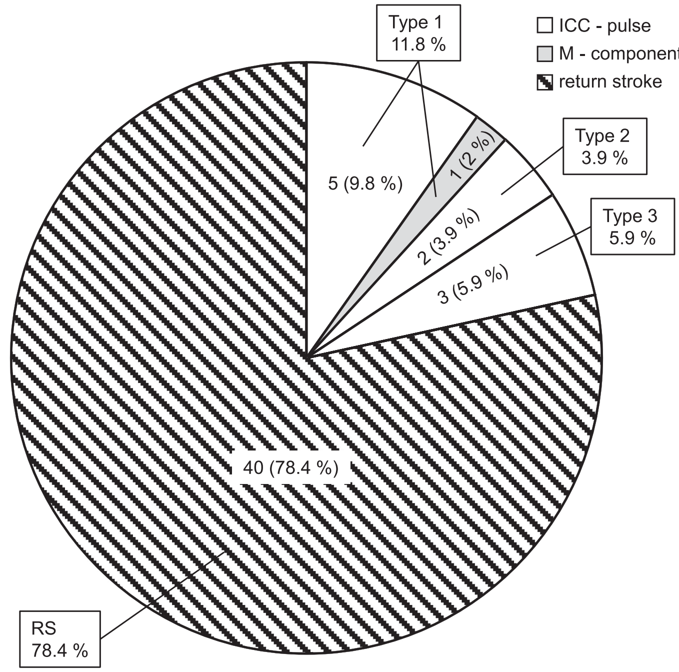

Fig. 3. Frequency distribution of the different types of current pulses detected by EUCLID.

described above. Out of 199, 178 were current pulses of type 1, type 2, or type 3 or RSs. The remaining 21 events were combined current pulses.

IV. ANALYSIS OF THE EUCLID LLS PERFORMANCE

Each EUCLID dataset contains the inferred peak current, the polarity, the number of the used sensors, and the location of the calculated strike point. The EUCLID data were correlated with the Peissenberg Tower data on the basis of their GPS-timestamps and their distances. The average time synchronization error was less than 11 μs. For each current pulse measured at the Peissenberg Tower, we tried to find a corresponding EUCLID event within a radius up to about 3000 m from the tower and a timing error up to 120 μs. About 90% of the matched datasets are within a radius of 250 m and a timing error less than 20 μs.

From the total of 199 current pulses, 51 (25.6%) of them were detected by EUCLID. Fig. 3 shows the frequency distribution of these 51 current pulses detected by EUCLID, classified based on their waveforms. Out of 51 events, 44 (86.3%) were of negative polarity, 2 (3.9%) were bipolar ones, and the remaining 5 (9.8%) were of positive polarity.

From the total of 129 single ICC-pulses and M-component current, only 11 (8.5%) of them could be detected by EUCLID, 6 (6.3%) out of 96 current pulses of type 1, 2 (10%) out of 20 current pulses of type 2, and 3 (23.1%) out of 13 current pulses of type 3. From the 21 combined ICC-pulses and M-component currents, none of them was detected.

In contrary, from 49 RSs, 40 (81.6%) of them could be detected. From the detected 40 RSs, 12 (30%) of them were misclassified as intra-cloud pulses. A similar rate of

TABLE II
OVERALL VALUES FOR THE 51 CURRENT PULSES DETECTED BY EUCLID (10 ICC-PULSES, 1 M-COMPONENT CURRENT, 40 RETURN STROKE CURRENTS)

Parameters of the current pulses measured at the Peissenberg Tower

	Abs. $I_{p,PBT}$ (kA)	FWHM (µs)	Q (C)	$t_{10\text{-}90\%}$, (µs)
Min.	0.1 a)	6.3	0.074	0.99
Max.	40.8	985.73	10.62	649.5
AM	10.1	60.8	0.799	15.7
GM	6.6	35.7	0.345	2.5

Parameters of the current pulses reported by EUCLID

	Abs. $I_{p,EUCLID}$ (kA)	Abs. $\Delta I_{p,abs}$ (kA)	$\Delta I_{p,rel}$ (%)	LE (m)	Num. of sensors
Min.	3.9	0.18	3	14	2
Max.	121.2	121.0	62364	3108	56
AM	18.8	9.65	2350	366	14
GM	13.3	3.59	55	187	11

a): The minimum value of the rise time may be increased due to the numerical filtering with 350 kHz, i.e. the real minimum rise time may be shorter
AM: Arithmetic mean GM: Geometric mean LE: Location error

TABLE III
OVERALL VALUES FOR THE DETECTED NINE IMPULSIVE CURRENTS WITH $\Delta I_{p,\text{rel}} > 100\%$ (6 ICC-PULSES, 3 RETURN STROKE CURRENTS)

	Abs. $I_{p,PBT}$ (kA)	Abs. $I_{p,EUCLID}$ (kA)	$t_{10\text{-}90\%}$ (µs)	LE (m)	$\Delta I_{p,rel}$ (%)	Num. of sensors
Min.	0.1	4.2	1.1 a)	25	108	3
Max.	9.6	121.2	649.5	1499	62364	56
AM	2.8	41.1	75.7	709	13175	21
GM	1.2	23.7	5.6	376	1573	14

a): The minimum value of the rise time may be increased due to the numerical filtering with 350 kHz, i.e. the real minimum rise time may be shorter.

misclassification is reported from the measurements at the Gaisberg Tower. There, 31% of the RSs were misclassified as cloud pulses [18].

Table II summarizes the overall values for the 51 current pulses detected by EUCLID (10 ICC-pulses, 1 M-component current, 40 RS currents). The upper part of Table II contains the parameters of the current pulses measured at the Peissenberg Tower such as the absolute value of the peak current ($I_{p,\text{PBT}}$), the FWHM, the transferred charge (Q), and the 10%–90% rise time ($t_{10\%90\%}$).

The lower part of Table II contains the parameters of the current pulses reported by EUCLID such as the inferred absolute value of the peak current ($I_{p,\text{EUCLID}}$), the absolute ($\Delta I_{p,\text{abs}}$), and relative ($\Delta I_{p,\text{rel}}$) deviation of the peak current from the corresponding Peissenberg Tower data, the location error, and the number of sensors which contributed to the LLS-data. The GM of the relative peak current deviation was 55%. The AM of the location error was 366 m (GM is 187 m).

Two groups of current pulses could be identified: For the first group, the inferred peak current by EUCLID ($I_{p,\text{EUCLID}}$) was significantly higher ($\Delta I_{p,\text{rel}} > 100\%$) compared to the peak current measured at the Peissenberg Tower ($I_{p,\text{PBT}}$). For the second group, the inferred peak current ($I_{p,\text{EUCLID}}$) was only a little bit higher ($\Delta I_{p,\text{rel}} < 100\%$) compared to the peak current measured at the Peissenberg Tower ($I_{p,\text{PBT}}$).

As an example for the first group, in one case, EUCLID reported an inferred peak current of 121.2 kA. This event was detected by 56 sensors. The corresponding current pulse measured at the Peissenberg Tower had a much lower peak value of 0.2 kA (deviation more than 60 000%). The location error was 1337 m and no other lightning event could be observed within the time interval of 100 μs. Therefore, it is likely that the current measured at the Peissenberg Tower is caused by a branch

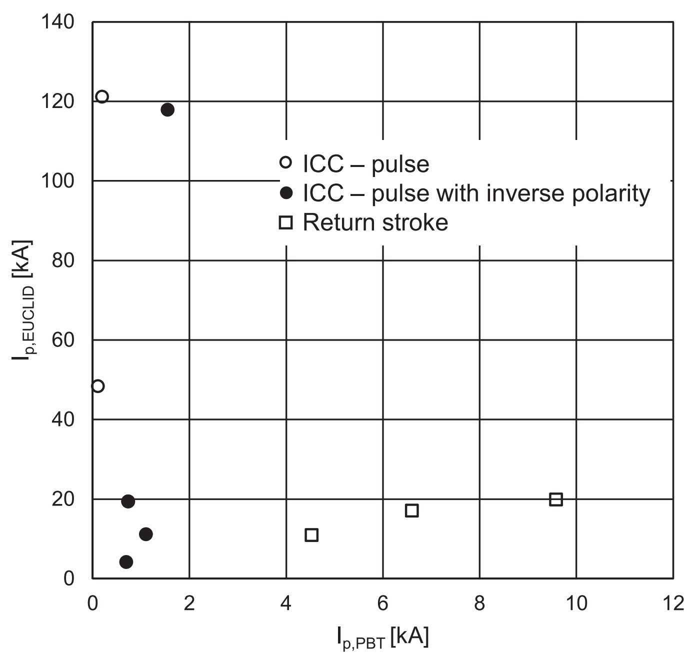

Fig. 4. Correlation between the measured absolute peak current $I_{p,\text{PBT}}$ and inferred absolute peak current $I_{p,\text{EUCLID}}$ of detected current pulses, with relative peak current deviation of more than 100%.

(connecting leader) of a downward lightning which occurred in the vicinity of the tower. Obviously, the LLS detected the nearby downward lightning, but not the current event measured at the Peissenberg Tower.

A. *Peak Current Deviation Much Greater Than 100%*

For nine current pulses, the relative deviation ($\Delta I_{p,\text{rel}}$) between the peak current measured at the Peissenberg Tower ($I_{p,\text{PBT}}$) and the inferred peak current ($I_{p,\text{EUCLID}}$) from EUCLID was much higher than 100%. Table III summarizes the data. From nine current pulses, eight of them were of negative and only one was of positive polarity.

The current pulses measured at the Peissenberg Tower had very low peak currents ($I_{p,\text{PBT}}$), which varied between 0.1 and 9.6 kA resulting in a the GM of 1.2 kA, which is extremely

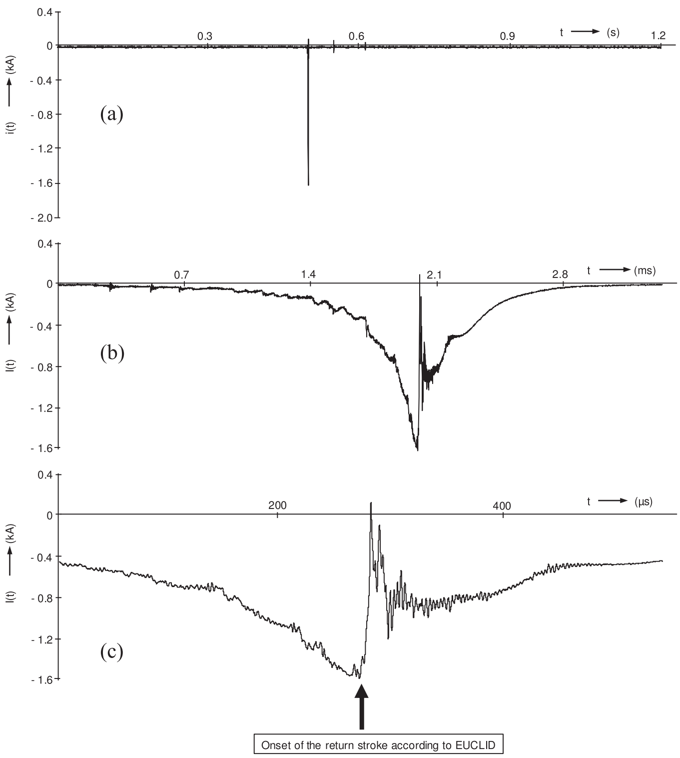

Fig. 5. (a) Waveform of the entire lightning current measured on July 3, 2015 at the Peissenberg Tower. (b) Waveform of the current pulse. (c) Enlarged section of the current pulse.

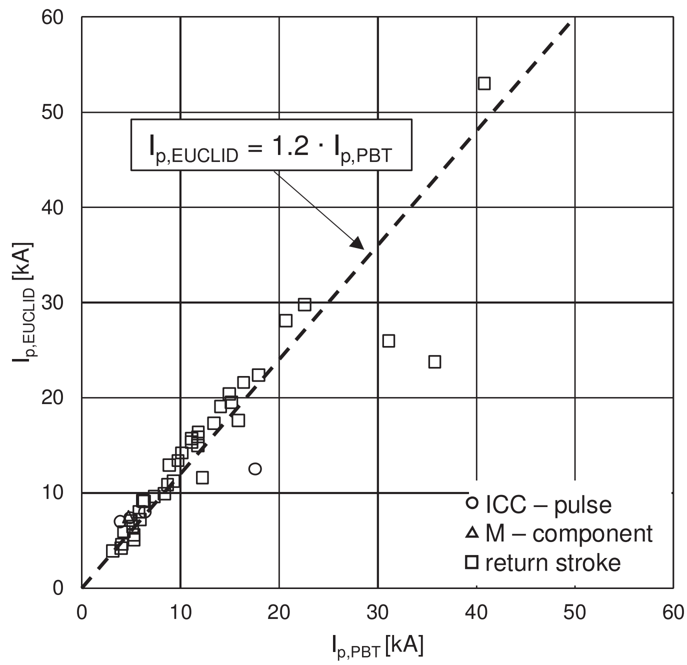

Fig. 6. Correlation between the measured absolute peak current $I_{p,\mathrm{PBT}}$ and inferred absolute peak current $I_{p,\mathrm{EUCLID}}$ of the detected current pulses, with relative peak current deviation of less than 100%.

TABLE IV
OVERALL VALUES FOR THE DETECTED 42 CURRENT PULSES WITH $\Delta I_{p,\mathrm{rel}} < 100\%$ (4 ICC-PULSES, 1 M-COMPONENT CURRENT, AND 37 RETURN STROKES)

	Abs. $I_{p,\mathrm{PBT}}$ (kA)	Abs. $I_{p,\mathrm{EUCLID}}$ (kA)	$t_{10\text{-}90\%}$ (µs)	LE (m)	$\Delta I_{p,\mathrm{rel}}$ (%)	Num. of sensors
Min.	3.1	3.9	1.0[a)]	14	3	2
Max.	40.8	53.0	13.3	3108	81	46
AM value	11.6	14.0	2.8	293	31	13
GM value	9.4	11.8	2.1	161	27	10

[a)]: The minimum value of the rise time may be increased due to the numerical filtering with 350 kHz, i.e. the real minimum rise time may be shorter.

low compared to the 6.6 kA obtained for all detected current pulses (see Table II). From the EUCLID data, the inferred peak currents $(I_{p,\mathrm{EUCLID}})$ were much higher. They varied between 4.2 and 121.2 kA with a GM of 23.7 kA.

The GM location error of 376 m was significantly higher compared to the 187 m (see Table II) obtained for all detected current pulses, although more sensors (GM: 14 sensors) contributed to the lightning location.

Fig. 4 shows the correlation between the peak current $(I_{p,\mathrm{PBT}})$ from the Peissenberg Tower measurement and the inferred peak current $(I_{p,\mathrm{EUCLID}})$ from EUCLID. The correlation coefficient is 0.35. This rather low correlation coefficient indicates that there is no significant correlation between the peak current $I_{p,\mathrm{PBT}}$ and the inferred peak current $I_{p,\mathrm{EUCLID}}$. Furthermore, in four out of nine cases, EUCLID reported the opposite polarity of the current pulse compared to the Peissenberg data. These cases are indicated in Fig. 4 as events with inverse polarity.

We assume that a "classical" downward lightning occurred in a distance of a few hundred meter from the tower. The LLS detected the downward lightning. The downward lightning initiated an upward leader with a much lower amplitude from the top of the Peissenberg Tower.

As an example, Fig. 5 shows the waveform of a lightning current measured on July 3, 2015 at the Peissenberg Tower. Fig. 5(a) shows the entire current, Fig. 5(b) and (c) show the current pulse and an enlarged section of the current pulse. The peak current $(I_{p,\mathrm{PBT}})$ is about 1.6 kA. The corresponding peak current $(I_{p,\mathrm{EUCLID}})$ is estimated from EUCLID to be 117.9 kA. From Fig. 5(c) it can be seen that there is a significant change of the current at about 270 μs. This change was time-correlated with the onset of an RS of the EUCLID data.

Wang *et al.* assumed that the appearance of a downward lightning initiates an upward lightning on tall structures. They described an upward lightning which is triggered by preceding nearby lightning activity as "other-triggered" [1], [2], [31]. However, in contrast to Wang *et al.*, we think that the upward lightning is immediately initiated by the approaching leader of a downward lightning. This would explain why the current [see Fig. 5(c)] was initiated a certain time before the RS occurred.

B. Peak Current Deviation Much Less Than 100%

From a total of 42 current pulses, the relative deviation $(\Delta I_{p,\mathrm{rel}})$ between the peak current measured at the Peissenberg

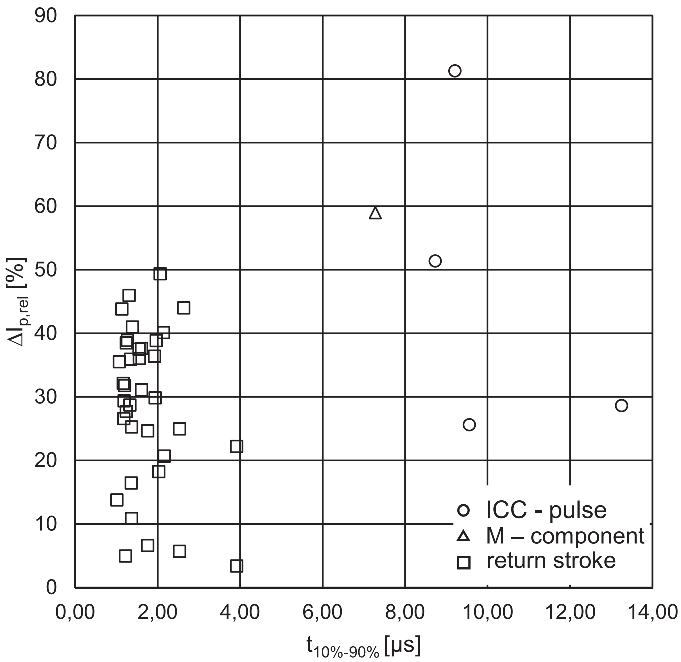

Fig. 7. Correlation between the peak current deviation $\Delta I_{p,\mathrm{rel}}$ and the 10%–90% rise time $t_{10\%–90\%}$.

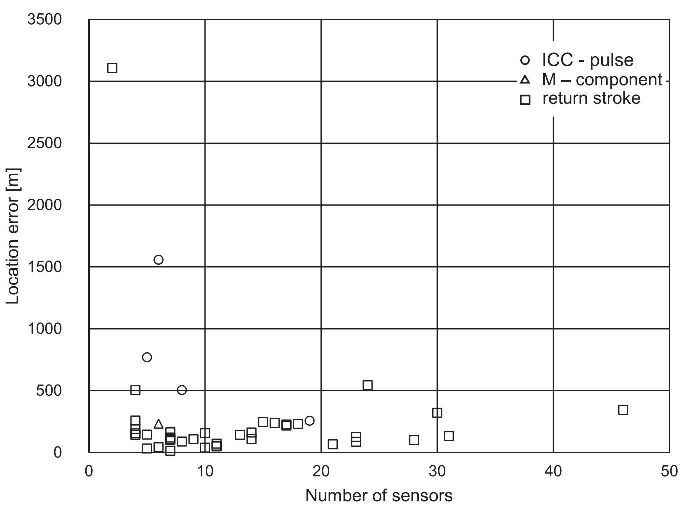

Fig. 8. Correlation between the number of sensors and the lightning location error.

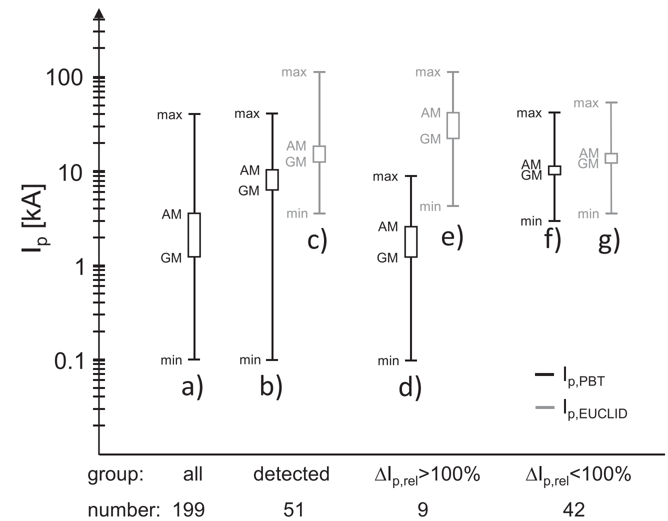

Fig. 9. Comparison of the measured and inferred peak currents split into different groups.

TABLE V
DETECTION EFFICIENCY OF VARIOUS CURRENT PULSES

	Type of pulse	Total num. of pulses	Num. of detected events	DE (%)
Peissenberg	1	96	5	5.2
	2	20	0	0
	3	13	0	0
	RS	49	37	75.5
Gaisberg [28]	RS	668	469	70
Saentis [17]	RS	2795	2040	73

Tower $(I_{p,\mathrm{PBT}})$ and the inferred peak current $(I_{p,\mathrm{EUCLID}})$ from EUCLID was much lower than 100%. The highest deviation was about 81%. Table IV shows the overall values for the 42 detected current pulses. All of them were of negative polarity.

The peak current $(I_{p,\mathrm{PBT}})$ measured at the Peissenberg Tower varied between 3.1 and 40.8 kA with a GM of 9.4 kA. The inferred peak current $(I_{p,\mathrm{EUCLID}})$ varied between 3.9 and 53.0 kA with a GM of 11.8 kA. The location error of 161 m (GM) was slightly lower compared to the 187 m (see Table II) obtained for all detected current pulses. Considering only the RSs, the location error was 132 m. On average, ten sensors contributed to the lightning locations.

Fig. 6 shows the correlation between the peak current $(I_{p,\mathrm{PBT}})$ measured at the Peissenberg Tower and the inferred peak current $(I_{p,\mathrm{EUCLID}})$ from EUCLID. The correlation coefficient is 0.92 (0.92 for the RSs and 0.98 for the ICC-pulses). The data follow in good approximation the relationship according to the following equation (see Fig. 6):

$$I_{p,\mathrm{EUCLID}} = 1.2 \cdot I_{p,\mathrm{PBT}}. \tag{1}$$

Equation (1) indicates that EUCILD overestimates the peak currents by about 20%. The overestimation is obviously caused by the field enhancement due to the transient processes in tower [20], [32]. In comparison, Mallick *et al.* analyzed 290 RSs in rocket-triggered lightning, detected by the National Lightning Detection Network. For the analyzed RSs, they found a relative peak current deviation of 14% and an average location error of 334 m [33]. Furthermore, Azadifar *et al.* used lightning currents measured at Saentis Tower to validate the performance of EUCLID. They obtained a current overestimation of about 75%, which is more than three times higher compared to the results in this paper [17]. The reason might be that the tower is located on the very high mountain "Saentis" with an altitude of 2500 m. Therefore, the effective tower height is increased.

Fig. 7 shows the correlation between the relative peak current deviation ($\Delta I_{p,\mathrm{rel}}$) and the 10%–90% rise time ($t_{10\%–90\%}$) of the current pulses. The low correlation coefficient of 0.3 indicates that there is no significant correlation for the RSs or for the ICC-pulses.

Fig. 8 shows the correlation between the location error and the number of EUCLID sensors, which contributed to the lightning location. It is obvious that the number of sensors did not influence the accuracy of the lightning location of the RSs as long as four sensors or more contributed to the lightning location.

V. Conclusion

In this study, we analyzed the performance of the lightning location system EUCLID on the basis of 199 current pulses. It was found out that EUCLID detected 51 out of these 199 current pulses. The inferred peak current of 42 out of these 51 detected current pulses revealed a relative peak current deviation $\Delta I_{p,\mathrm{rel}}$ lower than 100%. The remaining nine current pulses revealed a relative peak current deviation higher than 100%. Fig. 9 shows the graphical comparison of the inferred and measured peak currents split into different groups according to their relative peak current deviation $\Delta I_{p,\mathrm{rel}}$. Bar a) referred to all 199 current pulses measured at Peissenberg Tower. Bar b) concerned only the measured current pulses, which were detected by EUCLID, it can be seen that the AM and GM is higher compared to bar a), but the minimum and maximum peak currents are equal. Bar c) referred to the inferred peak currents by EUCLID, the minimum peak current is much higher compared to bar b), further the AM and GM is higher. Bars d) and e) concerned nine current pulses with a relative current deviation higher than 100%. Comparing bars d) and e), it can be seen that the range of peak currents as well as the GM and AM are completely different. As described before, we assume that these current pulses are related to nearby lightning events. Bars f) and g) concerned all current pulses with a relative current deviation lower 100%. It can be seen that the range of peak currents are more or less similar. The AM and GM of bar g) seems to be a little bit higher compared to bar f). As described before, we assume an average overestimation of the inferred peak current by EUCLID in a range of about 20%.

Because of the miscorrelation between measured and inferred peak currents in 9 (17.6%) out of 51 cases, the peak current was overestimated by more than 100%, therefore we must reduce the detection efficiency to 20.6% (41 out of 199 current pulses). Table V shows the DE of the various current pulse types measured at the Peissenberg Tower compared to the measurements at the Gaisberg Tower and the Saentis Tower. The data for the Peissenberg Tower are based on the 42 (21.1%) current pulses with a relative peak current deviation ($\Delta I_{p,\mathrm{rel}}$) of less than 100%, which are assumed to be from lightning events which struck the tower. In total, only 5 out 96 (5.2%) current pulses of type 1, 0 out of 20 (0%) current pulses of type 2, and 0 out of 13 (0%) current pulses of type 3 could be detected. RSs could be detected in 37 out of 49 cases (75.5%). Compared to the results obtained from the Gaisberg Tower, the detection efficiency is by 5.5% higher [28]. Measurements at the Saentis Tower revealed also a somewhat lower DE of 73% for the RSs [17].

It can be seen that the LLS offers the best performance in case of RSs ($I_p > 2$ kA, $t_{10\%–90\%} < 4\ \mu$s), in these cases the location error and the relative current deviation ($\Delta I_{p,\mathrm{rel}}$) is lowest.

Acknowledgment

The authors would like to thank EUCLID for providing the LLS data for this study.

References

[1] D. Wang, N. Takagi, T. Watanabe, H. Sakurano, and M. Hashimoto, "Observed characteristics of upward leaders that are initiated from a windmill and its lightning protection tower," *Geophys. Res. Lett.*, vol. 35, 2008, Art. no. L02803, doi: 10.1029/2007GL032136.

[2] D. Wang and N. Takagi, "Characteristics of winter lightning that occurred on a windmill and its lightning protection tower in Japan," *IEEJ Trans. Power Energy*, vol. 132, no. 6, pp. 568–572, Jan. 2012, doi: 10.1541/ieejpes.132.568.

[3] M. Miki *et al.*, "Initial stage in lightning from tall objects and in rocket-triggered lightning," *J. Geophys. Res.*, vol. 110, no. D2, Jan. 2005, doi: 10.1029/2003JD004474.

[4] M. Miki, T. Miki, A. Wada, A. Asakawa, Y. Asuka, and N. Honjo, "Observations of lightning flashes to wind turbines," in *Proc. 30th Int. Conf. Lightning Protection*, Cagliari, Italy, 2010, pp. 1–7.

[5] F. Heidler, M. Manhardt, and K. Stimper, "The slow-varying electric field of negative upward lightning initiated by the Peissenberg Tower, Germany," *IEEE Trans. Electromagn. Compat.*, vol. 55, no. 2, pp. 353–361, Apr. 2013.

[6] F. Heidler, M. Manhardt, and K. Stimper, "Characteristics of upward positive lightning initiated from the Peissenberg tower, Germany," *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 1, pp. 102–111, Feb. 2015.

[7] C. Romero, M. Paolone, M. Rubinstein, F. Rachidi, D. Pavello, and D. Giri, "A statistical analysis on the risetime of lightning current pulses in negative upward flashes measured at the Saentis Tower," in *Proc. 31st Conf. Lightning Protection*, Vienna, Austria, Sep. 2012, paper 114.

[8] D. Flache, V. A. Rakov, F. Heidler, W. Zischank, and R. Thottappillil, "Initial-stage pulses in upward lightning: Leader/return stroke versus M-component mode of charge transfer to ground," *Geophys. Res. Lett.*, vol. 35, 2008, Art. no. L13812, doi: 10.1029/2008GL034148.

[9] D. Wang *et al.*, "Characterization of the initial stage of negative rocket-triggered lightning," *J. Geophys. Res.*, vol. 104, no. D4, pp. 4213–4222, Feb. 1999.

[10] G. Diendorfer, H. Pichler, and M. Mair, "Some parameters of negative upward-initiated lightning to the Gaisberg Tower (2000–2007)," *IEEE Trans Electromagn. Compat.*, vol. 51, no. 2, pp. 443–452, Aug. 2009.

[11] D. J. Malan and H. Collens, "Progressive lightning III - the fine structure of return lightning stroke," *Proc. Roy. Soc. Lond. A, Math. Phys. Sci.*, vol. 162, no. 909, pp. 175–203, 1937.

[12] Ch. Paul and F. H. Heidler, "Properties of three types of M-components and ICC-pulses from currents of negative upward lightning measured at the Peissenberg tower," *IEEE Trans. Electromagn. Compat.*, vol. 59, no. 60, pp. 1825–1832, Feb. 2018, doi: 10.1109/TEMC.2018.2802720.

[13] C. Paul and F. H. Heidler, "Electric field characteristics of subsequent return strokes, M-components and ICC-pulses from negative upward lightning measured at the Peissenberg tower," *IEEE Trans. Electromagn. Compat*, to be published, doi: 10.1109/TEMC.2018.2845686.

[14] K. L. Cummins, M. J. Murphy, E. A. Bardo, and A. E. Pifer, "A combined TOA/MDF technology upgrade of the U.S. national lightning detection network," *J. Geophys. Res., Atmospheres*, vol. 103, no. D8, pp. 9035–9044, Apr. 1998, doi: 10.1029/98JD00153.

[15] K. L. Cummins, E. P. Krider, and M. D. Malone, "The U.S. national lightning detection network and applications of cloud-to-ground lightning by electric power utilities," *IEEE Trans. Electromagn. Compat.*, vol. 40, no. 4, pp. 465–480, Nov. 1998, doi: 10.1109/15.736207.

[16] K. L. Cummins, R. O. Burnett, W. L. Hiscox, and A. E. Pifer, "Line reliability and fault analysis using the national lightning detection network," in *Proc. Precise Meas. Power Conf.*, Arlington, VA, USA, 1993.
[17] M. Azadifar *et al.*, "Evaluation of the performance characteristics of the European lightning detection network EUCLID in the alps region for upward negative flashes using direct measurements at the instrumented Säntis Tower," *J. Geophys. Res., Atmospheres*, vol. 121, pp. 595–606, 2016.
[18] G. Diendorfer, H. Pichler, and W. Schulz, "LLS detection of upward initiated lightning flashes," in *Proc. Asia-Pacific Int. Conf. Lightning*, Nagoya, Japan, 2015.
[19] Y. Baba and V. A. Rakov, "Lightning electromagnetic environment in the presence of a tall grounded strike object," *J. Geophys. Res.*, vol. 110, no. D9, May 2005, doi: 10.1029/2004JD005505.
[20] J. L. Bermudez *et al.*, "Far field-current relationship for lightning return strokes to elevated strike objects," *IEEE Trans. Electromagn. Compat.*, vol. 47, no. 1, pp. 146–159, Feb. 2005.
[21] F. Rachidi *et al.*, "Current and electromagnetic field associated with lightning-return strokes to tall towers," *IEEE Trans. Electromagn. Compat.*, vol. 43, no. 3, pp. 356–367, Aug. 2001.
[22] F. Heidler and W. Schulz, "Lightning current measurements compared to data from the lightning location system BLIDS," in *Proc. CIGRE Int. Colloq. Lightning Power Syst.*, Bologna, Italy, 2016, Paper 24.
[23] V. Djurica and J. Kosmač, "LLS accuracy improvements by measurements collected by the RLDN," in *Proc. 19th Int. Lightning Detection Conf.*, Tucson, AZ, USA, 2006.
[24] V. Djurica, G. Milev, and J. Kosmač, "Lightning location networks performance validation with RLDN," in *Proc. 16th Int. Symp. High Voltage Eng.*, 2009.
[25] G. Berger and S. Pedeboy, "Comparison between real CG flashes and CG flashes detected by a lightning detection network," in *Proc. Int. Conf. Lightning Static Elect.*, 2003.
[26] W. Schulz, C. Vergeiner, H. Pichler, G. Diendorfer, and S. Pack, "Validation of the Austrian lightning location system ALDIS for negative flashes," in *Proc. CIGRE C4 Colloq. Power Quality Lightning*, 2012.
[27] D. R. Poelman, W. Schulz, and C. Vergeiner, "Performance characteristics of distinct lightning detection networks covering Belgium," *J. Atmospheric Oceanic Technol.*, vol. 20, pp. 942–951, 2013, doi: 10.1175/JTECH-D-12-00162.1.
[28] W. Schulz, G. Diendorfer, S. Pedeboy, and D. R. Poelman, "The European lightning location system EUCLID – Part 1: Performance analysis and validation," *Natural Hazards Earth Syst. Sci.*, vol. 16, pp. 595–605, 2016, doi: 10.5194/nhess-16-595-2016.
[29] K. L. Cummins and M. J. Murphy, "An overview of lightning locating systems: History, techniques, and data uses, with an in-depth look at the U.S. NLDN," *IEEE Trans. Electromagn. Compat.*, vol. 51, no. 3, pp. 499–518, Aug. 2009.
[30] V. Cooray and V. Rakov, "On the upper and lower limits of peak current of first return strokes in negative lightning flashes," *J. Atmospheric Res.*, vol. 117, pp. 12–17, 2012.
[31] D. Wang and N. Takagi, "Three unusual upward positive lightning triggered by other nearby lightning discharge activity," in *Proc. 22nd Int. Lightning Detection Conf.*, Broomfield, CO, USA, 2012.
[32] Y. Baba and V. A. Rakov, "Lightning strikes to tall objects: Currents inferred from far electromagnetic fields versus directly measured currents," *J. Geophys. Res.*, vol. 34, no. 19, pp. 1–5, 2007, doi: 10.1029/2007GL030870.
[33] S. Mallick *et al.*, "Performance characteristics of the NLDN for return strokes and pulses superimposed on steady currents, based on rocket-triggered lightning data acquired in Florida in 2004–2012," *J. Geophys. Res.*, vol. 119, no. 7, pp. 3825–3856, Apr. 2014, doi: 10.1002/2013JD021401.

Christian Paul was born in 1991. He received the B.Sc. degree in electrical drives and M.Sc. degree in the field of high voltage equipment from the RWTH Aachen University, Aachen, Germany, in 2013 and 2015, respectively.

Since 2016, he is with the Institute of High Voltage Technology and Lightning Research, University of the Federal Armed Forces Munich, Germany. His current research interests include lightning measurement, lightning research, and high voltage and high current testing.

Fridolin H. Heidler (SM'12) was born in 1955. He received the B.Eng. and the M.Eng. degrees in electrical engineering from Technical University Munich, Munich, Germany, in 1978 and 1982, respectively, and the Ph.D. and Dr.-Ing. habilitation degrees in high-voltage engineering from the University of the Federal Armed Forces, Munich, in 1987 and 1999, respectively.

From 1987 to 1991, he was with Industrial Engineering Company, where he was engaged in the field of electrodynamic calculations. In 1991, he joined the Chair of High Voltage Technology and Lightning Research, University of the Federal Armed Forces Munich, where he is currently a Professor for high-voltage engineering. His current research interests include the fields of lightning research and lightning protection with main emphasis on numerical calculations of lightning discharge process, and the measurement of the currents and electric or magnetic fields from lightning striking the Peissenberg telecommunication tower nearby Munich, Germany. He has authored or coauthored more than 160 scientific papers on lightning protection, lightning research, and electromagnetic compatibility.

Wolfgang Schulz was born in Vienna, Austria, in 1966. He received the Dipl.-Ing. degree in electrical engineering and the Ph.D. degree from the Technical University of Vienna, Vienna, Austria, in 1992 and 1997, respectively.

In 1992 he joined the Technical University of Vienna as an Assistant Professor. Currently, he is with the Austrian Lightning Detection & Information System, Vienna, with a research focus on the performance of lightning location systems and E-field measurements of lightning discharges. He has authored or coauthored more than 100 scientific papers published in reviewed journals and presented at international conferences.