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Analyses of negative cloud-to-ground flashes and their ground strike points in Austria

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ABSTRACT

This paper presents an analysis of flashes and their Ground Strike Points (GSPs) by using Video and Field Recording System (VFRS) data and Lightning Location System (LLS) data from Austria. Analyses of the multiplicity of flashes and strokes per GSP have been performed. A comparison between strokes per flashes and strokes per GSPs has been conducted. By using the calculated strike point locations from the LLS, distances between different GSPs have been calculated. The used VFRS and LLS data set includes records from 2015, 2017, 2018 and 2021 recorded in the Austrian Alpine region. Atmospheric discharges have been recorded at 22 different measurement locations in Austria. For the present work a data set of 519 flashes including 1683 strokes were analyzed. Results for the mean multiplicity (3.3) revealed a lower value compared to multiplicities from other countries, but similar to the ones determined by former studies from Austria. Calculations of distances between the first GSP of a flash to the other GSPs of the same flash showed a median of 1.4 km, an arithmetic mean of 1.6 km and a geometric mean of 1.2 km. The maximum determined distance between two GSPs was 6.9 km for the analyzed data set.

1. Introduction

Anderson and Eriksson [1] already discussed the influence of multiple strokes per flash, which is described by the parameter multiplicity, on lightning protection measures in 1980. The authors discussed the influence of repetitive discharges, which follow the same channel to ground, on the lightning protection of, e.g., overhead lines. In terms of Lightning Location System (LLS) data, strokes are grouped into flashes by the system if they meet certain temporal and spatial criteria. To be spatially assigned to a flash, the stroke must have been located within a radius 10 km of the first stroke. Temporally, the stroke must have occurred within a time interval of 500 ms after the previous stroke and not later than one second after the first stroke [2]. The LLS mean flash multiplicity can then be calculated and, if the quality of the network is sufficient, already be considered for lightning protection measures.

In Austria, the quality of LLS data has been analyzed by using data of upward direct lightning strikes recorded at the instrumented Gaisberg tower in the region of Salzburg (see e.g. [3]). To study Cloud-to-Ground (CG) downward flashes in continental and mountainous regions of Austria during the main storm season from May to August, an electrical field measurement system was developed [4]. Subsequently, a high-speed camera was included [5] to complete the now used Video and Field Recording System (VFRS). The system was built for mobile use and has an independent power supply. A lively exchange about weather forecasting and especially thunderstorm forecasting with the Austrian meteorological service GeoSphere Austria is a cornerstone for the performed investigations. Only with perfect weather forecasts, a planned observation with measurement sites distributed across the country can be realized (see [4–8]). In Fig. 1 the observed area in Austria is shown.

The VFRS used for the recording of the data shown in this publication has been in use since 2015, and during that time, ground truth data have been recorded at 22 different measurement locations. For this investigation, ground truth data from measurement campaigns of 2015, 2017, 2018 and 2021 were used. The gathered data of the used high-speed video camera give proof of the occurrence of flashes and strokes and provide additional information about Ground Strike Points (GSPs). In this way, the multiplicity for VFRS data can be calculated and then compared to LLS data. In addition, analyses of strokes per GSP and distances between GSPs for flashes with multiple GSPs can be carried out.

Parameters such as the estimated strike point location or the return stroke peak current cannot be determined directly from VFRS

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measurements. To complement the ground truth data for this study, Austrian Lightning Detection and Information System (ALDIS) LLS data were correlated to obtain, e.g., information on the estimated strike point location and the return stroke peak current.

The results published so far on flash multiplicity are based on numerous studies published in international publications. Kitagawa et al. [9] correlated electric field measurements and moving film camera recordings. The measurements of Rakov and Uman [10] are based on electric field recordings and a TV system with multiple stations, and Cooray and Pérez [11] made broadband electric field recordings in Sweden. Cooray and Jayaratne [12] analyzed electric field measurements from Sri Lanka and Qie et al. [13] analyzed data recorded in China's Gansu province using a slow broadband antenna system. Saba et al. [14] analyzed high-speed video camera recordings correlated with LLS data from Brazil. Schulz and Saba [5] and Vergeiner et al. [15] performed earlier analyses for Austria. For both publications, VFRS data correlated with LLS data was used for their analyses. Poelman et al. [16] used VFRS data from Belgium correlated with LLS data. Ballarotti et al. [17] and Antunes et al. [18] used a similar data set from Brazil for their analyses and Saraiva et al. [19] used data from high-speed video observations from Arizona. Zhu et al. [20] used data from electric field measurements from Florida for their analyses, as Baharudin et al. [21] did for data from Malaysia. Rojas et al. [22] analyzed data of electric field measurements recorded in the Bogota Savanna and correlated the data with LLS data from Colombia.

In terms of GSPs per flash (i.e. number of ground strike points per flash), Kitagawa et al. [9] and Rakov and Uman [10] showed an analysis based on correlated electric field measurements and moving-film camera recordings and measurements based on electric field recordings and a multi-station TV system, respectively. Furthermore, Berger et al. [23] and Hermant [24] analyzed data from video observations in France and Valine and Krider [25] for observations in Arizona. Fleenor et al. [26] and Saraiva et al. [19] analyzed data from high-speed video recordings in correlation with LLS data from the central Great Plains and Arizona and Brazil, respectively.

Previously performed analyses of ground truth data with respect to the spatial distances between strikes to a new GSP in a given flash have been shown by Thottappillil et al. [27] and Stall et al. [28]. Thottappillil et al. [27] used the same data from electrical field recordings and a TV system with multiple stations as Rakov and Uman [10] for their analyses regarding flash multiplicity. For the analyses of data from Arizona Stall et al. [28] used video recordings from correlated with LLS data for their analysis.

As early as 1935, Schonland et al. [29] described strokes propagating almost simultaneously towards the ground but terminating in different GSPs. For the performed analysis a flash with two different stepped leader channels propagating downward within an interstroke interval of 73 μs and initiating a return stroke from different GSPs was described. The authors referred to such strokes as forked strokes, whether or not they share a section of the upper channel below the cloud base. Their quasi-simultaneous occurrence was considered as a classification factor. Such forked strokes were detected in the present data set too but were excluded for the present analysis. It shall be noted that the frame rate of the high-speed camera limits the temporal resolution.

Poelman et al. [30] validated a clustering algorithm of strokes to GSP for LLS data based on the k-means method [31–33]. The validation of the LLS determined GSPs in different countries was performed with ground truth data from Austria (2012, 2015), Brazil (2008), France (2013 to 2016), Spain (2017, 2018), and the United States (2015). In 93% of the cases, the GSP algorithm was able to correctly identify new GSPs. The algorithm correctly detected 82% of strokes that followed preexisting channels and hit the same GSP. However, Poelman et al. [30] reported that the performance of the algorithm strongly depends on the location accuracy of the LLS and a specific parameter called distance criterion (minimum distance between observable GSPs). In a newer publication, Poelman et al. [34] showed analyses of the global strike point characteristics for negative downward flashes from different regions over the world, including data from Austria, Brazil, South Africa and the United States of America. Furthermore, Poelman et al. [35] applied three different algorithms to the data used in [34] and

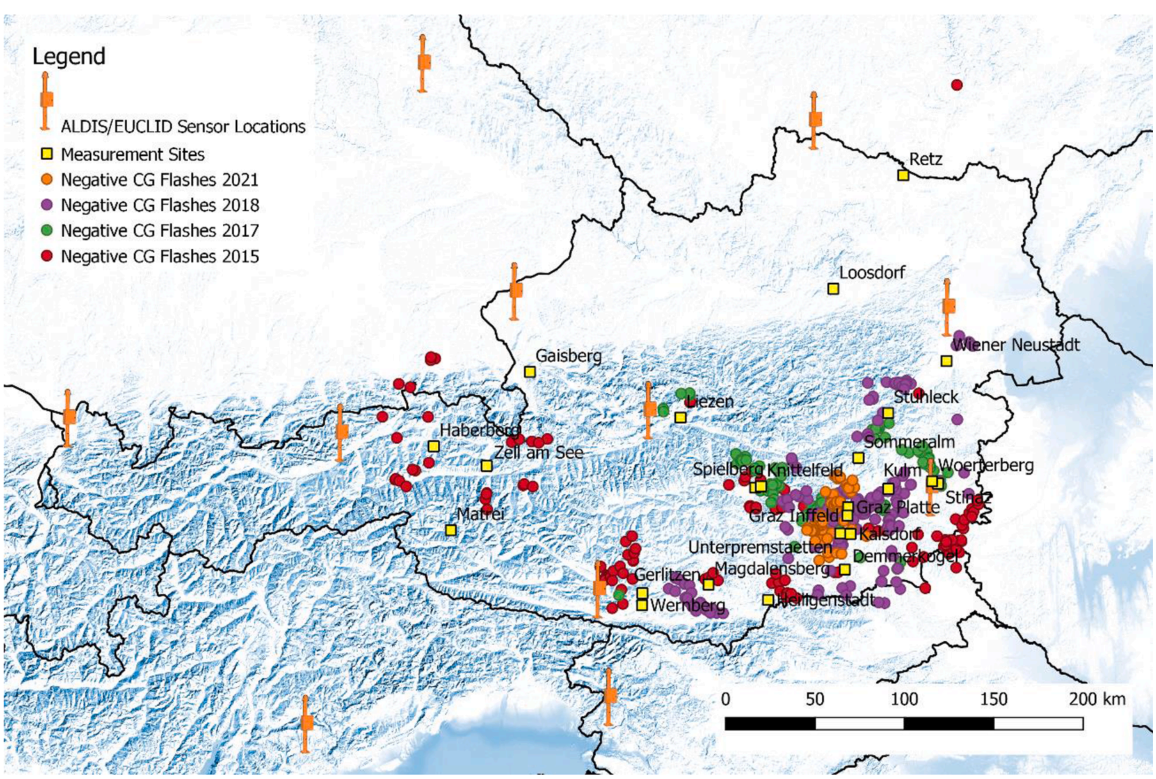

Fig. 1. Recorded data for negative CG flashes for 2015, 2017, 2018 and 2021, VFRS measurement sites and sensor locations of ALDIS/EUCLID.

additionally included data from France and Spain to group strokes into individual GSPs. All three algorithms showed success rates of up to 90% of determining the correct number of GSPs in a flash. It shall be noted that for the daily operation of the Austrian LLS, no clustering algorithm was in use during the years under investigation.

Schwalt et al. [36] analyzed part of the present data set with respect to return stroke peak current analysis. They compared return stroke peak currents of the first return strokes with return stroke peak currents of the first strokes in a GSP for 39 measurement days. In total 381 negative CG flashes and 1230 negative CG strokes were analyzed. The median return stroke peak current for both first strokes of flashes and first strokes per GSP showed similar values of -14 kA and -13 kA, respectively. In addition, Schwalt et al. [36] analyzed first return stroke peak currents versus the multiplicity of a flash and versus the multiplicity per GSP. As stated in the literature, results revealed an increase for both cases leading to higher return stroke peak currents for the first strokes with increasing multiplicity [36].

The current work presents an analysis of the flash multiplicity and compares them with values from the literature. Furthermore, GSPs per flash and the distances between GSPs for flashes with multiple GSPs were analyzed for the Austrian Alpine region. This publication represents an extension of the preliminary analyses presented in [37]. The recorded VFRS data give information about the CG lightning activity during warm season thunderstorms of the four investigated years of 2015, 2017, 2018 and 2021. The included data from 2021 was recorded at Campus Inffeld of Graz University of Technology and shows regional data of the area with the highest lightning activity in Austria. The results are therefore compared to former measurement campaigns, were measurements have been conducted at 22 measurement locations over Austria. For this work, negative cloud-to-ground (CG) lightning data was analyzed only. The used data give proof on the real occurrence of flashes and strokes and provide additional information about GSPs, multiplicity and leader propagation properties. The analysis of the behavior and parameters of CG flashes helps to get a deeper view in these processes and provides results regarding GSPs and the distances between GSPs. By comparing the time correlated data set from the VFRS and the Austrian LLS it has been shown that the performance of the Austrian LLS is high in terms of location accuracy and detection efficiency [38]. A precise knowledge of the CG processes with respect to strikes to different GSPs occurring within each flash helps to statistically classify, e.g., related distances between GSPs.

2. Instrumentation

2.1. Video and field recording system (VFRS)

The Video and Field Recording System (VFRS) is used to record data on lightning strikes in the alpine region of Austria. This system allows on-site observations at selected locations where thunderstorms are predicted to occur over a certain time (see Fig. 1) [15]. The system consists of two main components: a high-speed camera to study the visual characteristics of each flash and an electric field measurement system to record the transient electric field. Synchronization of both components with GPS time ensures proper linkage and comparability of each VFRS data (video and field measurements) with LLS data.

The electric field measurements are used to investigate the polarity and field characteristics of each stroke. A flat plate antenna, an integrator, an amplifier, a fiber optic link, a digitizer, and a PXI system including GPS time synchronization are used to acquire the measurements [4]. The overall system was first developed, calibrated and tested by ALDIS. During this project the system had a bandwidth of 300 Hz to 1.0 MHz. The bandwidth of the integrator and amplifier limits the overall bandwidth of the system. The analog/digital sampling rate of the used digitizer is 10 MS/s for all four channels. The vertical resolution of the digitizer is 16 bits. For the electric field measurement, just one of the channels is used. In the case of a trigger impulse, five seconds (the actual second, two seconds before and two after the trigger impulse) are recorded, in order to not miss any stroke. The recording software was developed by ALDIS and is LabVIEW based. This software also synchronizes the measurements to GPS time [39].

The camera used is a Vision Research Phantom V9.1. The camera model has an available internal memory of 6 GB and a maximum resolution of 1632 × 1200 pixels. Because the frame rate of the recorded video influences the resolution, a balance between a sufficient frame rate and the image format has to be found. In the measurements, as described previously in [5] and [14], a frame rate of 2000 frames per second, a frame depth of 14 bits, and a resolution of 1344 × 400 pixels was most appropriate. These settings allow two videos of 1.6 s to be captured. Once a video is recorded, the camera software immediately starts transferring the video to the computer used to control the camera via Ethernet connection [39].

During the thunderstorm season of 2021 lightning observations and measurements were conducted at the Campus Inffeld of the Graz University of Technology for the first time. The conditions to perform lightning measurements using a VFRS were best served on the roof of a building on the campus. The field of view from the measurement site includes approximately 270°. The measurement equipment is located in a newly set up measurement cabin, which has an additional window to operate the high-speed video camera from a rain-protected spot and was mounted on a rotatable platform to observe the entire field of view. In addition, the measurement cabin also provides adequate personal protection against other hazards that go along with thunderstorms, i.e. hail, strong wind, and gusts.

All VFRS measurement data were first correlated with ALDIS LLS data using a time criterion (both systems were synchronized with GPS time). This resulted in accurate temporal correlation on a microsecond basis. The video and electrical field data are then analyzed and documented. This process allows the determination of LLS performance parameters, e.g., location accuracy and detection efficiency of the LLS (see [6,38,40,41]). Furthermore, the multiplicity and return stroke peak current distribution of the CG flashes can also be determined from the LLS data [3]. In addition, parameters such as the distances between the GSPs of the flashes can be calculated using the correlated data set.

2.2. Lightning location system ALDIS

ALDIS, the Austrian Lightning Detection and Information System, began monitoring lightning activity in Austria in 1991. ALDIS operates eight sensors and is also one of the two main operating centers of the European Cooperation for Lightning Detection (EUCLID), which processes currently data from 166 sensors distributed throughout Europe. Ongoing comparison of detected flashes with ground truth data recorded by the VFRS or the instrumented Gaisberg tower is used to determine the system's performance in terms of location accuracy, detection efficiency and return stroke peak current distribution. Through continuous adjustment and improvement of the system, the median location accuracy of the network is about 100 m determined from analyses of ground truth VFRS data from 2015, 2017 and 2018 for Austria including 463 negative CG flashes. The detection efficiency for this data set showed a flash detection efficiency between 96% and 99% and a stroke detection efficiency between 76% and 86% [38]. In addition, publications have shown analyses of the key LLS performance parameters for former years (see, e.g., [6,40,41]).

3. Data

In 2015, 2017, 2018, and 2021, the measurements were performed in Austria during warm season thunderstorms from May to August. These four months represent the main thunderstorm season for the region studied (see [42] and [43]). Schulz et al. [42] found that 96% of all LLS detected flashes occurred during these four months and that this time of year can be considered the convective season. During a total of

58 days, 519 negative CG flashes including 1683 negative CG strokes were recorded. Thereby, a total of 796 GSPs were detected in the video recordings of the analyzed flashes.

In the present analysis, a new GSP is defined as a ground contact point that is spatially separated from the previously formed channel within a flash. Similar to the analysis of Rakov and Uman [10], no attempt was made to visually distinguish between entirely new channels (no previous section of a stroke was used) and a new termination on the ground (strikes that share part of the upper channel section but have different lower sections).

Fig. 1 shows the analyzed data of negative CG flashes for the entire observation period (2015, 2017, 2018, and 2021). In addition, the measurement locations and sensor positions of the ALDIS/EUCLID network are shown on an elevation map in the background. With the help of the measurements distributed over the southern and eastern Alpine region, the quality of the LLS data can be analyzed for different points over Austria and thus also for the region in the center of the EUCLID network.

The new research approach of 2021, in which measurements were performed at Campus Inffeld, allows a regional statement about the lightning parameters in the surrounding area of Graz. For the present analysis of negative CG lightning data, the data from 2021 fits geographically into the already existing data from 2015, 2017 and 2018 (see Fig. 1).

Poelman et al. [35] showed a graphical distribution of annual and monthly lightning flash densities for Europe detected by the EUCLID system for data from 2006 to 2014. They found the highest flash densities at the cross-border section between Austria, Slovenia and Italy (7 flashes/km^2/year; location southeast). Results shown in Fig. 1 data go along with the findings by Poelman et al. [35].

Table 1 shows the analyzed thunderstorms, the number of recorded flashes and strokes for each measurement season and in total.

Each individual ground truth record was considered for this analysis only if the GSP was visible in the video. If this was not the case, the data were ignored. Possible contamination of the channel bottom sections a few tens of meters above the real GSP, e.g. by trees, needs to be kept in mind.

4. Methodology

4.1. Multiplicity

The multiplicity describes the number of strokes per flash (flash multiplicity) or per GSP (GSP multiplicity). To be counted for flash multiplicity, the strikes do not have to follow the same channel to the ground. Multiplicities derived from LLS data for flashes are based on LLS sensor detections, which depend, e.g., on the LLS intracloud and cloud-to-ground (IC/CG) classification accuracy, and on LLS detection efficiency. Actual values for the detection efficiency have been given in Section 2.2. In the case of GSP multiplicity, this classical flash grouping cannot be used. In such a case, the first stroke and subsequent strokes terminating in the same GSP have to be counted using the high-speed video recordings (see Section 4.2).

The mean flash multiplicity of the VFRS and LLS data is compared for each year and in total. In addition, the calculated VFRS multiplicity values are compared with values from previous national and international studies on this topic. The distribution of strokes per flash (flash multiplicity) and strokes per GSP (GSP multiplicity) is analyzed as well.

Table 1
Analyzed thunderstorms, negative CG flashes and strokes for 2015, 2017, 2018, 2021 and in total.

Season	Thunderstorms	Flashes	Strokes
2015	24	153	514
2017	13	94	317
2018	14	217	693
2021	7	55	159
Total	58	519	1683

4.2. Groud strike points per flash

VFRS ground truth video data were used to categorize the strokes that terminated in the same GSP. Such ground truth data provide an unambiguous assignment of strokes to the same GSP. These assignments of strokes to a particular GSP can then be used to analyze various parameters, such as, e.g., GSPs per flash. When analyzing individual GSPs the strokes per GSP (GSP multiplicity) can also be determined.

4.3. Distance between ground strike points

To calculate the distances between different ground strike points, the LLS estimated locations of the first strokes to new GSPs (FIx) were used. The estimated locations for subsequent strokes striking the same GSP as the FIx where not used for the present calculations. If the FIx was not detected by the LLS, the data for this flash was excluded.

Figs. 2 and 3 represent an example of a flash recorded in the surrounding area of Graz at 14:10:10 UTC on August 13, 2021, containing seven strokes with four individual GSPs (first stroke per GSP is shown). To calculate the distance between GSPs, a spherical distance between the first stroke (FI1) and all other first strokes to individual GSPs was calculated for a given flash with spherical trigonometry using an earth radius of 6378 km. The second stroke (FI2) strikes the ground in a distance of 0.96 km to the first stroke (FI1). The following third stroke (FI3) has a calculated distance of 0.33 km to the FI1 and a distance of 0.26 km for the fourth (FI4) stroke to FI1 was determined. Three additional subsequent strokes five, six and seven followed the channel of stroke four (FI4) to ground, terminating in GSP four (see Fig. 3). The flash had a duration of 402 ms and shows interstroke intervals from 31.8 ms to 127.1 ms between the strokes. The calculated return stroke peak current for the FI3 showed the highest value within this flash (|- 24.7| kA, determined by the LLS).

Fig. 4 shows the corresponding electric fields of the four strokes (FI1 to FI4). All fields show a negative peak at the beginning of the strokes and a flattening of the field after that. The recorded electric field of the third stroke shows an additional peak. In the video (see Fig. 3) no further discharge channel is visible at this time, neither to the ground nor in the cloud. The return stroke is followed by a continuing current of 3 ms. However, this peak could also have been triggered by an M-pulse or by a nearby discharge, which occurred during the same time period. In this case, the LLS did not detect any further discharge within a radius of 100 km during this period. The electric field of FI4 striking the fourth GSP also shows a varying field after the return stroke peak. This stroke is also followed by a continuing current of 5 ms. In this case, it is assumed that this change in the electric field is triggered by the continuing current. Again, the LLS detected no further discharge within a radius of 100 km during this period.

In contrast to the analyses of Thottappillil et al. [27], which analyzed the distances between all possible pairs of ground terminations occurring within each flash, the distances between the first LLS strike location (FI1) and all other GSP locations (FIx locations) have been calculated for the present analysis.

5. Results and discussion

5.1. Multiplicity of analyzed VFRS and LLS data

For each year and in total, the mean flash multiplicity was determined for both the VFRS and LLS data. The mean multiplicity values for VFRS and LLS data for all analyzed years are shown in Table 2.

As mentioned in Section 3, the 2021 data were recorded in the surrounding area of Graz. The reason for the differences in the multiplicity

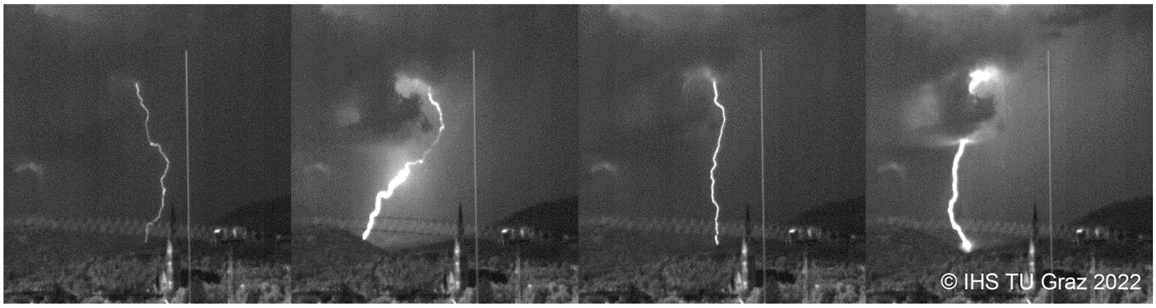

Fig. 2. Flash recorded at 14:10:10 UTC on August 13, 2021, in the surrounding area of Graz; First (FI1), second (FI2), third (FI3) and fourth (FI4) stroke terminating in a different GSP (from left to right).

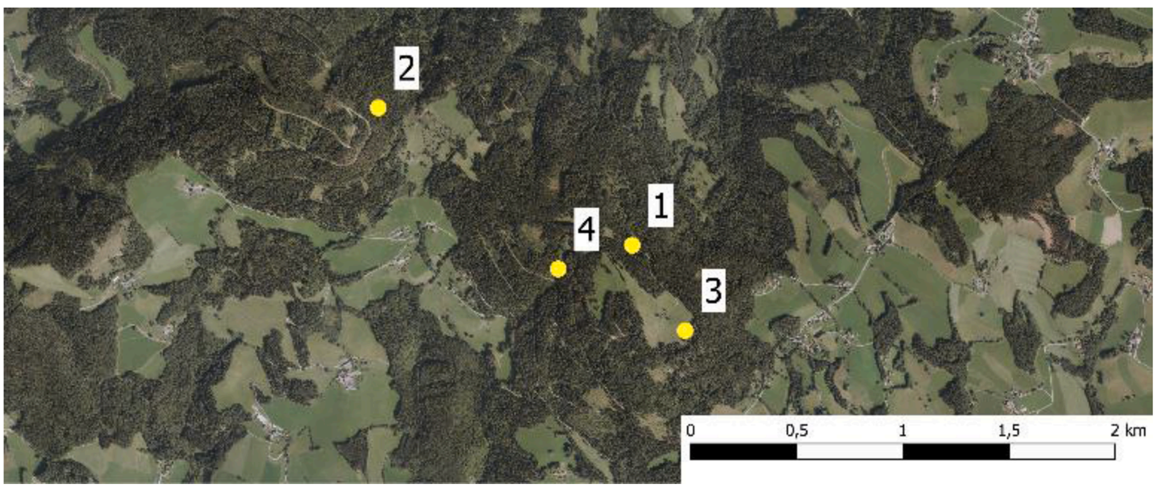

Fig. 3. LLS detection of the flash recorded at 14:10:10 UTC on August 13, 2021, in the surrounding area of Graz, position 1 to 4 for each GSP (FI1 to FI4)[11] .

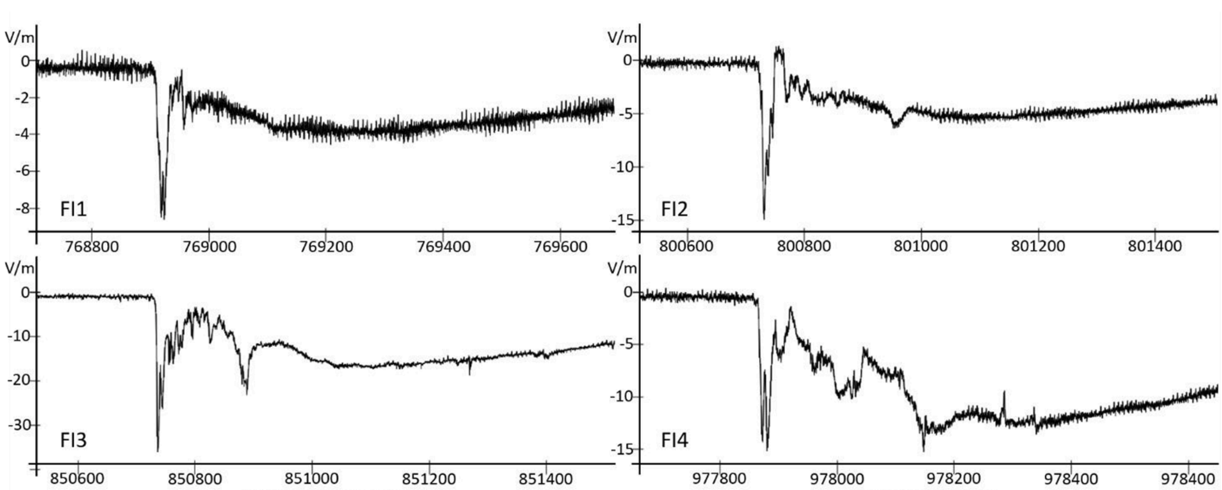

Fig. 4. Electric field record in V/m of flash recorded at 14:10:10 UTC on August 13, 2021, in the surrounding area of Graz; First (FI1), second (FI2), third (FI3) and fourth (FI4) stroke terminating in a different GSP (from top left to bottom right).

values for negative flashes, for VFRS and LLS data, in the four measurement periods may be due to different properties of the observed thunderstorms, but also due to not detected or misclassified strokes. Antunes et al. [44] have already observed day-to-day variances in thunderstorm properties.

Overall, a mean flash multiplicity of 3.3 and 3.1 was calculated for the VFRS and LLS data, respectively. The mean flash multiplicity values for VFRS data resulted in values between 2.9 and 3.4 for the period of analysis. In 2009 and 2010, the mean flash multiplicity values obtained with the VFRS data were comparable to the results of measurements in the Austrian Alps (3.3 for the mean multiplicity of the merged data set [15]).

The analysis of the LLS data shows that the mean values for flash multiplicities for 2017, 2018 (both 2.8) and 2021 (2.6) are at least 28% lower than the values for 2015 (3.6). This decrease in the mean LLS flash multiplicity for 2017, 2018, and 2021 compared to the VFRS flash

Table 2
Mean multiplicity for VFRS and LLS data of negative flashes.

Year	Mean VFRS Multiplicity	Mean LLS Multiplicity
2015	3.4	3.6
2017	3.4	2.8
2018	3.2	2.8
2021	2.9	2.6
Total	3.3	3.1

multiplicity for the same years is caused by the LLS IC/CG classification. In 2016, a new software version was introduced by the sensor manufacturer. When CG strokes are misclassified as IC strokes, a lower LLS multiplicity value appears. The new IC/CG classification performs worse for negative CG strokes below a return stroke peak current with an absolute value of |-15| kA [45]. A deeper analysis of these misclassified strokes shows four strokes with return stroke peak currents greater than |-15| kA for 2017 (35 misclassified in total) and for 2018 (117 misclassified in total). For 2021, there are no misclassifications for strokes with return stroke peak currents greater than |-15| kA (36 misclassifications in total). For 2017 a percentage of approximately 90% of misclassified strokes with a negative return stroke peak currents less than |-15| kA was obtained. For 2018, more than 95% of misclassified strokes had a return stroke peak current less than |-15| kA. All misclassifications for 2021 were for strokes with a negative return stroke peak currents less than |-15| kA.

In 2017, two of the misclassified strokes (i.e., CG strokes classified as IC strokes) were detected by the LLS as single stroke flashes. These showed a return stroke peak current of -2.9 kA and -5 kA, respectively. Also, in 2018, four of the non-correctly detected strokes were categorized as single-stroke flashes (return stroke peak currents ranging from -2.0 kA to -5.6 kA). In 2021, six miscategorized strokes were single stroke flashes, with return stroke peak return currents in a range of -3.4 kA to -6.4 kA. An analysis on the percentage of single-stroke flashes related to different thunderstorm types by Schwalt et al. can be found in [8].

Compared to the strokes detected by the VFRS a percentage of 11% in 2017 (total number of strokes 317 versus 35 non-correctly detected) and 17% for 2018 (total number of strokes 693 versus 117 non-correctly detected), respectively have not been correctly detected. For 2021, 23% (total number of strokes 159 versus 36 non-correctly detected) have not been correctly detected.

To determine the distribution of strokes per flash (i.e. flash multiplicity) and strokes per GSP (i.e. GSP multiplicity), the VFRS data were analyzed and both distributions were compared. Fig. 5 shows the percentage of strokes per flash and the strokes per GSP. For numbers higher than seven strokes per flash or per GSP, the data were merged because of their small proportion. The determined maximum multiplicity of the analyzed flashes is 14 strokes in a flash and 13 strokes in one GSP.

The multiplicity analysis for flashes shows the highest percentage for single stroke flashes (28.4%), and the percentages then decrease log-normally as the number of strokes per flash increase (see Fig. 5). The evaluation of the GSP multiplicity shows that the percentage of single strokes GSPs is also the highest (74.0%), but the decrease with a higher number of strokes per GSP is greater compared to the flash multiplicity (see Fig. 5). The probability of the same GSP being struck more than twice is 16.0% in the present analysis.

The values for flash multiplicity published so far are based on numerous studies from different regions of the world over the last decades. These values show a variation from 3.3 to 6.4 strokes per flash, with the lowest values coming from Austria. Table 3 shows already published results for different regions of the world, which will be compared with the present VFRS analyses. Data from VFRS measurements in Austria in 2009 and 2010 [16] were additionally considered. As described in Section 1, the authors used different recording methods for their analyses. In Table 3, the used measurement equipment is labeled as "Electric Field" for electric field measurements only. If video and possibly also electrical field measurements were performed, they were assigned as recorded by “Video”.

The proportion of single stroke flashes of 28.4% of the present data set (see Fig. 5) directly affects the flash multiplicity (3.3) and influences the multiplicity towards lower values. The analyses in Sweden (multiplicity of 3.4) resulted in a share of 18% of single stroke flashes [11], which should have a lower influence on the multiplicity.

Baharudin et al. [21] noted that it may appear that the number of strokes per flash does not vary significantly from one geographic region to another. The results of Kitagawa et al. [9], Rakov et al. [46] (analysis based on the data of Rakov and Uman [10]), and Saba et al. [14] were reviewed by Baharudin et al. [21] in this case. Despite this, the results for the European region together with results from Colombia [22] show the lowest values compared to the results from other parts of the world (see Table 3).

Based on data of 83 negative flashes recorded in 1996 in Gansu Province, China, using a slow broadband antenna system, Qie et al. [13] found a flash multiplicity of 3.8. These data contain 40% single stroke flashes (i.e., a number of 33 single stroke flashes). This appears to be a fairly high percentage of single stroke flash flashes (40%), considering that the mean flash frequency is 3.8. Rakov et al. [47] noted that more data are needed from China.

As described in Section 1, Poelman et al. [35] showed a comprehensive analysis on global ground-strike point characteristics for negative downward flashes for data from different geographic regions. High-speed video data from the USA, South Africa, Brazil and Austria, recorded during different periods, were used (see Section 1). A total of 1174 flashes including 4302 strokes were analyzed. The mean multiplicity for the total data set was 3.67.

5.2. Ground strike points per flash

In addition to the flash multiplicity, the GSPs per flash were analyzed. Table 4 shows the results of this analysis for each year and in total. The variance of GSP per flash from 1.89 to 1.69 for the measurement period from 2015 to 2018 could be caused by the observation of different thunderstorm types over the years. For 2021, a value of 1.55 GSPs per flashes can be observed (see Table 4). This value could again be influenced by the observation of different thunderstorm types over the year. Another hypothesis would be that the thunderstorms in the southeastern part of Austria contain a lower number of GSPs per flashes. This parameter will be further investigated in future years.

The average value of 1.75 GSPs per flash is comparable with results from Saraiva et al. [19] and Saba et al. [14], who used high-speed video data from Arizona and Brazil [19] and from Brazil only [14]. Both found an average value of 1.70 GSPs per flash for their data. For their analyses of electric field recordings and a TV system with multiple stations, Rakov and Uman [10] reported an average of 1.67 GSPs per flash. This value is similar to the findings by Kitagawa et al. [9] (electric field and moving-film camera records) and Fleenor et al. [26] (high-speed video observations in correlation with LLS data), who reported values of 1.64 and 1.60 GSPs per flash, respectively. Both Berger et al. [23] (France) and Valine and Krider [25] (Arizona) showed lower values (1.48 and 1.45 GSP per flash, respectively) compared to the above mentioned publications. They both analyzed data recorded by video camera/-recorder systems (see [23,25]).

The findings by Valine and Krider [25] that the number of GSPs is roughly 50% higher than the number of flashes is exceeded by the analyzed data in all the years. The average value of 1.75 GSPs per flash for the present data set would suggest that the number of GSPs is 75% higher than the number of flashes. Findings by Poelman et al. [30] confirm the range between 50% to 80% for ground truth measurement

[1] Source: basemap.at; CC BY 4.0

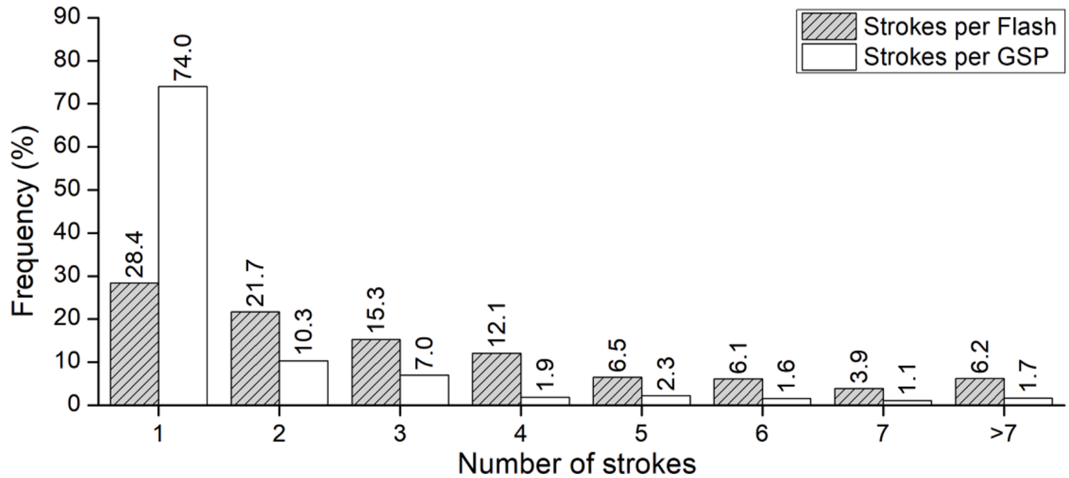

Fig. 5. Percentage of strokes per flash (i.e. flash multiplicity) and the strokes per GSP (i.e. GSP multiplicity); data are merged for numbers higher than seven strokes per flash or per GSP.

Table 3
Summary of results for flash multiplicity of negative flashes from present and previous studies by various authors.

Location	Year	Measurement System	Flash Sample Size	Mean Multiplicity
New Mexico [9]	1959 - 1960	Video	83	6.4
Florida [10]	1979	Video	76	4.6
Sweden [11]	1992 - 1993	Electric Field	137	3.4
Sri Lanka [12]	1993	Electric Field	81	4.5
China [13]	1997	Electric Field	83	3.8
Brazil [14]	2003 - 2004	Video	233	3.8
Austria[1]	2009 - 2010	Video[1]	154	3.3
Arizona [19]	2007	Video	209	3.9
Brazil [17]	2003 - 2010	Video	883	4.6
Belgium [16]	2011	Video	57	3.7
Brazil [18]	2012 - 2013	Video	357	4.2
Malaysia [21]	2009	Electric Field	100	4.0
Florida [20]	2013 - 2014	Electric Field	478	4.6
Bogota [22]	2016	Electric Field	329	2.6
Austria (present study)	2015, 2017, 2018, 2021	Video	519	3.3

[1] Measurements with a different video system (200 fps).

Table 4
Analysis of GSPs per flash for first strokes (FI1) and all additional first strokes to new GSPs (FI) within the analyzed flash.

Year	FI1 Strokes	FI Strokes	GSP per Flash
2015	131	248	1.89
2017	75	127	1.69
2018	198	343	1.73
2021	49	76	1.55
Total	453	794	1.75

data correlated with LLS data for Spain (1.50), the US (1.57), France (1.58), Austria (1.71 for data from 2012 and same data set of 2015 as analyzed for the present publication) and Brazil (1.80). The latest work of Poelman et al. [34] from 2021 presents data from Austria, Brazil, South Africa and the United States of America. Their investigations showed an average value of 1.56 GSPs per flash. The results of the GSP per flash for the individual regions ranged between 1.29 and 1.90. The mean value of strokes per GSP ranges from 1.82 to 2.94 and results in a value of 2.35 across all regions [34]. Interestingly, the results of Saraiva et al. [19] and Valine and Krider [25], both for Arizona, differ (1.70 and 1.45, respectively). The different values of GSPs per flash in the different measurement periods could be caused due to different characteristics of the observed thunderstorms.

A maximum of five GSPs per flash has been detected for the four investigated periods. Saraiva et al. [19] reported a maximum of five GSPs per flash too. Thottappillil et al. [27] and Fleenor et al. [26] reported a maximum of four GSPs in one flash whereas Berger et al. [23] and Hermant [24] reported a maximum of six and Rakov and Uman [48] reported seven GSPs per flash.

5.3. Distance between ground strike points

To calculate the distance between the location of the first stroke of a flash and the other GSPs the stroke locations of the LLS data was used. Fig. 6 shows the distribution of distances between the GSP of the first stroke in a flash and the remaining GSPs within the same flash in km. The distances showed a median of 1.4 km, an arithmetic mean of 1.6 km and a geometric mean of 1.2 km. The maximum distance between GSPs within one flash was 6.9 km. For this analysis, only values larger than 0.1 km have been used because this is the median location accuracy of the LLS [38].

Thottappillil et al. [27] and Stall et al. [28] already analyzed ground truth data regarding distances between GSPs in a given flash. Stall et al. [28] showed a median of 2.1 km and a mean of 2.3 km (plane surface calculations for first stroke to every new GSP within the flash). They calculated the maximum distance between GSPs only for distance

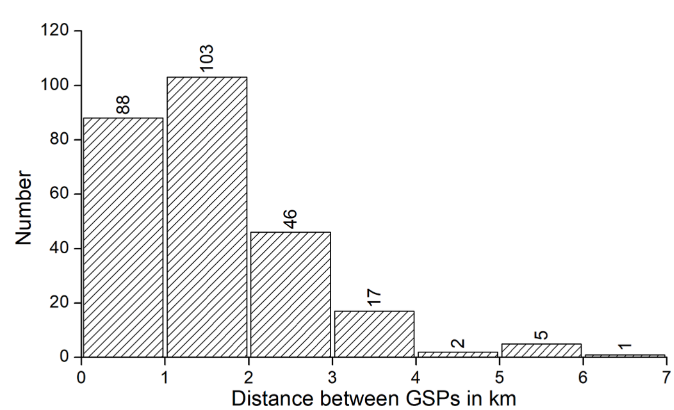

Fig. 6. Distribution of distances between the GSP of the first stroke in a flash and the remaining GSPs within the same flash in km for the total data set.

calculations between all pairs of GSPs, which showed a value of 7.3 km. Improvements in LLS technology resulting in lower location errors or differences in the thunderstorms analyzed could be a reason for the difference in the median of distances between GSPs in each flash found in this work (1.4 km) compared to the median reported by Stall et al. (2.1 km).

Thottappillil et al. [27] calculated the distances between GSPs for every pair of the GSPs in a flash, and showed a geometric mean of 1.7 km, a maximum of 7.3 km and a minimum of 0.3 km. Stall et al. [28] did the same for their data, and calculated a mean, maximum, and minimum of 2.6 km, 7.5 km, and 0.1 km. No information whether they calculated the arithmetic or geometric mean was included.

6. Conclusion

The analyzed data show calculated and detected key parameters for atmospheric discharges in the Austrian Alpine region. The results lead to a better understanding of the physical processes of CG discharges in continental and mountainous regions during the main storm season. The investigated CG discharges can have a direct impact on existing power generation and transmission systems as well as living beings. Parameters for technical applications and characteristic values for future work in lightning protection can be derived from the recorded VFRS data in the best case. The data set of VFRS measurements and corresponding LLS data was only used if both measurements are of high quality (e.g., lightning channel visible in the video).

The analyses of the present work resulted in mean flash multiplicity values for VFRS data between 2.9 and 3.4 for the period of analysis. In 2009 and 2010, the mean flash multiplicity values obtained with the VFRS data were comparable to the results of measurements in the Austrian Alps (3.3 for the mean flash multiplicity of the merged data set [15]). The observed decrease of the mean flash multiplicity value for 2017, 2018, and 2021 for the LLS from 3.6 in 2015 to 2.6 in 2021 is attributed to the IC/CG classification introduced by ALDIS in 2016.

The multiplicity analysis for flashes and for strokes per GSP shows the highest percentage for single stroke flashes (28.4%) and single strokes per GSPs (74.0%). Both multiplicity statistics decrease log-normally as the number of strokes per flash or per GSP increases. The evaluation of the GSP multiplicity shows that the decrease with a higher number of strokes per GSP is greater compared to the flash multiplicity. For the present analysis, in 16% of the cases a GSP was struck more than twice.

Comparing the values for flash multiplicity the results for the European region together with results from Colombia [22] show the lowest values compared to the results from other parts of the world (2.6 to 3.4). Contrary to the observation by Baharudin et al. [21] that the number of strikes per flash does not appear to vary significantly from one geographic region to another, the reported values for flash multiplicity vary from 2.6 to 6.4.

The results of the GSPs per flash found in the literature ranged between 1.29 and 1.90. The reported maximum numbers of GSPs per flash varied between four and five. The mean value of strokes per GSP ranges from 1.82 to 2.94 and the average for all reagions is 2.35 [34]. The comparisons showed that the results for Arizona from Saraiva et al. [19] and Valine and Krider [25] differ (1.70 and 1.45, respectively). This could be caused due to different characteristics of the observed thunderstorms.

Analyses of ground truth data by Stall et al. [28] regarding spatial distances between strokes to a new GSP in a given flash resulted in a higher median value (2.1 km) compared to the present results (1.4 km). This could be caused by the improvements in LLS technology resulting in lower location errors or differences in the thunderstorms analyzed. The maximum distance between GSPs in diagram 6(a) of Stall et al. [28] is between 7 km and 8 km, which is slightly higher than the calculated maximum for the present data set (6.9 km).

With a calculated value of 1.75 (i.e. 75%) of GSPs per flash for the merged data set and the calculated maximum distance between two GSPs within a flash of 6.9 km, the usefulness of considering lightning events from the GSP perspective, especially with respect to risk analyses, to safety and security issues, is emphasized.

CRediT author statement

Lukas Schwalt: Conceptualization, methodology, data recording and analysis, writing, first corresponding author

Wolfgang Schulz: Provision of LLS data, reviewing and editing.

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

The authors do not have permission to share data.

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