CURRENT AND ELECTRIC FIELD CHARACTERISTICS OF 35 RETURN STROKES FROM NEGATIVE LIGHTNING MEASURED AT PEISSENBERG TOWER GERMANY

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Abstract: In this paper, we analyse the currents and electric fields of 35 negative return strokes, which have been measured since 2012 at Peissenberg Tower, Germany. 27 were pure return strokes and 8 were return strokes with superimposed symmetrical M-components. 2 out of this 8 were first return strokes. The measured peak currents ranged from 3.1 kA to 40.8 kA, the arithmetic mean value (AM) was 12.3 kA. Further we estimated the 10%-to-90% rise time, which ranged from 1.0 µs to 7.4 µs, the AM was 1.9 µs. The transferred charge varied from 0.1 C to 10.6 C, the AM was 1.0 C. The radiated electric field was measured in a distance of about 180 m to the tower. The electric field exhibits a first field change due to the descending leader. For the description of this first field change we introduced ΔE_1. The values of ΔE_1 varied from 0.8 kV/m to 10 kV/m, the AM was 2.8 kV/m. The first field change is immediately followed by a second field change of opposite polarity. We introduced ΔE_2 to describe this field change, which is caused by the return stroke process. The values of ΔE_2 varied from 1 kV/m to 14.2 kV/m, the AM was 3.5 kV/m. All analysed return strokes were detected by the lightning location system (LLS) EUCLID. The peak current inferred by EUCLID varied between 3.9 kA and 53.0 kA, the AM was 15.0 kA. 10 out of 35 detected return strokes were misclassified as cloud-to-cloud discharge.

1 INTRODUCTION

A classical downward lightning contains one or more return strokes. Each of these return strokes can be followed by a continuing current (CC), typical in the range of several hundred of amperes [1-5]. The continuing current can be superimposed by various impulsive currents, mostly symmetrical current pulses, called M-components [6]. M-components were first mentioned in the literature by Malan et al. in the thirties of the last century. They found out that there is a temporary increase in luminosity of the lightning channel after a return stroke [7]. Further, Kitagawa et al. observed different brighter components, superimposed on the illumination caused by the CC [8].

On the contrary, high rising structures with heights of more than 100 m are typically struck by upward lightning. Because of the building height, the electric field strength at the top of the building is high enough to initiate a lightning strike. Therefore, the upward lightning is triggered by the building itself [9-15]. The beginning of a classical upward lightning is characterized by a slow-varying initial continuous current (ICC), due to the leader moving upward from the top of the building. The initial continuing current has a typical magnitude between some tens to some thousands of amperes, the duration varies from some tens up to some hundreds of milliseconds [16-17]. Similar to the CC, the ICC can be superimposed by various impulsive currents [6].

The electric field of the return strokes exhibits at close distance typically a V-shape with a first field change, which is followed by a second field change of opposite polarity. The first field change is caused by the approach of the downward leader. The second field change is caused by the charge transfer to ground due to the return stroke process [18]. The bottom of the V-shape is time-correlated with the onset of the current, which indicates the transition from the leader stage to the return stroke stage [19]. Rakov et al. reported that return strokes with larger peak currents generate larger changes in the electric field [20]. In addition it can be assumed that the second field change is commonly higher than the first field change [21].

The record of the radiated electric and/or magnetic field with different stations builds up the basis of a classical lightning location system (LLS). The LLS derives the striking point of the return stroke generally by the use of two different techniques. On the one hand, the striking point can be calculated from the time of arrival of the field at different recording stations (TOA-method), and on the other hand, the direction of the incident magnetic field at the different stations can be used to determine the striking point (MDF-method). Modern LLSs make use of a combination of both methods (IMPACT-method) [22]. Furthermore the LLS estimates a peak current (called inferred peak current) for each detected return stroke, out of the recorded electric or magnetic field [23-24]. In Europe the detection of lightning activity is organized in EUCLID (European Cooperation for

Lightning Detection) since 2001. As of January 2018 EUCLID employs in total 165 sensors containing 34 analog sensors (IMPACT ES/ESP) and 131 digital sensors (LS700X). The performance of the European LLS can be evaluated by using the measurements at high buildings as ground truth data. There are various projects like the Saentis Tower in Switzerland and the Gaisberg Tower in Austria, which were used as references [25-26]. In addition to that, different studies showed, that there is a local field enhancement due to the presence of the high building, which influences the inferred peak current of the LLS. This effect is called "tower enhancement effect" and depends on the height of the structure as well as on the rise time of the lightning current [27-30].

In this paper, we analyse 35 return strokes which were measured at Peissenberg Tower and use them as a reference for the performance evaluation of the EUCLID LLS. The main emphasis of this analysis is the quality of the inferred peak current of the LLS determined from the recorded magnetic field.

2 EXPERIMENT AND DATA OVERVIEW

The mountain "Hoher Peissenberg", about 940 m above mean sea level, is located about 60 km west of Munich. On this mountain, there is located an about 150 m high television broadcasting tower, called Peissenberg Tower. We instrumented the top of this tower with a current probe and a di/dt-probe for measurement of the lightning current and its time-derivative. In addition to that, we installed a field measuring station in a distance of about 180 m to the tower. With this station we have measured the radiated electric and magnetic field and their time derivatives. The tower measurement system as well as the field measurement system is GPS time synchronized. The time synchronization accuracy between the current and field record can be assumed as better than 0.1 µs. The lightning current and the electric field is recorded with a measuring device (Ni PXI 5122) with a resolution of 14 bit with a sample rate of 100 MS/s (for more details see [31][32]). The current records were filtered numerically with a 350 kHz low pass filter (2nd order butterworth). For each return stroke, we determined the peak current (I_p), the 10%-to-90% rise time ($t_{10\text{-}90\%}$) and the transferred charge (Q). The current duration is characterized by the full width at half maximum (FWHM). An impulsive lightning current is classified as return stroke as soon as its 10%-to-90% rise time is smaller than 2 µs and its peak current I_p is greater than 2 kA, because the smallest peak current of a return stroke that can exist in nature is estimated to be 2 kA [33].

Table 1 gives an overview of the analysed return strokes, measured between January 2012 and August 2017. The peak current (I_p) ranged from 3.1 kA to 40.8 kA. The AM was 12.3 kA (GM: 10.1 kA). The 10%-to-90% rise time ($t_{10\text{-}90\%}$) ranged from 1.0 µs to 7.4 µs. The AM was 1.9 µs (GM: 1.7 µs). The current duration (FWHM) varied between 6.3 µs and 79 µs. The AM was 39.5 µs (GM: 33.5 µs). The transferred charge (Q) ranged from 0.1 C up to 10.6 C. The AM was 1.0 C (GM: 0.6 C).

Table 1: Overall values for the analysed 35 return stroke currents

	I_p [kA]	$t_{10\text{-}90\%}$ [µs]	FWHM [µs]	Q [C]
Min.	3.1	1.0*	6.3	0.1
Max.	40.8	7.4	79.0	10.6
AM	12.3	1.9	39.5	1.0
GM	10.1	1.7	33.5	0.6

*The minimum rise time may be increased due to the numerical filtering with 350 kHz. AM: arithmetic mean value GM: geometric mean value

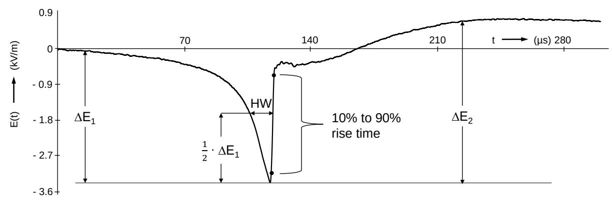

Figure 1: Typical waveform of a radiated electric field showing the used field parameters.

Figure 1 shows a typical waveform of an electric field pulse caused by a return stroke. The waveform exhibits a first field change, which is described by ΔE_1, followed by a second field change of opposite polarity. The second field change is described by ΔE_2. The fast rise of the electric field is characterized by the 10%-to-90% rise time ($t_{10\text{-}90\%,E}$) shown in Figure 1. The duration of the electric field pulse is characterised by the half width (HW).

Table 2: Overall values for the analysed 35 return stroke electric field records

	ΔE_1 [kV/m]	ΔE_2 [kV/m]	HW [µs]	$t_{10\text{-}90\%,E}$ [µs]
Min.	0.8	1.0	2.3	0.4
Max.	10.1	14.2	142.3	5.7
AM	2.8	3.5	45.6	1.0
GM	2.3	2.8	35.6	0.9

Table 2 shows the overall values of the electric field records. The first field change (ΔE_1) varied between 0.8 kV/m up to 10.1 kV/m. The AM was 2.8 kV/m (GM: 2.3 kV/m). The second field change (ΔE_2) ranged between 1.0 kV/m and 14.2 kV/m. The AM was 3.5 kV/m (GM: 2.8 kV/m). The duration of the electric field pulse varied from 2.3 µs up to 142.3 µs. The AM was 45.6 µs (GM: 35.6 µs). The 10-to-90% rise time ranged from 0.4 µs up to 5.7 µs. The AM was 1.0 µs (GM: 0.9 µs).

Figure 2 shows the cumulative frequency distribution (probability) of ΔE_1. The values fit the logarithmic normal distribution sufficiently. 95% of all data points had a value of 0.8 kV/m or higher. The highest value of ΔE_1 was 10.1 kV/m.

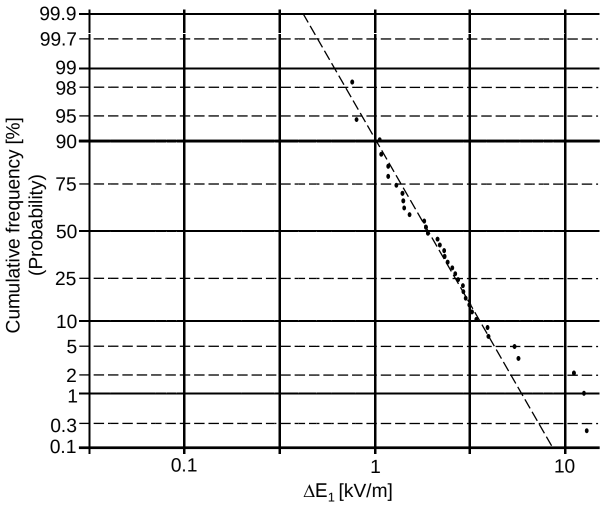

Figure 2: Cumulative frequency distribution of ΔE_1 of the 35 analysed electric field records.

Figure 3 shows the cumulative frequency distribution (probability) of ΔE_2. Similar to the values of ΔE_1, the values of ΔE_2 fit the logarithmic normal distribution sufficiently. 95% of all data points had a value of 1.0 kV/m or higher. The highest value of ΔE_2 was 14.2 kV/m.

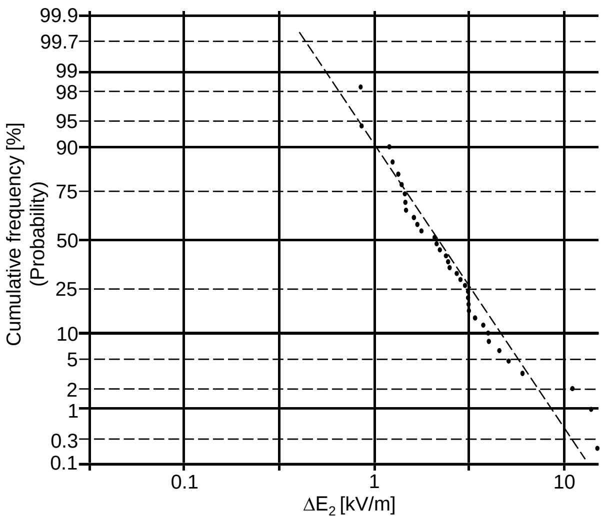

Figure 3: Cumulative frequency distribution of ΔE_2 of the 35 analysed electric field records.

3 ELECTRIC FIELD OF RETURN STROKES

Figure 4 shows the characteristic waveform of the current (a) and the time-synchronized electric field (b) of a return stroke (B343). For all 35 negative return strokes, the electric field shows this characteristic "V-shape", which is based on two field changes of opposite polarity. The first one is due to the descending leader, this phase is called leader mode. The second one with opposite polarity is related to the beginning of the current flow in the lightning channel, when the return stroke front develops upwards, in opposite direction of the preceding descending leader. This phase is called return stroke mode. The beginning of the current flow was always time-correlated with the bottom of the "V-shape" of the electric field. Thus, the bottom of the "V-shape" marks exactly the time, when the transition from the leader mode to the return stroke mode occurs.

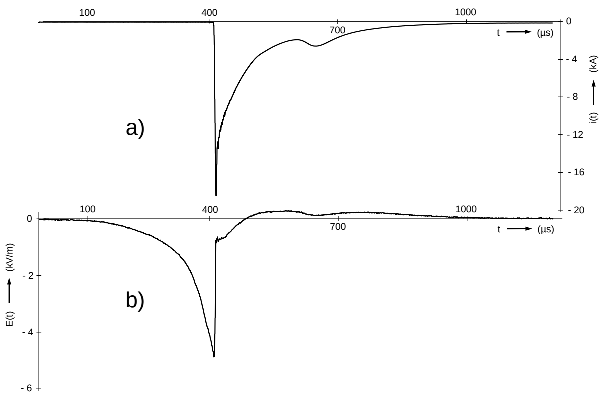

Figure 4: Characteristic current waveform (a) and corresponding time-synchronized electric field (b) of a return stroke (B343), measured on 20th January 2012.

The comparison of the lightning current and the electric field revealed that the rise of the electric field is much faster compared to the current rise. The 10%-to-90% rise time of the electric field $t_{10\text{-}90\%,E}$ is almost half of the 10%-90% rise time of the current $t_{10\text{-}90\%}$. On contrary, the duration of the current pulse (FWHM) is nearly the same as of the duration of the electric field pulse (FWHM), with the very small deviation of 6% for the GM.

For the analysis of the first (ΔE_1) and the second (ΔE_2) field change we introduced a field ratio factor f according to equation 1:

$$f = \Delta E_2 / \Delta E_1 \qquad (1)$$

The AM as well as the GM of the field ratio factor f is 1.2. This means, that the second field change (ΔE_2) is typically 20% higher compared to the first field change (ΔE_1) (see Table 2).

Figure 5 shows the correlation between the electric field changes ΔE_1 and ΔE_2 and the measured peak current I_p. 33 out of 35 were subsequent return strokes (SRS) and 2 out of 35 were first return strokes (FRS). The field changes follow approximately the linear regression according to equation 2a and 2b. The correlation coefficient is 0.96 for the correlation between ΔE_1 and I_p and 0.94 for the correlation between ΔE_2 and I_p.

$$\Delta E_1 = 0.23 \cdot I_p \qquad (2a)$$
$$\Delta E_2 = 0.3 \cdot I_p \qquad (2b)$$

where: ΔE_1 and ΔE_2 in kV/m I_p in kA

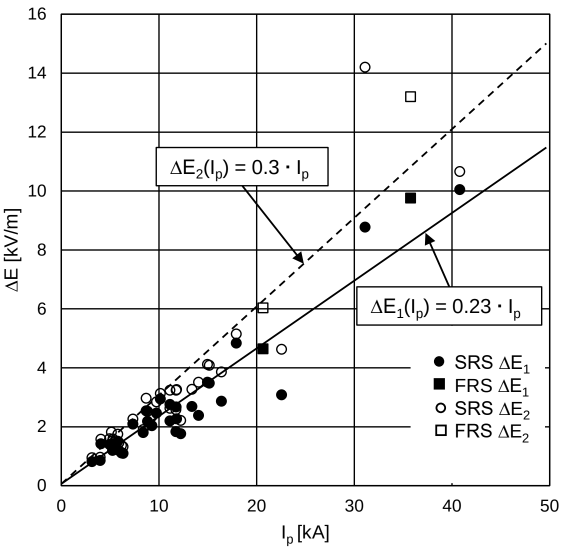

Figure 5: Correlation between the electric field changes ΔE_1 and ΔE_2 and the current peak value I_p for the analysed 35 return strokes.

4 PERFORMANCE OF THE LLS EUCLID

All 35 analysed return strokes were detected by the LLS EUCLID. For each return stroke, the LLS inferred a peak current $I_{p,LLS}$ from the recorded field. The values of the inferred peak current varied between 3.9 kA and 53.0 kA. The AM was 15.0 kA (GM: 12.5 kA).

Figure 6 shows the correlation between the measured peak current I_p at Peissenberg Tower and the inferred peak current $I_{p,LLS}$ by the LLS EUCLID. The correlation coefficient is 0.92. Due to the good correlation, the data points are quite close to the regression line according to equation 3:

$$I_{p,LLS} = 1.2 \cdot I_p \qquad (3)$$

Due to equation 3, the inferred peak current of the LLS is overestimated by about 20%. The measured peak current I_p has a GM of 10.1 kA and the inferred peak current $I_{p,LLS}$ has a GM of 12.5 kA. It is likely that the difference is due to “tower enhancement effect”.

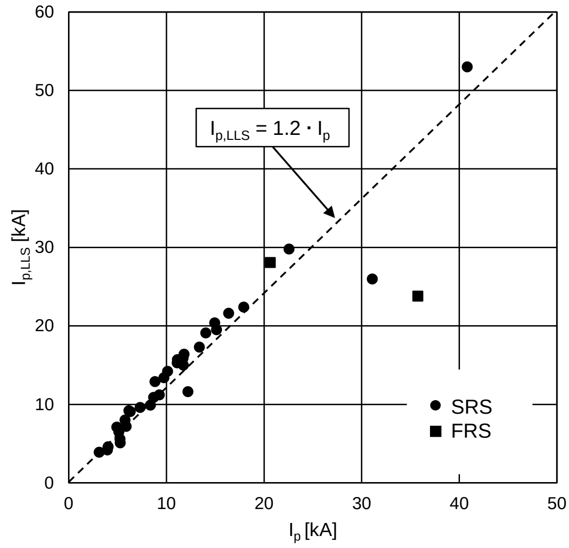

Figure 6: Correlation between the measured absolute peak current I_p and the inferred absolute peak current $I_{p,LLS}$ by the LLS.

Figure 7 shows the correlation between the number of sensors, which contributed to the localization of the return strokes, and the location error of the striking point (inferred by EUCLID). It can be seen, that at minimum 4 sensors are necessary to achieve a location error less than 500 m (from the Peissenberg Tower). There is no significant difference between the location error of first (FRS) and subsequent (SRS) return strokes.

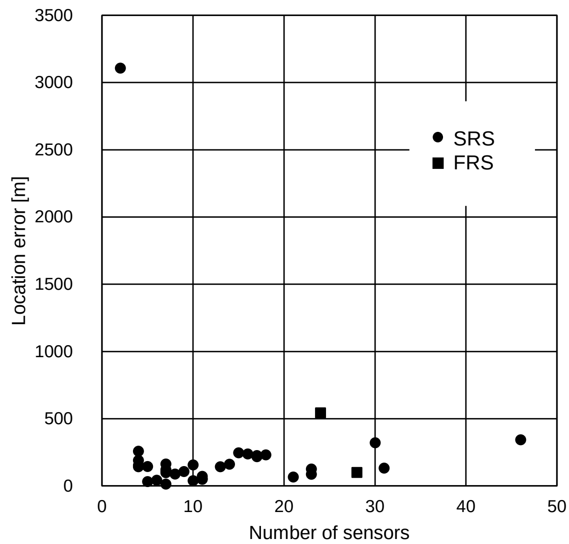

Figure 7: Correlation between the number of sensors and the location error between the striking point inferred by the LLS and the Peissenberg Tower.

Figure 8 shows the correlation between the number of sensors, which contributed to the localization of the return strokes, and the relative current deviation ΔI. The current deviation ΔI is given by the difference between the peak current I_p

measured at the Peissenberg Tower and the peak current $I_{p,LLS}$ inferred by EUCLID. The correlation coefficient is 0.1, which means that there is almost no significant correlation between these two parameters. Thus it can be assumed, that the relative deviation between measured and inferred peak current does not depend on the number of sensors, which contribute to the detection of the lightning event.

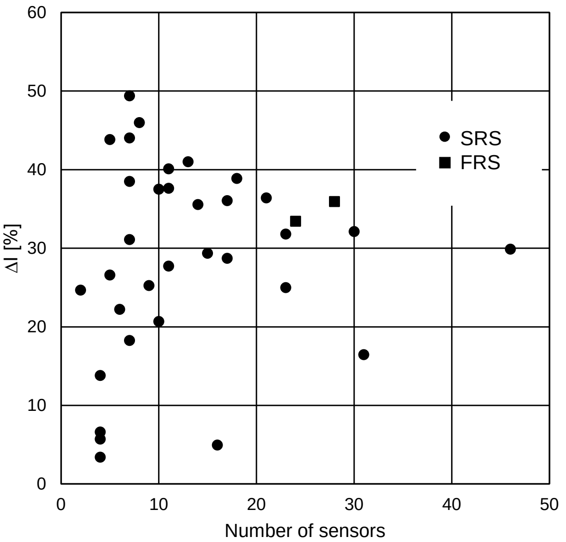

Figure 8: Correlation between the number of sensors and the relative deviation ΔI between measured (I_p) and inferred ($I_{p,LLS}$) peak current.

5 CONCLUSION

In this paper we give an overview of the current and electric field waveforms which were caused by a return stroke. The electric field waveform of a return stroke showed a characteristically "V-shape", where the bottom of the "V" is time-correlated to the beginning of the current flow. Further we figured out, that on average the first field change ΔE_1 due to the descending leader is 20% smaller compared to the second field change ΔE_2 due to the return stroke process. The LLS EUCLID detected all return strokes to the Peissenberg Tower. The electric field was used (by EUCLID) to localize the strike point and to evaluate the peak current. EUCLID overestimated the peak current of return strokes by about 20%. This value was independent from the number of sensors which contributed to the localization. At minimum four sensors were required to localize the strike point with an error less than 500 m.

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