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LIGHTNING PEAK CURRENTS MEASURED ON TALL TOWERS AND MEASURED WITH LIGHTNING LOCATION SYSTEMS

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ABSTRACT:
Recently Diendorfer et al. [2002] compared lightning peak currents measured at the Gaisberg tower with correlated lightning peak currents reported by the Austrian lightning location system ALDIS. They found a surprisingly good agreement between the measurements at the tower and the amplitudes reported by the lightning location system (LLS). There are several factors which might influence the relation between the directly measured current at the tower and the current reported by the LLS. The effect of the striking object height and the field attenuation are the key elements for a comparison between the two current values. In this paper we will show the possible range of influence for some of the most important parameters.

1. INTRODUCTION

There are several factors which might influence the relation between the directly measured current at the tower and the current reported by the LLS:

- The tower construction itself, because lightning striking an elevated object radiate higher field peaks due to the presence of two current wave fronts traveling in opposite directions [Diendorfer and Uman, 1990; Borghetti et al., 2003]
- Lightning current parameters (front duration)
- The return stroke velocity
- The applied signal normalization factor of the LLS
- The field attenuation along the traveling path from the tower to the sensors caused by finite ground conductivity
- The performance of the field measurement (bandwidth of the sensor)

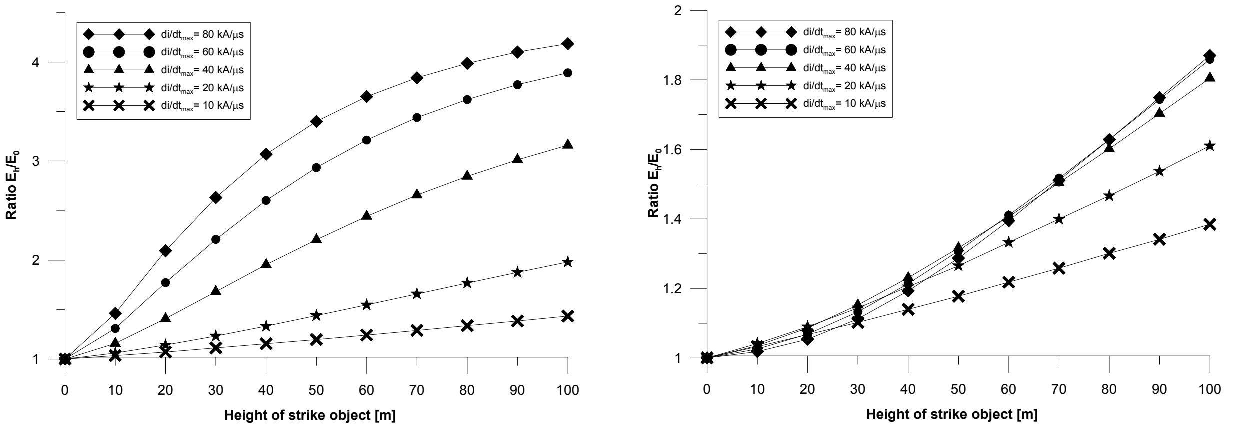
In this paper we will compare the peak current data recorded at the Gaisberg tower with data from the European LLS EUCLID (about 90 sensors during 2000-2002) and the Austrian LLS ALDIS (8 sensors) which is also integrated in the EUCLID network. We will show how the tower itself, the attenuation parameter and different network configurations influence the peak current reported by the LLS.

2. INFLUENCE OF THE TOWER AND LIGHTNING CURRENT STEEPNESS di/dt

We estimate the influence of the tower height with field calculations based on the Diendorfer-Uman (DU) return stroke model [Diendorfer and Uman, 1990]. We ignore in our calculations current reflections at the tower top and the tower base and we calculate fields over infinitely conducting ground. Therefore the results of the relative field enhancements are independent of the distance to the stroke. For our calculations we use the CURRENT 1 in Diendorfer and Uman [1990] and vary the front time constant of the breakdown current τ_{b1} to simulate different di/dt values. All di/dt values given in the following figures are maximum di/dt values.

Fig. 1 shows calculations with the DU return stroke model of the field enhancement due to the impact to an elevated strike object over perfectly conducting ground with a return stroke speed of v_{rs}=1.3e8 m/s and a breakdown time constant of τ_{bd}=0.3µs. Fig.1A shows the theoretical maximum enhancement if the finite ground conductivity and the sensor bandwidth are ignored whereas Fig.1B takes into account the limited sensor bandwidth but still ignores the finite ground conductivity. In Fig. 1B the sensor is modeled with a Butterworth bandpass filter of 2nd order with a lower cutoff frequency of f_l=1kHz and an upper cutoff frequency of f_u=350kHz, representing the frequency response of an IMPACT sensor.

In Fig. 1 E_0 is the reference field for an object of height h=0m and E_h is the field for an object of height h. It can be seen from Fig. 1A that with increasing di/dt the field enhancement due to the tower increases significantly. Fig.1B shows that the sensor bandwidth reduces the ratio E_h/E_0 especially for large di/dt significantly.



A) B)

Fig. 1: Field enhancement as a function of height and di/dt when lightning strikes an elevated object (v_{rs}=1.3e8 m/s, τ_{bd}=0.3µs).
A) infinite ground conductivity and sensor bandwidth
B) infinite ground conductivity, sensor bandwidth 1kHz – 350 kHz

Because the radio tower at the Gaisberg has a height of 100m, we calculated the field enhancement for a 100 m high tower for different di/dt values (Fig. 2). For a di/dt_{max} of 20 kA/µs and a 100m high tower our calculations result in a field increase of about 100% when we ignore the sensor bandwidth. Even for small di/dt values as 20 kA/µs the limited sensor bandwidth reduces the enhancement to about 60%. It is important to note that the conductivity and especially the low conductivity in Austria, would result in a cutoff frequency of lower than 350 kHz and will therefore further decrease the enhancement.

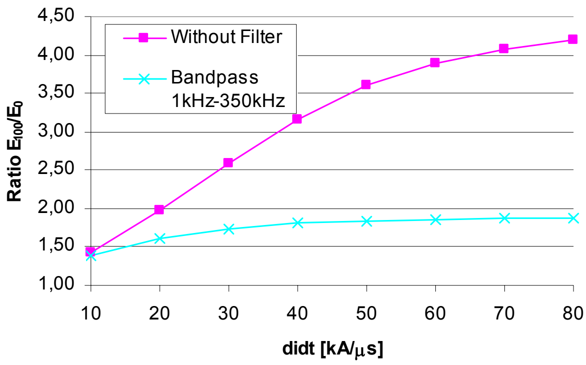
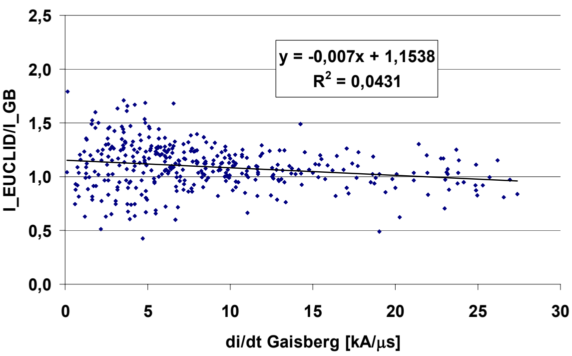


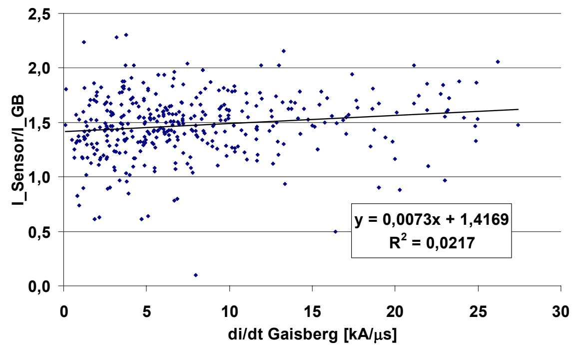
Fig. 2: Field enhancement for a 100m high tower (v_{rs}=1.3e8 m/s, τ_{bd}=0.3µs)

From the Gaisberg data of 2002 a mean di/dt_{max} of -7.5 kA/µs (maximum di/dt of the individual stroke waveshapes) was determined from the current measurements with the shunt. Comparing with our recently started direct di/dt measurements with higher bandwidth we get an agreement if we filter the di/dt measurement with a low pass with cutoff frequency of 500 kHz. If the cutoff frequency is increased to 5 MHz we also see reflections in the di/dt records and the di/dt_{max} increases to about 25kA/µs. This value is similar as reported by Fuchs [1999] for measurements at the Peissenberg tower. For the small di/dt at the Gaisberg (mean value) the field enhancement is almost independent of the peak current, the return stroke speed and the time constant τ_{bd} of the DU-model. For the calculation with infinite ground conductivity there is also no dependence on the distance.

To see if the effect of an increasing enhancement for higher di/dt values is also evident in the real data we evaluated current data measured at the Gaisberg tower and compared them with correlated data from the EUCLID network and data from the sensor closest to the tower. Fig. 3 shows the ratio I_{LLS}/I_{GB} of the peak currents determined with the LLS (I_{LLS}) and the currents measured at the Gaisberg (I_{GB}) as a function of di/dt. In Fig. 3A I_{LLS} is the peak current inferred from all the contributing EUCLID sensors and in Fig. 3B I_{LLS} is the peak current inferred from sensor 1 only. Sensor 1 is the sensor of the network next to the Gaisberg tower at a distance of about 40km.



A)



B)

Fig. 3: Enhancement versus di/dt measured at the Gaisberg tower for peak currents inferred from A) all EUCLID sensors and B) peak currents inferred from sensor 1 data only (both calculated with a signal normalization factor of 0.23 and without attenuation parameters)

It is interesting to note that apparently there is no correlation between the enhancement and the di/dt measured at the Gaisberg tower for the EUCLID peak current I_EUCLID and the peak current determined from sensor 1 I_Sensor. The peak current enhancement determined with the EUCLID network even shows a negative relation to the di/dt of the Gaisberg tower.

The previous estimations of the field enhancement due to the tower (Fig.1 and Fig. 2) were all calculated with the assumption of infinite ground conductivity. The tower adds mainly high frequency components to the resulting field. The sensor bandwidth of 1kHz to 350 kHz reduces the field enhancement already to smaller values. Taking into account that the 3dB cutoff frequency for ground with a conductivity less than 0.01 S/m and for distances greater than 50 km is even smaller than 350 kHz (M. Murphy, 2004, personal communication) it is likely that finitely conducting ground is the reason for the non existence of an increased enhancement with higher di/dt in Fig.3.

2. EFFECT OF APPLIED ATTENUATION PARAMETER AND OF LLS EXTENSION

In the Austrian and in the European network peak currents are inferred from fields according to Eq. (1) [Diendorfer et al., 1998] by using a signal normalization factor of 0.23. This factor originally supplied by the manufacturer of the LLS was theoretically derived assuming a transmission line model with a return stroke velocity of 1/3 of the speed of light.

$$I[kA] = 0.23 * \overline{RNSS} \qquad (1)$$

The range normalized signal strengths (RNSS) of the individual sensors are calculated using Eq. (2) (see also Cummins et al. [1998]). In this equation SS is the signal strength reported by a sensor and r is the distance from the sensor to the stroke in km. The exponential damping factor b and the e-folding length λ in km are used to account for attenuation over ground of finite conductivity.

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

Herodotou et al. [1993] have shown that an attenuation model with an e-folding length λ is the best approximation of finitely conducting ground. To determine the optimum e-folding length for Austria, raw data from August 2001 were recalculated with different e-folding lengths ranging from 500 km to 1000 km for the EUCLID and for the ALDIS network respectively. The optimum if λ is determined by evaluating the deviation of the individual sensors RNSS to the mean RNSS. The mean of those deviations should be as close as possible to “1” and the relative standard deviation (relative to the mean) should be a minimum. The optimum was found to be λ=1100 km for the EUCLID network. A weak optimum for the ALDIS network with λ=900 km was found.

During the three years 2000 to 2002, 632 negative strokes with a peak current greater than 2kA hit the Gaisberg tower. We recalculated LLS data from all negative strokes hitting the Gaisberg tower with different attenuation parameter b and λ. To account for changes in the network setup we used for reprocessing one representative sensor database for each year. Table 1 shows the number of detected strokes and the stroke detection efficiency (DE) for peak currents greater than 2kA of the recalculation. It is necessary to take into account that the actual stroke DE of the network is even higher because in the Gaisberg data there are some strokes included where the GPS clock had a failure and therefore it is not possible to correlate these data correctly with the LLS data.

Table 1: Number of strokes to the Gaisberg tower detected by the LLS and assigned as "OK" by the location algorithm (2000-2002) with different attenuation parameter

	EUCLID (DE %)	ALDIS (DE %)
A) b=1.0 λ=10000000km	391 (62%)	331 (52%)
B) b=1.0 λ =1100km	388 (61%)	352 (56%)
C) b=1.0 λ =900km	385 (61%)	357 (56 %)
D) b=1.13 λ =10000km	391 (62%)	381 (60%)

Due to the reason that the LP2000 location algorithm uses the individual sensor amplitudes for a consistency check, depending on the applied attenuation parameters different numbers of strokes are located. It is interesting to note that changes of the attenuation parameter do not influence the number of detected strokes for the EUCLID network significantly but the smaller eight IMPACT sensor ALDIS network detects more strokes if attenuation parameters are used. The reason for this is the higher redundancy of information in the more extended EUCLID network. Even when one or more sensor messages fail the consistency check there is still a sufficient number of sensor messages available to locate a stroke.

We recalculated with these specific parameter because A) is the currently used configuration in the EUCLID network, B) is the optimum in Austria for the EUCLID network, C) is the optimum in Austria for the ALDIS network and D) is the default configuration of the manufacturer and also used in the National Lightning Detection network (NLDN) in the US.

After the recalculation we correlated located ALDIS strokes with a time criterion (time difference < 1ms) to the Gaisberg measurements and compared the peak currents of the LLS with the peak currents from the Gaisberg tower. The mean absolute time difference between the correlated LLS data and the Gaisberg data is about 60µs. In Fig. 2 we have plotted the directly measured peak currents at the Gaisberg versus the correlated peak currents reported by ALDIS for negative strokes located at distances less than 2 km to the Gaisberg tower.

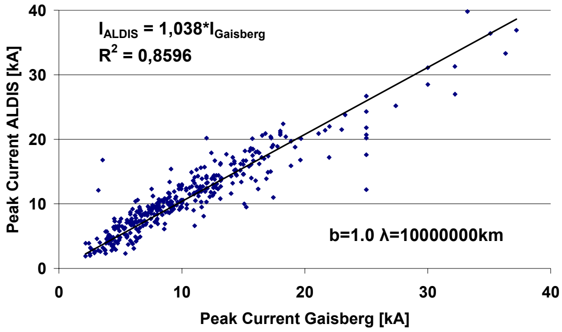


Fig. 3: Comparison of peak current measurements at the Gaisberg tower with peak currents of correlated strokes reported by ALDIS (distance less than 2km to the tower).

We calculated for all the different data sets A, B, C and D in Table 1 a linear regression line with the fit forced to go through the origin according to Eq. (3).

$$I_{ALDIS} = K * I_{GB} \tag{3}$$

Table 2 shows for all the different recalculations the resulting slope K of the linear regression and the regression coefficient R^2.

Table 2: Slope K and regression coefficient R^2 for different attenuation parameter

	EUCLID		ALDIS	
	K	R^2	K	R^2
A) b=1.0 λ=10.000.000km	1.04	0.78	0.91	0.74
B) b=1.0 λ =1100km	1.27	0.79	0.91	0.74
C) b=1.0 λ =900km	1.33	0.79	0.95	0.75
D) b=1.13 λ =10.000km	1.20	0.79	0.92	0.75

For Table 2 we used all time correlated data independent of the distance of the located stroke to the tower. Using only data within 2km distance of the tower increases the correlation coefficient R^2 to about 0.86 but does not change the value of the slope K.

For the ALDIS network the slope K varies for the four recalculations between 0.91 and 0.95. This means the mean error of the peak current inferred by the LLS is within 5% and 9% of the directly measured peak current what is surprisingly good.

It can be seen from Tab. 2 that the different attenuation parameters change the result for the EUCLID network more significantly than for the ALDIS network. The reason for the bigger changes is the existence of more distant sensors in the EUCLID network which normally bias the RNSS toward lower values if no attenuation is taken into account (case A). This is the reason why we searched for the optimum λ value. We used for all recalculations a signal normalization factor of 0.23. Taking the K value of 1.27 (determined for λ value of 1100km in the EUCLID network) and reducing the signal normalization factor from 0.23 to 0.185, a value that was derived from rocket triggered lightning [Cummins et al., 1998] and is used in the NLDN, results in slope K of 1.02 what is again a surprisingly good agreement between directly measured and LLS reported peak currents. The normalization factor of 0.185 is probably more appropriate for the EUCLID network because it was also derived for a larger network with sensors at longer distances to the stroke locations. This value was originally derived with attenuation factors b=1.13 and λ=10000km in Florida [Cummins et al., 1998]. Using the K value of 1.2 calculated for attenuation coefficients b=1.13 λ =10000km and the signal normalization factor 0.185 results in slope K=0.97 which is again only 3% smaller than the optimum value of 1.0.

3. SUMMARY

We have shown based on somewhat idealized calculations (with e.g. infinite ground conductivity) that the tower theoretically enhances the electromagnetic field peaks by about 40% for peak currents with di/dt_{max} of about 10kA/µs even if we take into account the limited bandwidth of the sensor. In the available LLS data there is no evidence for such a peak enhancement with higher di/dt values. Possible reason for this is field attenuation over finitely conducting ground. Further investigations are necessary to clarify this issue.

A recalculation of strokes correlated with tower measurements with different attenuation parameter showed a small change of the correlation factor K for the ALDIS network but a more significant change for the much larger EUCLID network. This effect was expected because in a network with large extent more distant sensors bias the resulting peak current to lower values when no attenuation correction is applied.

Nevertheless using appropriate attenuation and signal normalization parameter for the EUCLID network, results in an uncertainty of the inferred peak current of only a few percent. This means that for small networks the used attenuation parameter is not very important whereas for larger networks such as the EUCLID network it is important to choose those parameters appropriate.

REFERENCES

Borghetti A., C.A. Nucci, M. Paolone: Effect of Tall Instrumented Towers on the Statistical Distributions of Lightning Current Parameters and Its Influence on the Power System Lightning Performance Assessment, ETEP Vol. 13, No. 6, November/December 2003.

Cummins, K. L., Murphy, M. J., Bardo, E. A., Hiscox, W. L., Pyle, R. B., Pifer, A. E.: A combined TOA/MDF technology upgrade of the U. S. National Lightning Detection Network, J. Geophys. Res. Vol. 103 , No. D8 , p. 9035, 1998.

Diendorfer G. and Uman M.A.: An improved return stroke model with specified channel-base current. J. Geophys. Res. Vol. 95, No. D9, p. 13621-13644, 1990.

Diendorfer G., Schulz W., Rakov V.: Lightning characteristics based on data from the Austrian lightning location system. IEEE Transactions on EMC, Vol. 40, No. 4, 1998.

Diendorfer G., Hadrian W., Hofbauer F., Mair M., Schulz W.: Evaluation of Lightning Location Data Employing Measurements of Direct Strikes to a Radio Tower. CIGRE Session Paris, 2002.

Fuchs F.: Ströme und Nahfelder von Blitzeinschlägen in hohe Bauwerke als Störquelle für elektronische Systeme. Ph.D. Thesis, Universität der Bundeswehr München, 1999.

Herodotou N., Chisholm W.A., Janischewskyj W.: Distribution of lightning peak stroke currents in Ontario using an LLP system, IEEE transactions on Power delivery, Vol. 8, Nb. 3, July 1993.