Charge transfer and waveforms of long continuing currents in negative and positive downward flashes

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***Abstract*—In this paper the results of a simple model for the calculation of continuing currents (CCs) and the corresponding transferred charge in natural negative and positive downward lightning are presented. The model takes into consideration the height of the charge center in the cloud, the distance of the measurement system to the lightning strike point and the true, undistorted E-field at the location of observation. The evaluation is based on ground truth data from field campaigns in 2015 and 2017 in Austria, where E-fields and simultaneous high speed video recordings of the lightning channels were obtained. 76 cases of negative and 12 cases of positive downward lightning containing long continuing currents (CC duration > 40 ms) were analysed. Parameters such as duration mean and median values of the amplitude and transferred charge of CCs were evaluated and compared to other studies. Further, the continuing current waveforms were divided into five equal segments of which the results on the statistics are presented by means of boxplots.**

Keywords—continuing currents, charge transfer, fast E-field, decay time constant compensation

I. INTRODUCTION

Transferred charge and therefore continuing currents (CCs) are important lightning parameters for lightning protection. Continuing currents that last from several tens to several hundreds of milliseconds give rise to a thermal effect due to the high transferred charge which is much more severe compared to lightning discharges without continuing currents. The possible damage ranges from ignition of (forest) fires (Fuquay et al., 1967 [1]), over power line damage (Nakahori et al., 1982 [2]) and destroyed blades of windmills, up to holes in metal skins of aircraft. This impacts the question of measures of safety in many fields, where exposure to lightning discharges is relevant. Therefore, a variety of studies have already been conducted, with the goal to quantify important parameters such as the duration of continuing currents and their transferred charge, as well as their statistical occurrence.

A detailed quantitative analysis of continuing currents and estimation of their transferred charge, based on remote E-field measurements, was done in (Brook et al., 1962 [3]). They reported an average duration of negative long CC (>40 ms) of 150 ms and the magnitudes in the range from 38 A to 130 A with an average of about 80 A. The transferred charges reached from 3.4 C to 29.2 C with an average of 12 C that were lowered to ground by a long CC. Kitagawa et al. (1962) [4] reported long CC durations between 40 and 500 ms, on average 180 ms.

By using magnetic field measurements, Williams and Brook, (1963) [5] analysed 14 continuing currents with an average of 184 A of magnitude, lowering a negative charge of -31 C to ground. The average duration of the CCs was 174 ms.

Krehbiel et al. (1979) [6] found negative continuing current magnitudes to be in the range of 50 A to 580 A with a peak current occurring at the initial stage and decreasing with time at a rate of about 3 to 6 A/ms.

Shindo and Uman (1989) [7] reported, based on a single-station E-field measurement, a geometric mean duration of negative long CCs of 115 ms with average amplitudes in the range from 30 to 200 A. The transferred charge for those events was between about 3 C to a maximum of almost 40 C.

Ferraz et al. (2009) [8], estimated values of CC following cloud-to-ground (CG) discharges, obtained from single-station E-field measurements and reported magnitudes in the range of 30 A to 1000 A with an average/median of 292 A/198 A and transferred charge ranging from 1 to 370 C.

For positive CG discharges Matsumoto et al. (1996) [9] reported the case of a CC with an amplitude of 10 kA and 35 ms duration, that followed a natural +CG hitting a powerline. A similar result was obtained by Schumann and Saba (2012) [10] by single-station remote E-field measurements, where they estimated currents ranging from 100 A up to 11.4 kA. Further Schumann and Saba (2012) [10] reported for +CG transferred charges of 18 C to 3070 C, which is significantly higher compared to CCs following -CG discharges.

Recently Schumann et al. (2016) [11] presented results, where they estimated the transferred charge from natural negative and positive downward lightning in the USA, in Austria and in Brazil. In the USA, the average magnitude of negative CC was 49.6 A with an average transferred charge of 10.2 C and average duration of 189.4 ms. For Austria and Brazil the values were 68.9 A, 10.3 C, 142.2 ms and 140.5 A, 21.2 C, 180.1 ms, respectively. For the positive cases in the USA / Austria / Brazil the following results were found: 223.3 A, 67.4 C, 285.6 ms / 291.8 A, 95.5 C, 119 ms / 865.9 A, 251.2 C, 257 ms.

The method to determine the CC, which was used in Schumann et al. (2016) [11], is the same as in this paper. The model takes into account the height of the charge center in the cloud, the distance of the observation point (location where the E-field was measured) from the lightning strike point and an E-field recording, representing the electrostatic field during the event. For this, an undistorted E-field waveform must be obtained. Since E-field measurement systems often utilize amplifiers that include an intentional decay time constant in order to be stable, the E-fields are distorted and represent the true E-field, present at the point where the waveform is recorded, only within a certain bandwidth. Due to the decay time constant, below a certain cut-off-frequency of several tens to several hundreds of Hz, slow signal changes will be attenuated differently for different frequencies which lie below the cut-off frequency. This time constant must therefore be compensated in an additional step. Methods for doing this are presented in Rubinstein et al. (2012) [12] or Kohlmann et al. (2017) [13]. The same approach was used in an earlier work by Mazur and Ruhnke (2003) [14] to treat the instrumentation decay of the signal amplifier used for their E-field recordings.

Ross et al. (2008) [15] extended the electrostatic field model by ionospheric phenomena, which give rise to image charge not only due the mirror plane at ground level, but also for the ionosphere as a mirror plane. They showed, that at large distances (>30 km) the E-field decline changes to exponential decay when more than ten image charge pairs are taken into account compared to the usual R^{-3} decay without ionospheric images. For the analysis in this paper, the distances were chosen close enough such that the E-fields had a good CC signature.

II. DATA & METHODOLOGY

The presence and duration of continuing currents was determined by inspection of the available high speed video material. In Diendorfer et al. (2003) [16] it was shown that the brightness of the channel correlates strongly with the amplitude of the CC. The current will be zero when there is no luminosity. Hence, for each case, the end time of the CC was obtained from the video when the luminosity of the channel has faded to invisible. Due to a gradual transition from high return stroke currents to CCs, the first 5 ms in the field, can be still considered to be part of the return stroke process. This is also described in Krehbiel et al. (1979) [6]. Therefore we also assumed that the actual CC process starts 5 ms after the radiation field peak in the E-field recording.

Before calculating the amplitude of the CC, it has to be determined first, how much charge was lowered from the cloud to ground by means of the available E-field. The following formula gives the relation of the charge Q and vertical electric field E at the point where the E-field was measured (Eq. (I)):

$$Q = 2\pi\varepsilon_0 \frac{(H^2 + D^2)^{\frac{3}{2}}}{H} E \qquad \text{(I)}$$

This is a simple model of a straight vertical lightning channel, where the charge center in the cloud is assumed to be a point charge Q at height H vertically above ground. It gives rise to a vertical electric field E at ground level at a distance D from the strike point. If the change of the electric field at time $n\cdot\Delta t$ is $\Delta E(n\cdot\Delta t) = E(n\cdot\Delta t) - E((n-1)\cdot\Delta t)$, then the transferred charge at time $n\cdot\Delta t$ is $\Delta Q(n\cdot\Delta t) = Q(n\cdot\Delta t) - Q((n-1)\cdot\Delta t)$ and can be calculated by applying Eq. (I). The resulting current at time $n\cdot\Delta t$ is then determined by

$$\mathrm{I}(\mathrm{n} \cdot \Delta \mathrm{t}) = \frac{\Delta \mathrm{Q}(\mathrm{n} \cdot \Delta \mathrm{t})}{\Delta \mathrm{t}} \qquad \text{(II)}$$

The height of the charge centers can be estimated by balloon or radio soundings in regions, where charge separation is usually assumed to take place (see Krehbiel et al., 1979 [6]).

Like in Schumann et al. (2016) [11] height H of the negative charge center in the cloud was determined by radio soundings. The values were obtained for the area around Vienna at the -10 °C temperature level for each day of measurement using the platform provided by University of Wyoming, Department of Atmospheric Science (http://weather.uwyo.edu/upperair/sounding.html).

The positive charge center was assumed to be 3 km higher. Schumann et al. (2016) [11] also made a sensitivity analysis, where the effect of a deviation of the values height H and distance D of the charge center from the true values on the calculated charge Q is shown. A similar sensitivity analysis can be found in Uman (1987) [17].

To record the E-field, a plate antenna connected to an amplifier with integrating behaviour was employed. The integrator has a short decay time constant of 0.47 ms (E-fast), which corresponds to a cut-off frequency of 340 Hz. The slow E-fields were obtained by the aforementioned compensation method (Rubinstein et al., 2012 [12], Kohlmann et al., 2017 [13]).

Furthermore, after compensation, a decrease of the field was observed after the current stopped. In theory we would expect to see a plateau in the E-field. Of course there are cases where further processes in the cloud will cause a visible change in the E-field, even though the CG event is practically over. Yet, there was a decline towards the time axis even in those cases, where obviously all processes have ended. Indeed, there are two phenomena that have to be considered:

- The amplifier consists of the well described fast integrator and of a second stage which is supposed to keep the offset at the output of the fast integrator low. This offset compensation is realized by a similar integrator circuit with a much longer time constant which is fed back to the (+) input of the OPA of the fast integrator. This does not disturb the results of the E-fast if it is active, but for the compensated waveform it introduces a correction towards zero, once a signal with a DC component is present (which it clearly is during a CC). The decline, which was measured in the laboratory, turned out to be not of clean exponential form. Still, a time constant best approximating the curve in the range of interest was estimated to be about 6 seconds. This additional time constant was also compensated, which lead to an average correction of +5% for the absolute value of transferred charge in the results.

- Secondly, there is a phenomenon called electric field recovery, which can occur after cloud-to-ground discharges. Depending on the distance of observation and the intensity of lightning activity, this can as well cause an exponential decay towards zero with relaxation time constants in the range of about 2 s up to 30 s or more. In cases of close E-field observation distances, even linear decay has been reported. This is mentioned for example in Krehbiel et al. (1979) [6] and described in Nakano (1975) [18].

The CC was then determined by means of the compensated waveforms, as described above in this section. For smoothing of the waveform, that contains measurement noise, a moving average of 10 samples was employed. Δt of Eq. (II) was in every case chosen to be ≤0.5 ms, but not too small, since this differentiation-like operation amplifies the measurement noise significantly and adds it to the resulting current waveform. The specific value for Δt resulted from the number N of Δt steps which were chosen for slicing the full CC duration (d_{CC}), hence $\Delta t = \frac{d_{cc}}{N}$. Therefore each case had a slightly different Δt, but in any case ≤ 0.5 ms. The influence of variations in Δt on the results of the analysis method, where the averages of segments of the CC are determined, is negligible.

For the analysis of the time dependence of the CCs obtained from the compensated E-fast with Eq. (I), the CC duration, starting 5 ms after the return stroke (see section II), was divided into 5 equal segments, for each case individually. The underlying assumption is, that the shape of the waveform does not depend (at least not heavily) on the total duration. For each of those segments, the mean I_{cc} was determined. The analysis and results of those processed I_{cc} waveforms are described in section III.

A total of 88 long CCs (CCs exceeding a duration of 40 ms) in the years 2015 and 2017 were analysed. The data set is composed of 76 long CCs following negative cloud-to-ground strokes (-CG) and 12 following positive cloud-to-ground strokes (+CG). Due to the high sensitivity of the charge Q in Eq. (I) with respect to the distance D from the strike point, only lightning discharges no closer than 5 km were used for the evaluation. The closest was 5.8 km and the most distant was 35 km. Also, fields that were clearly impacted by low frequency noise, for example caused by raindrops giving unwanted peaks and distortions in the field waveform, concurrent discharges at distant geographical locations, and field signatures which were implausible for CCs, were excluded from the evaluation.

In this paper, the term “magnitude” is used when the absolute value (for example $|I_{cc}|$) of a parameter is of interest rather than the “amplitude”, which is a signed value.

III. RESULTS & ANALYSIS

In the following, the main results for CCs in –CGs and +CGs are summarized and compared to results from other studies:

For CCs following a –CG, the arithmetic mean of the transferred charge, which was determined by applying Eq. (I), was -11.7 C (median -7.2 C) and the maximum charge observed was -82.6 C. The minimum transferred charge was -0.2 C, which occured in a subsequent RS with long continuing current. Together with a mean amplitude of -81 A (median -59 A), these values are in good agreement with values in the literature (see introduction). Further, they are in very good agreement with the results of the Austrian campaign obtained by Schumann et al. (2016) [11] for the years 2008-2012. This was expected, since the measurement system, the region and therefore the climatic conditions, and finally the methodology were all the same. The mean duration (2008 – 2012) was 142 ms and in this campaign (2015, 2017) it was 144 ms. The largest CC amplitude observed in this analysis was -398 A, where from 2008 to 2012 the maximum observed amplitude was -793 A. The longest duration of negative CC in our campaign was 438 ms which is in the same order as found by Schumann et al. (2016) [11], where it was 575 ms.

Cumulative probability plots for the negative CGs of the magnitude and duration are depicted in Fig. 1 and **Fig. 2**. The plots of current and duration are close to a straight line, hence the values are approximately lognormal distributed. The geometric mean value of the duration of negative CC was found to be 115 ms in Shindo and Uman, (1989) [7], which is as well in agreement with a median of 128 ms given by our analyses.

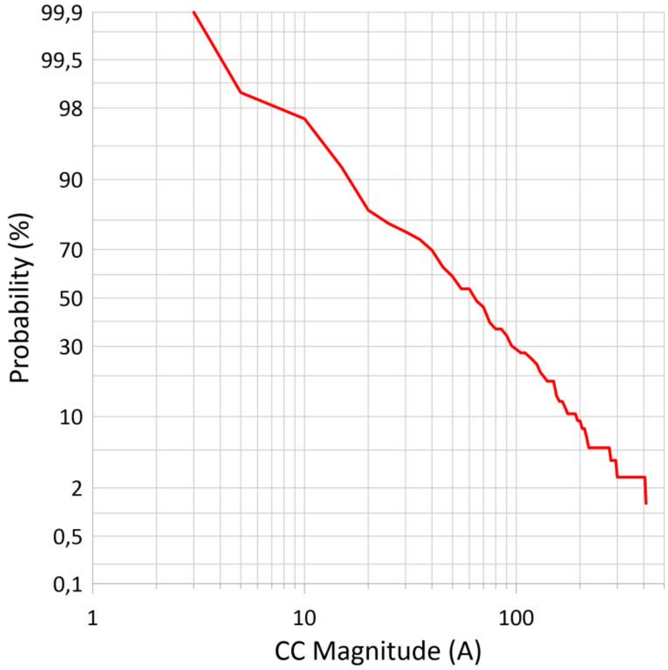

Fig. 1: Cumulative probability of CC magnitude

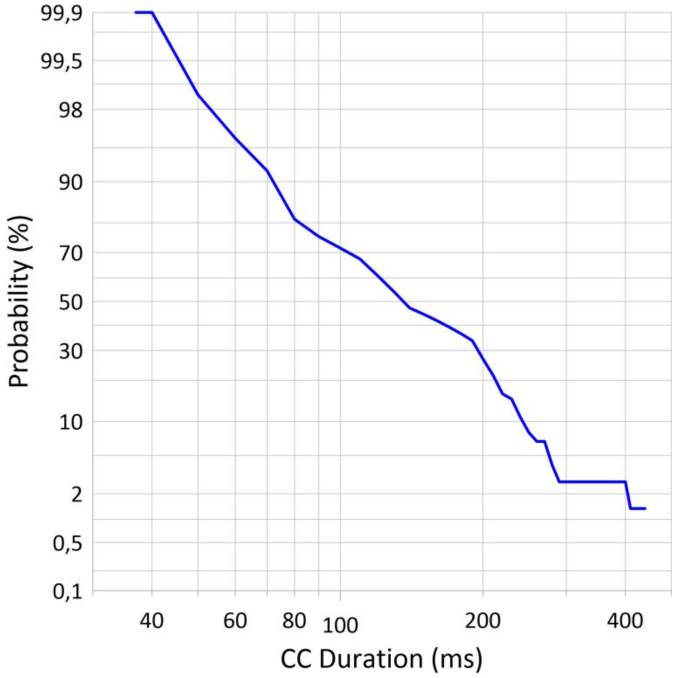

Fig. 2: Cumulative probability plot of CC duration.

The obtained arithmetic mean of the transferred charge for CCs following positive CGs was 234 C (median 205 C) with a mean current magnitude of 731 A. Maximum values of 433 C and 1.8 kA were measured. The average duration was 230 ms and geometric mean duration 200 ms. Since this data set is very small, the statements about the results in comparison to other studies have to be made with care.

The main results of the analyses are summarized in TABLE I.

TABLE I: CC parameters for the analyzed data

	-CG	+CG
Number of cases	76	12
Distance Min (km)	5.8	10.2
Distance Max (km)	35	27.9
Charge (mean / median) (C)	-11.7 / -7.2	151 / 92
Charge Min	-0.2	21
Charge Max	-82.6	433
I_{cc} (mean / median) (A)	-81 / -59	+731 / +612
I_{cc} min	-3	154
I_{cc} max	-398	1800
Duration (mean / median) (ms)	144 / 123	229 / 200
Duration min	37	37
Duration max	438	519

Further the I_{cc} of each event was averaged for each of the five segments, as mentioned in section II. In Fig. 3 these values (mean / median) of the average I_{cc} of each segment are visualized by means of Box plots for CCs following a negative CG. The values start from a median of -88 A in the 1st segment, descending to a median of -6 A in the 5th segment.

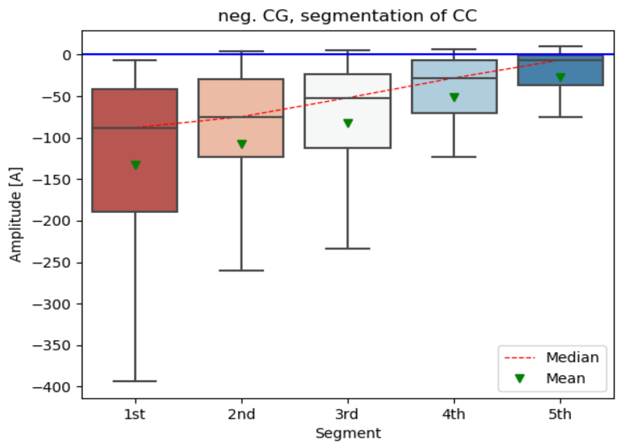

Fig. 3: Box plots of the segmented continuing currents following negative CG discharges (76 cases)

In Fig. 4 the segments for CCs following a positive CG are shown. Monotonically declining values can be observed for the mean, median and the maximum values for both negative and positive cases, which confirms the declining characteristic of continuing currents found in Krehbiel et al. (1979) [6], where a decrease rate of about 3 to 6 A/ms was observed for the three reported CCs following a -CG.

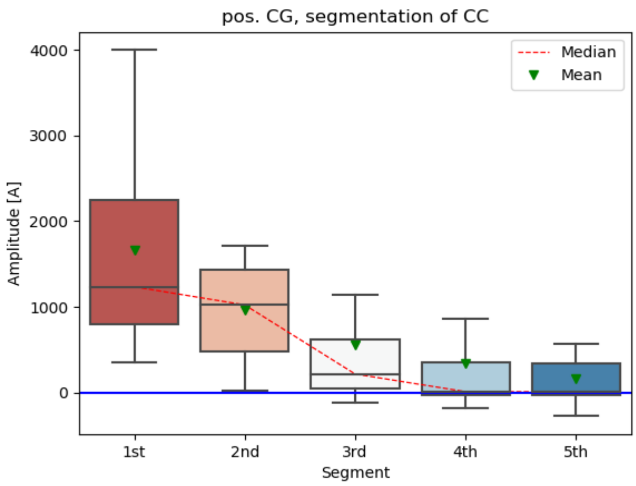

Fig. 4: Box plots of the segmented continuing currents following positive CGs for the corresponding segment (12 cases).

It is worth noting, that due to the small data set of positive CC cases, the mean and median values deviate a lot, since there are three outliers that pull up or down the average significantly. Still, the overall curve shows similar declining behaviour as in the –CG analysis. The results are summarized in TABLE II.

Further we analysed the magnitude of the current in the first 5 ms after the return stroke of a –CG with CC. It is on average 3.4 times stronger than the arithmetic mean of the amplitude over the full duration of the CC (see Table I). For +CG, a factor of 3.2 has been found.

TABLE II: Segmented analysis of CCs

	CC of –CG mean/median [A]	CC of +CG mean/median [A]
Continuing current [A]		
1st segment	-132 / -88	+1663 / +1235
2nd segment	-108 / -75	+960 / +1023
3rd segment	-82 / -52	+552 / +216
4th segment	-52 / -28	+342 / +11
5th segment	-26 / -6	+161 / +10

Another observation in this study was that in 42% of all CCs of –CGs the E-field change has faded to zero (resulting in vanishing calculated current amplitude) before luminosity in the video has faded to zero. In these cases, the currents were between 10 % and 69 %, on average 30 %, shorter than luminosity was observable on video. The effect might be related to charge motion during the CC processes, causing deviations from the static point charge model, leading to a smaller ΔE towards the end of the CC. Additionally, the process may be further influenced by a so-called electric field recovery triggered by the lightning discharge, which causes an exponential decay into the opposite direction. The relaxation time constant ranges from 2 s up to 30 s or more (see Krehbiel et al., 1979 [6], Nakano (1975) [18]), resulting in smaller calculated currents towards the end of the CC. The shorter the time constant is, the earlier the relaxation effect becomes dominant in the change of the E-field and the estimated current will fade to zero. This behaviour will be further analysed in the future.

IV. SUMMARY AND DISCUSSION

By using the method of compensating fast E-fields for their time constant, it is possible to recover undistorted E-fields. Consequently this allows a further step to estimate the magnitude and the transferred charge in a return stroke or CC by a point charge model. Although being a simplistic model to calculate transferred charge from single-station E-field recordings, the results show good agreement with values found in literature. Using that method for analysing 88 events in total, for 76 cases of CC of –CG, arithmetic mean values of -81 A amplitude, 144 ms duration and -11.7 C were obtained. For 12 cases of CC of +CG, the arithmetic means were 731 A, 229 ms and a charge of 234 C.

Although according to Fan et al. (2014) [19] it is not necessarily the case that CCs have their highest magnitude at the beginning of the CC process, in this study, the segmentation method showed that on average the CCs have a higher magnitude at the beginning, gradually descending towards the end of the process. The results showed a median amplitude of -88 A in the first segment and -6 A in the last segment for -CGs. For the positive CC cases, the same characteristic was observed although only 12 cases were considered. The first segment had a median amplitude of +1235 A and the last segment +10 A.

The sensitivity analysis in Schumann et al. (2016) [11] shows that at large distances (>15 km) a change in the height of the charge center towards lower altitudes results in bigger changes than towards higher altitudes. An error in distance is approximately as significant as an error in the height estimation towards lower values.

As a concluding remark it can be said, that despite the simple model that was used, this paper gives the overall impression that arithmetic and geometric mean values that were obtained, are in good agreement with the literature. Though, for the future, a more detailed, statistical study about the point charge estimation from single-station E-field measurements would be necessary with respect to the quality of data and estimation errors, in order to improve the quality of analyses and interpretation of the results.

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REFERENCES

[1] D. M. Fuquay, R. G. Baughman, A. R. Taylor, and R. G. Hawe, "Characteristics of seven lightning discharges that caused forest fires," *J. Geophys. Res.*, vol. 72, no. 24, pp. 6371–6373, 1967.

[2] K. Nakahori, T. Epawa, and H. Mitani, "Characteristics of Winter Lightning Currents in Hokuriku District," *IEEE Trans. Power Appar. Syst.*, vol. PAS-101, no. 11, pp. 4407–4412, Nov. 1982.

[3] M. Brook, N. Kitagawa, and E. J. Workman, "Quantitative study of strokes and continuing currents in lightning discharges to ground," *J. Geophys. Res.*, vol. 67, no. 2, pp. 649–659, 1962.

[4] N. Kitagawa, M. Brook, and E. J. Workman, "Continuing currents in cloud-to-ground lightning discharges," *J. Geophys. Res.*, vol. 67, no. 2, pp. 637–647, 1962.

[5] D. P. Williams and M. Brook, "Magnetic measurements of thunderstorm currents: 1. Continuing currents in lightning," *J. Geophys. Res.*, vol. 68, no. 10, pp. 3243–3247, 1963.

[6] P. R. Krehbiel, M. Brook, and R. A. McCrory, "An analysis of the charge structure of lightning discharges to ground," *J. Geophys. Res. Ocean.*, vol. 84, no. C5, pp. 2432–2456, 1979.

[7] T. Shindo and M. A. Uman, "Continuing current in negative cloud-to-ground lightning," *J. Geophys. Res. Atmos.*, vol. 94, no. D4, pp. 5189–5198, 1989.

[8] E. de C. Ferraz, "Measuring of Continuing Currents in Natural Negative Cloud-to-Ground Lightning on Brasil: Development of Equipment and First Results,"

PhD Thesis, 2009.

[9] Y. Matsumoto *et al.*, “Measurement of Lightning Surges on Test Transmission Line Equipped with Arresters Struck by Natural and Triggered Lightning,” *IEEE Trans. Power Deliv.*, vol. 11, no. 2, pp. 996–1002, 1996.

[10] C. Schumann and M. M. F. Saba, “Continuing current intensity in positive ground flashes,” in *Lightning Protection (ICLP), 2012 International Conference on*, 2012, pp. 1–5.

[11] C. Schumann *et al.*, “Charge transfer in natural negative and positive downward flashes,” in *Lightning Protection (ICLP), 2016 International Conference on*, 2016, vol. 4, no. 1, pp. 6–11.

[12] M. Rubinstein, J.-L. Bermúdez, V. A. Rakov, F. Rachidi, and A. M. Hussein, “Compensation of the Instrumental Decay in Measured Lightning Electric Field Waveforms,” *Electromagn. Compat. IEEE Trans.*, vol. 54, no. 3, pp. 685–688, 2012.

[13] H. Kohlmann, W. Schulz, and H. Pichler, “Compensation of integrator time constants for electric field measurements,” *Electr. Power Syst. Res.*, vol. 153, pp. 38–45, 2017.

[14] V. Mazur and L. H. Ruhnke, “Determining the striking distance of lightning through its relationship to leader potential,” *J. Geophys. Res. Atmos.*, vol. 108, no. D14, p. 4409, 2003.

[15] M. A. Ross, S. A. Cummer, T. K. Nielsen, and Y. Zhang, “Simultaneous remote electric and magnetic field measurements of lightning continuing currents,” *J. Geophys. Res. Atmos.*, vol. 113, no. D20, p. D20125, 2008.

[16] G. Diendorfer, M. Viehberger, M. Mair, and W. Schulz, “An Attempt to Determine Currents in Lightning Channel Branches from Optical Data of a High Speed Video System,” in *International Conference on Lightning and Static Electricity (ICOLSE)*, 2003, pp. 3–6.

[17] M.A.Uman, *The lightning discharge*, vol. 39, no. 11. 1987.

[18] M.Nakano, “Electric Field Recovery after Lightning Flash and Regeneration of Charge in Thundercloud,” *J. Meteorol. Soc. Japan*, vol. 53, no. 3, pp. 196–202, 1975.

[19] X. Fan, G. Zhang, Y. Wang, Y. Li, T. Zhang, and B. Wu, “Analyzing the transmission structures of long continuing current processes from negative ground flashes on the Qinghai-Tibetan Plateau,” *J. Geophys. Res. Atmos.*, vol. 119, pp. 2050–1063, 2014.