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Some Field Parameters of Return Strokes in Upward Lightning from Tall Objects

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***Abstract*—In this paper we show an analysis regarding the Peak-to-Zero (PTZ) time, the rise time, and the peak current for strokes to tall objects. It was previously shown that field pulses radiated by return strokes to the Gaisberg Tower (GBT) exhibit a smaller PTZ time than natural CG strokes [1]. We compare field data (LLS sensor reported field parameters) from strokes to the GBT to field data from strokes detected during winter thunderstorms. We show that winter thunderstorms exhibit smaller PTZ times independent if the strike is to a tall object or not. We also present evidence that the PTZ time does not depend on the lightning channel length, using the altitude of the -10° C isotherm as a proxy of the channel length. The -10° C isotherm is often assumed to be the altitude of the negative charge center. The results obtained in this study indicate that the hypothesis of an influence of the channel length on the resulting PTZ time is not valid.**

Keywords-lightning; electromagnetic fields; peak-to-zero times; lightning location systems; lightning to towers; upward initated lightning

I. Introduction

Field pulse widths and Peak-to-Zero (PTZ) times of lightning electromagnetic fields are of interest for various reasons in lightning research. E.g. Peak-to-Zero time is one of the parameters used by lightning location systems (LLS) to discriminate between cloud-to-ground (CG) and intra-cloud (IC) lightning or PTZ is a criterion to validate return stroke models [2].

The Austrian LLS ALDIS/EUCLID provides for each stroke an estimated peak current, a PTZ time, and a rise time. The ALDIS/EUCLID determines the rise-time and PTZ time as follows: Each sensor reports several parameters obtained from the measured magnetic field waveform to the central processor. The time between an initial detection threshold and the occurrence of the peak of the same polarity is identified as the rise-time and the time between the peak and the subsequent zero crossing is identified as the PTZ time. When the location of the stroke is calculated and hence the distance to each contributing sensor is known, rise time and PTZ for the given stroke are taken from the closest reporting sensor that is at least 50 km from the estimated ground strike point. By requiring a minimum distance of 50 km it is guaranteed that purely radiated fields are evaluated without any effect of near field components [3] on field rise time and PTZ.

For field pulses radiated from return strokes in upward lightning initiated from the Gaisberg Tower (GBT) and measured at a distance of about 100 km a PTZ time of 10 µs is reported by Pichler et al. [4]. This is significantly smaller than typical values of 30 – 40 µs obtained for strokes in downward lightning [5]. The relatively short lightning channel in case of return strokes in object initiated lightning is mentioned in [4] as a possible reason for the observed differences in the PTZ values .

Further Diendorfer et al. [1] presented an analysis regarding PTZ time differences between lightning strikes to the GBT and lightning strikes to ground. They compared the PTZ times obtained for three different data sets. (1) Strokes in upward lightning from the GBT, (2) CG strokes in a ring area (radius 2-10 km) around the GBT location, and (3) CG strokes validated with video data. Again they found a significantly smaller PTZ time for strokes to the GBT. In [1] the analyses of field parameters related to the GBT was based on individual sensor data contributing to the location of the stroke. Therefore, in this case, several sensors and not only the closest sensor (minimum distance 50 km) contributed to the resulting PTZ value of a given stroke.

In this paper we try to look into more detail to the cause of the observed PTZ (width) differences. There are different possible causes. One potential cause, a shorter lightning channel in case of an object triggered stroke [4], was already mentioned before. In order to test this hypothesis we have to estimate the altitude of the negative charge region which normally depends on the season and thunderstorm type [6]. It is generally assumed that the main negative charge region in a thundercloud is located in the temperature range from 0 to -25°C [7], [8]. The height of the negative charge center is often assumed to be at the altitude of the -10° C isotherm [9]. Therefore we will use the height of the -10° C isotherm as an estimate of the altitude of the negative charge region at the time of occurrence of a GBT flash.

Another potential cause of the observed shorter widths (PTZ) values is the preconditioning of the lightning channel due to the initial continuous current (ICC) prior to the return strokes in object triggered lightning. The ICC with amplitudes of some hundred amperes and lasting for several hundreds of milliseconds may affect the discharging conditions (channel temperature, channel conductivity, etc.) for the return strokes following the ICC. This potential cause is not subject to this paper.

In order to test if there are similar PTZ differences for strokes initiated from other high objects in Austria, independent of the GBT, we analyzed the PTZ time also for detected strokes in some winter thunderstorms in Austria, These winter storms often generate a high number of upward lightning. In order to select upward strokes only we analyzed the stroke location of each individual stroke on satellite images (e.g. Google Earth) and categorized the stroke as either a stroke at a tall tower (TT), a stroke to a wind turbine (WT), a stroke to another tall object (Others), or a stroke without any tall object nearby (No). Besides the PTZ time this analysis also provides the rise time and the peak current for each of those strokes. In order to make the results in [1] comparable with the current analysis we reanalyzed the GBT data from 2000-2009 according to the methodology used in this study (only closed sensor determines rise time and PTZ value).

II. Evaluation of Winter Thunderstorms - Data and Weather Situation

We analyzed all negative strokes located by the LLS in four typical winter thunderstorm days in Austria – see Table I. Winter thunderstorms in Austria are typically related to cold fronts passing over Austria and they are often accompanied by graupel showers and a significant temperature drop.

TABLE I. Number of Analyzed Strokes per Winter Thunderstrom Day

Day	Positive strokes	Negative Strokes[1)]	Negative CG	Negative IC
2012-02-15	34	112	43	69
2012-02-26	24	66	44	22
2015-04-01	62	419	269	150
2015-04-02	17	322	217	105

[1)] CG and IC strokes

For all four days we have obtained the altitude of the -10° C isotherm from radio sounding station in Vienna. The mean altitude of the isotherm for the four days was about 2000 m. As an example we show the meteorological situation before (Fig. 1) and after (Fig. 2) the winter thunderstorm on 2012-02-15.

The lightning activity for the day 2012-02-15 is shown in Fig. 3. It shows the lightning activity over Central Europe. It can be seen that the main activity occurred in Austria, mainly in eastern part of the country, and the passing cold front caused only some additional strokes in Germany. Fig. 4 shows the lightning activity within Austria in more detail. Only negative strokes located within the borders of Austria are analyzed in section IV of this paper.

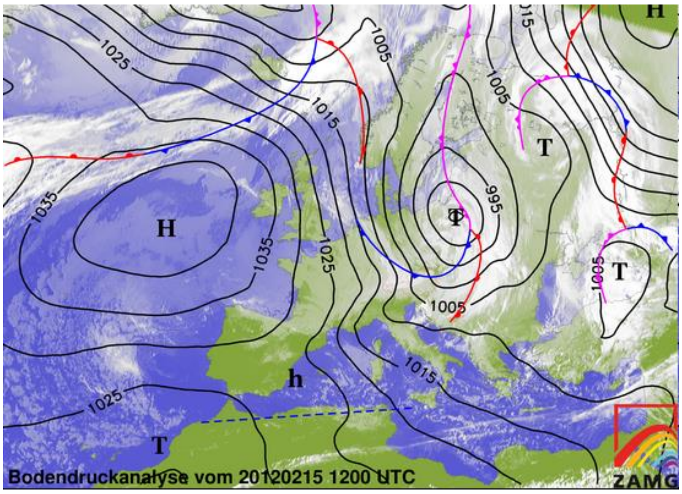

Fig.1: Cold front passing over Austria. Surface pressure analysis (Bodendruckanalyse) on 2012-02-15 before (12:00 UTC) the thunderstorm.

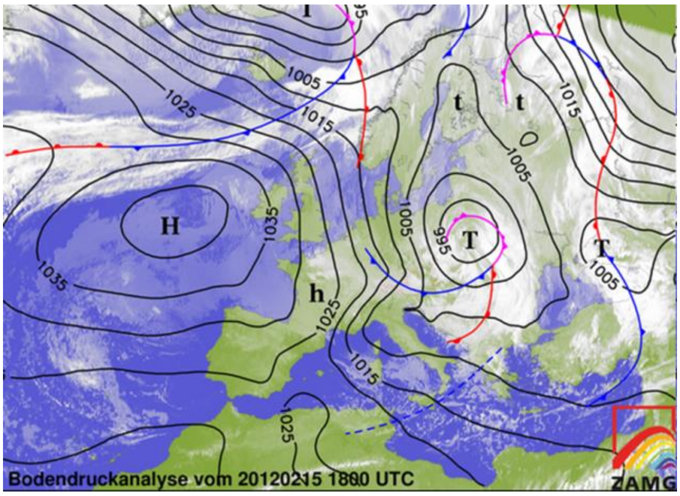

Fig.2: Cold front passing over Austria. Surface pressure analysis (Bodendruckanalyse) on 2012-02-15 after (18:00 UTC) the thunderstorm.

During the analysis of the lightning data by using satellite images (e.g. Google Earth) we assigned strokes to a certain object if the object was closer than 500 m to the LLS estimated strike point. Of course this method to determine strike points has some limitations which are:

- The satellite images may be outdated. New wind turbines may have been installed after the latest update of the satellite images.
- The median and the 95% locations accuracy of the LLS in Austria are about 100 m and 1500 m, respectively [10]. There is still a small chance to erroneously categorize a few strokes having location errors greater than 500 m.

Fig.3: Lightning activity on2012-02-15 in Europe. Individual strokes are shown as yellow dots (negative CGs), black stars (positive CGs) and red triangles (IC discharges).

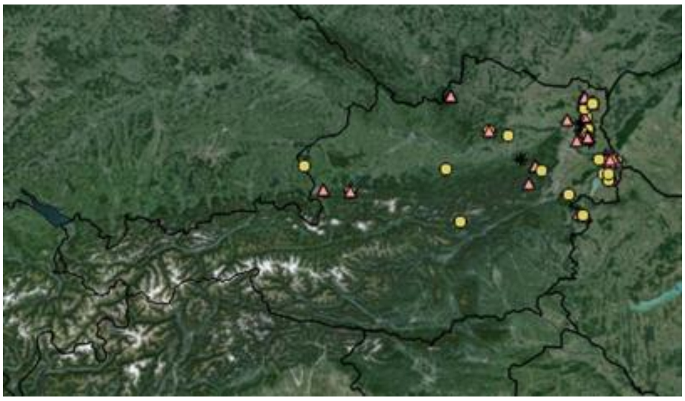

Fig.4: Lightning activity on 2012-02-15 within the border of Austria. Individual strokes are shown as yellow dots (negative CGs), black stars (positive CGs) and red triangles (IC discharges).

III. Gaisberg Data Evaluation

Because in Diendorfer et al. [1] no rise time and peak current was evaluated, and the evaluation of the PTZ time was done based on sensor data (2000-2009), we reevaluate these data for the same time period to make the analysis identical to the procedure used in the current study. Because there are no PTZ data available in the lightning location database before 2003, and a rise time is not assigned to all the strokes in the ALDIS database, the number of samples in Table II differs for the individual parameters.

In this analysis we use stroke data from the LLS and the LLS also classifies the strokes as IC or CG according to the PTZ time. As the fields mean PTZ time from strokes in upward lightning is smaller than from strokes in natural downward lightning [1], a significant part of the strokes in upward lightning is erroneously classified as IC stroke. Table II shows the median PTZ time, the median rise time, and the median peak current after the reevaluation of all GBT strokes (including IC classified strokes), and for those GBT strokes classified by the LLS as CG. Interestingly the median PTZ time of 11.6 µs obtained from the PTZ reported by the closest sensor for all strokes to the GBT is quite similar to the original value of 11 µs reported in [1]. In Table II we also show the results for the LLS classified CG strokes only. The median PTZ is greater for the CG strokes compared to all strokes because the PTZ is used by the LLS for classification as mentioned before. The LLS classifies a stroke as IC if the two best (closest) sensors report a PTZ time of less than 12 µs.

TABLE II. Median PTZ time, rise time and peak current for the GBT strikes located by the LLS (2000-2009)

	Median PTZ time (µs)	Median rise time (µs)	Median peak current (kA)
GBT all Strokes	11.6 (N=980)	3.0 (N=1392)	9.1 (N=1407)
GBT CG Strokes	12.6 (N=775)	2.8 (N=1185)	8.9 (N=1197)

It is important to note that sensors employed in the LLS network during the time period 2000-2009 reported PTZ times of up to 30 µs. For all PTZ times being greater than 30 µs the LLS sensors assigned a fixed PTZ value of 30.1 µs.

It is further important to note that the majority of the PTZ and rise times in the analysis for the GBT are measured by sensor #4 (Niederöblarn). This is because of the criteria applied to assign PTZ and rise time to a stroke mentioned above. Sensor #4 is the closest sensor with a distance of more than 50 km to the GBT and therefore it is used for the PTZ and rise time of a stroke whenever this sensor is contributing to the stroke location. We do not expect any significant influence on the resulting PTZ value, because the result for all GBT strokes (11.6 µs) in Table II is quite similar to the 11µs reported in [1], when PTZ values of several sensors contributing to the location of a stroke were used.

We analyzed the altitude of the -10° C isotherm for strokes to the GBT for the years 2007-2015. For this purpose we used the sounding data from the station in Munich, the closest station to the GBT, where a balloon with a radiosonde is launched every day at 00:00 UTC and 12:00 UTC. A further reason to use the station data from Munich is that in Austria there are often westerly flow situations, meaning that frontal systems are coming from the west. We determined the altitude of the -10° C isotherm from the last sounding available before and the first sounding available after the event, respectively.

Fig. 5 shows the average altitude of the -10° C isotherm versus month before and after the event at the GBT for all the flashes to the GBT independent of their categorization as ICC_{only}, ICC_{pulse}, or ICC_{RS}. Since many times cold fronts are causing those upward discharges, the average altitude of the -10° C isotherm after the event is often lower than it is before the event. Otherwise the results are as expected – the average -10° C altitude is higher during the summer months compared to the winter months.

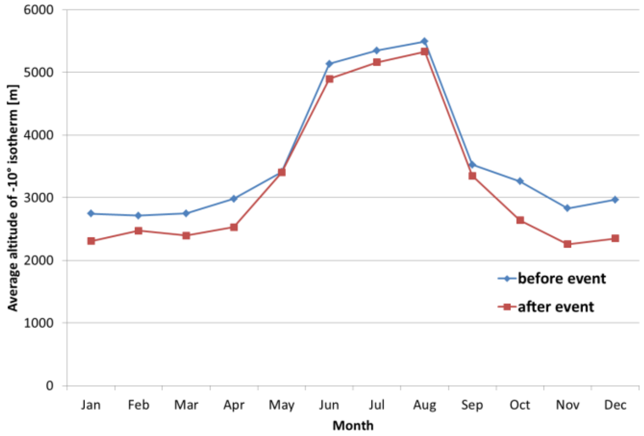

Fig.5: Average altitude of -10° C isotherm versus month for all GBT triggered flashes in the time period 2007 - 2015

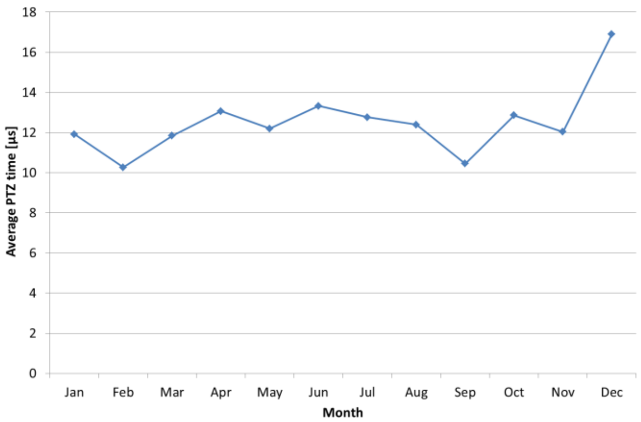

Fig.6: Average PTZ time versus month (B) for all GBT triggered flashes 2007 - 2015

The average PTZ values versus months in Fig. 6 are based on LLS detected stroke data from GBT, independent of their IC or CG classification. Assuming that the channel length correlates with the altitude of the -10° C isotherm, in case of any influence of the channel length on the PTZ time we would expect to see in Fig. 6 a similar trend as in Fig. 5. As this is obviously not the case, this indicates that there is no significant influence of the channel length on the lightning channel radiated field PTZ time.

Further Fig. 7 shows that there is also no relation between the altitude of the -10° C isotherm and the number of return strokes (multiplicity) in the flashes to the GBT. Because erroneously classified IC strokes (see above) are assigned by the LLS stroke to flash grouping algorithm to separate flashes, the multiplicity was obtained from the GBT current records. Only return strokes in the flashes to the GBT are used in Fig. 7.

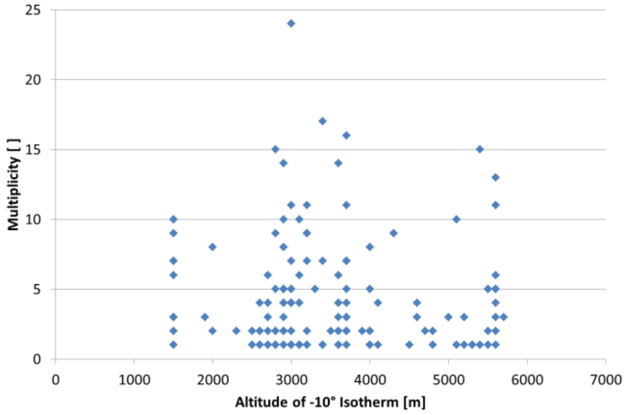

Fig.7: Multiplicity versus altitude of -10° C isotherm of the GBT flashes during the time period 2007 - 2015

IV. Evaluation of Winter Thunderstorms

From the analysis of the located lightning strokes placed on high resolution satellite images (e.g. Google Earth) we found that during the two winter thunderstorms in 2012 (see Table I) about 57% of the strokes (categories WT, TT and Others) were correlated with tall objects whereas during the 2015 winter thunderstorms about 70% were correlated with tall objects (see Fig. 8 and Fig. 9).

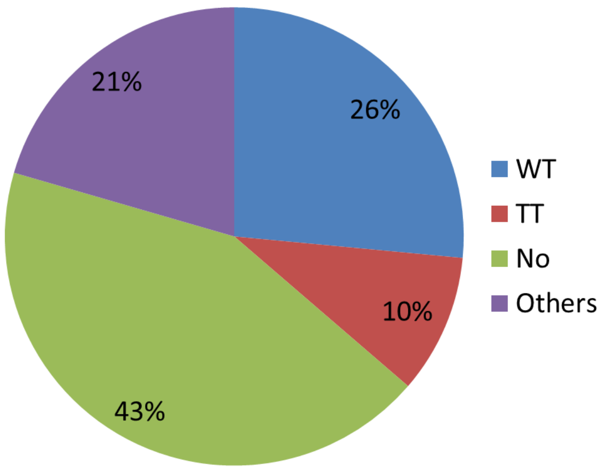

Fig. 8: Percentage of strokes to Wind Turbines (WT), tall Towers (TT), without any elevated object (No) and to other objects (Others) during the 2012 winter thunderstorms

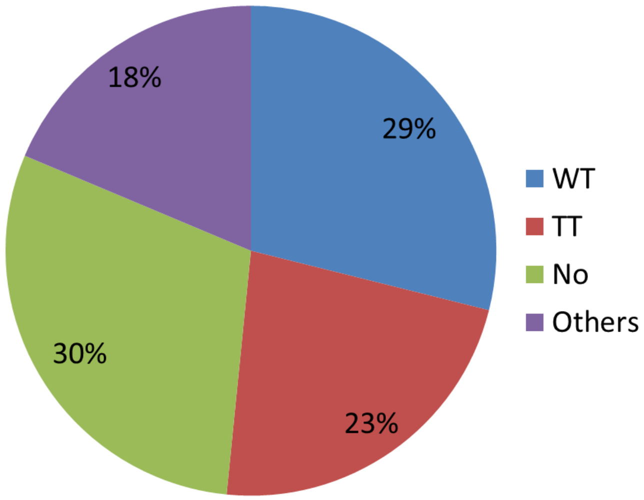

Fig. 9: Percentage of strokes to Wind Turbines (WT), tall Towers (TT), without any object (No) and to other objects (Others) during the 2015 winter thunderstorms

The category "Others" in Fig. 8 and Fig. 9 includes mountain tops, light masts, overhead line towers, church towers, and other tall objects visible from the satellite images.

For comparison with LLS data during typical summer thunderstorms we use a circular region in the north-east of Austria with the center located at 16.607° longitude and 48.566° latitude and a radius of 30 km. We searched for a flat region with a small number of tall objects.

An analysis of the mean multiplicity of all CG flashes during each of the four winter thunderstorm days in Austria is shown in Table III. The daily multiplicity of CG lightning in summer thunderstorms in the circular region described above and with more than 100 flashes per day is in the range from 1.7 to 3.2. The daily multiplicities of the winter thunderstorms (only 4 days) shown in Table III are in the same range and therefore not indicating any significant differences.

TABLE III. MEAN MULTIPLICITY FOR NEGATIVE CG FLASHES DURING WINTER THUNDERSTORMS AUSTRIA

	Mean multiplicity
2012-02-15	1.8 (N=24)
2012-02-26	2.5 (N=18)
2015-04-01	2.7 (N=98)
2015-04-02	2.8 (N=81)

Table IV and Table V show the analysis of the merged CG data of the two winter thunderstorms in 2012 (2012-02-15 and 2012-02-26) in 2015 (2015-04-01 and 2015-04-02), respectively.

TABLE IV. ANALYSIS OF FIELD PARAMETERS FROM STROKES IN UPWARD LIGHTNING IN WINTER THUNDERSTORM FOR 2012-02-15 AND 2012-02-26

2012-02-15 2012-02-26	N	Median PTZ time (µs)	Median rise time (µs)	Median peak current (kA)
All negative CG	87	16.0	4.4	8.8
Negative CG (No)	30	15.9	8.5	8.1
Negative CG (WT+TT)	34	15.7	2.2	9.4
Strokes in Circular area in summer 2012 (CG)	2479	22.8	4.2	12.1

TABLE V. ANALYSIS OF FIELD PARAMETERS FROM STROKES IN UPWARD LIGHTNING IN WINTER THUNDERSTORM FOR 2015-04-01 AND 2015-04-02

2015-04-01 2015-04-02	N	Median PTZ time (µs)	Median rise time (µs)	Median peak current (kA)
All negative CG	486	17.1	5.0	8.6
Negative CG (No)	115	18.4	6.8	8.8
Negative CG (WT+TT)	299	16.3	4.4	8.2
Strokes in circular area in summer 2015 (CG)	622	22.4	4.0	11.3

During the winter thunderstorms in both years the median PTZ time of the field pulses from all negative CGs, negative CGs without close tall object (No), and negative CGs close to tall towers and wind turbines (TT+WT) exhibit similar median PTZ times. Further those PTZ times are significantly smaller than the median PTZ times from summer thunderstorms. Also the median peak currents are smaller during winter thunderstorms and there is again no significant difference between strikes close to tall objects and strikes without any tall object nearby. Analyzing the combination of CG+IC data (not shown here) only increased the number of available data but did not change the overall result.

Median PTZ times during the two 2015 winter thunderstorms are slightly larger than during the two 2012 thunderstorms but similar for the summer thunderstorms. The reason for this is currently unclear.

V. DISCUSSION

The analysis of field pulses radiated by return strokes to the GBT shows a smaller PTZ time compared to natural CG strokes shown in [1]. One possible explanation is a shorter lightning channel (distance between the strike point and the negative charge region) in case of upward initiated lightning. If we use the altitude of the -10° C isotherm close to the GBT as a proxy for the altitude of the negative charge center we observe, as expected, a strong variation of this altitude by season (Fig. 5). Interestingly we do not observe a similar variation over season for the PTZ values for the field pulses radiated by the strokes to the GBT (Fig. 6). This indicates that the shorter length of the lightning channel is not causing the observed smaller PTZ values.

The analysis of strokes during winter thunderstorms in Austria independent of strikes to the GBT indicate that the PTZ time is more or less independent of the strike object (high object or ground) but the PTZ times in winter are remarkably different from strokes in summer thunderstorms. This also supports the hypothesis that there must be other reasons than a shorter channel length to explain the significantly smaller PTZ times measured in the field pulses radiated by strokes to the GBT.

Another possible explanation for the observation of smaller PTZ times in case of return strokes to the tower is the existence of an initial continuing current (ICC) in all upward initiated flashes, which may precondition the lighting channel in a certain way before it is followed by the return strokes.

Assuming that winter lightning without any nearby tall object (category "No" in this paper) is predominantly downward lightning and that downward lightning in winter exhibits the same probability of occurrence of continuing currents (CC) as during summer, we would expect for this category to obtain about the same PTZ times for strokes in summer and winter time Contrary to that, the PTZ values in Table IV and Table V do not show any pronounced differences between the category "No" and the tall objects (WT, TT), for lightning during winter thunderstorms. The hypothesis of a preconditioning effect by an ICC or CC was not further tested in this paper but will be analyzed in the future.

ACKNOWLEDGMENT

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REFERENCES

[1] G. Diendorfer, W. Schulz, and H. Pichler, "Zero-Crossing Time and Pulse width of Radiated Fields from Lightning to Elevated Objects," in *International Conference on Grounding and Earthing and International Conference on Lightning Physics and Effects (GROUND/LPE)*, 2010, pp. 241–243.

[2] V. A. Rakov and M. A. Uman, "Review and evaluation of lightning return stroke models including some aspects of their application," *Electromagn. Compat. IEEE Trans.*, vol. 40, no. 4, pp. 403–426, 1998.

[3] E. A. Bardo, K. L. Cummins, and W. A. Brooks, "Lightning Current Parameters Derived from Lightning Location Systems: What can we Measure?," in *18th International Lightning Detection Conference (ILDC)*, 2004, no. 39, pp. 1–13.

[4] H. Pichler, G. Diendorfer, and M. Mair, "Some parameters of correlated current and radiated field pulses from lightning to the Gaisberg tower," *IEEJ Trans. Electr. Electron. Eng.*, vol. 5, no. 1, pp. 8–13, 2010.

[5] V. Cooray and S. Lundquist, "Characteristics of the radiation fields from lightning in Sri Lanka in the tropics," *J. Geophys. Res. Atmos.*, vol. 90, no. D4, pp. 6099–6109, 1985.

[6] M. Stolzenburg, W. D. Rust, and T. C. Marshall, "Electrical structure in thunderstorm convective regions: 3. Synthesis," *J. Geophys. Res.*, vol. 103, p. 14079, 1998.

[7] V. A. Rakov and M. A. Uman, *Lightning - Physics and Effects*. Cambridge University Press, 2003.

[8] P. R. Krehbiel, "The Electrical Structure of Thunderstorms," in *The Earth´s Electrical Evironment*, Washington, DC: National Academy Press, 1986, pp. 90–113.

[9] A. C. V. Saraiva, "Study of the Determinant Aspects of the negative Cloud-to-Ground Lightning Paramters (in Portuguese)," 2010.

[10] W. Schulz, "Location Accuracy Improvements of the Austrian Lightning Location System During the Last 10 Years," in *Lightning (APL), 2015 9th Asia-Pacific International Conference on*, 2015.