21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

International Colloquium on
Lightning and Power Systems

Ljubljana 2017

NUMBER OF SINGLE-STROKE FLASHES IN THE ALPINE REGION DETERMINED WITH A VIDEO AND FIELD RECORDING SYSTEM

L. SCHWALT[1], S. PACK[1], W. SCHULZ[2], G. DIENDORFER[2], G. PISTOTNIK[3]
[1]Institute of High Voltage Engineering and System Performance, Graz University of Technology, Graz,
[2]OVE Service GmbH, Dept. ALDIS, Vienna
[3] Zentralanstalt für Meteorologie und Geodynamik, Vienna
Austria

SUMMARY

Since 2008, measurements of natural cloud-to-ground (CG) lightning were performed during warm season thunderstorms in the Alpine region of Austria to generate a ground truth data set of lightning strikes. Those measurements were performed with a mobile high speed video and an electric field recording system (VFRS) to observe the optical properties of lightning discharges and to record the ambient electric field. In 2015, the VFRS`s high speed camera was upgraded in order to significantly increase the optical and temporal resolution of the video data. Due to the upgrade it was possible to record a high quality data set during 20 thunderstorm days at 15 different sites between May and August 2015.
For this paper these data sets of the Alpine region are used to analyze possible reasons for the detected variation of single-stroke flashes. The ground truth data sets are also compared to formerly published values from different countries. To provide additional information, data of the Austrian Lightning Location System (LLS), ALDIS (Austrian Lightning Detection and Information System), is compared to the VFRS ground truth data, operated by Graz University of Technology, to analyze the reasons for the varying amount of single-stroke flashes in the considered region. Thunderstorm types are classified with radar data and with wind measurements in order to investigate the effect of thunderstorm organization on their lightning characteristics.
Compared to values from the literature the percentage of single-stroke flashes in this study present a higher value for negative flashes (26 %) and values in the same range for positive flashes (89 %).
Results of this report shall contribute to a better understanding of the lightning process in general and the behavior of thunderstorms in the Alpine region in particular.

KEYWORDS

Cloud-to-Ground lightning; Single-stroke flash; Ground truth data; Alpine region; Lightning Location System;

lukas.schwalt@tugraz.at

1. INTRODUCTION

Single-stroke flashes are cloud-to-ground (CG) lightning flashes that consist of one stroke only. More than 80 % of positive CG lightning flashes are single-stroke flashes, whereas 12 to 21 % of negative CG flashes consist of one stroke [1], [2]. These values are based on the results of numerous studies and international publications that have been conducted in various regions all over the world during the last decades. For several years Graz University of Technology and ALDIS have operated electric field and video measurements with a video and field recording system (VFRS) in the Alpine region of Austria (see for example [3], [4] and [5]).

First VFRS data were recorded during 2008 and 2010 and showed different percentage values for the number of single-stroke flashes than the ones stated in the literature. This value influences the multiplicity statistics, which describes the number of strokes per flash. Later extensive measurements were conducted during the warm seasons in 2012 and 2015. Especially in 2015 a large number of high quality measurements were recorded in a wide area of Austria. It was possible to get measurements of high quality for 165 negative flashes, 25 positive flashes and 5 bipolar flashes recorded on 15 different sites in Austria.

Graz University of Technology and ALDIS have collaborated on this research project since 2008 to analyze the behavior and parameters of cloud-to-ground flashes and to get a deeper view in the processes. The recorded ground truth data was also used to evaluate the performance of the EUropean Cooperation for LIghtning Detection (EUCLID) system [6].

Since the single-stroke flash density influences the multiplicity value, which is one of the main characteristics of lightning flashes and is for example relevant for the protection principles of a transmission line [7], this value is of special interest. The percentage of negative single-stroke flashes in our sample is higher than values reported in literature (12- 21%) [5]. The values for the percentage of positive single-stroke flashes are in the same range as the values given in the literature [8]. It is one goal of this research project to find possible reasons for a varying amount of single-stroke flashes in the considered region.

In the present study, we investigate a possible relation between thunderstorm types (single cells, multicells, supercells, or lines) and lightning characteristics. Thunderstorm organization into characteristic types is mainly governed by the amount of vertical wind shear, i.e. the change of the wind vector (both in speed and direction) with height ([9], [10]). We perform two alternative ways of thunderstorm classification for each measurement days: first a manual classification according to radar characteristics and second an automatic classification based on the strength of vertical wind shear.

2. MEASUREMENT SETUP

2.1. Description of the used VFRS

A mobile video and field recording system is used to record ground truth data of lightning strikes in the Alpine region. This system allows a targeted deployment for on-site observations at selected places where thunderstorms are particularly likely on a given day. The transportability of such a system therefore allows observing thunderstorms at variable locations, in contrast to instrumented towers or rocket-triggered lightning. The electric field and video data can be recorded for naturally occurring CG flashes in the given area [5].

The system consists of a high-speed camera and an electric field measurement system, which records the transient electric field. Synchronization of both components to GPS time ensures the proper assignment and comparability of the data of each lightning strike. The electric field measurement system is composed of a flat plate antenna, an integrator/amplifier, a fiber optic link, a digitizer and a PXI system (see [3]). The high-speed camera was a monochrome one with VGA resolution and a frame rate of 200 frames per second till 2015. To improve the video quality a new camera model, which can record up to 153846 frames per second, is in use since 2015. 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 a frame rate of 2000 frames per second, a 14 bit image depth and a resolution of 1248x400 pixels was most appropriate (see [4] and [5]). The recording after each lightning flash within the camera’s field of view was manually triggered.

2.2. Lightning Location System (LLS)

The Austrian Lightning Detection and Information System (ALDIS) operate a sensor network of eight lightning detection sensors in Austria since 1991. Since 2001 ALDIS is one of the processing centers of EUCLID and is therefore processing the data of 150 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, helped to determine the performance of the system regarding detection efficiency, peak current detection and location accuracy (for more detailed information see [6], [11] and [12]).

3. DATA AND METHODOLOGY

3.1. Analyzed data set

The recording of ground truth data in Austria by using a VFRS was started in 2008. Measurements were performed on few days in 2008 and 2009, and on large numbers of days in 2010, 2012 and 2015. In total, a set of 137 positive and 423 negative flashes were recorded (Table 1).

Table 1: VFRS data set for the whole measurement period

		Negative CG			Positive CG		
Date	**Measurement days**	**Number of flashes**	**Number of strokes**	**Single-stroke flashes**	**Number of flashes**	**Number of strokes**	**Single-stroke flashes**
2008	1	0	0	0	9	9	9
2009	2	45	135	9	1	1	1
2010	13	109	405	33	72	78	66
2012	8	117	388	30	27	31	23
2015	15	153	514	37	28	34	23
Total	39	423	1442	109	137	153	122

The camera upgrade in 2015 resulted in a significant improvement of the video data quality. The high number of 181 flashes recorded in 2015 makes the data after the upgrade even more valuable. Measurements were performed from May to August. These four months represent the main thunderstorm season in Austria (see [13] and [14]). Fig. 2 shows the measurement sites between 2008 and 2015 and the recorded negative single-stroke and multi-stroke flashes (no ground strike position is displayed in case that the flash was not detected by the LLS). Measurements are evenly distributed over the eastern part of Austria. Nevertheless, a possible spatial dependency cannot be resolved due to the limited number of recordings for each site.

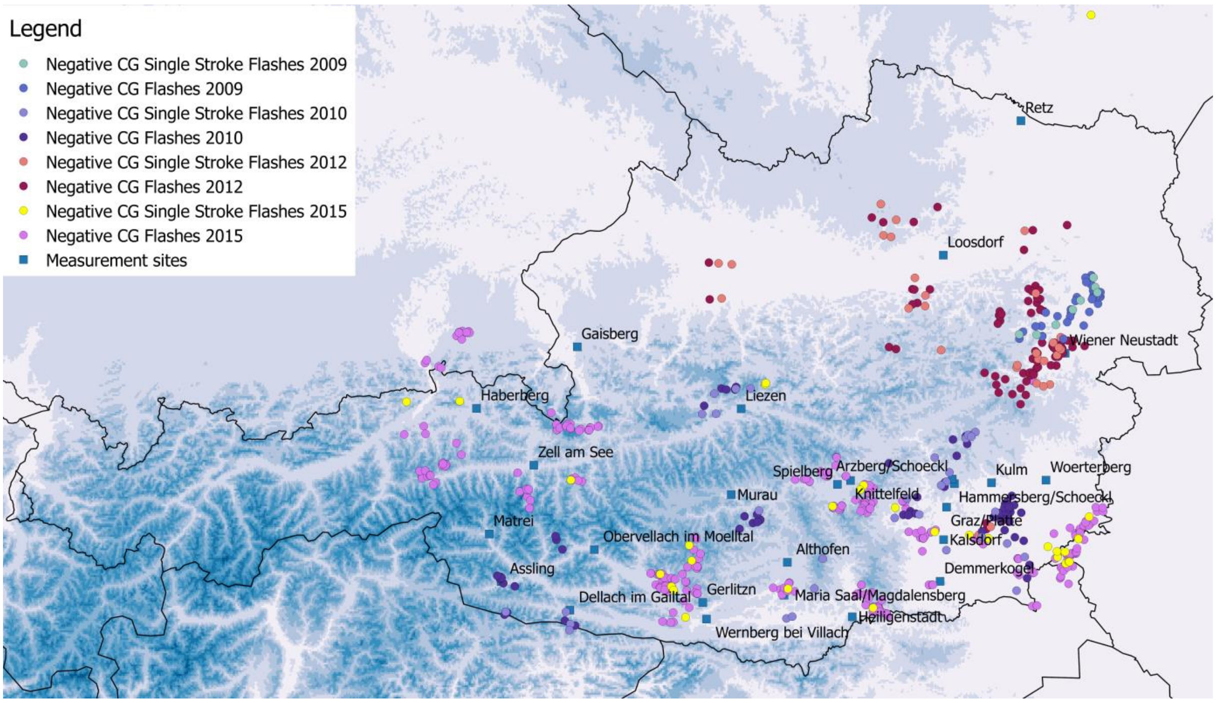

Fig. 1: VFRS measurement sites and recorded data for negative CG flashes and CG single-stroke flashes from 2009 to 2015 on an elevation map in the background (© LiOn IHS TUGraz 2017)

A classification of thunderstorms into types is done with radar data. The Austrian radar network is operated by the Aeronautical Meteorological Service (Austrocontrol GmbH). The data of five different radar stations are merged into a composite, which provides a three-dimensional picture of precipitation intensity at a spatial resolution of one kilometer and a temporal resolution of five minutes. An alternative classification is based on the amount of vertical wind shear, which is the best discriminator between unorganized single cell storms and higher forms of storm organization. We compute the vertical wind shear from upper-level winds from radiosondes (available twice daily at various sites) and surface winds from the automatic station network of the Zentralanstalt für Meteorologie and Geodynamik (ZAMG).

3.2. Methodology

Each VFRS measurement data is first correlated with the ALDIS LLS data by using the GPS time stamp. The video and electric field data are then analyzed and documented. This process allows a validation of the LLS data regarding correct stroke grouping to flashes or detection efficiency (see [15]). In this paper the detection of single-stroke flashes is analyzed in more detail. The varying detections of single-stroke flashes by the VFRS and the LLS are compared for each year and over the whole measurement period. The differences of the percentage of single-stroke flashes over the different measurement days, sites and years are analyzed as well. The calculated values for the percentage of single-stroke flashes are compared with values from international investigations in this field.

In order to investigate whether the architecture of different thunderstorm types systematically influences their lightning characteristics, we classify them into single cells, multicells, supercells, and lines. This classification is done in two alternative ways, first based on radar characteristics and second based on the underlying vertical wind shear.

The most widely used measure for vertical wind shear is the so-called “deep-layer shear” (DLS) between the surface and 6 km height. DLS is the best discriminator between the occurrences of different thunderstorm types [9]. Under weak vertical wind shear, a thundercloud is almost vertical (Fig. 3 left). It is built by a brief updraft of warm and moist air, which is then overwhelmed by a rain-cooled downdraft as soon as precipitation forms. As vertical wind shear increases, it starts to tilt the updraft; as a result, the precipitation falls in a separated area and does not choke off the updraft anymore. Thunderstorms therefore tend to live longer and become more intense when they organize into multicells (regenerated by repeated pulses of new updrafts at one particular side; Fig. 3 center), and finally, under strong vertical wind shear, into supercells (sustained by a continuous inflow and updraft at this particular side; Fig. 3 right). In addition to these types of discrete thunderstorms, convection may also organize into a line, which is favored when unstable air is lifted over an elongated area (e.g. along a cold front) and vertical wind shear is strong.

Fig. 3: Example for a single cell (left), a multicell (center) and a supercell thunderstorm (right). Note that the characteristic fuzzy ice shield ("anvil") which forms the cloud top is more or less symmetric in case of a single cell, whereas it becomes more and more asymmetric as the vertical wind shear and the thunderstorm organization increase. (Pictures: Georg Pistotnik)

Characteristic features of single cells, multicells, supercells or lines in radar data are used to undertake a manual classification of the thunderstorms whose ground truth lightning data have been recorded. For example, the asymmetric position of the updraft and downdraft within multicells and supercells results in a V-shaped appearance and in deviant motions, in contrast to round single cells which just move with the mean wind. While this classification is based on an expert's knowledge, it cannot be discounted that a small rest of subjectivity is left.

We therefore corroborate our results by using vertical wind shear information as an alternative classification, which is related to the atmospheric background conditions on a given day instead of each individual thunderstorm's behavior, but can be better objectified. Single cells usually dominate with DLS below 10 m/s, multicells between 10 and 20 m/s and supercells above 20 m/s. The wind vector at an altitude of 6 km is taken from the latest and closest available radiosonde (either Vienna, Udine or Munich at 12 UTC). The surface wind vector is extracted from the nearest ZAMG station, whose data are available at ten minute intervals. In order to minimize random noise, these wind measurements are averaged over the last hour before the onset of the thunderstorm.

4. RESULTS

4.1. VFRS: Analysis of the single-stroke flash percentages during the different measurement periods

Negative CG Flashes:

The percentage of single-stroke flashes for each measurement site is shown in Fig. 4 if ten or more flashes have been recorded during this day, to show the variation between the different thunderstorm days. The mean value of the percentage of single-strokes in 2015 is 24 % (total 153 flashes) and 27 % (total 271 flashes) for the measurement period of 2009 till 2012. During 2008 no negative strokes were recorded. This results in a total percentage of negative single-stroke flashes of 26% (total 423 flashes) for the whole measurement period.

The percentages of single-stroke flashes show a considerable variability for the individual thunderstorm events from 10 to 42 %. This observation is comparable with the analysis of Diendorfer et al. [16].

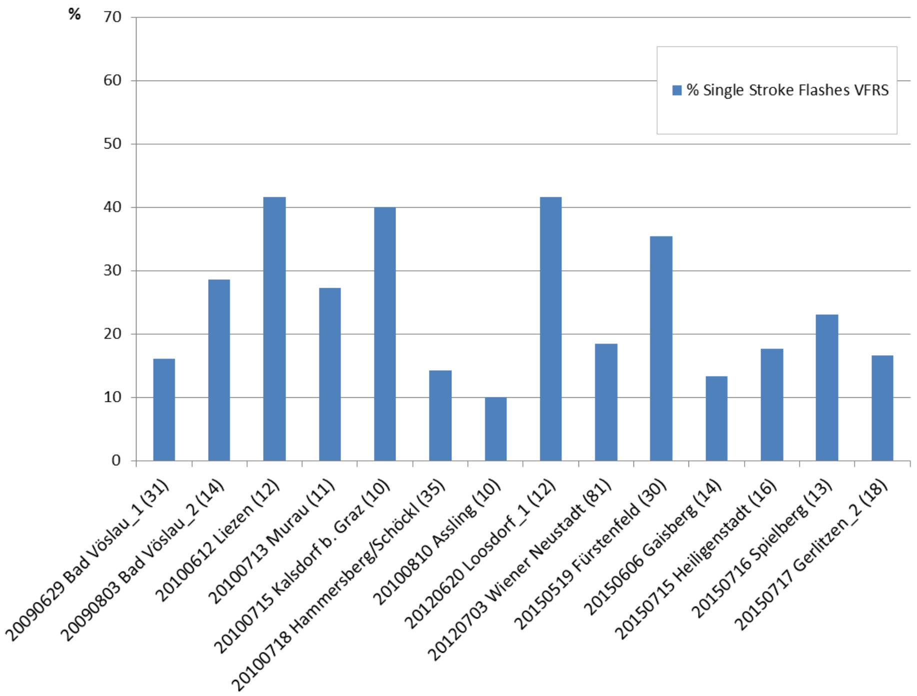

Fig. 4: Percentage of negative single-stroke flashes from 2009 to 2015 for VFRS data. X axis label: YYYYMMDD, measurement site, (Number of recorded flashes).

Positive CG Flashes:

In Fig. 5 the percentage of positive single-stroke flashes for the measurement periods is shown for measurement sites if ten or more flashes have been recorded during this day. The mean value of the percentage of positive single-strokes flashes for 2015 is 82 % (total 28 flashes) and 91 % (total 109 flashes) for the measurement period of 2008 till 2012. The percentage of single-stroke flashes for the whole measurement period is 89 %. This number does not change if we consider only measurements with ten or more records. The percentages of positive single-stroke flashes show a considerable variability for the individual thunderstorm events, but a much lower one than for the negative single-stroke flashes.

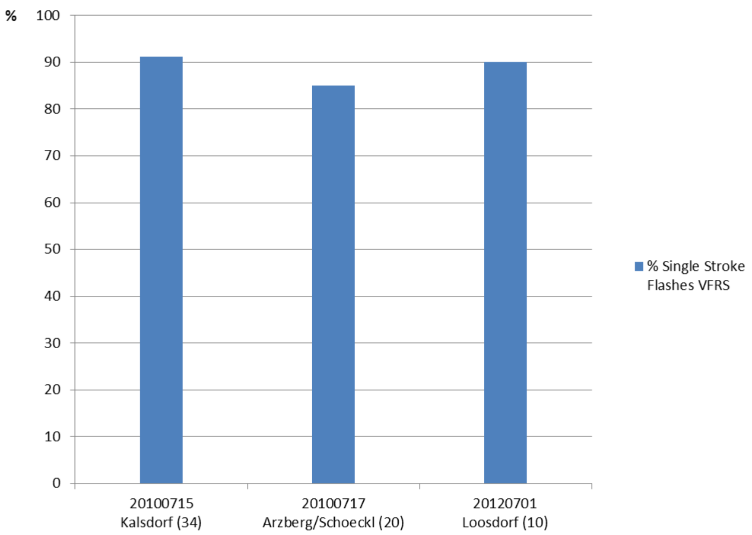

Fig. 5: Percentage of positive single-stroke flashes from 2008 to 2015 for VFRS data. X axis label: YYYYMMDD, measurement site, (Number of recorded flashes).

4.2. Comparison of VFRS ground-truth-data and ALDIS LLS-data

The comparison of the VFRS and LLS data for negative single-stroke flashes on specific measurement days is shown in Fig. 6. Also for this comparison we show only data for sites where more than 10 flashes have been recorded by the VFRS. The mean value of the percentage of single-strokes flashes in the VFRS data is 26 % (total 423 flashes) compared to 23 % in the LLS data. The measurements in Liezen on 12 June 2010 and Loosdorf on 20 June 2012 (12 flashes were recorded during each of these thunderstorms) show a large difference between VFRS and LLS detection of negative single-stroke flashes. The number of flashes per measurement day slightly differs between VFRS and LLS data because of limited detection efficiency, limited location accuracy and intra-cloud/CG misclassification of the LLS. The calculation for the mean value for the LLS measurements in Kalsdorf was computed from 8 flashes only instead of ten and more. The observed overestimation by other ground-based LLS networks (see [12]) does not appear for these ground truth measurements.

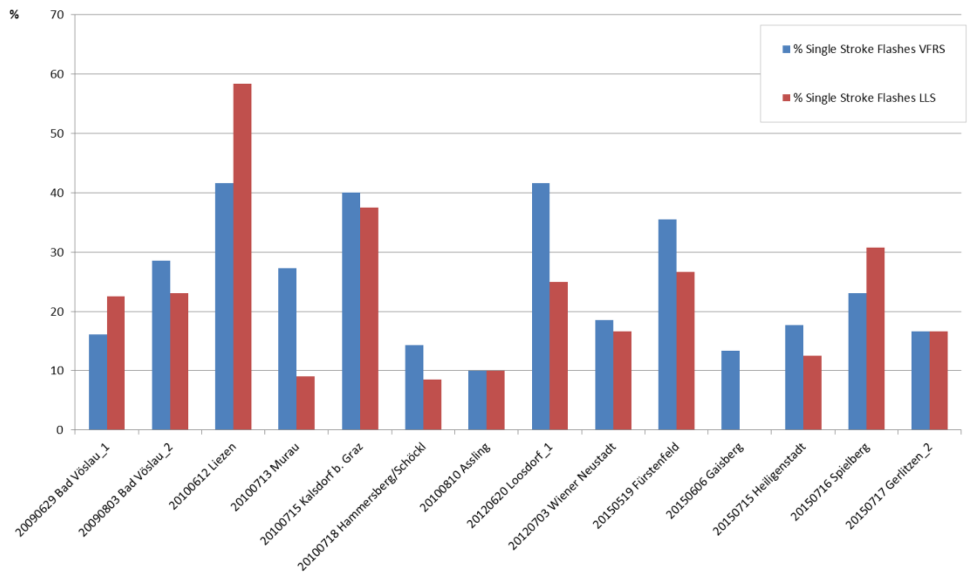

Fig. 6: Percentage of negative single-stroke flashes according to VFRS and LLS data from measurement days from 2009 to 2015.

The comparison of the VFRS and LLS data for specific measurement days (10 or more flashes recorded) for positive single-stroke flashes is shown in Fig. 7. The mean value for the VFRS data is 89 % (total 137 flashes) compared to 65 % of the LLS. The variance between VFRS and LLS detection of single-stroke flashes ranges from 20 to 38 %. Also the number of flashes per measurement day is differing slightly between VFRS and LLS data because of misclassification of the LLS. The reason why the LLS data shows a significant smaller percentage of single stroke flashes in Fig. 7 is that often cloud pulses are misclassified and grouped with other strokes to a positive flash.

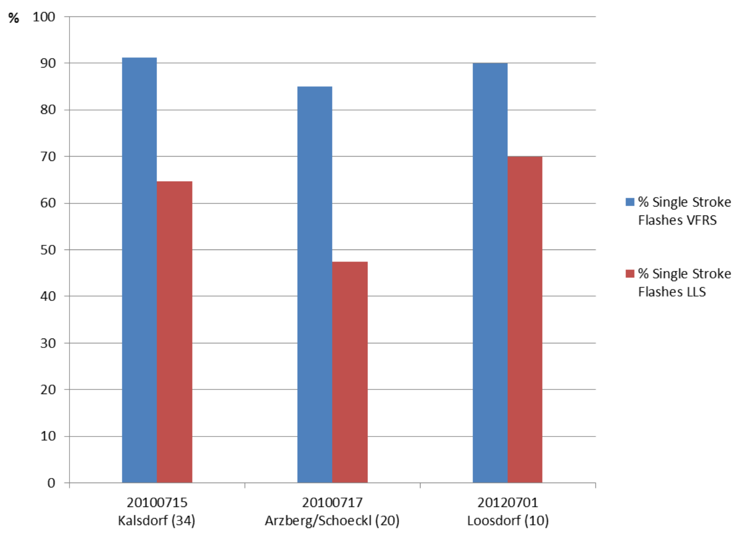

Fig. 7: Percentage of positive single-stroke flashes according to VFRS and LLS data from measurement days from 2009 to 2015.

4.3. Comparison to values for single-stroke flashes in the literature

Negative CG Flashes:

Our VFRS data shows a higher percentage of single-stroke flashes than most previous studies in other parts of the world (see Table 2). In 2010 we detected a percentage of single-stroke flashes of 30%. Even the average value of all data in Austria 2009 till 2015 (26 %) is greater than the maximum value given in Rakov et al. [2] (21 %). The percentage of single-stroke flashes is in the range of 20 to 30 % for individual years in our collected data set. For 2009 we calculated a value for the negative single-stroke flash percentage of 20% for 45 flashes, 2010 30% for 109 flashes, 2012 26% for 117 flashes and 2015 24% for 153 flashes. This variation could originate from year-to-year differences of the thunderstorm activity over the years. The sample sizes of our measurements by year are in the range of the ones stated in the literature. The percentage of single-stroke flashes of 45% described by Anderson and Eriksson [7] still exceeds even our highest values. The results of Ballarotti et al. [17] and Antunes et al. [18] are from measurements in the same region. However, larger percentage of single-stroke flashes reported by Antunes et al. [18] could be related to the limited number of thunderstorm days analyzed in this paper.

The percentage values shown in Table 2 were calculated by using data sets generated from different recording systems. For the records in New Mexico by Kitagawa et al. [20], electric field and moving-film camera records were correlated. The analyses of Rakov and Uman [21] in Florida were based on electric field records and a multiple-station TV system. For the records in Sweden, done by Cooray and Jayaratne [23], broadband electric field records were used. If analyses are based on electric field records only, those analyses are based on all flashes recorded up to a certain distance. If video records are recorded with a camera system or a VFRS the recorded data is limited to the field of view of the camera. Therefore the recorded data are just a sample of the whole lightning activity which occurs during the observed thunderstorm. This could explain at least partly the variation of the results in Table 2.

Table 2: Summary of results for the percentage of negative single-stroke flashes of our own and previous studies done by various authors.

Location	Measurement system	Sample size	Percentage of negative single-stroke flashes
Belgium [19]	Video	57	21%
New Mexico [20]	Video	83	13%
Florida [21]	Video	76	17%
Sweden [22]	Electric Field	137	18%
Sri Lanka [23]	Electric Field	81	21%
Brazil [17]	Video	883	17%
Arizona [24]	Video	209	19%
Malaysia [25]	Electric Field	100	16%
Florida [1]	Electric Field	478	12%
Brazil [18]	Video	357	24%
Austrian Alpine Region	Video	424	26%

Positive CG Flashes:
Compared to the percentages of single-stroke flashes recorded by using accurate stroke count methods in other parts of the world, the results of the analyses of VFRS is in the same range. The percentage of single-stroke flashes for our measurement period range from 82 to 93 %. For 2008 to 2010 we calculated a value for the positive single-stroke percentage of 93% (82 flashes), 2012 85% (27 flashes) and 2015 82% (28 flashes). Again the variation could originate from inter annual differences of thunderstorm behavior over the years. Further the sample size for the individual years 2012 and 2015 is lower than the ones stated in the literature.

Table 3: Summary of results for the percentage of positive single-stroke flashes of our own and previous studies done by various authors.

Location	Measurement system	Sample size	Percentage of positive single-stroke flashes
Indonesia [8]	Electric Field	77	83%
USA [26]	Video	204	96%
Sweden [27]	Electric Field	107	63%
Austria, Brazil and USA [28]	Video	103	81%
Florida [29]	Electric Field	53	81%
China [30]	Electric Field	185	95%
Austrian Alpine Region	Video	137	89%

4.4. Analysis of the negative single-stroke flash-data by thunderstorm type

Table 4 shows the percentage of negative single-stroke flashes with respect to thunderstorm classification. 20% of the negative flashes in single cells, 29% in multicells, 28% in supercells and even 38% in thunderstorm lines in our data set consisted of only one stroke (Table 4 top). Since supercells and lines are comparably rare, they could be merged with multicells into a joint category encompassing all sorts of organized thunderstorms in order to reduce possible effects due to small

sampling sizes. This combination results in a single-stroke percentage of 27% for organized thunderstorms, remarkably higher than 20% for unorganized single cells.
The objective classification according to vertical wind shear confirms these results (Table 4 bottom). It yields a single-stroke percentage of 21% for DLS below 10 m/s (mostly single cells expected), 27% for DLS between 10 and 20 m/s (mostly multicells expected) and 39% for DLS above 20 m/s (mostly supercells or lines expected). Since deep-layer shear in excess of 20 m/s is less common, all wind shear regimes favoring higher storm organization (DLS > 10 m/s) can again be merged into one category. This distinction results in a single-stroke percentage of 28% for moderate to strong vertical wind shear, in contrast to 21% for the regime of weak vertical wind shear.
Our data strongly suggest that single-stroke flashes tend to be more frequent with increasing thunderstorm organization. Antunes et al. [18] also found different lightning characteristics with different thunderstorm types, but could not find a direct relation between lightning frequency and thunderstorm type and stressed the necessity of future work on this topic.

Table 4: Percentage of negative single-stroke flashes calculated for thunderstorm categories (upper section) and for a categorization by 0 to 6 km wind shear

Individual thunderstorms	**Thunderstorm type**	**Flashes**	**Percentage of negative single-stroke flashes**
12	Single cell	95	20%
19	Multicell	262	29%
3	Supercell	43	28%
4	Line	24	38%
22	Multi- and Supercell	305	27%
26	Multi-, Supercell and Line	329	27%
Individual thunderstorms	**Vertical wind shear between surface and 6 km height (DLS)**	**Flashes**	**Percentage of negative single-stroke flashes**
13	0 to 10 m/s	121	21%
21	11 to 20 m/s	280	27%
4	> 20 m/s	23	39%
25	> 10 m/s	303	28%

5. DISCUSSION

The percentages of single-stroke flashes show a considerable variability for each individual thunderstorm day. For the performed measurements varying percentages of single-stroke flashes over the years are shown for both the LLS and the VFRS data. This can be caused by the different spectrum of thunderstorm characteristics in individual years. Also the different number of measurements per site and over the years could influence the result.

The percentages of negative single-stroke flashes found in this study are mostly greater than those from similar international studies. For positive flashes the percentage of single stroke flashes we found are placed in the mid and upper range compared to the values from other international publications.

The observed overestimation of the percentage of negative single-stroke flashes by ground-based LLS networks (see [12]) does not appear for these ground truth measurements. The reason for that is the comparison with ground truth data which do not contain misclassified intracloud flashes and flashes with bad location accuracy.

As already mentioned before, the data in Table 2 show just a sample of the whole lightning during activity during the observed thunderstorm for cases when a camera and/or VFRS is used. Only the CG flashes in the field of view of the camera are recorded. In contrast, every occurring CG flash around the recording system can be detected by using electric field records. This could be one possible reason for the variation of the results given in Table 2.

The percentages of negative single-stroke flashes for classified single cells, or alternatively for thunderstorms under weak vertical wind shear (DLS < 10m/s), are in the range of the values published in the literature. In contrast, thunderstorms classified as multicells, supercells or lines, or alternatively thunderstorms under enhanced vertical wind shear (DLS > 10 m/s), show a higher percentage of negative single-stroke flashes, which influences and increases the mean of our whole sample. This fact leads us to two possible hypotheses. First, organized storms could indeed be more common in the Alpine region than in many other parts of the world. Second, we cannot discount the possibility that our measurements are subject to a sampling bias. The short-lived nature of single cells makes them often elusive for measurements with a mobile system; in fact, a static system at one fixed place could be the better choice for thunderstorms of this type. In contrast, the longer lifetime of better organized thunderstorms enhances the planning and preparation time and makes them more attractive to record atmospheric discharges with a mobile system. The higher percentage of negative single-stroke flashes might therefore be (at least partly) an artifact, resulting from intrinsically more successful measurements on days when the thunderstorms were better organized.

During the thunderstorm season of 2017 we will continue our VFRS measurements in the Alpine region of Austria to get more information about atmospheric discharges in the Alps. This new dataset shall then help to test our hypotheses.

ACKNOWLEDGEMENT
This research work is supported by Graz University of Technology, Austrian Power Grid AG and National Institute for Space Research (INPE, Brazil). We thank all our colleagues who support this Lightning Observation Project “LiOn” in the Austrian Alps and will be a partner in the future too.

BIBLIOGRAPHY

[1] Y. Zhu, V. A. Rakov, S. Mallick, and M. D. Tran, “Characterization of negative cloud-to-ground lightning in Florida” Journal of Atmospheric and Solar-Terrestrial Physics, vol. 136, pp. 8–15, 2015.

[2] V.A. Rakov, A. Borghetti, C. Bouquegneau, W.A. Chisholm, V. Cooray, K. Cummins, G. Diendorfer, F. Heidler, A. Hussein, M. Ishii, C.A. Nucci, A. Piantini, O. Pinto Jr., X. Qie, F. Rachidi, M.M.F. Saba, T. Shindo, W. Schulz, R. Thottappillil, S. Visacro andW. Zischank, “Lightning Parameters for Engineering Applications” Working Group C4.407, CIGRE, 2013.

[3] W. Schulz, B. Lackenbauer, H. Pichler, G. Diendorfer, “LLS Data and correlated continuous E-field measurements” SIPDA, 2005.

[4] W. Schulz and M. M. F. Saba, “First Results of Correlated Lightning Video Images and Electric Field Measurements in Austria” SIPDA, 2009.

[5] C. Vergeiner, S. Pack, W. Schulz, and G. Diendorfer, “Negative Cloud-to-Ground Lightning in the Alpine Region: A new approach” CIGRE International Colloquium 2016.

[6] W. Schulz, G. Diendorfer, S. Pedeboy, and D. R. Poelman, “The European lightning location system EUCLID – Part 1: Performance analysis and validation”, Nat. Hazards Earth Syst. Sci., vol. 16, no. 2, pp. 595–605, 2016.

[7] R. B. Anderson and A. J. Eriksson, “Lightning parameters for engineering application”, Electra 69, vol. 1980, 1980.
[8] A. Hazmi, P. Emeraldi, M. I. Hamid, N. Takagi, D. Wang, “Characterization of Positive Cloud to Ground Flashes Observed in Indonesia”, Atmosphere, vol. 2017, 2017.
[9] J. P. Craven and H. E. Brooks, ”Baseline climatology of sounding derived parameters associated with deep, moist convection”, National Weather Digest 28.1: 13-24, 2004.
[10] P. Markowski and Y. Richardson, “Mesoscale meteorology in midlatitudes”, Vol. 2, John Wiley & Sons, 2011.
[11] G. Diendorfer, “A Review of 25 Years of Lightning Research in Austria from 1991-2015”, World Meeting on Lightning, 2016.
[12] D. R. Poelman, W. Schulz, G. Diendorfer, and M. Bernardi, “The European lightning location system EUCLID – Part 2: Observations”, Nat. Hazards Earth Syst. Sci., vol. 16, no. 2, pp. 607–616, 2016.
[13] W. Schulz, K. Cummins, G. Diendorfer, M. Dorninger, “Cloud-to-ground lightning in Austria: A 10-year study using data from a lightning location system”, Journal of Geophysical Research, 2005.
[14] D. R. Poelman, W. Schulz, G. Diendorfer, and M. Bernardi, “European cloud-to-ground lightning characteristics”, International Conference on Lightning Protection (ICLP), pp. 24–29, 2014.
[15] W. Schulz, “Validation of the Austrian Lightning Location System ALDIS for negative flashes”, CIGRE C4 Colloquium, 2012.
[16] G. Diendorfer, W. Schulz, and V. A. Rakov, “Lightning characteristics based on data from the Austrian lightning locating system”, IEEE Trans. Electromagn. Compat., vol. 40, no. 4, pp. 452–464, 1998.
[17] M. G. Ballarotti, C. Medeiros, M. M. F. Saba, W. Schulz and O. Pinto Jr., ”Frequency distributions of some parameters of negative downward lightning flashes based on accurate-stroke-count studies”, Journal of Geophysical Research: Atmospheres 117.D6, 2012.
[18] L. Antunes, A. C. V. Saraiva, O Pinto Jr., J. Alves, L. Z. S. Campos, E. S. A. M. Luz, C. Medeiros, T. S. Buzato, ”Characterization of lightning observed by multiple high-speed cameras”, International Symposium on Lightning Protection (XII SIPDA), pp. 17–25, 2013.
[19] D. R. Poelman, W. Schulz, and C. Vergeiner, “Performance Characteristics of Distinct Lightning Detection Networks Covering Belgium”, J. Atmos. Oceanic Technol., vol. 30, no. 5, pp. 942–951, 2013.
[20] N. Kitagawa, M. Brook, and E. J. Workman, ”Continuing currents in cloud-to-ground lightning discharges”, Journal of Geophysical Research 67.2 (1962): 637-647.
[21] V. A. Rakov and M. A. Uman, ”Some properties of negative cloud to ground lightning flashes versus stroke order”, Journal of Geophysical Research: Atmospheres 95.D5: 5447-5453, 1990.
[22] V. Cooray and H. Pérez, ”Some features of lightning flashes observed in Sweden”, Journal of Geophysical Research: Atmospheres 99.D5: 10683-10688, 1994.
[23] V. Cooray and K. P. S. C. Jayaratne, ”Characteristics of lightning flashes observed in Sri Lanka in the tropics”, Journal of Geophysical Research: Atmospheres 99.D10: 21051-21056, 1994.
[24] A. C. V. Saraiva, M. M. F. Saba, O. Pinto Jr., K. L. Cummins, E. P. Krider, and L. Z. S. Campos, ”A comparative study of negative cloud-to-ground lightning characteristics in São Paulo (Brazil) and Arizona (United States) based on high-speed video observations”, Journal of Geophysical Research: Atmospheres 115.D11, 2010.
[25] Z.A. Baharudin, N. A. Ahmad, J.S. Mäkelä, M. Fernando, V. Cooray, ”Negative cloud-to-ground lightning flashes in Malaysia”, Journal of Atmospheric and Solar-Terrestrial Physics 108: 61-67, 2014.
[26] S. A. Fleenor, C. J. Biagi, K. L. Cummins, E. P. Krider, X. Shao, ”Characteristics of cloud-to-ground lightning in warm-season thunderstorms in the Central Great Plain” Atmospheric Research 91.2: 333-352, 2009.
[27] Z. A. Baharudin, V. Cooray, M. Rahman, P. Hettiarachchi, N. A. Ahmad, ”On the characteristics of positive lightning ground flashes in Sweden” Journal of Atmospheric and Solar-Terrestrial Physics 138: 106-111, 2016.

[28] M. M. F. Saba, W. Schulz, T. A. Warner, L. Z. S. Campos, C. Schumann, E. P. Krider, K. L. Cummins and R. E. Orville, ”High-speed video observations of positive lightning flashes to ground” Journal of Geophysical Research: Atmospheres 115.D24, 2010.
[29] A. Nag and V. A. Rakov. ”Positive lightning: An overview, new observations, and inferences”, Journal of Geophysical Research: Atmospheres 117.D8, 2012.
[30] X. Qie, Z. Wang, D. Wang, and M. Liu, ” Characteristics of positive cloud-to-ground lightning in Da Hinggan Ling forest region at relatively high latitude, northeastern China”, Journal of Geophysical Research: Atmospheres 24: 13,393–13,404, 2013.