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Correction of Lightning Density and Lightning Current Distributions for Detection Efficiency

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ABSTRACT
Lightning location systems are primarily used to determine the coordinates of the lightning striking point. These systems also provide information about the peak amplitude of the lightning current.

In literature we can find several ground flash densities and lightning peak current distributions determined from data collected by lightning detection systems. Usually the effects of a limited detection efficiency of those systems to the ground flash density and the peak current distribution are not taken into account. Detection efficiency of a location system mainly depends on the network configuration (number of sensors and baseline) and the setup of the direction finder threshold.

In this paper we present a method for correcting at least partly errors caused by the limited detection efficiency based on a simple probability approach. We take into account the network configuration, the threshold and the saturation limits of the used DF's.

1. INTRODUCTION

Lightning detection systems are nowadays state of the art in thunderstorm monitoring all over the world. The most important performance parameters of these systems are the location accuracy and the so called detection efficiency (DE). Although the DE is a very important parameter, it is our experience that quite often too little attention is paid to the DE in literature dealing with data from lightning location systems. In many papers important system parameters as threshold values of the sensors and network configuration, which strongly affect the DE are not reported. Most of the published lightning current distributions or lightning density plots are presented without any comments on the DE. To be able to compare lightning peak current distributions for different regions or even for the same region determined by different location systems the detection efficiency has to be involved.

Determination of ground truth data (the real number of flashes or strokes occurring at a certain location) requires a high experimental effort (video cameras) [Mach et al., 1986] and therefore theoretical models are normally used to estimate the detection efficiency of a location system. It was our intention to develop a model providing an easy way to calculate the network DE for a certain current peak amplitude. With this model it should be possible to correct lightning peak current distributions or ground flash densities based on the location data. The resulting current distribution or ground flash density should be as close as possible to the ground truth data.

Talking about DE of a location system it is necessary to distinguish between two different types of DE, the stroke and the flash detection efficiency [Rubinstein, 1995]. The flash detection efficiency is defined as the fraction of flashes detected from the total number of really occurring flashes. The stroke detection efficiency is defined in the same way regarding the individual strokes. Rubinstein [1995] has shown that the relation between stroke and flash DE strongly depends on the distribution of the number of strokes per flash and that the flash DE can be appreciably higher than the stroke DE.

For a magnetic direction finder (MDF) system, the DE of an individual DF is determined and limited by the following parameters [Diendorfer et al., 1994]:

- Trigger level of the DF
- Saturation limit of the DF
- Waveform discrimination

To locate a lightning flash with a MDF system, a minimum of two sensors reporting the flash is required.

2. DETECTION EFFICIENCY MODEL

The model presented in this paper is applied to calculate the flash DE and therefore the DE mentioned in the following chapters always means the flash DE. In the summary we give a short comment, how this model could be easily extended to estimate also the stroke DE.

To be able to estimate the detection efficiency for a certain region covered by a given location network and for a specified lightning peak current we have to assume a sensor detection efficiency function. For a specified peak current this function of DE versus distance D is basically defined by three parameters

1) the maximum sensor detection efficiency,
2) the saturation limit and
3) the threshold limit.

Fig. 1 shows an idealized sensor DE function, where the distances D_1 and D_2 are related to the saturation and the threshold limits respectively. Both values depend on the lightning peak current and the angle of incidence. It is an idealized sensor DE function because no sensor will really detect 100% of all of the flashes within the limits of saturation and threshold. Local noise, dead times, waveform discrimination etc. will always cause a certain limitation of the DE to less than 100% even in the range of normal system operation.

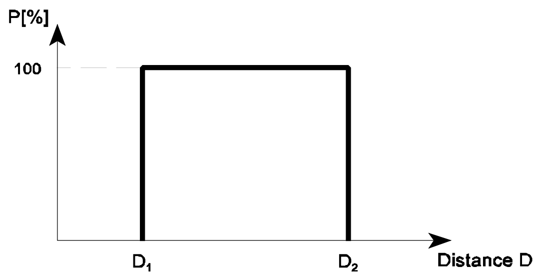

Fig. 1: Idealized sensor DE for a specified peak current and angle
D_1 ... saturation limit
D_2 ... threshold limit

We can calculate the distance limits D_1 and D_2 with the aid of the transmission line model and an exponential attenuation factor of 1.13 [Orville, 1991]. The attenuation of the electromagnetic field is caused by the propagation over ground of finite conductivity. If a flash of the specified peak current occurs at a distance $D<D_1$, the sensor will be saturated. If the striking point is at a distance $D>D_2$, the signal at the sensor site will not cross the threshold limit and therefore not trigger the sensor. A first step in the assumption of a more realistic sensor DE is to reduce the maximum sensor DE to less than 100% (see fig. 2). This reduction accounts for the missing of a certain percentage of flashes, e.g. when the flash occurs during the dead time of the sensor. If the sensors processes a flash it has a dead time of 6ms.

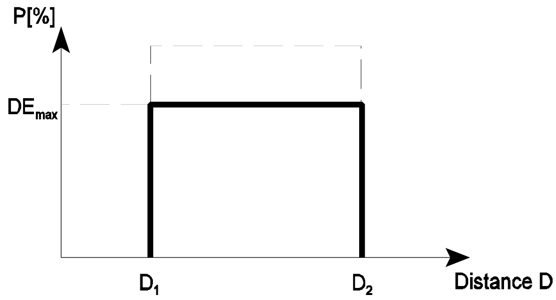

Fig. 2: Sensor DE function with DE_{max} < 100%

A direction finder (ALDF) triggers, if the absolute signal of one of the two magnetic antennas crosses the enable threshold. Therefore the sensor DE varies with the angle of incidence. To trigger the sensor, signals with an angle of incidence of 45° have to be about 40% higher than signals in direction of one of the antenna axis. The DF is already saturated, if only one of the signals of the two antennas is larger than the saturation limit. Thus, also the saturation limit depends on the angle. In our model we take into account the dependency of saturation and threshold limit from the angle of the field incidence as described above.

A field signal that is just crossing the trigger level will usually not satisfy the waveform criterias. Therefore we define the trigger level for our DE analysis as the level, where the field is at least twice as high as the adjusted threshold level.

A further improvement to make the sensor DE more realistic is an adaption of the instant change of the DE at the saturation and the threshold distance. It is very unlikely that the sensor doesn't detect any flashes if they are closer than the calculated saturation distance D_1 or more distant than the threshold distance D_2. Instead of the instant change we assume a more continuous increase and decrease of DE at the saturation limit and the threshold limit respectively (fig. 3).

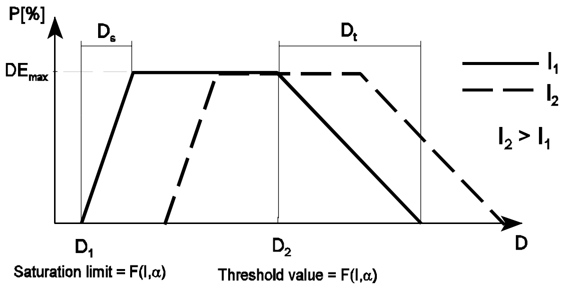

Fig. 3: Sensor detection efficiency for two different peak currents I_1 and I_2
D_s ... saturation range
D_t ... trigger range

Our analyses have shown that the slope at the saturation limit doesn't influence the result of the detection efficiency very much and it is high compared to the slope at the threshold limit. The saturation limit is a quite sharp limit. A more continuous decrease of DE was observed at the threshold limit. Fig. 3 shows a schematic function of the detection efficiency for two different peak currents I_1 and I_2. It is obvious that I_1 is less than I_2 because I_2 saturates the DF at longer distances D_1. On the other hand peak current I_2 triggers the sensor up to a longer distance D_2.

We estimated the unknown values of the sensor DE function by investigating the relative sensor DE of the sensor number 4, which is the central sensor of the Austrian network [Diendorfer et al., 1994]. Fig. 4 shows the percentage of flashes seen by DF4 from the total number of flashes seen by the entire network for different peak currents. For each peak current the area under investigation around the DF was adjusted to the trigger distance D_1 for the assumed peak current. Not only flashes with the exact peak current were extracted but also flashes with amplitudes of ±2.5 kA.

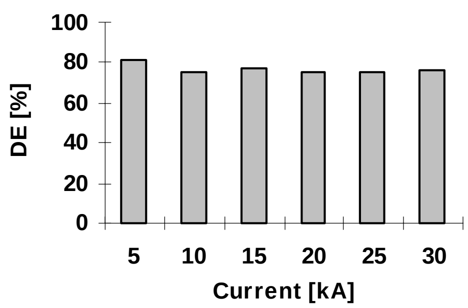

Fig. 4: Sensor DE for different current amplitudes

A relative sensor DE in the range from 75% to 80% becomes obvious from fig. 4. Because we still do not know how many flashes have not been detected by the system at all, the absolute sensor DE is assumed to be about 10% smaller than the relative sensor DE. A reduction by 10% seems to be an acceptable number for this part of the network.

To estimate the ranges D_s and D_t we have analyzed data from our location system to determine the change of the relative sensor DE with distance. Because the sensor DE depends on the angle and the peak current, it was necessary to do this investigation for different angles and peak currents. Fig. 5 shows as an example the results for DF 4 for an angle of 135° (±10°) and an amplitude of 20 kA (±2.5 kA). The calculated threshold distance D_2 for an amplitude of 20 kA, an angle of 135° and a threshold value of 70mV is 180 km.

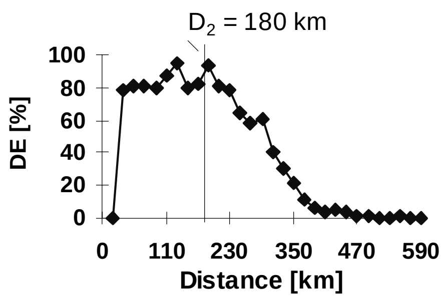

Fig. 5: Dependency of sensor DE on the distance for peak currents 20 kA, angle 135° and threshold 70mV

It can be seen from fig. 5 that for small distances there is a rapid increase of sensor DE to about 80% and that for a distance of about 430 km the sensor DE is almost zero. From similar investigations for different peak currents and directions we estimated the distance D_s, which does not influence the result significantly, to about 20 km and the distance D_t to 250 km. Fig. 5 also shows that the calculated threshold distance D_2 is reasonable.

Up to now we have only defined for a specified peak current and angle to the flash location the individual sensor detection efficiency function. We define the flash peak current as the highest peak current of all of the strokes of a flash. The efficiency for a two DF network to detect a specified peak current I_p is calculated by where p_1 and p_2 are the probabilities of sensor 1 and sensor 2 to register the flash (dependent on the distance to the flash) of a certain peak current respectively. We call this the **peak current network DE**. For a three DF network the DE is calculated by

where p_i is the probability that the flash is detected by the i-th DF and q_i is the probability for the i-th DF to miss the flash (p_i=1-q_i). Contrary to the probability approaches from e.g. Tuomi [1990] or Rubinstein [1994] we account with this model for threshold values and the modification of amplitude and waveshape. Therefore the DE should not be overestimated with this model as it is with the others [Sorenson, 1995].

Because we have to calculate the **peak current network detection efficiency** for many direction finders, we apply for this calculation a special algorithm [Billington, 1970]. This algorithm assumes an existing network of known DE, where a single DF is added and the DE for the total system is calculated. This process is continued till the number of detecting DF's is reached. We can for example calculate the detection efficiency (DE) for a 4 DF network in the following way:

- Calculation of the DE for a two DF network.
- One DF is added and the DE for the total system (additional DF and two DF network) is calculated. The result is the DE for the three DF network.
- A fourth DF is added and the DE for the additional DF and the three DF network is calculated. The result is the DE for the four DF network.

For a MDF system only two sensors reporting a flash are necessary and therefore the smallest possible network size is a two DF network. The DE in a region is greater than zero, when for flashes of a certain peak current the sensor DE for at least two DF is greater than zero.

Up to now we can only calculate the probability to detect a specified lightning peak current with the network (**peak current network DE**). Two different approaches are possible to calculate the **total network DE** in a certain region:

Method 1:

Correction of the detected peak current distribution in a region (e.g. 10km x 10km) to a "natural" lightning current distribution. The frequency of each current amplitude is corrected by the corresponding **peak current network DE** (fig. 6). The **total network DE** regarding the total distribution of peak currents is given by the ratio of the sum of corrected frequencies to the sum of detected frequencies.

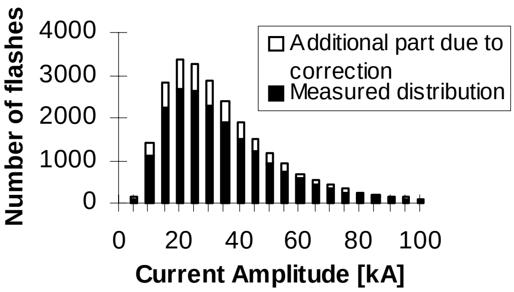

Fig. 6: "Natural" peak current distribution as the sum of detected flashes plus missed flashes due to limited DE

It is very important to note that for this approach of calculating the **total network DE** it is not necessary to assume a certain natural peak current distribution as required for the following method.

Method 2:

Calculation of a derived lightning distribution in a certain area from a theoretical distribution (e.g. Berger

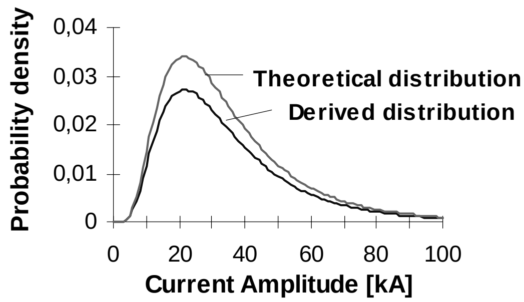

Fig. 7: Correction from a theoretical distribution

distribution). The relation of the two distributions is again the estimated **total network DE** in this area.

To get DE information over the entire network we have to calculate the **total network DE** for uniformly distributed areas over the network. From these data it is possible to produce contour plots. This process applies for both methods.

3. RESULTS

We analyzed with our model the dependence of the total network DE on different lightning peak current distributions. Fig. 8 shows a plot of the total network DE for the Austrian network. The network DE is calculated using method 2 and a peak current distribution with a median value I_{median}=16 kA and a mean value I_{mean}=19 kA is assumed. The threshold value is set to 100 mV.

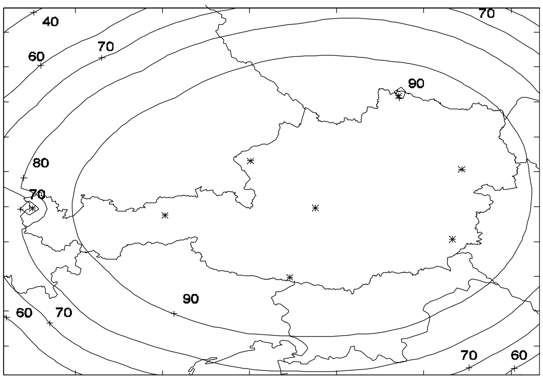

Fig. 8: Network DE with a peak current distribution of I_{median}=16kA and I_{mean}=19 kA

If a peak current distribution with higher mean and median value is used, the overall network DE will increase. To evaluate this behaviour we have calculated the total network DE with the BERGER distribution (I_{median}=30 kA and I_{mean}=34 kA)[Berger et al., 1975].

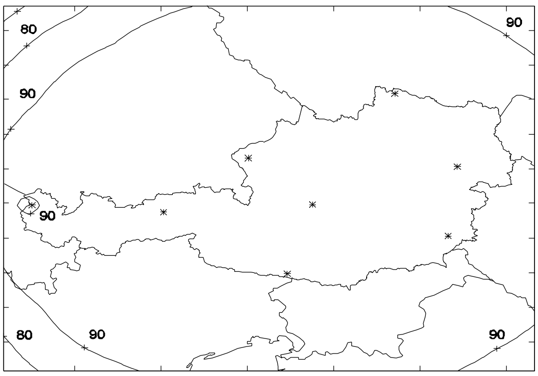

Fig. 9: Network DE with Berger's peak current distribution

A comparison of fig. 8 and fig. 9 shows that the assumed peak current distribution has a major influence on the resulting total network DE. For this reason we can compare DE plots only if they are based on the same peak current distribution. On the other hand, networks of different DE will give different peak current distributions.

4. DISCUSSION

For the analysis of the DE of a network it is necessary to distinguish between three different DE's:

- the sensor DE
- the peak current network DE
- the total network DE

It was our intention to make a nonsophisticated model for the total network DE. With this model, it is possible to correct every peak current frequency of a measured or assumed peak current distribution with the correspoding **peak current network DE**. This provides a way to correct the frequency of a certain peak current of a detected peak current distribution and the assumption of a peak current distribution can be avoided.

To be able to compare and analyze published DE plots it is absolutely necesary to know the peak current distribution assumed for the calculations.

To calculate the stroke DE for a network the sensor DE function has to be adapted. This also offers a possibility to adapt the model for calculating the stroke DE for a time of arrival system. While a MDF system requires only two sensors reporting a flash, for a time of arrival system a minimum of three sensors is necessary. Therefore the smallest network size for a time of arrival system is a three sensor network and the DE in a region is zero, when for strokes of a given peak current the sensor DE for only two sensors is greater than zero.

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