LLS Detection of Upward Initiated Lightning Flashes

Gerhard Diendorfer, Hannes Pichler, Wolfgang Schulz

***Abstract*—Upward initiated lightning from tall structures has become a major topic in lightning research and lightning protection. Wind turbines of heights of 150 m and more are frequently initiating upward lightning and these discharges may cause severe damage. Upward initiated lightning shows a wide variety of waveform characteristics and does often not contain any return strokes. Lightning location systems (LLS), such as the EUCLID network, are typically detecting return strokes and therefore performance of LLS in detecting upward lightning is very different from the performance to detect downward lightning. Analyzing the lightning data collected at the Gaisberg Tower (GBT) in Austria from 2000 – 2013 we determine a flash detection efficiency (DE) of 43 %. Different from natural CG, lightning where it is mostly the small peak current events that are not located, the low DE of upward lightning is determined by the occurrence of ICC_{Only} type discharges which are not detected at all. Some of these not located ICC_{Only} discharges showed a total charge transfer exceeding 300 As and in case of wind turbines those flashes have certainly the potential for severed blade damage. As a result of the significantly shorter peak-to-zero times of the radiated fields from return strokes to the GBT 31% of these return strokes were classified as IC discharges by the LLS.**

***Keywords*— detection efficiency, lightning, lightning location systems, tower measurements, upward lightning, wind turbine**

I. Introduction

Upward initiated lightning is a dominant risk of damage for higher objects, especially wind turbines. Several tens of flashes per year are not unusual, depending on the height of the structure and its local position (flat terrain or mountain top). At the 100 m high Gaisberg Tower (GBT) about 60 flashes per year are recorded [1]. There is some concern that lightning detection networks like the U.S. National Lightning Detection Network (U.S. NLDN) or EUCLID, the European Cooperation for Lightning Detection, may not report all of the upward-initiated lightning from wind turbines, although some of these upward flashes might lead to blade damage.

Similar to tower initiated upward lightning an initial stage (IS) is observed in artificially triggered lightning with some current pulses superimposed. The performance characteristics of a lightning location system (LLS) in terms of DE of superimposed pulses in triggered lightning was recently reported in [2]. In 80 triggered flashes at Camp Blanding, Florida, a total of 326 return strokes and 173 superimposed pulses (≥1 kA) (58 initial continuous current pulses and 115 M components) were measured. The U.S. NLDN detected 245 return strokes and 9 of the superimposed pulses. A NLDN flash detection efficiency (DE) of 94 %, a return-stroke DE of 75%, and a DE for superimposed pulses of 5 % for peak currents ≥1 kA and 32 % for peak currents ≥5 kA was determined. The percentage of misclassified events (CG strokes classified as IC) was 4 %, all of them being return strokes. For two out of the nine superimposed ICC pulses detected by the NLDN, authors found optical evidence of a re-illuminated branch (recoil leader) coming in contact with the existing grounded channel at an altitude of a few hundred meters above ground.

The behavior and effects of lightning to wind turbines were studied during a 3-month field campaign in north-central Kansas, USA in summer 2012 in [3]. Ground truth observation of lightning to the wind turbines was collected by employing auto-trigger cameras around the wind farm and current measurement devices installed to the root of the turbine blades. Thunderstorms were monitored using the (NLDN) data and electric field mills (EFMs) installed onsite at the wind farm. During the field campaign seven lightning strikes to wind turbines were captured by the video cameras with two causing damage. None of the return stroke like currents in 2 upward initiated flashes was reported by NLDN.

In [4] upward lightning observations from ten tall towers (tower heights ranging from 91 m to 191 m) in Rapid City, South Dakota, USA were compared with U.S. NLDN data. A total of 81 upward flashes were observed from 2004 – 2010 using GPS time-stamped optical sensors.

For 44% (36) of the upward flashes, the NLDN reported subsequent negative cloud-to-ground (-CG) strokes and/or “-IC” events at one or more tower locations. Of the 151 subsequent stroke events, 70% (105) of the strokes were classified as -CG and 30% (46) were misclassified as “-IC” events even though connections were made with the tower(s).

II. Data

A. *Measured lightning currents at the Gaisberg Tower*

Lightning currents are measured at the Gaisberg Tower (GBT) since 1998. A detailed description of the instrumentation of this measuring station and the

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characteristics of tower initiated lightning is given in [1]. Different from natural downward lightning a significant fraction of upward lightning is consisting of the upward propagating leader only and is not followed by any return strokes. In [1] these type of discharges was labeled ICC_{Only}. Almost 100% of the flashes to the GBT are upward initiated and using a shunt, which has no lower frequency limit, allows accurate measurement of lightning events even when they consist only of a slowly varying initial continuing current (ICC) of small amplitudes in the range of some tens of amperes.

B. Lighting Location System Data

The Austrian Lightning Detection & Information System (ALDIS) is an integral part of the European Cooperation for Lightning Detection (EUCLID) and LLS data used in this study are provided by the EUCLID network. Besides artificially triggered lightning tower initiated lightning is one of the few available ground truth data sets with known lightning current waveforms that can be used for the performance validation of LLS.

It is generally assumed that return strokes following the initial stage of upward and triggered lightning is similar to subsequent strokes in natural CG lightning and therefore an evaluation of LLS performance characteristics is typically done by pre-selecting upward lightning flashes that had at least one return stroke following the ICC. Using only flashes to the GBT that had at least one return stroke (ICC_{RS} type flashes) resulted in a flash- and stroke DE of 96 % and 71 %, respectively for the EUCLID network [5].

In recent studies [5] employing video captured natural cloud-to-ground lightning and corresponding E-field records a flash- and stroke DE of 98 % and 84 %, respectively, was obtained for the EUCLID network. The somewhat lower DE values at the GBT are most likely a result of the missing first strokes in tower initiated lightning, compared to natural downward lightning. First strokes are assumed to have larger peak currents than subsequent strokes and hence there is a higher probability to detect first strokes and therefore the DE values determined for the GBT can be seen as the lower limit of DE.

In upward lightning a fraction of the pulses superimposed on the ICC is detected by the LLS, depending on the risetime of the ICC-pulse current. ICC-pulses at the GBT exhibit a wide range of risetimes and two examples are shown in Fig. 1 and Fig. 2, respectively.

Based on video records of upward lightning initiated from the Peissenberg Tower in Germany it was observed in [6] that ICC-pulses with shorter risetimes developed in a newly-illuminated branch, and ICC-pulses with longer risetimes occurred in already luminous (current-carrying) channels. These results support the hypothesis that longer risetimes are indicative of the M-component mode of charge transfer to ground, while shorter risetimes are associated with the leader/return stroke mode.

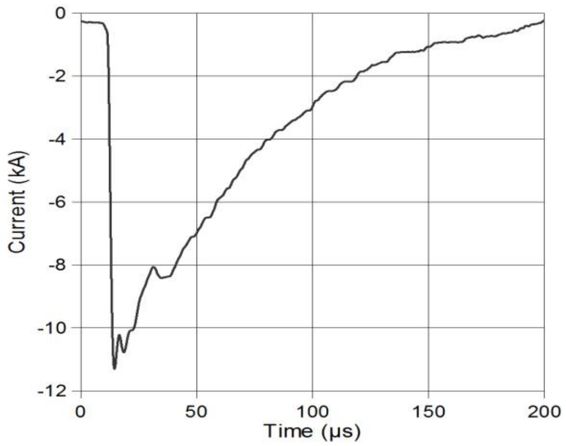

Fig. 1. Return stroke type ICC-pulse in GBT flash #759

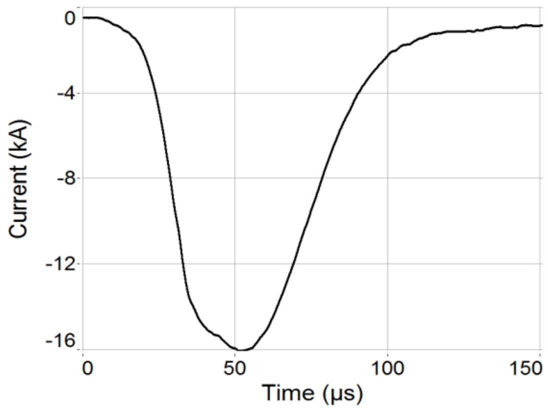

Fig. 2. M-component type ICC-pulse in flash #542

III. RESULTS

A. Detection Efficiency

There are many lightning detection networks worldwide that employ instrumentation operating in the VLF/LF frequency range. Detection of lightning discharges with such systems requires fast rising current pulses in the lightning channel in order to radiate electromagnetic field pulses of amplitudes that are high enough to be detected by a minimum number of sensors (typically 4 or more sensors are required) at distances of up to several hundreds of kilometers. In tower initiated lightning only return strokes and some of the superimposed ICC-pulses, like the return stroke type ICC pulse shown in Fig. 1, are detected by the LLS. As a consequence only ICC_{RS} type discharges initiated from tall objects are typically detected with a DE in the same range (above 90%) as stated by the LLS manufacturer for natural CG lightning. A fraction of the tower initiated discharges of ICC_P type is also detected when they have one or more ICC-pulses with sufficiently short rise time, whereas the ICC_{Only} type discharges are typically not detected by LLS at all.

In the period 2000 – 2013 a total of 765 flashes have been recorded at the GBT. 93 % of these flashes had negative polarity (positively charged upward propagating leader) and there was about the same percentage of positive and bipolar flashes (see Table I).

TABLE I: LIGHTNING OCCURRENCE AT THE GAISBERG TOWER IN THE PERIOD 2000-2013

	N	Percentage
negative flashes	713	93.0 %
positive flashes	28	3.7 %
bipolar flashes	24	3.3 %
TOTAL	765	100 %

Results of the classification of the 713 negative flashes in ICC_{Only}, ICC_P, and ICC_{RS}, as introduced in [1], is shown in Table II.

Overall about 32 % (224) of the flashes recorded at the GBT from 2000 – 2013 exhibited one or more return strokes (ICC_{RS}), 21 % (151) of the tower flashes were ICC_P with superimposed pulses, and 47 % of the flashes were categorized as ICC_{Only}.

In Table III the corresponding numbers and percentages of flashes detected by the LLS are given for each of the flash categories ICC_{RS}, ICC_P and ICC_{Only}.

In Table II and Table III the corresponding numbers for convective season (April – August) and non-convective season (September–March) are given separately.

TABLE II: OCCURRENCE OF UPWARD INITIATED NEGATIVE LIGHTNING FLASHES AT THE GAISBERG TOWER IN THE PERIOD 2000-2013

	Number			Percentage		
	Total	NCS	CS	Total	NCS	CS
ICC_{Only}	338	207	131	47%	29%	18%
ICC_P	151	113	38	21%	16%	5%
ICC_{RS}	224	157	67	32%	22%	9%
Total	713	477	236	100%	67%	33%

TABLE III: LLS DETECTED NEGATIVE UPWARD INITIATED FLASHES

	Number			Detection Efficiency (DE)		
	Total	NCS	CS	Total	NCS	CS
ICC_{Only}	0	0	0	0%	0%	0%
ICC_P	88	69	19	58%	61%	50%
ICC_{RS}	215	149	66	96%	95%	99%
Total	303	218	85	42%	46%	36%

NCS... Nonconvective Season (September – March),
CS… Convective Season (April – August)

The LLS detected 303 (42 %) out of the total of 713 negative flashes initiated by the GBT. The flash DE for ICC_P type flashes to the GBT is 58 % (88/151), and as expected none of the ICC_{Only} type flashes was located by the LLS.

It is interesting to note, that the overall flash DE of 46 % in the non-convective season (NCS) is higher than the flash DE of 36 % in the convective season (CS). On the other hand, the DE of ICC_{RS} flashes is higher (99 %) in the CS than in the NCS (95 %).

The relatively low overall flash DE of LLS for upward initiated lightning of less than 50% needs to be considered in any application of LLS data regarding lightning to tall objects. At the GBT it is not unusual that several upward initiated lightning flashes occur within a short period of time (some minutes to some hours). In the following section we are using thunderstorm days at the GBT. A thunderstorm day at GBT is defined as a calendar day with one or more flashes recorded at the tower. Fig. 3 shows a histogram of the number of flashes recorded per thunderstorm day at the GBT in the period 2000 – 2013 also indicating the seasonal occurrence. A maximum of 27 flashes occurred within 24 hours on 2008-03-01, and 17 flashes per day were recorded three times.

As depicted in Fig. 3 all of the GBT thunderstorm days with high numbers of flashes per day occurred during non-convective season.

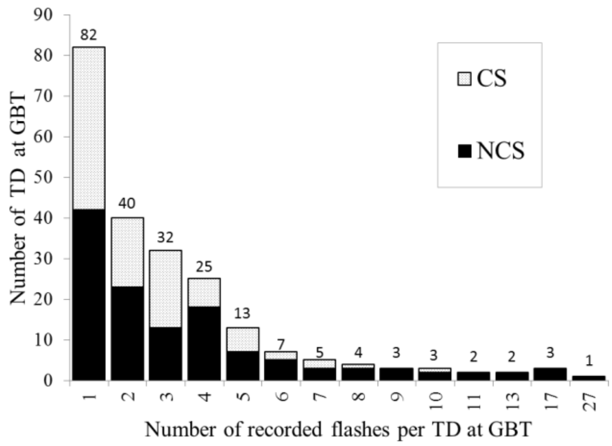

Fig. 3. Seasonal dependency of number of Flashes per Thunderstorm Day at the GBT (CS Convective Season, NCS Nonconvective Season)

In lightning damage investigations LLS data are often requested and analyzed for a given day, when the damage or outage of equipment was reported. In order to obtain the probability that none of the upward lighting events from the elevated object was located by the LLS we have divided the bins in the histogram in Fig. 4 according to the detection of any of the upward initiated flashes that occurred on a given day. As an example at the GBT the number of days with 3 (x-axis) recorded flashes within 24 hours was 32. On 11 days out of those 32 days (34 %) none of the 3 flashes was reported by the LLS and thus the LLS data would not provide any indication for lightning activity in the area of the considered object. At least one flash was detected by the LLS on all days that had 7 or more flashes per day and therefore none of those days was labeled as a missed thunderstorm day in Fig. 4.

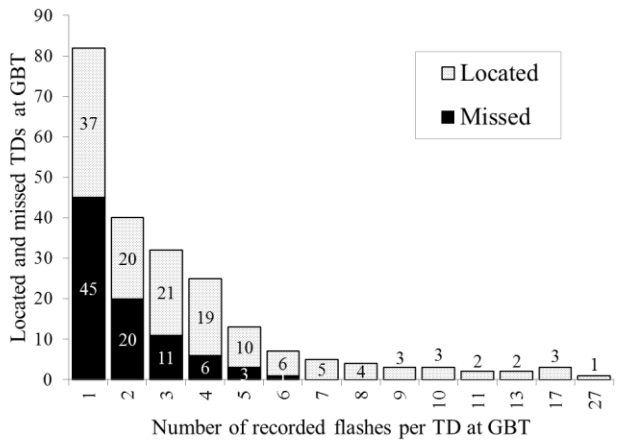

Fig. 4. Thunderstorm Days (TD) at the GBT

B. Detection Efficiency and flash total charge transfer

The detection of flashes to the GBT as a function of the total charge transfer is shown in Fig. 5. There is a tendency of increasing DE of flashes with larger flash charge transfer. On the other hand the two neg. flashes with a flash charge greater than 512 As (outer right bin in Fig. 5) were missed by the LLS.

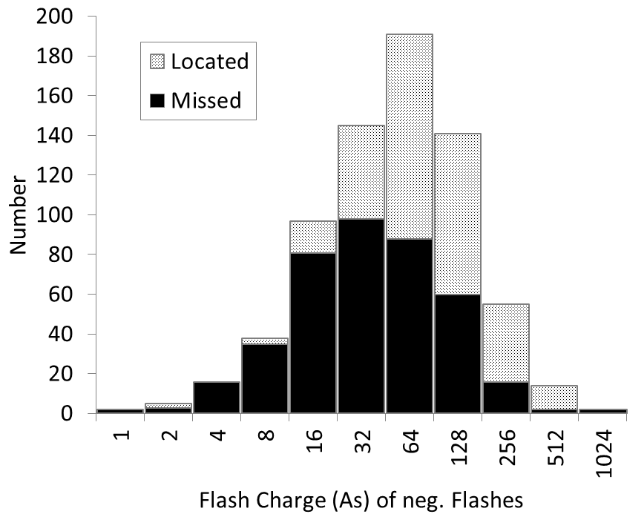

Fig. 5. Detection of negative GBT flashes as a function of Flash Charge

Upward initiated lightning, especially during winter time, is known to transfer high amounts of charge. Highest transferred charge values exceeding 1000 As were reported in [7] for winter lightning in Japan. The international standard on lightning protection IEC 62305 [8] specifies a total charge transfer of Q_{FLASH} = 300 As for lightning protection level (LPL) I. It is assumed that only 1% of lightning discharges exceed the lightning current parameters specified for LPL I.

When also considering positive and bipolar flashes at the GBT we obtained for 13 (1.7%) of the 767 flashes measured at the GBT in the period from 2000-2013 a total charge transfer exceeding 300 As. Details of those events are summarized in Table IV. It is worth noting that all these 13 flashes occurred during non-convective season and only 54 % (7/13) of those high charge transfer upward lightning discharges were located by the LLS. Flash #878 with a total charge transfer of 783 As, the flash with the highest charge ever recorded at GBT up to the end of 2013, was an ICC_P type negative flash and was not located by LLS. The current waveform of this flash is shown in Fig. 6. It is also interesting to note that flash #879 with a flash charge of 430 As occurred just about 6 minutes later at the same day and was not located either. Risetime of the superimposed pulses in both flashes was not sufficiently short to radiate field pulses detectable at larger distances. Actually not a single flash was located by the LLS during the day of 2012-10-15 (non-convective season) within a range of about 20 km around GBT.

TABLE IV: FLASHES RECORDED AT GBT WITH A TOTAL FLASH CHARGE GREATER THAN 300 As IN 2000-2013

# ID	Date	Time	Flash Charge (As)	Comment	LLS located	Neg. Flash Category
112	2000-01-21	16:25:28	356	Pos. Flash	NO	-
405	2005-02-12	22:36:25	385	Neg. flash	YES	ICC_P
407	2005-02-12	22:42:16	> 305	Neg. flash 1)	YES	ICC_{RS}
446	2005-12-16	16:59:29	426	Pos. Flash	NO	-
511	2007-01-12	01:51:51	405	Neg. flash	YES	ICC_P
520	2007-02-09	01:24:09	320	Bipolar Flash	NO	-
614	2008-03-01	10:21:10	546	Neg. Flash	NO	ICC_{Only}
631	2008-03-01	10:41:14	> 365	Neg. flash 1)	YES	ICC_P
633	2008-03-01	10:43:17	310	Neg. flash	YES	ICC_P
693	2008-11-21	13:52:01	314	Neg. flash	YES	ICC_P
806	2011-12-07	23:17:08	313	Neg. flash	YES	ICC_P
878	2012-10-15	17:32:12	783	Neg. flash	NO	ICC_P
879	2012-10-15	17:38:41	430	Neg. flash	NO	ICC_P

1) Flash duration exceeded recording time of 800 ms

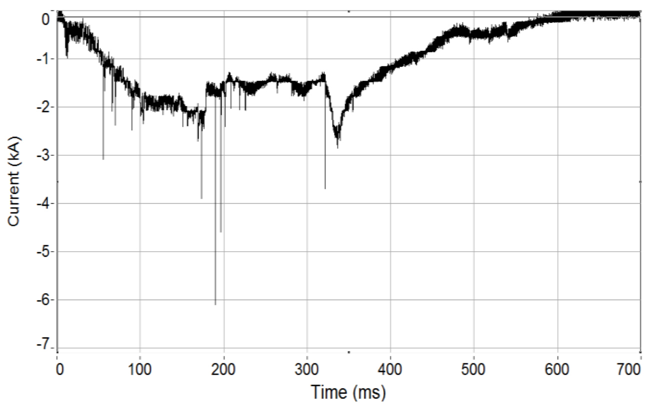

Fig. 6. Current record of flash #878 with a total charge transfer of 783 As

C. LLS classification of return strokes

The subset of 226 ICC_{RS} flashes used in this study contained a total of 992 return strokes. In [9] it was shown that upward initiated lightning from the GBT has a median peak-to-zero time of 10 µs which is significantly lower than 40 µs typically reported for return strokes in natural downward lightning [10],[11].

A geometric mean (GM) initial half-cycle durations of 86 µs and 62 µs is reported in [12] for radiated fields from first and subsequent strokes in natural downward lightning, respectively. Assuming that the initial half-cycle duration is essentially the sum of the rise-time (7.9 and 4.6 µs for first and subsequent strokes, respectively) and the peak-to-zero time, we can estimate a peak-to-zero time of greater than 50 µs, which is also in the same range as reported in [10] and [11] and much higher than the 10 µs obtained for the return strokes in GBT upward initiated lightning. Peak-to-zero time of the lightning radiated field is one of the most important parameters used by LLS for the classification as CG or IC. The small peak-to-zero times of radiated fields from the GBT strokes results in a misclassification of some of the return strokes as IC discharges. In Table V the LLS classification of the GBT measured return strokes and ICC-pulses is summarized for the period 2008 – 2013. Limitation to the period 2008 – 2013 is necessary because the LLS was basically not detecting any IC discharges before 2008.

31 % (112/366) of the return strokes were classified as IC by the LLS. The 20 % misclassification rate for the located ICC-pulses is lower than for return strokes (31%) and this is assumed to be a result of the longer current risetimes of ICC-pulses, but further studies are needed to confirm this assumption.

TABLE V: LLS STROKE CLASSIFICATION OF RETURN STROKES AND ICC PULSES MEASURED AT THE GBT IN 2008-2013

	GBT	Located as CG	Located as IC
Return Strokes	366	254 (69 %)	112 (31 %)
ICC-Pulses	484	385 (80 %)	99 (20 %)
Total	850	639 (75 %)	211 (25%)

Note: Analysis shown in Table V is limited to the period 2008 – 2013 as before 2008 the LLS was not detecting any IC discharges

IV. CONCLUSIONS

Upward initiated flashes are very different from downward flashes in terms of their detectability by LLS. For the 715 flashes measured at the GBT in Austria we obtained an overall DE of 43 %. These relatively low DE is mainly a result of the 338 ICC_{Only} type discharges, all of them not detected by the LLS. This observation is important whenever LLS data are used to investigate lightning caused damage and when upward initiated lightning might be involved (e.g. damage to wind turbine blades).

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