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33-206

Session 2002

Evaluation of Lightning Location Data Employing Measurements of Direct Strikes to a Radio Tower

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ABSTRACT

A Lightning Location Systems (LLS) provides large scale information for lightning strikes to ground. In addition to the event time and strike point position, the LLS gives estimates for the lighting peak current. For the end user of LLS data it is important to know the technical limits of the applied network in terms of detection efficiency, accuracy of the stroke location and peak current estimate. To establish a ground truth reference for comparison of natural lightning current parameters and the data of ALDIS (**A**ustrian **L**ightning **D**etection & **I**nformation **S**ystem), a telecommunication tower on Gaisberg near the city of Salzburg (Austria) was instrumented for direct lightning current measurement. Since the start of the tower experiment in 1998 we have recorded more than 200 lightning flashes to the tower. Based on the analysis of the current waveforms nearly all of them are so called upward initiated discharges. GPS time synchronization of both data sets allows a precise correlation of individual events measured at the tower and reported by the lightning location network.

Detection efficiency (DE)
During the years 2000 and 2001 we have recorded 463 strokes to the tower with peak currents greater than 2kA. Correlation with the ALDIS data shows that the flash DE of the location system is about 94% for flashes with a at least one stroke with an amplitude exceeding 5 kA. The DE depends on the presence of current pulses of sufficient peak amplitude and di/dt. Only current pulses with sufficient electromagnetic field radiation are detected by sensors of the LLS at distances of more than 100 km. Some of the upward initiated discharges - which are typical for high towers and other elevated objects - only showed continuing current wave shapes without any pronounced current pulses.

Location accuracy
Distance between the strike point position determined by ALDIS and the ground truth position of the tower are in the range of some hundred meters. We observe a systematic shift of the calculated locations to the north-east by about 500 m with a median distance of 450 m.

Peak current estimate
Peak current estimate of a LLS is based on remotely measured peak fields. For the 295 strokes located during 2000 and 2001 we determined a relation I_ALDIS = 0,95*I_TOWER (r= 0,95). Therefore on average differences of LLS peak currents and directly measured peak currents are in the range of measuring errors of both systems.

This raises the question, why the median value of the peak current distribution determined by ALDIS over a large area in Austria is in the range of 12 kA, whereas the median value specified in many lightning standards is as high as 30 kA. Keeping in mind, that the distribution of lightning peak currents is one of the most fundamental input parameters in all kind of lightning protection analysis and insulation coordination, a reexamination of lightning peak current parameters in existing standards seems to be necessary.

1. INTRODUCTION

The use of data from lightning detection networks by power utilities and other operators of large network (e.g.telecommunication) has increased heavily over the last decade. Today lightning location networks provide real-time information about the lightning activity as well as historical data for past time failure analysis. Lightning location is a complex subject where the quality of data provided to the end user is effected by various parameters like the employed type of location sensors, the setup

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parameters of the central analyzer and effects to lightning electromagnetic fields propagation over ground of finite conductivity. For an appropriate application of data from LLS by the user it is important to know the performance limits of the used location system. In literature we can find data for peak current distributions, flash density maps, values for maximum lightning peak currents from various location systems that are often quite different in their mean values and maximum detected peak currents.

In this paper we will mainly focus on the three major performance parameters of a LLS as (1) detection efficiency (DE), (2) location accuracy (LA) and (3) accuracy of peak current estimate. We limit our analysis to the magnetic direction finding (MDF) and time of arrival (TOA) technology used by the sensor types IMPACT, LPATS III and LPATS IV, respectively, manufactured by Global Atmospherics Inc. (GAI), Tucson, although other commercial and/or experimental systems exist. Many networks of this manufacturer of different size (a few sensors up to large scale networks of more than 100 sensors) are installed in various countries all over the world.

Fig.1: Gaisberg Tower

In the past different approaches have been made to evaluate the performance of LLS. As an example IDONE et al. (1998a) used a large set of video observations of cloud-to-ground lightning. A strong dependency of the DE from peak current amplitude was observed.

2. DIRECT LIGHTNING CURRENT MEASUREMENT

In 1998 we started in Austria to measure currents when lightning strikes a radio tower (Fig.1). The radio tower on Gaisberg with a height of about 100 m is located 1287 m above sea level about 5 km east of the city of Salzburg. This tower was selected because analysis of historical data from the lightning location system ALDIS showed a flash rate of about 40 – 50 flashes per year to the tower.

The distances to the 8 IMPACT sensors of the ALDIS system are in the range from 32 km to 261 km. To the north-west several LPATS sensors of the German LLS BLIDS are installed and participate frequently in the location of lightning strikes to the tower.

The overall setup of the measurement system for direct lightning current registration is shown in Fig.2.

An appropriate air termination was installed on top of the tower in order to capture most of the lightning discharges to the tower (Fig.3). The lightning current is measured at the base of the air termination by a wide band current viewing resistor (shunt) of 0.25 mΩ with a bandwidth of 0 Hz to 3.2 MHz, manufactured by T&M Research Products Inc. A fiber optic link for data transmission and the recording system were installed in a building next to the tower.

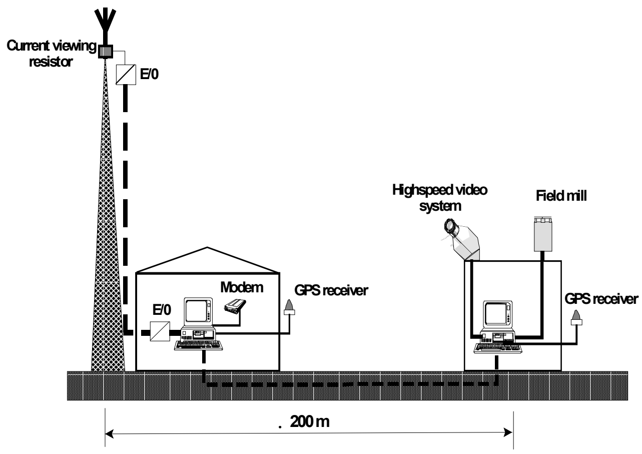


Fig.2: Schematic overview of the experimental measuring setup at Gaisberg tower (E/O: Electrical/Optical signal converter).

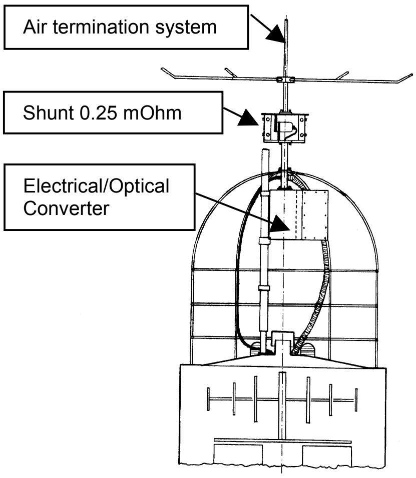


Fig.3: Installed equipment on the tower top

Due to the wide range of expected current peak amplitudes two separate fiber optic channels of different sensitivity are installed:

- Channel 1: 0 - 2.1 kA
- Channel 2: 0 - 40 kA

The shunt output signal is recorded by an 8 bit digitizing board installed in a Personal Computer. The digitizing board (National Instruments PCI-5102) with a bandwidth of 15 MHz and a memory of 16 MB per channel is operated with a sampling rate of 20 MS/s. The trigger of the recording system is set to a corresponding lightning current level of ±200A. All recorded waveforms are time stamped using the time information provided by a GPS clock (Meinberg GPS167PC) in order to be able to time correlate them with the data from the lightning location system. GPS timing is appropriate to identify correspondence of individual strokes recorded at the tower and located by ALDIS.

In summer 1999 some additional measurement equipment for recording the static atmospheric electric field (field mill) and a high-speed video system was installed at a distance of about 200 m from the tower (Fig.2).

3. ALDIS SYSTEM

The Austrian Lightning Detection & Information System (ALDIS) started operation in 1992. A comprehensive description of the ALDIS network can be found in Diendorfer et al. (1998). Today eight IMPACT type sensors provide coverage of the Austrian territory. Since 1998 ALDIS participates in the European Cooperation for Lightning Detection (EUCLID), a network of about 100 sensors in 14 countries all over Europe. Projected Detection Efficiency (DE) of the EUCLID network is better than 90% and the projected location accuracy is better than 500 m all over Austria.

4. ANALYSIS OF THE DETECTION EFFICIENCY

The objective is to establish the flash and stroke DE of ALDIS for the lightning strikes to the instrumented tower. It is worth to note that elevated objects like the radio tower experience primarily upward initiated discharges similar to rocket-triggered lightning. Typical for this upward initiated discharges is a so called initial continuing current (ICC) with a duration of some hundred milliseconds and an amplitude of some tens to some hundred of amperes, often followed by one ore more downward leader - upward return stroke sequences. There is still the question of whether current pulses occurring during the ICC stage, that is, pulses superimposed on the long-lasting, low-level continuous current, are due to return strokes or due to an M-component-type lightning process.

In many of the upward initiated discharges all the superimposed current pulses have amplitudes of a few hundred amperes up to 1 - 2 kA. Often these current pulses of even higher amplitudes show a very slow rising front and therefore do not radiate electromagnetic field pulses of sufficient magnitude to be detected by the LLS-sensors (see Fig.4).

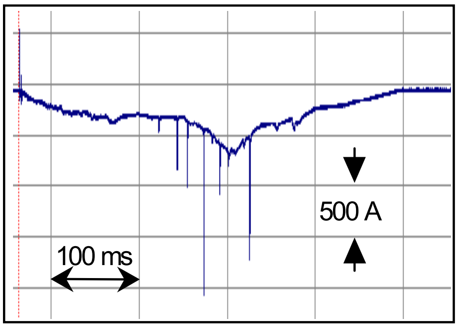


Fig. 4a: ICC-current with 5 ICC pulses flash #182

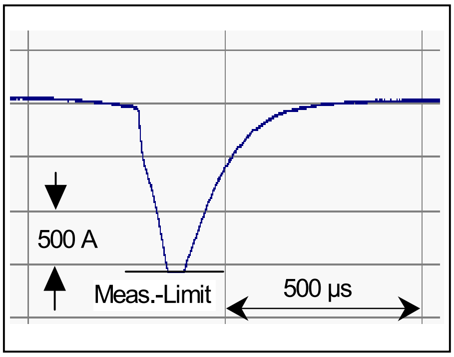


Fig. 4b: ICC-pulse # 3 I_{peak}= -3 kA

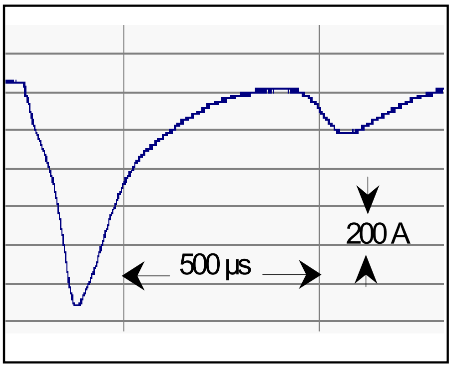


Fig. 4c: ICC-pulse # 5
I_{peak}= -1,2 kA

In our evaluation of the DE of the LLS therefore in a first step we have selected directly measured strokes to the tower with amplitudes greater than 2 kA. Only strokes of negative polarity are considered, because very few discharges to the tower have been either of positive polarity or showed bipolar pulses.

In Table 1 the results of a comparison to the parameters of directly measured lightning current pulses and the time correlated data reported by ALDIS are summarized. The analysis was done for directly measured minimum peak currents of 2kA, 4kA, 6kA, 8kA and 10 kA respectively.

Table 1: Number of flashes/strokes measured at the tower and located by ALDIS in year 2000 and 2001 (Fl...Flashes, St...Strokes)

	Tower		ALDIS			
I_min [kA]	N Fl.	N St.	N Fl.	N St.	DE Fl.	DE St.
2	77	463	66	296	86%	64%
4	68	365	63	282	93%	77%
6	62	272	58	234	94%	86%
8	51	206	50	187	98%	91%
10	47	147	46	137	98%	93%

Obviously from Table1 and Fig.5 the LLS has a DE of 94% for flashes with at least one stroke of a peak current amplitude greater then 6 kA. As expected the stoke DE is smaller than the flash DE and is 86% for all strokes of peak currents greater than 6 kA. For the detection of a flash with several strokes it is sufficient to detect at least one of the strokes.

When we lower in our analysis the minimum peak current of a stroke to 2 kA the Flash DE reduces to 86%, whereas the Stroke DE reduces to 64%. The reason is, that several small peak current strokes that are detected by only one or two sensors close to the tower site, don't provide sufficient information for a location and therefore are missed by the LLS.

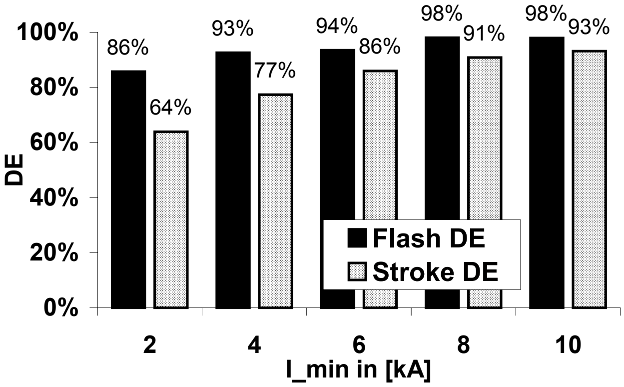


Fig.5: ALDIS flash and stroke detection efficiency as a function of minimum peak current

These results are similar to those reported by IDONE et al. (1998), where also a steadily drop of likelihood of detection with decreasing current was observed. When strokes of less than 4 kA were excluded, the ALDIS flash DE of 93% (I_min > 4kA) is significantly higher than the flash DE of 84% for the NLDN reported by IDONE at al.(1998). This higher flash DE is most likely a result of the shorter baselines between sensors in the ALDIS network which provide a higher sensitivity of the network to small electromagnetic field pulses.

We have to note, that a high fraction of the directly measured strokes with amplitudes between 2 kA and 10 kA not located by ALDIS exhibit waveforms very similar to the current pulse shown in Fig. 4b with a maximum di/dt values of less than 2-3 kA/µs. This current wave shape with its slow rising front is expected to radiate an electromagnetic field pulse of insufficient amplitude to be detected by two or more sensors at distances of more than 100 km.

5. ANALYSIS OF THE LOCATION ACCURACY

The radio tower provides a perfect ground truth reference for the evaluation of the location accuracy. In Fig.6 we have plotted the striking point locations provided by ALDIS for the set of correlated strokes to the tower.

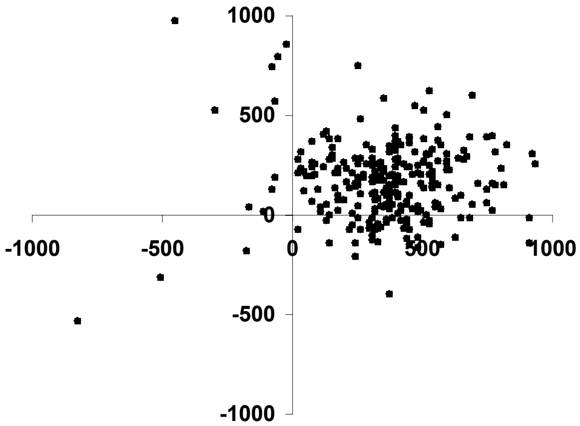


Fig.6: Plot of ALDIS locations for correlated strokes - the tower is located in the origin

As shown in Fig.6 the majority of the ALDIS locations are shifted to the north-east from the tower location (0/0) by about 500 m. The source of this systematic error in the locations is still unknown. The corresponding distribution of location distances is shown in Fig.7. The resulting median value of 450 meters is within the expected location accuracy range of 500 meters.

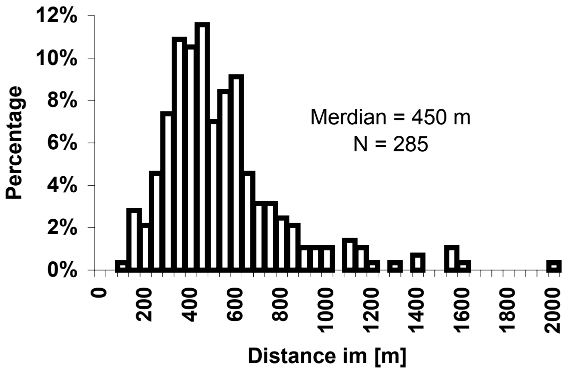


Fig.7: Distribution of distances between ALDIS location and tower site

In case of a successful elimination of the systematic shift of locations to the north-east the median value of location error could be reduced to about 200 m.

6. ANALYSIS OF THE PEAK CURRENT ESTIMATES

Estimation of the lightning peak current by ALDIS is based on a range-normalized electromagnetic field pulse amplitude S_n

$$|i_p| = 0{,}23 . |S_n|$$

where i_p is the lightning peak current in kA and S_n is the mean of the signal strengths from the DF's participating in the location in LLP-units range-normalized to 100 km. The coefficient 0.23 is the standard setting proposed by the manufacturer for a high-gain network.

To test the validity of the above mentioned relation between electromagnetic field pulses measured by the sensor and the estimated peak current amplitude, we have plotted in Fig.8 the directly measured peak currents I_TOWER versus the peak amplitudes reported by ALDIS. Calculation of a linear regression line results in I_ALDIS = 0,95*I_TOWER with a correlation coefficient r = 0,954, with the fit forced to go through the origin.

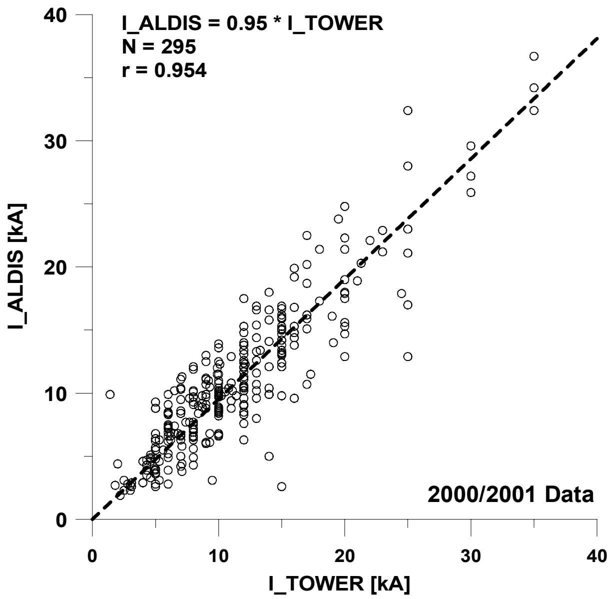
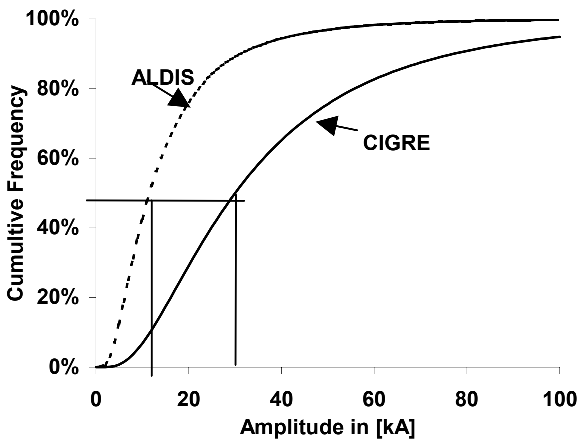


Fig.8: Comparison of directly measured currents I_TOWER with the current estimates from ALDIS
NOTE: Absolute values of negative stroke peak currents are plotted

This result shows, that on average ALDIS underestimates the lightning peak current amplitude by about 5% compared to the directly measured current amplitude at the instrumented tower. This is within the range of the estimated accuracy of the current measurement system (+/- 10%).

Considering this evidence of an acceptable estimate of peak current by ALDIS raises the question how the observed significant differences between the distribution of lightning peak currents reported by ALDIS and the peak current distribution specified by CIGRE (e.g. Anderson et al. 1980) shown in Fig. 9 could be explained.



CIGRE: Median 30 kA, Sigma-log 0,32
ALDIS: Median 12 kA, 98%-value 58 kA

Fig.9: Differences between lightning peak current distributions specified by CIGRE and provided by ALDIS for neg. discharges

The peak current distribution reported by ALDIS for first strokes in negative flashes in 1995 -1997 with a median value of about 12 kA and a 98%-value of 58 kA is much different from the CIGRE distribution with a median of 30 kA. We do not see any reason that could explain such a big difference by the performance of the location system. When ALDIS is within an accuracy of 10% for strokes to the Gaisberg tower, why should there be an error of about 100% and more for strokes to ground all over the country. Keeping in mind the importance of peak current distributions for different areas of lightning protection and insulation coordination a reexamination of lightning parameters seems appropriate.

DISCUSSION

Systematic comparison of directly measured lightning peak currents with the corresponding reports from a LLS provides some insight in the performance of a location system. LLS have developed over the last decades to a new valuable source of information about lightning activity and individual stroke parameters. Tower measurements and triggered lightning experiments are always limited to single stations and a more specific type of lightning (upward initiated).

Lightning Location Systems provide a full set of information about several parameters of „natural" lightning discharges to ground over large areas. This is the only type of lightning relevant for general lightning protection issues.

In all our discussions about the validity of data from LLS we have also to be aware of the limitations and possible errors in the data from historical experiments. Some of these experiments have been performed decades ago with measuring equipment much different from what is available today. Nowadays fiber optic communication, high speed digitizers and GPS time synchronization is available for experiments in an extreme electromagnetic environment existing nearby the lightning channel.

We conclude from our analysis, that there is still a number of open questions to be addressed like the performance of LLS for positive lightning.

We are convinced that a combined evaluation of data from triggered lightning, tower measurements and LLS will help to make some steps forward to provide a better understanding of the lightning phenomenon.

Acknowledgements

The Gaisberg tower experiment is supported by VERBUND and KELAG (contract V08/4500021357), by the Austrian Science Fund (Project Nr. P12977-TEC) and by Hochschuljubiläumsstiftung der Stadt Wien (Project H77/98). The authors would also like to thank the staff of the Austrian Broadcasting Corporation (ORF) for their support and hospitality at the tower site.

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