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Preliminary continuing current charge transfer estimates of downward lightning over Johannesburg, South Africa

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***Abstract*—The charge transferred during the continuing current phase of lightning events has been studied extensively, either through direct current measurements or electric field estimations, but has never been examined in South Africa. This paper describes a flat-plate antenna system installed in Johannesburg used to measure changing electric fields and infer continuing current charge transfer. This is done using charge estimation models. A preliminary dataset of 51 downward negative strokes and 5 positive strokes is discussed in this paper. Of the 51 negative strokes, 34 had continuing currents greater than 40 ms. Preliminary results indicate continuing current charge transfer arithmetic mean of 18.3 C. This is comparable with studies performed in Brazil, but larger than average values obtained in Austria and USA.**

***Keywords*—charge transfer; continuing current; electric field measurements; South Africa**

I. INTRODUCTION

Lightning protection systems and their robustness rely on the ability of the materials to safely and reliability conduct lightning current to ground. This is of particular concern during the continuous current phase of a lightning event, as this is where heating can occur. Hence, many studies estimating the amount of charge delivered during the continuous current phase of lightning events have been performed to establish parameters for lightning protection standards and designs. But in South Africa, studies of this nature have not yet been performed. With the South African National Standard 10313: Lightning Protection Standard currently under revision by the South African Standards Bureau (SABS) [1], estimates of the charge transferred during the continuous current phase of lightning events are needed.

This paper details the preliminary results of a study estimating the continuous current charge transfer of lightning events over Johannesburg utilizing flat-plate electric field measurements and methods similar to those utilized in studies performed in Brazil, USA and Austria.

II. BACKGROUND

On the subject of charge transfer during downward flashes, some different techniques have been used. One of these techniques utilizes electric field sensors. As Jacobson and Krider noted [2], the charge distribution in a cloud can be modelled as a spherically symmetrical point-charge that is neutralised from a cloud-to-ground lightning discharge as shown in figure 1.

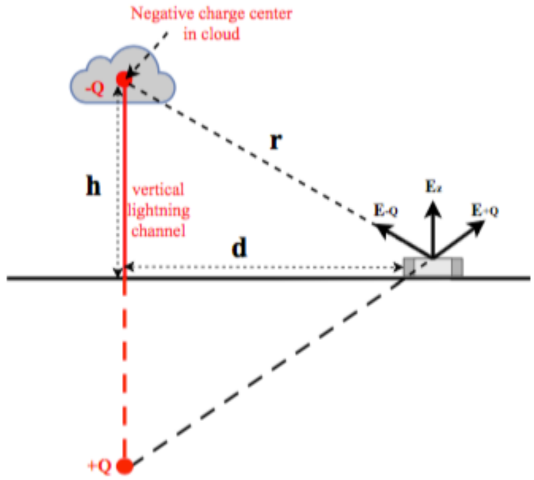

Fig. 1. Model used to estimate the charge transferred during a cloud-to-ground lightning event.

Using the geometry in figure 1, the change in charge as it moves from the height *h* can be related to the change in electric field ΔE measured at distance *d*. Therefore, the following equations can be derived:

$$E_Q = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r_i^2}$$

$$E_T = \frac{2Q}{4\pi\varepsilon_0 r_i^2}\cos\alpha$$

$$\Delta E_T = \frac{1}{2\pi\varepsilon_0}\frac{\Delta QH}{[H^2+D^2]^{3/2}}$$

$$\Delta Q = \frac{2\pi\varepsilon_0[H^2+D^2]^{3/2}}{H}\Delta E_T \quad (1)$$

The charge transfer (ΔQ) can then be calculated from equation (1) based on ΔE, which is the electric field change due to the continuing current.

Brooks et al. [3] and Kitagawa et al. [4] estimated charge transfers of 3.4 C to 29.2 C with an average of 12 C for negative downward flashes (-CG) in New Mexico. Ferraz et al. [5] found that -CG transferred charge values from 1C to 370 C in Brazil. Krehbiel et al. [6] combined multiple electric field stations and estimated –CG current ranges from 50 A to 580 A. Schumann et al. [7] presented average charge transfer values for Brazil, Austria and the USA. In Brazil, 251 C was found for positive flashes and 21.2 C for negative flashes. In Austria, 95 C for positive flashes and 10.3 C for negative flashes. In the US, an average of 67.4 C was found for positive flashes and 10.2 C for negative flashes.

Another technique to estimate the charge transfer utilizes a magnetometer. Williams and Brook [8] found a negative downward flash transferred 31 C with an average current of 184 A in New Mexico. The charge transfer can also be determined by direct strike measurements. Berger and Vogelsanger [9] found that 50% of the negative downward flashes transferred charge values of more than 25 C and the current ranged from 100A to 300A in Switzerland. In Brazil, Silverio et al. [10] found that the charge transferred from the first stroke of the positive downward flashes (5.75 C) is 4 times more than the charge transferred during the subsequent strokes (1.44 C). Miyake et al. [11] found values of transferred charge values were in the order of 1000C for positive strokes.

III. Equipment and Data

The following equipment is used to estimate charge transfer during the continuing current phase of lightning events over Johannesburg, South Africa.

A. *Flat-plate electric field equipment*

To estimate the charge transferred during the continuing current phase of lightning events over Johannesburg capacitive, flat-plate antenna is used. The antenna is located on the roof of a four story building, 19 m above the ground, at a location in the centre of Johannesburg.

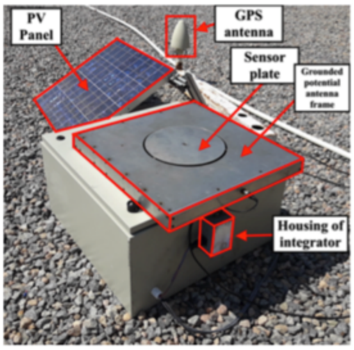

Fig. 2. Flat plate antenna system used to record fast changing electric fields.

Figure 2 shows the setup as installed. The flat plate antenna output is fed to an integrator with an approximate bandwidth of 300 Hz to 1.5 MHz and a decay time constant of 0.47 ms. The calibration factor (CF) is 4.34 mV/V/m. The output of the integrator is sampled by a PCI N-6110 National Instruments data acquisition unit at 5 MS/s with 12 bit resolution. Power to the integrator is maintained with a battery and PV panel. a Meinberg PCI-170GPS board is used to ensure that all recordings are accurately time-stamped. Given the height of the building, field enhancement is expected. this was experimentally determined to amplify the measurements by a factor of building factor (BF) =1.55.

B. *SALDN data*

To determine the distance of a recorded lightning event from the location of the electric field sensor, Lightning Location System (LLS) data was used. South African Lightning Detection Network (SALDN) data was acquired from the South African Weather Service (SAWS). The SALDN was first established in 2005 and is currently made up of 26 Vaisala LS7000 sensors distributed throughout South Africa [12]. Figure 3 shows the distribution of Vaisala LS7000 sensors around South Africa in 2014.

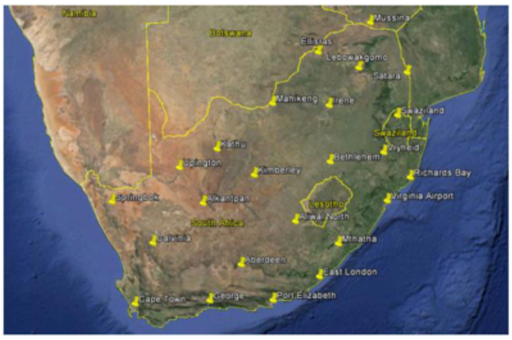

Fig. 3. Location of SALDN Vaisala sensors throughout South Africa. Courtesy Morné Gijben.

C. *Radio Sounding*

To measure the height of the charge center for lightning events over Johannesburg, radio sounding data was obtained and used. Radio sounding technology is used to determine the height of different isotherms in the atmosphere. The height of the negative charge center was obtained from the -10°C isotherm each day and was approximately 6 km on average, with a maximum of 6.5 km and minimum 5.5 km for the days investigated. The height of the positive charge center was estimated to be 3 km higher above -10°C isotherm [13].

IV. METHOD

Figure 4. shows the overall methodology applied to calculate charge transferred during the continuing current phase of downward lightning events over Johannesburg.

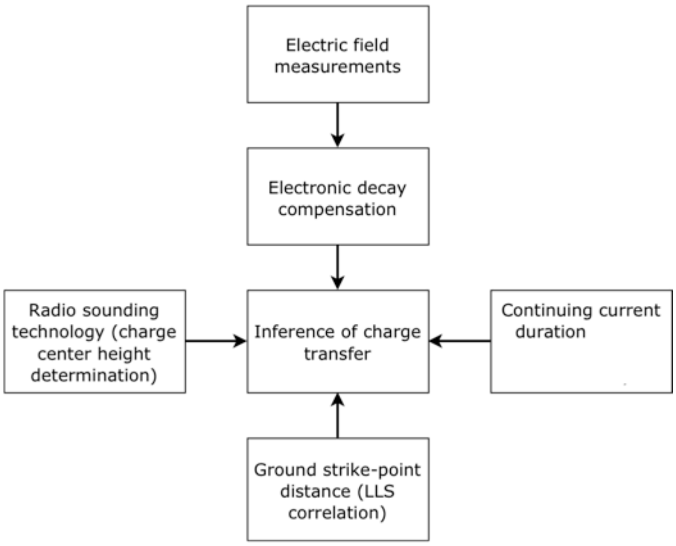

Fig. 4. Methodology followed in the charge transfer inference process.

This methodology is the application of the model described by Equation 1. The charge transferred is calculated from the flat plate antenna measurements, the distance provided by the SALDN and the charge center height provided by the radio sounding data. Electric field measurements of lightning events are time correlated with SALDN detections. The SALDN reported location is then used to confirm the distance between the flat plate antenna location and the location of the lightning stroke. Strokes located less than 5 km or greater than 45 km from the flat plate antenna location are discarded. Schumann et al. [7] showed that cases closer than 5 km have large impact on the estimated charge using this methods. To process the electric field waveforms, the same algorithms applied in Schumann et al. [7] were used. These algorithms were developed in Scilab [14]. Figure 5 shows the high level approach.

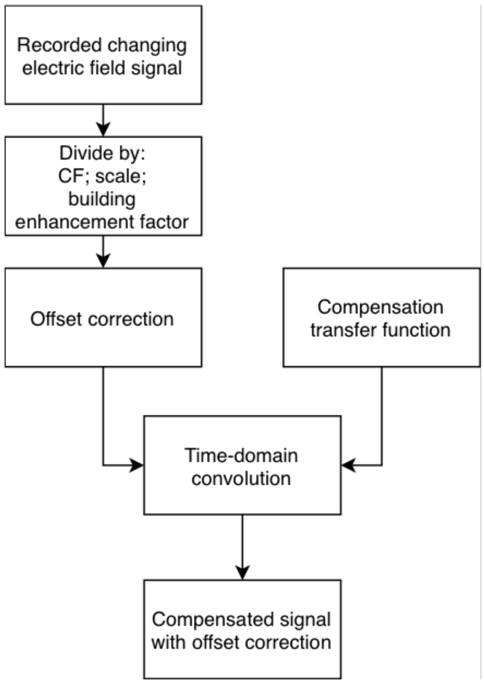

Fig. 5. High-level structure of the offset correction and decay compensation algorithm.

Firstly, offset correction is performed followed by compensation of the measured waveform (with integrators) from one time constant to another. This was developed by Kohlmann et al. [15] and based on Rubinstein et al. [16].

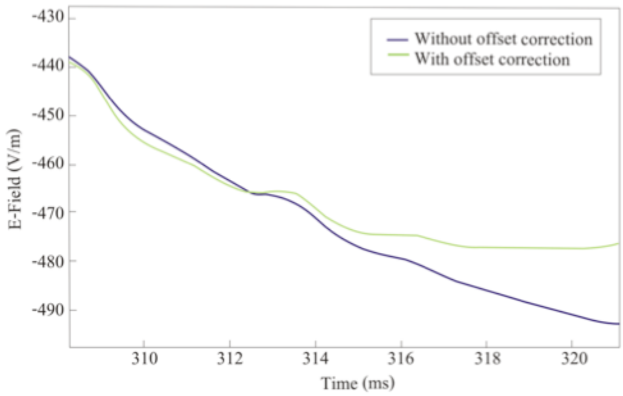

Fig. 6. The effect of offset correction on the final compensated output.

Figure 6 shows the effect of offset correction on an electric field waveform recorded from a lightning flash on 14 November 2017. Similarly, Figure 7 shows the uncompensated waveform and its corresponding compensated form for the same lightning flash. Finally, a subsequent algorithm is used to calculate the charge transferred using the compensated electric field waveforms from the first Scilab algorithm.

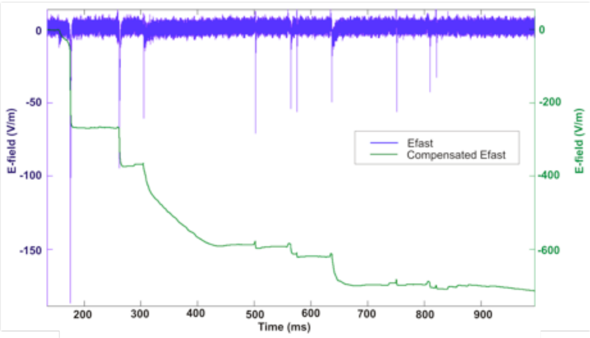

Fig. 7. Uncompensated changing electric field waveform (Efast) and corresponding compensated waveform (compensated Efast).

V. RESULTS

Table I shows a summary of the strokes used in the analysis. All strokes were recorded by the flat-plate antenna measurement system and the ground strike-point distances were all within the 5−45 km of the flat-plate antenna. These strokes were collected between February 2017 and November 2018.

Of the 51 negative strokes, 34 of them had a continuing current duration greater than 40 ms, 14 of them had a continuing current duration between 10 ms and 40 ms and 3 of them had a continuing current duration between 3 ms and 10 ms. All 5 positive strokes had a continuing current duration greater than 40 ms.

A. Charge Transfer results

Table II shows the results of applying the charge transfer estimation to the 51 negative and 5 positive strokes shown in table I. All values are arranged by continuing current durations: long (≥40 ms), short (10≥d>40ms) and very short 3≥d>10. The continuing current durations range from 4.0 ms to 926 ms for the 51 recorded negative strokes. The 34 recorded negative strokes with long continuing current have an average duration of 190.7 ms, the 14 negative strokes with short continuing current have an average duration of 21.1 ms and the 3 with very short continuing current have an average duration of 6.7 ms. The continuing current durations of the 5 recorded positive strokes range from 43 ms to 564 ms with an average of 253 ms.

TABLE I. THE DATA USED IN THE CHARGE TRANSFER INFERENCE PROCESS

Quantity		Value
Flashes	Negative	34
	Positive	5
Strokes	Negative	51
	Positive	5
Continuing current duration (ms) (negative strokes)	Long (> 40 ms)	34
	Short (10≥d>40ms)	14
	Very Short (3≥d>10)	3
Distance (km) (negative strokes)	Minimum	5.2
	Maximum	25.4
	Mean	12.3
Estimated height of charge center (negative strokes)	Minimum	5530
	Maximum	6650
	Mean	6225

For the negative polarity, 34 strokes with long continuing current transferred an average of 18.3 C with a maximum of 145.5 C and a minimum of 0.3 C. The 14 strokes with short continuing current durations transferred an average of 0.7 C and the 3 strokes with very short continuing current durations had an average charge transfer of 0.2 C. From the 5 positive strokes, the maximum charge transferred was 66.6 C and the minimum was 3.7 C. With only 5 positive strokes in the data set, the mean charge transfer is statistically insignificant and therefore, omitted from the results.

TABLE II. PRELIMINARY CC CHARGE TRANSFER ESTIMATES SOUTH AFRICA

	Negative CG Strokes			Positive CG Stroke
	Long CC (>40ms)	Short (10≥d>40ms)	Very Short (3≥d>10)	Long CC (>40ms)
Samples	34	14	3	5
Continuing Current duration (ms)				
Minimum	41.0	12.0	4.0	43
Maximum	926.0	36	8.0	564
Mean	190.7	21.1	6.7	253
Distance (km)				
Minimum	5.2	5.7	8.0	5.3
Maximum	25.4	17.4	13.8	15.0
Mean	13.1	11.4	10.0	10.7
Estimated height of charge center				
Minimum	5530	5850	5850	8865
Maximum	6650	6650	6650	9450
Mean	6205	6314	6133	9160
Charge Transferred (C)				
Minimum	0.3	0.1	0.1	3.7
Maximum	145.5	3.0	0.3	66.6
Mean	18.3	0.7	0.2	-

B. Discussion

Figure 8 provides a comparison between the results obtained in this study and those obtained in studies conducted in Brazil, Austria and the USA by Schumann, et al. [7]. The data set consists of 59 samples from Brazil, 70 from Austria, 36 from the USA and 34 from this preliminary study. All of these studies make use of flat-plate antennas to perform charge transfer inference using the same methodology. All strokes in these studies have continuing current durations greater than 40 ms and were recorded within 5−45 km of the flat plate antenna location.

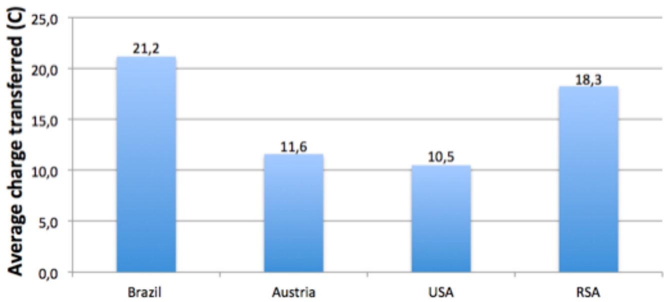

Fig. 8. Average charge transfer in negative lightning strokes for Brazil, Austria, USA and South Africa.

The figure shows that the average charge transferred in negative lightning strokes from measurements taken in Brazil, Austria and the USA is 21.2 C, 11.6 C and 10.5 C, respectively. In South Africa, these preliminary results indicate an average charge transfer of 18.3 C. Table III shows the full comparison between the studies conducted in Brazil, Austria and the USA and the preliminary South African results. The continuing current durations are shown and all are greater than 40 ms and have mean values of 185.1 ms, 133.0 ms, 197.1 ms and 190.7 ms respectively. The mean charge transferred within each region is 21.2 C, 11.6 C, 10.5 C and 18.3 C respectively. There is a noticeable difference in the average charge transfer values between the two countries in the northern hemisphere (USA and Austria) and the two countries in the southern hemisphere (South Africa and Brazil). The average air temperature in the northern hemisphere is approximately 1 − 2 ◦C warmer than the southern hemisphere [17]. This temperature difference could be a contributing factor to the difference in charge transfer quantities during lightning events.

As seen in Table III, the data set of positive strokes consists of 20 samples from Brazil, 35 from Austria, 45 from the USA and 5 from South Africa. The mean charge transfer obtained in this study is therefore statistically insignificant. However, the ranges from the studies conducted in Brazil, Austria and the USA are 2.5−1329 C, 2.9−434 C and 1.7−358 C respectively [7]. From the 5 positive samples in this study, the quantity of charge transferred ranges from 3.7 C to 66.6 C - within the same bounds.

VI. CONCLUSION

From 34 negative downward lightning strokes over Johannesburg, South Africa, it was estimated that the charge transferred from strokes with long continuing current (ie. > 40 ms) ranges from 0.3 C to 145.5 C and has a mean value of 18.3 C. For positive strokes, the relatively small sample size rendered the mean quantity insignificant, however, the results range from 3.7 C to 66.6 C. Both the mean charge transfer in negative strokes and the range of charge transferred in positive strokes are congruous with similar studies conducted in Brazil, Austria and the USA. The mean charge transfer values of negative strokes attained from this study are approximately 60 % greater than values calculated in Austria and the USA and are approximately 15 % less than the negative charge transfer quantities calculated in Brazil.

TABLE III. PRELIMINARY SA RESULTS COMPARED TO BRAZIL, AUSTRIA AND USA

	Negative CG Strokes - Long CC (≥40ms)				Positive CG Stroke - Long CC (≥40ms)			
	Schumann et al [7]			South Africa (this work)	Schumann et al [7]			South Africa (this work)
	Brazil	Austria	USA		Brazil	Austria	USA	
Number of cases	59	70	36	34	20	35	45	5
Continuing Current duration (ms)								
Minimum	42	40	41	41	40	40	43	43
Maximum	570	580	527	926	800	355	689	564
Mean	185.1	133.0	197.1	190.7	262	124	290	253
Distance (km)								
Minimum	5	5.5	5.0	52.	6.9	6.5	9.8	5.3
Maximum	35	34.1	35.4	25.4	44.1	32.8	35.5	15.0
Estimated height of charge center								
Minimum	6121	4564	5182	5530	8683	7970	8182	8865
Maximum	7043	5906	6809	6650	9896	9115	9618	9450
Mean	6501	5702	5848	6205	9266	8818	8683	9160
Charge Transferred (C)								
Minimum	0.6	0.4	0.2	0.3	2.5	2.9	1.7	3.7
Maximum	127	115	46	145.5	1329	434	358	66.6
Mean	21.2	11.6	10.5	18.3	255.4	50.1	74.9	-

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