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Effect of Lightning Location Network Setup on evaluated Lightning Characteristics

Schulz W.
Diendorfer G.
Austrian Lightning Detection and Information System (ALDIS)

Pedeboy St.
Meteorage
French LLS operator

Abstract:
In this paper we compare various lightning characteristics measured by the Austrian and the French lightning location system. Both systems are lightning location networks using an APA283 position analyzer and IMPACT sensors. The two lightning location systems differed during the period of investigation mainly by the mean baseline between the direction finder (DF) and by the configuration parameter "number of sent strokes" of the DF. This parameter is set at the sensor itself (LINK_FORMAT: strokes) and limits the number of strokes per flash sent by the DF to the position analyzer.

We show in this paper how the difference in the mean baseline and the configuration parameters influence the lightning peak current distributions, the interstroke intervals, the number of strokes per flash, and the average flash duration. We also compare the lightning parameters reported by these two lightning location systems to lightning parameters available in literature.

1. Introduction

Lightning parameters are the basis for the design of lightning protection equipment and for the calculation of lightning radiated fields and their interaction with power and telecommunication lines.

There are different methods to measure lightning parameters as outlined below:

- Direct current measurements at tall towers [e.g., Berger et al., 1975]
- Direct current measurements in triggered lightning [e.g., Fisher et al., 1993]
- Inferences from electric and magnetic field measurements (natural and triggered lightning) [e.g., Rakov et al., 1994]
- Lightning location systems [e.g., Orville et al., 1987]

In this paper, we consider only those lightning parameters that can be extracted from the lightning database of the Austrian and the French lightning location system respectively.

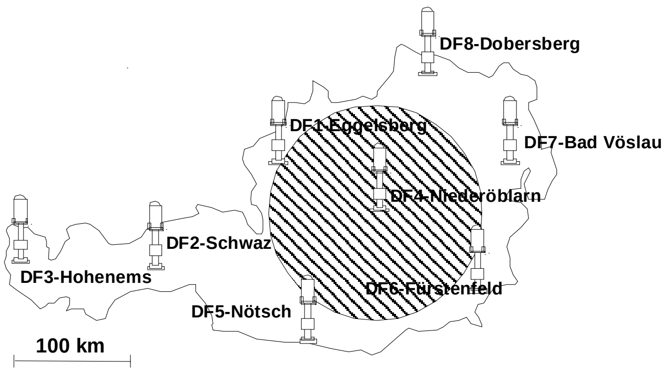
Both lightning location systems (described in section 2) used for this study are manufactured by Lightning Location and Protection, Inc. (LLP), a subsidiary of Global Atmospherics Inc. (GAI). The systems consist of several sensors and a central processing unit. In general a minimum of two sensors are required to find the stroke location. Each sensor determines (1) the angle to the lightning stroke and (2) the time of the lightning incidence. From these sensor data the central processing unit, the so-called position analyzer (PA), calculates the lightning location. For a comprehensive description of lightning locating technique see Krider et al. [1976] and Cummins et al. [1996].

2. The used lightning location systems

At the end of 1991, a lightning detection system based on magnetic direction finding was first installed in Austria [Diendorfer et al., 1992] and upgraded to the so-called IMPACT technology in 1994. The French lightning location network was first installed in 1987 and upgraded to the IMPACT technology at the end of 1996. The IMPACT (**IMP**roved **A**ccuracy from **C**ombined **T**echnology) technology combines the advantages of a magnetic direction finding system and a time of arrival system. Time synchronization by GPS signals keeps the absolute timing error between sensors smaller than 300 ns. Each IMPACT-DF reports angle, absolute time, amplitude, polarity, risetime and pulse width for each individual stroke of a multistroke flash. Risetime in this case is the time from threshold crossing to peak and pulse width is the time between peak and threshold crossing.

The Austrian lightning detection system is a high gain network of eight direction finders with a mean baseline between sensors of about 120 km (see Fig. 2.1). Six of these direction finders are installed at small airports, two of them being located on private property. The sites in Austria were selected very carefully to achieve a measurement of the lightning electromagnetic fields with minimal distortion by local objects.

Fig. 2.1: Direction finder locations of the Austrian system



The low electromagnetic noise level at the carefully selected sensor sites allowed to reduce the threshold level of all the sensors from 100 mV (manufacturer's standard configuration) to 70 mV for negative flashes in summer. Lowering the threshold of the sensors improves the detection efficiency of the network and lowers the minimum peak signal the system is able to detect. Threshold setting of 70 mV corresponds to a minimum electric field of 0.36 V/m. A reduction of threshold also causes an increase of the area covered by the network and therefore during periods of very high lightning activity some flashes may not processed (deferred flashes). Therefore, further decrease of threshold level in summer is not justified due to the limited processing capability of the APA. During winter time, when lightning activity in Austria and Central Europe is generally low, the threshold is lowered to 50 mV. For positive flashes, threshold is preset by the manufacturer at 350 mV and is not adjustable by the operator.

The French lightning detection system is also a high gain network. 20 direction finders with a mean baseline of about 200 km - somewhat longer than in Austria - (see Fig. 2.2) cover the French territory. The threshold is set to 75 mV and is not changed during periods of weak lightning activity.

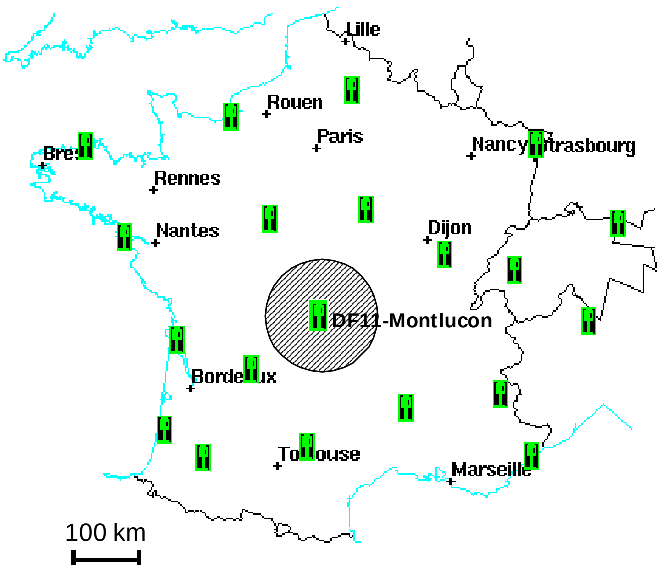


Fig. 2.2: Direction finder locations in France

In both networks the minimum signal width criterion was changed from the standard setting of 11 µs to lower values (6 µs in Austria and 7 µs in France). The relaxation of the width criterion was prompted by the observations of CG-strokes with a pulse width smaller than 11 µs [Ishii et al., 1989], particularly during winter thunderstorms. Thus, any signal wider than 6 µs in Austria and 7 µs in France (above threshold level) is identified as CG-stroke provided that this signal meets all other waveform criteria, some of which are given in Table 2.1. Most of the signals from cloud lightning are expected to fail this width criterion.

Table 2.1: Waveform criteria used in both networks for both positive and negative lightning strokes

	minimum	maximum
E/B ratio	0.2	3.0
pulse rise time	0	24 µs
pulse width	6 µs in Austria 7 µs in France	31 µs

The position analyzer (APA 280-T) installed in Austria is the so-called single processor APA. The limited processing capability of the single processor APA requires operation in All Stroke Reporting (ASR) mode for real time lightning. In ASR mode all the stroke data received from the DF are first correlated based on the time and then the strokes are assigned to flashes based on angle coincidence of the reporting DFs. The flash location is calculated using data for the stroke detected by the largest number of DF assuming that this will provide the most accurate flash location. This flash location is assumed to be the same for all the strokes in the flash.

In France the so called triple processor APA (APA 283-T) is installed. This APA is also operated in the ASR mode because the higher number of sensors in France is already consuming the higher processing capability provided by this APA.

Besides the small difference in the threshold setting and the pulse width criteria, the only difference in sensor configuration parameters of the two lightning location networks is the limitation of the number of sent strokes of a DF. In Austria this parameter is set to the maximum value of 15 whereas in France this number is limited to 3 strokes in a flash. The reason for this is to avoid any overload of the used APA 283-T during periods of high lightning activity in France.

Estimation of the lightning peak current is based on a range-normalized field signal S_n and Eq. (2.1).

$$i_p = 0.23*S_n \qquad (2.1)$$

where i_p is the lightning peak current in kA and S_n is the mean of the signal strength from the DFs participating in the location in LLP-units range-normalized to 100 km. The coefficient 0.23 in Eq. (2.1) is the standard setting proposed by the manufacturer for a high-gain network .

3. Comparison of the lightning parameters

3.1 Dataset

All lightning parameters of the Austrian network are evaluated from flashes located in 1996 in a circular area of 100 km radius around DF4 (14.009° E, 47.480° N) as shown in Fig. 2.1. Data from the French network are taken from flashes located in 1997 in a circular area of 100 km radius around DF11 (2.3587° E, 46.2268° N) as shown in Fig. 2.2.

The limited areas were chosen because these regions are characterized by presumably the best detection efficiency within the individual lightning location system. Analyzing data from the entire network instead of the selected area would result in a significant bias in the lightning parameters. Outside the network, as the distance increases, only strokes of higher peak current are detected, resulting in an increase of the mean value of the peak current distribution [Diendorfer et al., 1994]. Analyzed here are data over one entire year including all different types of thunderstorms, e.g., air-mass (convective) and frontal, occurring in Austria and in France.

We have to note, that the detection efficiency for a flash is higher than for a stroke. For a multistroke flash, it is sufficient to detect at least one of the strokes by a minimum of two DF to have a flash detection. To detect all strokes of a flash, each individual stroke requires a minimum of two reporting DF to obtain a solution. This certainly has a lower probability especially for smaller strokes.

The multiplicity of a flash assigned by the APA in ASR mode to a flash includes not only located strokes but also strokes detected by one DF. In ASR mode strokes are grouped by the DF to flashes by means of the angle information. A stroke reported by a single DF which is time correlated (within 1 second) and whose reported angle is within ±2.5° (Austria) or ±2.0° (France) to another stroke of a flash is assigned to that same flash.

All the following analyses are limited to negative flashes only.

3.2 Lightning peak current

Lightning peak current is one of the most important lightning parameters. Almost all of the national and international standards on lightning protection are based on data collected in Switzerland [Berger et al.,1975]. The lightning parameters were derived from measurements on two instrumented towers on top of the mountain Monte San Salvatore. Minimum peak current in Berger's data is 2 kA. Lightning peak currents are lognormally distributed and usually described by a median value and the standard deviation or by the 5 %, 50 % and 95 % values (see Table 3.1).

Table 3.1: Peak current distribution obtained by Berger et al. [1975]

	Unit	95 %	50 %	5%
negative first strokes	kA	14	30	80
negative subsequent strokes	kA	4.6	12	30

Estimation of the lightning peak current from electric field measurements in Florida was done by Rakov and Uman [1990] and Rakov et al. [1992a].

The lightning location systems in Austria and France estimate the peak current from the measured peak magnetic fields. Compared to the single-station field measurements by Rakov and Uman [1990] the field peak in this study is the mean of the range-normalized signal strengths of all reporting sensors (up to eight).

Fig. 3.1. illustrates the major differences between the initial electric field peaks.

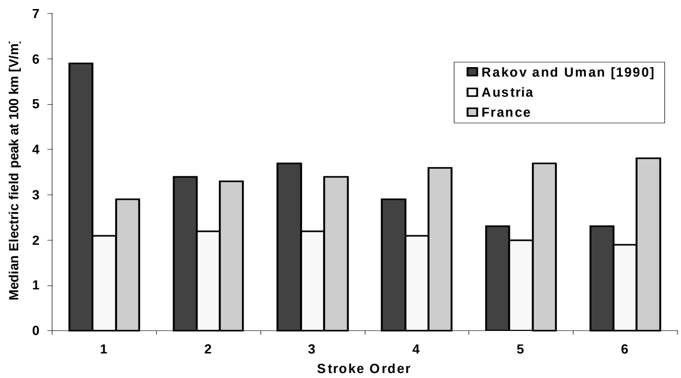


Fig. 3.1: Median initial electric field peak normalized to 100 km versus stroke order

Detected median electric field peaks in France are slightly higher than in Austria. The main reason for this being the larger mean baseline in France compared to Austria. Of course also the lower threshold in Austria during winter time contributes to this result. The tendency of an increasing field peak with stroke order in France is a result of the limited number of strokes sent by the DF in France.

Obviously the data from both lightning location systems do not show the ratio of about 2:1 between the median values of the electric field peaks of first and subsequent strokes as given by Rakov and Uman [1990]. A reason for this could be that the lightning location systems misses a significant number of first strokes. We tested this hypothesis by an independent field measuring experiment in Austria [Maier et al., 1996]. This independent field measurements revealed that in about 10% of all events, the location system in Austria misses the first stroke and assigns the second stroke as the first stroke. This percentage seems to be too low to explain the significant differences between the measured median electric field peaks of first strokes by lightning location systems and by Rakov and Uman [1990]. Also the field waveshapes recorded in Austria, independently from the location system, using a flat plate antenna do not show a 2:1 ratio for peak fields of first and subsequent strokes. If we assume that cloud discharges which might be erroneously accepted as CG strokes with small peak fields are mostly detected as single-pulse events, we can eliminate the misidentified events considering only multiple-stroke flashes. Therefore, we calculated for the Austrian data the median value for first strokes in multiple-stroke flashes (excluding single-stroke flashes). The resulting median of 2.5 V/m is only about 20 % greater than 2.1 V/m for all first strokes and thus we can also rule out the hypothesis regarding a significant influence of cloud discharges (provided they are indeed detected as single-pulse events).

In order to compare values of wide band antenna field measurements from the lightning location system (Fig. 3.1) with the peak current values determined by Berger et al. [1975] (Table 3.1) a calibration function has to be applied to convert peak field values to peak currents. The DF measures the peak field and reports this peak to the position analyzer in arbitrary units called LLP-Units. The relation between the LLP-Units and the electric field is given by the manufacturer in the form:

$$1158 \text{ LLP-Units} = 52 \text{ V/m} \tag{3.1}$$

For the comparison of field measurements with the peak currents of Berger et al. [1975] we use the GAI calibration (Eq. 3.2).

$$I = -5.12 * E_{100} \tag{3.2}$$

The median electric field of 2.1 V/m in Austria and 3.4 V/m in France for subsequent strokes correspond to a median peak current of about 11 kA and 17 kA respectively. The value measured in Austria is similar to the 12 kA reported by Berger et al. [1975] and about 10 kA found by Rakov et al. [1992a]. The 17 kA measured in France are higher for the reasons already mentioned above.

Applying this calibration we investigated the dependence of the first stroke amplitude on the multiplicity. The result is an increasing first stroke amplitude by increasing multiplicity independent of the network (see Fig. 3.2). Altogether the French network shows again higher values.

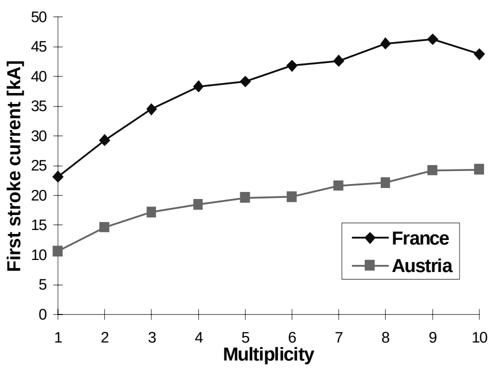


Fig. 3.2: Mean peak current of first strokes as a function of multiplicity of the flash

3.3 Percentage of single-stroke flashes

40% of all the flashes detected in Austria and 44 % of all the flashes detected in France were single-stroke flashes. Different percentages of single-stroke flashes are reported in the literature (e.g. Rakov et al. [1994] 17 %, Cooray and Perez [1994] 18%, Cooray and Jayaratne [1994] 21%, Kitagawa et al. [1962] 14%, Anderson and Erikson [1980] 45%). Rakov et al. [1994] argue that their data are similar to that of Kitagawa et al. [1962] and superior to that of Anderson and Erikson [1980] in terms of reliability of stroke count.

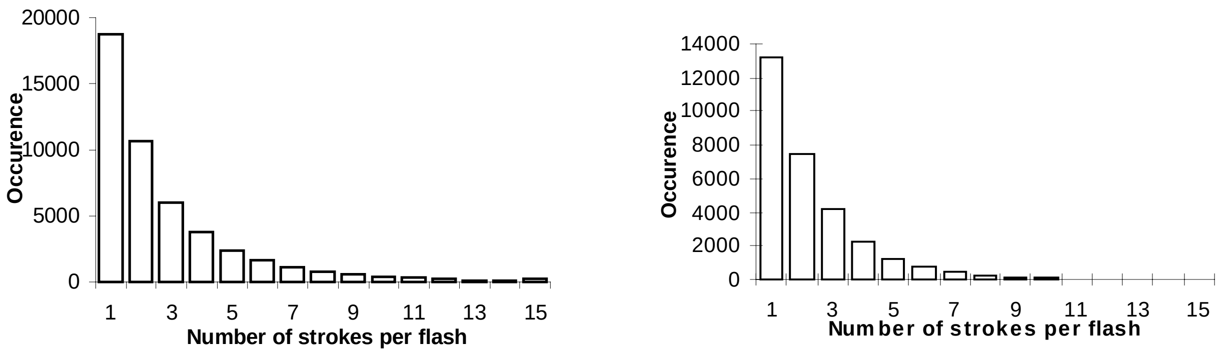
In Austria, the percentage of single-stroke flashes in individual storms ranges from 30 % to 80 % with a mean of 40 %. The percentage of single-stroke flashes varies significantly from storm to storm and probably depends on season, type of thunderstorm, etc. The minimum value of 30 % measured in Austria is still above the 17 % of Rakov et al. [1994] or the 14 % of Kitagawa et al. [1962]. A reason for this could be the limited stroke detection efficiency of the detection system, that causes missing of smaller strokes.

3.4 Average number of strokes per flash

Rakov et al. [1994] reported an average number of 4.6 strokes per flash in Florida. The Austrian LLS detected an average number of 2.7 strokes per flash and the French LLS detected an average number of 2.3 strokes per flash. The distribution of the detected number of strokes per flash in Austria and France is shown in Fig. 3.3. The IMPACT sensors are generally limited to a maximum number of 15 strokes. Therefore the bar in Fig. 3.3 for stroke number 15 is the total of flashes with 15 or more strokes. Only a very small percentage of flashes has more than 15 strokes and therefore this sensor limitation should not cause any appreciable bias in the data.

Austria France

Fig. 3.3: Distribution of the number of strokes per flash in Austria and France



The higher value of strokes per flash in Austria (2.7) compared to France (2.3) is definitely related to the configuration parameter „Number of sent strokes“ which is limited to a value of 3 strokes in France and the smaller angle criterion of the grouping algorithm in France.

Although the number of strokes is limited to 3 in the French network it is possible to detect flashes with more than 3 strokes. The reason for this is that the final grouping of strokes into flashes is done by the APA and often different DF detect different groups of strokes from the same flash. In this case the grouping algorithm assigns a multiplicity higher than 3 to that flash.

Analyzing the individual thunderstorm days in Austria shows a significant variability of the average number of strokes per flash in the range from 1.2 to 4.2 Austria, probably due to dependency on season (winter/summer) and thunderstorm type (convective/frontal). The limited stroke detection efficiency of the location system could also cause some bias toward lower values.

3.5 Interstroke interval

For a sample of 270 subsequent strokes, Rakov et al. [1994] determined that the geometric mean interstroke interval is 60 ms. They also reported a dependency on stroke order, as shown in Table 3.2. Berger et al. [1975] gives a geometric mean for the interstroke interval of 33 ms (N=133).

Table 3.2: Preceding interstroke interval versus stroke order [Rakov et al., 1994]

Stroke order	2	2-4	5-18
Geometric mean [ms]	56 (63)	66 (155)	54 (115)

The numbers in the parentheses are the sample sizes.

The interstroke intervals as a function of stroke order for both networks are given in Fig. 3.4. In this Figure all interstroke intervals up to 1 s are included.

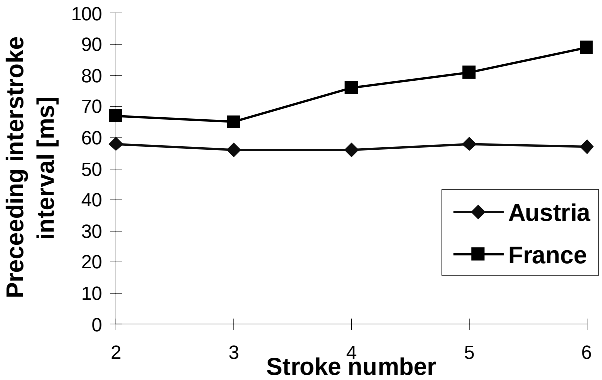


Fig. 3.4: Preceding interstroke interval depending on stroke order

The interstroke intervals of the Austrian data (50 – 60 ms) are similar to those observed by Rakov et al. [1994]. No significant dependency on stroke order was found in the Austrian data. Whereas the French data show an increase of the interstroke interval starting from stroke number three. This is caused by the limitation of sent strokes at the DF site and the angle criterion of the flash grouping algorithm in France. The generally higher values in France for strokes number 2 and 3 compared to Austria are due to the larger mean baselines and due to the slightly higher threshold value in France.

3.6 Flash duration

Berger et al. [1975] reported for negative multiple-stroke flashes a median duration of 180 ms (see Table 3.3).

Table 3.3: Flash duration measured by Berger et al. [1975] and determined from LLS data in Austria and in France

	95%	50%	5%
Berger et al. [1975], [ms]	31	180	900
Austria, [ms]	23	175	725
France, [ms]	70	400	900

The flash duration measured by the lightning location systems is defined as the duration between the onset time of the first stroke and the onset time of the last stroke of the flash. We limited the investigation to a maximum flash duration of 1 s. Although the sample size is much larger than that of Berger et al. [1975] and the measuring technique is completely different from Berger et al. the results in Austria are similar to that of Berger et al. [1975]. The higher flash duration estimated in France is assumed to be a result of the flash grouping algorithm when very distant sensors contribute to a flash. Fig. 3.5 shows the frequency distribution of the flash duration in Austria and in France.

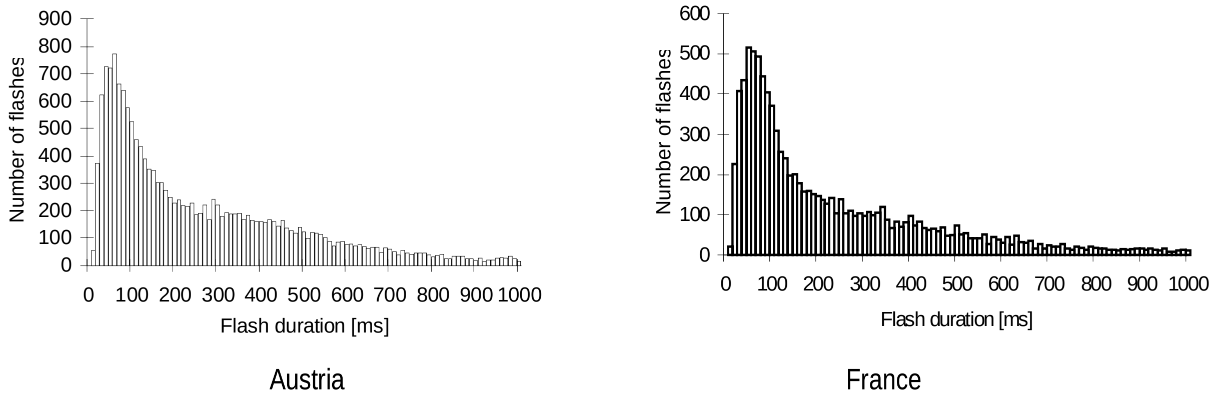


Fig. 3.5: Histogram of flash duration for the Austrian and the French LLS-data

4. Discussion

We have selected for this presentation areas of maximum detection efficiency in the two individual networks. Besides the DE, the stroke grouping algorithm may have some influence on the resulting lightning parameters from the lightning location networks and causes some discrepancies between the lightning parameters from the location systems and those found in previous literature.

Some differences between lightning parameters estimated from the lightning location system data and from field or tower measurements could be caused by one or a combination of the following reasons:

Possibly, first strokes in the mountainous regions in Austria and France are different from first strokes measured in Florida, confirming that in general lightning parameters are different in different topographic and climatic regions. Perhaps many negative flashes in mountainous area are initiated by upward discharges. As a result, the high-current first stroke would be missing and the location system assigns a subsequent stroke as the first stroke.

Contrary to that, Thomson [1980] showed that neither interstroke intervals nor the number of strokes per flash exhibits a significant dependence on latitude and also Cooray and Jayaratne [1994] concluded that there are strong similarities in the characteristics of cloud to ground flashes between different geographical regions. On the other hand, several investigators reported that frontal and air-mass storms differ in terms of the average number of strokes per flash.

Second, measurements in previous studies usually included data from a limited number of thunderstorms. The LLS-data are covering an entire year with all different types and stages of development of thunderstorm, ranging from severe frontal and convective thunderstorms in July and August to winter thunderstorms with a very low flash rate.

Data from Rakov et al. [1994] are for lightning within 20 km in Florida, whereas the LLS data involve longer propagation distances (up to a few hundred kilometers) and generally lower ground conductivity.

Lightning peak fields of subsequent strokes measured in Austria are similar to measured lightning peak fields of subsequent strokes found in the literature. The lightning peak fields in France are more biased by network limitations than the Austrian data.

One of the most interesting results is that both LLS data do not show the 2:1 ratio between the median values of the field peaks of first and subsequent strokes. On the other hand, the spatial resolution of a location system does not allow to distinguish between subsequent strokes in the same channel and strokes creating a new channel as observed on multiple-station TV records [Rakov et al. 1990], as long as the separation of termination points is in the range of some hundreds of meters or more. If strokes creating new terminations on ground radiate higher initial field peaks [see Rakov and Uman, 1990] and those strokes are assigned as subsequent strokes by the location system, this would increase the mean of initial field peaks for subsequent strokes and make this value more similar to first strokes.

The limited detection efficiency (which is partly due to propagation effects) results in biases in the number of strokes per flash toward lower values.

The interstroke intervals measured by LLS are similar to those measured by Rakov et al. [1994]. This parameter is probably less dependent on DE because only located successive strokes (according to the APA) are used. We have shown that the interstroke interval strongly depends on the number of strokes sent by the DF.

The flash duration measured by the lightning location system in Austria is similar to the flash duration measured by Berger et al. [1975]. This parameter should not be influenced by the DE because we only used flashes with a detected first stroke (according to the lightning location networks) and in this case it does not matter if one of the strokes between the first and the last stroke is missing due to a too small signal, and therefore not detected by at least two sensors.

The majority of the analyzed parameters (median initial electric field peak for subsequent strokes, interstroke interval, flash duration) are in more or less good agreement with parameters independently measured by other techniques.

The system configuration parameter „Number of sent strokes“ at the DF has a major impact on some of the lightning parameter.

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