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LLS-ESTIMATED VERSUS DIRECTLY MEASURED CURRENTS BASED ON DATA FROM TOWER-INITIATED AND ROCKET-TRIGGERED LIGHTNING

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Abstract - LLS infer lightning peak currents from remotely measured electric and magnetic peak fields assuming a linear relationship between peak field and peak current. Directly measured currents at either instrumented towers (e.g Gaisberg Tower, CN Tower, Peissenberg Tower) or at the channel base of rocket triggered lightning are the only available ground truth data to verify the accuracy of LLS peak current estimates.

We compare the directly measured peak currents versus LLS inferred peak currents for lightning to towers of different height, ranging from 100 m (Gaisberg) to 553 m (CN Tower) and for triggered lightning, where the lightning channel termination point is typically close to the ground level. In recent publications [1-4], different relations between measured and inferred peak currents were reported. At the CN Tower, the NALDN peak currents were notably larger than the measured peak currents probably because the assumed relationship between field and current does not account for the transient process in the tower.

Differences in the estimated peak current (relative to the measured one) may also result from differences in the configuration of the employed LLS. A propagation model is used in the NALDN to account for field attenuation due to finite ground conductivity, whereas in the ALDIS system a pure 1/r distance dependency of the fields was used until 02/2005. The effect of the propagation model is expected to be more pronounced when sensors at larger distances from the striking point are used for locating the strokes. After applying the attenuation correction to the ALDIS network, the LLS shows a tendency to underestimate the Gaisberg tower lightning peak currents slightly more than the US-NLDN underestimates the triggered lightning. Significant field enhancement due to strokes to tall towers is only seen for the CN Tower.

1 INTRODUCTION AND BACKGROUND

Today Lightning Location Systems (LLS) are covering many countries around the globe and the data represent a significant resource in lightning research and engineering applications. Performance characteristics of these networks were evaluated in different studies based on the use of tower-initiated or rocket-triggered lightning as the source of ground-truth data. In this presentation, we compare and discuss the results of some of these studies and we evaluate possible differences in the observed accuracy of inferred peak currents compared to the directly measured peak currents.

LLS infer the peak current from the range normalized peak fields (range normalized signal strength RNSS) and by employing a simple linear relations between peak field and peak current shown in Eq.(1). The various LLS discussed in this study employ a field-to-current conversion constant (SNF) of either 0.23 or 0.185 [3]. The factor SNF = 0.23 was originally supplied as default setting by the manufacturer of the LLS and was theoretically derived assuming a transmission line model with a return stroke velocity of 1/3 of the speed of light (10^8 m/s). The factor SNF = 0.185 was derived from triggered lightning and correlated U.S. NLDN data analysis (see also [5]).

$$I[kA] = SNF * \overline{RNSS} \tag{1}$$

In Eq. (1) $\overline{RNSS}$ is the mean of the RNSS values of all sensors allowed by the central analyzer to participate in the peak current estimate. A typical reason to prohibit a sensor from participating in the peak current estimate is when the sensor is not yet calibrated after a new installation or the sensor's distance is exceeding the specified maximum distance for a sensor to be used for the computation of stroke location and related peak current estimate (typically set to 620 km). The range normalized signal strength (RNSS) of the individual sensor is calculated using Eq. 2 (see [5]). In this equation SS is the raw signal strength and r is the distance in km from the sensor to the estimated ground strike point. Parameters b and L are related to the effects of field propagation over ground of finite conductivity.

$$RNSS = SS * \left(\frac{r}{100}\right)^{b} . \exp\left(\frac{r-100}{L}\right) \tag{2}$$

When we assume a purely inverse-distance dependency of the lightning radiated field, which is valid only in the case of infinite ground conductivity, we have to set b = 1.0 and the space constant L to a very large value (e.g. $L = 10^5$ km). Different values for attenuation "power law" constants have been proposed in literature, e.g. -1.13 by Orville et al. [6] or -1.09 by Idone et al. [7], when they related signal strength to distance. We note that exponent b in Eq.(2) needs to be positive in order to compensate for attenuation effects in the distance-normalization.

Ideally, for a given stroke, the RNSS values from all contributing sensors should be equal. In reality these values show some scatter as a result of uncorrected attenuation effects, measurement errors, or site error effects [8], etc. Using the mean $\overline{RNSS}$ in Eq.(1) is an attempt to minimize those effects on the resulting inferred peak current of the located stroke.

Peak electromagnetic fields measured by a number of sensors at various distances contribute to the inferred peak current. In the flow chart shown in Fig.1, we summarize the various steps and processes involved in the entire procedure from the occurrence of a strike up to the resulting inferred peak current I_p for that given stroke. On the right hand side we show the related parameters and give some key references.

The height of an object struck by lightning can have a significant impact on the field-to-current conversion. The relation of zero-to-peak current rise-time (RT) to the current round-trip propagation time along the tower (t_r =2h/c) has been identified as one of the most critical parameters for the peak radiated fields from lightning to towers (e.g., [12, 18]). One can expect a pronounced effect of the strike object on the radiated peak field when RT < 2h/c. Under this condition, some waveform changes (e.g. earlier zero crossing time) are also expected.

Directly measured peak current amplitudes from lightning to instrumented towers and triggered lightning are a unique dataset to evaluate the accuracy of LLS inferred peak currents. It is important to distinguish between the ability of a LLS to infer the correct peak current for a given stroke and the ability to provide correct values for peak current distributions. The former are typically used for case studies (e.g. investigation of power line flashover caused by a given lightning stroke) whereas peak current distributions are used in lightning protection standards and many lightning related statistical analyses. Although, due to the high variability of key parameters such as the return stroke speed, it may not be possible to determine the lightning current from the remotely measured electric or magnetic field with an uncertainty less that 20-30%. However, it has been shown by Rachidi et al. [19] that accurate statistical estimation (e.g. in terms of mean values and standard deviations) is possible.

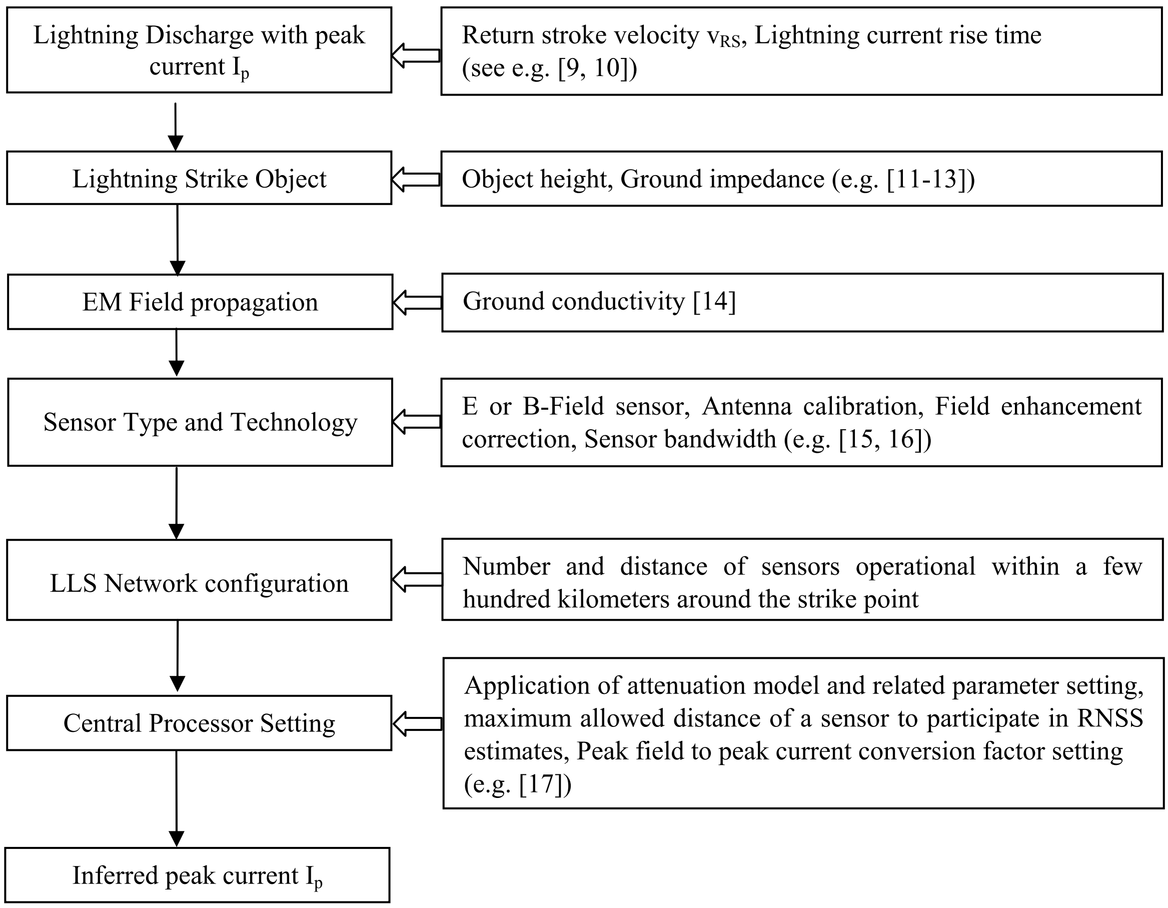


Fig. 1: Schematic flowchart of the procedure to infer the peak current of a given lightning discharge

2 DATA SOURCES

In this paper we compare experimental data from three instrumented towers, namely Gaisberg Tower in Austria, Peissenberg Tower in Germany and the CN-Tower in Toronto, Canada, and from triggered lightning at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding (CB), Florida. A comprehensive review of the interaction of lightning with tall objects is given in [20]. Only data from negative subsequent strokes are considered because there are not enough data available for any reliable statistical analysis from negative first strokes and positive discharges. For all the data sets considered here, the time correlation between directly measured and LLS data was based on GPS time stamping of the events, which normally allows a straightforward time correlation without any uncertainties. The following subsections summarize these sources.

2.1 Peissenberg Tower Current Measurements

Lightning peak current values used in this study were measured by a 200 kHz current transformer (Pearson coil) at the top of the Peissenberg tower in Germany during the time period from January 1997 to March 1998. For a detailed description of the measuring system see Fuchs et al. [21]. Over this period a total of 12 flashes with 86 strokes were recorded by the tower monitoring equipment and 30 subsequent strokes were located by the Austrian Lightning Detection System (ALDIS). Five sensors of ALDIS network are within 300 km distance from the Peissenberg tower. The closest sensor is at a distance of 72 km, with and an average distance of 182 km for the next four closest sensors. No conductivity-based attenuation was implemented in the peak current estimate algorithm at that time.

2.2 Gaisberg Tower Current Measurements

A direct lightning current measurement system was installed at a 100 m tall radio tower on Gaisberg near the city of Salzburg in 1998 [22]. The overall current waveforms are measured at the base of the air terminal installed on the top of the tower with a current-viewing shunt resistor of 0.25 mΩ having a bandwidth of 0 Hz to 3.2 MHz. A fiber optic link is used for the transmission of the shunt output signal to a digital recorder installed in a building next to the tower. The signals are recorded by an 8 bit digitizing board (upper frequency response 15 MHz; memory 16 MB) installed in a personal computer. The trigger threshold of the recording system is set to 200 A with a pre trigger recording time of 15 ms. The lower measurement limit given by the 8 bit digitizer resolution is about 20 A. A digital filter with an upper frequency of 250 kHz and offset correction is applied to the current records before the lightning peak current is determined. Ten sensors of EUCLID (European Cooperation for Lightning Detection) are located within 300 km around the Gaisberg tower site. The closest sensor is at a distance of 31 km, with an average distance of 113 km for the next four closest sensors.

Until February 2005, the EUCLID network did not employ a conductivity-based attenuation in the propagation mode and pure 1/r distance dependence (b = 1.0 and L = 10^5 in Eq.(2)) was assumed. The Field-to-current conversion factor SNF was set to the manufacturers default value SNF = 0.23. In March 2005 an attenuation model (b = 1.0 and L = 1000 in Eq.(2)) was implemented in the EUCLID network and at the same time the field-to-current conversion factor was reduced from 0.23 to 0.185. The “best” value for the space constant L was determined for the EUCLID network with the same procedure as described by Cummins et al. [17] for the US-NLDN and resulted in the same value of L = 1000 km. This setting is identical to the setting applied in the US-NLDN since 2004. These model changes resulted in partly compensating effects. The exponential term in Eq.(2) with the space constant L is a correction factor to account for peak field attenuation due to finite ground conductivity and results in an increase of the RNSS for sensors at distances greater than 100 km. On the other hand, the reduction of field to current conversion factor reduces the peak current estimate by about 20% (0.185/0.23 = 0.8) in general. Fig.2 contains a graph of the term k = (0.185/0.23)exp((r-100)/L) as a function of distance r, where k embodies the change (correction) in the propagation model. We observe a nearly linear increase of this correction term with distance and it becomes equal to 1.0 at about 300 km. For signals from sensors that are closer than 300 km, the changes of SNF and L in Eq. (2) result in a peak amplitude reduction, whereas there is an increase of the estimated peak current when sensors at distances greater than 300 km are involved. The implications of these changes are presented in section 3.

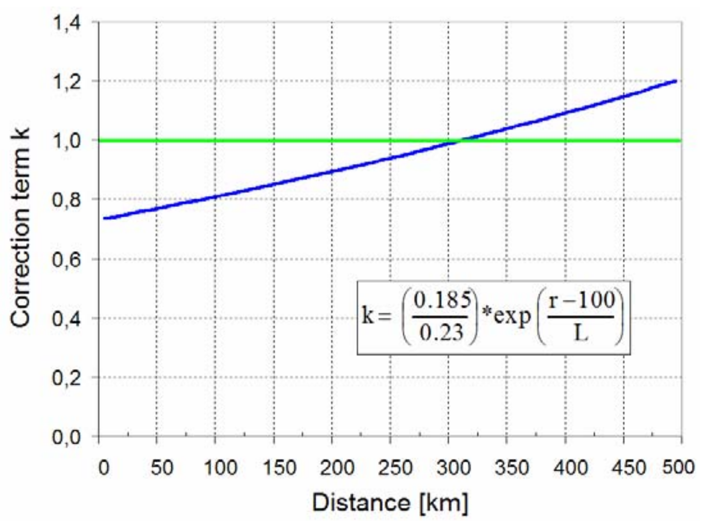
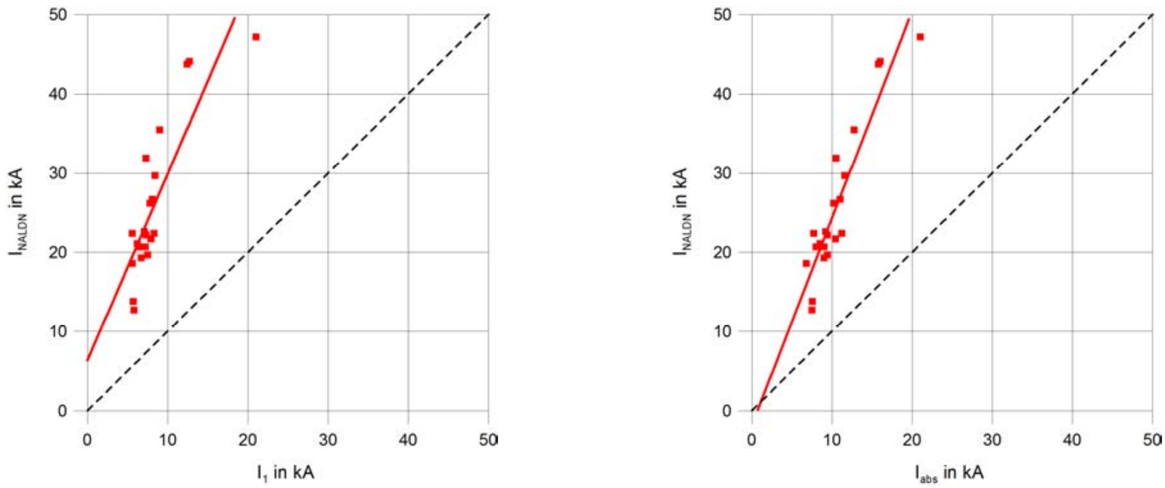


Fig. 2: The term “k” for the peak current estimate when L is set to 1000 km, b = 1 and SNF is reduced from 0.23 to 0.185 in the EUCLID network

2.3 CN Tower Lightning Current Derivative Measurements

Since 1991, the CN Tower has been equipped with a current derivative measurement system, including a 3-m long 40-MHz Rogowski coil, which encircles one fifth of the tower's pentagonal steel structure at the 474-m above ground level [23]. Because of the symmetry, the captured signal is assumed to correspond to 20% of the total current derivative. The coil is connected via a triaxial cable to a recording station, utilizing an 8-bit, 2-ns, double-channel LeCroy LT362 digitizer. During the summer of 2004, a Global Positioning System (GPS) was added to the CN Tower current derivative measurement system, allowing a time stamping, accurate to 1 µs, for each recorded return stroke. NALDN (North American Lightning Detection Network) operates 5 sensors within a radius of 300 km around the CN Tower. The closest sensor is at a distance of 67 km, with an average distance of 241 km for the next four closest sensors. Pavanello et al. [13] inferred significant peak field enhancement by the CN Tower, which was in reasonable agreement with theoretically calculated so-called tower factor of $k_{tall} = 3.9$ (see also [18]).

As a result of the current reflection at ground level, lightning current waveforms measured at or near the top of high objects typically show an initial peak I_1 in the front section, followed by a maximum peak I_{abs}. In Fig. 3, we show reasonably strong linear correlations between the NALDN estimated peak current (I_{NALDN}) and the corresponding CN Tower measured I_1 and I_{abs} , respectively. The coefficient of determination (R^2) of each regression line is included in the caption of Fig. 3 as an indicator for the quality of the linear fit. Fig. 3 shows that the slope of the I_{NALDN} versus I_{abs} regression line is 11% higher than that of the I_{NALDN} versus I_1 regression line. We have to note that regression lines I_{LLS} versus I_{TOWER} given in Fig. 3 and Fig. 4 in this paper are not directly applicable to determine a corrected SNF in Eq. (1) for a better fit. For such an application regression lines of the form y = a + b.x with I_{LLS} on the x-axis are needed.



$I_{NALDN} = 6.34 + 2.35*I_1$
N = 21, R^2 =0.7238

Fig. 3a: NALDN inferred peak current I_{NALDN} versus initial current peak I_1 measured at the CN Tower

$I_{NALDN} = – 1.83 + 2.61*I_{abs}$
N = 21, R^2 = 0.8624

Fig. 3b: NALDN inferred peak current I_{NALDN} versus absolute current peak I_{abs} measured at the CN Tower

2.4 CB Triggered Lightning Current Measurements

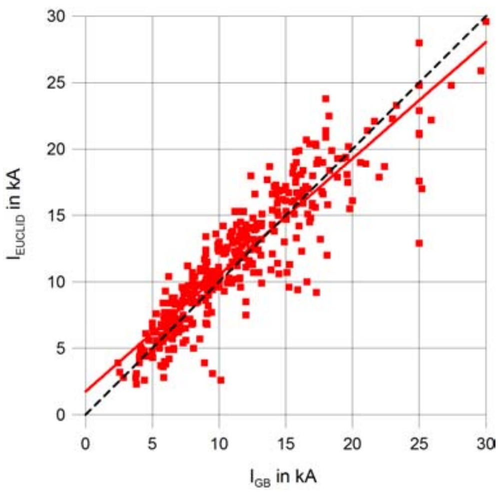
Lightning currents in rocket triggered lightning at Camp Blanding were measured at the base of the launcher with a non-inductive current-measuring resistor (shunt). Different shunts were used at different launchers, but in all cases the upper frequency response of the shunt exceeded 5 MHz. Shunt output signals were recorded by different digitizers either continuously or in segmented memory mode. The uncertainty of the calibration of the current measuring system at CB is estimated to be at most about 10%. For a detailed description of the CB current recording system see Jerauld et al. [1]. US-NLDN operates 5 sensors within a 300 km radius of the Camp Blanding triggering site. The closest sensor is at a distance of 89 km, with an average distance of 242 km for the next four closest sensors.

Prior to July 1st, 2004 in the US-NLDN, a power law model (b = 1.13 in Eq.(2)) was used to compensate for attenuation effects. This was changed to an exponential model (setting b = 1 and L = 1000 km in Eq.(2)) to improve accounting for propagation losses, especially for sensors that are more than 300 km from the strike location (see Cummins et al. [17]).

3 RESULTS

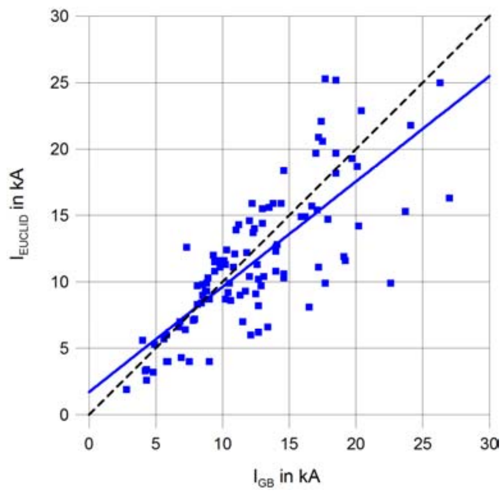
Results from all four validation sources have been reported elsewhere in the literature (see references), and are summarized in Table 1. Detailed results from CB for 2004-2007 are reported by Nag et al. at this conference. The unpublished results for the Gaisberg Tower during the period (2005-2007) are briefly discussed below, before we describe Table 1.

Fig. 4 contains scattergrams of LLS-inferred (I_{EUCLID}) vs. measured (I_{GB}) peak current for periods before and after modifying the propagation model. After implementation of the attenuation model the EUCLID network slightly underestimates the peak current, similar to the findings in Cummins et al. [17] when they reprocessed 2002-2003 data from Florida triggered lightning with identical attenuation model parameters (SNF = 0.185, b = 1, L = 1000). It is interesting to note the reduced coefficient of determination ($R^2 = 0.5943$) after implementation of the attenuation model. A check of the directly measured current waveforms of the widely scattered data points in Fig. 4b ($I_{GB} \geq 20$ kA) revealed some atypical current waveforms possibly caused by a temporary equipment failure at the Gaisberg tower instrumentation resulting in an overestimate of the directly measured current. More data in the current range greater than 15 kA and an equipment check at the tower top are needed before reaching a final conclusion concerning this issue.



$I_{EUCLID} = 1.75 + 0.88 * I_{GB}$
N = 385, $R^2 = 0.8046$

Fig. 4a: EUCLID inferred peak currents versus directly measured peak currents from lightning to the Gaisberg tower before implementation of an attenuation model and SNF = 0.23



$I_{EUCLID} = 1.71 + 0.79 * I_{GB}$
N = 106, $R^2 = 0.5943$

Fig. 4b: EUCLID inferred peak currents versus directly measured peak currents from lightning to the Gaisberg tower after implementation of an attenuation model (L = 1000) and SNF = 0.185

Results of a comparison of directly measured peak currents and LLS inferred peak currents for the three instrumented towers (Peissenberg, Gaisberg and CN Tower) and the triggering site at CB are summarized in Table 1. For all data sets, a crude ‘‘correction factor’’ is given in Table 1 as the arithmetic mean of the ratio of measured current $I_{MEAUSRED}$ and the LLS inferred peak current I_{LLS}. As described in paragraph 2.2 and 2.4, the US-NLDN and EUCLID lightning location networks implemented parameters changes related to the peak current estimate in July 2004 and March 2005, respectively. Therefore data from CB and Gaisberg in Table 1 are given for two distinct time periods with the corresponding parameter settings.

In Table 1 we note that GM of measured peak currents in all data sets is in the range from 8.2 to 16.2 kA, typical for subsequent strokes. Except for the CN Tower data, the GM of the LLS inferred peak current is a similar range of 8.5 to 13.9 kA with a tendency of the LLS to underestimate the peak currents, when an attenuation model is implemented. Lightning to the CN Tower is significantly overestimated by the LLS ($I_{CN}/I_{NALDN} = 0.41$) also obvious in Fig.3.

Table 1: Summary of directly measured versus LLS inferred peak currents from various experiments on instrumented towers and triggered lightning

Strike Location	Peissenberg Tower		Gaisberg Tower		Gaisberg Tower		CN Tower		Triggered Lightning CB		Triggered Lightning CB	
Strike object height h	160 m		100 m		100 m		553 m		14.3 or 11.5 m		14.3 or 11.5 m	
Current round-trip time (2h/c)	1.06 µs		0.67 µs		0.67 µs		3.69 µs		0.10 or 0.08 µs		0.10 or 0.08 µs	
Current measuring position	Tower top		Tower top		Tower top		474 m		11 or 8 m		11 or 8 m	
Current Sensor	Pearson Coil		Shunt 0,25 mΩ		Shunt 0,25 mΩ		Rogowski Coil		Shunt 1 mΩ		Shunt 1 mΩ	
Upper frequency response	200 kHz		250 kHz		250 kHz		40 MHz [1]		500 kHz		500 kHz	
Time Period	1997 - 1998		2000 – 02/2005		03/2005–10/2007		2005		2001 - 2003		2004, 2005 and 2007	
Data Source	I_{PB}	I_{ALDIS}	I_{GB}	I_{EUCLID}	I_{GB}	I_{EUCLID}	I_{CN} [3]	I_{NALDN}	I_{CB}	$I_{US-NLND}$	I_{CB}	$I_{US-NLND}$
Arithmetic Mean (AM), kA	8.9	9.5	11.9	12.2	12.4	11.6	10.6	25.9	17.6	14.8	17.4	16.3
Standard Deviation (SD), kA	3.9	4.5	6.1	5.9	5.4	5.4	3.4	9.6	7.4	6.3	10.3	10.3
Geometric Mean (GM), kA	8.2	8.5	10.1	10.4	11.2	10.3	10.2	24.4	16.2	13.5	15.0	13.9
Median, kA	8.3	9.5	10.7	11.2	12.0	10.8	9.4	22.4	15.7	13.1	14.3	12.7
Minimum, kA	4.7	3.0	2.4	2.3	2.2	1.9	6.8	12.7	6	5.9	5.8	6.0
Maximum, kA	20	19.6	37.2	40.8	30.1	25.3	21	47.2	42.9	34	44.9	45.1
Sample Size	30	30	385	385	105	105	21	21	70	70	18	18
Mean ($I_{MEASURED}/I_{LLS}$)	0.98		1,0		1.2		0.41		1.19		1.12	
	LLS used attenuation model parameters and field to current conversion factor											
b	1		1		1		1		1.13		1	
L [2]	10^5		10^5		1000		1000		10^5		1000	
SNF	0.23		0.23		0.185		0.185		0.185		0.185	
Distance to closest sensor, km	72		31		31		67		89		89	
Average Distance of 2nd to 5th sensor, km	182		113		113		241		242		242	
	subsequent strokes (beta) only		subsequent strokes (beta) only				subsequent strokes (beta) only		subsequent strokes only			

[1] Peak currents are determined by integrating measured di/dt values in one fifth of the tower's pentagonal steel structure (see Hussein et al. [23])

[2] Setting L to 10^5 km in Eq.(2) is equal to the assumption of infinite ground conductivity (1/r distance dependency)

[3] The largest peak current (and not initial peak current) is used in this table

Note that all strokes in both tower-initiated and rocket-triggered lightning are of "subsequent" (as opposed to first strokes in downward lightning) type.

4 DISCUSSION

Accuracy of LLS inferred peak currents from subsequent strokes to Gaisberg Tower, Peissenberg Tower and triggered lightning is quite similar, although the height of the striking point is close to ground in triggered lightning and 100 m and 160 m at the Gaisberg Tower and Peissenberg Tower, respectively. The calculated mean of the ratio $I_{MEASURED}/I_{LLS}$ is in the range from 0.98 to 1.2 for the different sites and parameter settings, and this variation is within the uncertainties of other factors affecting the peak current estimate. In case of identical parameter setting for the US-NLDN and EUCLID, the lightning events to the Gaisberg tower are slightly more underestimated (mean I_{GB}/I_{EUCLID} =1.2) than the US-NLDN underestimates the triggered lightning (mean $I_{CB}/I_{US\text{-}NLDN}$ =1.12). We see two factors that may contribute to this difference. First, the average propagation distance to nearby sensors is quite low for the Gaisberg measurements (113 km), compared to 242 km for Camp Blanding. Imperfections in the propagation model for short propagation distances are a likely contributor to this difference. Second, the low soil electrical conductivity in the alpine region may lead to more pronounced field attenuation of signals produced by lightning to the Gaisberg tower.

Significant differences in measured and LLS inferred peak currents exist for strokes to the CN Tower in Toronto, Canada with a height of 553 m. This was not the case for the Gaisberg and Peissenberg towers. This indicates that we can consider the towers with heights up to 160 m as “electrically short”, in that they do not cause a significant field enhancement as a result of the elevated striking point. The CN Tower findings are in agreement with the model assumptions of TR < 2h/c for electrically short towers. In Table 1 of Pavanello et al. [13] the 10-90 % current rise time is given for the 2005 strokes to the CN Tower and we determine a arithmetic mean of 10-90 % current rise time of 0.84 µs (STD 0.6 µs). This is much shorter than the round trip time of 3.7 µs. On the other hand, Fuchs [24] reports for the log-normal distributed 10-90 % current rise time of subsequent strokes to the Peissenberg tower a mean (50% value) of 0.581 µs ($N = 59$, $\sigma_{log} = 2.2$). This is also shorter than the round-trip time of $h/2c = 1.06$ µs for the Peissenberg tower, so model calculations would predict field enhancement that is not confirmed by our analysis. One possible reason for the absence of the enhancement in the Peissenberg LLS data (and to a lesser degree the Gaisberg data) could be more significant field attenuation due to lower conductivity in the Alpine region compared to Florida and Toronto regions. This may also be affected by the limited bandwidth of the LLS sensors interacting with the fast current rise time for tower strikes, as shown by Schulz and Diendorfer [15], although we would expect this to also apply to the CN Tower data.

Finally we have to note that no "ground truth" results have been published regarding LLS current estimates for (1) first strokes in natural lightning, (2) natural positive strokes, or (3) lightning peak currents exceeding 45 kA. It follows that LLS current estimates should be viewed with caution for strokes other than negative subsequent strokes with inferred peaks below 45 kA.

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