Paper presented at the 24th Int. Conference on Lightning Protection (ICLP), Birmingham, Sept. 1998

EFFECT OF SIGNAL ATTENUATION ON THE PEAK CURRENT ESTIMATES FROM LIGHTNING LOCATION SYSTEMS

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Abstract - With lightning location systems an estimation of the peak current of the lightning discharge can be performed. The accuracy of this estimation is influenced by the finite ground conductivity of the propagation path of the electromagnetic field. In this paper we present an empirical method for taking into account the attenuation due to real ground conditions on the estimation of the lightning peak current. The resulting peak current distribution is compared to the results when the traditional method is used.

1. Determination of the lightning peak current from far electromagnetic field

The relation between lightning peak current I_p and the vertical component of the electric field E_p in the far field can be described by the Transmission Line Model [1]. According to the traditional sign convention in atmospheric electricity, a positive cloud-to-ground discharge causes a negative field change:

$$I_p = -\frac{2\pi D}{\mu_0 v} E_p \qquad \textbf{(1)}$$

D Distance to the lightning discharge in km
E_p Peak electric field in V/m
I_p Amplitude of the lightning peak current in kA
v Lightning return stroke velocity in m/s

Eq.1 is valid for flat earth of infinite ground conductivity and is used to infer lightning peak currents from electromagnetic fields. The only unknown term in Eq.(1) is the return stroke velocity v. Idone et.al. [2] e.g. found a wide spread in the range from $0.29\cdot10^8$ m/s to $2.4\cdot10^8$ m/s in natural lightning discharges. As an average in many applications (e.g. [3]) a constant value of $1.5\cdot10^8$ m/s is used.

Contrary to this assumption Lundholm [4] and Wagner [5] give a relation Eq.(2) between the return stroke velocity and the peak current based on theoretical and experimental investigations.

$$v = \frac{c_0}{\sqrt{1 + \frac{W}{I_p}}} \qquad \textbf{(2)}$$

v Lightning return stroke velocity in m/s
c_0 Speed of light 2,998 10^8 m/s
I_p Lightning peak current in kA
W Empirical constant of 40kA

The relation in Eq.2 has been confirmed by triggered lightning experiments (e.g. Hubert et.al [6] and Idone et.al. [7]), whereas in other experiments (e.g. Mach et.al. [8] and Willett et.al [9]) it was not confirmed. By combination of Eq.(1) and Eq.(2) we obtain a modified relation Eq.3 for the Transmission Line Model.

$$I_p = -\frac{2\pi D E_p}{\mu_0 c_0}\sqrt{1 + \frac{W}{I_p}} \qquad \textbf{(3)}$$

A more general problem of all measurements of lightning return stroke velocity is that the velocity is not a constant along the lightning channel. Lightning peak current estimation from field pulses is based on the first field peak, that occurs within the first few microseconds of the lightning discharge. Therefore accurate knowledge of the return stroke velocity occuring over the lower 100 m of the lightning channel would be required. Unfortunately data on this detail have not been published until now.

Eq.(1) and Eq.(3) are only valid for a vertical lightning channel and infinite ground conductivity. The first assumption is met approximately for the lower 100 m of the lightning channel, whereas the second assumption is not valid in general. The finite ground conductivity causes attenuation of the lightning electromagnetic field pulses.

2. Determination of the lightning peak current with a lightning location system

The field peak of a lightning discharge is detected by N Direction Finders (DF) of the location system. Each DF_i at a distance D_i reports an amplitude E_i of the electromagnetic field. These signals are normalized to a distance of 100 km by the simple inverse distance relation Eq.(4)

$$E_{100,i} = E_i \frac{D_i}{100} \qquad \textbf{(4)}$$

As a reference for the peak current estimation the mean value $\overline{E_{100}}$ of the range normalized signal strength Eq.(5) of all sensors DF_i (i=1...N) is used.

$$\overline{E_{100}} = \frac{1}{N}\sum_{i=1}^{N} E_{100,i} \qquad \textbf{(5)}$$

The lightning location system manufactured by Global Atmospherics Inc. (Tucson, Arizona), reports the field peaks in arbitrary units (LLP-units) proportional to the horizontal magnetic field strength.
For the estimation of the lightning peak current Eq.(6) is used. The structure of this calibration function is similar to Eq.(1) with the assumption of a return stroke velocity of $1.15\cdot10^8$ m/s. The signal attenuation due to finite ground conductivity is not taken into account.

$$I_p = \frac{1}{4.36}\cdot\overline{LLP_{100}} = 0.23\cdot\overline{LLP_{100}} = -5.108\cdot\overline{E_{100}} \quad \textbf{(6)}$$

3. Effect of signal attenuation due to finite ground conductivity

Various approaches to take into account the effects of nonlinear attenuation on the lightning peak current determination from far electromagnetic fields are published in literature. The application of some of those approaches for range normalization of the electromagnetic peak signal strength is shown in Tab. 1.

Tab. 1: Comparison of different approaches for signal strength range normalization

Orville [3] Idone et.al. [10]	$E_{ref,i} = E_i\left(\frac{D_i}{D_{ref}}\right)^{1.09}$ (7)
Herodotou et.al.[11]	$E_{ref,i} = E_i\left(\frac{D_i}{D_{ref}}\right) e^{\alpha(D_{ref}-100)}$ (8)
Cooray et.al. [12],[13]	$E_{ref,i} = E_i\left(\frac{D_i}{D_{ref}}\right)^{1.064}$ (9)

In Tab.1 D_{ref} is the distance for range normalization (usually 100km). In the approach of Herodotou α is an empirical constant ($1/582\ km^{-1} < \alpha < 1/1050\ km^{-1}$).

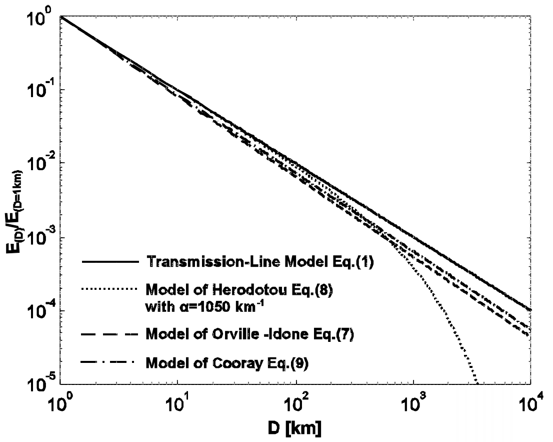

Fig. 1: Comparison of the different attenuation models. The peak field strenght at a distance of 1 km is used as a reference.

All these models do not consider an explicit value of the effective ground conductivity of the various propagation paths and therefore they are only valid for homogeneous areas.
Eq.(7) and Eq.(9) give nearly identical results as evident from Fig. 1. The attenuation given by Eq.(8) is also in the same order for distances less than 500 km, the usual operating range of lightning detection sensors.
The difference between the models could be explained by the fact that the effective ground conductivities of the areas where the investigations were carried were different. An independent reference for the determination of the lightning peak current from far field component would be the unattenuated field value $E_{\infty,D}$ at each sensor site. $E_{\infty,D}$ could be normalized by a simple inverse distance relation and the lightning peak current could be calculated using Eq.(1).
For the calculation of $E_{\infty,D}$ the effective ground conductivity σ_{eff} along each signal propagation path would be required. Generally these data are not available. In the following we show an empirical method to estimate $E_{\infty,D}$ from attenuated field values $E_{\sigma,D}$, reported by the DF's of a lightning location system.

4. Attenuation effects observed by the Austrian Lightning Detection and Information System ALDIS

In a previous paper [14] we reported a first indication of inhomogeneous attenuation effects on the lightning electromagnetic field pulses in a limited area in Austria. In this paper we extend the investigation to an area of 520 km x 630 km. For this analysis we use the sensor reports of the ALDIS system for the years 1996 and 1997.
To reduce errors due to incorrect stroke positions we only use strokes located with time and angle optimization and detected by more than three DF's. Signal attenuation parameters are calculated for geographical subareas of 10 km x 10 km, where we assume approximately homogenous attenuation conditions.

4.1. Comparison of the range normalized signal strength of the DF's

In a first step of our investigation we calculate for each stroke and for each DF_i the ratio γ_i given in Eq.(10) between normalized signal strength $E_{100,i}$ and the mean normalized signal strengths $\overline{E_{100}}$ of all DF's reporting this stroke.

$$\gamma_i = \frac{E_{100,i}}{\overline{E_{100}}} \qquad (10)$$

Then we can calculate the mean value of all ratios γ_i for each geographical subarea and each $DF_{i.}$.

So we can produce for each DF a plot as shown in Fig. 2, where differences in signal attenuation for different propagation paths in the order of ±50% for similar distances are evident. Results for other DF's are similar. Therefore at least in Austria application of an attenuation model given in Eq.(7), Eq.(8) and Eq.(9) seems questionable.

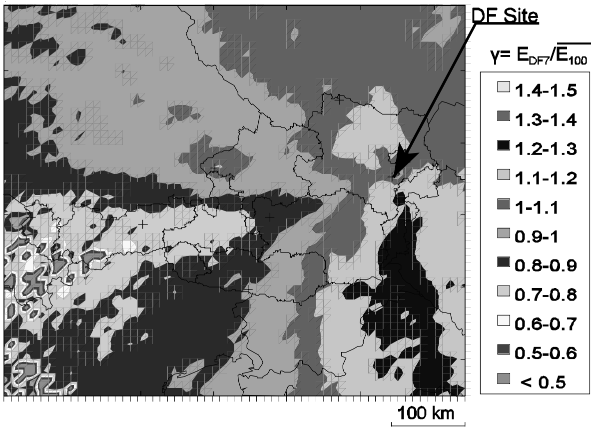

Fig. 2: Qualitative estimation of the signal attenuation for field propagation to DF#7.

4.2. Peak current estimation from measured peak fields

In a more general form we have to solve Eq.(11) to infer lightning peak currents from measured peak fields. There are different ways to determinate this general calibration function f in Eq.(11).

$$I_p = f(E_p, D) \qquad (11)$$

Apart from theoretical and statistical approaches the calibration of lightning location systems by triggered lightning is one of the most reliable methods. The disadvantage of this method is, that triggered lightning only represents subsequent strokes and it is questionable if all the characteristics of triggered lightning discharges are sufficiently similar to natural lightning.

Until now [3] and [10] are the only publications of a calibration of a lightning location network by triggered lightning at distances between trigger site and DF-sensor sites from 118 km to 427 km. In [15] measured peak currents from natural lightning to a tower are compared with LLS data

Performing a linear regression from measured peak current I_p of triggered lightning versus the mean range normalized signal strength $\overline{E_{100}}$ a relation Eq.(12) between current and field peak amplitudes was found in [3] and [10], with a correlation coefficient r=0.881 and a standard deviation s=4.6 kA.

$$|I_p| = 4.20 + 0.171 \cdot |\overline{LLP_{100}}| = 4.20 + 3.81 \cdot |\overline{E_{100}}| \qquad (12)$$

Unfortunately this calibration function shows an intercept on the ordinate of 4.2 kA. Therefore a regression with a nonlinear function seems to be more appropriate.

For range normalization a simple inverse distance relation was applied, probably applicable in Florida with a more homogeneous soil structure than in other countries. Especially for longer distances a direct application of this calibration function to other countries may be questionable.

4.2.1. An alternative method to determine the I_p versus $\overline{E_{100}}$ relation

This investigation is based on the data set published by Idone et.al. [10]. In this data set we have two DF at a distance of 379 km and 427 km respectively reporting only few data. For these distances a normalization with the simple inverse distance relation is not appropriate due to significant influence of the finite ground conductivity (see Fig. 1), and therefore we don't use data from those DF for the determination of the I_p versus E_p relation. For the distance range of the remaining DF (118 km-259 km) a simple inverse distance relation is applied for range normalization, assuming average uniform attenuation for all sensors. In Tab. 2 and Tab. 3 the results of different least-squares analysis of I_p versus $\overline{E_{100}}$ are shown.

Tab. 2: Regression functions for least-squares analysis based on triggered lightning data [10]

	Regression function
Version A	$I_p = A + K\,\overline{E_{100}}$
Version B	$I_p = K\,\overline{E_{100}}$
Version C	$I_p^3 - \frac{E_{100}^2\, 10^4}{K^2} I_p - \frac{W\, E_{100}^2\, 10^4}{K^2} = 0$

Tab. 3: Results of the least squares analysis using the functions in Tab. 1.

	Parameter of the regression function	Correlation coefficient r	Standard deviation s
Version A	A=4.59 K=3.71	0.885	4.49
Version B	K=4.47	0.861	4.82
Version C	K=34.9	0.881	4.56

Version A shows the best fit to the data set, with the disadvantage of an intercept on the y-axis. The fit of version B is not as good as the other versions. Version C is based on the modified Transmission Line Model Eq.(3) and the fit is almost equal to version A.

Contrary to this Idone et.al. [10] found a substantial decrease of r by applying version C. This is obviously the effect of including data from distant DF. In the following we are using the calibration function Version C.

In Fig. 3 the regression functions from Tab. 2 are shown. It results that the calibration function of the location system in Austria (labeled ALDIS) and suggested by the manufacturer (Global Atmospherics Inc.) results in up to 40% higher peak currents than the other versions.

5. Application of the attenuation factors σ_{DF} for the calculation of the lightning peak current

As shown in the previous paragraph we can estimate for each geographical unit (10 km x 10 km) the empirical attenuation factors σ_{DF} for each DF. Based on this information we can recalculate the lightning peak current by taking into account the attenuation due to propagation using the following algorithm:

– Calculation of the theoretically unattenuated peak electromagnetic field at the DF-site $E_{DF,\infty}=E_{DF}/\sigma_{DF}$ for each DF-sensor
– Determination of mean range normalized signal strength $\overline{E_{100}}$ with the inverse distance model.
– Calculation of the lightning peak current amplitude with the modified Transmission Line Model Eq.(3).
– DF reports with σ_{DF}=0 were not taken into account for the lightning peak current calculation.

5.1 Estimation of the effect of attenuation to the lightning peak current determination with the lightning location system in Austria

For this investigation we use the data of the lightning database of the Austrian Lightning Location System ALDIS for the period from 15.07.1997 until 31.12.1997. This data were processed by the LP2000 position analyzer. Therefore separate evaluation of first and subsequent strokes is possible. We use data from positive and negative strokes located by at least three DF's with optimization on time and angle. For subsequent strokes we selected strokes of the order 2-4. This selections results in a data set shown in Tab.4.

Tab. 4: Number of strokes selected from the ALDIS database

	Pos. polarity	Neg. polarity
First strokes	8583	121683
Subsequent strokes	961	123703

As an indicator for the reduction of the spreading of the range normalized signal strength by taking into account signal attenuation due to finite ground conductivity we introduce the variation coefficient defined in Eq.(15)

$$v = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(E_{100,i} - \overline{E_{100}}\right)^2}}{\frac{1}{N}\sum_{i=1}^{N}E_{100,i}} \qquad (15)$$

where N is the number of DF's reporting a given stroke. Comparing the mean value $\overline{v}$ for all strokes calculated with and without taking into account signal attenuation we find a significant reduction of the mean variation coefficient $\overline{v}$ from 0.144 to 0.065 for first strokes. The effect on subsequent strokes is similar.

5.2. Comparison of the lightning peak current distribution based on different calculation methods

In this paragraph we compare results of the peak current estimation using three different methods:

1. Peak current determination based on the calibration given by the manufacturer for the ALDIS system
2. Peak current determination based on the calibration function version C in Tab.2, without taking into account the attenuation coefficients σ_{DF}.
3. Peak current determination based on the calibration function version C in Tab.2, by taking into account the attenuation coefficients σ_{DF}.

As an example the resulting distribution function for negative first strokes is shown in Fig. 5. The results for positive discharges as well as for subsequent strokes are similar.

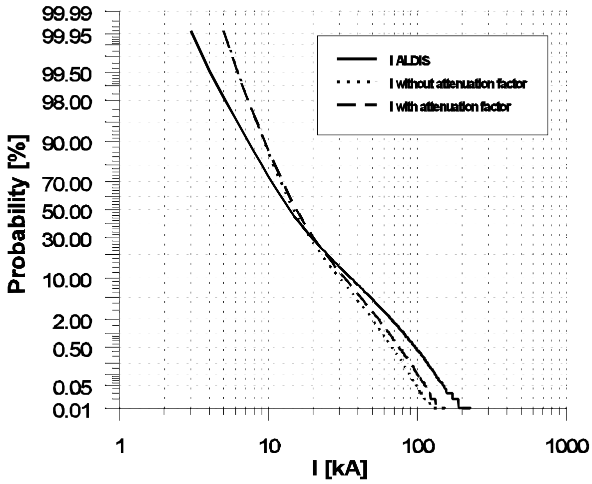

Fig 6: Negative first strokes. N=121273
I ALDIS: $I_{0.}$ = -15kA, $I_{0.05}$= -49kA, s= 1.8kA.
I without attenuation factor:
$I_{0.5}$= -15kA, $I_{0.05}$= -39kA, s= 1.6kA.
I with attenuation factor:
$I_{0.5}$= -16kA, $I_{0.05}$= -42kA, s= 1.6kA.

The difference between the calibration function of ALDIS and that of version C in Tab.1 becomes evident in the peak current distribution. The ALDIS calibration always gives significantly higher amplitudes in the range above 15-20 kA and lower amplitudes below this limit (see also Fig. 3).

The effect of signal attenuation to the peak current distribution can be described by a comparison of the remaining two distributions.

In general we obtain an about 10% higher value for the median of the lightning peak current by taking into account the attenuation with our model. The differences are more pronounced for higher amplitudes than for smaller amplitudes (up to 20% at the 0.05 value).

This effect could be explained by the fact that weak amplitudes normally are reported by a few nearby DF's with small attenuation effects, whereas strokes with higher amplitudes are usually also reported by more distant sensors, where attenuation becomes more pronounced.

6. Conclusion

To determine lightning peak currents with lightning location systems two significant factors have to be taken into account:

– Calibration function of the location system
– Attenuation of the signal by propagation effects

We found a significant influence on the distribution of the peak current amplitude due to the calibration function. The effect of the signal attenuation on the distribution function of the lightning peak current is in the order of up to 20%. For the peak current estimation of a single event the effect of signal attenuation may be even more pronounced.

Acknowledgements
This work has been supported by the Austrian Science Fund FWF (Proj. Nr. P10562-ÖTE).

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