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Lightning properties derived from lightning location systems and tower measurements

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Abstract — Cloud-to-ground (CG) lightning parameters and the spatial distribution of lightning flashes are of fundamental interest for the design of lightning protection systems. In the past lightning location systems (LLS) have been installed in many countries around the world and these systems can provide large scale observation of the lightning occurrence together with some additional information about polarity and peak current of the individual strokes.

On the other hand instrumented towers have been used in the past and nowadays to measure the lightning current directly, when a discharge occurs to the tower. The most complete characterization of the return stroke in negative downward flashes, the type that normally strikes flat terrain and structures of moderate height, that is, shorter than 100 m or so, is due to K. Berger and co-workers [e.g 1,2,3], measured at Mont San Salvatore in Switzerland. Their results are still used to a large extent as the primary reference source for both lightning protection and lightning research.

I. INTRODUCTION

In current standards for lightning protection [4] parameters of the lightning current are specified as listed in Table 1.

Table 1: Maximum values of lightning parameters according to lightning protection levels (LPL)

First short stroke			LPL			
Current parameters	**Symbol**	**Unit**	**I**	**II**	**III**	**IV**
Peak current	I	kA	200	150	100	
Short stroke charge	Q_{short}	C	100	75	50	
Specific energy	W/R	MJ/Ω	10	5,6	2,5	
Time parameters	T_1/T_2	µs/µs	10 / 350			
Subsequent short stroke			**LPL**			
Current parameters	**Symbol**	**Unit**	**I**	**II**	**III**	**IV**
Peak current	I	kA	50	37,5	25	
Average steepness	di/dt	kA/µs	200	150	100	
Time parameters	T_1/T_2	µs/µs	0,25 / 100			
Long stroke			**LPL**			
Current parameters	**Symbol**	**Unit**	**I**	**II**	**III**	**IV**
Long stroke charge	Q_{long}	C	200	150	100	
Time parameter	T_{long}	s	0,5			
Flash			**LPL**			
Current parameters	**Symbol**	**Unit**	**I**	**II**	**III**	**IV**
Flash charge	Q_{flash}	C	300	225	150	

Most of the values given in Table 1 are based on Berger's tower measurements in the 1960's and 1970's. In the meanwhile there has been considerable progress in the development of LLS to monitor lightning occurrence on large scale areas. Compared to LLS towers provide lightning data only for the given tower location and there is considerable discussion about the effect of the tower itself on the measured lightning parameters [e.g. 5,6].

II. LIGHTNING LOCATION SYSTEM

In Austria a LLS named ALDIS (Austrian Lightning Detection & Information System) was first installed in 1991. The system is based on eight so called IMPACT sensors employing a combination of magnetic direction finding and time of arrival method to locate cloud to ground lightning discharges (see Figure 1). A comprehensive description of design and configuration of the ALDIS network is given in [7]. In this paper also the sensitivity of various lightning parameters derived from data from LLS is analyzed.

Figure 1: ALDIS network sensor locations

ALDIS is participating in the project of EUropean Cooperation for LIghtning Detection (EUCLID – see also http://www.euclid.org). Currently EUCLID is a network of 123 sensors installed in 17 European countries.

Most interesting parameters that are typically derived from LLS are the Ground Flash Density (GFD) and the distribution of lightning peak currents.

Ground Flash Density

Ground flash density N_g, typically presented as the number of Cloud-Ground (CG) flashes per square km per year is a fundamental input parameter in evaluating the risk of occurrence of a lightning flash at a given location.

In the past the average number of Thunderstorm days T_d provided by meteorological services has been used as a measure to describe the regional lightning risk. In areas, where no LLS data are available N_g may be estimated from T_d by

$$N_g \approx 0.1 T_d$$

This relation has been derived in moderate climate regions and other relations have been proposed for tropical regions [8].

Lightning "flash" reports from LLS are typically related to the location of the first return stroke and a count of all strokes (multiplicity) associated with this meteorological event. On average, there appears to be about 1.5 - 1.7 strike points for each CG flash [9]. Hence, for a complete evaluation of the threat from CG lightning, one should use the area density of ground strike points as N_g. At the moment, commercial LLS's are limited in that they can resolve only strike points that are separated by several hundred meters.

For the evaluation of N_g the grid size should not be finer than the median location accuracy of the employed LLS. For most practical purposes a grid size of 2 km x 2 km or 1 km x 1 km is sufficiently small to represent any regional variation in ground flash density, and is quite consistent with the location accuracy of modern LLS's.

Figure 2 shows the detected annual lightning frequency in Austria. The annual number of lightning flashes is varying by about a factor of 2 (from about 100.000 flashes per year to about 200.000 flashes). With an area of Austria of about 80.000 km^2 this results in an average ground flash density of 1.25 to 2.5 flashes/km^2 and year.

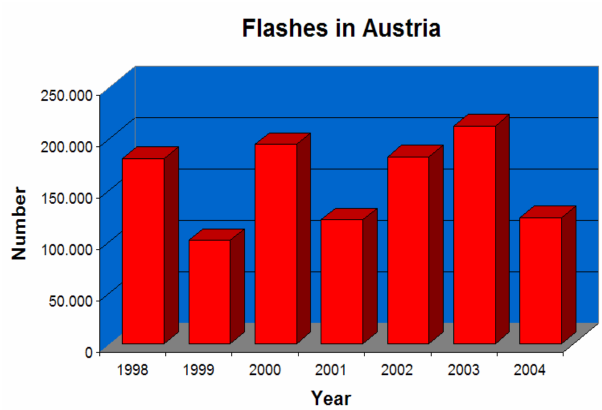

Figure 2: Annual number of located CG flashes within the geographical borders of Austria

In local areas flash densities of up to 5 flashes/km^2 and year are observed.

Peak Current Estimates from LLS

Up to the beginning of 2004, ALDIS inferred the peak current I_P of a stroke from the range normalized signal strength (RNSS) by

$$I_P = 0.23 * RNSS$$

RNSS was calculated from the raw sensor signal strength SS, the distance D assuming purely inverse distance dependency for the peak fields. Since the beginning of 2004 an attenuation model [10] is applied and now RNSS is calculated by

$$RNSS = SS * \left(\frac{D}{100}\right)^b * \exp\left(\frac{D-100}{L}\right)$$

The attenuation model accounts for effects of field propagation over ground of finite conductivity to the measured peak field.

When signal strength reports from E-field sensors (e.g. LPATS III, LPATS IV) are used to infer peak currents it is necessary to do a careful sensor calibration. Typically E-field sensors measure the electric field deploying a vertical rod antenna. It is well known that depending on local site conditions the measured electric field is different from the undisturbed incident field as an effect of local field enhancement. Therefore E-field sensors placed on objects of different height will measure and report different absolute fields. In mixed networks (LPATS + IMPACT sensors) it is possible to calibrate the E-field sensors with the aid of the magnetic field signals reported by the absolutely calibrated IMPACT sensors. Other approaches have to be used in pure E-field sensor networks.

Figure 3 shows the peak current distribution of negative flashes in a circular area of 200 km radius within Austria in the period from 2000-2005.

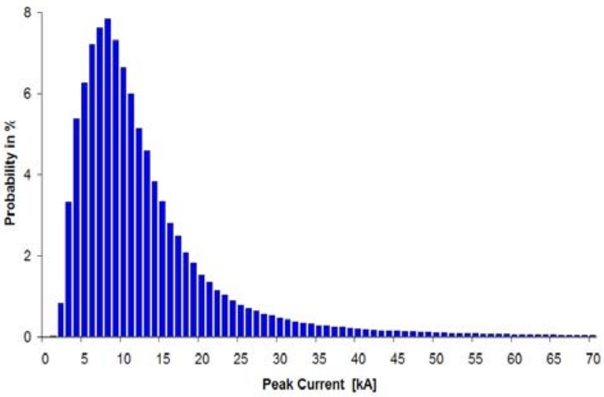

Figure 3: Peak Current Distribution of Negative Flashes in Austria (2000-2005)

A median of 10 kA for negative first strokes is somewhat lower then determined in other networks and this is a result of the high sensitivity and therefore high detection efficiency of the ALDIS network. This network with its small sensor baselines (120 – 140 km) is able to detect flashes with minimum peak currents as low as 2 kA.

III. TOWER MEASUREMENTS

Since 1998 direct lighting strikes to a radio tower are measured at Gaisberg, a mountain next to the City of Salzburg in Austria [11]. The Gaisberg tower is located on the top of a 1.287 m mountain and the height of the tower is 100 m (see Figure 4).

Lightning flashes to the tower occur in summer as well as during winter time. The overall current waveforms are measured at the base of the air terminal installed on the top of the tower with a current viewing resistor of 0.25 mΩ having a bandwidth of 0 Hz to 3.2 MHz.

Figure 4: Gaisberg Tower (height 100 m)

It is worth to note, that a significant fraction of discharges to the tower occurs, when there is almost no or very little lightning activity in the area around the city of Salzburg. Up to know only a few flashes were recorded during typical summer thunderstorms with higher flash activity. The number of recorded flashes per year is shown in Figure 5.

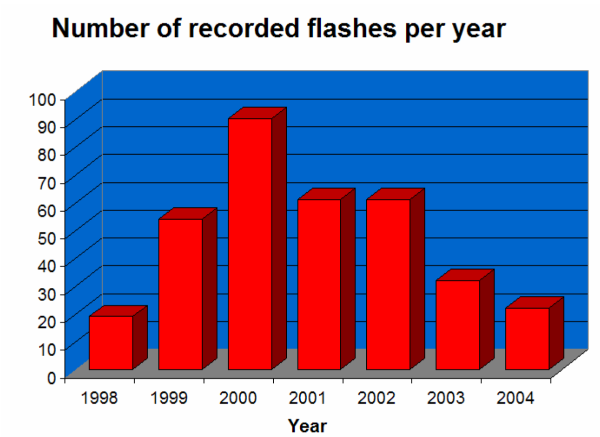

Figure 5: Annual number of events recorded at the Gaisberg tower.

As typical for elevated objects, more than 90% of the flashes to the tower are upward initiated. The upward leader bridges the gap between the grounded object and cloud and establishes an initial continuous current (ICC) with a duration of some hundreds of milliseconds and an amplitude of some tens to some thousands of amperes. In most cases current pulses are superimposed on the slowly varying continuous current. These pulses are often referred to as Initial Continuous Current pulses or α-pulses. After the cessations of the ICC, one or more downward leader/upward return stroke sequences may occur – the associated current pulses are called β-pulses. Typically α-pulses are relatively small, less than 10 kA, while β-pulses have peaks mostly in the range above 5 kA [12].

Figure 6 shows a typical overall current waveform recorded at the Gaisberg tower with the ICC superimposed by α–pulses and followed by several β-pulses.

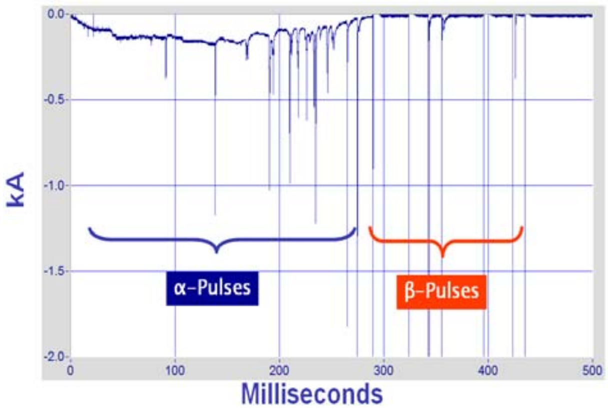

Figure 6: ICC and α and β-pulses of a typical upward initiated flash

In general β-pulses are assumed to be the best representation of subsequent strokes in natural downward lightning. An example of a measured β-pulse with a peak current of -15 kA is shown in Figure 7.

Peak current distributions of the two distinct pulse categories are shown in Figure 8. For the α-pulses a median peak current of 1.8 kA (N=648. σ=0.45) was determined with a minimum current of 0.16 kA and a maximum of 22 kA.

For the distribution of β-pulses a median of 9.2 kA (N=400, σ=0.24) was determined, where the smallest peak current measured was 2.1 kA and the maximum was 68 kA (NOTE: the 68 kA pulse was above the 40 kA measuring limit of Gaisberg instrumentation and therefore the peak current provided by the LLS was used).

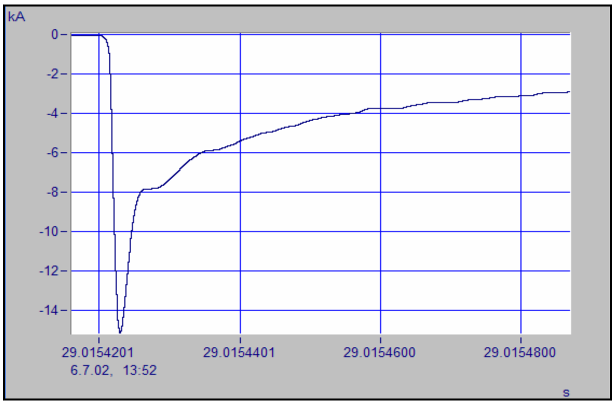

Figure 7: Typical β-pulse current wave shape

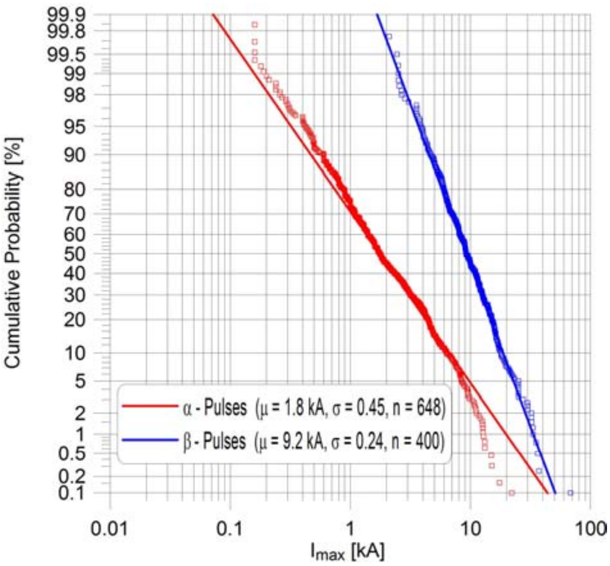

Figure 8: Peak current distribution of α - and β - pulses measured at Gaisberg tower (2000 – 2003)

Compared to downward flashes, upward flashes can drain significant amounts of charge to ground by the ICC. The maximum charge in a single upward flash observed at the Gaisberg was about 450As and this flash occurred during a winter storm. This value significantly exceeds the flash charge of 300As as specified in Table 1 for lightning protection level I. This underlines the importance of considering upward initiated flashes when elevated objects (e.g. large wind turbines) are installed.

The distribution of total flash charge observed at the Gaisberg tower during the period 2000-2003 is shown in Figure 9.

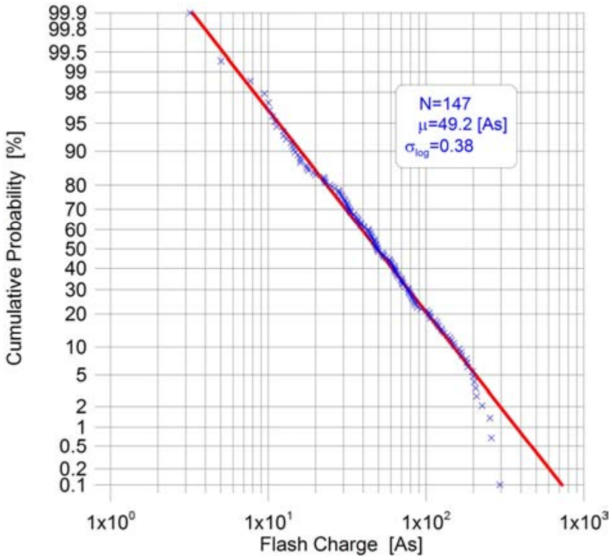

Figure 9: Total Charge of the flashes to the Gaisberg tower

IV. SUMMARY AND DISCUSSION

ALDIS lightning location data together with the direct measurement of lightning to the Gaisberg tower are a valuable tool to gain more insight into the physics of lightning on one hand and to test the performance of the LLS on the other hand. GPS timing on both data sets allows straightforward correlation of individual stroke events.

Although the fast majority of flashes to the tower are upward initiated, the observed β-pulses are assumed to be similar to subsequent strokes in natural lightning and they can be used as a reference to evaluate the performance of the lightning location system. In [7] it is demonstrated, that flash and stroke detection efficiency of LLS have a significant effect on the resulting lightning parameters statistics. Special care is required, when LLS data from positive lightning are analyzed. Recent observations revealed, that small positive CG events (<10 kA) reported by a LLS are actually misclassified cloud discharges [13].

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Gerhard Diendorfer obtained diploma and PhD degrees in electrical engineering from the Vienna University of Technology, Austria, in 1982 and 1987, respectively. During 1982 - 1990 he was research assistant at the Vienna University of Technology.

He spent the academic year 1988-1989 at the Lightning Research Laboratory, University of Florida, Gainesville, working in return stroke modelling. For the past 15 years he has focused primarily on the performance of lightning location systems. Presently, he is heading the Austrian Lightning Detection & Information System (ALDIS) and he is the Secretary of the Austrian national committee on lightning protection.