Review of 10 years of lightning measurement at the Gaisberg Tower in Austria

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Abstract: First instrumentation for lightning measurements at the Gaisberg Tower (GBT) has been installed in 1998. During the 10-years period from 2000 – 2009 a total of 652 lightning events have been recorded. Fast majority of the lightning to the GBT was upward initiated and only very few records are candidates for downward flashes when the recorded current waveform is used for discrimination between upward and downward lightning. Most of the lightning to the GBT (about 60%) is observed during cold season, comparable to winter lightning in Japan. 3% (21/652) of the flashes were bipolar and 4% (26/652) were positive. Maximum measured charge transfer to ground in a single flash was 546 C. 10 out of the 652 flashes (1.5 %) transferred charge values exceeding 300 C and all those events occurred during cold season. Median peak current of return strokes following the initial continuing current is 9.2 kA and similar to values observed in triggered lightning and to peak current estimates for subsequent strokes from lightning location systems.

Keywords: lightning, measurements, tower, current parameters, charge

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 [1]. 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 high mountains a so called "effective height" being larger than the physical height of the object is assigned to the structure (see e.g.[2]). The effective height accounts for the additional field enhancement at the tower top due to the presence of the mountain. There is an ongoing discussion whether the upward lightning is initiated by an intra-cloud/cloud-to-ground discharge or by the slow charge build-up in the cloud above the tall object. The high number of lightning events to elevated towers makes those objects preferential for direct lightning current measurements. Instrumented towers and triggered lightning are the most widely used possibilities to perform direct measurements of lightning current waveforms.

2. INSTRUMENTATION

Since 1998 direct lightning strikes to a radio tower have been measured at Gaisberg, a mountain next to the City of Salzburg in Austria. 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 a small mountain Gaisberg (see Fig. 1). Tower coordinates are 47.805 N and 13.112 E, and the mountain top is 1287 m above sea level, which is about 800 meter above the surrounding terrain of the city of Salzburg.

Fig. 1. Radio tower at Gaisberg with nearby operational buildings

As shown later in this paper, lightning flashes to the Gaisberg Tower (GBT) occur in summer as well as during winter. The overall current waveforms are measured at the base of the air terminal installed on the top of the tower with a current-viewing shunt resistor of 0.25 mΩ (T&M Research Products, Type W13.2K16-6.5s-00025) having a bandwidth of 0 Hz to 3.2 MHz and shown in Fig. 2.

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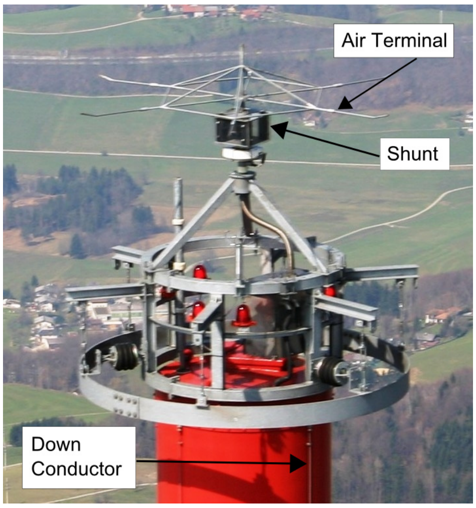

Fig. 2. Top of the GBT with installed air terminal and current-viewing shunt for lightning current measurements

The measuring system and the main steps in the data processing are described in detail in [3]. Two separate fiber optic channels of different sensitivity are used: Channel 1 with a current range of ± 2 kA to measure low amplitude currents like the initial continuous current (ICC) and Channel 2 with a range of ± 40 kA to measure return stroke peak currents. The applied 8-bit vertical resolution corresponds to 15 A/bit on the sensitive (± 2 kA) channel and to 312 A/bit in the ± 40 kA channel. The trigger threshold of the recording system is set to ± 200 A with a pre-trigger recording time of 15 ms. A digital filter (Butterworth, 2nd order) with a cut-off frequency of 250 kHz and appropriate offset correction is applied to the current records before lightning parameters (peak current, charge transfer, action integral) of the entire flash or individual strokes are determined.

For some events optical images of the lightning strikes to the tower were recorded by a current triggered high-speed camera (Kodak Motion Corder Analyzer SR 500) running with 500 frames per second. Unfortunately, in many cases the local visibility was too poor to capture any useable images of the lightning channel.

3. DATA

3.1 Flash Occurrence

For the analysis in this study we use data recorded at the GBT from 2000 to 2009. A total of 652 lightning events were recorded during this ten years period (on average about 65 flashes per year), although the annual numbers varies between 22 and 92 flashes as shown in Fig. 3.

It is interesting to note in Fig. 4, which is showing the monthly occurrence of lightning events to the GBT, that the highest number of flashes was observed during the cold season in March and November, respectively. About 95% of the overall lightning activity in Austria occurs during convective season from April to August. March and November contribute only 0.2% and 0.1%, respectively, to the overall lightning activity in Austria.

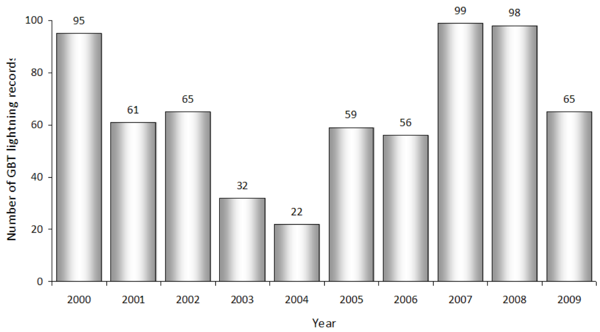

Fig. 3. Annual number of lightning events recorded at the GBT 2000-2009

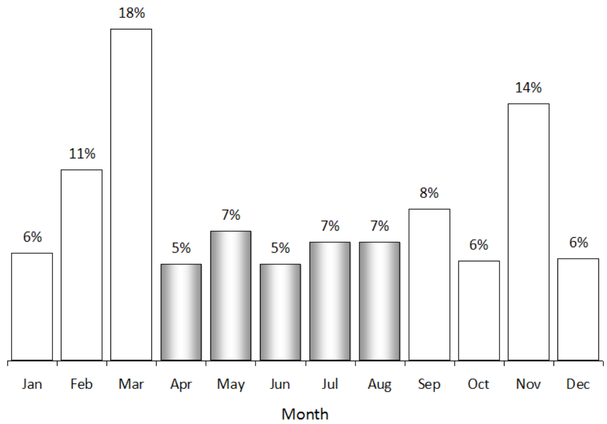

Fig. 4. Monthly occurrence statistics of upward lightning flashes from the GBT (2000 – 2009). Shaded bars indicate the convective season in Austria

For a more detailed analysis of the parameters of negative upward flashes we are using the three categories introduced in [3].

(1) ICC_{RS}	ICC followed by one or more return strokes (RS),
(2) ICC_{P}	ICC not followed by any RS but with one or more ICC pulses > 2 kA,
(3) ICC_{Only}	ICC not followed by any RS and no ICC pulse > 2 kA occurred.

A schematic current record of an ICC_{RS} type flash is shown in Fig. 5.

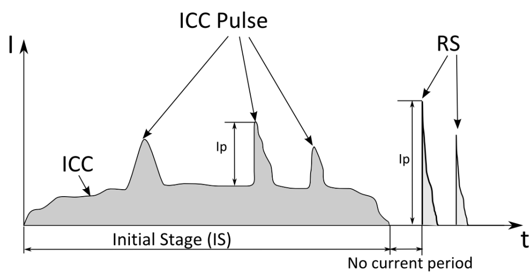

Fig. 5. Schematic current record for an ICC_{RS} type upward initiated flash. The initial stage (IS) phase is characterized by initial-continuous current (ICC). Superimpose are three ICC-pulses. The IS phase is followed by two return strokes (RS) after a period of no current flow

A typical example of a measured ICC_{RS} type lightning current is plotted in Fig. 6, where the ± 2kA channel record is shown. An ICC current lasting for about 270 ms is followed by three return strokes and labeled ①, ②, and ③. Peak currents of the return strokes (I_1=11 kA, I_2=10.2 kA and I_3=8.6 kA) is clipped by the ± 2kA measuring limit.

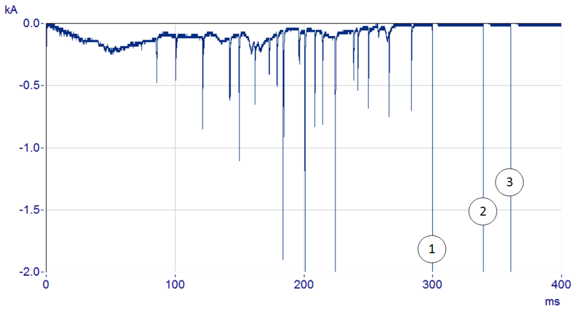

Fig. 6. Example of an ICC_{RS} type discharge, where 3 return strokes follow the ICC (GBT #481)

The waveform of the first return stroke ① in Fig. 6 is shown in Fig. 7 in microsecond time scale.

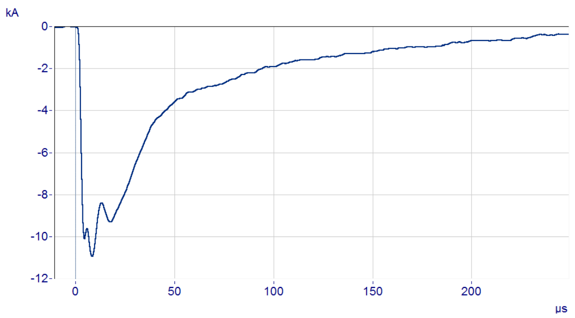

Fig. 7. Current pulse waveform of stroke ① of GBT #481 in microsecond time scale

Based on the described three categories we can divide the total of 652 measured events at the GBT according to Fig. 8. A total of 604 (93 %) discharges lowered negative charge to ground, 26 (4%) lowered positive charge and 21 (3 %) records exhibited bipolar current waveforms. 73 % negative and 27 % positive discharges are reported in [4] for winter lightning on the west coast of Japan when magnetic links were used to determine the characteristics of 66 lightning flashes to a 150 m high tower.

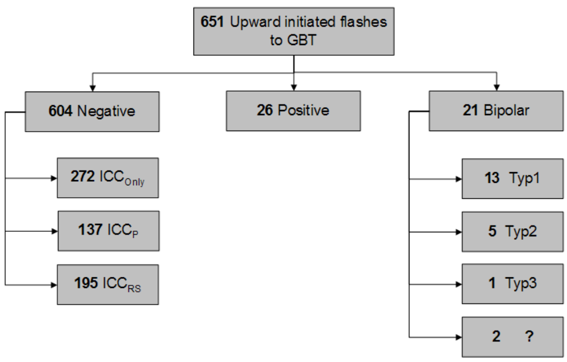

Fig. 8. Different types and subcategories of upward lightning observed at the GBT from 2000-2009

3.2 NEGATIVE FLASH PARAMETERS

Typically used parameters to describe upward flashes are the IS duration T_{IS}, the total flash charge Q_{Flash}, the Action Integral W/R and the IS average current given by Q_{Flash}/T_{IS}.

In this section of the paper we will consider only negative upward discharges. These discharges are initiated by an upward positive leader and transfer negative charge to ground. As shown in Fig. 8, in 32% (195 out of 604) flashes the ICC was followed by a downward leader/upward return stroke sequence and 45 % (272 out of 604) of the flashes did not show any pulses exceeding 2 kA peak currents. On the other hand some of the measured ICC pulses had amplitudes up to 20 kA. We assume that most of these large amplitude ICC pulses were actually associated with leader/return stroke mode discharges that attached to a previously formed and still existing upward propagating leader channel. This assumption is supported by the observation of shorter risetimes with increasing peak currents of the ICC pulses in agreement with correlated current and video observations of lightning to the Peissenberg Tower described in [5].

3.2.1 Total Flash Charge Q_{Flash} and Action Integral W/R

By numerical integration of the flash current records we have calculated the total flash charge Q_{Flash}. Statistical distributions of the total flash charge for all 604 flashes and the three subcategories ICC_{Only}, ICC_P, and ICC_{RS}, are shown in Fig. 9. It is interesting to note, that ICC_P type flashes with a median of 75 C obviously transfer on average three times larger amounts of charge than examined for ICC_{Only} type discharges with a median of 21 C. A summary of the statistical parameters of transferred charge Q_{Flash} and action integral W/R is given in Table 1.

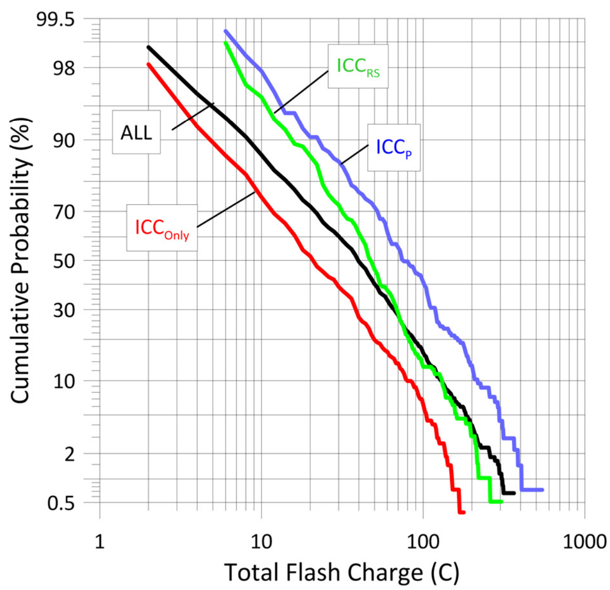

Fig. 9. Distribution of total flash charge transfer (QFlash) by upward negative lightning from the GBT (2000 – 2009)

TABLE 1: GEOMETRIC MEAN (GM), MEDIAN (MED) AND ARITHMETIC MEAN (AM) OF CHARGE TRANSFER Q_{FLASH} AND ACTION INTEGRAL W/R OF UPWARD NEGATIVE FLASHES TO THE GBT FROM 2000 -2009

		GM		MED		AM	
	N	Q_{Flash} (C)	W/R (kJ/Ω)	Q_{Flash} (C)	W/R (kJ/Ω)	Q_{Flash} (C)	W/R (kJ/Ω)
ICC_{Only}	272	98	2,4	21	2,5	34	14.6
ICC_P	137	74	25	75	27	106	54
ICC_{RS}	195	45	16	47	16	61	28
ALL	604	36	7,6	40	10	59	28

3.2.2 Duration T_{IS} of IS phase in negative upward flashes

Several IS parameters from triggered lightning in Florida and upward initiated lightning from three tall objects, including 74 flashes to the GBT and measured during the year 2000, were examined in [6]. The following Table 2 is an updated version of Table 3 in [6], which we have extended by the last line, showing the same parameters for the much larger 2000-2009 data set from the GBT.

TABLE 2: GEOMETRIC MEAN VALUES OF THE IS OF ROCKET-TRIGGERED AND NATURAL UPWARD LIGHTNING (ADOPTED FROM [6])

Experimental Site	N	Duration T_{IS} (ms)	Charge Transfer Q_{Flash} (C)	Average Current (A)	Action Integral W/R (kJ/Ω)
ICLRT, Florida	45	305	30.4	99.6	8.5
GBT, Austria	74	231	29.1	126	1,5
Peissenberg Tower, Germany	21	290	38.5	133	3.5
Fukui chimney, Japan	36	>82.5	>38.3	465	40
GBT, ALL (2000 – 2009)	604	266 [a)] (N=431)	35.6	113 [a)] (N=431)	7.6

[a)] 2000-2007 GBT data only

The cumulative distribution of the IS duration T_{IS} is shown in Fig. 10. No significant differences in the IS duration are observed for flashes with and without return strokes.

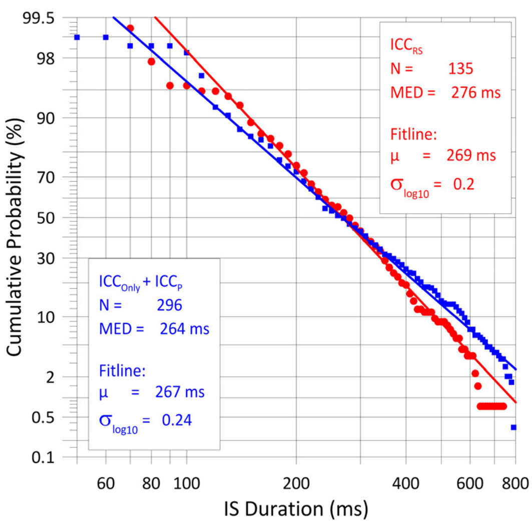

Fig. 10. Distribution of IS duration T_{IS} for flashes with (ICC_{RS}) and without (ICC_{Only} + ICC_P) return strokes (2000-2007)

3.3 POSITIVE FLASH PARAMETERS

Upward positive lightning is initiated by negatively charged leaders. Based on the recorded current waveforms, a total of 26 flashes were identified as upward positive discharges from the top of the GBT, consisting of initial stage current only, without any leader-return-stroke sequences. No downward positive flashes were observed. The occurrence of upward positive flashes accounts for 4% (26/652) of the total recorded flashes at the GBT during the 10-year observation period. Nineteen (73%) of the 26 flashes occurred during non-convective or cold season (September- March). Median values of peak current, flash duration, charge transfer, and action integral were determined as 5.2 kA, 82 ms, 58 C and 0.16 kJ/Ω, respectively. Current pulses of high frequency were found during the initial portion of the initial stage current for all of these upward positive flashes (example see Fig. 11). Based on simultaneous current and electric field records at a distance of 170 m from the GBT these fast pulses are inferred to be associated with the stepping process of the upward propagating negative leaders initiated from the tower top.

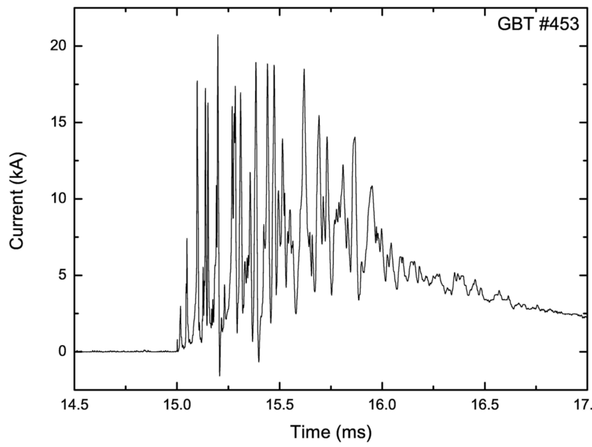

Fig. 11. The first 2.5 ms current waveform (with 0.5 ms pre-trigger time) for upward positive flash GBT #453 on high-amplitude scales

A more detailed analysis of the fast pulses observed in positive flashes at the GBT is presented in [9] and a separate paper on this subject will be presented during this symposium [10].

3.4 BIPOLAR FLASH PARAMETERS

The 21 bipolar flashes recorded at the GBT from 2000 – 2009 have been analyzed in detail in [7]. For one of the bipolar flashes to the GBT images from the high speed video camera are available and they could be used to assign opposite polarity current pulses to individual channel branches.

Thirteen (62%) of 21 bipolar flashes to the GBT occurred in non-convective season (September- March) and twelve (57%) of them occurred in seasonal transmission periods of March, August, and November. Thirteen (62%)of them belong to Type 1 associated with a polarity reversal during the initial stage current, based on the classification as suggested in [8]. An example of a Type 1 bipolar flash with polarity reversal during the IS phase is shown in Fig. 12. It was also found that the initial polarity reversal from negative to positive occurs more often (16 of 21), than that from positive to negative within a bipolar flash, in agreement with observations in other studies. The geometric mean of the total charge transfer is 99.5 C which is almost three times larger than the GM value of 35.6 C for all 604 negative upward lightning flashes observed from the Gaisberg tower.

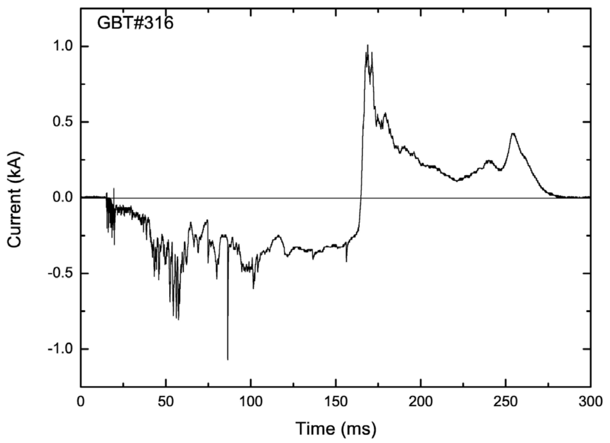

Fig. 12. Example of a Type 1 bipolar flash with polarity reversal after about 170 ms from negative to positive during the ICC phase

3.1.2 NEGATIVE STROKE PARAMETERS

A total of 3945 different current pulses have been observed during the 10 years period. 913 of them were classified as return strokes based on the ±2kA current record (see Fig. 13).

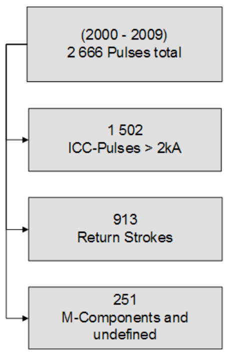

Fig. 13. Classification of current pulses measured at the GBT from 2000 – 2009

Return strokes follow the ICC after a period of no current in the lightning channel. Return strokes in upward lightning are assumed to be identical to return strokes in downward lightning and therefore the current parameters of those pulses are of special interest in order to gather current parameter information for lightning protection applications or to validate the peak current estimates of lightning location systems.

Distribution of peak current of the 913 return strokes is depicted in Fig. 14.

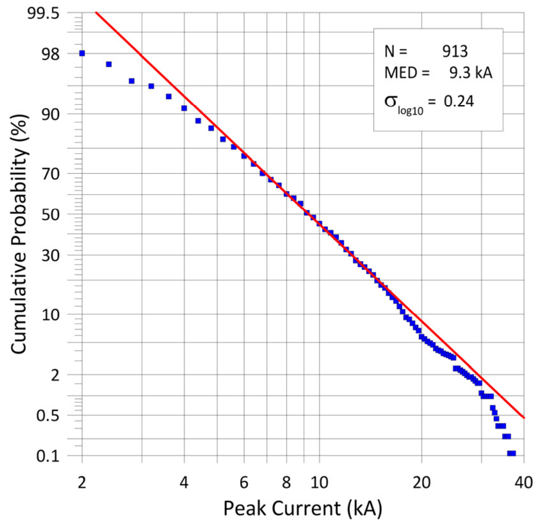

Fig. 14. Return stroke peak current distribution. Line represents best fit log-normal distribution with μ=9.3 kA and σ_{log10}=0.24

We have to note, that during the 10 years period there have been only 2 negative return strokes to the GBT that exceeded the 40 kA limit of the measuring system and therefore the distribution in Fig. 14 is almost unaffected by this 40 kA limit of the instrumentation. The median value of 9.3 kA is close to peak currents measured at other towers or in triggered lightning [11-15].

Probability distributions of stroke charge and action integral W/R together with their log-normal fit lines are shown in Fig. 15 and Fig. 16, respectively.

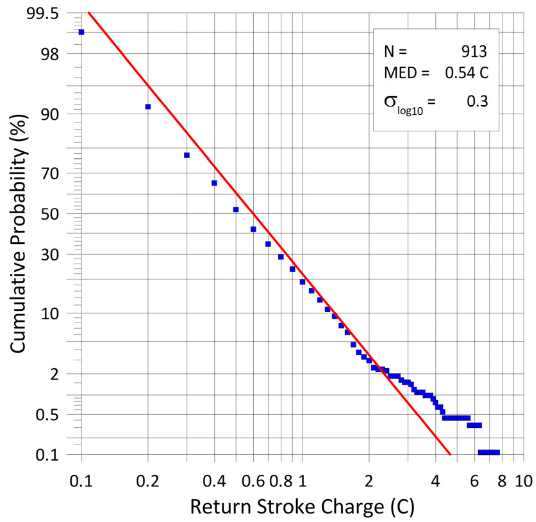

Fig. 15. Return stroke pulse charge distribution. Line represents best fit log-normal distribution with μ=0.6 C and σ_{log10}=0.3

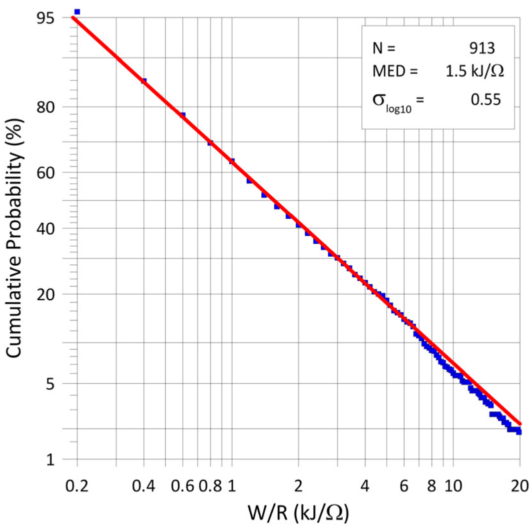

Fig. 16. Return stroke action integral distribution. Line represents best fit log-normal distribution with μ=1.5 kJ/Ω and σ_{log10}=0.55

4. SUMMARY

In Table 3 we present a summary of a number of flash and stroke parameters examined from the GBT data and given in brackets with in comparison with the data from [12].

TABLE 3 COMPARISON OF FLASH AND STROKE PARAMETERS OF UPWARD NEGATIVE LIGHTNING REPORTED BY BERGER (1978) [12], AND MEASURED AT THE GBT (VALUES IN BRACKETS)

Parameter	Unit	N	% exceeding tabulated value		
			90%	50%	10%
Maximum return stroke current	kA	176 (913)	4.2 (4.5)	10 (9.3)	25 (19)
IS charge in flashes without return strokes (ICC_{Only} + ICC_P)	C	638 (409)	1.9 (7.3)	12 (35)	69 (167)
Total charge in flashes **with** return strokes (ICC_{RS})	C	172 (195)	5.4 (19)	23 (47)	100 (117)
IS duration in flashes **without** return strokes (ICC_{Only} + ICC_P) (2000-2007)	ms	639 (294)	65 (131)	163 (268)	407 (548)
Return stroke charge	C	579 (913)	0.14 (0.3)	0.77 (0.6)	4.1 (1.4)
Action integral for return strokes	kJ/Ω	398 (913)	0.5 (0.3)	2.3 (1.6)	10 (7.9)

From Table 3 we can see that for return stroke peak currents the 9.3 kA value is in good agreement with the 10 kA reported in [12]. IS charge of flashes without return strokes at the GBT (35 C) is about three times larger than reported by Berger (12 C) and about 2 times larger for flashes with return strokes (47 C versus 23 C). The 50%-value of return stroke charge at the GBT is 22 % smaller (0.6 C versus 0.77 C) than in [12] and also the action integral with 1.6 kJ/Ω is 30 % smaller than the 2.3 kJ/Ω reported in [12].

At present the reasons for the significant differences in the IS charge is unclear. They could be either a feature of the selected tower site including specific, local meteorological conditions or a result of data analysis used to examine the data. Integrating the current record over several hundred milliseconds is very sensitive to any offset in the current record, to the vertical resolution and to the sampling rate. Further research and comparisons with other tower experiments using today's available digital data processing tools are needed in order to clarify this question.

5. ACKNOWLEGDEMENTS

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