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LLS PERFORMANCE VALIDATION USING LIGHTNING TO TOWERS

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1 Introduction

Grounded vertical objects produce relatively large electric field enhancement near their upper extremities so that upward-moving connecting leaders from these objects start earlier than from the surrounding ground and, therefore, serve to make the object a preferential lightning termination point. A comprehensive review of the interaction of lightning with tall objects is given by Rakov (2003). With increasing height of an object an increase in the number of lightning discharges is observed with an increasing percentage of upward initiated flashes. Objects with heights ranging from 100 to 500 m experience both types of flashes, upward and downward. To account for the observation of increased lightning activity to towers of moderate height (less than 100 m) on mountains a so called "effective height" concept has been introduced (see e.g. Pierce, 1972; Eriksson, 1978; Zhou et al., 2009). The effective height being larger than the physical height of the object accounts for the additional field enhancement at the tower top due to the presence of the mountain. The high number of lightning events to elevated towers makes those objects preferential for direct lightning current measurements and hence in the past and today instrumented towers are used to perform direct measurements of lightning current waveforms. In addition, lightning data collected at instrumented towers are a perfect ground truth reference for the validation of various performance parameters of a lightning location system (LLS).

When the effective height of the tower becomes large enough, an upward-moving leader from the object tip can be initiated. There is an ongoing discussion whether this upward lightning is initiated by an intra-cloud discharge or by the slow charge build-up in the cloud above the tall object. In case of upward lightning, opposed to downward lightning, the discharge would not occur if the object were not there. Towers of heights ranging from about 100 to 500 m experience both types of lightning, downward and upward flashes, the proportion being a function of object height. From observations of the lightning strikes to structures of heights ranging from 20 to 540 m in different countries, the corresponding local values of the annual number of thunderstorm days T_D, and an empirical formula relating N_g and T_D Eriksson (1987) derived the following equation for the annual lightning incidence N (in yr^{-1}) to ground-based objects, including both downward and upward (if any) flashes:

$$N = 24 \; x \; 10^{-6} . H_s^{2.5} . N_g \qquad (1)$$

where H_s is the object height in meters and N_g is the ground flash density in km^{-2} yr^{-1}.

The percentage of upward flashes as a function of structure's height is given by Eriksson (1987) by the following expression:

$$P_U = 52.8 \; x \; \ln(H_s) - 230 \qquad (2)$$

where P_u is the percentage of upward flashes and H_s, is the structure height in meters. Eq.(2) is valid only for heights ranging from 78 to 518 m, since $P_u = 0$ for $H_s = 78$ m and $P_u = 100$ % for $H_s = 518$ m. Structures with heights less than 78 m are expected to be struck by downward flashes only, and structures with a height of greater than 518 m are expected to experience upward flashes only.

2 Lightning current parameters derived from tower measurements

The most complete characterization of all types of lightning to a tower (upward, downward, positive, and negative) is due to Karl Berger and co-workers (e.g., Berger 1955a,b; 1962; 1967a,b; 1972; 1980; Berger and Vogelsanger 1965, 1969; Berger and Garbagnati 1984; Berger et al., 1975). Lightning parameters of downward negative and positive lightning from Berger et al. (1975) summarized in Table 1 and Table 2, respectively, are still used to a large extent as the primary reference source for both lightning protection and lightning research.

Table 1: Current parameters of **downward negative** lightning. Adapted from Berger et al. (1975)

Parameters	Units	Sample Size	% Exceeding Tabulated Value		
			95%	50%	5%
Peak current (minimum 2 kA) First strokes Subsequent strokes	kA	101 135	14 4.6	30 12	80 30
Charge (total charge) First strokes Subsequent strokes Complete flash	C	93 122 94	1.1 0.2 1.3	5.2 1.4 7.5	24 11 40
Impulse charge (excluding continuing current) First strokes Subsequent strokes	C	90 117	1.1 0.22	4.5 0.95	20 4
Front duration (2 kA to peak) First strokes Subsequent strokes	µs	89 118	1.8 0.22	5.5 1.1	18 4.5
Maximum di/dt First strokes Subsequent strokes	kA/µs	92 122	5.5 12	12 40	32 120
Stroke duration (2 kA to half peak value on the tail) First strokes Subsequent strokes	µs	90 115	30 6.5	75 32	200 140
Action integral ($\int i^2 dt$) First strokes Subsequent strokes	A^2s	91 88	6.0×10^3 5.5×10^2	5.5×10^4 6.0×10^3	5.5×10^5 5.2×10^4
Time interval between strokes	ms	133	7	33	150
Flash duration All flashes Excluding single-stroke flashes	ms	94 39	0.15 31	13 180	1100 900

Table 2: Parameters of **downward positive** lightning. Adapted from Berger et al. (1975)

Parameters	Units	Sample Size	% Exceeding Tabulated Value		
			95%	50%	5%
Peak current (minimum 2 kA)	kA	26	4.6	35	250
Charge (total charge)	C	26	20	80	350
Impulse charge (excluding continuing current)	C	25	2.0	16	150
Front duration (2 kA to peak)	μs	19	3.5	22	200
Maximum di/dt	kA/μs	21	0.20	2.4	32
Stroke duration (2 kA to half peak value on the tail)	μs	16	25	230	2000
Action integral ($\int i^2 dt$)	A^2s	26	2.5×10^4	6.5×10^5	1.5×10^7
Flash duration	ms	24	14	85	500

The two instrumented towers at Monte San Salvatore were of moderate height of 70 m, but because the mountain contributed to the electric field enhancement near the tower tops, the majority of lightning strikes to the two towers were of the upward type. The effective height of each tower was estimated by Eriksson (1978) to be 350 m. Table 3 and Table 4 show a summary of the lightning parameters of negative and positive upward initiated lightning reported by Berger (1978). For comparison we have included in Table 3 and Table 4 some recently published results by Diendorfer et al. (2009) from similar measurements performed at the Gaisberg tower (GBT) in Austria.

Table 3: Lightning current parameters for **upward** (tower initiated) **negative** flashes. Adapted from Berger et al. (1978) and values in red and in () indicate results derived from GBT measurements (see Diendorfer et al., 2010)

Parameters	Units	Sample Size	% Exceeding Tabulated Value		
			90%	50%	10%
Maximum initial-stage current in flashes without return strokes	A	639	40	203	1030
Maximum initial-stage current in flashes with return strokes	A	195	47	248	1310
Maximum return stroke current	kA	176 (615)	4.2	10 (9.2)	25
Initial-stage charge in flashes without return strokes	C	638 (318)	1.9	12 (33)	69
Total charge in flashes with return strokes	C	172 (139)	5.4	23 (44)	100
Return stroke charge	C	579 (615)	0.14	0.77 (0.51)	4.1
Front duration for return strokes	µs	696	0.3	1	4
Maximum di/dt for return strokes	kA/µs	710	5.6	26	123
Action integral for return strokes	A^2s	398 (455)	5×10^2	2.3×10^3 (9.6×10^3)	10^4
Duration of flashes without return strokes	ms	639	65	163	407
Duration of flashes with return strokes	ms	212	144	338	791
Return-stroke duration	ms	888	0.57	3.6	22

Table 4: Lightning current parameters for **upward** (tower initiated) **positive** flashes. Adapted from Berger et al. (1978)

Parameters	Units	Sample Size	% Exceeding Tabulated Value		
			90%	50%	10%
Maximum current in flashes without large impulsive components	kA	132	0.21	1.5	11
Maximum current in flashes with large impulsive components	kA	35	10	36	127
Charge in flashes without large impulsive components	C	137	3.7	26	187
Charge in flashes with large impulsive components	C	35	20	84	348
Front duration for impulsive components	µs	23	4.5	39	340
Maximum di/dt for impulsive components	kA/µs	24	0.28	1.9	12
Action integral for impulsive components	A^2s	35	5×10^4	6.6×10^5	9×10^6
Duration of flashes without large impulsive components	ms	138	24	72	215
Duration of flashes with large impulsive components	ms	34	19	68	240

Direct measurements of lightning on instrumented towers have also been made by researchers in the United States (McCann, 1944), in Italy (Garbagnati et al., 1978; Garbagnati and Lo Piparo, 1982), in Russia (Gorin et al., 1977; Gorin and Shkilev, 1984), in South Africa (Eriksson, 1978), in Canada (Hussein et al., 1995; Janischewskyj et al., 1997), in Germany (Beierl, 1992; Fuchs et al., 1998), in Japan (Miyake et al., 1992; Goto and Narita 1992, 1995; Asakawa et al., 1997), in Switzerland (Montandon, 1992), in Austria (Diendorfer et al., 2009), and in Brazil (Lacerda et al., 1999; Visacro et al., 2004). In most studies, the towers experienced predominantly upward discharges.

Current parameters of downward lightning derived from measurements on the 60-m Morro do Cachimbo tower near Belo Horizonte in Brazil were presented by Visacro et al. (2004). 80 strokes were recorded in a total of 31 negative downward flashes during a period of 13 years. Values of the median peak current of first and subsequent strokes with 45 kA and 16 kA, respectively, are higher than the corresponding values 30 and 12 kA, reported by Berger et al. (1975).

2.1 Lightning to the Gaisberg Tower (GBT) in Austria

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. Lightning flashes to the tower occur in summer as well as during winter. Tower instrumentation is described in detail in Diendorfer et al. (2009).

As typical for elevated objects almost all flashes to the tower are upward initiated. The upward leader initiated at the tower top bridges the gap between the grounded object and the 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.

A total of 489 lightning events were recorded during this eight year period from 2000 – 2007 (on average about 60 flashes per year). 457 (93%) discharges lowered negative charge to ground, 19 (4%) positive charge and 13 (3%) records exhibited bipolar current waveforms. Goto and Narita (1995) determined 73 % negative and 27% positive discharges for winter lightning on the west coast of Japan when they used magnetic links to determine the characteristics of lightning flashes (N=66) to a 150 m high tower.

As shown in bottom line of Table 1 in 22 % of the negative upward flashes current pulses with peaks greater than 2 kA were superimposed on the slowly varying continuous current and these pulses are often referred to as ICC pulses or α-pulses. In 30% of the recorded flashes to the GBT, one or more downward leader/upward return stroke (RS) sequences occurred after the cessations of the ICC – the associated current pulses are also called β-pulses. Typically ICC pulses are relatively small, less than 10 kA, while RS have peaks mostly in the range above 5 kA.

2.1.1 Seasonal Occurrence of Flashes to the GBT

Interestingly, lightning to the GBT is observed to occur more or less uniformly distributed over the year (Fig.1a) and is not correlated with the pronounced lightning season in Austria (Fig.1b).

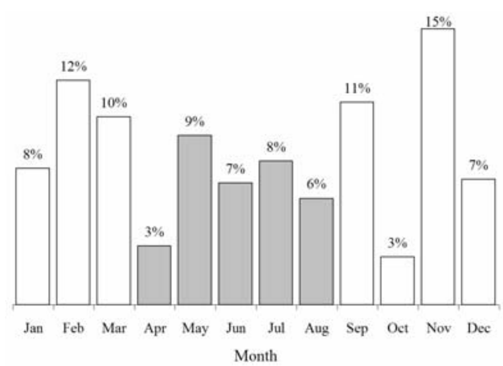


Fig.1a: Monthly lightning activity observed to the GBT from 2000 - 2007.

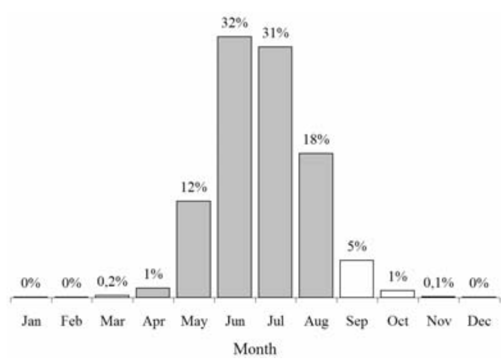


Fig.1b: Monthly lightning activity observed all over Austria from 2000 - 2007.

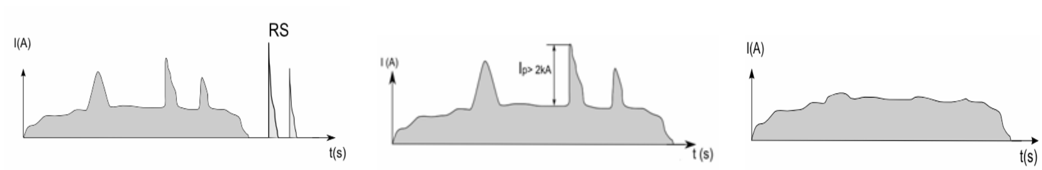
Note: Shaded diagram bars in Fig.1a represent the convective season (April – August) and unshaded bars represent the cold (non-convective) season (September – March)

Slightly more (56%) negative upward lightning was recorded during the cold season (fall and winter) compared to 44% recorded during the warm season (spring and summer). Seasonal occurrence of positive flashes is similar with 11 (58%) of the 19 positive flashes recorded during cold and 8 (42%) during warm season. Convective season in the Salzburg area lasts from about April to August. The flashes triggered by the tower during the cold season are assumed to be comparable to so called winter lightning observed and measured most frequently on the coast of the Japan Sea and described in detail e.g. by Asakawa et al. (1997), Goto and Narita (1995), and Rakov and Uman (2003).

2.1.2 Characteristics of Negative Upward Flashes

Upward initiated negative discharges are initiated by an upward positive leader and transport negative charge to ground. As described before, only in 30% of the negative flashes is the ICC followed by a downward leader/upward return stroke sequence.

We have subdivided the 457 negative flashes into the following three categories depicted in Fig.2:



ICC_{RS}: ICC is followed by one or more RS

ICC_{P}: ICC is not followed by any RS but with one or more ICC pulses >2 kA

ICC_{Only}: ICC is not followed by any RS and no ICC pulse > 2 kA occurred.

Fig.2: Schematic records of upward initiated lightning flash currents

Table 1 shows the seasonal occurrence and values of transferred charge of the distinct flash categories, ICC_{RS}, ICC_{P} and ICC_{Only} for the four meteorological seasons.

Fig.3 depicts in log-probability format the distribution of the total charge transfer for the flash categories ICC_{RS}, ICC_{P}, and ICC_{Only}, respectively, as well as for all recorded events at the GBT. Obviously the largest amounts of charge are transferred by the ICC_{P} type flashes. From 2000 to 2007 the maximum transferred charge measured in a single flash to the GBT was 405 C.

Table 1: Seasonal occurrence and total charge transfer of the three upward initiated flash types

	ICC_{RS}	ICC_{P}	ICC_{Only}	Total	Q_{tot} (GM)	Q_{tot} (MED)
Spring	19 (4%)	28 (6%)	57 (12%)	104 (22%)	33 C	39 C
Summer	31 (7%)	7 (2%)	56 (12%)	94 (21%)	27 C	27 C
Fall	43 (9%)	31 (7%)	63 (14%)	137 (30%)	33 C	38 C
Winter	46 (10%)	31 (7%)	45 (10%)	122 (27%)	40 C	40 C
TOTAL	139 (30%)	97 (22%)	221 (48%)	457 (100%)	33 C	37 C

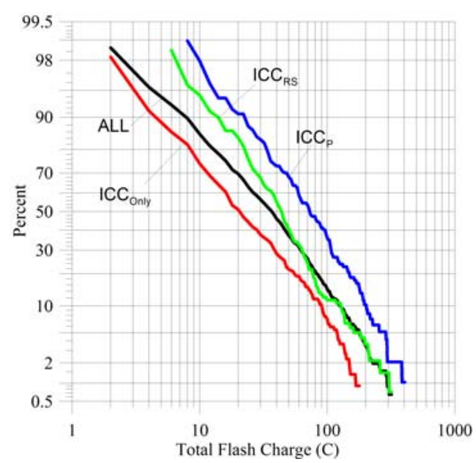


Fig.3: Cumulative frequency distribution of total charge for all negative upward flashes and the three categories ICC_{RS}, ICC_{P} and ICC_{Only} at the GBT (2000 – 2007)

In general RS-pulses are assumed to be the best representation of subsequent strokes in natural downward lightning. Hence, the results of our analysis are thought to be applicable to subsequent strokes occurring in a pre-existing channel in natural lightning, but not necessarily to negative first strokes, new-channel subsequent strokes, or positive strokes.

The peak current distributions of RS-pulses and ICC-pulses are shown in Fig.4 and Fig.5, respectively. For the distribution of RS-pulses a median of 9.2 kA (N = 615, σ_{log10} = 0.25) was determined. With a median of 4.2 kA (σ_{log10} = 0.26), the ICC-pulses are significantly smaller than the RS pulses. In addition, the more or less arbitrary applied lower limit of 2 kA also affects the resulting median value. But it is worth noting that 10% of the 728 ICC-pulses had peaks exceeding 9.1 kA and the largest measured peak current of an ICC-pulse was 22 kA.

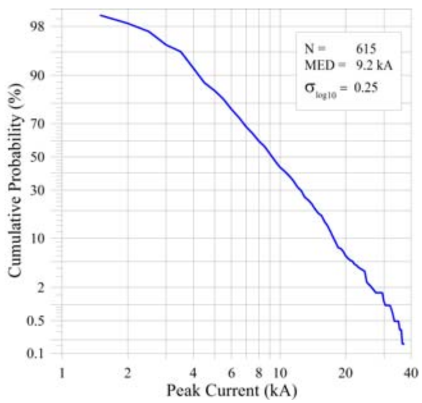


Fig.4: Distribution of the peak current of return strokes in upward initiated lightning to the GBT (2000- 2007)

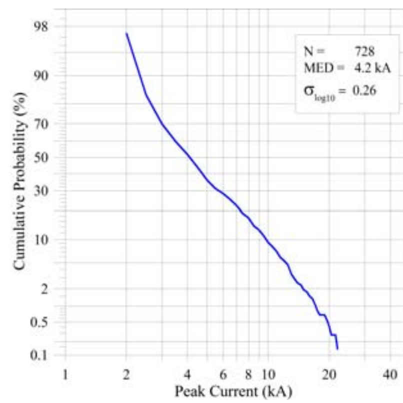


Fig.5: Distribution of the peak current of ICC-pulses in upward initiated lightning to the GBT (2000- 2007)

2.2 Radiated electric field from strokes to the GBT

Simultaneous measurements of lightning currents and associated radiated electromagnetic fields are of fundamental interest for various applications in lightning research. These data can be used for the evaluation of return stroke models or to investigate the so called tower effect when lightning hits an elevated object. Pichler et al., (2010) presented results of simultaneous measurements of current pulses from lightning strikes to the GBT and the correlated vertical E-field components at a distance of 78.8 km (Wels) and 108.7 km (Neudorf), respectively, with an example shown in Fig.6 and a summary of the results in Table 2.

Some lightning current parameters (peak current I_p, 30-90 percent risetime $T_{I\_30\text{-}90}$, and full width at half maximum T_{I_FWHM}) and the time correlated field waveform parameters (E_p, 30-90 percent risetime $T_{E\_30\text{-}90}$, T_{E_FWHM}, and the peak-to-zero time T_{E_PTZ}) as depicted in Fig.7 have been analyzed.

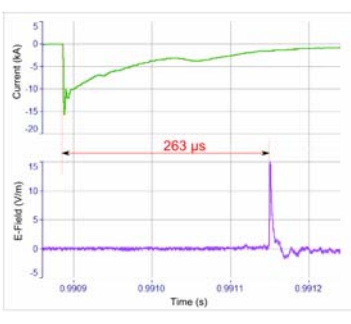


Fig.6: Current and correlated E-field measured at a distance of 78.8 km of a typical RS-pulse (pulse #554-10). I_p = -15.9 kA, E_p = +15 V/m (according to the "atmospheric electricity sign convention" a negative stroke produces a positive E-field pulse)

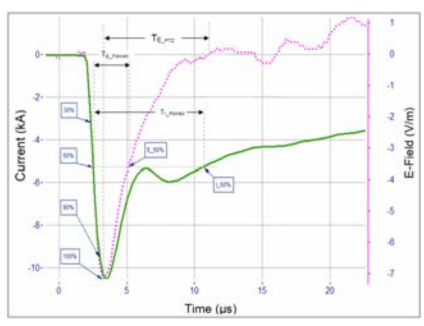


Fig.7: Current and vertical E-field wave form for GBT stroke #558-2. Current and field pulse are aligned in terms of starting point and peak amplitude (right hand side scaling applies to inverted E-field waveform) (adopted from Pichler et al., 2010)

Table 2: Parameters of correlated current and electric field pulses from lightning to the GBT (Pichler et al., 2010)

	N	I_p (kA)		T_{I_FWHM} (µs)		$T_{I\_30\text{-}90}$ (µs) a)	
		Mean	MED (GM)	Mean	MED (GM)	Mean	MED (GM)
Wels ICC pulses	103	4.7	3.8 (3.9)	42.5	32.8 (33.9)	3.8	1.4 (2.1)
Neudorf ICC pulses	42	6.5	5.2 (5.7)	44.3	44.1 (41.8)	2.5	1.5 (2.1)
All ICC	145	5.2	4.2 (4.3)	43.0	35.7 (36.1)	3.5	1.4 (2.1)
Wels RS	42	10.2	9.5 (9.2)	26.0	22.6 (20.4)	1.5	1.0 (1.1)
Neudorf RS	31	11.2	10.2 (10.2)	20.4	20.3 (17.3)	1.0	1.0 (1.0)
All RS	73	10.6	9.8 (9.6)	23.6	21.9 (19.0)	1.3	1.0 (1.1)

	N	E_p (V/m)		T_{E_FWHM} (µs)		$T_{E\_30\text{-}90}$ (µs)		T_{E_PTZ} (µs)	
		Mean	MED (GM)	Mean	MED (GM)	Mean	MED (GM)	Mean	MED (GM)
Wels ICC pulses	103	4.7	3.5 (3.8)	3.9	3.3 (3.6)	1.4	1.0 (1.0)	9.7	8.6 (8.6)
Neudorf ICC pulses	42	6.5	5.6 (6.1)	3.3	2.7 (3.0)	2.0	1.5 (1.6)	7.0	7.6 (6.3)
All ICC	145	b)		3.7	3.3 (3.4)	1.6	1.0 (1.2)	8.9	7.9 (7.9)
Wels RS	42	10.0	10.3 (8.9)	3.4	3.0 (3.1)	1.0	0.8 (0.8)	10.2	9.8 (9.5)
Neudorf RS	31	9.5	8.0 (8.6)	3.7	3.9 (3.5)	1.5	1.2 (1.3)	8.3	7.5 (7.4)
All RS	73	b)		3.5	3.1 (3.3)	1.2	0.9 (1.0)	9.4	9.5 (8.6)

With a geometric mean (GM) of T_{I_FWHM} =19 µs and I_p = 9.6 kA (N = 73) of the return stroke current pulses used in this study those strokes were very similar to the strokes in triggered lightning in Florida and Alabama (Fischer et al., 1993). With a T_{E_PTZ} of about 10 µs the zero crossing time of the radiated E-fields from the tower strokes are significantly shorter than the typical values of 30 – 40 µs (Cooray et al., 1985). The reason for the observed short zero-crossing time is still unclear. The relatively short lightning channel in case of the return strokes in object triggered upward flashes is one of the potential reasons.

3 Validation of LLS Performance Based on Lightning to the GBT

3.1 General

The most fundamental performance parameters of a LLS are:

- Detection Efficiency (DE): We have to distinguish between flash detection efficiency (DE_f) and stroke detection efficiency (DE_s), where DE_f is typically higher than the DE_s, because a flash is successfully located whenever at least one of the strokes within a multi-stroke flash is located.
- Location Accuracy (LA): LLS-reported locations are defined by the centroid of the LLS error ellipse. For a given stroke, the distance between the LLS location and the ground truth striking point is defined to be the stroke location error.
- Peak Current Estimate (PCE): LLS infer peak currents from measured peak fields. Simple models to account for field attenuation are partially integrated into the lightning location software. It is important to distinguish between the ability of a LLS to infer the correct peak current for a given stroke and the ability to provide correct values for peak current distributions. The former are typically use for case studies (e.g. investigation of power line flashover caused by a given lightning stroke) whereas peak current distributions are used in lightning protection standards and many lightning related statistical analyses.

Measurements of natural lightning to a tower provide an excellent set of ground truth reference data for the performance evaluation of LLS. The data include precise knowledge of time, type of discharge (only CG), location (latitude/longitude) and peak current of all the strokes in a flash. As the majority of the discharges to the GBT is initiated by upward propagating leaders, unfortunately only a very few first stroke data are available, the sample being too small for any statistical analysis.

GBT is located at the border area between Austria and Germany and is well covered by sensors contributing to the EUCLID network. Sensor locations, sensor type and distance to the tower of the 5 nearest sensors are listed in Table 3.

Table 3: Type and distance of the five EUCLID sensors next to the GBT

Sensor Location	Sensor Type	Sensor distance to Gaisberg Tower [km]
Eggelsberg (A)	IMPACT 141T	31
Niederoeblarn (A)	IMPACT 141T	77
Schwaz/T (A)	IMPACT ES	116
Muenchen (D)	LPATS III	118
Noetsch (A)	IMPACT 141T	142

3.2 Flash Detection Efficiency (DE_f)

In Table 4 we have summarized the GBT flash data for the period 2000–2005 when we consider only negative flashes to the tower having at least current pulse with a peak greater than - 2 kA. Flash peak current I_{FL} is defined as the largest amplitude of all pulses within the flash. Detection of at least one stroke of a multiple-stroke flash was required to consider the flash to be detected. Detection efficiency values were computed from this information as ratios of the LLS-detected events to all directly measured lightning events.

N_{tot} in Table 4 refers to the total number of flashes independent of the type of pulses (ICC- or RS-pulse). N_{RS} refers to flashes only where the ICC phase of the upward discharge was followed by at least one RS-pulse. The overall flash detection efficiency $(DE_f)_{tot}$ is 89% (154 out of 174) for all flashes with I_{FL} > 2 kA and increases to 97% for I_{FL} > 5 kA (139 out of 144). EUCLID detected 108 out of 110 [$(DE_f)_{RS}$=98%] of the flashes with at least one RS-pulse.

Table 4: GBT flash data (2000-2005)

I_{FL} [kA]	N_{tot} Gaisberg	N_{tot} LLS	$(DE_f)_{tot}$	N_{RS} Gaisberg	N_{RS} LLS	$(DE_f)_{RS}$
> 2	174	154	89%	110	108	98%
> 3	165	153	93%	110	108	98%
> 4	158	149	94%	110	108	98%
> 5	144	139	97%	109	107	98%
> 6	139	135	97%	105	103	98%
> 7	130	129	99%	102	101	99%
> 8	124	123	99%	99	98	99%
> 9	115	114	99%	95	94	99%
> 10	104	104	100%	86	86	100%

3.3 Stroke Detection Efficiency (DE_s)

We have also analyzed DE_s as a function of stroke type (ICC- or RS-pulses) and peak current range (see Table 5). In upward lightning initiated on high towers some of the ICC-pulses have waveforms similar to the waveform characteristic of return stroke pulses. Their risetimes are in the range of a few µs and the peaks are larger than 2 kA. Flache et al. (2008) analyzed high-speed video images and corresponding current records for eight upward lightning flashes initiated by the Peissenberg tower (160 m) in Germany. ICC current pulses with shorter risetimes developed in a newly-illuminated branch, ICC pulses with longer risetimes occurred in already luminous (current-carrying) channels. These results support the hypothesis that longer ICC pulse risetimes are indicative of the M-component mode of charge transfer to ground, while shorter risetimes are associated with the leader/return stroke mode.

Table 5: DE_S of strokes of different amplitude ranges (2000 – 2005)

	GAISBERG			Lightning Location System (LLS)				
I [kA]	N	N_{ICC}	N_{RS}	N_{ICC}	N_{RS}	Stroke $(DE_s)_{ICC}$ [%]	Stroke $(DE_s)_{RS}$[%]	Stroke DE_s[%]
2 – 3	150	139	11	21	4	15,1	36,4	16,7
3 – 4	98	83	15	29	3	34,9	20,0	32,7
4 – 5	119	90	29	50	17	55,6	58,6	56,3
5 – 6	72	33	39	23	27	69,7	69,2	69,4
6 – 7	79	36	43	31	31	86,1	72,1	78,5
7 – 8	66	23	43	19	37	82,6	86,0	84,8
8 – 9	61	26	35	23	31	88,5	88,6	88,5
9 – 10	60	20	40	20	37	100,0	92,5	95,0
> 10	269	48	221	47	219	97,9	99,1	98,9
Total	**974**	**498**	**476**	**263**	**406**	**52,8**	**85,3**	**68,7**

The DE_S increases with increasing peak currents. About 70% of the strokes with peak currents in the range from 5-6 kA were detected, whereas the DE_S increases to 99% for all strokes with I_p > 10 kA. For practical purposes it is interesting to know the overall DE_S for all strokes exceeding a given value (e.g. 5 kA). Fig.8 shows a plot of the observed DE_S as a function of minimum peak current.

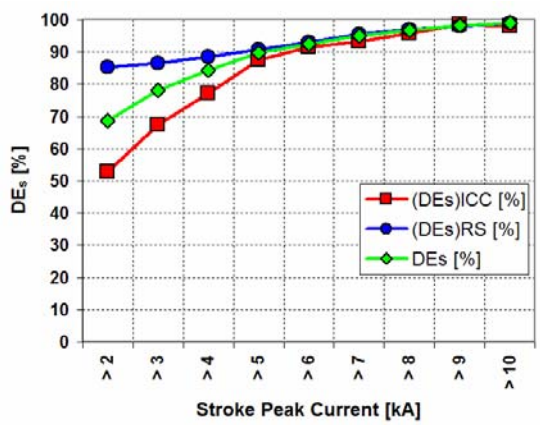


Fig.8: Stroke DE_S as a function of minimum peak current

It is interesting to note in Fig.8, that the DE_S for all ICC-pulses (I_S > 2 kA) is 53%, which is significantly lower then for RS-pulses (DE_S = 85%). Reasons for the lower DE_S for ICC-pulses are (1) the overall higher fraction of small amplitude ICC-pulses and (2) a considerable number of ICC-pulses exhibit a slow rising current front which is not seen in natural CG flashes. Considering all directly measured RS-pulses with a peak current I_S > 2 kA (N = 476) the LLS detected 406 and therefore missed 70 ($(DE_S)_{RS}$ = 85,3%); for I_S > 5 kA (N = 421) the LLS located 382 and missed 39 strokes ($(DE_S)_{RS}$ = 91%).

As model based calculations of the DE_S of the EUCLID network for the Gaisberg region result in a very low probability to miss strokes with amplitudes > 10 kA, we have analyzed in detail the 2 missed strokes with I_S > 10 kA. In both cases the strokes were actually located by a number of sensors but sensor messages indicate that a separate stroke occurred within 1 – 2 milliseconds at a different location and hence the central processor location algorithm did not successfully group the correlated sensor messages to the two different strokes and failed to provide a correct location.

These results allow us to infer a lower bound on flash and stroke DE for the EUCLID LLS in this region. When we postulate that (1) subsequent strokes in typical downward CG lightning are well represented by the RS-pulses in this analysis and (2) the peak current distribution of downward subsequent CG strokes is comparable to the analyzed sample, we can conclude that for strokes with minimum peak currents of 2 kA we can achieve a DE_S in the range of 85% and a DE_f of greater than 95%. This result should be representative of performance for other LLS when the network is comparable to the EUCLID network (in this region), in terms of mean sensor baseline, sensor- and central processor configuration. Given that natural first strokes typically have higher peak currents than subsequent strokes in existing channels, overall flash DE for natural lightning should be even higher.

3.4 Location Accuracy

Lightning strikes to the GBT are a perfect reference to evaluate the location accuracy of the EUCLID network, because the tower location (47.805°N / 13.112°E) is known with high accuracy. Fig.9 is a plot of the EUCLID stroke location error. The plot origin corresponds to the actual tower location. There is no significant difference in the location accuracy of ICC- and RS-pulses. A median location error of 368 m and a standard deviation of 768 m were determined for all the 674 strokes (see Fig.9). Typically location errors exceeding 2 km (only 2.4% of the cases) were observed for strokes located by only two or three sensors or when the location was calculated based on erroneously grouped sensor messages resulting from discharges that occurred almost simultaneously at two separate locations.

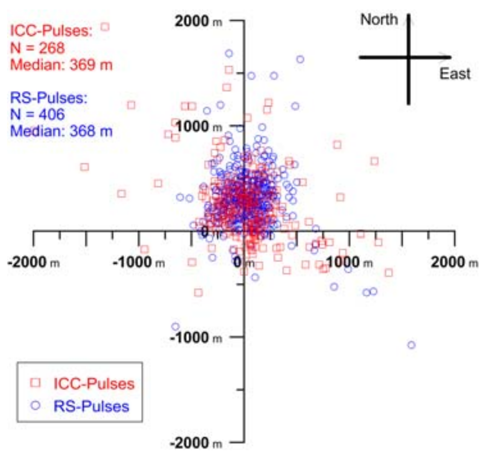


Fig.9: Plot of EUCLID stroke locations for 674 strokes during 2000–2005 (the origin corresponds to the tower location).

The plot in Fig.9 exhibits a bias of the LLS stroke locations by about 300 meters to the north. Reasons for that bias are assumed to be a combination of (1) timing errors as a result of pulse propagation over ground of finite conductivity and different sensor bandwidth and (2) a result of propagation elongation caused field propagation over high mountains (Schulz and Diendorfer, 2000). Recent developments at Vaisala are expected to eliminate this bias and reduce the random location error to about 50% of the current values, without requiring any changes to the sensors.

3.5 Peak Current Estimate

LLS infer the peak current from the range normalized signal strength (RNSS) which is calculated from the raw sensor signal strength (SS), corrected for the propagation distance and attenuation due to the finite conductivity propagation path.

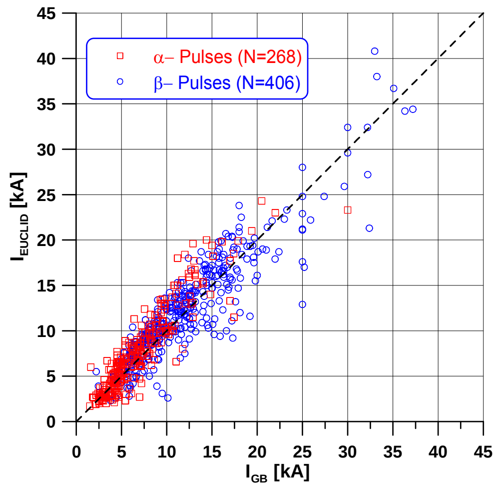


Fig.10: EUCLID peak currents plotted versus peak currents measured at the GBT during the season 2000–2005.

Note: During the period 2000 – 02/2005 (N = 612) in the EUCLID network no attenuation model was applied and a peak field to peak current conversion coefficient SNF=0.23 (see Eq.(6.1)) was used. Since 03/2005 (N=62) attenuation parameters are set to SNF=0.185, b=1.0 and L=1000 (see Eq.(6.2)) and test showed that there are negligible effects when these two data sets are analyzed together.

Fig.10 shows the EUCLID estimated peak current versus peak current measured directly at the tower, plotted separately for ICC- and RS-pulses recorded during 2000–2005. There is a strong positive linear correlation between the measured and EUCLID-estimated peak currents and no obvious differences in the quality of peak current estimates of ICC- and RS-pulses are observed.

3.6 Summary

Measurement of lightning to towers was in the past, and it is still today, a very effective method to gather information about this natural phenomenon. We can gain insight in the statistical distribution of various current parameters (peak value, transferred charge, and action integral, etc.) that are essential for lightning protection design. On the other hand tower lightning is perfect ground truth dataset for the performance analysis of lightning location systems.

Available technology for detecting and locating lightning to ground has significantly improved over the last decade, and continues to evolve. Direct measurements of lightning striking instrumented towers allow estimation of all three major performance parameters of a LLS - detection efficiency (for strokes and flashes), location accuracy, and peak current estimates. Evaluation of lightning to the GBT in Austria using the ALDIS LLS shows a flash DE of 98% and a stroke DE of 85% for stroke peak currents greater than 2 kA. For similar analysis of triggered lightning in Florida a triggered-flash DE (no first stroke) of 84% and stroke DE of 60% is reported by Jerauld et al. (2005). The main reason for the lower DE of triggered lightning flashes in Florida compared to tower lightning in Austria is the significantly larger sensor baseline in Florida and employment of a mixture of TOA and MDF/TOA sensors, requiring 3-4 sensors to compute a location. The location accuracy determined with ground truth data from the GBT is about 370 m.

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