Global ground strike point characteristics in negative downward lightning flashes

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Abstract—**Information about lightning properties are important in order to advance the current understanding of lightning and consequently to improve lightning protection as well. Especially ground strike point (GSP) properties are helpful to improve the risk estimation for lightning protection. In this study, lightning properties of negative downward lightning flashes are analyzed. The high-speed video recordings are taken in different regions, including Austria, Brazil, South Africa and U.S.A., and are analyzed in terms of flash multiplicity, duration, and ground strike point properties. Although the results vary among the data sets, the analysis reveals that a third of the flashes are single-stroke events, while the overall mean number of strokes per flash equals 3.67. From the video imagery an average of 1.56 GSPs per flash is derived, with about 60% of the multiple stroke flashes striking ground in more than one place. It follows that a ground contact point is struck 2.35 times on average. Multiple-stroke flashes last on average 371 ms. Additionally, the observations are linked to the observations made by local a LLS. It follows that median values of the separation distance between the different GSPs within flashes varies between 1.57 km and 2.82 km. Finally, it is observed that the median peak current of the first stroke to the first GSP in a flash is the highest compared to the median peak current of the first stroke in subsequent GSPs. A similar trend is found for the peak current as a function of stroke order within a particular GSP.**

Keywords—negative ground flashes, ground strike points

I. INTRODUCTION

Observations from ground-based LLSs as well as from space have, besides governing many advantages, one fundamental drawback as it observes the lightning discharge indirectly. Hence, the role of high-speed camera observations. Such observations gradually dissect the flow of the electrical charged particles through the air and provide, linked to electric field measurements, a means to investigate in great detail the associated optical and electromagnetic properties of natural downward lightning flashes. With frame rates of 200 per second (fps) or more, the different strokes that compose a multi-stroke flash can each be captured individually, while it is the electric field measurement that undisputably identifies the polarity of each stroke. Furthermore, video imagery enables us to determine, if not too distant and/or obscured by precipitation, whether each individual stroke creates a new ground strike point (GSP) or follows a pre-existing channel (PEC). The characteristics deduced from this is not only relevant from a pure scientific perspective, but is essential in developing adequate lightning protection solutions as the level of lightning protection and risk to be mitigated is derived from the density of lightning terminations in a region. Typically, this is based on flash density values but there have been recommendations to increase calculated densities by a factor of two to account for multiple ground strike point flashes, e.g., [1-3]. Understanding these characteristics is essential for evaluating whether such a factor is relevant.

In what follows a synthesis is given of the results published in [4] and [5].

II. DATA ACQUISITION

Ground-truth campaigns are time consuming in order to gather enough data to be statistically relevant. To reach this objective, ground-truth datasets are collected from different geographical regions and taken over various periods in time, i.e., Austria (AT, EUCLID) in 2012, 2015, 2017 and 2018, Brazil (BR, RINDAT) in 2008, South Africa (SA, SALDN) in 2017-2019 and U.S.A. (US, NLDN) in 2015.

In this study, only flashes where a clear visible channel to the ground is observed for all the associated strokes are included. However, it should be noted that even though such a selection of flashes is made, it does not undeniably resolve the true contact point all of the time. This is certainly true when the observations are made at ground level. As such, the

Table 1. Flash characteristics

Parameter	Location ground-truth observations				
	AT	BR	SA	US	ALL
N(flashes)	490	122	484	78	1174
N(strokes)	1539	619	1839	305	4302
Mean multiplicity	3.14	5.07	3.8	3.90	3.67
Max multiplicity	14	17	26	14	26
Percentage of single stroke flashes	29.2	23.0	38.4	25.6	32.1
N(GSP)	845	232	626	129	1832
Average *N*(GSP/flash)	1.72	1.90	1.29	1.65	1.56
Max *N*(GSP/flash)	5	4	5	4	5
Average *N*(strokes/GSP)	1.82	2.67	2.94	2.36	2.35
Average flash duration[1,2] (ms)					
All flashes	233	415	262	236	264
Multiple-stroke flashes	306	538	394	328	371
Occurrence of forked strokes[3]					
Percentage of flashes at least 1 forked stroke	9.4	10.7	7.0	10.3	8.3
Percentage of forked strokes in flashes containing at least 1 forked stroke	34.4	21.8	20.8	42.8	24.1
Percentage of forked strokes in the overall data set	3.7	2.3	2.2	2.9	2.5
Continuing Current (CC)					
Mean (ms)	67.1	36.5	38.5	/	44.5
Median (ms)	15.0	8.0	9.0	/	10.0
Max (ms)	540	705	929	/	929
Percentage of strokes followed by CC ≥ 3 ms	33.7	71.7	73.0	/	57.7
Percentage of strokes followed by CC ≥ 500 ms	0.26	0.32	0.38	/	0.33
Percentage of flashes containing CC ≥ 10 ms	37.8	61.5	61.8	/	51.0
Distance between GSPs					
Sample size	473	104	148	53	778
Mean (km)	2.53	3.15	4.31	1.72	2.89
Median (km)	2.15	2.82	2.72	1.57	2.23
99th percentile (km)	9.82	8.09	20.87	5.65	17.69
Maximum (km)	23.16	9.93	21.6	5.89	23.16

[1] Flash duration is defined as the time interval between the occurrence of the first return stroke and the end of the continuing current following the last return stroke, if present.

[2] Values for US do not include continuing current duration.

[3] For AT only based on data taken in 2018.

amount of ground strike points retrieved from the video fields as discussed later on in this study should be regarded as a lower limit. In the cases where the time interval between subsequent strokes is less than 1 ms, the case is considered to be a forked stroke rather than a stroke creating a new GSP, which in turn reduces the multiplicity of the flash. All the data sets, except US, indicate the duration of the continuing current (CC) for each stroke if present in the recorded video fields.

A. Austria

A so-called video and field recording system (VFRS) is used to document lightning strikes in the alpine region of Austria. The VFRS consists of a high-speed camera and an electric field measurement system, and both are GPS time synchronized. The camera used for the data recorded in 2015, 2017 and 2018 is the Vision Research Phantom v9.1, operated at a frame rate of 2000 fps with a record length of 1.6 s, while in 2012 a monochrome Basler camera was used at 200 fps with a record length of 5 s.

B. *Brazil*

A Photron 512 PCI high-speed digital camera, operating at 4000 fps, was used to record the flashes in southeastern Brazil in 2008. The high-speed video images are GPS time-stamped to an accuracy of better than 1 ms with a 1 s pre-trigger time and a total recording time of 2 s.

C. *South Africa*

The setup utilizes two high-speed cameras (a Phantom v7.1 and a Phantom v310) which are located northwest of Johannesburg. Frame rates used are in the range of 5000 to 15000 fps, and all captured videos are GPS time-stamped. A 1.8 s buffer time is used and events are manually triggered.

D. *USA*

The observations used in this study are taken from the Kennedy Space Center and Cape Canaveral Space Force Station (KSC–CCSFS). A compact network of 13 high-speed cameras record cloud-to-ground lightning return strokes terminating on KSC–CCSFS property. The high-speed cameras sample at either 3200 or 16 000 fps.

III. RESULTS

The combined data sets comprise of 1174 flashes and 4302 strokes. The characteristics of each individual data set regarding flashes, strokes, ground strike points, forked stroke occurrence, multiplicity, flash duration and length of the continuing current (CC) are presented in Table 1. The largest data set in terms of amount of flashes is the one of Austria with 490 flashes, closely followed by the South African data set containing 484 flashes. On the other hand, the data set of South Africa includes by far the largest amount of strokes.

The flash multiplicity depends on the ability to identify all the respective strokes that occurred during the flash. The video frame rates that were used for the observations are believed to be more than sufficient to meet this. Mean flash multiplicities range from 3.14 (AT) to 5.07 (BR) strokes per flash, with an observed overall combined flash multiplicity of 3.67.

As mentioned earlier, video observations allow classification of each stroke as a discharge creating either a new ground strike point (GSP), or following a PEC. As such, a total of 1832 GSPs are resolved within the different data sets; yielding an average of 1.56 GSPs per flash, while the mean amount of GSPs per flash for the different data sets ranges from 1.3 (SA) to 1.9 (BR). It follows that the average number of lightning strike points is 56% higher than the number of flashes. In total, about 62% of the flashes strike ground at only one point. However, this value drops to 44% when single stroke flashes are excluded. In other words, the majority (56%) of multiple stroke negative downward flashes strike ground in more than one place. The maximum number of GSPs in a flash is found to be 5, observed in Austria as well as in South Africa. Finally, adopting the values in Table 1 for the multiplicity and average number of strike points for each data set, the average number of strokes observed per GSP varies between 1.82 (AT) and 2.94 (SA). For all the data sets combined it turns out that a ground contact point is struck 2.35 times on average.

Forked strokes, i.e., strokes whereby the lightning channel towards ground branches off, are an additional source of ground contact points. The occurrence of such strokes within each data set is indicated in Table 1. Averaged over all the data sets, it is found that 8.3% of the observed flashes comprise of at least one forked stroke. Examining those latter flashes that contain one or more forked strokes, 24.1% of the strokes within those flashes are forked, whereas overall this is only the case in 2.5% of all observed strokes in this study. If one would apply a percentage associated to the individual data sets of the observed strokes being forked, this results in an increase of the average amount of ground strike points per flash, N(GSP/flash), as indicated in Table 1, by this same factor.

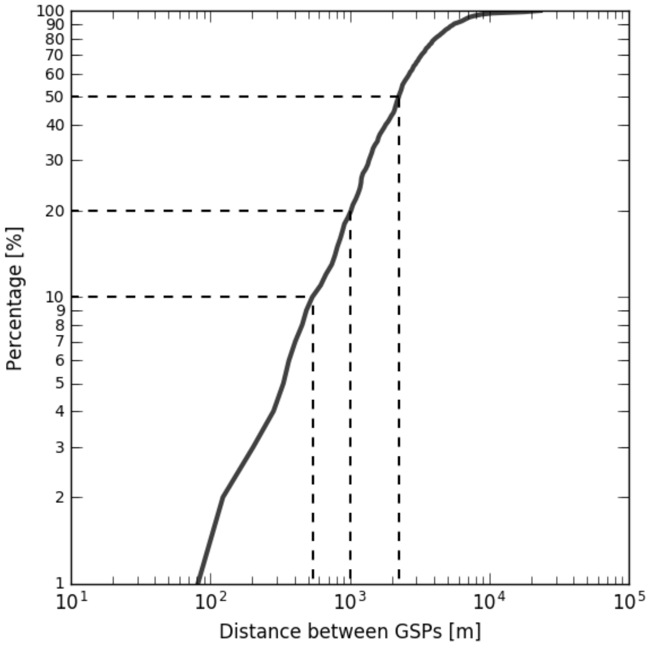

Figure 1: Cumulative statistical distribution of the distance between GSPs within flashes.

Since the duration of a flash is defined as the time span between the first and last stroke in the flash, increased by the duration of an eventual continuing current following the last stroke, it is worthwhile to further highlight the occurrence and specifics of CCs. Following the approach as in [6], a 3 ms minimum CC duration is applied in order to eliminate what could just be return-stroke pulse tails in the high-speed camera records. Considering all ranges of CCs (≥ 3 ms), the mean CC duration ranges from 38.5 ms in SA up to 67.1 ms as observed in AT, with an overall average of 44.5 ms. Median values are considerably lower with an overall median of 10 ms. The maximum value of 929 ms was measured in South Africa, which is about 200 ms longer than the maximum value found in [6]. Out of 1096 flashes recorded with CC information, 51% contained continuing currents with duration greater than 10 ms and 57.7% of all strokes were followed by any CC greater than 3 ms. Only a small portion, i.e., 0.33%, of the strokes are followed by a CC longer than 500 ms.

The mean and median duration of multiple stroke flashes is found to be 371 ms and 313 ms, respectively. Ninety-five percent of the flashes have a duration below 926 ms. The flash with the longest duration of 1379 ms is observed in SA for a six stroke flash and is in line with the maximum flash duration values found in [6] and [7].

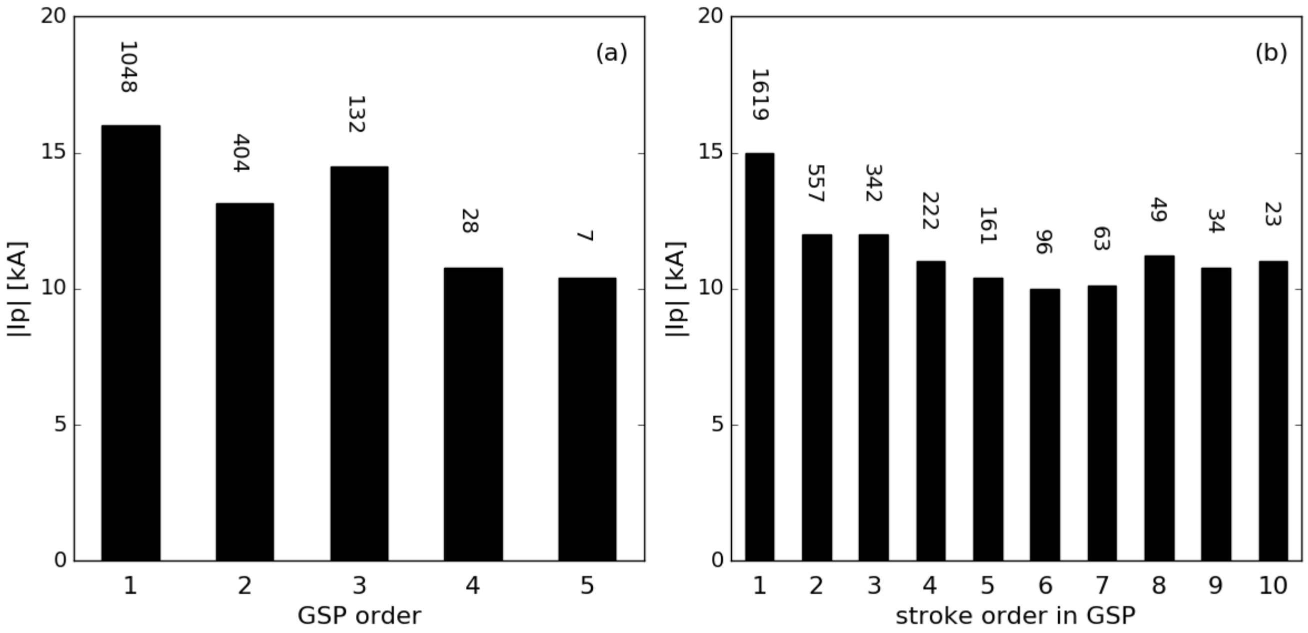

Figure 2: Median peak current distribution a) as a function of GSP order in a flash and b) as a function of stroke order in a GSP. The actual number of a) GSPs and b) strokes within each bin is listed above the bars.

Finally, the ground-truth observations are linked to the observations made by local a LLS. Those LLSs include ALDIS [8-10], RINDAT [11], SALDN [12-16] and NLDN [17, 18] for Austria, Brazil, South Africa and U.S.A, respectively. Values for the mean and median separation distance between the different GSPs within flashes are illustrated in Table 1 as well. The position of the respective GSPs is calculated as the mean location of the strokes assigned to the GSP, whereby a weight is given inversely proportional to the respective semi-major axis of the stroke. The 99th percentiles are indicated together with the maximum estimated separation distance. In case this maximum is found to be much larger than the 99th percentile, it indicates that the maximum is a one-off. Median value of the separation distance varies between 1.57 km (US) and 2.82 km (BR). In addition, Figure 1 indicates the cumulative statistical distribution of the distance between GSPs. It follows that, for instance, only 10% of the distances between GSPs fall below 540m.

Similarly, LLS observations provide an estimate of the peak current, I_p, of each stroke. In here, the peak current of a GSP is considered to be the peak current of the first stroke in the GSP. Figure 2a plots the median GSP peak current as a function of the GSP order in the flash. It follows that the median peak current of the first GSP is the highest with an absolute value of 16 kA and drops slightly for GSP occurring later in the flash. On the other hand, Figure 2b depicts the median peak current distribution as a function of stroke order within a GSP. It is found that the first stroke in the GSP has the highest absolute median peak current of 15 kA, and this value drops thereafter for subsequent strokes within the same GSP.

IV. SUMMARY

Ground strike point characteristics in negative ground lightning flashes have been investigated by means of high-speed camera observations taken in different parts around the globe. It follows that the ground strike point statistics differ in different regions. The values quoted in this study are in line with those found in the literature, and reconfirms the necessity to take ground strike points into account to estimate the risk for lightning protection purposes. While the number of flashes and strokes involved in this study is statistically relevant and, above all, larger compared to any other similar study undertaken in the past, it remains a snapshot of that particular moment in time and place. Consequently, more detailed investigation of the regional and seasonal trends that might exist is required. In order to overcome this, one could make use of the observations made by LLSs. Present-day LLSs provide, with a high degree of accuracy in terms of both efficiency and location, the different strokes that compose a flash. Ingesting those observations into a so-called ground strike point algorithm, in order to group individual strokes into ground strike points, would provide a means to study the characteristics of ground strike point densities on a larger temporal and spatial scale. The interested reader is referred to [5] to learn more about the ability of three such algorithms to determine the observed ground strike points correctly based on the data set presented in this study.

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