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Ground truth data of atmospheric discharges in correlation with LLS detections

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ABSTRACT

This paper presents recent ground truth data analyses in the Austrian Alps run by Graz University of Technology in cooperation with Austrian Lightning Detection and Information System (ALDIS). Atmospheric discharges are observed at different measurement locations by using a Video and Field Recording System (VFRS). This system consists of a high speed video camera (2000 frames per second) and a flat plate antenna to measure the electric field. For the present analysis a data set of the measurement periods 2015, 2017 and 2018 was used for validation of the Lightning Location System (LLS) data of ALDIS. In total 463 negative cloud-to-ground (CG) flashes and 1527 negative CG strokes were recorded in Austria during 51 days. Values for LLS location accuracy are in the range of 90 m to 130 m. LLS flash detection efficiencies in the range from 96.08% to 98.62% and stroke detection efficiencies in the range from 76.36% to 85.60% have been determined. Mean multiplicity values determined with the VFRS data are comparable to the results of previous analyses in the Austrian Alps.

1. Introduction

Lightning research is carried out at Graz University of Technology for several years. For the present investigation ground truth data of the latest measurements from the on-site Video and Field Recording System (VFRS) was used. To enhance the research in this field, the project "Lightning Observation in the Alps – LiOn" was established at the Institute of High Voltage Engineering and System Management in 2017. The VFRS consists of a high-speed video camera and an electric field measurement system. This system was designed to be mobile with an independent power supply. Data recording with a portable VFRS has the advantages of recording atmospheric discharges over a large area of Austria (Fig. 1 shows the observed area). An active exchange about weather forecast and especially thunderstorm prediction with the national meteorological service "Zentralanstalt für Meteorologie und Geodynamik (ZAMG)" is a cornerstone for such investigations.

Only with perfect weather forecasts a planned observation with measurement sites distributed all over Austria can be realized (see Refs. [1–4]). Using data of locally restricted approaches to determine the Lightning Location System (LLS) performance, like lightning measurements at instrumented towers and artificial rocket triggered lightning, give just insight of the performance for these sites [5]. An advantage of those measurement methods is that the stroke current can be determined. VFRS measurements cannot provide ground truth information about the return stroke peak current, only models, like the transmission line model, can be used to estimate the return stroke peak current from the electric field data for return strokes [6]. For that reason, return stroke peak current data of the LLS was used to complement the ground truth data for this investigation. Further the stroke locations are also used from the Austrian Lightning Detection and Information System (ALDIS).

The monitoring of lightning activity in Austria by ALDIS was started in 1991. ALDIS operates eight sensors and is additionally one of the two main operating centers of the European Cooperation for Lightning Detection (EUCLID). Several improvements over the last decades increased the detection efficiency (DE) and the location accuracy (LA) of the system [7]. Ongoing analyses of these two main parameters together with the flash multiplicity and the return stroke peak current distribution have been shown in publications in the past (see for example Refs. [3,7–11]). Similar investigations have been carried out in different other countries. E.g. in the U. S. analyses are available from Biagi et al. [12] (southern Arizona, Texas and Oklahoma), Warner et al. [13] (South Dakota), Zhu et al. [15] (Florida) and Mata et al. [14] (Kennedy Space Center).

We evaluate in this publication negative cloud-to-ground (CG) lightning only. With the VFRS we recorded the whole CG lightning activity during an observed thunderstorm but the dataset for positive lightning of the investigated years is much smaller because of the lower

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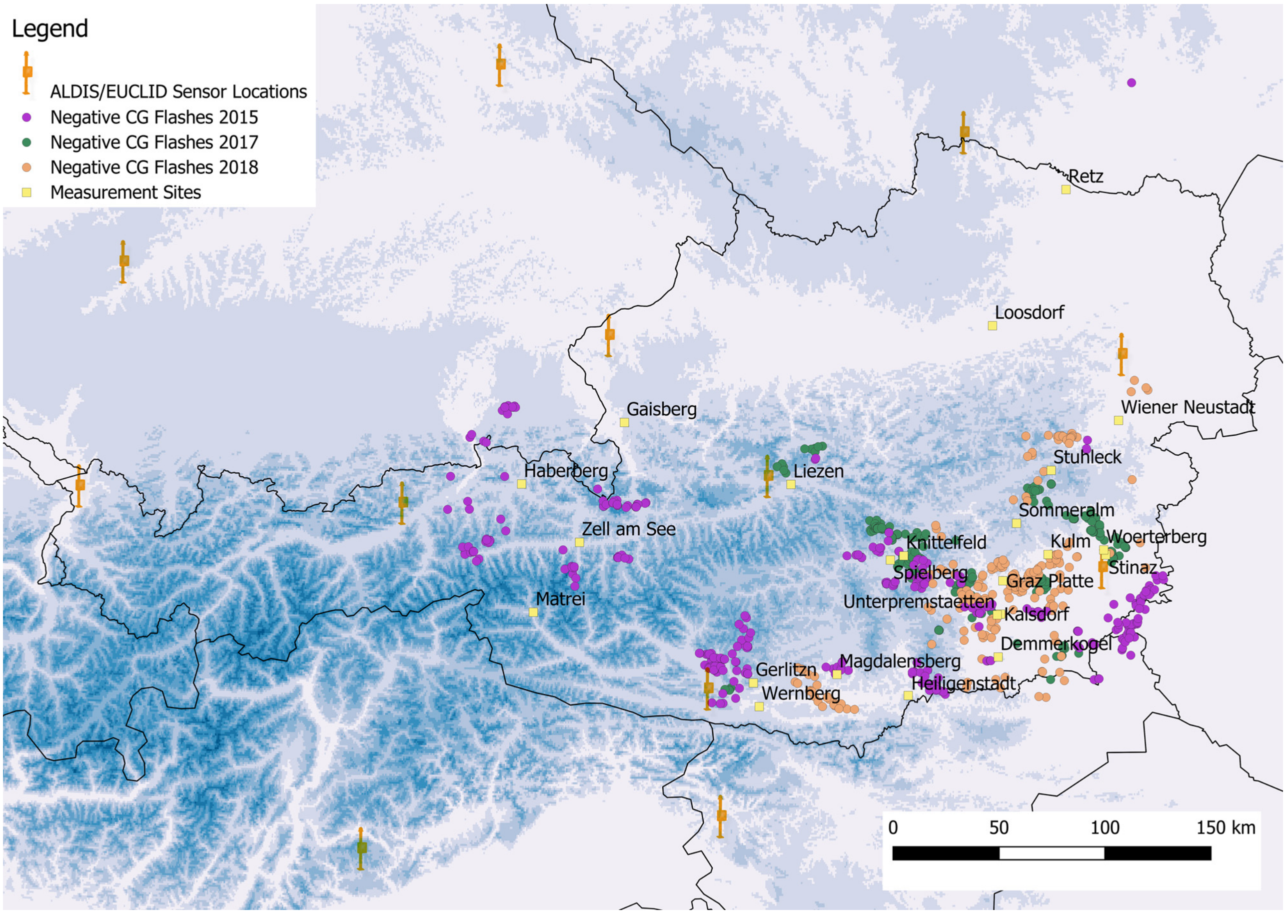

Fig. 1. VFRS measurement sites, recorded data for negative CG flashes for 2015, 2017 and 2018 and sensor locations of ALDIS/EUCLID.

occurrence of positive flashes in general. The data of the used high speed video camera gives a proof on the occurrence of flashes and strokes and provides additional information about ground strike points (GSP), multiplicity, leader propagation properties and continuing current durations. Latest results for LA and DE, multiplicity and return stroke peak current distributions of CG flashes are shown in the following chapters.

2. Observed area

Fig. 1 shows the analyzed data set of negative CG flashes for the observation period of 2015, 2017 and 2018. In addition, the measurement sites of the LiOn project and the sensor positions of the ALDIS/EUCLID network are depicted on an elevation map in the background. The measurements, distributed over the southern and eastern alpine area in Austria, help to analyze the quality of the LLS data for different spots over Austria and therefore for the region in the center of the EUCLID network too.

3. Instrumentation

3.1. Video and field recording system

The VFRS is used to record ground truth data of lightning strikes in the alpine region of Austria. With this system on-site observations at selected places, where thunderstorms will be predicted for a certain time, are possible. Such a transportable system therefore allows observing thunderstorms at variable locations. For naturally occurring CG flashes, electric field and video data can be recorded in the observed area [16]. The system consists of two main components: a high speed camera 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 atmospheric discharge.

The electric field measurements are used to examine the polarity of each stroke. This system is composed of a flat plate antenna, an integrator and an amplifier, a fiber optic link, a digitizer and a PXI system (see Ref. [1]). As camera, the Vision Research Phantom V9.1, which can record up to 153,846 frames per second, is in use. Due to the fact that the frame rate influences the resolution, a balance between a sufficient frame rate and the picture format has to be found. During the measurements in 2015, 2017 and 2018 a frame rate of 2000 frames per second, a 14-bit image depth and a resolution of 1248 × 400 pixels was most appropriate (see Refs. [2,16]).

All the VFRS measurement data are first correlated with the ALDIS LLS data by using a time criteria (both systems synchronized to GPS time). These leads to an accurate temporal correlation within a few micro seconds. The video and electric field data are then analyzed and documented. This process allows to determine the LA and the DE of the LLS and further multiplicity and return stroke peak current distribution of CG flashes (see Ref. [8]).

3.2. Lightning location system ALDIS

ALDIS operates a sensor network of eight lightning detection sensors in Austria. In 2001 ALDIS became one of the processing centers of EUCLID and is therefore processing the data of currently 166 sensors distributed all over Europe. 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 LA, DE and return stroke peak current distribution. Due to continuous adaptation and improvement of the system (new location algorithm in 2008, sensor based onset time calculation in 2011, propagation correction in 2012 and sensor upgrade to LS7002 in 2015), the median LA is in the range of 100 m (for more detailed information see Refs. [3,7,9]).

4. Analyzed dataset

The measurements were performed during warm season thunderstorms from May to August of 2015, 2017 and 2018 respectively. These four months represent the main thunderstorm season for the investigated area (see Refs. [17,18]). In total 463 negative CG flashes and 1527 negative CG strokes were recorded in Austria during 51 days. Every dataset was analyzed manually to determine the performance parameters of the LLS. The individual ground truth measurements are only being taken into account for the analysis if the stroke channel and its GSP was visible in the video, otherwise the dataset was ignored. Data of 2015 and 2017 have been discussed in Ref. [19]. The results for theses two years show some differences towards lower results compared to Ref. [19] because of a reanalysis, especially for the LA and the return stroke peak current.

The analyzed thunderstorms, the total number of recorded flashes and strokes and the number of subsequent (SU) strokes in a preexisting channel, which were used for the LA calculation are given in Table 1 for each measurement season. The position of the analyzed flashes is shown in Fig. 1.

5. Methodology

5.1. Location accuracy (LA)

To analyze the strokes, which follow the same channel from the cloud to the ground, the VFRS video data was used. For such strokes it can be assumed that they have the same GSP. In such a case the LLS should calculate the same position for every stroke in the same channel [10]. If a flash consists of at least two strokes following the same channel to ground, the LA of the LLS can be calculated. The location difference between the first initial (FI) and every SU stroke within the same channel can be calculated by using the stroke location of the LLS data. It has to be mentioned, that the resulting LA distribution would lead to the same results if such calculations were performed for two SU strokes following the same channel. Such calculations always lead to a Rayleigh distribution of the LA (see Ref. [10]) for that reason no implication on the final result is expected.

To compare video determined location errors with absolute location errors, e.g. determined by using data of instrumented towers, the calculated location differences have to be scaled by using a factor of $1/\sqrt{2}$ in general (see Refs. [10,12]). All calculated distances are scaled by the factor of $1/\sqrt{2}$ for that reason. Figs. 2 and 3 show an example for a flash with seven strokes, recorded in the center of the Alps. The first stroke (FI1) strikes the ground in a distance of 1.27 km to the second stroke (FI2). The following five strokes are terminating at the same GSP as FI2. Table 2 shows the LLS data including the LA for this flash (recorded on August 8, 2018 at 13:29:48 UTC). For this case, the LA of the SU2 strokes relative to FI2 is in the range from 0.42 to 0.73 km. Since the real GSPs are not always visible, particularly in mountainous regions, the calculated values show upper limits of the LA [12] (e.g. changes in channel direction within the last few 100 m may not always be visible because of mountainous terrain).

Table 1
Analyzed thunderstorms, total flashes and strokes and number of SU strokes in a pre-existing channel for the LA calculation.

Year	Thunderstorms	Total flashes	Total strokes	SU strokes for LA calculation
2015	24	153	514	173
2017	13	94	317	77
2018	14	216	696	237

5.2. Detection efficiency (DE)

For analyzes of the DE of a LLS it is necessary to consider two different types of DEs, the flash and the stroke DE. The flash DE is defined as percentage of detected flashes to really occurred flashes (detected by video). The stroke DE is calculated in the same way but we additionally separated into detected and completely correct detected strokes, to get deeper insights about stroke classification performance of the LLS. A stroke is categorized as correctly detected, if every assignment of the LLS detection (e.g. polarity, categorization as CG stroke) can be confirmed as correct with the VFRS data.

5.3. Multiplicity and return stroke peak current

To determine the multiplicity distribution and to calculate the mean multiplicity, for each year and in total, the VFRS and LLS data of the same events have been compared.

For analyzes regarding the median, mean and 95% return stroke peak current values of all strokes, FI and SU strokes, ALDIS LLS peak current data of each analyzed return stroke have been used for the investigated periods (peak currents were not determined from VFRS electric field peaks, just return stroke peak currents given by the LLS are used).

6. Results

6.1. Location accuracy

Figs. 4–6 show the calculated LA for the years 2015, 2017 and 2018 respectively. For all years, only distances up to 3.5 km are shown. Just for 2015 four values greater than 3.5 km have been calculated.

The median LA of the LLS during 2015 is 95 m and the value for the 95% LA is 2.76 km. For the year 2017, these values are 130 m and 1.53 km and 90 m and 0.86 km for 2018 respectively. A bug in the location algorithm causes the large 95% LA value for 2015 compared to 2017 and 2018. Again all calculated distances are scaled by $1/\sqrt{2}$ to make a comparison of video determined location errors with absolute location errors, e.g., determined by using data of instrumented towers possible [10,12].

6.2. Detection efficiency

Table 3 shows the number of events recorded by the VFRS, the LLS and the results for the flash and stroke DE for the three years.

The reason for the decrease of the stroke DE for correctly detected strokes in 2017 and 2018 is a new intra-cloud/could-to-ground (IC/CG) classification, which was introduced by ALDIS in 2016. A more detailed analysis about IC/CG classification performance can be found in Ref. [20]. For 2018 the stroke DE for correctly detected strokes show an increase of around 3% compared to 2017. The stroke DE for detected strokes show a strong increase to 96.10% in 2018.

6.3. Multiplicity

The mean multiplicity for each year and in total, determined with the VFRS and LLS data of the same events is shown in Table 4. Values for the true multiplicity, determined with the VFRS data, are comparable to the results from previous measurements in the Austrian Alps (see Ref. [21]). The decrease of the mean LLS multiplicity value for 2017 and 2018 could be caused by the new IC/CG classification, which was introduced by ALDIS in 2016.

Fig. 2. Second (FI2), fifth (SU2) and seventh (SU2) stroke following the same channel to ground (from left to right).

Differences in multiplicity distributions for the three investigated measurement periods could also be caused by variances in the observed thunderstorm characteristics (see Ref. [4]). Another reason for such differences could be not detected or misclassified strokes. The detected multiplicity maxima of the VFRS data are 14 strokes in one flash for 2015, 13 strokes for 2017 and 14 strokes for 2018 respectively. Fig. 7 shows the merged distribution of negative strokes per flash for 2015, 2017 and 2018 respectively.

6.4. Return stroke peak current

Table 5 shows the median, mean and 95% values of LLS return stroke peak currents for all strokes, FI and SU strokes for each investigated period (see section V.C). Figs. 8, 9 and 10 show the detected return stroke peak current distributions for all strokes, for FI and SU strokes merged for all three years. Attention – the abbreviation FI and SU is related to the GSP and not to the flash – see definition above. In total 434 return stroke peak currents for 2015, 204 for 2017 and 586 for 2018 respectively, have been analyzed. For all strokes in this chapter, the same field to current conversion factor is used by the LLS [22]. We have to keep in mind that the used current conversion factor is validated for negative subsequent strokes only [8].

The detected minimum and maximum return stroke peak current was −1.8 kA and −90.1 kA for 2015, −1.4 and −83.0 kA for 2017 and −1.1 kA and −84.5 kA for 2018 respectively. The resulting values for negative median return stroke peak currents are around 16% lower for 2015, around 9% lower for 2017 and about a 30% lower for 2018 than results of older VFRS measurement campaigns in the Alps (−12 kA; see [7]).

The number of FI and SU strokes is 259 and 188 for 2015. For 2017, we analyzed 127 FI and 77 SU strokes and for 2018 343 FI and 243 SU strokes. Maximum, mean and median return stroke peak currents for FI strokes are greater compared to SU strokes for all three years. For 2015, a maximum of −90.1 kA for FI and −41.2 kA for SU strokes have been detected. For 2017 a maximum of −55.6 kA for FI and −45.8 kA for SU strokes and −84.5 kA for FI and −54.2 kA for SU strokes for 2018 respectively, have been detected. Nevertheless, for some individual GSP we found higher return stroke peak currents for SU strokes than for the corresponding FI in the data.

Table 2
LLS data with LA calculation in km (calculated distances scaled by $1/\sqrt{2}$; return stroke peak current in kA, sn = stroke number, nbdf = sensor detections, nbdfit = sensors data with succifient quality, maxis = major axis, ki2 = quality criteria, ToS = type of Stroke, FIx = first stroke to GSP x, SUx = subsequent stroke to GSP x).

Latitude	Longitude	Return stroke peak current	sn	nbdf	nbdfit	maxis	ki2	ToS	LA
47.7164	15.9306	−48.9	1	59	23	0.1	0.7	FI1	
47.7224	15.9451	−12.0	2	18	7	0.2	1.3	FI2	
47.7226	15.9353	−6.7	3	14	11	0.1	0.3	SU2	0.52
47.7247	15.9380	−18.3	4	25	17	0.1	1.2	SU2	0.42
47.7230	15.9350	−25.1	5	56	30	0.1	0.8	SU2	0.54
47.7235	15.9314	−5.1	6	5	2	0.5	0.2	SU2	0.73
47.7230	15.9352	−6.3	7	7	4	0.1	0.3	SU2	0.53

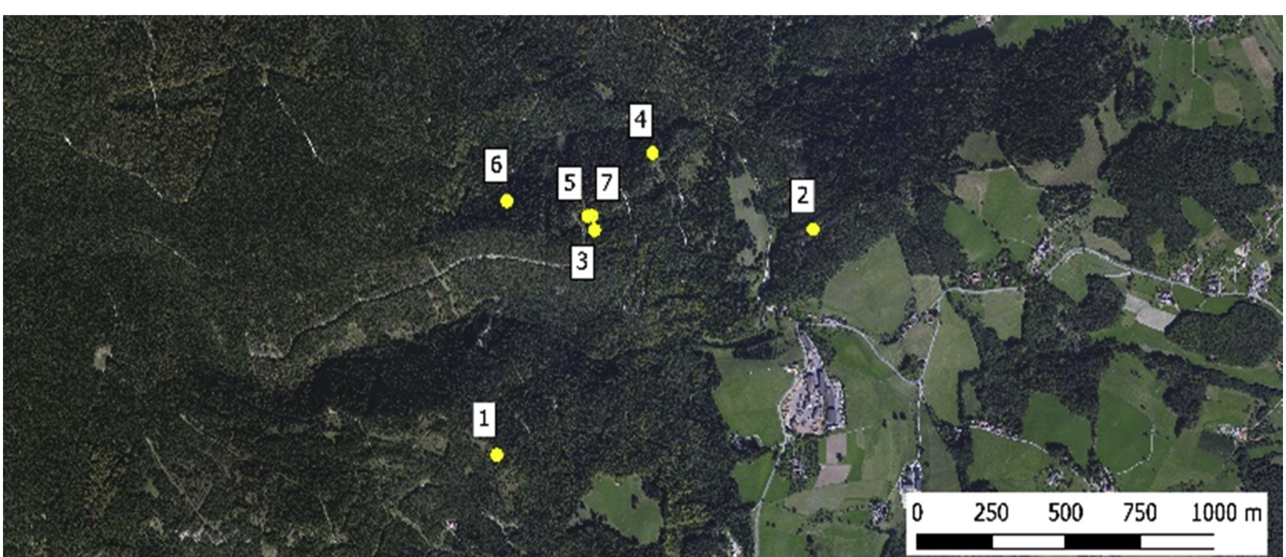

Fig. 3. LLS detection of the flash. Stroke two to seven strike the same GSP; ESRI satellite map in the background.

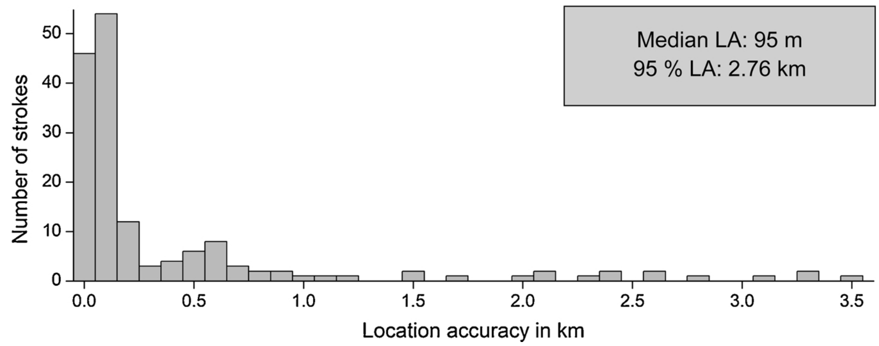

Fig. 4. Location accuracy distribution, median and 95% value for 2015.

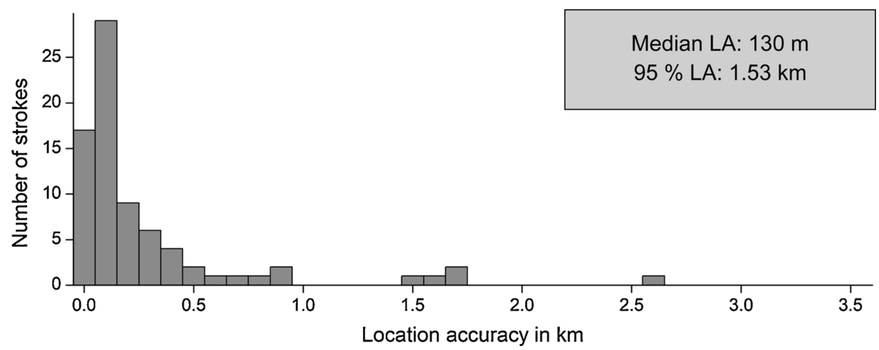

Fig. 5. Location accuracy distribution, median and 95% value for 2017.

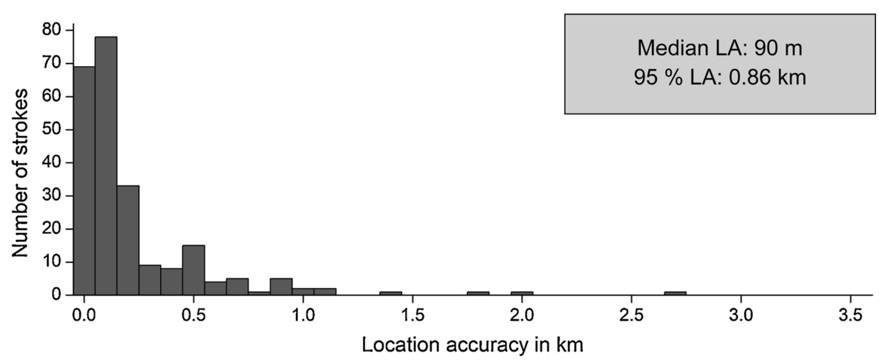

Fig. 6. Location accuracy distribution, median and 95% value for 2018.

Table 3
DE of the ALDIS LLS for flashes, detected strokes and correctly detected strokes for the year 2015, 2017 and 2018.

Year	Type	VFRS	ALDIS LLS correctly detected	DE – detected strokes in %	DE – correctly detected flashes/ strokes in %
2015	Flashes	153	147	–	96.08
	Strokes	514	440	87.94	85.60
2017	Flashes	94	93	–	98.49
	Strokes	317	242	88.01	76.34
2018	Flashes	217	214	–	98.62
	Strokes	693	548	96.10	79.08

Table 4
Mean multiplicity for VFRS and LLS data (2015, 2017, 2018 and total).

Year	Mean VFRS multiplicity	Mean LLS multiplicity
2015	3.36	3.57
2017	3.37	2.82
2018	3.19	2.78
Total	3.29	3.11

7. Discussion

LA results for 2015, 2017 and 2018 show slightly higher values than reported for strokes recorded at the Gaisberg tower (median LLS LA of 95 m in 2015, 130 m in 2017 and 90 m in 2018 versus 89 m in 2014 for the Gaisberg tower location) [7]. This is related to the fact that the radiation field waveforms for lightning strikes to such vertical metallic structures make a location calculation by the LLS easier, than for natural CG lightning attaching to ground [5]. The resulting LA values of this analysis show an ongoing improvement compared to the median LA values of 2009–2010 (326 m) and 2012 (157 m) in Austria (see Ref. [7]). This is caused by the fact, that LLS calculations, prior to 2011, have been performed without the implementation of the sensor-based onset time calculations and prior to 2013 no propagation corrections were used (see Ref. [7]).

The 95% LA of this analysis showed a higher value for 2015 (2.76 km) and similar ones for 2017 (1.67 km) compared to previous

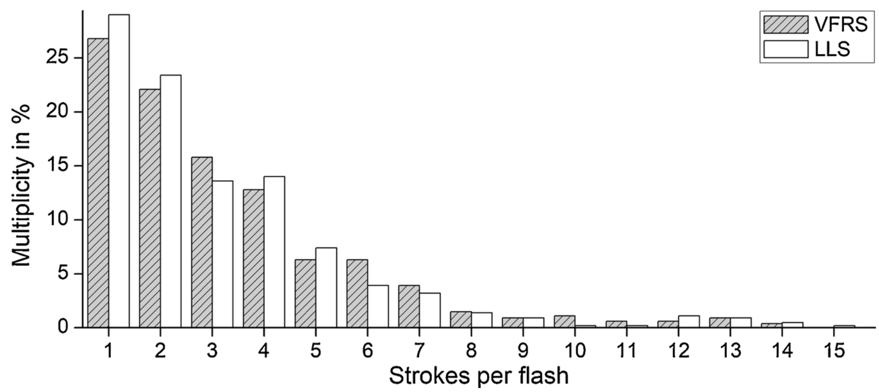

Fig. 7. Multiplicity of the VFRS and LLS data (2015, 2017 and 2018).

Table 5
Mean, median and 95% value of LLS return stroke peak currents of all strokes, FI and SU strokes for the year 2015, 2017 and 2018.

Year	Type of strokes	Number of strokes	Mean in kA	Median in kA	95% value in kA
2015	All	434	−13.4	−10.1	−28.7
	FI	248	−16.0	−12.1	−41.6
	SU	186	−9.9	−7.2	−27.3
2017	All	204	−13.6	−11.2	−31.9
	FI	127	−14.6	−12.1	−31.9
	SU	77	−12.1	−9.1	−29.6
2018	All	586	−11.3	−8.0	−29.7
	FI	343	−11.8	−8.8	−30.6
	SU	243	−10.6	−7.5	−27.7

analyses of 2009–2010 (1.63 km) and 2012 (1.53 km) in Austria [7]. A bug in the location algorithm caused the larger 95% LA for 2015. The 95% LA analysis for 2018 showed developments towards a lower value of 0.86 km. This reduction could be caused at least partly by updates within the sensor systems around Austria. The Italian LLS operator changed their sensors two a newer version during 2015. The operator of the German and the Czech Republic LLS did the same in 2016. These new sensors are equipped with an antenna board with higher sensitivity, and this affects the number of sensors reporting per stroke. Almost all LA values larger than 1 km in 2015 are caused by locations calculated with data of two sensors only.

For 2017 and 2018, LA values larger than 1 km have been caused additionally by strokes to same GSPs but different channels to ground (see Fig. 11). For such cases, the observation method with one camera only limits the GSP categorization accuracy. Forked strokes are responsible for LA values larger than 1 km too. Such terminations are not detectable with sensor systems only. Fig. 12 shows two successive video frames of such a forked stroke. Both channels terminated almost simultaneously in the two GSPs (video recording speed limits the time resolution).

A categorization of all analyzed strokes in strokes with a straight or inclined channel from cloud to ground showed almost no difference in the LA analysis. Median LA values of 100 m for straight (369 strokes) and 99 m for inclined channels to ground (58 strokes) have been determined. For the 95% LA again similar values have been calculated (1.39 km for strokes with straight and 1.52 km for strokes with inclined channels from cloud to ground). For these video based analyses a similar LA is expected because systematic location errors can not be determined. In general we should keep in mind that videos recorded for one direction show two-dimensional data only. This leads to a certain inaccuracy for such categorizations.

Those results for the LLS LA determined by video data have to be considered as upper limits because of potential visibility problems of the lightning channel close to ground, particularly in mountainous areas. Note – All calculated distances are scaled by $1/\sqrt{2}$ to make a comparison of video determined location errors with absolute location errors, e.g., determined by using data of instrumented towers possible [10,12].

The flash DE increased from 96.08% in 2015 to 98.62% in 2018 and is comparable to the merged DE value of 98% for the years 2009 to 2012 (see Ref. [7]). The stroke DE for 2017 (76.34%) and 2018 (79.08%) is lower than the stroke DE for 2015 (85.60%) and the one for investigations of 2009 until 2012 (84%; see Ref. [7]). The reason is a new IC/CG classification, used in 2017 and 2018, which performs worse for negative CG strokes below −15 kA [20]. In the analyzed data, approximately 90% of the negative return stroke peak currents of non-correctly detected (misclassified) strokes of 2017 are below −15 kA. In 2018, more than 95% of the non-correctly detected strokes had a return stroke peak current lower than −15 kA. The misclassified strokes below −15 kA showed a distribution of 30% FI1, 30% SU1, 15% FI2 and 15% SU2 strokes for the merged data set (2017 and 2018).

Differences regarding the multiplicity values of the three

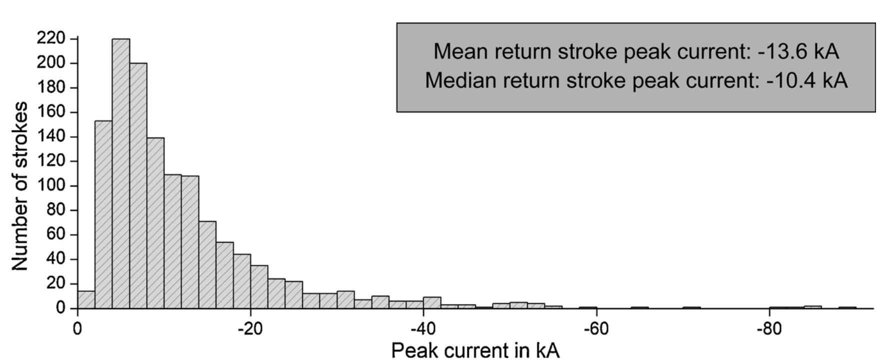

Fig. 8. Return stroke peak current distribution for all strokes (2015, 2017 and 2018).

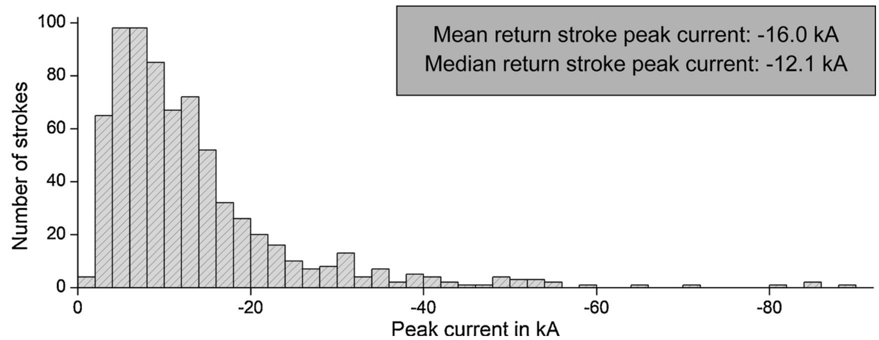

Fig. 9. Return stroke peak current distribution for FI strokes (2015, 2017 and 2018).

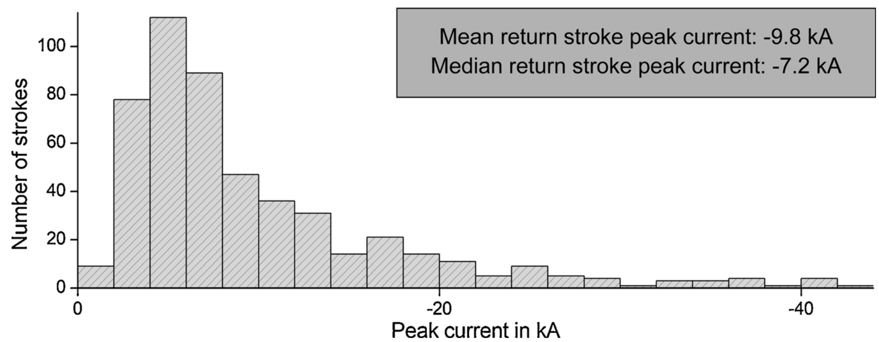

Fig. 10. Return stroke peak current distribution for SU strokes (2015, 2017 and 2018).

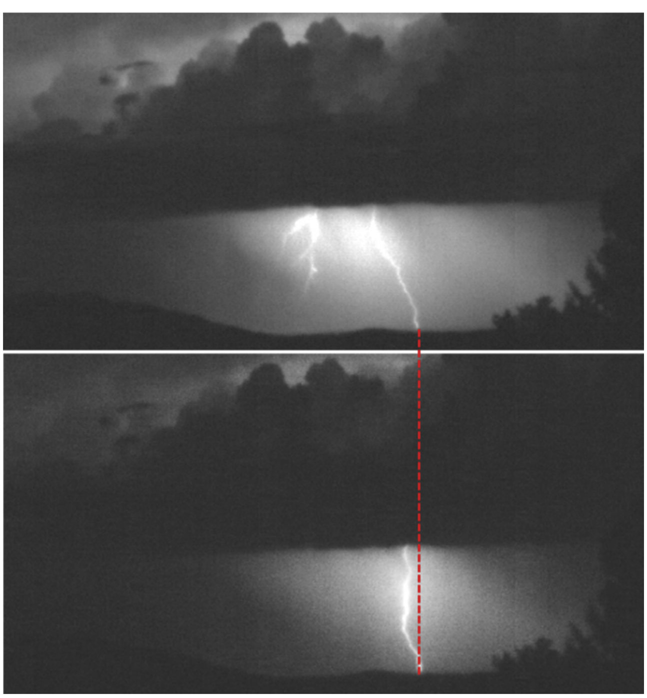

Fig. 11. FI and SU stroke with the same GSP but different channels to ground; dashed red line shows GSP.

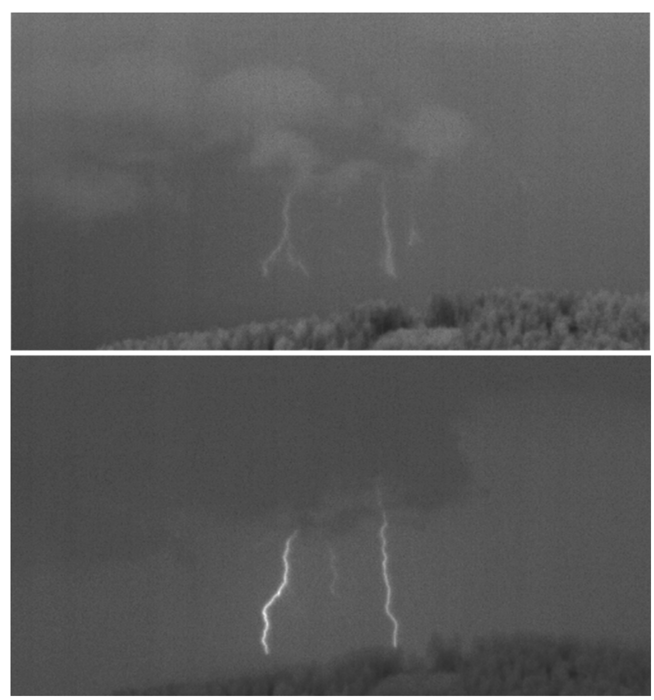

Fig. 12. Two successive video frames of a forked stroke stepped leader and its two return strokes from different GSPs.

measurement periods can be caused by variances in the observed thunderstorm characteristics (see Ref. [4]), but could be also related to not detected or misclassified strokes. Mean multiplicity values determined with the VFRS data are comparable to the results for measurements in the Austrian Alps of 2009, 2010 and 2012 (3.42 for the mean multiplicity of merged data; see Ref. [21]). In this paper we determined values from 3.19 to 3.37 for 2015, 2017 and 2018. Analyzing the LLS data, the mean multiplicity values for 2017 (2.82) and 2018 (2.78) are much lower than the one for 2015 (3.57). This decrease of the mean LLS multiplicity value for 2017 and 2018 is also caused by the new IC/CG classification, which was introduced by ALDIS in 2016.

The median values for negative return stroke peak currents are around 16% lower for 2015 (−10.1 kA), around 9% lower for 2017 (−10.9 kA) and about 30% lower for 2018 (−8.0 kA) respectively, than for detections of older VFRS measurements in the Alps (−12 kA for measurements from 2009 to 2012; see Ref. [7]). Reasons for these differences could be variances of the observed thunderstorms per measurement period or among the analyzed years in general (see Ref. [4]). Maximum, mean and median return stroke peak currents for FI strokes show, as expected, higher values than the ones for SU strokes.

The hypothesis that SU strokes with larger return stroke peak currents than FI strokes of the flash originate from strokes to new GSP was analyzed in Ref. [23] by using ground truth data. This analyses revealed that 14% of the SU strokes per GSP have a return stroke peak current larger than the first stroke of the same GSP. This result leads to the conclusion that the larger SU return stroke peak currents within LLS grouped flashes are unlikely to originate from FI strokes in a new GSP (see Ref. [23]).

8. Conclusion

The presented values show calculated and detected key parameters for atmospheric discharges in the Austrian alpine region. The data set of VFRS measurement and corresponding LLS data was only used if both measurements are of high quality (e.g. lightning channel visible in the video, electric field not noisy). LLS performance estimation with VFRS measurements, recorded in a certain area, can be rated as superior compared to locally restricted approaches to determine the LLS performance, since the results are valid for a larger region.

Overall, the values for LA and DE are within the expected range, even if the thunderstorm activities and especially the measurement days and measurement locations varied for the three investigated time periods. Mean multiplicity values for the Austrian Alps, determined with the VFRS data for all three measurement seasons are comparable with previous measurements conducted with a similar system. The median values of negative return stroke peak currents are 10% to 30% lower than values of older VFRS measurement campaigns in the Alps.

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.

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