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A five-year analysis of ground truth data for positive flashes

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ABSTRACT

Flashes with positive polarity, representing about 10 % of all cloud-to-ground flashes, were analyzed for this publication. Data from positive cloud-to-ground flashes recorded in the Austrian Alps over five years from 2015 to 2022 were used. The measurements were performed to record ground truth flash data at 23 selected locations and to compare their characteristics with values from the literature. The used measurement system consists of a high-speed Video camera and an electric Field Recording System (VFRS). Data of both systems are correlated with Lightning Location System (LLS) data by using a GPS time stamp. The overall dataset showed 107 positive flashes, comprising 121 strokes (11 multi-stroke flashes). The percentage of positive single-stroke flashes is 90 % for VFRS data and 84 % for LLS data. The mean multiplicity for VFRS data is 1.1. The LLS estimated median return stroke peak current of all analyzed positive strokes is 47.4 kA. The mean duration for 67 continuing currents of the 121 strokes is 126.1 ms. The detection efficiency of correctly detected positive flashes and strokes is 96.3 % and 89.3 %, respectively. A better understanding of positive flashes in general and in the Alpine region in particular shall be provided by the presented results.

1. Introduction

Even though Berger et al. [1] published parameters of 26 positive flashes as early as 1975, which are still used today, scientific papers on this subject remain rare. In addition, results of Berger et al. [1] are still controversial to this day, because the attribution of the recorded waveforms is likely to be a combination of two different types of lightning discharges [2]. Positive flashes represent only about 10 % of all Cloud-to-Ground (CG) flashes [1] and therefore those datasets are more difficult to investigate and to analyze statistically. Nevertheless, they are of great interest because they tend to have larger return stroke peak currents and high charge transfers [3].

For the present investigation, ground truth data of positive flashes from the Austrian Alpine region are used. The data were recorded during warm season thunderstorms from May to August in 2015, 2017, 2018, 2021 and 2022, hereafter referred to as the investigated years. The data were recorded at 23 different measurement sites by using a Video and Field Recording System (VFRS). The VFRS consists of a high-speed video camera and an electric field measurement system. This system was built up mobile with an independent power supply.

To fulfill all needs of on-site observations of CG flashes at several measurement locations in Austria, an active exchange about weather forecast and especially thunderstorm prediction with the national meteorological and geophysical service GeoSphere Austria was crucial for the performed investigations (see [4–7]). Data recording with a portable VFRS has the advantages of recording flashes over a large area. Fig. 1 shows the measurement sites in Austria.

Visual information on the sequence, Ground Strike Points (GSP) and multiplicity can be derived from the VFRS measurement data. In addition, the electric field can be analyzed to better understand the sequence of each stroke. To obtain additional information on the estimated GSP, the calculated return stroke peak current and the polarity, all VFRS datasets are correlated with Lightning Location System (LLS) data from the Austrian Lightning Detection and Information System (ALDIS). This correlation allows the statistical evaluation of the obtained dataset related to lightning parameters. Furthermore, the quality parameters Detection Efficiency (DE) and location accuracy for the LLS data can be analyzed.

The previously published analyses of positive flashes are based on numerous studies and international publications, conducted in various regions all over the world. Fleenor et al. [8] have shown analyses, where they used data of video records (60 frames per second) from central Great Plains in correlation with LLS data. Saba et al. [9] analyzed high-speed video records correlated with LLS data from Austria, Brazil

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and the U.S. (Arizona and South Dakota). Nag and Rakov [10] used electric field records in correlation with data from U.S. National Lightning Detection Network (NLDN) for their analyses from Florida. Zhu et al. [11] used measurements of the electric field and its derivative together with high-speed video camera records and compared them with NLDN data, again for Florida. In addition, Zhu et al. [12] evaluated the performance characteristics of the Earth Networks Total Lightning Network (ELTLN) based on the ground truth natural and rocket-triggered lightning data acquired in Florida including analyses of positive CG (+CG) flashes. Qie et al. [13] used data of a VLF/LF lightning detection network for their analyses in northeastern China. Baharudin et al. [14] and Hazmi et al. [15] published analyses of electric field measurements from Sweden and Indonesia, respectively. Schulz et al. [16] have correlated VFRS data with LLS data for former analyses for Austria. Li et al. [17] showed recent analyses of broadband VHF observations of two natural +CG flashes from China. Their data were mapped by improved broadband VHF antennas. They described two +CG flashes including one leader return stroke sequence for each flash, which is assumed to be a single stroke flash by the authors of the present publication.

Regarding subsequent positive leaders of multi-stroke +CG flashes Zhu et al. [18] found that they behave similar to negative multi-stroke flashes. Their data came from 84 +CG flashes recorded during one supercell thunderstorm using a Lightning Mapping Array (LMA) in Argentina. Zhu et al. [18] reported that 64 % of the 84 multiple-stroke +CG flashes had subsequent strokes developing in the same channel to ground. Urbani et al. [19] observed two multi-stroke +CG flashes, each including two strokes following the same channel (i.e. multi-stroke single-channel flashes). The flashes were recorded in Colombia using a VHF broadband interferometer and an LMA [19]. Wu et al. [20] recorded 47 multi-stroke +CG flashes in Japan, with 18 % being of multi-stroke +CG type, using a 14-site fast antenna LMA. This led to a multiplicity of 1.24 with the absence of multi-stroke single-channel +CG flashes [20]. Yuan et al. [21] analyzed one multi-stroke +CG flash from China consisting of three strokes, terminating in three GSPs (i.e. multi-stroke multi-channel +CG flash) mapped by multi-frequency radiation sensors comprising several slow, fast and VHF antennas. The strokes were preceded by an intra-cloud discharge, sharing the negative leader channel inside the cloud [21].

Boccippio et al. [22] observed the effect of strong transient electric fields generated by +CG flashes leading to mesospheric streamer discharges such as elves and sprites. Van der Velde et al. [23] also studied 35 +CG flashes that produced sprites. Their data were obtained by a 3D LMA for which they did not specify any particular number of multi- or single-stroke flashes [23].

In the present work, the data of +CG flashes were analyzed regarding the occurrence of single and multi-stroke flashes, their multiplicity, the LLS estimated return stroke peak currents of all strokes, the Continuing Current (I_{CC}) duration evaluated using VFRS data and the LLS DE.

For analyses of the DE of the LLS two different types of DE have been considered, the flash DE and the stroke DE. Due to the limited quantity of data of strokes following the same channel for +CG flashes, the LLS location accuracy was not obtained.

Only completely correctly detected strokes have been used for VFRS data analysis (i.e. every assignment of the LLS detection confirmed as correct with VFRS data). Additionally, each individual ground truth dataset was only considered if the GSP was visible in the video. Possible obscurations of the channel bottom sections some tens of meters above the real GSP because of, e.g., trees shall be kept in mind.

During the investigated years, no positive upward flash was observed. A distinction of propagation directions of the leader channels is possible due to the high-speed video recording.

2. Instrumentation

2.1. Video and field recording system (VFRS)

As stated by Schwalt et al. [24], the VFRS is used to record ground truth data of lightning strikes in the alpine region of Austria. With such a system, on-site observations at selected locations where thunderstorms

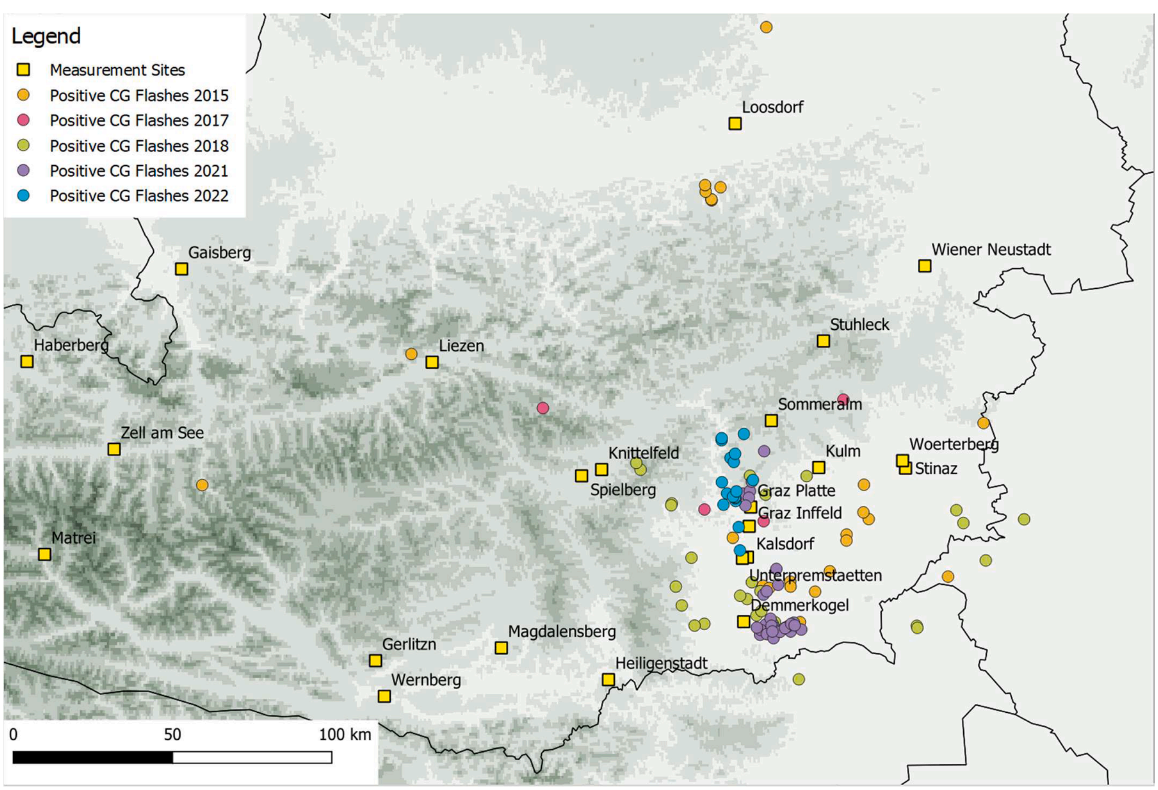

Fig. 1. Recorded data for +CG flashes for 2015, 2017, 2018, 2021 as well as 2022 (colored circles) and VFRS measurement sites (yellow rectangles).

are predicted for a certain time, are possible. For naturally occurring CG flashes, electric field and video data can be recorded in the observed area. The system consists of two main components: a high-speed video camera, to study the visual properties of each stroke, and an electric field measurement system, which records the transient electric field. The synchronization of both components to GPS time provides the proper conjunction and comparability of the data of each flash [25].

To record the electric field a flat plate antenna, an integrator and an amplifier, a fiber optic link, a digitizer and a PXI system are in use. The electric field measurements are used to examine the polarity of each stroke. For the high-speed video records, the Vision Research Phantom v9.1 camera was used. For the measurements, a frame rate of 2000 frames per second, a 14-bit image depth and a resolution of 1344 × 400 pixels was selected. A more detailed description of the VFRS can be found in, e.g., [4,5,7,24].

For the analysis of the raw data, all VFRS measurement data are first correlated with the ALDIS LLS data by using a time criterion (both systems synchronized to GPS time, temporal correlation within a few microseconds). The video data are then analyzed and documented. The electric field data was analyzed for all flashes and strokes used for the presented analyses in detail. For this reason, a misclassification of return strokes and M-components has not to be expected. The described process allows determining specific parameters for each stroke, as GSPs and their I_{CC} duration. In addition, LLS performance parameters, e.g., the DE and lightning parameters like multiplicity as well as the return stroke peak current of CG flashes can be determined [26].

2.2. Lightning location system ALDIS

ALDIS started the monitoring of the lightning activity in Austria in 1991 by operating eight LLS sensors [24]. Today ALDIS is additionally one of the two main operating centers of the European Cooperation for Lightning Detection (EUCLID), processing the data of currently 166 sensors distributed over Europe. CG strokes are grouped into flashes by using a time criterion and a spatial criterion. First, a stroke is grouped to a flash if it occurs within a second after the first stroke and within an interstroke interval of less than 500 ms. As a second criterion the stroke location has to be within a radius of 10 km around the first stroke [27,28]. It shall be noted that the LLS grouping criteria does not affect our results due to the use of video data for grouping strokes into flashes. The ongoing comparison of detected strokes with ground truth data, as recorded by VFRS or at the instrumented Gaisberg Tower, helps to determine the performance of the system regarding DE, location accuracy and return stroke peak current detection. Continuous adaptation led to an improvement of the system, so that the median location accuracy in the center of the network is in a range of 100 m. Detailed analyses of the LLS performance parameters can be found in, e.g., [6,29,30].

3. Dataset

The measurements were performed during warm season thunderstorms from May to August for the investigated years. For the investigated area, these four months represent the main thunderstorm season [31,32]. In total 107 +CG flashes containing 121 +CG strokes were recorded in Austria during 31 thunderstorms. Table 1 shows the analyzed thunderstorms and the VFRS data of flashes and strokes for each year. Fig. 1 shows the recorded data for +CG flashes for each investigated year and the VFRS measurement sites on an elevation map in the background.

Table 1
Analyzed thunderstorms, VFRS recorded +CG flashes and strokes for each year.

Year	Thunderstorms	Total flashes	Total strokes
2015	9	28	34
2017	4	4	4
2018	7	27	33
2021	5	31	33
2022	6	17	17
Total	31	107	121

Since the thunderstorm season of 2021, VFRS measurements were carried out for the first time at “Campus Inffeld” of Graz University of Technology. This recent research approach also allows a regional statement about the flash parameters in the area of Graz and its surroundings. For the present analysis of +CG flash data, the dataset from 2021 and 2022 fits geographically into the already existing data from 2015, 2017 and 2018 (see Fig. 1).

The distances from the measurement site to the GSPs of the analyzed +CG strokes are in a range from 3.3 km to 85.4 km. The average distance from the measurement locations to the GSPs is 26.7 km.

4. Methodology

4.1. Single-stroke flashes, multi-stroke flashes and multiplicity

Single-stroke flashes are CG flashes that consist of one stroke only. Due to the analysis of ground truth flash observations, every stroke can be assigned unambiguously to a flash. The detections of single-stroke flashes by the VFRS and the LLS are compared for each year and over the whole measurement period. In addition, the values of the percentage of single-stroke flashes obtained from the VFRS measurements are compared with values from former national and international studies of this topic. As a counterpart to the positive single-stroke flashes, there are positive multi-stroke flashes, which are characterized by the fact that they consist of several strokes. Positive multi-stroke CG flashes represent a small proportion of all +CG flashes [19]. The strokes of positive multi-stroke flashes can terminate in different GSPs (i.e. multi-channel) or follow the same channel (i.e. single-channel) to ground.

The multiplicity, which describes the number of strokes per flash, is one of the main characteristics of flashes and is, for example, relevant for the protection principles of transmission lines [1]. Strokes do not have to follow the same channel to ground to be counted for the flash multiplicity. LLS derived multiplicities for flashes are based on LLS sensor detections and depend on the LLS location accuracy and the quality of the LLS Inter/Intra Cloud (IC) and CG categorization. Mean multiplicity values for each year are analyzed for VFRS and LLS data. The determined VFRS multiplicity values are additionally compared with values from former national and international studies on this topic.

4.2. Estimated return stroke peak current and continuing current

Return stroke peak currents estimated by the LLS shall be analyzed for the investigated periods too. The LLS determines the return stroke peak current of each stroke from the measured electric field by using the linear relation between the measured field peaks and the return stroke peak currents (i.e. transmission line model). For more detailed information see [27]. For the present analysis LLS return stroke peak currents and their distributions for all correctly detected strokes will be carried out. All strokes are analyzed per year regarding their median, mean and 95 % return stroke peak current values.

For the present analysis and the previous analyses by Schulz et al. [16] and Saba et al. [9] the same field to current conversion factor was used for all detected strokes. Especially for an analysis of flashes with positive polarity, it has to be noted that the used current conversion factor is validated for negative subsequent strokes, with a return stroke peak current lower than |60| kA only. A validation of the field to current conversion factor used by the LLS for positive return strokes is still needed [25], therefore the shown return stroke peak currents should be seen as rough estimates.

The continuing current duration, referred to as I_{CC} duration, is a measure of how long a CG stroke dissipates charge to ground, i.e. how

Table 2
Percentage of positive single-stroke flashes determined with VFRS and LLS data from 2015 to 2022, number of single-stroke flashes in parenthesis.

Measurement period	Number of flashes	Single-stroke flashes of VFRS data	Single-stroke flashes of LLS data
		% (Number)	% (Number)
2015	28	82 (23)	71 (20)
2017	4	100 (4)	100 (4)
2018	27	81 (22)	74 (20)
2021	31	97 (30)	94 (29)
2022	17	100 (17)	100 (17)
Total	107	90 (96)	84 (90)

long the channel remains visually uninterrupted after a return stroke. Due to its optical emission an I_{CC} duration was calculated by using high-speed video recordings of CG flashes (time of ground termination of a stroke to the fading of the channel in the video, frame rate of high-speed video recordings represents the limit of accuracy). When comparing positive and negative CG strokes, it can be seen that +CG strokes show a longer I_{CC} duration [9].

4.3. Detection efficiency

For analyses of the DE of the LLS, the flash and the stroke DE will be analyzed separately. The DE is defined as percentage of detected strokes by the LLS to really occurred strokes (detected in the video record). A strict categorization of completely correctly detected strokes, where every assignment of the LLS detection (e.g. polarity, IC/CG stroke categorization) can be confirmed as correct with the VFRS data, should give additional insights into the quality of the LLS detections. The flash DE is calculated in the same way for the strict categorization of correctly detected flashes (only the first stroke of the flash must be classified correctly).

All calculations will be carried out for flashes and strokes for the five investigated years and for the merged dataset. Since continuous technical improvements of the LLS over the last decades strongly influence the resulting DE, values from recent publications shall be compared with the calculated DE values of the present analysis.

5. Results

5.1. Positive single-stroke flashes of VFRS and LLS data

In this section, data from positive single-stroke flashes, detected by the VFRS and the LLS, are compared. Table 2 shows the calculated percentage of single-stroke flashes for the investigated years for VFRS and LLS data.

The calculated percentage for LLS data shows lower values in 2015 and 2018 and similar values for 2021 compared to VFRS analyses. The years 2017 and 2022 show 100 % single-stroke flashes (see Table 2). The lower number of single-stroke flashes of the LLS in 2015 originate from some double detections of the same stroke by the LLS (detected by the LLS as multiple stroke flashes). The two missing single-stroke flashes in the LLS data in 2018 (20 for LLS data versus 22 for VFRS data; see Table 2) are caused by the misclassification by the LLS of an initial breakdown pulse as CG stroke and the grouping of an IC stroke with a CG single-stroke flash to a multi-stroke flash. The CG stroke missed by the LLS for 2021 was misclassified as IC stroke. All 17 flashes from 2022 were completely correctly detected as single stroke flashes, which leads to a percentage of 100 %.

The percentage of single-stroke flashes for VFRS data in 2015 and 2018 show the lowest values, ranging from 81 % to 82 % (see Table 2). This lower percentage is also reflected in the calculations for the whole dataset (90 %). The variation could originate from inter annual

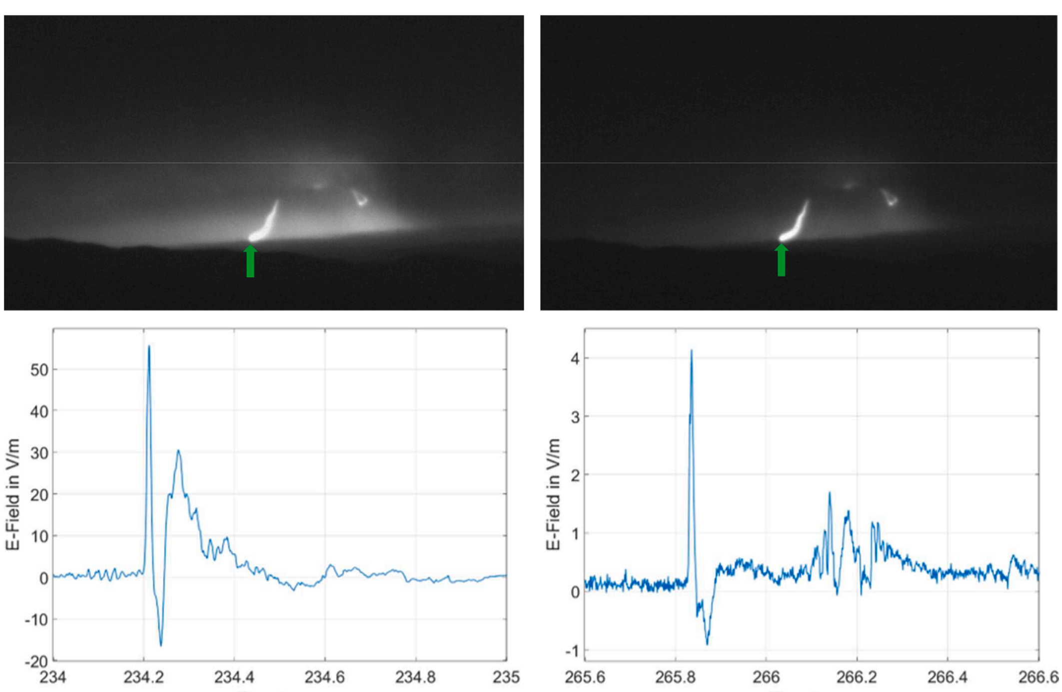

Fig. 2. Multi-stroke single-channel flash recorded in 2018; high-speed video frames (top) as well as electric field record (bottom) for first (FI1 at 234.21 ms, left) and subsequent (SU1 at 265.84 ms, right) stroke, GSP shown by green arrow.

Table 3
Mean multiplicity of positive flashes for VFRS and LLS data.

Year	Mean VFRS multiplicity	Mean LLS multiplicity
2015	1.2	1.6
2017	1.0	1.0
2018	1.2	1.2
2021	1.1	1.0
2022	1.0	1.0
Total	1.1	1.2

Table 4
Mean, median and 95 % value for return stroke peak currents of the ALDIS LLS detections for all correctly detected positive strokes for the investigated years.

Year	Number of strokes	Mean	Median	95% value
		kA	kA	kA
2015	27	59.4	43.7	163.0
2017	4	40.7	*	57.9
2018	28	54.4	41.8	120.6
2021	32	62.5	61.4	119.6
2022	17	65.5	54.7	148.0
Total	108	59.3	47.4	143.1

* Calculation of median not possible because of small amount of data.

differences of thunderstorm behavior for 2015 and 2018. A comparison on an annual basis is just reasonable for the measurements of 2015, 2018, 2021 and 2022 because of the small dataset in 2017.

5.2. Positive multi-stroke flashes of VFRS and LLS data

The dataset of the investigated years includes 11 multi-stroke +CG flashes. In three flashes the subsequent strokes occur in the same channel as the previous strokes (i.e. single-channel flash). For multi-channel flashes, different strokes develop different channels and thus strike different GSPs (see Section IV.A).

In the present analysis, there were 5 multi-stroke flashes in 2015. For 2018, the dataset contains 5 multi-stroke flashes and 1 multi-stroke flash in 2021. In 2017 and 2022, all of the analyzed data showed single-stroke flashes and were therefore not considered for this analysis. Of the data described, 2 flashes in 2015 contained multi-stroke single-channel flashes (3 strokes and 2 strokes per GSP, respectively). Fig. 2 shows the one multi-stroke single-channel flash with two strokes per GSP recorded in 2018. The distance from the measurement site to the GSP of the analyzed +CG strokes is approx. 68.7 km. All subsequent strokes have an estimated return peak current of less than 10 kA. Furthermore, there were misclassified strokes with a return stroke peak current of 5 kA or strokes which were not detected by the LLS. As described in Section IV.B, it shall be noted that the used current conversion factor is validated for negative subsequent strokes, with a return stroke peak current lower than |60| kA only [25].

5.3. Multiplicity

To calculate the mean multiplicity for positive flashes for each year, the VFRS and LLS data of the same events have been compared. The results of this analysis are shown in Table 3.

The calculated values for the true multiplicity, determined with the VFRS data, are comparable with the results from previous measurements in the Austrian Alps by Schulz et al. [16] (1.1 for the present analyses and 1.1 for analyses of VFRS data from 2008 to 2012). The analyzed LLS data for 2015 shows a multiplicity of 1.6 compared to the ground truth VFRS data of 1.2 for the same year. This difference is mainly caused by IC pulses misclassified as CG strokes (e.g. one stroke visible in the video was grouped with eight IC strokes that were misclassified as CG strokes by the LLS). Multiplicity parameters for the investigated years show comparable results. Nevertheless, the relatively small dataset from 2017 (see Table 1) should be noted. The VFRS multiplicity for measurements from 2022 is 1.0.

5.4. Estimated return stroke peak currents and continuing currents

Table 4 shows the mean, median and 95 % values of LLS return stroke peak currents for all correctly detected positive strokes for each investigated period. For this analysis, a total of 108 strokes have been included.

For this analysis, no discrimination between first and subsequent strokes was carried out because of the small dataset of multi-stroke flashes. The estimated minimum return stroke peak currents for all strokes were 8.1 kA, the estimated maximum was 331.9 kA. A distribution of +CG return stroke peak currents of the investigated years

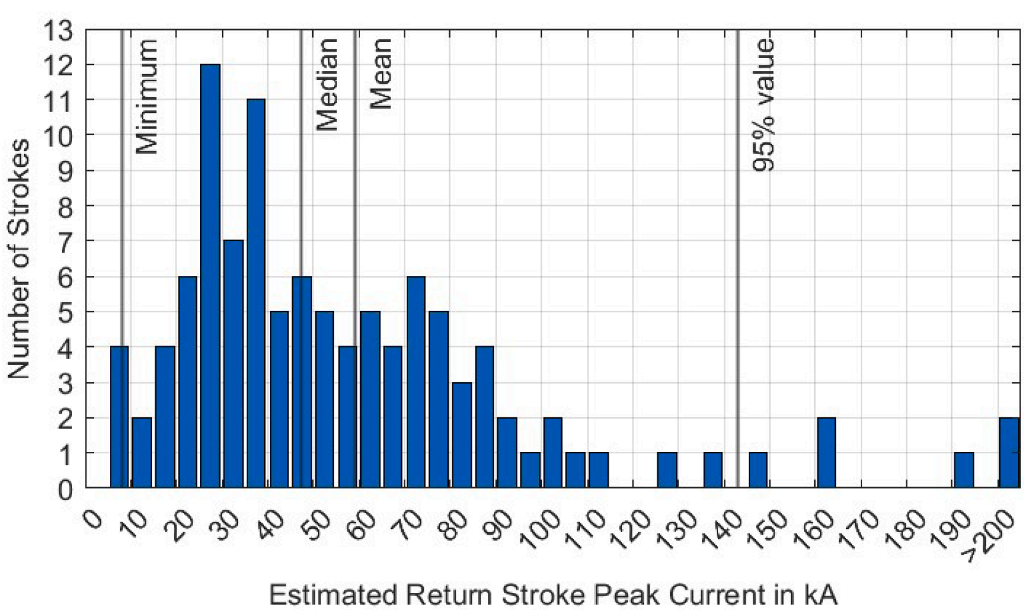

Fig. 3. LLS estimated return stroke peak current distribution for the investigated years, the total values for minimum, median, mean and the 95 % value are highlighted.

Table 5
Minimum, maximum, mean and median duration for strokes showing continuing currents, determined from data of the high-speed video recordings.

Year	Number of strokes	Min I_{CC} duration	Max I_{CC} duration	Mean I_{CC} duration	Median I_{CC} duration
		ms	ms	ms	ms
2015	22	4.0	486.0	142.6	75.2
2017	2	165.5	523.6	344.6	*
2018	8	92.5	413.0	178.1	135.5
2021	28	5.0	386.5	94.0	53.5
2022	7	11.5	252.5	80.7	48.0
Total	67	4.0	523.6	126.1	88.7

* Calculation of median duration not possible because of small amount of data.

is shown in Fig. 3.

Schulz et al. [16] showed a median return stroke peak current of 34 kA for a merged dataset of 2008 to 2010 and 2012. In the present case, the median return stroke peak current for the merged dataset is about 39 % higher than the value reported by Schulz et al. [16]. The median return stroke peak current is about 20 % higher than reported for similar observations for a merged dataset from Austria, Brazil and the U.S. by Saba et al. [9] too (39.4 kA). Schulz et al. [16] showed a minimum return stroke peak current of 7 kA and a maximum 208 kA. Saba et al. [9] showed a minimum and maximum return stroke peak current of 4.8 kA and 142 kA, respectively.

The continuing current duration was analyzed for each year. Table 5 shows the minimum, maximum, mean and median value for continuing current durations determined with data from the high-speed video recordings. In total, a continuous current was detected for 67 of 108 (62 %) correctly detected strokes. For 41 strokes, which were misclassified by the LLS, I_{CC} were not analyzed.

The relationship between the continuing current duration and corresponding estimated return stroke peak currents is shown in Fig. 4.

5.5. Detection efficiency

For analyzes of the DE of the LLS two different types of DE have been considered, the flash DE and the stroke DE. Table 6 shows the number of +CG flashes and strokes recorded by the VFRS and the LLS as well as the results for the flash and stroke DE for the five years.

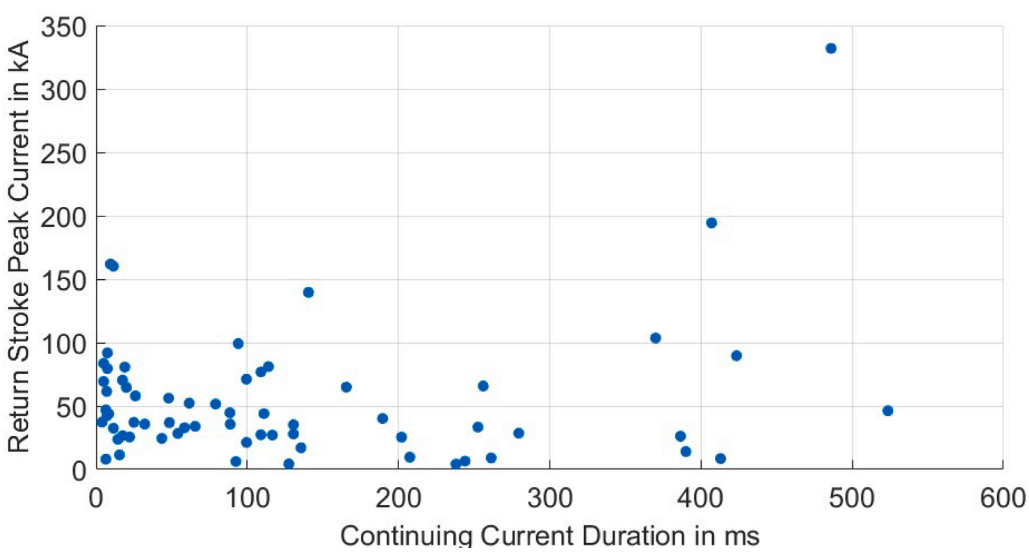

Fig. 4. LLS estimated return stroke peak current in kA versus continuing current duration in ms.

Table 6
DE of the ALDIS LLS for positive flashes for correctly detected flashes and strokes for the investigated years.

Year	Type	VFRS	ALDIS LLS correctly detected	DE - correctly detected flashes/ strokes
				%
2015	Flashes	28	26	92.9
	Strokes	34	27	79.4
2017	Flashes	4	4	100
	Strokes	4	4	100
2018	Flashes	27	26	96.3
	Strokes	33	28	84.8
2021	Flashes	31	30	96.8
	Strokes	33	32	97.0
2022	Flashes	17	17	100
	Strokes	17	17	100
Total	Flashes	107	103	96.3
	Strokes	121	108	89.3

Table 7
Single stroke flash percentage, flash multiplicity, median return stroke peak current and geometric or arithmetic mean as well as range for interstroke intervals for the present and previous studies by various authors.

Author, Location	Year	Data	Flash sample size	Single stroke flashes	Multi-plicity	Median return stroke peak current	Interstroke interval	
							GM (AM*)	Range
				%		kA	ms	ms
Saba et al. [9], Austria, Brazil, USA	2003 - 2007	Video	103	81	1.2	39.4	94	14 - 406
Fleenor et al. [8], USA	2005	Video[a]	204	96	1.0	44.8	27	–
Nag and Rakov [10], USA	2007 - 2008	Video	52	81	1.2	56	54	8.5 - 201
Schulz et al. [16], Austria	2008 - 2012	Video[b]	109	91	1.1	34	202*	–
Qi et al. [13], China	2009 - 2010	E-Field	185	94.6	1.1	–	64.2	6.5 - 290.7
Baharudin et al. [14], Sweden	2010 - 2011	E-Field	107	63	1.5	–	70	2.9 - 518
Hazmi et al. [15], Indonesia	2014	E-Field	77	83	1.2	–	113.3	16 - 458
Wu et al. [20], Japan	2019 - 2020	LMA	263	82.1	1.2	–	61.4	1.0 - 469.2
Present study	2015 - 2022	Video	96	90	1.1	47.4	49	3 - 322

[a] Video records with 60 fps^{1}.
[b] Different video system for data from Austria (200 fps).

The flash DE for correctly detected flashes shows an improvement over the investigated period with data from 2015, 2018 and 2021 considered (92.9 % to 96.8 %). Again, a comparison on an annual basis is not reasonable for 2017 because of the small dataset. The stroke DE shows comparable values for 2015 and 2018 (79.4 % and 84.8 %, respectively). For the year 2021, there was a significant increase for the stroke DE to 97.0 %. It shall be noted that a stroke DE higher than the flash DE is not reasonable and is caused by the relatively small sample size for the analysis of data from 2021. The latest measurements of 2022 show a flash and stroke DE of 100 %, comprising 17 single-stroke flashes with a minimum return stroke peak current of 19.9 kA. Also, for 2022, a specific statement on DE requires more data (Table 6).

6. Discussion

The dataset of positive flashes was analyzed regarding single-stroke flash percentage, multiplicity, return stroke peak currents of all strokes, continuing current durations and the DE of the LLS data. The overall dataset for the five investigated years showed 107 flashes comprising 121 strokes (see Table 1). Due to the limited quantity of data from strokes following the same channel for +CG strokes, the location accuracy for the LLS estimated ground strike points could not be obtained for positive CG strokes. The location accuracy has been investigated for negative flashes for the same region and the years of 2015, 2017 and 2018. This analysis showed a location accuracy of around 100 m [7].

Table 7 shows a comparison of already published results for different countries with the present VFRS analyses for positive flashes. Data from VFRS measurements in Austria by Schulz et al. [16] were additionally considered. As described in Section 1, the authors used different recording methods for their analyses. The used measurement equipment is labeled as “E-Field" for electric field measurements only. If video and possibly also electrical field measurements were performed, they were assigned as recorded by “Video”, Wu et al. [20] used data of an LMA.

The percentages of single-stroke flashes are 90 % for the VFRS data and 84 % for the LLS data, for the investigated years (2015, 2017, 2018, 2021 and 2022). The values for the percentage of single stroke flashes over the investigated years are comparable to those from previous analyses for VFRS data from Austria (91 % for data of 2008 to 2010 and 2012 [16]).

The analysis of previously published results of international studies on positive single-stroke flashes shows that Baharudin et al. [14] published the lowest single stroke flash percentage in the literature for measurements from Sweden conducted in 2010 and 2011 (63 %). Measurement analyses for Florida from Nag and Rakov [10] and for the merged dataset from Austria, Brazil and the U.S. (Arizona and South Dakota) published by Saba et al. [9] show a percentage of 81 %. Recent measurements by Hazmi et al. [15] for Indonesia showed a percentage of 83 % for positive single-stroke flashes. Fleenor et al. [8] and Qie et al. [13] have reported the highest percentages of positive single-stroke flashes (96 % and 95 %, respectively), which are comparable to the present results for 2021.

The mean multiplicity of 1.1 is identical to a previous analysis by Schulz et al. [16] for Austria. Saba et al. [9] reported a multiplicity of 1.2 for data from Brazil but also for a merged dataset from Austria, Brazil and the U.S. They all used high-speed video observations correlated with LLS data for their analyses [9,16]. Overall, all values for multiplicity from previous publications are between 1.0 and 1.2 except those of Baharudin et al. [14] (1.5).

The analyzed return stroke peak currents estimated by the LLS show variations over the five investigated years (see Table 4). These annual variations could be caused, at least partly, by different observed thunderstorms. The analysis for return stroke peak currents for all strokes in Austria (median of 47.4 kA, see Table 4) show higher values than reported by Berger et al. [1] (median of 35 kA) for their direct current measurements. The presented median return stroke peak current of the merged dataset is also higher compared to previous analysis of

VFRS data by Schulz et al. [16] for Austria and by Saba et al. [9] for a merged dataset from Austria, Brazil and the U.S. They showed median return stroke peak currents in the range of 34 kA (Schulz et al. [16]) and 39.4 kA (Saba et al. [9]) for all strokes, see Table 7). Both Fleenor et al. [8] and Nag and Rakov [10] published values for the USA, one for the central Great Plains and one for Florida. Fleenor et al. [8] reported a value of 44.8 kA which is in the range of the presented data. Nag and Rakov's [10] median value is the highest with 56 kA (see Table 7).

As Rakov and Uman [3] found for CG flashes, the present dataset from Austria also reveals higher values for the median return stroke peak current of positive strokes (47.4 kA) compared to analyses of the median of negative return stroke peak currents (-10.4 kA) [7]. Rakov et al. [33] stated that it is still recommended to use the peak current distribution for engineering applications shown by Berger et al. [1] because of the absence of other direct current measurements for return strokes with positive polarity. The uncertainty that not all analyzed cases of Berger et al. [1] are of return strokes type should be kept in mind [33].

The geometric mean (GM) values for the interstroke intervals listed in Table 7 range from 27 ms to 113.3 ms for data from Fleenor et al. [8] and Hazim et al. [15], respectively. Schulz et al. [16] published only an arithmetic mean (AM), which is why this value was omitted for the consideration of the variance of the GM. With a GM of 49 ms, the interstroke intervals of the presented values are in the lower range in an international comparison.

The analyzed dataset contains 11 multi-stroke +CG flashes of which 8 flashes are of multi-stroke multi-channel type, the other 3 flashes were categorized as multi-stroke single-channel type. Interstroke intervals for the 8 analyzed multi-channel multi-stroke flashes (10 strokes) exhibit a minimum of 3 ms, a maximum of 322 ms and revealing a geometric mean value of 65 ms. These values are comparable with values for negative flashes [25]. The intervals between the strokes for the three single-channel multi-stroke flashes, including four strokes, show values at the lower end of the range (geometric mean 24 ms, minimum 17 ms, maximum 33 ms). The small amount of data for single-channel multi-stroke flashes (3) should be considered. Regarding the LLS estimated return stroke peak currents for these cases multi-stroke multi-channel flashes show values between 4.2 kA and 202.2 kA. In comparison, multi-stroke single-channel flashes show return stroke peak currents between 4.2 kA and 86.1 kA (based on 7 strokes). Urbani et al. [19] showed the first observation of multi-stroke single-channel flashes with a VHF broadband interferometer and an LMA and stated that it is rarely observed. Overall, the proportion of these flashes and the conditions of origin are still unclear. Zhu et al. [18] also reported and examined this type of +CG flashes using an LMA and found that the initiation scenario for subsequent positive leaders is comparable with the one for their negative counterparts. In both cases, there are recoil leaders that develop in a similar manner.

The analyzed continuing currents reveal a lower median duration of 126.1 ms than the ones published by Saba et al. [9] (149 ms). Continuing currents occur more frequently with +CG flashes than with negative CG flashes, according to Saba et al. [9]. In the present data from the investigated years, a continuous current was detected for 67 of 108 (62 %) correctly detected strokes. This number differs from the analyses of Saba et al. [9], in which 85 of 87 (98 %) strokes produced a continuing current. A comparison of the estimated return stroke peak currents with the continuing current durations shows a wide spread of values (see Fig. 4). This agrees with the results for positive flashes shown for such a comparison by Saba et al. [9].

Data from 2015 and 2018 showed a DE of 79.4 % and 84.8 %, respectively. The DE for +CG strokes for data from 2021 showed an increase to 97.0 %. This data includes one misclassified stroke with an estimated return stroke peak current of 11.5 kA (see Table 6). The DE for positive flashes and strokes in 2017 is 100 %, but in this year a limited quantity of 4 flashes including 4 strokes have been analyzed (minimum peak current of 8.1 kA). The latest measurements of 2022 also show a flash and stroke DE of 100 %, whereby the data consists of 17 single-stroke flashes and a minimum return stroke peak current of 19.9 kA.

Schulz et al. [16] obtained a DE of 97 % for positive flashes and 92 % for correctly detected strokes. They used VFRS data in correlation with LLS data recorded from 2008 to 2010 and in 2012. The flash DE is in the range of the presented analysis of the merged dataset (96.3 %; see Table 6). The stroke DE of correctly detected strokes of Schulz et al. [16] is about 3 % higher than the one of the present analysis (92 % compared to 89.3 %). The improved IC/CG classification algorithms implemented in 2016 may be the cause of this difference. In 2022, all recorded flashes were single-strokes. All strokes have been completely correctly detected by the LLS, which led to a flash and stroke DE of 100 %. Kohlmann et al. [34] stated that the IC/CG classification performs worse for CG strokes with a return stroke peak current below 15 kA. As expected, the 17 single-stroke flashes in 2022, which showed a minimum LLS return stroke peak current of 19.9 kA, were detected correctly.

Fleenor et al. [8] analyzed data of the NLDN in correlation with high-speed videos from 2009 recorded in the U.S. (Central Great Plains). They showed a DE for detected flashes and strokes of 89 % and 88 %, respectively (no strict categorization between detected and correctly detected flashes/strokes implemented). The lower value for the flash DE could be caused by the higher average distance between neighboring sensors in the U.S. compared to Austria [16] and the newer Vaisala LS7002 sensors used in Austria during the period of investigation. Zhu et al. [11] performed an analysis of electric field and high-speed video camera data correlated with NLDN data for Florida from 2014. The analysis revealed a DE of 100 % for the 26 positive strokes analyzed. In 2013, the previous NLDN sensors were replaced with Vaisala LS7002 sensors [11]. In 2017, Zhu et al. [12] evaluated ENTLN performance for natural CG lightning data but also for rocket-triggered lightning data. Regarding +CG the ENTLN showed a stroke DE of 98 %, 100 % and 98 % for first, subsequent and the overall dataset of +CG strokes, respectively.

CRediT authorship contribution statement

Lukas Schwalt: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sebastian Schatz:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Stephan Pack:** Supervision. **Wolfgang Schulz:** Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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