# A Review of 25 Years of Lightning Research in Austria from 1991-2015

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Abstract—With the installation of the Austrian Lightning Detection & Information System (ALDIS) in 1991 a new area of lightning research started. Austria has a rather complex terrain and the south eastern regions of the country together with Northern Italy and Slovenia show one of the highest flash density values observed in all Central Europe. Performance evaluation of lightning location system (LLS) and validation of the data provided by the LLS became the main focus of the research activities from the very beginning. As ground truth reference lightning current measurements on an instrumented tower (Gaisberg Tower) and GPS time synchronized video and field recordings are used. This paper is an overview of some of the main research results collected and published in the last 25 years by the ALDIS research team. Although lightning research in general has made significant progress in the last decades, supported by new and improved observation technologies (e.g. high speed cameras or 3D-lightning location systems) there is still a number of open questions. Some of the topics waiting for better understanding or experimental validation are briefly discussed at the end of this paper.

Keywords—lightning, upward lightning, lightning location, lightning current measurement

# APRIL 6 TO 8, 2016 - CARTAG I. INTRODUCTION

The region of the southeast of Austria, Slovenia and Northern Italy is one of the regions with the highest lightning activity observed in Europe [1]. Annual ground flash densities of 5 flashes per km<sup>2</sup> and year are observed and therefore also lightning protection has a long tradition in Austria. The first national standard on lightning protection was published in the 1950's and today the European standard on lightning protection EN 62305 parts 1-4 [2]–[5] is used for the design of state of the art lightning protection systems. Lightning is still one of the major reasons for interruptions in the electric power supply, causes damage to buildings and infrastructure and kills several people every year. In order to improve our protection measures, a better understanding of the phenomenon lightning is requested.

In 1991a major step forward in lightning research activities in Austria was done with the installation of ALDIS (Austrian Lightning Detection & Information System), a nationwide lightning location system (LLS). With this system it was possible for the first time to monitor the lightning activity nationwide and this newly available data triggered also other lightning research activities with the main focus on the validation of the performance of the LLS.

# II. THE AUSTRIAN LIGHTNING LOCATION SYSTEM ALDIS

The LLS was installed in fall 1991 and started its normal operation in 1992. ALDIS employs eight sensors based on VAISALA Inc. technology and since 2000 these eight sensors are an integral part of the European Cooperation for Lightning Detection (EUCLID). Since the initial installation in 1991 the sensors have been upgraded several times following the technological improvements in the lightning detection. Today the sensors in Austria are LS7002 type sensors, which is currently the state of the art sensor offered by the vendor VAISALA for lightning detection in the LF frequency range.

We have to note that there was a significant improvement in the lightning detection technology during this last 25 years. In 1991, when these activities started in Austria, lightning detection technology just started to convert from pure regional lightning research networks to larger scale or national networks, and lightning location data were offered to end users for implementation in more practical and commercial applications. From the very beginning, power utilities, meteorological services, and other large scale infrastructure services sensitive to lightning activity, were the main users of LLS provided lightning data.

In the early 1990's there was only detection of cloud to ground (CG) flashes assigned with a number for the strokes multiplicity and location accuracy was in the range of 1 km. Individual strokes or intracloud discharges were not detected, mainly due to existing limitations in the available and affordable computation power and data communication bandwidths. Today's state of the art LLS provide detection of each individual stroke in a CG flash with high location accuracy in the range of 100 m and also a high percentage of intracloud discharges is located. Availability of high speed communication even allows capturing and transferring field waveforms of each stroke that is seen by a sensor.

A map showing the 2015 setup of the total EUCLID network is given in EUCLID network status in 2015, where Austria (ALDIS) is highlighted in the central area of the figure. EUCLID employs about 150 sensors distributed all over Europe.

A comprehensive description of the various upgrades of the ALDIS sensors and the central processor and their effects on the resulting lightning data can be found in [6].



Fig. 1. EUCLID network status in 2015

### III. LIGHTNING TO THE GAISBERG TOWER

# A. Gaisberg Tower (GBT) instrumentation

Direct lightning strikes to a radio tower are measured at Gaisberg, a mountain next to the City of Salzburg in Austria, since 1998. This project was initially started with the aim to evaluate the performance of the Austrian lightning location system ALDIS. This 100 m tower is located on the top of the mountain Gaisberg. The tower coordinates are 47.805 N and 13.112 E, and the mountain top is 1287 m above sea level. Tower instrumentation is described in detail in Diendorfer et al. (2009). Using a shunt for the current measurements is one of the unique features of this instrumentation. Compared to any other type of inductive current probe, often used for lightning current measurements, the shunt allows precise measurement of the slowly varying initial continuing current components, because it does not suffer from a lower bandwidth limit. Some of the following tables and diagrams are updated versions of previously published results where the time period is extended to 2000 – 2015.

# B. Lightning Occurance at the GBT

Lightning at the GBT is initiated all over the year, although there is a pronounced lightning season in Austria in the months from April to August (convective season). The fast majority of flashes at the GBT is of the so called upward lightning type (negative or positive), initiated by the tall object located on top of a mountain. The number of flashes recorded at the GBT per month is shown in Fig. 2, and obviously the highest number of flashes from the GBT is initiated in the months March and November. The observations at the GBT provide also some insight in the occurrence of lightning from wind turbines. Modern wind turbines, with heights of up to 200 m and more, trigger upward lightning frequently. In addition to serving as ground truth for the LLS validation, the GBT measurements are providing lightning current parameters for this type of discharges. Upward initiated lightning starts with the so called initial stage (IS), a current component not present in any cloud to ground (CG) lightning. Parameters of the negative flashes to the GBT are analyzed in detail in [7].



Fig. 2. Monthly occurrence of upward initiated lightning from the GBT (2000-2015)

As shown in Fig. 3, most (93%) of the upward initiated flashes from the GBT transfer negative charge to ground and according to the categorization given in [8] they are called negative upward discharges. 3,5 % of the upward flashes are positiv and and 3.1 % or bipolar, where four categories of bipolar flashes are distinguished. Detailed analysis of positive and bipolar flashes to the GBT are given in [9], [10].



Fig. 3. Type of flashes that occurred at the GBT from 2000-2015

Interestingly only a very few flashes (less than 10) to the GBT were possibly downward (cloud to ground) discharges, compared to the more than 100 negative, downward lightning discharges to the tower(s) at Mont San Salvatore, Switzerland, reported by some pioneers in lightning research, K. Berger, R.B. Anderson, and H. Kröninger [11].

Lightning discharges, especially return strokes in upward lightning from the GBT, serve as a ground truth for the validation of the Austrian/European LLS ALDIS/EUCLID, as the GPS time of occurrence, the peak current and the striking point coordinates are exactly known.

# IV. PERFORMANCE VALIDATION OF THE LIGHTNING LOCATION System

### A. EUCLID/ALDIS lightnging location system

When analyzing the LLS performance by using flashes to an elevated object it is necessary to define the type of discharges, which is applied as a ground truth reference. Upward initiated lightning of  $ICC_{Only}$  type is typically not located by LLS at all, because of the low current amplitude (100 – 300 A) of the ICC and because of the absence of any fast rising current pulses, like the return strokes in downward lightning. A comprehensive analysis of the detection of all types of flash types (ICC<sub>Only</sub>, ICC<sub>P</sub>, and ICC<sub>RS</sub>) in upward lightning from the GBT is given in [12].

In the following section of this paper we are considering only flashes with at least one return stroke ( $ICC_{RS}$  type discharges in Fig. 3). It is generally assumed, that these return strokes are similar to subsequent strokes in natural CG lightning and hence the best available representation of natural CG lightning. First strokes in CG discharges are assumed to have typically larger peak currents then subsequent strokes and hence there is a higher probability of detection. Consequently the DE values derived from subsequent strokes only can be seen as a lower bound of DE of a system for natural lightning flashes and strokes.

# 1) Flash Detection Efficiency

Flash DE is always higher than stroke DE. In a multi stroke flash it is sufficient to detect one out of several strokes in order to detect the flash. When we consider ICC<sub>RS</sub> type flashes to the GBT only, the LLS detected 247 out of 255 flashes (97%). We have to note that some of the return strokes in the flashes missed by the LLS showed current waveforms similar to Mcomponents (slow rising current wave front). This mostly occurred when the stroke followed the ICC with a very short (a few milliseconds) of no current interval. The no current interval is the criterion used to classify a current pulse as a return stroke. Overall the obtained Flash DE of 97% can be seen as a lower bound for the ALDIS/EUCLID network for natural lightning in any region with similar network configuration and sensor baselines.

#### 2) Stroke Detection Efficiency

Stroke DE as a function of minimum stroke peak current is shown in Fig. 4. Overall (all strokes with peak currents > 2 kA, which is also about the smallest return stroke peak current observed in lightning to the GBT) a stroke DE of 75% is obtained. For strokes with I > 8 kA the DE increases to 90%, as it is mostly the small peak current events that are missed by the LLS.

# B. Location Accuracy

Location accuracy of the LLS has improved year by year (see Fig. 5) since the installation of the network as a result of various hardware and software upgrades. Currently the median location accuracy of the last 100 strokes detected at the GBT is better than 100 m.

Significant improvements of the location accuracy were achieved with the implementation of an advanced propagation correction method. Angle and distant dependent propagation time corrections are determined and implemented for each and every sensor (see Fig. 6).



Fig. 4. Stroke detection efficiency as a function of peak current for N=1129 returs strokes directly measured at the GBT(2000 -2015)



Fig. 5. Median location error over time calculated as moving median over the last 100 return strokes measured at the GBT. The vertical lines show the time when the new location algorithm was introduced (A), the introduction of the sensor based onset time calculation (B) and the application of the propagation correction (C)

The actually achieved location accuracy also allows doing more precise stroke to flash grouping in order to define a correct number of ground strike points oa a flash. In risk analysis to determine proper lightning protection measures for structures (houses, transmission lines, etc.) the ground strike points are the critical parameter. Two or more ground contacts in the same flash are not unusual. In [13] an average number of 1.5 to 1.7 ground contacts per flash is given based on different high speed video studies.



Fig. 6. Example of a propagation correction determined and implemented for Austrian sensor #2 (Schwaz). The sensor is located in the center of the circular area

### C. Peak current estimates

Peak current  $I_p$  of a LLS located strokes is inferred from measured peak fields, either from electric field  $E_p$  or magnetic field  $B_p$  according to Eq.(1), as in case of a purely radiated field they are related by  $E_p = c \cdot B_p$ .

$$\mathbf{I}_{\mathbf{p}} = \mathbf{K} \cdot \mathbf{E}_{\mathbf{p}} \tag{1}$$

According to the transmission line model (TLM), for a given return stroke speed  $v_{RS}$  and a distance D, the peak current  $I_p$  is directly proportional to  $E_p$ 



Fig. 7. EUCLID peak current estimates  $I_{EUCLID}$  versus directly measured stroke peak currents at the GBT  $I_{GB}$  during the time period 2005–2014. Blue, green, black and yellow lines represent the LLS peak currents for different return stroke speeds and assuming TLM according to Eq.(2)

The plot in Fig. 7 supports the assumed linear correlation between  $E_p$  and  $I_p$  given in Eq. (2). The observed scatter in Fig. 7 is likely a result of variations in the return stroke velocity  $v_{RS}$ , observed to vary in a wide range [14].

# V. OPEN QUESTIONS

# A. Peak current distributions of negative first strokes

IEEE and CIGRE published peak current distributions for first strokes in negative flashes with a median of about 30 kA (e.g. [15]). These distributions were derived from data mainly based on the measurements on Mont San Salvatore in the 1970s. These IEEE and CIGRE distributions are used for lightning protection applications, e.g. to determine the lightning performance of transmission lines. The stated median peak current of about 30 kA is significantly higher than according values obtained from LLS data in different regions of the world, where median peak currents of first strokes are more in the range from 15 kA - 20 kA (e.g. [16], [17]). At this time it is not clear if these lower values are correct and the 30 kA need to be revised or if these lower results are caused by one or a combination of the following reasons: (1) LLS first stroke data are contaminated by lower current subsequent strokes or by misclassified IC discharges, or (2), that Eq.(2) is not applicable to first strokes in CG lightning in general or (3) the Eq.(2) is valid but a smaller value for the return stroke velocity needs to be used in this equation for first strokes.

#### B. Peak currents of positive strokes and IC discharges

Similar to first stroke peak currents in negative CG lightning, up to now no validation is available for the LLS peak current estimates for positive discharges and IC discharges.

To the authors best knowledge all LLS apply one and the same conversion coefficient to infer peak currents from measured peak fields of the different stroke types (first, subsequent, negative, positive, and intra cloud). Inferred peak current values for IC discharges need to be handled very carefully. There is no evidence for the applicability of the TLM to this type of discharge at all, and there is actually not even a defined position along an IC discharge, where this peak current actually exists. In CG lightning this peak current exists (and is actually measured) at the ground contact point, although the classical TLM assumes an unaltered travelling current pulse along the lightning channel, which is not supported by optical observations and results from more sophisticated return stroke models.

#### C. Misclassification rates of LLS

With improved detection efficiency of IC discharges the misclassification rate of LLS became a critical performance parameter. Especially in lightning protection applications, knowledge of the true distribution of peak currents of first and subsequent strokes is essential. Today the contamination rate of the CG stroke peak current distributions by misclassified IC discharges (erroneously classified as CG) is not well understood and likely one of the most significant differences in data from different LLS. Unfortunately this topic needs new experimental approaches as the typically used ground truth

references, such as triggered lightning or measured lightning to instrumented towers, is not applicable to investigate this issue. Triggered lightning and tower measurements do not allow to investigate the number of IC lightning classified as CG. They only allow determining the number of CG strokes classified as IC (see e.g. [18], [19])

# D. Parameters determining initiation of upward lightning from tall objects

In order to estimate the percentage of upward lightning initiated from tall objects the concept of the effective height was introduced [20]. More than 15 years of observations of upward lightning from the GBT show that there is a number of open questions regarding the driving parameters for the observed lightning occurrence. Lightning was observed at very different levels of ambient electric field around the tower just prior to the initiation of the upward leader from the top of the tower. On the other hand no upward lightning was observed during some days of intense thunderstorm activity in the area around the GBT site and when the ambient electric field at ground level was much higher than normally observed in case of lightning initiation from the tower.

#### VI. SUMMARY AND DISCUSSION

Significant progress was made in lightning research in the last decades. New instrumentation, like high speed cameras, Lightning Mapping Array (LMA) systems, high performance LLS in the LF frequency range, etc., allowed to gain improved insight in the processes during lightning discharges, that take place within a few milliseconds or even less. On the other hand new questions are on the table (x-ray production by lightning, lightning related NO<sub>x</sub>, lightning attachment, etc.) and they are waiting for answers. Lightning and its effects in all its details and complexity is still far from being well understood and remains one of the fascinating and great mysteries of nature.

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