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LIGHTNING CURRENT MEASUREMENTS COMPARED TO DATA FROM THE LIGHTNING LOCATION SYSTEM BLIDS

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SUMMARY

In this paper we show the first performance analysis of the BLIDS/EUCLID lightning location system (LLS) with data from direct current measurements at the Peissenberg Tower. We evaluate the performance of the BLIDS/EUCLID LLS in terms of detection efficiency (DE), location accuracy (LA) and peak current estimation. The flash/stroke DEs determined in this paper (100%/81%) are in good agreement to the results determined at the Gaisberg Tower in Austria. We further show that at the Peissenberg Tower all strokes greater than 10 kA were detected by the LLS.

KEYWORDS

Lightning location systems, Performance, Tower measurements

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1. Introduction

Lightning current measurements on towers were used for years to determine lightning parameters [1]. Recently this type of measurement is more often used to validate lightning location systems (LLS), e.g. at the Gaisberg Tower (GBT) in Austria [2], [3], [4] at the Säntis Tower in Switzerland [5] or at the Morro do Cachimbo in Brazil [6], [7]. Regarding the validation of LLS performance parameters, such as location accuracy (LA), detection efficiency (DE), peak current calibration or IC/CG classification accuracy, tower measurements exhibit similar characteristics compared to measurements with rocket triggered lightning, e.g. they provide both peak current estimation accuracy. Compared to LLS validation with E-field and video measurements there are different advantages (e.g. the current is measured directly) and disadvantages (e.g. there are only few measurements of positive strokes and negative first strokes) of tower measurements [8].

2. Peissenberg measurement system

The mountain called "Hoher Peissenberg" is an isolated ridge topping the surrounding terrain by about 250 m. The mountain is located in the South of Germany close to the mountains of the Alps, about 60 km southwest of Munich. On this mountain, the Peissenberg Tower (PBT) is located in an altitude of about 940 m above mean sea level. In 1978, the lightning current measurement started with the installation of a di/dt-sensor at the top of the tower [9], [10]. In April 1999 the various measurement programs ended and the Peissenberg Lightning Measurement Station was shut down.

In 2007 the top section of the PBT was removed and substituted by a new construction due to the requirements for new digital TV broadcast. With the replacement of the tower top section, a new current probe was installed on the top of the tower. The lightning current is now measured with different sensitivities by two channels of an A/D converter (NI-PXI 5122) with 14 bit resolution. The sampling interval is 10 ns and the recording period is 2.56 s. The upper frequency limit is about 30 MHz.

In 2011 a GPS-clock was installed in order to get a time stamp of the lightning events. Due to the synchronization with the GPS-time, it is now possible to compare the currents recorded at the PBT to the data from the lightning location system BLIDS/EUCLID. More details of the measurement setup can be found in [11].

3. BLIDS/EUCLID

The LLS BLIDS is part of the European lightning location network EUCLID. BLIDS/EUCLID operates the lightning location sensors in Germany and in some surrounding countries. All the employed lightning location sensors are newest technology sensors (LS700X) manufactured by Vaisala Inc. with individually calibrated sensor gains and sensitivities in order to account for any local sensor site conditions [3]. Fig. 1 shows the location of the PBT and the surrounding BLIDS/EUCLID sensors, respectively. The sensor numbers are the internally used sensors IDs in the BLIDS/EUCLID network

The performance of the BLIDS/EUCLID system was validated during the last years with data from lightning current measurements at the GBT and with data from video and E-field measurements in Austria, Belgium and France [3].

Fig. 1: Location of the PBT and EUCLID sensors locations.

The results of the comparison in [3] show a DE of 96 % and 70 % for negative flashes and strokes, respectively, determined from data to the GBT. This data is in good agreement with the DE values determined from video and E-field recordings in Austria (98 % and 84 % for flashes and strokes, respectively), considering that the DE from GBT data is based on subsequent strokes only and first strokes normally exhibit peak currents greater than subsequent strokes.

4. Used data

For our comparison with data from the lightning location system BLIDS/EUCLID, we use the fast-varying impulsive lightning currents recorded at the PBT. Slow-varying lightning currents with relatively low amplitude as the initial continuous current (ICC) or continuing currents are not taken into account, because the radiated electric (far) field is commonly much too low. The fast-varying impulsive currents comprise the currents of the return strokes, some M-components and some initial stage (IS)-pulses superimposing the ICC. For this analysis we use only return strokes (RS).

Although the measurements at the Peissenberg started in 2007 we use data from 2011-2015 because only for this time period GPS time synchronization was available. Table 1 shows the tower measured RS per year. It can be seen that the number of flashes to the PBT per year is rather small. In total only 11 negative flashes exhibiting 37 RS were detected at the PBT during the 5 years of operation.

Table 1: Number of tower recorded flashes and return strokes per year measured at the PBT

Year	Flashes with RS	Number of RS
2011	2	3
2012	7	32
2013	0	0
2014	0	0
2015	2	2
Total	11	37

Because tall structures as the PBT are commonly struck by upward lightning, current data of first strokes of downward lightning are rather rare. At the PBT, the current of two first negative lightning strokes in downward lightning were recorded, one stroke in 2011 and one in 2015. It is important to mention that the LLS data used for all the analyses in this paper are data from the LLS realtime stream. There was no reprocessing performed in order to determine the performance of the operational BLIDS/EUCLID LLS.

5. Results

5.1 Detection efficiency

The data to determine the flash/stroke DE of the BLIDS/EUCLID LLS are used independently of the IC/CG categorization of the LLS because it is known that strokes to high towers exhibit smaller peak-to-zero (PTZ) times and therefore they are sometimes misclassified as IC. In the used data, 11 out of 30 detected strokes were misclassified as IC discharges.

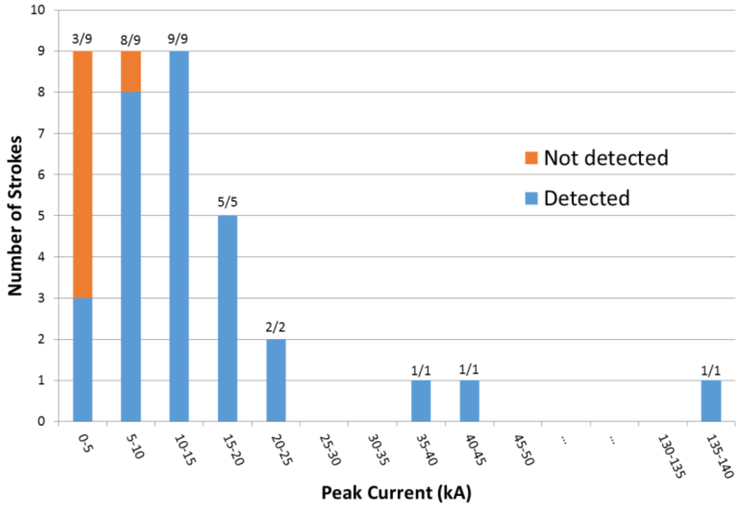

Fig. 2: Number of detected strokes versus peak current. For each peak current range (bin size of 5 kA), the ratio given on top of the column indicates the number of strokes detected by the BLIDS/EUCLID (numerator) and the number of strokes recorded at the Peissenberg (denominator), for that peak current range.

81 % of the return strokes and 100% of the flashes measured at the PBT were detected by the BLIDS/EUCLID LLS. To be able to compare the above mentioned flash DE with natural downward lightning it is important to know the mean multiplicity (number of return strokes) of the Peissenberg flashes. The mean multiplicity of the flashes measured at the Peissenberg was 3.4 what is comparable to downward lightning and therefore the flash DE determined at the Peissenberg is comparable to flash DE of natural downward flashes. Fig. 2 shows the number of detected strokes for different peak current intervals. All strokes with peak current greater than 10 kA are detected by the BLIDS/EUCLID LLS. A similar behavior was reported from the GBT measurements [12], [3], where also basically all strokes with peak current greater than 10 kA were detected.

5.1 Location accuracy

The BLIDS/EUCLID LLS experienced during the last years major upgrades with significant influence on the LA. In 2011 a new feature of the LS700X sensor, the so called sensor based onset time calculation [13], was introduced. Further at the end of 2012 range and angle dependent time propagation corrections were implemented for each sensor. Both new features improved the LA of the network significantly [14].

The majority of the stroke locations used to determine the LA was calculated with sensor based onset time correction. Only the two strokes in 2011 were calculated with the old onset time correction. Those two strokes, indicated as red diamonds in Fig. 3, exhibit the worst LA in our data set. Only the two stroke locations from 2015 were calculated with applied time propagation corrections. Both events exhibit a LA better than the median (54 m and 34 m)

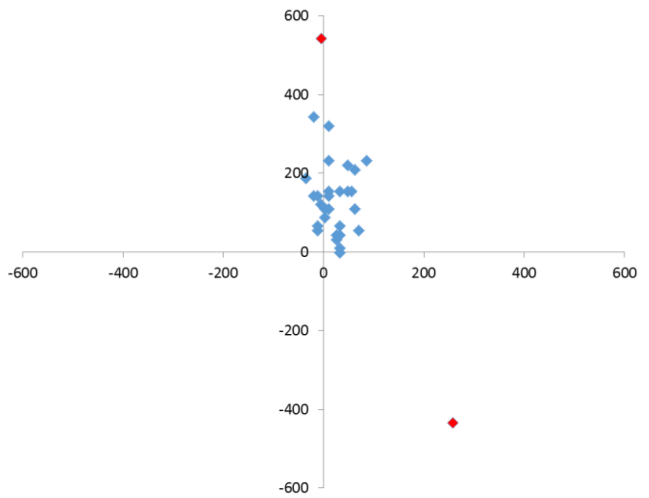

Fig. 3: LA at the PBT for data from 2011-2015 (N=30). The tower position is in the origin of the coordinate system. Red diamonds indicate strokes from 2011.

In Fig. 3 the Peissenberg is located at the origin of the coordinate system. It can be seen that the LLS exhibits a location bias to the north. This could be related to the missing propagation correction in the majority of the data (except the two strokes in 2015) during the time period of the measurements.

Nevertheless the median (50%) and 90% LA for all N=30 detected strokes is 144 and 324 m, respectively. Using only data from stroke locations calculated with sensor based onset time calculation, excluding the two strokes in 2011, the median LA decreases to 135 m.

5.3 Peak currents of subsequent strokes

The BLIDS/EUCLID LLS infers the peak current from the range normalized signal strength which is calculated from the raw sensor signal strength, corrected for the propagation distance and attenuation due to the finite conductivity propagation path. In Fig. 4 we compare the peak currents given by the BLIDS/EUCLID LLS and the peak currents measured at the PBT. Ideally all data points should line up on the dashed red line. Fig. 4 shows that the BLIDS/EUCLID LLS in average overestimates the peak current of subsequent strokes.

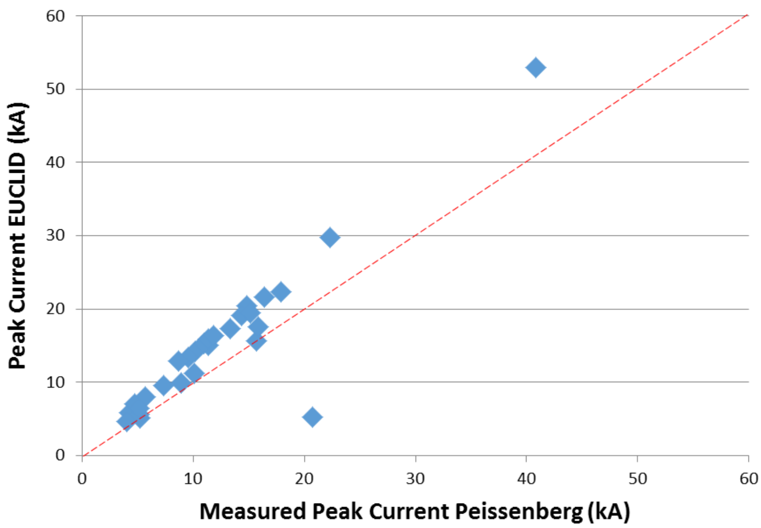

Fig. 4: Measured peak currents at the PBT versus BLIDS/EUCLID peak currents for subsequent strokes. Dashed red line (slope=1) is the locus of points for which the BLIDS/EUCLID peak currents and Peissenberg peak currents are equal.

It is interesting to note that the measurements at the GBT in Austria, which is not far away from the Peissenberg (distance is about 160 km), the LLS estimated currents of strokes to the GBT do not show any overestimation [3]. The stroke peak currents measured at the GBT are obtained from data records after applying a digital filter (upper frequency limit 250 kHz [15]) and the peak currents measured at the Peissenberg are only filtered if an oscillation during the first microseconds of the waveform makes a reliable estimation of the peak current impossible (the upper frequency bandwidth is also 250 kHz [11]). This means that both data sets are basically prepared in the same way for the analysis. A hypothesis to explain the difference is related to the fact electrically tall towers enhance the electromagnetic field and the PBT (150 m) is taller than the GBT (100 m). In order to test a possible influence of the tower height we have made a simple estimation with the program “CONCEPT II” (see [16], [17], [18]). This program is based on the so-called Method of Moments (MOM) and it solves the full Maxwell equations in the frequency domain. Therefore, the time-domain solutions are obtained from the inverse Fourier transformation.

In the computer model, the GBT and the PBT were simulated by metallic cylinders with heights of 100 m and 150 m, respectively. For both towers, the diameter of the cylinders was set to 1 m. The cylinders were assumed to consist of solid steel with a conductivity of $8.33 \cdot 10^6$ S/m. For both towers, the grounding system was taken into account by a grounding resistor of 0.5 Ω. The ground was simulated by an ideal conducting plate.

The lightning was assumed as a straight and vertical channel striking the top of the towers. The diameter of the lightning channel was chosen to 1 cm. The return stroke process was taken into account by the well-known transmission-line (TL) model [19]. In the simulations, the return stroke velocity was chosen to c/3 = 100 m/µs. Further we assume a lightning channel perpendicular to the ground plane. Different channel-base currents were assumed with 10%-to-90% risetimes ranging from 0.4 µs to 5 µs.

The vertical electric field was calculated at a distance of 50 km. The results of the calculations, shown in Fig. 5, revealed that the presence of a tower increases the electric field especially for shorter risetimes compared to strokes to ground (see “PBT versus Ground” and “GBT versus Ground” in Fig. 5). As expected the enhancement is decreasing with increasing 10-to-90% risetimes. Because the PBT is about 50 m taller than the GBT, the electric field radiated by the strokes to the PBT are slightly larger compared to the case that the GBT is struck by a stroke with the same risetime.

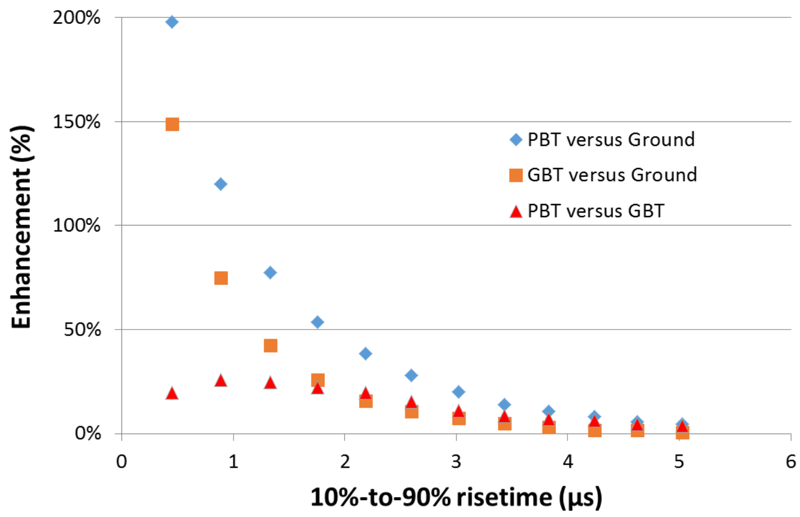

Fig. 5: Tower enhancement effect

The simulation results in Fig. 5 support the observation of LLS overestimation of the stroke peak currents, as for the same lightning stroke to the two towers the LLS sensors will see slightly higher peak fields in case of the PBT.

5.4 Measured first strokes

Because tower measurements of first strokes are rare, we show some more details for the two detected first strokes. Figure 6 shows the current of a negative first stroke measured at the PBT on August, 22, 2011 (#331). The current maximum was -35.7 kA, the transferred charge was 7.8 C and the specific energy ($\int i^2dt$) was $115 \cdot 10^3$ A^2s. The 10%-to-90% risetime of this first stroke was about 9.4 µs.

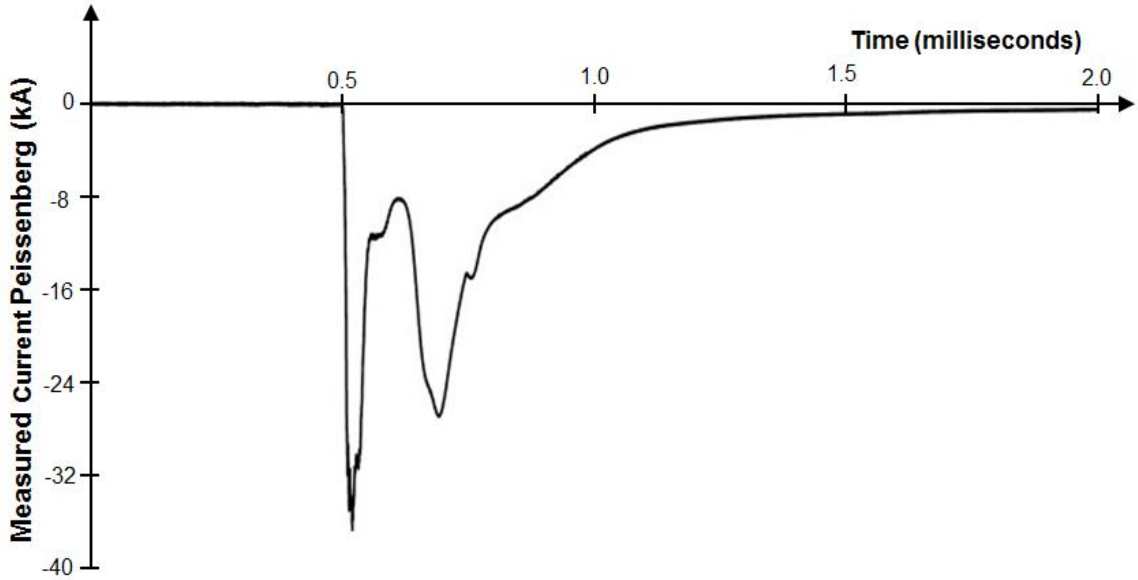

Fig. 6: Current of a negative first stroke measured at the PBT on August, 22, 2011 (#331).

Figure 7 shows the current of a negative first stroke measured at the PBT on July, 03, 2015 (#365). The current maximum was -137 kA, the transferred charge was 68 C and the specific energy ($\int i^2dt$) was $4.4 \cdot 10^6$ A^2s. The 10%-to-90% risetime was 50 µs. The inset shows the rising portion of the current for the duration of 110 µs. The current has a first maximum of about -44 kA which can be seen in the current curve of the inset. For the current front up to the first maximum, the 10%-to-90% risetime was 7.9 µs.

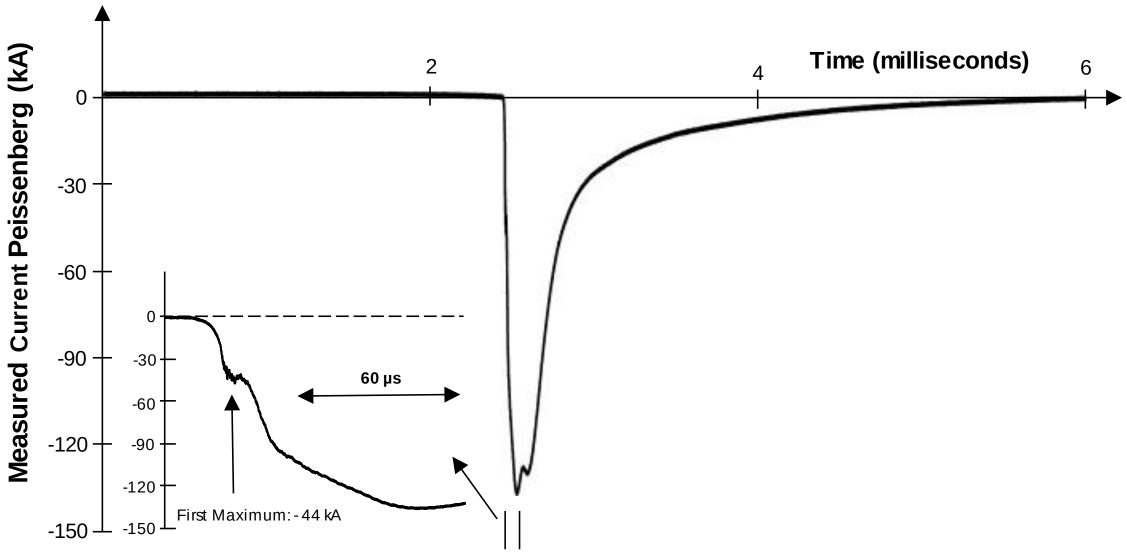

Fig. 7: Current of a negative first stroke measured at the PBT on July, 03, 2015 (#365).

The stroke related field risetimes reported by the BLIDS/EUCLID network (risetime of the closest sensor with a distance of more than 50 km – see [20]) for the two strokes are 10.5 µs

(#331) and 9.4 µs (#356) respectively. Although current and field risetimes cannot be compared directly, they should be of the same order of magnitude. Because the risetime of #365 (50 µs) is significantly larger than the EUCLID reported risetime (9.4 µs) we assume that the LLS reported the first peak (-44 kA) of flash #365 with a risetime of 7.9 µs.

Table 2: Peak currents (I_p) measured at the PBT and inferred by EUCLID for two first strokes

	I_p PBT (kA)	I_p EUCLID (kA)	Difference (%)
Flash #331	-35.7	-23.8	-33%
Flash #365	-137 (-44)	-32.4	-76% (-35%)

Table 2 shows the reported peak currents from the PBT recordings and the corresponding BLIDS/EUCLID data. Even if we use, as argued above, the first maximum of flash #365 (-44 kA), we can see that both first stroke peak currents are underestimated by the BLIDS/EUCLID LLS.

6. Summary/Discussion

Although only limited data are available the results of this analysis give a clear picture of the performance for the BLIDS/EUCLID LLS at the location of the PBT. The determined performance parameters are basically in good agreement to the performance parameters determined at the GBT [3], [4]. This is not too surprising because the distance between the two tower locations is not very large (156 km) and therefore the LLS network is expected to show similar performance at both locations. Table 3 presents a comparison of the results from the GBT with the results presented in this paper form the PBT.

Table 3: Comparison of LLS performance evaluation results at the PBT and the GBT [3],[4].

	PBT	GBT
Stroke DE	81 % (N=37)	71 % (N=675)
Flash DE	100 % (N=11)	96 % (N=161)
LA	144 m (N=30)	100 m* (N=38)

*Median for 38 strokes in 2012 to make the LA results comparable with the PBT measurements.

All measured return strokes at the PBT exhibit peak currents greater than 2 kA (minimum 2.2 kA). The median peak current measured at the PBT (first and subsequent strokes) is 10 kA and therefore about the same as for GBT measurements (9.2 kA [15]). This means that the obtained DE values are based on basically the same peak current distribution and the results should therefore be comparable. The number of strokes per flash at the PBT (3.4) is somewhat smaller compared to the GBT (4.3) and should therefore bias the flash DE towards lower values. Therefore we believe that the higher stroke and flash DE at the PBT compared to the GBT may be a result of the field enhancement due to the tower. The influence of this field enhancement is estimated by a simple model and should only be significant for 10%-to-90% risetimes of less than ~6 µs.

In Table 3 we further compare the LA determined with the PBT data to the LA results from the GBT measurements during 2012 only. The reason that we use a limited time period of the GBT data is that we want to eliminate any influence of later improvements of the LLS technology. Comparing the LA values from Table 3 we can see a reasonable agreement having in mind that in the PBT data two strokes from 2011 are included.

It is interesting to note that peak currents for subsequent strokes are overestimated by the BLIDS/EUCLID LLS, but the two first stroke peak currents are underestimated (attention: there are only two first strokes available).
There are several possible explanations for this behavior:

- The return stroke velocity for first strokes may be lower than for subsequent strokes resulting in lower field peaks and therefore lower LLS peak currents.
- In general first strokes exhibit longer rise times compared to subsequent strokes. Therefore the enhancement effect of the tower, mentioned in section 5.3, may not be visible for first strokes.
- The electric field is composed by (1) the tower electric field produced by the current flowing through the tower and by (2) the channel electric field produced by the current flowing in the return stroke channel. Due to the, in general, longer risetimes of first strokes currents, the contribution of the tower electric field to the electric field maximum of the first stroke is rather small, in contrast to subsequent strokes. It appears that the electric field maximum of the subsequent strokes is mainly determined by the tower electric field which is always perpendicular to ground. Because the electric field of the first return strokes is mainly determined by the channel electric field, the inclination of the lightning channel mitigates the electric field of first return strokes to a much greater extent compared to subsequent return strokes. Further, because first return strokes are associated with cloud-to-ground (downward) lightning, it is expected that the cloud charge is not located directly above the tower, because in this case the field enhancement of the tower would initiate an upward lightning. In case of the subsequent strokes it is opposite, because they are part of a ground-to-cloud (upward) lightning where it is expected that the cloud charge is more or less located directly above the tower. Therefore, it might be possible that the inclination of the return stroke channel is higher and the resulting field peak is smaller for first strokes compared to subsequent strokes.

Further analyses are necessary to determine which effect is the real cause of the differences.

As usual for tower measurements a significant percentage of strokes at the PBT were misclassified as IC (37 %). This number is slightly higher compared to the measurements at the GBT (31 % [21]) and could also be a result of the more pronounced field enhancement.

Is it planned to repeat this type of analysis in some years with more data.

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