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MASTERS DISSERTATION

Modelling of electric fields at mid-range locations for upward lightning at the Sentech tower, South Africa

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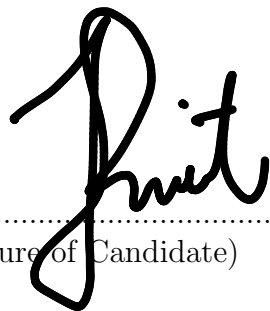
UNIVERSITY OF THE
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Johannesburg Lightning Research Laboratory,
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Declaration of Authorship

I declare that this dissertation is my own unaided work. It is being submitted to the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.



.....
(Signature of Candidate)

23rd day of August year 2022

Abstract

This research compares the transmission line, modified transmission line linear and modified transmission line exponential models to determine the best suited model for simulating the electric field at mid ranges (2 km to 10 km). The current and results electric fields for lightning events to the Sentech tower, in Johannesburg South Africa, are used as the primary data. Data from the 2020-2021 lightning season is presented, analysed and compared to similar work done in other regions. There were a total of 42 lightning events during the season. Measurements showed agreement with measurements made in Europe and Japan for peak current distribution, charge transfer and inter-stroke time distribution. However, the measurements showed a multiplicity which is twice that seen in Austria and Japan. Two of the measured flashes were used to simulate and compare remote electric fields to measurements at 2 km and 6 km. The two flashes had a total of 26 subsequent return strokes and 5 initial current fast pulses. The electric field simulations show a strong linear relationship for the initial peak current for measured and simulated values across return stroke models. This relationship increases as the contribution of the electrostatic component becomes less (over increases distance). The modified transmission line exponential model however, performed best when reproducing the electric field waveform characteristics.

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List of Symbols

i_h	—	[A]	Heidler current
I_0	—	[A]	Peak current
η	—		Peak current correction
n_h	—		Heidler steepness factor
τ_1	—	[S]	Rise time
τ_2	—	[S]	Fall time
ω_0	—	[rad/S]	Rise time
i_{RS}	—	[A]	Return stroke current
i_{BC}	—	[A]	Base current
z	—	[m]	Channel segment height
v_c	—	[m/s]	Return stroke speed
H	—	[m]	Channel height
λ_c	—		Decay constant
L	—	[m]	Actual channel length
L'	—	[m]	Observed channel length
z'	—	[m]	Channel segment height
θ	—	[rad]	Angle between channel base and the observation point
r	—	[m]	Distance between the channel base and the observation point
α	—	[rad]	Angle between dz and the observation point
R	—	[m]	Length from dz to the observation point

Nomenclature

FPS	Frames per second also referred to as IPS in other sources.
ICC	Initial continuing current.
ICC_P	ICC pulses.
ICC_{RS}	ICC followed by return strokes.
LDN	Lightning Detection Network.
MTLE	Modified Transmission Line Exponential.
MTLL	Modified Transmission Line Linear.
RS	Return Stroke.
SRS	Subsequent return stroke.
STP	Standard temperature and pressure.
TL	Transmission Line.

1. Introduction

Lightning events to tall towers are common. Towers with an effective height above 100 m are additionally more prone to upward lightning events than downward events [1]. Tall towers are a convenient location for measuring lightning event current due to the high frequency of events [2]. Upward current in South Africa were first measured by Eriksson and high-speed video studies have been done on lightning activity to Sentech tower [3, 4]. For the first time, this work measures current for upward lightning to the Sentech tower in South Africa. The measurement of upward current has been done in Japan, Europe and the Americas. The Sentech measurements are compared to the measurements done in these regions in this work.

Each lightning event causes a change in the electric field as described by the available models. Using the direct current measurements this dissertation evaluates prominent return stroke models with the finite antenna method to simulate electric fields and compare these to the changes in the measured electric field. This chapter presents the areas of potential contribution. The two research questions are presented with the associated considerations and a brief overview of the chapters to follow.

Return stroke models are used in modelling the electric fields for lightning events using current for a lightning event. Return stroke model parameters are shown to vary based on the location of research [5]. While these return stroke models have previously been compared to electric field measurements, they had never been applied and compared with real measurements made in South Africa. Several models are available which relate the electric field at a remote location to the current due to a lightning stroke. These models make different assumptions and have different model variables.

The current characteristics for upward lightning to the Sentech tower have not been analysed and compared to the work done by others in other countries. The most robust upward lightning current measurements comes from Erikson with his work from 1989 [6]. The work done by Erikson was limited by the resolution available at the time and as such there is no information on characteristics such as the rise time of subsequent strokes.

1.1 Problem statement

A large body of work reproduces the electric fields at the close range (below 2 km) and far range (above 100 km), but not within the 2-10 km range [7–11]. The close range field (below 2 km) is dominated by the electrostatic field allowing for simplifying assumptions about the propagation of the produced fields, while the far field (above 50 km) is dominated by the radiant field components allowing for simplification [12]. Between 2 km and 100 km the electric field has considerable contributions from all three components (electrostatic, radiant and induction).

1.2 Research question

This work sets out to answer the following 2 questions:

1. Which of the three engineering return stroke models (TLM, MTLL, MTLE), best reproduce radiated lightning electric field peaks measured within the 2-10 km range for upward lightning in Johannesburg, South Africa?
2. What are the characteristics of lightning currents to the Sentech tower?

1.3 Approach

To answer the research questions, the following approach is used:

- Measure the current that flows during lightning events to the Sentech tower in Johannesburg.
- Perform validation analysis of the current data and compare to measurements made elsewhere.
- Simulate the electric fields using different return stroke models (TL, MTLL, MTLE) using a Heidler current model of the measured current waveforms.
- Use data from remote electric field measurements at 2 km and 6 km from the tower to compare the simulated and measured data.
- Competitively evaluate the performance of the models by calculating the difference between the real and simulated electric fields.

1.3.1 Scope

The scope of research would be restricted to Johannesburg, specifically lightning that occurred to the Sentech tower. The dissertation is focused on three well established return stroke models (Transmission line (TL) model, modified transmission line linear (MTLL) model and modified transmission line exponential (MTLE) model). The work only considers upward lightning events with subsequent return strokes (SRS) only.

1.4 Structure of the dissertation

Chapter 2 presents the *background* information that is relevant to this work. This section provides the reader with context as well as an understanding of the simplifying assumptions that were used and places the work in context. This chapter also provides for a brief history of lightning research within South Africa as it relates to this work.

Chapter 3 details all the *equipment* that was used. The equipment includes the current measurement equipment at Sentech tower, the video footage and the electric field sensors. Details about all the sensors performance parameters are detailed in this section (such as sampling time).

Chapter 4 presents the *methodology* used for the work. The methodology will discuss the manner in which ground truth data was recorded, how the simulations are created, the manipulations that allow for comparison as well as how the simulations and the measurements can be compared in order to arrive at the conclusion.

Chapter 5 shows the results of the physical *measurements*. The measurements of interest are the current at the Sentech tower and the remote electric field associated with a lightning event. An overview of the all the data is presented. This selection presents the criteria for using measurements as part of the data analysis.

Chapter 6 provides the *simulation* results based on the measured current (based on the measured currents) alongside the measured current waveforms. Finite antenna simulations of the electric field for each return stroke model is performed.

Chapter 7 shows *comparisons and evaluations* between the measured and simulated electric waveforms. This section details the comparisons drawn as well as evaluates the performance of each return stroke model at 2 km and 6 km from the Sentech tower. The analysis involves both a numerical analysis and a descriptive analysis.

Chapter 8 is the *conclusion* reached by the research as well as discussion and future work that may be derivative of this work. This includes additional return stroke model evaluation, the use of a different electric field model such as FDTD and determining the effects that the tower characteristic frequency may have on distance electric field measurements.

For a reader seeking further insight, appendix A presents the calibration of the electric field flat plate sensor. Appendix B shows the plots of all the measurements for all the events that were used in this work. Appendix C shows the ICLP papers that were submitted during the completion of this dissertation and contributed to the contents of this work.

2. Background

This chapter provides the necessary context for understanding the work done and the historical progression, with a section dedicated to the of the study of lightning in South Africa. This chapter provides a summary that can be used as a base for understanding the context of the dissertation.

2.1 History of lightning research

Lightning has been around on earth longer than life and may have contributed to the formation of life, by playing a role in the formation of organic molecules [13]. For humans, lightning has been fascinating for as long as there are available records. Lightning tends to appear in mythology in cultures from across the globe. These mythologies are found in writing from the ancient Egyptians, ancient Greeks and Scandinavians among others. This fascination is tied to the danger and damage that comes with lightning. Records of lightning damage litter historical records especially through the middle ages with building becoming taller [14]. The formal study of lightning though is credited to Franklin and his ideas on lightning and spark similarities, in 1752.

Rakov and Uman provide a comprehensive summary of the history of lightning in [14]. A brief chronology is presented here showing the progression of the field. The first lightning photography was taken by Hoffert in 1889 [15]. The first estimates of peak lightning currents were done in 1900 by Pockels [16]. The method used the residual magnetism on basalt near a strike location to estimate the current. The first remote electric field measurements were done in 1926 in an attempt to quantify and mitigate the affects of lightning on radio signals [17]. In the same year Boys produced and recorded the first photo time series (simplistic video) of a lightning event [18]. In 1937 the first lightning current measurement was produced by Stekolnikov and Valeev as well as the first close range electric field measurement by Simpson and Scarse [19, 20]. Upward lightning was first observed on the Empire State building in 1939 and photographed by McEachron [21]. The first current measurement of an upward

lightning event was recorded in 1967 by Berger [22].

2.1.1 History of lightning study in South Africa

South Africa has a rich history of lightning research. Of the first ‘videography’ of lightning recorded occurred in South Africa, by Schonland et al. in 1933 where they used streak photography as described by Boys [18, 23]. Further work was conducted by Schonland, Malan, Anderson and Eriksson among others [6, 24–26]. The work done by these researchers introduced much of the terminology used currently in lightning research and spurred research elsewhere [14]. Notably, the first tower lightning research in South Africa published, was the work done by Eriksson with the CSIR [6]. Understanding that lightning has remained important to a developing South Africa, as the electrical grid (especially on the highveld) is impacted by lightning [27]. The interest in lightning in South Africa has remained strong. There has been work done developing and evaluating the lightning location system in South Africa [28, 29]. Recently high-speed lightning footage research was conducted by Schumann and others [4]. Tasman and others used electric field measurements to estimate the charge transfer for tower lightning [30]. Frensham and others evaluated the performance of the South African lightning detection network [31]. Interest in the field has been increased with new measurement instrumentation being installed by the Johannesburg Lightning Research Laboratory [32]. This research will for the first time compare the electric field measurements and current measurements in South Africa for tower lightning.

2.2 Lightning as a physical phenomenon

Lightning and its formation can be divided into three broad but distinct phases. The formation of clouds and charge accumulation that precedes any lightning event, the development of a leader and the return stroke. Each of these processes is briefly discussed in following subsections.

2.2.1 Charge separation

The formation of lightning requires cumulonimbus clouds that are found in a height region above freezing temperatures, specifically between $-10^{\circ}C$ and $-30^{\circ}C$ isotherms [33]. The process starts with the movement and change of state of super-cooled water within the *mixed phase* zone. The conditions within this region allow for water to be in at least two distinct phases: super cooled liquid and solid (graupel/hail) [34]. This region is important to the electrification of the clouds as the graupels have been shown to directly correlate with the formation of

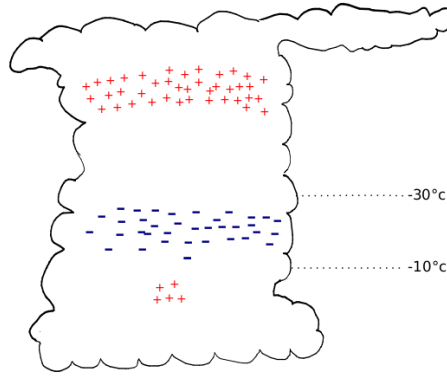


Figure 2.1: Sketch demonstrating the normal tripole charge distribution within a electrified cloud.

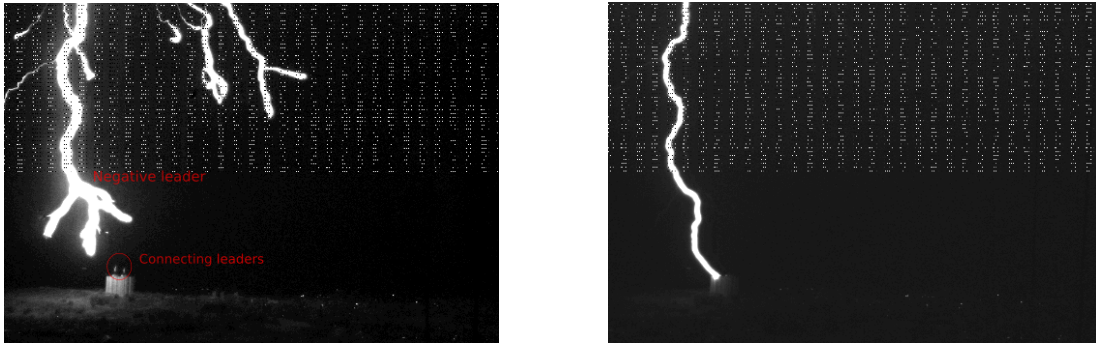
thunder storms by causing charge distribution in the clouds [35, 36]. The charge can be represented by a tripole structure, this is shown in figure 2.1. From below the cloud, the small positive charge center is negligible while the central negative charge center dominates the formation of the electric field [37].

2.2.2 Leader formation

Charge continues to accumulate within the cloud, until the electric field produced by the charge distribution produces an electric field that exceeds the critical value for the local conditions ($2.8 - 3 \times 10^{-6} \text{ V/m}$ at STP). This leads to the formation of the avalanche process described in more detail in Cooray's and Rakov's books [2, 12, 38]. Under the correct conditions the avalanche process leads to the formation of the streamer process, which leads to heating of the channel (thermal ionization). This ionization allows for charge to move into the heated region. The increased charge leads to a repetition of the avalanche and streamer processes, thus the leader process is formed. The leader progresses toward the ground as a result of all the local electric fields (cloud to ground and lightning induced). As the leader nears the ground, the electric field due to the charge of the leader and the induced distribution of the ground structures causes *connecting leaders* to form from the grounded structures [12, 38]. These *connecting leaders* attempt to make contact with the progressing leader. An example of a negative leader with the connecting leaders is presented in figure 2.2.

2.2.3 Return stroke

When contact is made between the leader and a connecting upward leader, which is at ground potential, the ground potential causes charge to flow from the leader



(a) Frame showing a negative leader and attempted connecting leaders.

(b) Frame showing the established lightning channel after the return stroke.

Figure 2.2: Two selected frames for a lightning event on 27 October 2020. Frame 1 shows two attempted connecting leaders while the leftmost connecting leader is the successful connecting leader as seen in frame 2.

channel, and this is termed the *return stroke* [1]. The movement of charge towards the ground does not occur instantly, but progresses from the point of contact upwards towards the cloud (which can be viewed as the upward progression of the return stroke). The charge flow has the effect of bringing the potential of the leader down to that of the ground. Charge moves up the established channel and recombination occurs. This has the effect of emitting electromagnetic waves, including light, leading to an increased luminosity. The increased luminosity is responsible for the characteristic ‘flash’ associated with lightning.

2.3 Lightning classifications

Lightning can be broadly categorised based on the polarity of the *charge within the cloud* relative to ground and by the direction of the initial leader. This broadly leads to four basic lightning event types: Downward negative, downward positive, upward negative and upward positive [39]. Bipolar events are possible too.

Negative downward lightning is the most common form of lightning, due to the proximity of the negative charge centre to ground [2]. It occurs when the negative charge centre within the cloud has accumulated enough charge for the centre to enable the formation of a leader. This form of lightning is visibly more branched compared to positive downward events and tends to progress quicker initially [2]. Figure 2.3a shows an example of a negative downward lightning event.

Positive downward events are less common due to the height of these charge centres within the cloud and the affects of the negative charge centre below. Positive lightning occurs from the anvil portions of the clouds. Positive downward lightning is associated with more tortuous, slower moving leaders that have a relatively bright leader tip. Positive lightning is associated with a lower number



(a) A single frame of a negative downward leader filmed on Thursday 06 April 2017 at 12:14:24.



(b) A single frame of a positive downward leader filmed on 06 February 2020.



(c) A single frame of a positive upward leader filmed on Wednesday 24 January 2018 at 18:20:48.



(d) A single frame of a negative upward leader filmed on Friday 24 November 2017 at 17:04:21.

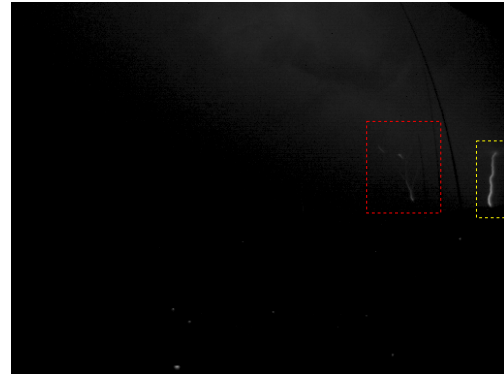
Figure 2.3: Collection of individual frames, from four separate lightning events that demonstrate the basic classification of lightning based on the initial leader. These frames show the initial leaders from each of the respective lightning events. All the footage was recorded from Northcliff, located north west of Johannesburg.

of return strokes, but higher peak current values [2]. Figure 2.3b shows an example of a positive downward lightning event.

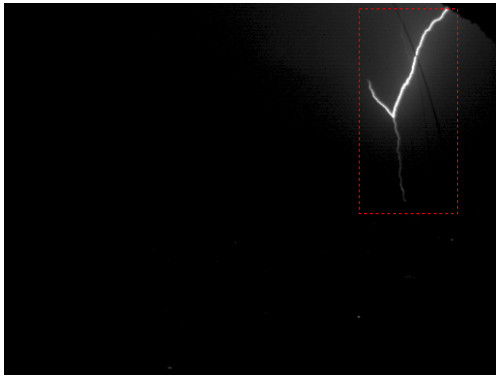
In the case of upward lightning, the background electric field caused by a charge distribution within the clouds induces charge on the ground. The background electric field is enhanced at the tip of tall objects due to the small effective radius of curvature (i.e. sharp point). The enhanced electric field at the tip of a tall structure/object reaches the critical value (see section 2.2.2) and initiates a leader process. This mechanism is the reason that upward lightning is also referred to as tower initiated lightning. Upward lightning events are mostly associated with a pre-cursory event, as seen in figure 2.4a [4, 40]. A combination of these events cause the electric field magnitude to meet the conditions needed for breakdown to occur. In figure 2.4a there is an example of a triggering event highlighted in yellow. The event is a visible downward event, but it could be another type of lightning activity [4].



(a) Frame of the preceding/triggering event. In this case the triggering event is a visible downward positive (yellow).



(b) Frame showing the initial continuing current (red) with the lingering triggering event (yellow).



(c) Frame showing ICC pulses that can occur in the ICC phase of an upward event (red).



(d) Frame showing the first subsequent return stroke (red) for the upward lightning event.

Figure 2.4: Frame progression showing the formation of an upward lightning event, with emphasis on the recognised phases that can occur in a upward lightning event and the terminology used to describe the sub-events in the lightning event. The event was recorded on 06 January 2020. The building from which the event initiates is the Sentech Tower.

The leader of an upward event will be of the opposite polarity of the charge within the cloud that initiates it. Therefore, a positive upward leader would have negative charge dominating within the leader and would visually resemble a negative downward event (branching and fast progression).

Figure 2.3c shows an example of a positive upward lightning event. Whereas a negative upward would visually resemble a positive downward (slow, tortuous and a bright leader tip). Figure 2.3d shows an example frame of a negative upward lightning leader, the frame was taken from the event shown in figure 2.4. The formed leaders progress towards the charge centre within the cloud as governed by the local electric field [41]. This is referred to as the initial continuing current (ICC) an example is presented in figure 2.4b. The ICC can experience increased current pulses as is presented in figure 2.4c. When contact between the leader

Table 2.1: Table presenting some measured data observations at towers in different regions over multi-year periods of study.

Structure	Height	Observed Upward Events	Period of observation
CSIR tower (South Africa)	60 m	21	1972-1985 [3]
Morro do Cachimbo Station (Brazil)	60 m	10	1985-2012 [51]
Peissenberg tower (Germany)	160 m	46	1996-2014 [52]
Säntis tower (Switzerland)	124 m	326	2011-2012 [50]
Gaisberg tower (Austria)	100 m	759	2000-2013 [53]
Windmill (Japan Coastal region)	100 m	53	2005-2010 [54]
Skytree Tower (Japan)	634 m	22	2012-2014 [55]
CN Tower (Canada)	553 m	306	1992-2001 [56]

and a charge centre is made, a return stroke is initiated just as occurs in the downward lightning return stroke. An example of a return stroke for an upward event is presented in figure 2.4d. From this point on the channel behaves in a similar manner as a downward stroke does [1, 38]. Return strokes occurring in the same upward event are termed subsequent return strokes (SRS).

2.3.1 Tower lightning

Tall buildings (specifically 60 m and above) exhibit different characteristics with respect to lightning [42, 43]. Tall buildings are struck more often by lightning and are susceptible to upward lightning due to the field enhancing effect [44, 45]. Since tall buildings have a higher occurrence of lightning they are ideally suited for measuring lightning currents.

Eriksson, in conjunction with the Council for Scientific and Industrial Research (CSIR), started his research on lightning in 1972 with a focus on understanding lightning in the highveld region. This work dealt with comparing lightning research in other regions to South African measurements [46]. The work done by Eriksson led to the creation of a measurement mast that was used for observing and characterising lightning within the region. Eriksson and co-workers were the first to research lightning to tall towers in South Africa and to do analysis on upward lightning events separately from other events [3].

Research on upward lightning has since been conducted in the United States, Beijing, Japan, Germany, Austria and Brazil among others [7, 8, 44, 47–49]. Of particular interest are the Gaisberg tower, the Peissenberg tower and the Säntis tower as there are recently published current measurements [7, 8, 50]. Table 2.1 presents an overview of some of the multi-year studies on upward lightning to tall towers.

2.4 Measuring and estimating lightning currents

Lightning events produce a large transfer of charge that can be measured/observed using different measurement techniques. This section introduces the measurements that are commonly deployed for measuring or estimating lightning currents. There are however many methods of measurement, some with very specific applications. This includes acoustic stroke distance detection, satellite storm detection and others that are not within the scope of this dissertation.

2.4.1 Lightning currents

The current can be directly measured. This is normally done on tall towers as they are more susceptible to lightning. Towers with an *effective* height above 100 m are additionally more prone to upward lightning events than downward events [1]. The measurement of current can be done using a shunt resistor or a Rogowski coil. Shunt resistor measurements are made by placing a suitably sized resistor in series with the down conductor of a building and measuring the corresponding voltage formed across the resistor [57]. Since the resistor is in series with the down conductor the voltage forms across the resistor for a given current. The installation process of a shunt resistor requires an addition to the mast of the building. The current is determined by measuring the voltage across the resistor and using ohms law to calculate the current. Shunt resistor based measurements were done on the CSIR tower, and the Gaisberg tower [3, 53].

The current produces electromagnetic fields. A Rogowski coil is an application of Faraday's law where the down conductor couples with the coil inducing an emf on the coil. Rogowski coils work by measuring the induced current as a result of the coupling of the electromagnetic field, due to flowing current through the instrumented tower [58]. As part of the measurement an integrator circuit is required. Integrator circuits require a compensator(referred to as an RC constant) that prevents the circuit from saturating. The integrator compensator combination has a high pass filter characteristic. For an integrator circuit the RC constant is chosen so that it does not dramatically attenuate the low frequency components of a measurement, while preventing the measurement from being saturated. This produces a challenge for measuring lightning as the initial continuing current has a low frequency in comparison to the high frequency return stroke component. Rogowski coil measurements therefore often make use of separate integrator circuits to measure the two components(initial continuing current and return stroke). The benefit of using a Rogowski coil based measurement is that the procedure does not require an intrusive installation process, and that the coil can be installed at any point along a building, provided all current paths are enclosed by the coil. Rogowski coil based measurements

were done at the Säntis tower, Peissenberg tower, Gaisberg tower, and the CN tower [50, 52, 53, 56]. While the measurement at Gaisberg tower compared and confirmed the two measurement methods[59]. The Sentech tower is an active radio-telecommunications tower, and thus the Rogowski coil based measurement is preferred over using a shunt resistor.

For a measured lightning current the current can be analysed using defined conventions. This allows for comparing and contrasting this work to work done by other researchers. There are several established naming conventions that are commonly used. The naming conventions used for current and its components are presented in section 2.4.2.

2.4.2 Electrical current naming conventions

ICC is the initial continuing current that is associated with an initiated upward lightning event. *ICC_P* is a current pulse that exceeds 2 kA superimposed on the *ICC*. A return stroke (*RS*) is a current pulse that exceeds 2 kA once the *ICC* has diminished. Flashes are classified by the type of pulses within a flash. *ICC_P events* are events where there are pulses superimposed on initial continuing current that exceed 2 kA, however there are no return strokes following the *ICC* phase. *ICC_{RS}* refers to events with an *ICC* that is followed by one or more return strokes (ie. Subsequent return strokes) exceeding 2 kA. An *ICC_{only}* event has no current pulses or return strokes exceeding 2 kA. Unknown events are events that cannot be classified. This is due to lack of supporting evidence (video, LDN or otherwise).

2.4.3 Propagated electromagnetic fields

Electric fields are caused by charge distributions and are developed between charged surfaces. Therefore, an electric field is created between charge that accumulates in the clouds and the ground. A magnetic field forms due to current (movement of charge). For a lightning event there is an associated magnetic field that is formed by the current and a changing electric field as the charge distribution changes. For a more in-depth analysis of these fields see reference [60].

When current flows between two charged surfaces the current induces a magnetic field by the Ampere-Maxwell equations. The electric field is also affected since charge has been transferred by the current. These changes can be measured remotely. The electric field measurements are made using a flat plate antenna while the magnetic field is measured using a coil. The wave-shapes normally seen at different distances are presented in section 2.5

For the electric field component, this can be measured near or far from the lightning event [61]. Electromagnetic fields measured within 250 km can be used

to estimate the current waveforms of a lightning event [62]. Above this distance the fields are better used in the lightning location of lightning events [63], such as in the World Wide Lightning Location Network (WWLN).

2.4.4 Video and photographic footage

Photography and videography are important in the understanding of lightning phenomena and have assisted in the research of the physics associated with lightning. These are still used in conjunction with other measurements to confirm lightning characteristics as well as measurements made by other devices. For instance the polarity of a lightning strike can be confirmed by video footage with as few as 100 fps. While metrics about lightning can be directly determined from video footage with frame rates above 1000 fps, this includes number of return strokes, duration of events among others [64]. From either video or still photography, one is also able to determine the strike point.

2.5 Electric field waveforms

The present work uses the ‘*Physics convention*’ when plotting electric fields. This convention plots the charge transfer to the ground with the same polarity for the electric fields. The vertical electric field can be represented by components (as shown is equation 2.10). These components are distance dependant therefore the electric field measurements waveform shapes are expected to vary with varying distance from the lightning event. Generally the electric field is dominated by the electro-static component when close to the lightning event. This component acts as an integrator and therefore the fast changes in the current are less pronounced in the electric field for close measurements. Further away from the measurement the radiative field component is dominant. The radiative component acts like a derivative and therefore fast changing components of the current have greater emphasis further away from the measurement. A generic electric field measurement is presented in figure 2.5. Figure 2.5 presents the naming convention that is used when discussing the electric field waveforms in this work. The names are used as listed and described below figure 2.5. The naming convention is based on the work by Lin et al. and Rakov [62, 65].

Initial rise segment Is the fast rising initial portion of an electric field associated with a return stroke.

Initial peak Is the component of the waveform that is related to the peak current from a return stroke.

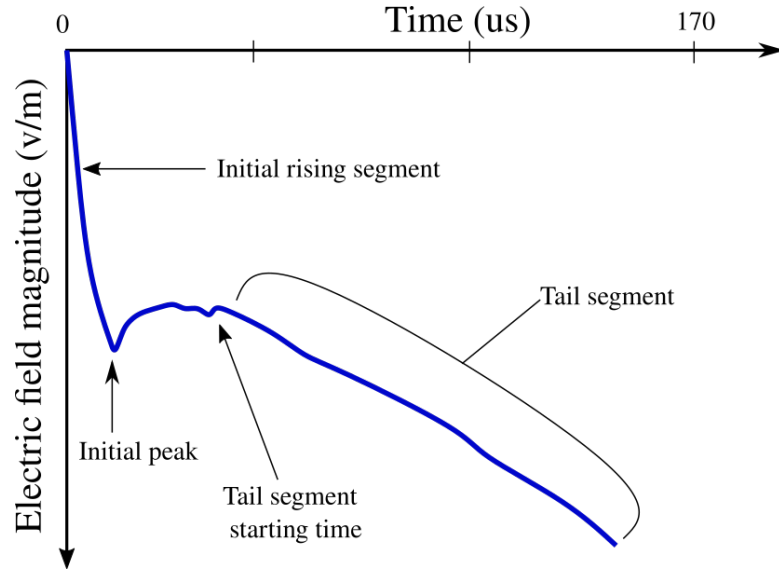


Figure 2.5: Sketch showing the generic electric field waveform for a return stroke and the labels for the segments of the waveform.

Tail segment Referred to as ramp for measurements under 50 km. This segment crosses zero for measurements above 50 km.

Tail segment start The point at which the tail segment starts to tend away from zero. This point occurs later with respects to the initial peak as the measurement move further from the lightning event.

As discussed above the electric field waveform would change as the distance between the lightning return stroke location and the electric field measurement changes. For measurements near the stroke location the dominant component of the electric field is the electrostatic component. In distant electric field measurements the radiant electric field becomes dominant.

Figure 2.6 shows a sketch of the expected vertical electric field based on the work by Lin et al. and Rakov [62, 65]. At 2 km the waveform is expected to have the greatest magnitude for the initial peak (in the region of 200 V/m), with a ramp tending away from the origin. The ramp occurs soon after the initial peak. The reason the fast dominant ramp is due to the integral present in the dominant electrostatic field at this range. An example is presented in figure 2.6a. For the 6 km waveform the initial peak is less than the 2 km waveform (in the region of 50-100 V/m). The ramp segment will start later than in the 2 km case and the gradient will be less than for the 2 km case. Here the other radiative, inductive and electrostatic field components equally contribute to the waveform seen. However over time as the current waveform tends to zero the integral in the electrostatic component still contributes heavily. This accounts for the ramping nature that starts later than is seen in the 2 km waveform. For the 100 km waveform the initial peak will be very small in comparison to the other graphs

(in the region of 4-10 V/m). The tail segment is expected to cross zero before stabilising. An example is presented in figure 2.6c.

For the modelling in the mid-ranges the simulations would show a contribution from the electrostatic field that would as the images indicate cause ramping. Unlike near (< 1 km) or far (> 100 km) electric field simulations the work here would need to consider all components that make up the electric field.

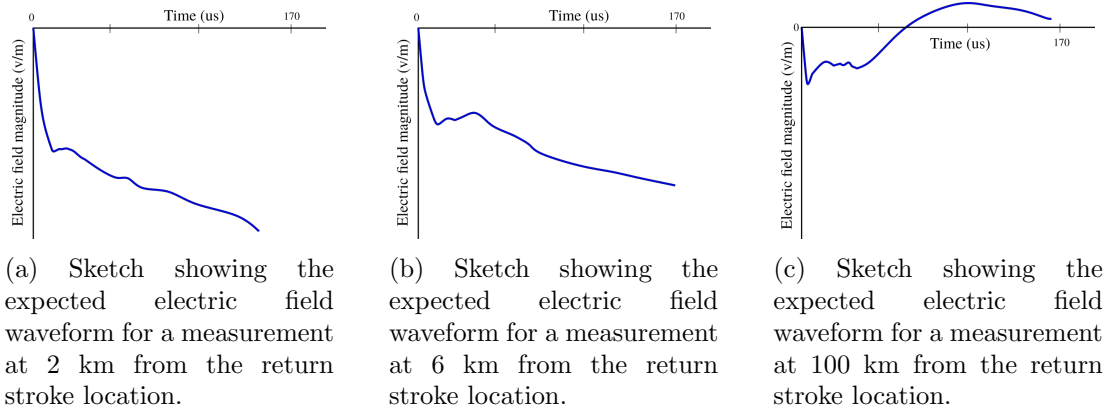


Figure 2.6: Sketches showing the vertical electric field over changing distances from the stroke location. The images are not representative of the true y-axis magnitudes but rather are drawn to show the overall waveshapes.

2.6 Modelling lightning currents and electromagnetic fields

The different aspects of lightning that can be modelled are briefly discussed in this section with a focus on using measured current values to arrive at a modelled electric field.

2.6.1 Current modelling

The most common way to model lightning currents is the Heidler function [66]. Using a simulated version of the current waveform provides benefits such as having a function that has a defined shape. The Heidler function can be differentiated but it does not have a trivial integral. The extended Heidler representation by Terespolsky [67] have an integral and derivative that are easily computed. Using the Heidler function reduces the need for numerical integration and differentiation at the cost of reduced waveform complexity. When working with several functions where the integral and derivative are required there is a clear computational benefit to using the Heidler current.

The Heidler function is presented in equation 2.1. For the approximation the model requires the rise time – 10-90 % value – (2.1d), the fall time – peak to 50 % – (2.1e), the peak current (2.1a) and a steepness factor (2.1c). The current correction factor (2.1b) is calculated using equation 2.2.

$$i_h(t) = \frac{I_0}{\eta} \frac{\left(\frac{t}{\tau_1}\right)^{n_h}}{1 + \left(\frac{t}{\tau_1}\right)^{n_h}} e^{-\frac{t}{\tau_2}} \quad (2.1)$$

Where:

$$i_h(t) = \text{Heidler current} \quad (2.1a)$$

$$I_0 = \text{Peak current [A]} \quad (2.1a)$$

$$\eta = \text{Peak current correction} \quad (2.1b)$$

$$n_h = \text{Heidler steepness factor} \quad (2.1c)$$

$$\tau_1 = \text{Rise time [S]} \quad (2.1d)$$

$$\tau_2 = \text{Fall time [S]} \quad (2.1e)$$

$$\eta = \exp[-\tau_1/\tau_2(n_h\tau_2/\tau_1)^{1/(n_h+1)}] \quad (2.2)$$

Although the Heidler function approximates the current waveform with great accuracy, the Heidler function does not have an analytical integral. To overcome this limitation, Terespolsky derived a function that retains the accuracy of the Heidler function but can be integrated using common integration techniques [67]. The Terespolsky function is presented in equation 2.3.

$$i_a(t) = \frac{I_0}{\eta} \left(1 - e^{-\omega_0 t} \left(\sum_{i=0}^{n_a} \frac{\omega_0^i t^i}{i!} \right) \right) e^{-\frac{t}{\tau_2}} \quad (2.3)$$

Where:

$$i_h(t) = \text{Heidler current}$$

$$I_0 = \text{Peak current [A]}$$

$$\eta = \text{Peak current correction}$$

$$n_h = \text{Heidler steepness factor}$$

$$\omega_0 = \text{Rise time [rad/S]}$$

$$\tau_2 = \text{Fall time [S]}$$

The Terespolsky function has a derivative that is presented in equation 2.4.

$$i'_a(t) = \frac{I_0}{\eta} \left[e^{-\omega_0 t} \left(\frac{\omega_0^{n_a+1} t^{n_a}}{n_a!} \right) - \frac{1}{\tau_2} \left(1 - e^{-\omega_0 t} \left(\sum_{i=0}^{n_a} \frac{\omega_0^i t^i}{i!} \right) \right) \right] e^{-\frac{t}{\tau_2}} \quad (2.4)$$

The integral is presented in equation 2.5. Where C is some arbitrary constant of integration.

$$\int i_a(t)dt = \frac{I_0\tau_2 e^{-t\left(\frac{1}{\tau_2} + \omega_0\right)}}{\eta} \left(-e^{-\omega_0 t} + \sum_{i=0}^{n_a} \frac{\omega_0^i}{i!} \sum_{j=0}^i \frac{i!\tau_2^j t^{i-j}}{(i-j)!(\tau_2\omega_0 + 1)^{j+1}} \right) + C \quad (2.5)$$

2.6.2 Return stroke models

For a lightning event the current measured at the base of a tower does not represent the current at the same instant along the lightning channel. The charge moving from the ground toward the cloud neutralises charge within the lightning channel. The current along a lightning channel thus attenuates as the base current progresses up the lightning channel over time.

Return stroke models allow one to simulate the current values along the whole length of a lightning channel, based on the base current. There are many different return stroke models, all with different assumptions and stated model objectives. The models can be broadly characterised by the effects they attempt to simulate. Cooray introduces four categories, *Electro-thermodynamic models*, *LCR transmission line models*, *Electromagnetic models* and *Engineering models* [68]. The *Electro-thermodynamic models* focus on simulating multiple portions of the lightning phenomena from a physics understanding. This may include current, thermal properties, acoustics and plasma. *LCR transmission line models* model the return stroke as a transmission line with resistive, capacitive and inductive components. The components vary along the lightning channel and attenuate the waveform accordingly. *Electromagnetic models* are conceptual models that model the lightning channel according to electromagnetic theory. The models attempt to recreate the current based on the assumption that the lightning channel is a perfectly conducting wire in a medium with different properties along the lightning channel. *Engineering models* use the transmission line model but assume an ideal transmission line. These models have good agreement in terms of current waveforms and are thus used in practical applications. This masters focuses on *Engineering models* as they best represent observable electric fields and often have better agreement with the measurable electric fields [69].

The following subsections present the models to be evaluated in order to determine whether they would be appropriate for the region in question. The general formula

for the return stroke models are presented in equation 2.6

$$i_{RS}(z, t) = \alpha(z) \times i_{BC}(t - \frac{z}{v_c}) \quad (2.6)$$

where:

α = Decay factor

i_{RS} = Return stroke current

i_{BC} = Base current

z = Channel segment height

v_c = Return stroke speed

The formula above shows the current along the channel is a time shifted and decayed version of the base current. The models that follow implement different functions for α to account for the decay of current along the lightning channel.

Transmission line model

The transmission line model (TLM) of lightning is developed by Uman and McLain is presented in [70]. The TLM is a comparatively simple model, however it is used as a means to estimate the peak electric field for a given current [71]. This model does not accurately model the current through the leader channel but rather assumes a constant current as a simplification. This assumption is not valid in a real stroke as the current decreases the higher the current moves up the channel. This is due to the affect of the charge that is within the branches of the leader as well as the corona sheath [1]. However, the model does show reasonable agreement between real peak current and peak electric field values [71]. The current for TLM for a segment is expressed in equation 2.7.

$$i_{RS}(z, t) = i_{BC}(t - \frac{z}{v_c}) \quad (2.7)$$

where:

i_{RS} = Return stroke current

i_{BC} = Base current

z = Channel segment height

v_c = Return stroke speed

Modified transmission line linear model

The modified transmission line linear decay model (MTLL) was the first attempt at correcting for the constant current assumption that is present in TLM, introduced by Rakov and Dulzon [72]. By including a linear attenuation of the current based on height the MTLL model attempts to account for attenuating

current. This model has shown greater agreement with the expected electric field based on the current at a location [71]. However, the model requires knowledge or the assumption of the height of the lightning channel. The equation relating base current to return stroke current for MTLL is presented in equation 2.8.

$$i_{RS}(z, t) = (1 - \frac{z}{H})i_{BC}(t - \frac{z}{v_c}) \quad (2.8)$$

where:

- H = Total channel height
- i_{RS} = Return stroke current
- i_{BC} = Base current
- z = Channel segment height
- v_c = Return stroke speed

Modified transmission line exponential model

The modified transmission line exponential model (MTLE) by Nucci et al. expands on the previous model by modelling the decrease in current as an exponentially decreasing function [73]. This assumption is a better match for the expected height dependant current [73]. Equation 2.9 is the expression for the MLTE model.

$$i_{RS}(z, t) = (\exp(-\frac{z}{\lambda_c}))i_{BC}(t - \frac{z}{v_c}) \quad (2.9)$$

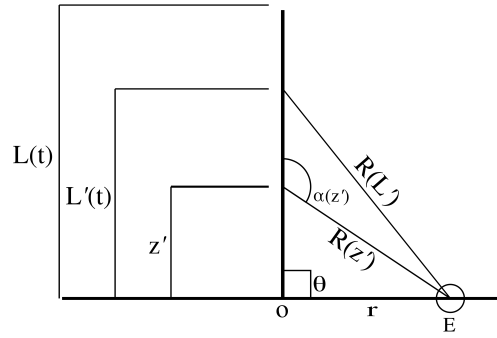
where:

- λ_c = Decay constant
- i_{RS} = Return stroke current
- i_{BC} = Base current
- z = Channel segment height

Each of the above models have previously been evaluated using rocket triggered lightning [74–76].

2.7 Modelling electric field propagation caused by lightning

Lightning models start with the assumption that the channel is a straight vertical current carrying conductor (or transmission line) such as is in Cooray's book [41], and are built from this assumption. Using the current carrying assumption as a base to a model, the current flowing in the wire(channel) would cause the propagation of electric field as described by the Maxwell's equations.



where:

L = Actual channel length

L' = Observed channel length

z' = Channel segment height

o = Strike point

θ = Angle between channel base and the observation point

r = Distance between the channel base and the observation point

E = Observation point

α = Angle between dz and the observation point

R = Length from dz to the observation point

Figure 2.7: Geometry of the finite antenna model.

2.7.1 Finite Antenna Model

The finite antenna model (as shown in figure 2.7) simulates the lightning strike as a finite antenna, that is perpendicular to the strike point, with a finite length. Since the electric field is viewed from a remote location the observed effects are delayed by the propagation speed of the produced electromagnetic disturbance. The observed length (L') of the return stroke channel at a given time is also dependant on the speed of propagation. The lightning channel is divided into spatial segments (dz) and time segments (t). The complete electric field waveform is calculated by evaluating the contribution of all dz elements for the complete time of the lightning event.

There are three mathematically equivalent approaches to evaluate the electric field emission; the Lorentz condition, the monopole technique and apparent charge density technique as discussed in Cooray et al. [5].

After all considerations and assuming a ground level measurement, each of the methods would arrive at an equation as presented in equation 2.10. The overall equation is made up of distinct terms that represent the contributions of different electric field components. Term 2.10a involves the integral of the current and this component is termed the electrostatic ('static') term. Term 2.10b has the current as the variable and corresponds to the induction field (induced field).

Term 2.10c has the derivative of the current as a variable and is called the radiation field. Term 2.10d is zero when there is no current discontinuity as occurs in real current measurements [5]. It should be noted that each of the terms have a different power of R (distance) in the denominator. Since the static field has a $\frac{1}{R^3}$ distance relationship, the static field can be used for approximations of the total electric fields near (under 1 km) the point of a lightning strike. While the radiation field has a distance relationship of $\frac{1}{R}$. This term best approximates the total electric field at greater distances (above 50 km). It is clear that at mid-ranges all three components have contributions to the total electric field and any simplifying assumption would produce considerable error in the estimation, and is the focus of this work.

$$E_v(r, t) = \frac{1}{2\pi\epsilon_0} \int_0^{L'(t)} \frac{2 - 3\sin^2 \alpha(z')}{R^3(z')} \int_{t_b}^t i(z', \tau - R(z')/c) d\tau dz' \quad (2.10a)$$

$$+ \frac{1}{2\pi\epsilon_0} \int_0^{L'(t)} \frac{2 - 3\sin^2 \alpha(z')}{cR^2(z')} i(z', \tau - R(z')/c) d\tau dz' \quad (2.10b)$$

$$- \frac{1}{2\pi\epsilon_0} \int_0^{L'(t)} \frac{\sin^2 \alpha(z')}{c^2 R(z')} \frac{\partial i(z', \tau - R(z')/c)}{\partial t} dz' \quad (2.10c)$$

$$- \frac{1}{2\pi\epsilon_0} \frac{\sin^2 \alpha(L')}{c^2 R(z')} i(L', t - R(L')/c) \frac{dL'}{dt} \quad (2.10d)$$

2.8 Chapter summary

This chapter has showed that humans have had a deep fascination with lightning. Lightning events can be categorised into 4 broad categories based on direction and the charge within the cloud. Lightning events are common to tall structures and thus are desirable locations for lightning measurements, especially due to the occurrence of tower initiated lightning events. Lightning current can be measured using shunt resistors or Rogowski coil based measurements. Lightning, due to the current, cause measurable changes in electromagnetic fields. The current can be inferred from the electromagnetic emissions. The nomenclature used in this work to describe current waveforms and electric field waveforms was presented in this chapter. A current waveform can be modelled using the Heidler Function which provides benefits especially when calculating the current along a lightning channel. Accurate representation of the current in the lightning channel require the use of a return stroke model. There are several types, but the one of interest are the engineering type, since they are used widely with strong agreement with measurements. The specific models discussed are the transmission line, modified transmission line linear and the modified transmission line exponential models. Therefore this work seeks to identify the electric field model that best related the current with the electric field that is measured at mid-range locations where all components play a role. Measurements on the Sentech tower are used to verify the models and analyse the performance of each model.

3. Equipment

This chapter details the equipment used to answer the research questions. The emphasis of this chapter is on how the equipment is used, the location of the equipment and the performance metrics of the equipment.

In this chapter, the measurement equipment used is described. The current measurement system on the Sentech tower is presented and discussed in section 3.1. The vertical electric field measurements equipment is discussed in section 3.2. Section 3.3 discusses the video footage and its use as a redundancy for confirmation of lightning events. Figure 3.1 shows the locations of points of interest for the project. The image is a top-down view of a mapped portion of Johannesburg. The map is oriented so that North is located toward the top of the map. Near the center of the graphic one can see the location of the Sentech tower. The current measurements are done at this location. The University of the Witwatersrand is 2 km to the east of the Sentech tower. There is a vertical electric field measurement that is present at the University, on top of the Chamber of Mines building. Additionally, there are cameras facing both towers at the university. To the North West, in the suburb Northcliff, there is a vertical electric field sensor. The Northcliff location also has a high-speed camera that has a field of view as indicated by the blue lines. The Northcliff location is 6 km from the Sentech Tower. Also indicated on this map is the Hillbrow tower (most easterly indicated point). The tower is included for reference as there are several lightning events that have contributions from this tower.

3.1 Lightning current measurement on the Sentech tower

The Sentech tower is regularly struck by lightning [4]. In 2020, a system was installed to measure lightning currents that flow in the tower when struck. The system is the *DEHNDetect*, similar to that installed on the Gaisberg tower and Peissenberg tower in Europe [7, 8]. The system is based on the principles

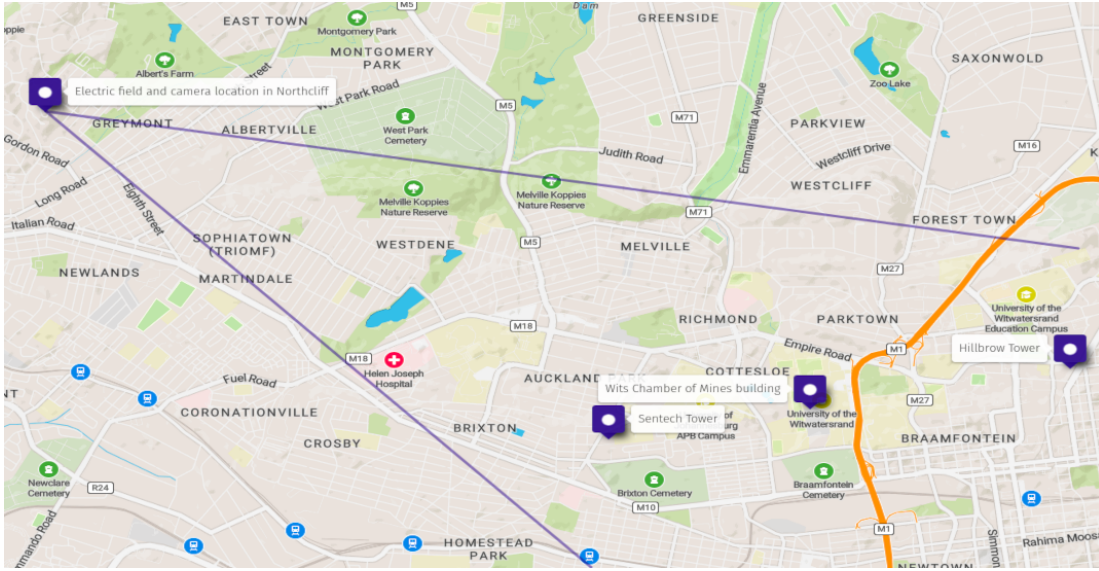


Figure 3.1: Map showing the location of labelled points of interest to this project. The map is a zoomed in section of the Johannesburg region. The black bars indicate the field of view of the high speed cameras that are used.

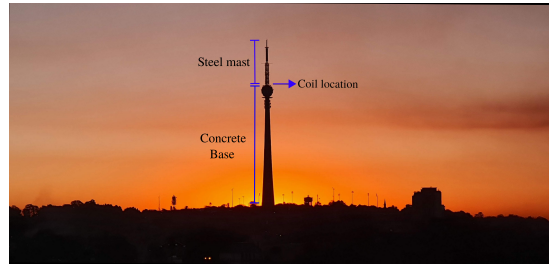


Figure 3.2: Photograph showing the location of the Rogowski coil as indicated by the arrow. The metal mast and concrete base are additionally indicated.

of a Rogowski coil as discussed in the background section 2.4.1. The current measurement at the Sentech tower is performed by a *DEHN detect* system that comprises of two Rogowski coils in a single housing. The coils are installed at the junction of the mast and the concrete base of Sentech tower in Brixton, South Africa.

The Sentech tower is a cylindrical concrete broadcasting tower located in Brixton a suburb of Johannesburg, South Africa. The tower is 237 m tall. Figure 3.2 shows an image of the Sentech tower. From the image it is clear that the tower has a concrete base (which is indicated) and a metal mast on top of the concrete base. The coil is installed near the junction of the concrete base and the mast. The location of the installation on the tower is indicated by the arrow in figure 3.2. The location on the tower where the coil is installed was chosen as it allows for measuring all the current from a stroke as there are no connections to building



Figure 3.3: Photograph showing the installed Rogowski coil at the base of the mast on top of Sentech Tower. Within the protective tube is 2 separate coils.

above this point. Current injected by the lightning event therefore passes through this point. The *DEHNdetect* system has been evaluated and compared to a shunt resistor at both the Peissenberg and Gaisberg towers, and have showed strong agreement with shunt measurements [77].

Figure 3.3 shows an image taken on the Sentech tower with the Rogowski coil installed. The coil wraps around the mast portion of the tower. This image shows that the coil encloses all the possible current pathways. Within the housing labelled Rogowski coil there are two loops of wire. The two coils are connected to amplifier circuits. One circuit is primarily set to make measurements of the initial continuing current and hence has a higher amplifier gain. While the second circuit has a gain that can capture the full range for a lightning stroke. The coils are connected to the measurement unit via a coaxial cable. The coaxial cable is not clearly visible in this image.

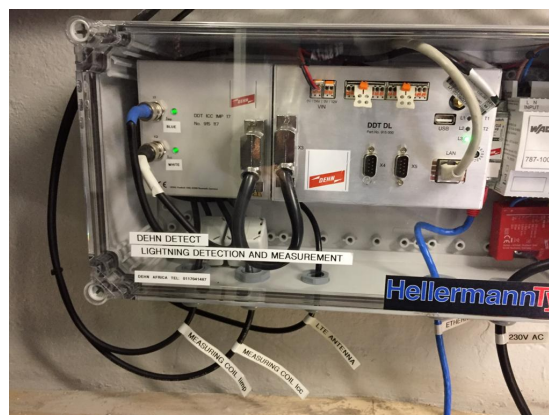


Figure 3.4: Photograph of the DEHN detect measurement unit.

Figure 3.4 shows the measurement unit that records the current measurements. The measurement unit measures the two coils (channels) independently. The system has a sampling rate of 4 MHz. The two channels have different gains to allow for observing different characteristics of an event (continuing current and high peak impulse currents). The high gain channel is intended to measure the initial continuing current (*ICC*) while the lower gain channel is best suited to the peak current and is called the current impulse *I_{imp}* channel. The *ICC* channel can resolve current values between positive and negative 2 kA while the *I_{imp}* channel can record values between positive and negative 100 kA. For accurate measurement the system requires a minimum rise time of 500 A/ μ s. The system further has a maximum rise time of 50 kA/ μ s. The recording device has 8 GB of recording space, where a single trigger uses 10 MB. All the data can be transferred via the internet or via direct access to the device. Timing of events is done using NTP with the device set as a stratum 2 device. The system has automatic triggering that saves an event if the high gain channel measures current in excess of 500 A or the *I_{imp}* channel has currents that exceed 2 kA. Each recording is 1 s long with a pre-trigger value of 40 % or 50 %. The pre-trigger is used to ensure that the initial portions of the lightning event are recorded.

3.2 Electric field measurement

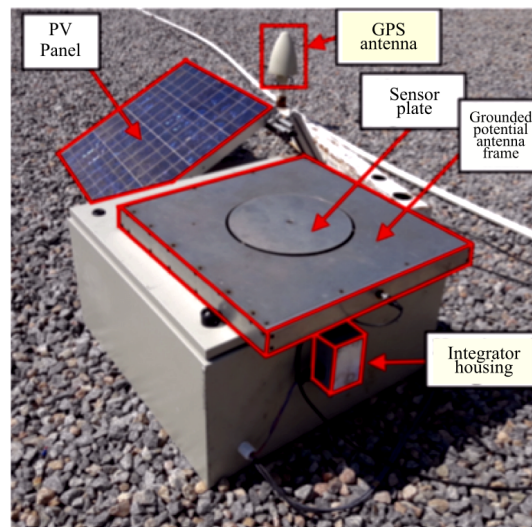


Figure 3.5: Photograph of the electric field plate sensor and accompanying electronics found at the University of The Witwatersrand, South Africa.

A flat plate vertical electric field measurement is used in many lightning studies [78–81]. A flat plate vertical electric field measurement device is capacitive. Figure 3.5 presents one of the flat plate antennas used. The labelled photograph shows the flat plate antenna at the measurement location. The measurement device is an aluminium box. The labelled central plate has a radius of 12.5 cm

and an air gap of 1 cm between the plate and the grounded frame. The sensor is connected to an analogue circuit with a 50 Ω , 25 cm coaxial cable. The size of the cable was selected to match impedance (reduce the reflections).

The flat plate antenna has a capacitive effect, therefore for a measurement that is proportional to the electric field an integrator is used. The integrator gain has been determined in the laboratory to produce a unity gain for the electric field. A further analysis is presented in Appendix A. The output of the integrator is sampled at 5 MS/s using a PCI-N-6110 National Instruments data acquisition unit, measuring with a 12 bit resolution.

In addition to the above, figure 3.5 shows the labelled GPS antenna. A GPS unit is used to accurately time the data samples. The board used to provide the GPS time is a Meinberg PCI-170 GPS board. The power supply for the circuitry is provided by a 12 V lead-acid battery. The battery is charged using the labelled solar panel. The use of a battery is to reduce the effects of the grid frequency on the measurements and to avoid the grid instability.

The measurement software measures the electric field in 1 S data-files, The recording is done in a continuous manner. The data can then be browsed by time or by scanning the data-files for measurements that exceed a specified electric field value.

3.3 Video footage

Although the video footage is not directly used as data input to this work, footage is required to confirm a lightning event to the tower. The video footage also serves to distinguish different types of lightning events (direction and leader polarity) and strikes which involve multiple strike points.

3.3.1 High-speed footage

Each storm is recorded from the Northcliff hill (to the North West of the Johannesburg CBD), where events of interest are recorded using a Phantom cine v310 camera and a Phantom cine V7. The v310 is set to record at 10 000 frames per second and each frame is GPS timestamped, while the V7 records at 3 000 frames per second. A photograph of the high speed camera setup is presented in figure 3.6



Figure 3.6: Photograph showing the high speed cameras and the view that is recorded. The camera on the left is the Phantom v310 while the camera on the right is the Phantom v7.

3.3.2 Slow-speed footage

The slow-speed cameras are setup at the University of the Witwatersrand, in the Chamber of Mines building. A 30 fps webcams and a 100 fps USB cameras are set to automatically record footage when there is a detected change in frame, these can be seen in figure 3.7. These cameras serve to provide a different viewpoint of strikes, they serve as a fail-safe for events that are obscured by rain or events that are missed by the high speed camera recording procedure.



Figure 3.7: Image of the slow speed cameras and the view they film. The camera on the left is a webcam with a maximum record speed of 30fps. The camera on the right has a maximum record speed of 100fps.

3.4 Chapter summary

This chapter presents the equipment used for primary data collection as well as the supplementary equipment. The current is measured using a *DEHNDetect* system that is made of two Rogowski coils with different gain values. The coils have gain values that allow for capturing the Initial Continuing Current (ICC) and the Impulse current (I_{imp}) with adequate resolution. The electric field measurements are done using a flat plate antenna with an analogue integrator circuit. There are two flat plate antennas. One is located 2 km from Sentech tower (at the University of the Witwatersrand) and one is located 6 km from the Sentech tower (Northcliff). The data collected is supplemented with video footage which is used to confirm lightning events and the polarity of the events.

4. Methodology

This chapter gives an overview of the methodology used to answer the research questions in chapter 1. The methodology is a linear process that starts with the measurement of lightning events and works towards comparing the remote electric field measurements to simulations with various models, based on the measured current.

4.1 Methodology overview

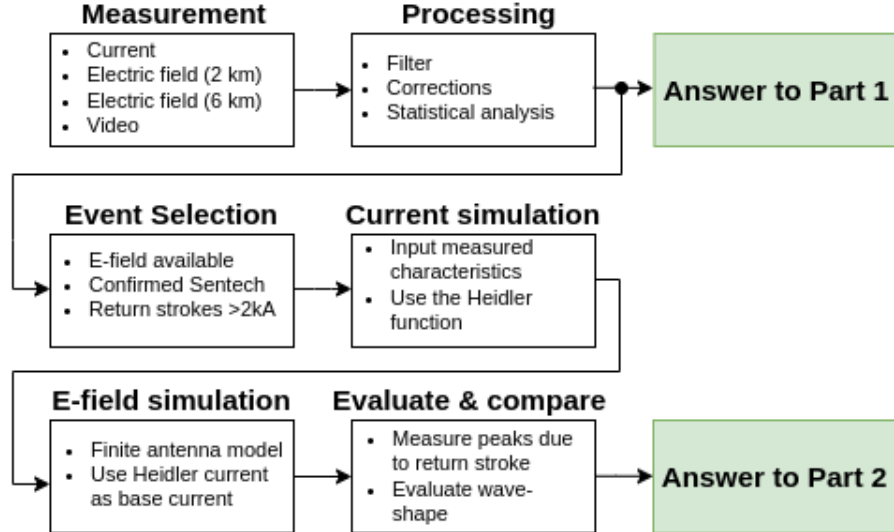
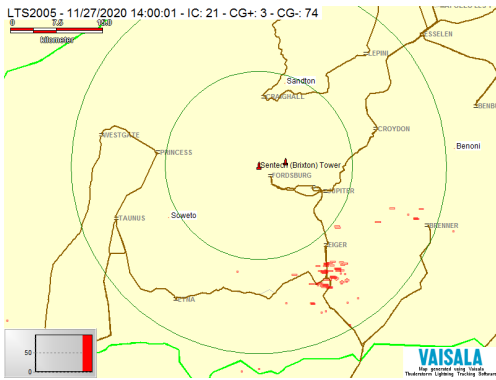


Figure 4.1: Block diagram showing the general method used to arrived at the results. The detailed explanation of each block is presented in the sections this chapter.

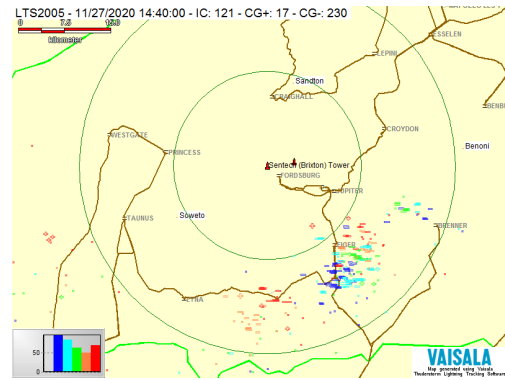
Figure 4.1 presents a flowchart of the basic methodology used for this work. Lightning events to the Sentech tower produces a current that is measured by the *DEHNDetect* system. The lightning event induces a change in the remote vertical electrical field, measured using the electric field plate sensors. The measured current is used in each return stroke model to simulate the current within the

lightning channel. The modelled current is used in the finite antenna model which allows for modelling the remote vertical electric field. The simulated electric fields are compared to the real measured electric field to determine the suitability of each model to the problem. Figure 4.1 only shows the idealised methodology. The final result compares the performance of each of the models. Each block is described in a section in this chapter.

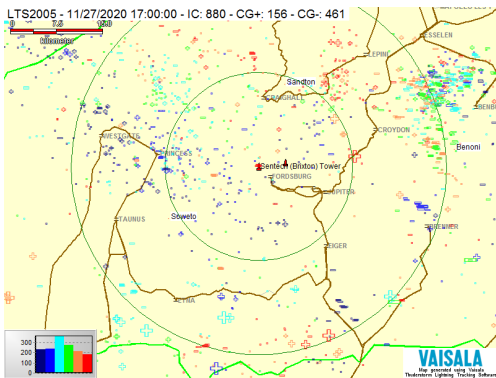
4.2 Measurement



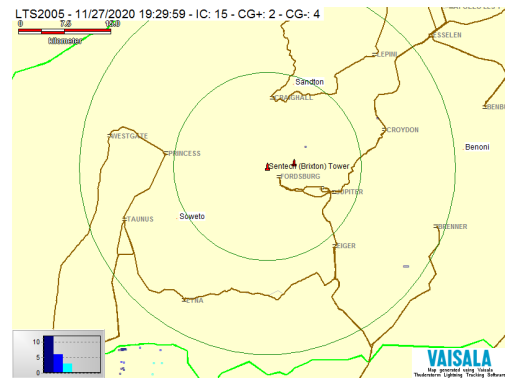
(a) This frame shows a storm cell and its associated lightning activity. The activity within the outer circle (30km) triggered the alert system.



(b) This frame shows a storm cell and its associated lightning activity. Lightning activity occurs within 15km marking the point at which the recording procedure is started.



(c) This frame shows lightning activity to the Sentech tower.



(d) This frame shows the point at which the recording of a storm would end.

Figure 4.2: Figure showing lightning activity of a storm in Johannesburg of 27 November 2020. The circles indicate 30km and 15km from the Sentech Tower. The symbols indicate the lightning polarity and the colour indicate 5 minute time bins for the events. The colour order is red, orange, green, turquoise, blue (red being within 0-5 minutes and blue indicating events that occurred up between 25-30 minutes prior).

The South African Lightning Detection Network (SALDN) is used to monitor

storm activity in and around Johannesburg. If a storm develops or moves into the thirty kilometre radius of the Sentech tower an email alert is sent. The storm is monitored and if the storm moves into the fifteen kilometre radius of Sentech the *recording* procedure is followed as detailed below. An example of the SALDN data is presented from the approaching storm that occurred on 27 November 2020, in figure 4.2. Figure 4.2a shows a storm cell that has moved within a 30 km radius (as indicated by the outer green circle) of the Sentech tower. The polarity of each event is indicated where the colour of event indicates how recently the event occurred. The storm movement is monitored to determine if the storm cell moves within 15 km of the Sentech tower.

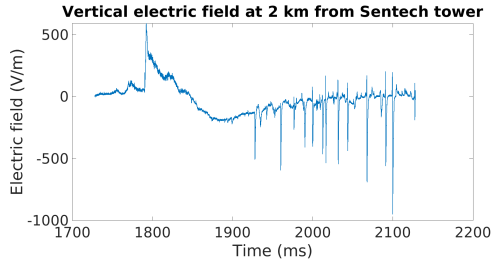
Figure 4.2b show a cell that moved within 15 km of the Sentech tower (inner green circle). Once a storm cell moves within a 15 km radius of Sentech tower the following procedure is followed:

- Turn on the electric field measurement equipment.
- Turn on GPS and High speed cameras
- Manual recordings are triggered for lightning channels within view of the cameras.

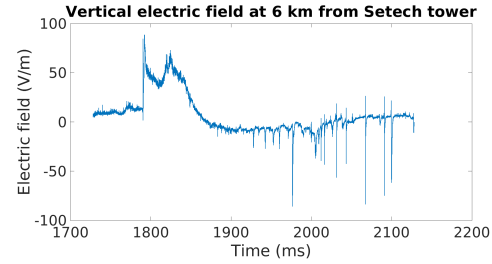
Figure 4.2c shows the lightning activity of a storm over the Johannesburg region. The image shows there has been activity in the last 5 minutes to the Sentech tower. From the image the LDN detected this lightning activity as Negative lightning events.

Figure 4.2d shows a the Johannesburg region clear of all lightning activity. Once lightning activity has ended within the region of interest, the procedure is carried out as detailed below:

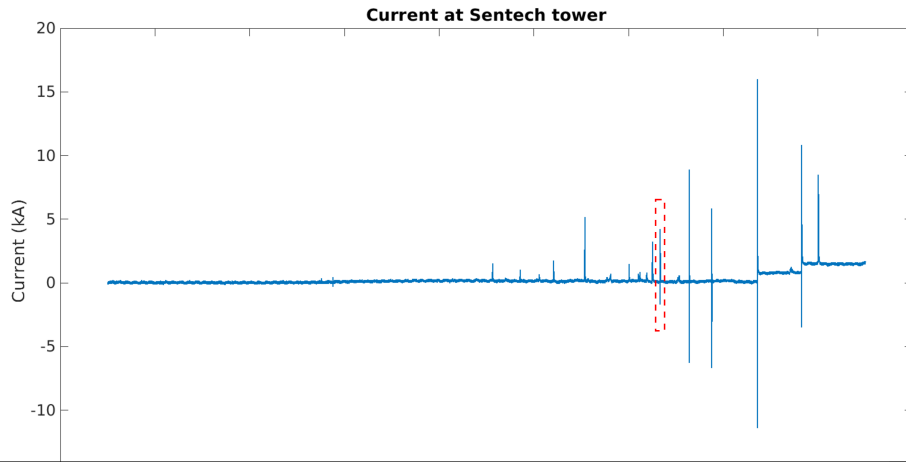
- Review, crop and name videos according to the time of a stroke.
- Extract the electric field measurement corresponding to each video with a buffer of 2 seconds.
- Review slow speed footage and current measurements to ensure all events are accounted for.
- Erase electric field data that does not have lightning events.
- Extract the lightning current from the Sentech tower measurement equipment.



(a) A portion of the electric field measurement 2 km from the Sentech tower for the upward flash measured on 27 November 2020.



(b) A portion of the electric field measurement 6 km from the Sentech tower for the upward flash measured on 27 November 2020.



(c) A portion of the current measurement made at the Sentech tower for the upward flash measured on 27 November 2020.

Figure 4.3: An example of the measurements for a lightning event. The sub-figures show the same time portion of the three measurements made for the upward lightning event on 27 November 2020. The time in each graph is the millisecond after the first available recording. The electric field measurements in the sub-figures do not have the same y-axis scale to allow for one to see the detail in each plot. The return stroke enclosed by the red box will be used to demonstrate the rest of the methodology.

All the data, once recorded, is 3-way redundant to avoid loss or corruption of data. The video recordings are used as supplementary to this work. The electric field and current are considered to be primary measurements. An example of the current and electric field measurements is presented in figure 4.3.

Figure 4.3a shows a vertical electric field measurement that was recorded on 27 November 2020, at the University of the Witwatersrand (2 km from Sentech). The graphic shows a zoomed in section (1.7 s to 2.15 s) of the 5 s of recording that was saved around the event time. From the image the greatest change seen was approximately -1000 V/m. Figure 4.3b shows the same time portion of the vertical electric field measurement for the 6 km measurement. Notice that

the waveform shows the spikes (return strokes) at the same times as the 2 km measurement. The magnitudes are however much smaller than in the 2 km case. The peak electric field change was approximately -80 V/m. Figure 4.3c shows the full current measurement at the Sentech tower over the same time period. The current is the raw measurement from the *DEHNDetect* system. The pulses seen correspond to the return strokes and subsequent return strokes for the event. Some of these strokes dip below zero due to the characteristic oscillation caused by the tower. The current characteristics and processing is discussed at length in chapter 5 and briefly in this chapter. The red box indicates a return stroke that is used from illustration purposes in this chapter.

4.3 Processing

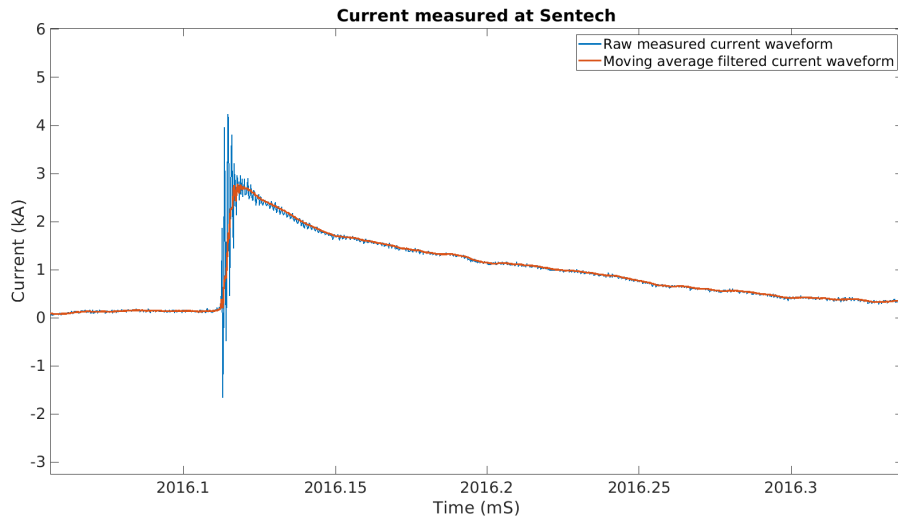


Figure 4.4: Showing the filtering that was applied to the stroke highlighted in figure 4.2c alongside the raw measured current data.

The current waveform shown in figure 4.3c is the raw measurement. To compare the measurements at Sentech to other work the ‘undisturbed’ current is required [82]. The raw current measurements shows oscillations as was seen by Heidler et al. and Romero et al. [83, 84]. Figure 4.3 in blue shows the highlighted stroke from figure 4.3c. The undisturbed (processed) current is plotted in orange. The undisturbed current is obtained by performing a 10-point moving average filter to the raw measurement. This filter is equivalent to a lowpass filter with a 3 dB cutoff of 115 kHz. From the plot in figure 4.3 the filtered current has a peak current value of approximately 3 kA, while the peak value for the raw data was approximately 4.2 kA.

In order to answer part 1 of the research question the current waveforms required

additional processing and categorisation. The categories used are described in chapter 2.4.1 and is summarised below.

ICC The initial continuing current for an upward event.

ICC Pulses Pulses superimposed on an ICC that exceed 2 kA.

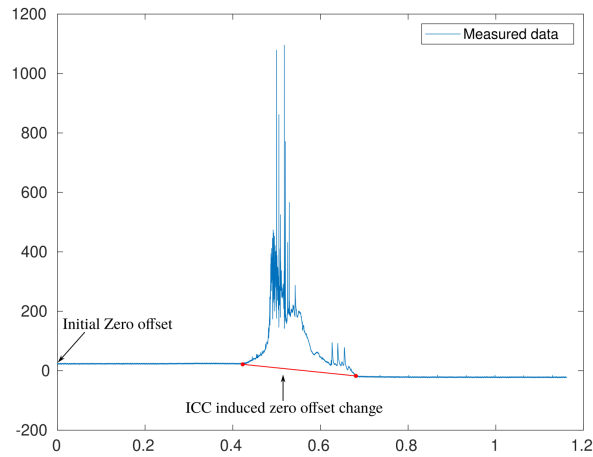
Return stroke A pulses that occur once the ICC has subsided and exceed 2 kA.

These categories are used to divide lightning events into named categories. Lightning events that only have ICC are called ICC events. If there are ICC pulses (above 2 kA) but no return strokes following the ICC the event is an ICC_P event. If there are any return strokes the event is a RS (return stroke) event. Processing is performed on the current waveforms. The current measurement over time may develop an offset drift (fixed offset). This drift value is often detected by the system and corrected for automatically or can be manually reset. Zero drift does however, still occur on some measurements and requires post processing. Lightning events that have a continuing current near or below the lower limit of the sampling rise time specification of the *DEHNDetect* see an additional offset. The offset caused by long ICC events changes the offset of the measurement. In figure 4.5 there is an example of forms of offset and the corrections applied. Figure 4.5a shows an initial zero offset and an offset induced by the ICC. The corrections that are applied to the *initial zero offset* is the negative of the offset and is applied to the whole measurement. The *ICC induced* offset increases as the duration of the ICC increases. The offset that is applied as a trigonometric function that rotates the measurement from the start of the ICC event back to base zero value. The an example of both corrections is presented in figure 4.5b. A summary of the correction used is listed here.

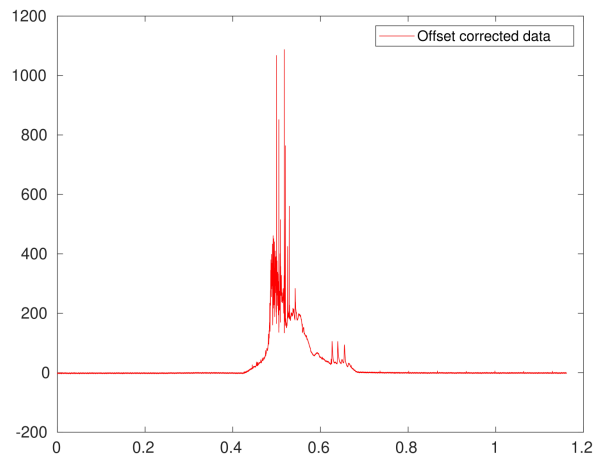
Initial zero-offset correction This is a pure offset that is present throughout the measurement. The correction therefore is a vertical shift that is applied to all the measured values.

Continuing current zero offset correction This offset occurs following a long continuing current and is an artefact of the integrator circuit and the decay time of the circuit. To correct for this, it is assumed that the effect is linear and thus a trigonometric correction can be applied from the start of the continuing current. This pivots(rotates) the ICC current towards the origin.

Once the recording have been filtered and conforms to the the standards set, statistical analysis is performed on the measurements. The statistic include current distribution, charge transfer, inter-stroke and inter-pulse duration distribution and overall statistic on the nature of the lightning events.



(a) Graph showing initial zero-offset and continuing current offset



(b) Graph showing the applied offset corrections

Figure 4.5: An example of current offsets (a) that may occur in the measurements and the corrections applied (b).

4.4 Event selection

To perform the simulations and to ensure available comparisons for the resultant electric fields, the following criteria is set as a minimum for events to be used in the remaining portion of the methodology:

- At least one electric field measurement
- A confirmation (video or LDN) that the event occurred to Sentech only
- Return strokes present in the event
- Complete current waveform

The current waveforms that meet the listed criteria above may have multiple strokes in an event. Each stroke is isolated from the current and electric field measurements and catalogued.

4.5 Current simulation

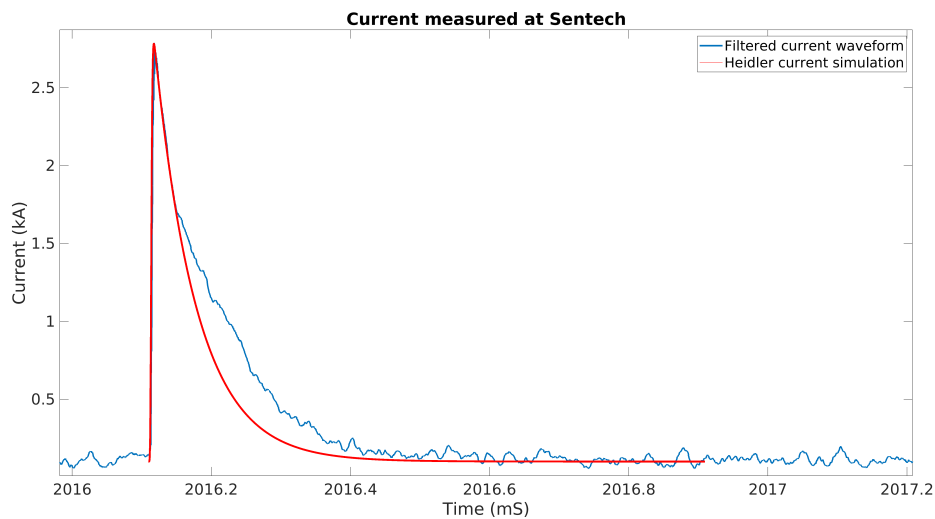


Figure 4.6: The simulated Heidler current alongside the filtered current from the highlighted stroke in figure 4.3.

On a stroke by stroke basis for catalogued events from the previous section current simulations are produced. Current simulations are advantageous as they provide a functional representation that is easily implemented in the return stroke models. The process of producing a current simulation for a stroke requires measuring

Table 4.1: Table of the parameters of the simulated and measured plots

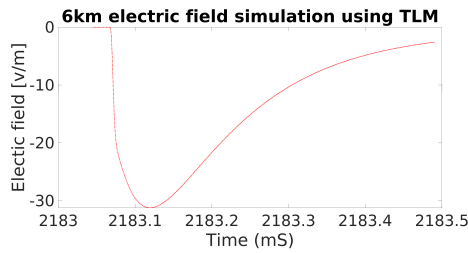
Parameter	Measurement	Simulation
Peak Current (kA)	2,76	2,782
Rise time (us)	3,7	3,5
Fall time (us)	61	45,1

the rise time, peak current and fall time. The measured attributes of each stroke and the additional variables set to value recommended by Heidler [66] are used as inputs to the Heidler function. The specific representation of the Heidler function used is from Terespolsky [67]. Terespolsky's representation has the benefit of having a functional representation of the integral of the current. In figure 4.6 the blue plot is the current for the stroke high-lighted in figure 4.3c. The orange plot is the Heidler representation of the measured current. The simulations parameters are chosen to produce the best agreement of the rise time, peak current and fall time of the waveforms. The comparison of the metrics for both plots are presented in table 4.1.

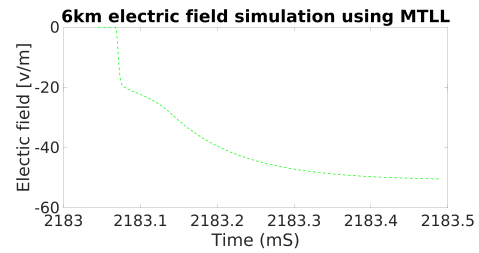
4.6 Electric field simulation

A simulated current generated by matching a Heidler function to a return stroke from one of the lightning current measurements to Sentech is then used as an input for the return stroke models. The return strokes models are used as part of the finite antenna model. The finite antenna model requires the current as a function of time along the full path of the stroke, hence use of return stroke models. The return stroke models used are the Transmission Line model (TL), the Modified Transmission Line Linear model (MTLL) and the Modified Transmission Line Exponential model (MTLE). The simulations are performed using a Matlab implementation of the finite antenna model. The simulations are computed for 2 km and 6 km for each of the return stroke models used, for each of the catalogued strokes.

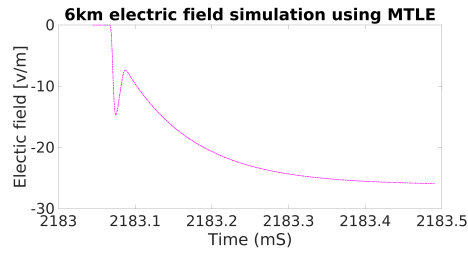
Figure 4.7 is an example of the results of a completed simulation at 6 km for the reference stroke used (the stroke highlighted in figure 4.3c). Figure 4.7a shows the TL model for the stroke. Figure 4.7b shows the MTLL model for the stroke. Figure 4.7c show the MTLE model for the reference stroke. For a comparison the measured electric field is presented in figure 4.7b.



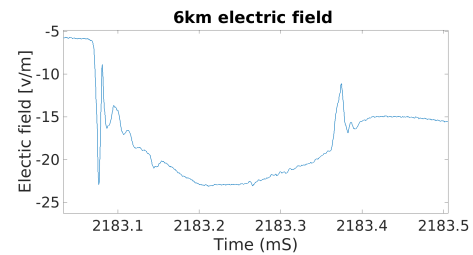
(a) A TLM simulation at 6 km from the Sentech tower for the upward flash measured on 27 November 2020, using the return stroke highlighted in figure 4.3.



(b) A MTLL simulation at 6 km from the Sentech tower for the upward flash measured on 27 November 2020 using the return stroke highlighted in figure 4.3.



(c) An MTLE simulation at 6 km from the Sentech tower for the upward flash measured on 27 November 2020 using the return stroke highlighted in figure 4.3.



(d) The vertical electric field measured at 6 km from the Sentech tower, for the return stroke highlighted in figure 4.3.

Figure 4.7: An example of the electric field simulations using the finite antenna model presented alongside the measured electric field. Figures 4.7a 4.7b and 4.7c show the simulation at 6 km from Sentech tower using the same Heidler representation of the event highlighted in figure 4.2c. Figure 4.7d shows the measured electric field for the same event.

Table 4.2: Check list for evaluating a models shape. If a model has all three elements it is considered to have accurately modelled the shape of the electric field waveform at that distance.

2 km electric field	6 km electric field
Fast Rise	Initial peak
Initial peak	‘Hump’
Slow ramp Electric field	Slow ramp after hump

4.7 Evaluate and compare

The evaluation is primarily focused on the estimation of the *initial peak* as this is directly related to the peak current of the stroke. A secondary consideration of this work is the overall wave-shape produced by the simulation.

The initial peak values from the simulation may not accurately match the measurement. due to the multitude of variables that could affect the output and increase the error. Precision is however beneficial as a fixed error can be offset and corrected for when using the simulations. The method used to evaluate each return stroke model is to measure initial peak value in the electric field and the simulated initial peak values to plot these against one other. It is expected that there would be a linear relationship between these values. The return stroke model that produces the greatest linear relationship between these values would be best suited to model the electric field. The method of evaluating the return stroke models performance would be to compare the deviations from the line of best fit for all the return strokes measured

To avoid subjectivity in evaluating the wave-shape produced by the simulations, a pre-decided check list is used to check each return stroke simulation. The check list is presented in table 4.2. This table is based on the work done by Baba et al. [85]. Finally the wave-shape evaluation would return a score indicating the number of return strokes correctly represented by each return stroke simulation model used. The return stroke model that has the highest score (ideally perfect score) is considered to have modelled the wave-shape the best.

4.8 Chapter summary

This chapter details the method applied to arrive at the conclusion of this dissertation. The method requires current measurement to an instrumented tower, along with 2 km and 6 km fast electric field measurements and video recordings to supplement the work. All the collected data is processed with emphasis on retaining only Sentech tower lightning events and filtering as is appropriate. The current measurements are compared to work done elsewhere in

order to answer part one of the research question. Lightning events that meet the criteria required for simulations are selected and further processed. The current waveforms are filtered and then simulated using Terespolsky's implementation of the Heidler function. This removes artefacts and allows for flexibility with the current waveforms. The vertical electric fields are simulated using the simulated current and the finite antenna model for each return stroke that is evaluated. The linear relationship between the models and the real electric fields are evaluated. The models' wave-shapes are compared to the physical measurements.

5. Characteristics of Sentech Tower lightning Currents

This chapter presents the measurements made during the course of this dissertation. An analysis is presented for the current measurements. The analysis compares the current to the Sentech tower to currents measurements made elsewhere. Chapter 5.2 presents the events that meet the criteria for simulations. Basic statistics for the electric fields are also presented.

The current measurements are the first upward lightning current measurements that have been conducted in South Africa. The analysis of these currents are presented. Section 5.1 shows the analysis of all the current measurements made in the 2020-2021 lightning season in Johannesburg. Section 5.2 shows the currents and electric field measurements used to perform and evaluate the simulations.

5.1 Current measurements on the Sentech Tower

This section describes the current waveforms measured over the 2020-2021 Johannesburg thunderstorm season, that were analysed. The analysis is based on the post-processed current as was detailed in the methodology (chapter 4.3).

For the 2020-2021 (November 2020 - April 2021) lightning season there were multiple triggered current measurements to the Sentech Tower [32]. A summary of the flashes is presented in table 5.1. Of the recorded events, 41 upward measurements are verifiable lightning attachments events to the Sentech tower. 26 upward flashes contained return strokes involving the Sentech tower. There were a total of 175 strokes for the upward events. For the events that had return strokes there were 71 ICC pulses above 2 kA. Six events had ICC with pulses exceeding 2 kA, but did not have a return stroke following the ICC. There were 30 ICC pulse on events that did not have return strokes. Nine events had ICC

Table 5.1: Summary of the current measurements at Sentech tower, Johanneeburg (2020-2021)

Event type	Flashes (Events)	Pulses and strokes
ICCRS	26	257 (175RS, 71P)
ICCP	6	30
ICConly	9	0
Downward RS	1	1
Total	42	288

Table 5.2: Median and geometric mean of peak currents for different event types

Event type	No. of flashes	Number of fast pulses	Current Peak [kA]	
			Median	GM
ICCRS	26	257	7,51	7,69
ICCP	6	30	3,75	3,96
Total	32	287	-	-

without pulses that exceeded 2 kA. There is a single negative downward lightning event to the Sentech tower during this measurement period. All recorded flashes were negative flashes.

Of the 42 (downward event excluded) events, 25 (59.52 %) have return strokes following the ICC (ICC_{RS}). This amount far exceeds the 13 % in Japan [86] and the 30 % seen at the Gaisberg Tower in Austria [87]. Only 7 (16.67 %) events had fast pulses (ICC_P) superimposed on the ICC and did not have return strokes following the ICC. This percentage is lower than the 41 % seen in Japan and the 22 % seen at Gaisberg. However, the amount is clearly reduced due to the much higher percentage of ICC_{RS} . ICC events without any fast pulse or return strokes (ICC_{only}) amounted to 10 (23.81 %).

Table 5.2 shows the median and geometric mean for ICC events and RS events. The peak median and geometric mean for events that have return strokes (ICC_{RS}) is 7.51 kA and 7.69 kA respectively. The median and geometric peak current for events with ICC pulses only (ICC_P) is 3.75 kA and 3.96 kA respectively. The mean and median when compared to the tower measurements in Europe and Japan are comparable [83, 86–88].

For the 26 ICCRS flashes, there were a total of 175 return strokes and an average multiplicity of 6.4. This value is higher than the observed values in Brazil (2.0), at the CN Tower (2.4), in the United States (3.4), at the Japanese Wind Turbines (3.5), the Beijing meteorological tower (4.3), at the Gaisberg Tower (4.4), and even when compared to the winter only flashes for the Gaisberg Tower (4.8) [83, 84, 86, 88–91].

An overview of the multiplicity is presented in figure 5.1. The y-axis shows the

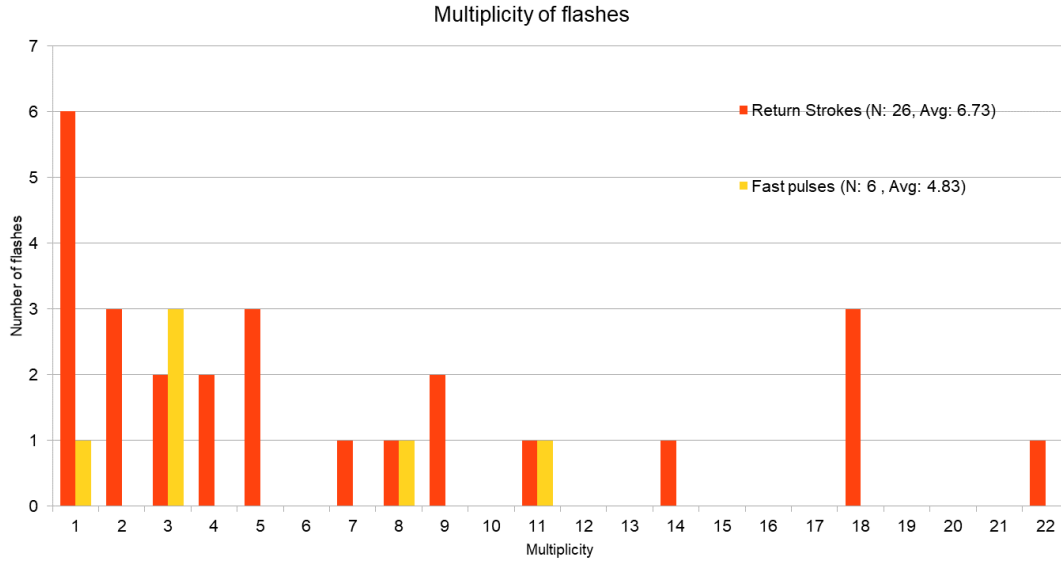
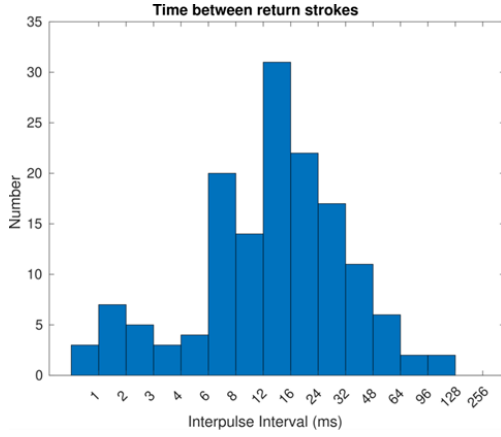


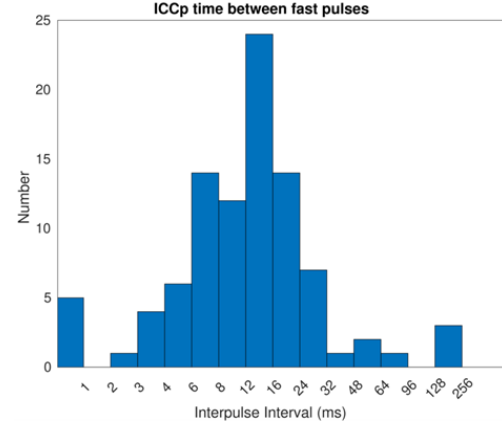
Figure 5.1: Graph of the multiplicity of the recorded flashes. Flashes with return strokes are presented in red and the ICCp flashes are presented in yellow

number of events (flashes) that had a given multiplicity. The x-axis are the multiplicity for an event, i.e. the number of strokes or ICC_P pulses an event has. The red bars show the multiplicity for events with return strokes. The yellow bars show the results for ICC pulses on ICC events without return strokes. It is worth noting that there were 6 (20.69 %) flashes that had a multiplicity greater than 10. The multiplicity of the fast pulses (ICCP) was less than that of the return strokes (ICCRS), as well as the range of multiplicity values. This contrasts with Michishita et al., who showed a greater range in multiplicity of the fast pulses when compared with the multiplicity of the return strokes but a similar average multiplicity between the two [86].

Figure 5.2 shows plots of the inter-stroke or inter-pulse distributions. The y-axis on both plots is the number of pulses that fall within a bin. The x-axis is separated into duration bins. The inter-stroke duration distribution is presented in figure 5.2a. It is noted that the distribution is similar to that seen by Diendorfer et al., although within a smaller range. The geometric mean inter-stroke interval is 15.30 ms (median: 17.32 ms) which is comparable to the values seen by Diendorfer et al. and Michishita et al. [86, 87]. The histogram in figure 5.2b shows the time between ICC fast pulses. The distribution is similar to that of the inter-stroke distribution however this is for fewer events (115 vs. 175). The geometric mean between pulses is 13.7 ms (median: 15.67 ms) and hence is less than that seen for the time between return strokes. This result is similar to, but not as pronounced, as seen by Michishita et al. With the range of time intervals also being greater for the fast pulses compared to the inter-stroke value for the return strokes.

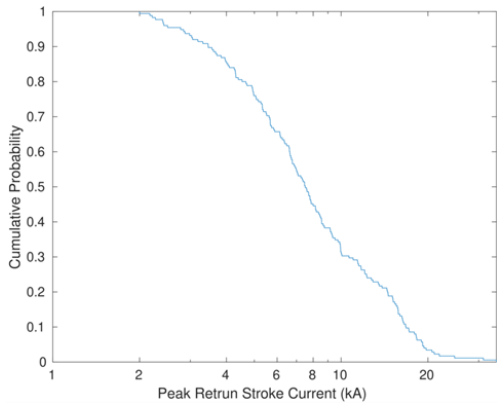


(a) Graph showing the distribution of times between successive strokes.

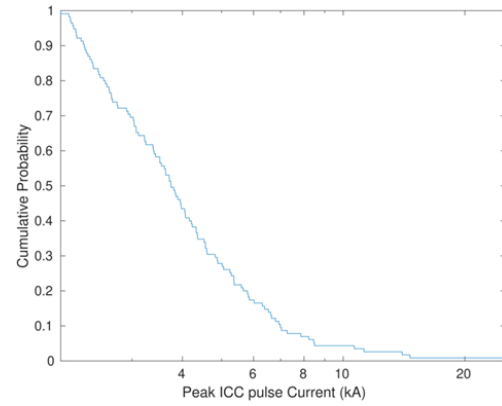


(b) Graph showing the distribution of times between successive ICC fast pulses.

Figure 5.2: Graphs showing the distribution of time between successive stroke or ICC fast pulses.



(a) Graph of the peak current distribution of the return strokes.



(b) Graph of the peak current distribution of the ICC fast pulses.

Figure 5.3: Graphs showing the cumulative probability distribution of the peak current for return strokes and ICC fast pulses for events to Sentech tower in the 2020-2021 lightning season.

The cumulative probability of the peak currents of the ICCRS return strokes is presented in figure 5.3a. The probability distribution shows a near-linear log-normal relation as seen by Romero et al and Diendorfer et al. [84, 87]. The highest recorded peak current for the period was 34.56 kA. The same analysis was performed for the fast pulses superimposed on the ICCP cases. The cumulative probability is presented in figure 5.3b. This again shows a near linear log-normal distribution however the gradient is far steeper with 99.9% of fast ICC pulses being below 8 kA. The highest peak current measure was 25.18 kA for the fast ICC pulses. Similar was seen by Michishita et al. The total charge transfer

Table 5.3: Charge transfer characteristics and results comparison between this work and that done elsewhere

Study	Charge transfer (C)					
	ICCP		ICCP		ICCRS	
	GM	Median	GM	Median	GM	Median
Sentech 2021 (this study)	23.41	26.08	29.31	35.51	34.49	41.36
Michishita et al. [86]	24.50	25.30	38.60	36.90	29.30	38.80
Gaisberg[87]	-	-	-	-	41.00	44.00

for each event was determined by numerically integrating the current waveforms after offset correction was completed. The results are presented in table 5.3. The charge transfer for return stroke events is comparable to the values that were seen at the Gaisberg tower and slightly higher than those seen by Michishita et al. [86, 87]. However, the charge transfer for ICC_{Only} and ICC_P is comparable to values measured by Michishita et al.[86, 87].

In summary the lightning currents to the Sentech tower had similar characteristics to the currents seen on other towers across multiple metrics. However, the lightning measurements at the Sentech tower did show a much higher multiplicity for events than was seen elsewhere.

5.2 Event selection for simulation

Table 5.4: Table showing the number of fast pulses and return strokes observed for each flash used

Flash	Flash A	Flash B	Total
ICC fast pulses	2	3	5
Return Strokes	11	15	26
Total	13	18	31

The simulation procedure is performed on current measurements that can be evaluated using electric field measurements. The minimum requirement is that

the observed lightning events have vertical electric field measurements at 2 km and 6 km alongside the current measurement. Additionally flashes that have other tower interaction are not considered. Only two flashes meet all the requirements imposed. The analysis for these two flashes is presented in table 5.4. The filtered current waveforms for flash A and flash B are presented in figure 5.4 and figure 5.5 respectively, alongside the electric field measurements associated with the lightning events.

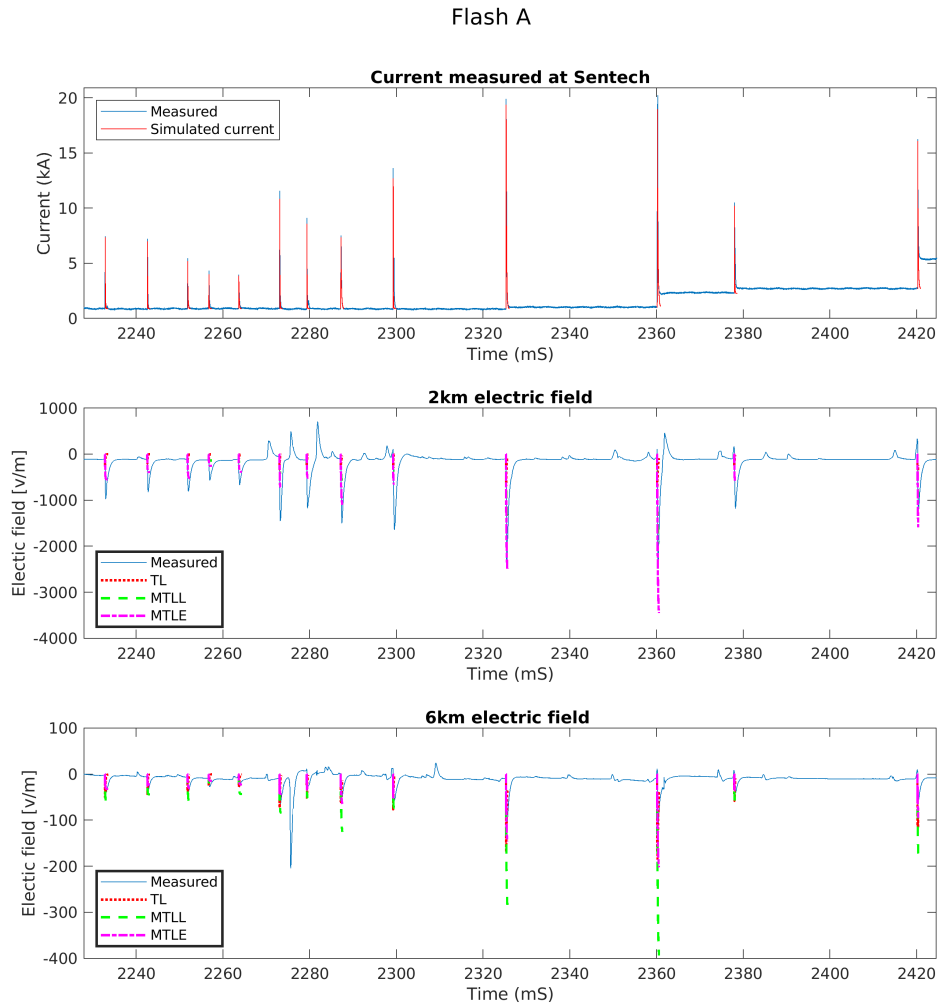


Figure 5.4: Graph showing measured vertical electric field at 2 km and 6 km for flash A alongside the current showing the relationship.

In both figure 5.4 and figure 5.5 the current is the top sub-figures. On the y-axis is the current in kA. The x-axis is the time in ms since the time of the first available recording. The measurements presented have been filtered of noise. In figure 5.4 the current shows 13 pulses that exceed 2 kA where the first two pulses are ICC fast pulses (as confirmed by analysis of the high gain channel). In figure 5.5 the

current shows 18 pulses that exceed 2 kA where the first three pulses are ICC fast pulses, confirmed by the high gain current channel.

The middle and lower sub-figures show the vertical electric field at 2 km and 6 km respectively. The y-axis on both plots are the electric field values in V/m. While the x-axis is the time in ms after the initial measurement point. Note that the y-axis for the middle and lower sub-figures are not of the same scale. The magnitudes of the 2 km electric field are an order of magnitude greater than the 6 km fields.

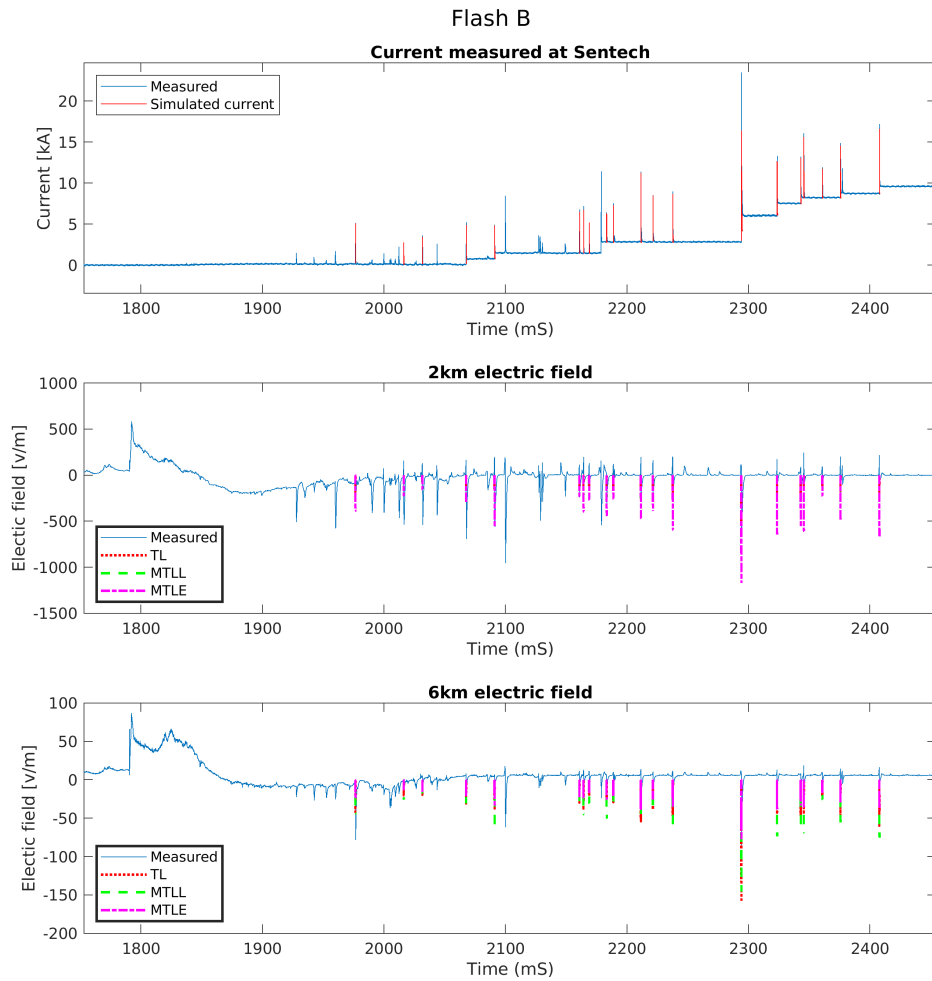


Figure 5.5: Graph showing measured vertical electric field at 2 km and 6 km for flash 2 alongside the current showing the relationship.

5.3 Chapter summary

In the 2020-2021 season 42 verifiable lightning flashes occurred that involved the Sentech tower in Johannesburg. The season produced, 175 return strokes, 30 ICC fast pulses and 9 ICC_{Only} events. The return stroke median current and median ICC fast pulse peak currents are comparable to the values seen in literature at 7.51 kA and 3.75 kA, respectively. The median charge transfer also agrees with literature for return strokes this is 41.36C, while it is 35.51C for ICC_P events and 26.08C for ICC_{Only} events. The return stroke multiplicity however is higher for the Sentech tower than elsewhere, for the season the value is 6.41.

Of the measured flashes, two flashes met all the criteria set in chapter 4 for use in simulating electric fields. The selected flashes have 5 ICC pulses and 26 strokes (return strokes or subsequent strokes) that are used for the simulations (referred to henceforth as strokes). The electric fields are available for both flashes and are lined up with the current to allow for analysis and comparison.

6. Simulations

This chapter discusses how to produce a current simulation for a measured lightning current using the Heidler current model. The chapter presents an example of the procedures using a 10/350 μs waveform, which is used to model lightning. The procedure for creating an electric field simulation using the finite antenna model is presented. A simulation of the 10/350 μs waveform is presented with varying distances and using different return stroke models.

6.1 Current simulation

As discussed in chapter 2 it is more convenient to work with a function that closely represents the current as opposed to using the measurements directly in the electric field simulations. This section discusses the simulation of the flow of current in a channel for a lightning return stroke. The simulation is computed for a 10/350 μs 200 kA waveform as an example of the procedure used for the measured currents. A 10/350 μs and the characteristics of the waveform are presented in the IEC 62305-1 standard. For a Heidler simulation the peak current, Heidler correction factor, rise time, fall time and the steepness factor are required. The peak current is the measured peak value. The rise time is determined by calculating the time from 10% of the peak to 90% of the peak value. The fall time is calculated by measuring the time from the peak to 50% of the peak value. The steepness factor is normally set to 10 and the Heidler correction factor is calculated. From the IEC 62305-1 standard the characteristics are obtained as was done by Wang and Zhang, the values are presented in table 6.1 [92, 93]. The reproduced waveform for the 10/350 μs is presented in figure 6.1. This is produced using the function as defined by equation 6.1. This equation is discussed further and the variables are presented in chapter 2.6.1.

$$i_a(t) = \frac{I_0}{\eta} \left(1 - e^{-\omega_0 t} \left(\sum_{i=0}^{n_a} \frac{\omega_0^i t^i}{i!} \right) \right) e^{\frac{-t}{\tau_2}} \quad (6.1)$$

Table 6.1: Values of variables for the Heidler function to reproduce the 10/350 μ s 200 kA waveform

Variable name	Value in Heidler function
I_p	200kA
η	0.93
n_h	10
τ_1	19
τ_2	485

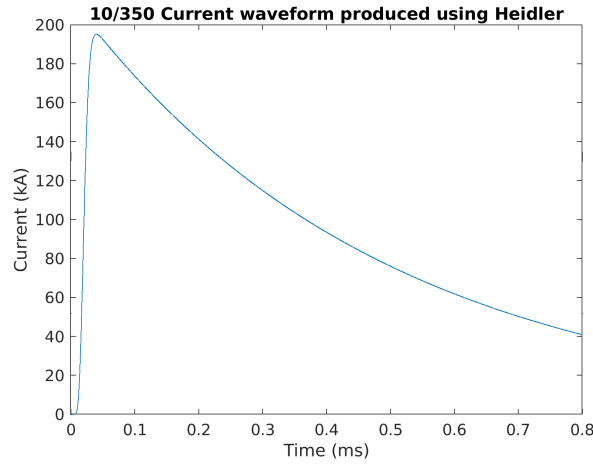


Figure 6.1: A waveform showing a reproduced 10/350 μ s current waveform using the Terespolsky representation of the Heidler function for the first 800 μ s.

6.2 Electric field simulation

Chapter 2.7 shows that a simulated electric field can be computed given the current for a lightning event as input. An electric field can be simulated using the finite antenna model. This section presents the procedure for producing an electric field simulation specifically when using the Heidler current derived above.

6.2.1 Electric field simulation procedure

Listing 6.1: Simplistic procedural code flow for arriving at a simulated electric field

```

t= simulation run time
n = simulation step size

for each n in t
    calculate upper integral from 0 to n
    calculate time at step n

    Terespolsky Derivative at n
    Terespolsky current at n
    Terespolsky integral at n

    Multiply each by the decay factor
    Perform trapezoidal integration on each component
    Multiply each component by constants
    return(sum of the components)
done

```

A generalised coding procedure for simulating the electric field (e-field) is presented in listing 6.1. The simulation of the e-field requires the simulation time and the time steps to use. The e-field simulation is performed at each step value up to the simulation time. At each time step the upper limit of the integral is calculated. The integral is divided into a finite sum (by the trapezoidal method) from 0 to the calculated upper limit in dz components. The dz components are steps determined by the upper limit divided by a large integration step constant.

For each integration step (dz), the effective time is calculated at step n . The calculated time is used to determine the current and the decay constant to use for the current function, this is the return stroke model used. Since the electrostatic, radiative and inductive components of the electric field are independent they are calculated separately. Once all the components are calculated for the step they are summed and saved as the total electric field for that time step. This procedure is done for each time-step and results in the complete current waveform over time.

6.2.2 Electric field simulation output

Given the current function as determined in the previous section for the 10/350 μs impulse, the electric field can be simulated using the procedure above. For the simulation the parameters listed in table 6.2 are used.

To illustrate the different return stroke models (TL, MTLL and MTLE) figure

Table 6.2: Parameters used in the electric field simulations

Simulation Parameter	Value
Step size	100 ns
End time	800 μ s
Channel speed	1.5×10^{-8}
Integration steps	100 000
Channel Height (MTLL)	10 000
Decay λ (MTLE)	2 000

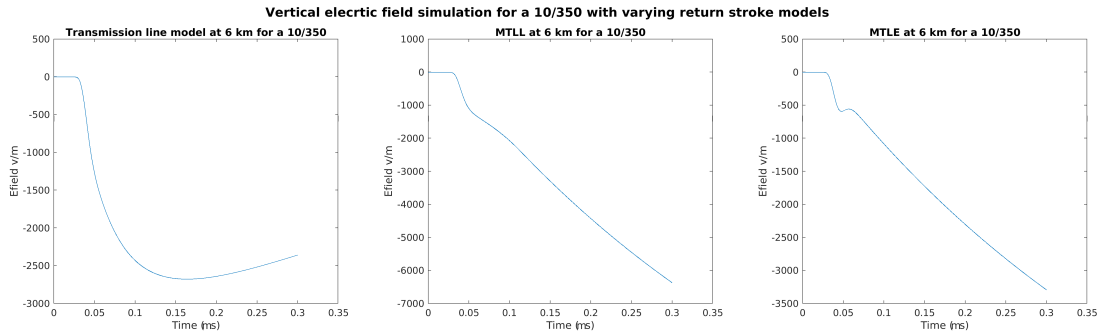
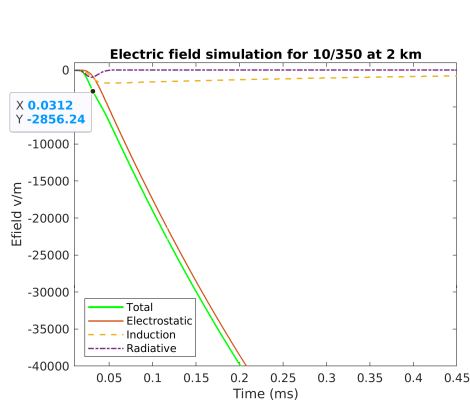


Figure 6.2: A waveform showing the resultant vertical electric field simulation at 6 km for the 10/350 current waveform above for each of the return stroke models.

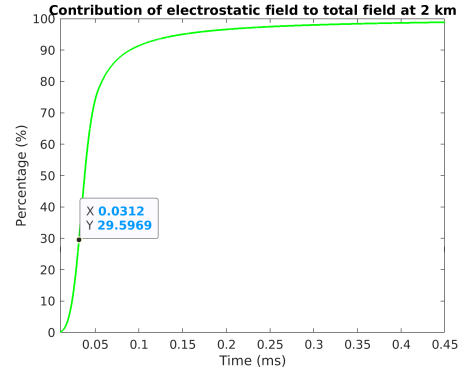
6.2 presents the simulation of the electric field using each model at 6 km from the stroke location. The leftmost plot shows the result of the simulation when using the transmission line (TL) return stroke model. From the plot it is evident that the initial (only) peak occurs at approximately 0.15 ms, with a value of approximately -2300 V/m. The middle plot shows the result of the simulation when using the modified transmission line linear model (MTLE). The models shows more detail overall when compared to the TL model. The initial peak value is seen at approximately 0.05 μ s with an approximate value of 1200 V/m. Following the initial peak the graph tends negatively. The rightmost plot shows the simulation result when using the modified transmission line exponential model. The graph has an initial peak value at approximately 0.05 μ s with an approximate value of 700 V/m. The graph shows a more pronounced deviation following the initial peak prior to tending negatively just like the MTLL model.

The simulations are distance dependant as discussed in further detail in chapter 2.5. Figure 6.3 shows plots of the electric field simulations of the 10/350 μ s at 2 km, 6 km and 100 km with the components that make up each electric field alongside a figure showing the contribution of the electrostatic field to the magnitude of each electric field. Except for the distance, the simulations were performed with all other characteristics kept constant.

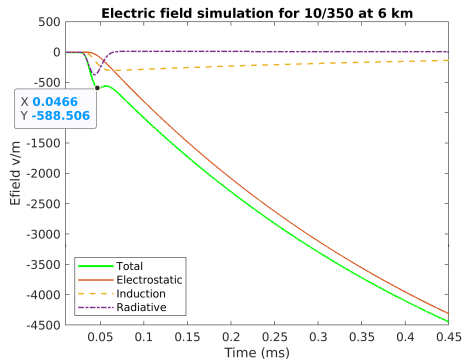
Figure 6.3a, 6.3c and 6.3e show the total electric field plotted in the solid green



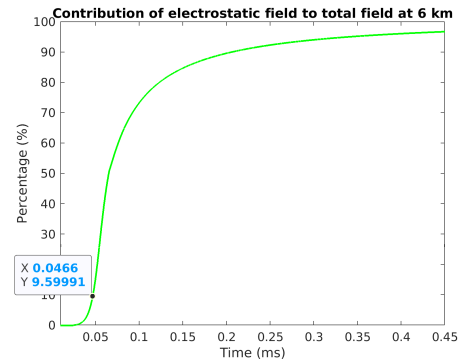
(a) Graph showing the electric field and electric field components simulated for a 10/350 us impulse at 2 km over 0.08 ms.



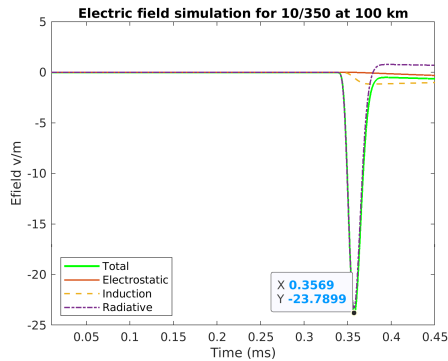
(b) Plot of the relative contribution of the electrostatic component of the electric field as a percentage of the electric field value at 2 km.



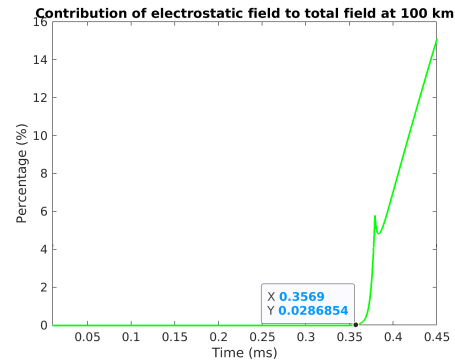
(c) Graph showing the electric field and electric field components simulated for a 10/350 us impulse at 6 km plotted over 0.3 ms.



(d) Plot of the relative contribution of the electrostatic component of the electric field as a percentage of the electric field value at 6 km.



(e) Graph showing the electric field and electric field components simulated for a 10/350 us impulse at 100 km plotted over 0.5 ms.



(f) Plot of the relative contribution of the electrostatic component of the electric field as a percentage of the electric field value at 100 km.

Figure 6.3: Graphs showing the electric field simulations and the components of the electric field at different distances from the stroke location using the MTLE model. For each distance the contribution of the electrostatic field to the magnitude of the total electric field over time is plotted. Each plot has the point where the initial peak occurs labelled.

line. The components of the electric field for each plot are plotted on the same axis as the total electric field for each. The electrostatic component is plotted in the solid red line, the inductive component is plotted in the dashed orange field while the radiative field is plotted with the broken purple line.

Figure 6.3b, 6.3d and 6.3f show the contribution of the electrostatic field to the magnitude of the total electric field. The components of the electric field for each plot are plotted on the same axis as the total electric field for each. The electrostatic component is plotted in the solid red line, the inductive component is plotted in the dashed orange field while the radiative field is plotted with the broken purple line.

Figure 6.3a shows that the initial peak value is difficult to discern and that the overall wave-shape follows the electrostatic component. From 6.3b, the contribution of the electrostatic field for the initial peak is approximately 30% and the contribution is greater than 90% before 0.1 ms. Figure 6.3c shows that the initial peak at 6 km is mostly composed of the contributions made by the inductive field and radiative fields. The overall wave-shape initially follows the addition of the radiative and inductive fields but after the initial peak thereafter the total electric field is best represented by the electrostatic field. From 6.3d, the contribution of the electrostatic field for the initial peak is approximately 10%. Following the initial peak the contribution of the electrostatic component increases reaching a 90% contribution by approximately 0.2 ms. From figure 6.3e it is clear that the total electric field is almost exclusively comprised of the radiative field, with a minor contribution from the inductive field. From figure 6.3f the electrostatic field has a negligible contribution for the initial peak at less than 1%. The contribution does increase thereafter but not as steeply as was seen for closer simulation distances.

6.3 Chapter summary

This section showed that given a current measured (or its characteristics), it can be reproduced using the Heidler current model. The electric field simulation can be produced using the Heidler current model as input to the finite antenna model. The resultant electric field will have differing shapes based on the return stroke model used as well as the distance from the stroke. In measurement locations that are near the stroke the field is dominated by the electrostatic component. This contribution shifts to the inductive and radiative field, where at greater distances (such as 100 km) the radiative field dominates the electric field. The simulations in this chapter were done using the iconic 10/350 μ s waveform as an illustration. For the work, the simulations presented in this chapter were produced for each of the strokes identified in chapter 5.

7. Model comparison and evaluation

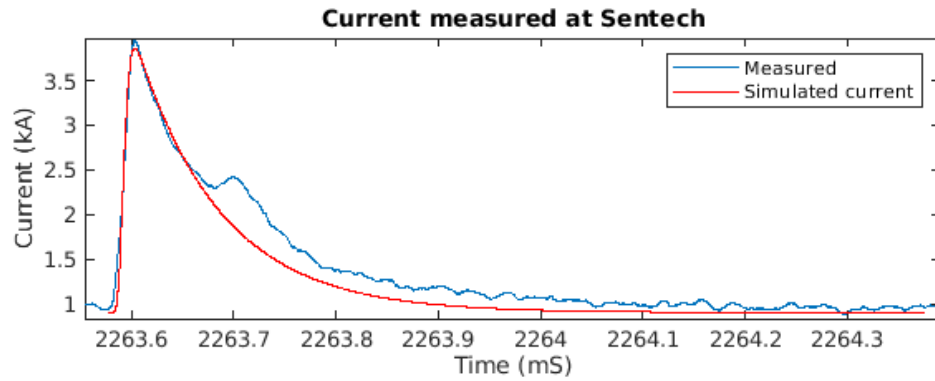
This chapter analyses the simulations from the previous chapter. The analysis performed on the strokes compare each simulation to the measurements. For each simulated electric field the simulation is visually inspected for expected characteristics. The evaluation also compared to initial peak magnitude as this value is directly related to the return stroke.

A brief review of the nomenclature is presented here. *Initial rising segment* is the first rising limb of an electric field measurement associated with a return stroke. *Initial peak* is the component that is related to the return stroke peak. It appears as a bump/spike in the electric field and is more prominent in electric field measurement at locations further from the return stroke. *Tail segment* refers to the ramp portion that follows closely after the initial peak. The portion of the waveform between the *initial peak* and the *tail segment* will be referred to as a *hump* in this text. For all the returns strokes that meet the criteria set out in section 5, the simulations are performed. Section 7.1 presents two example simulations and discusses the comparisons between the simulations and measurements. Section 7.2 presents the plots of the measured vs the simulated initial peak values. This section presents the linear relationship between these value for the different return stroke models used at 2 km and 6 km.

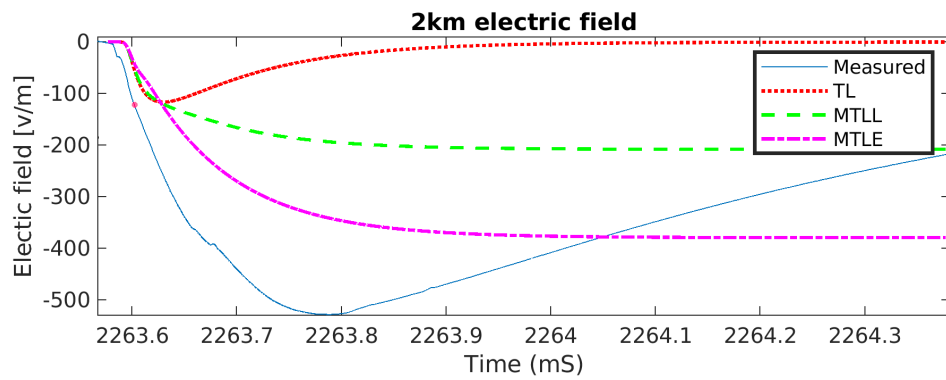
7.1 Results

Two lightning events to the Sentech tower had correlated lightning current and electric field measurements (as discussed in chapter 5). Between these two events, a total of 31 strokes were measured as part of these events (5 ICC fast pulses and 26 subsequent return strokes). As described in the methodology chapter 4, each of these strokes were isolated and labelled alphabetical-numerically for each flash (Flash A 1-11 and Flash B 1-20).

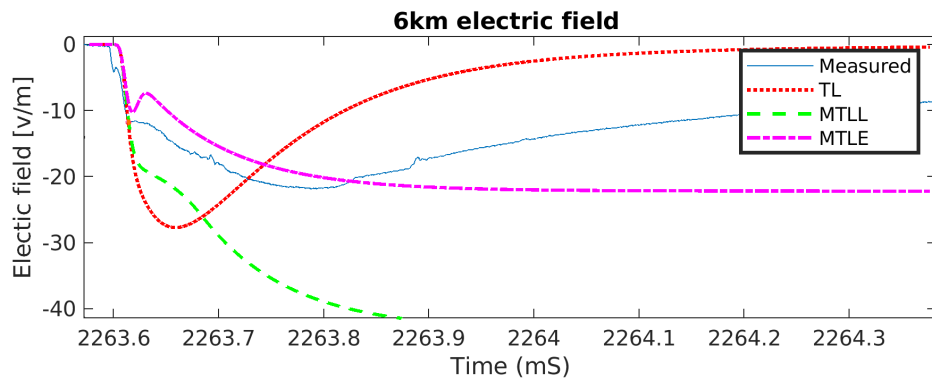
Figure 7.1 shows the measurements for stroke 5 from flash A, plotted in blue. Plotted alongside the measurements are the simulations for the measurements.



(a) A portion of the current measurement made at the Sentech tower for the upward flash A showing return stroke 5.



(b) The measured and simulated electric field at 2 km from flash A stroke 5.



(c) The measured and simulated electric field at 6 km from flash A stroke 5.

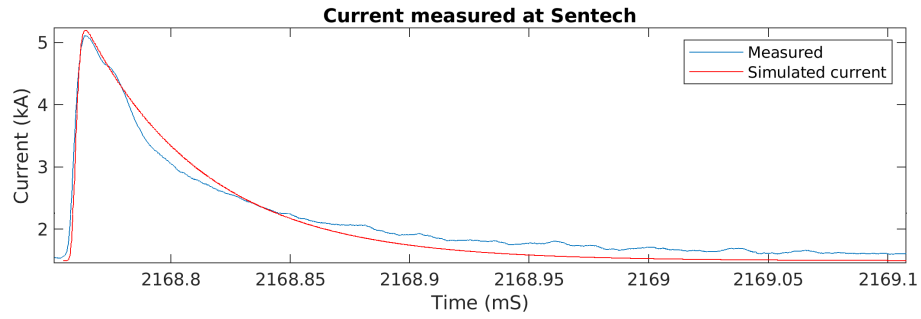
Figure 7.1: The measurements and simulations for the return stroke 5 for flash A, which occurred on 05 October 2020.

This stroke was measured 180 ms after the initial continuing current and 31 ms after the first subsequent return stroke. Figure 7.1a shows the measured current waveform between time 2263.5 ms and 2264.4 ms in which this subsequent return stroke (SRS) occurred. The time is measured with respect to the first electric field measurement time. As can be seen, this SRS reached a peak current of approximately 3 kA (since there is an offset of approximately 1 kA). It rose to this peak in approximately $13.5 \mu\text{s}$ and fell to 50% of the peak current in $56 \mu\text{s}$. Using the measured values, the Heidler simulation is produced for a measurement. The simulation of the current in blue is plotted in red. An artificial offset has been included to show that plots on the same axis. This offset is used for illustration only and is not used in the electric field simulations. The simulation shows a peak current, rise time, and fall time that matches the measurement.

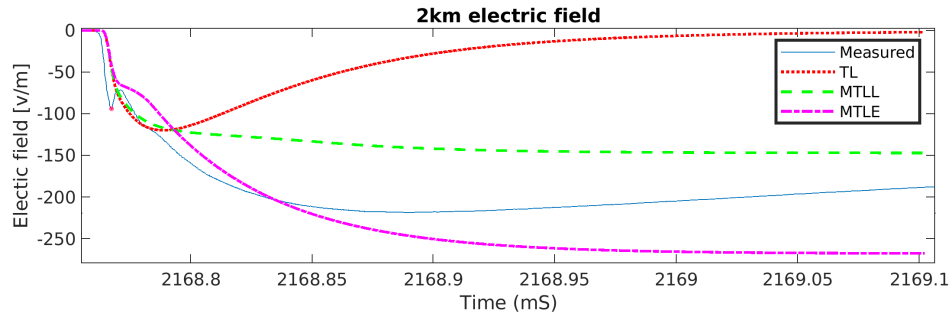
Figure 7.1b shows the measured vertical electric field at 2 km between the time 2263.5 ms and 2264.4 ms in which this subsequent return stroke (SRS) occurred. As can be seen, the field had an initial peak value of approximately -125 V/m. The graph continues to rise after this value and the electric field reached an overall peak of approximately -525 V/m. The graphs are presented alongside the measurement in the simulations of the electric field using different return stroke models. The red plot is the simulation when using a transmission line model (TL). The green plot shows a simulation when using a modified transmission line linear model (MTLL). The purple plot is the simulation using a modified transmission line exponential model (MTLE).

Figure 7.1c shows the measured vertical electric field at 6 km between the time 2263.5 ms and 2264.4 ms in which this subsequent return stroke (SRS) occurred. As can be seen, the field had an initial peak value of approximately -12 V/m. The graph reaches the overall peak of -22 V/m before tending back towards zero. The graphs are presented alongside the measurement in the simulations of the electric field using different return stroke models. The red plot is the simulation when using a transmission line model (TL). The green plot shows a simulation when using a modified transmission line linear model (MTLL). The purple plot is the simulation using a modified transmission line exponential model (MTLE).

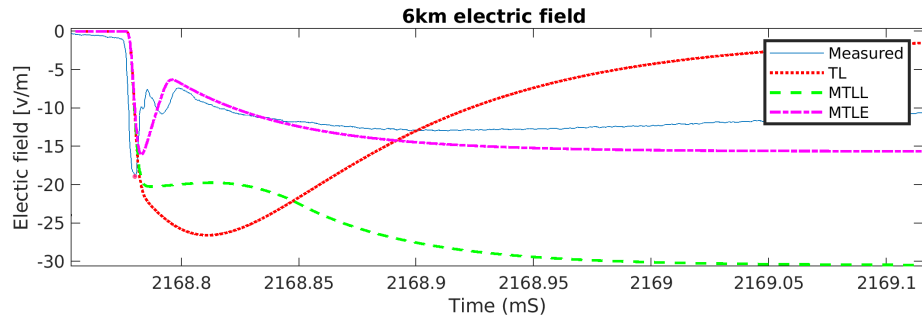
Figure 7.2 shows the measurements for stroke 8 for flash B, plotted in blue. Plotted alongside the measurements are the simulations for the measurements. This stroke was measured 193 ms after the initial continuing current and 298 ms after the first subsequent return stroke. Figure 7.1a shows the measured current waveform between time 2168.75 ms and 2169.1 ms in which this subsequent return stroke (SRS) occurred. As can be seen, this SRS reached a peak current of approximately 3.5 kA (since there is an offset of approximately 1.5 kA). It rose to this peak in approximately $5 \mu\text{s}$ and fell to 50% of the peak current in $30 \mu\text{s}$. Using the measured values, the Heidler simulation is produced for a measurement. The simulation of the current in blue is plotted in red. An artificial offset has been included to show that plots on the same axis. This offset is used for illustration only and is not used in the electric field simulations. The simulation shows a peak



(a) A portion of the current measurement made at the Sentech tower for the upward flash B showing return stroke 8.



(b) The measured and simulated electric field at 2 km from flash B stroke 8.



(c) The measured and simulated electric field at 6 km from flash B stroke 8.

Figure 7.2: The measurements and simulations for the return stroke 8 for flash B, which occurred on 27 November 2020.

current, rise time, and fall time that matches the measurement.

Figure 7.2b shows the measured vertical electric field at 2 km between the time 2168.75 ms and 2169.1 ms in which this subsequent return stroke (SRS) occurred. As can be seen, the field had an initial peak value of approximately -100 V/m. The graph continues to rise after this value and the electric field reached a overall peak of approximately -220 V/m. The graphs are presented alongside the measurement in the simulations of the electric field using different return stroke models. The red plot is the simulation when using a transmission line model (TL). The green plot shows a simulation when using a modified transmission line linear model (MTLL). The purple plot is the simulation using a modified transmission line exponential model (MTLE).

Figure 7.2c shows the measured vertical electric field at 6 km between the time 2168.75 ms and 2169.1 ms in which this subsequent return stroke (SRS) occurred. As can be seen, the field had an initial peak value of approximately -18 V/m. The graph tends to zero before tending to flatten out at approximately -10 V/m. The graphs are presented alongside the measurement in the simulations of the electric field using different return stroke models. The red plot is the simulation when using a transmission line model (TL). The green plot shows a simulation when using a modified transmission line linear model (MTLL). The purple plot is the simulation using a modified transmission line exponential model (MTLE).

The plots of the remaining SRS/pulses are presented in appendix B. From the figures the electric field shows the direct effect of the return stroke with the red dot on each plot (referred to in this work as the initial peak as a result of the return stroke). This ‘initial peak’ becomes more pronounced, in comparison to the rest of the waveform, as the distance increases from the location of the lightning event as can be seen in the figures. See chapter 2.4.3 for a more in depth discussion on this.

In chapter 2.4.3 the components of the electric field were discussed. The components were shown to be dependant on the distance from the measurement (discussed in chapter 6 as well). The electrostatic component is dominant near the lightning strike point, the radiant component is dominant in the distant electric field and between these extremes the electric field has contributions from the electrostatic, inductive and radiative components. It is also important to note that the electrostatic field has an integral of the current as a factor, the inductive component has the current as a factor, while the radiative component has the derivative of the current waveform as a factor.

7.1.1 2 km visual evaluation

These evaluations are based on the general observations made for the measurements, however for this section the example images will be used

as a reference. The reference figures are figure 7.1b and figure 7.2b, for flash A and flash B respectively.

For the transmission line models in both figures 7.1b and 7.2b the initial peak value is closest to the measured value, in comparison to the other models. However, the TL model does not ramp to the initial peak as quickly as the other models nor the measured value. The waveform moves to the peak value and back to zero and does not reproduce the characteristic ‘hump’. This is because of the simple current model assumption (no decay).

The modified transmission line linear model (MTLL) has an initial peak that is less prominent than the other models. The model reaches the initial peak faster than the TL line model. From the graphs it is clear that it is comparable to the MTLE model as well as the measured electric field.

The modified transmission line exponential model has a rise time that is similar to the rise time seen in the measurement. This model better reproduces the dynamics seen in the measurement. The tail segment (see chapter 2.5) has the same wave-shape and the slope of the decay is similar to the measurement.

7.1.2 6 km visual evaluation

The reference figures are figure 7.1c and figure 7.2c, for flash A and flash B respectively.

For the transmission line (TL) model the initial peak value is greater than that seen in the measured electric field. The TL model rises to the initial peak slowly compared to the other models and the measured value. The waveform lacks complexity, in that the waveform moves to the peak value and back to zero as discussed above.

The MTLL model best matches the initial peak value, but is less than the values seen in the measurements. The shape of the modelled electric field suffers the same deficiencies seen in the 2 km electric field especially with respect to the tail segment of the waveform.

The MTLE model has a peak that is less than the initial peak value seen in the measurement. Just as was seen in the 2 km case the tail segment best matches the measured electric fields. For the 6 km case the match is closer than was seen in the 2 km case due to the reduced weighting of the electrostatic component of the electric field.

7.1.3 General comments on the models

Overall each model showed that there is a linear relation between the initial peak and the simulated initial peak. This relationship groups tightly around the trend line across different flashes but does show some variance. This variance may be due to the differing cloud base heights and simulation parameters used among other possible factors. Overall all the models greatly under-estimated these initial peaks of the SRS/pulses in the 2 km range. In the 6 km range the estimation were closer but still offset by a fixed multiple. While based on the metrics used all three models showed reasonable agreement, but by looking at the waveforms it is clear that for overall wave-shape the MTLE model performs best. The initial peak was far further depressed in comparison to the other models, but this can be accounted since this underestimation is consistent at a given distance. The MTLE model consistently approximated the initial rise, hump and subsequent tail best. The TL model did not, in most cases, show any of the characteristic features. Where the MTLL model did show some of these features, especially at the 6 km mark, it often over-estimated the ramping nature of the waveform. From the root mean squared values it is clear that the simulations at 6 km have fewer variance around the predicted gain factor for the initial peak. This can be attributed to the reduced effect of the electrostatic component of the electric field.

7.2 Linear fit for initial peak simulated plotted against measured

This section presents the initial peak electric field values of the simulations plotted against the simulated initial peak values. Each plot is from a different return stroke model at either 2 km or 6 km from the location of the lightning current.

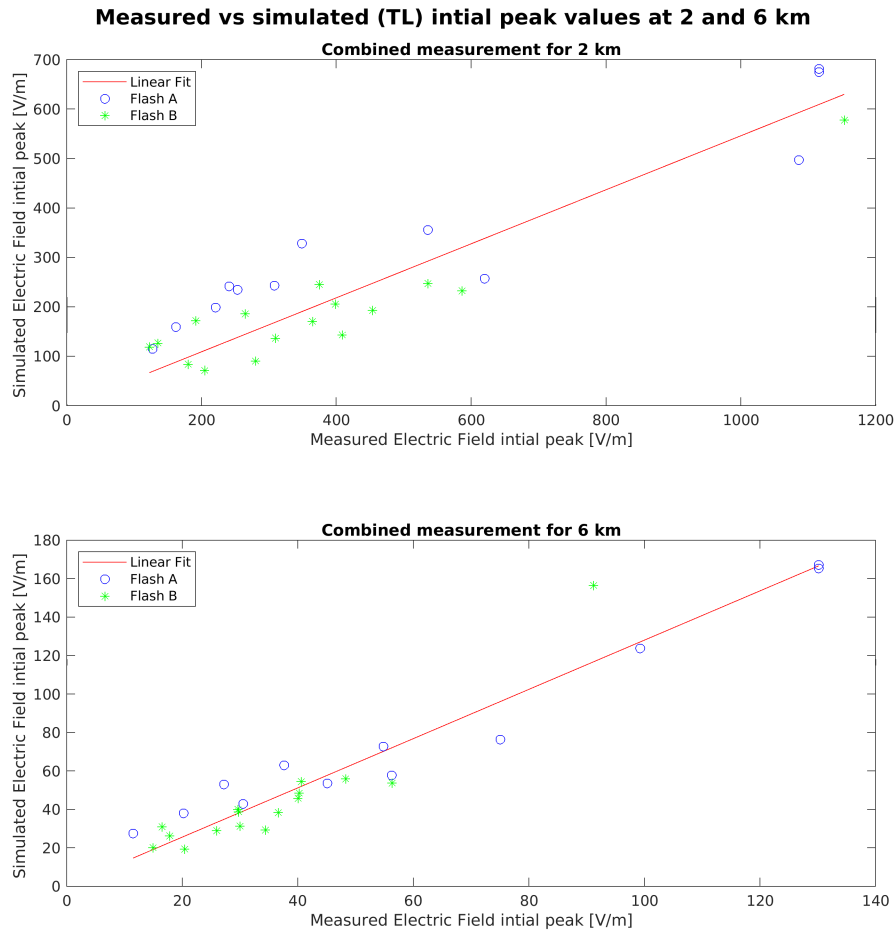


Figure 7.3: Graph showing a plot of the TLM simulated electric field peak plotted against the measured electric field peak for multiple strokes/pulses in a single lightning event at 2 km and 6 km from the Sentech. The top plot shows the results for the 2 km electric fields. The bottom figure shows the results for the 6 km electric fields.

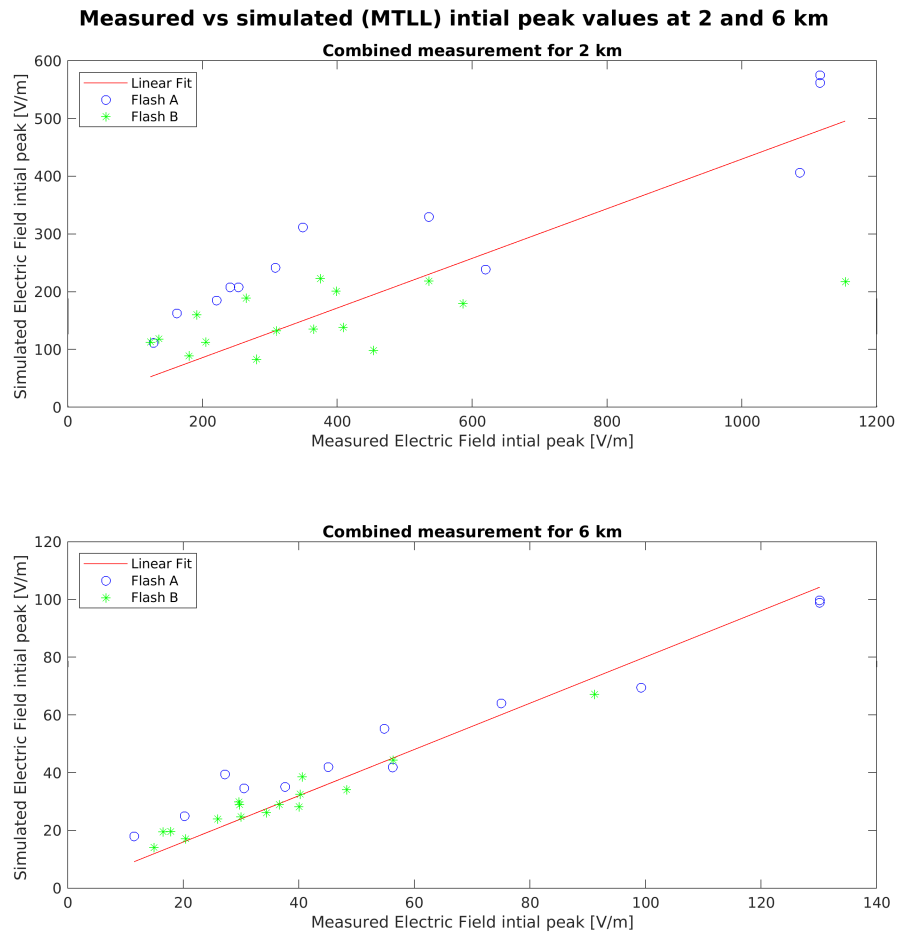


Figure 7.4: Graph showing a plot of the MTLL simulated electric field peak plotted against the measured electric field peak for multiple strokes/pulses in a single lightning event 2 km and 6 km from the Sentech. The top plot shows the results for the 2 km electric fields. The bottom figure shows the results for the 6 km electric fields.

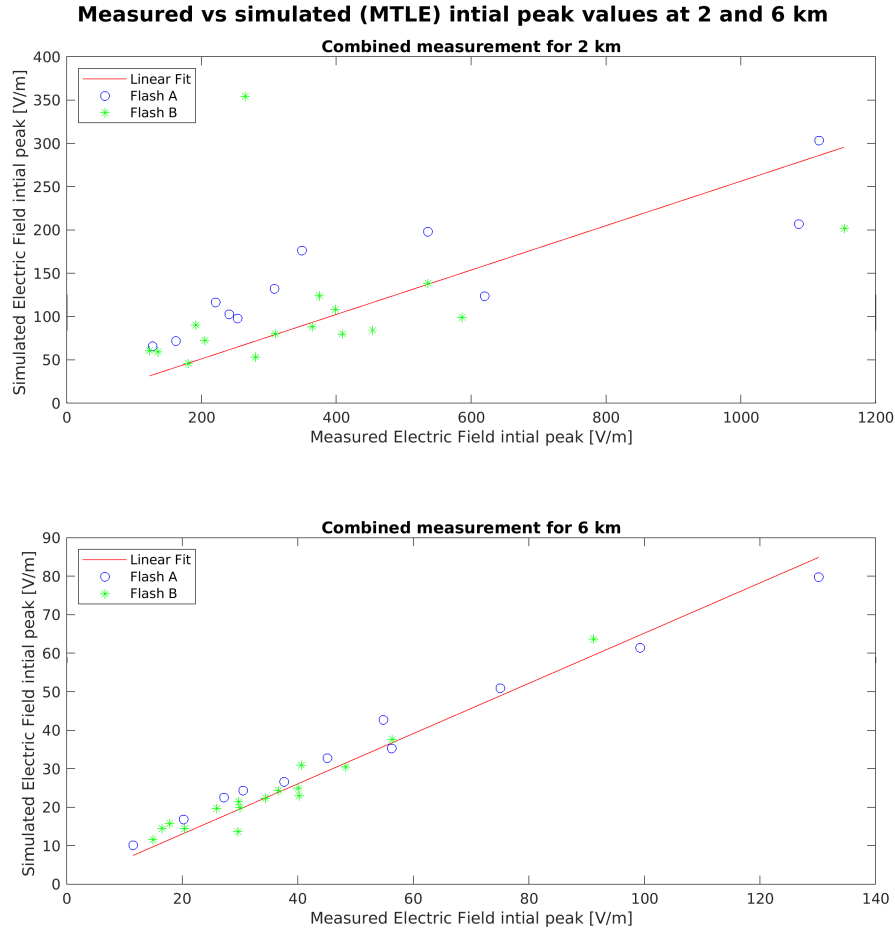


Figure 7.5: Graph showing a plot of the MTLE simulated electric field peak plotted against the measured electric field peak for multiple strokes/pulses in a single lightning event at 2 km and 6 km from the Sentech. The top plot shows the results for the 2 km electric fields. The bottom figure shows the results for the 6 km electric fields.

Figure 7.3 show the measured initial peak current plotted against the simulated initial peak current for the transmission line model. The graph shows the plot for all the strokes identified for flash A and flash B at both 2 km and 6 km from the current measurement. Each plot has the linear line of best fit plotted in red. The gradient of the line of best fit for the 2 km graph is 0.54 with a standard error of 0.0248 and root mean error of 65.2. For the 6 km graph the gradient of the line of best fit is 1.28 with a standard error of 0.0415 and root mean error of 12.2

Figure 7.4 shows the plot of the measured initial peak current plotted against the simulated initial peak current for the modified transmission line linear model. The graph shows the plot for all the strokes identified for flash A and flash B in chapter 5 at both 2 km and 6 km from the current measurement. Each plot has

the linear line of best fit plotted in red. The gradient of the line of best fit for the 2 km graph is 0.43 with a standard error of 0.0327 and root mean error of 87. For the 6 km graph the gradient of the line of best fit is 0.8 with a standard error of 0.0227 and root mean error of 6.68.

Figure 7.5 shows the plot of the measured initial peak current plotted against the simulated initial peak current for the modified transmission line exponential model. The graph shows the plot for all the strokes identified for flash A and flash B in chapter 5 at both 2 km and 6 km from the current measurement. Each plot has the linear line of best fit plotted in red. The gradient of the line of best fit for the 2 km graph is 0.26 with a standard error of 0.0246 and root mean error of 69.3. For the 6 km graph the gradient of the line of best fit is 0.65 with a standard error of 0.0119 and root mean error of 3.5.

From figure 7.3, 7.4 and 7.5 it is clear that each model had a strong linear relationship for a given distance. This relationship remained the same across the two flashes, with slight variation. The 6 km simulations showed a better linear relationship for each of the models in comparison to the 2 km simulations, as is evident by the reduced standard error and root mean error values. The linear relationship was the strongest for the 6 km modified transmission line exponential model overall. Among the 2 km simulations the modified transmission line exponential model also had the best linear fit. None of the simulations at any distance produced a 1:1 relationship between the measured and simulated initial peak values. However, the consistent linear relationship can be used to correct for the difference between the values.

7.3 Chapter summary

This chapter presented an example of the strokes that were analysed in each flash. The analysis showed the manner in which the simulations were compared to the measured electric fields. The visual analysis demonstrated that the modified transmission line exponential model is able to reproduce key characteristics (initial peak, hump and decaying tail segment) more consistently than the other two models. The transmission line model only produces the initial peak value and does not reach this value as quickly as the measurements. There is a clear linear relationship for all the models when plotting the measured initial peak value against the simulated initial peak value. The agreement is stronger at 6 km for all the models. The agreement is not 1:1 and suggests that when using these models a correction factor should be applied to the simulated initial peak values. The modified transmission line exponential model performed better than the other models in terms of wave-shape as well as the linear agreement between measured and simulated initial peak values.

8. Conclusion

This work studied lightning within the Johannesburg region. Measurements of lightning currents were recorded using a Rogowski coil for lightning events to the Sentech tower. The electric fields as a result of the lightning events were recorded with flat plate antenna at 2 km and 6 km for the Sentech tower. Two research questions were investigated. These questions are listed below, with the findings underneath each question.

‘What are the characteristics of lightning currents to the Sentech tower?’

The first measurements of current to the Sentech tower were recorded. The measurement of the current was done using a Rogowski coiled based system. Alongside the current measurement video footage and electric field measurements were recorded for the lightning events. The measurements are from the 2020-2021 lightning season and show that Sentech experience prominently upward initiated lightning with the characteristics listed below.

- 42 Flashes in the season with only 1 downward flash.
- 186 return strokes, 30 ICC fast pulses and 7 ICC_{Only} events for the season.
- ICC_{RS} events had a peak current median of 7.51 and geometric mean of 7.62.
- ICC_P events had a peak current median of 3.75 and geometric mean of 3.96.
- Median charge transfer for return strokes is 41,36 C.
- Median charge transfer for ICC_P is 35.51 C and 26.08 C for ICC_{Only} events.
- Return stroke multiplicity is 6.41.

These measurements are show similar characteristics and distributions to the work done elsewhere expect for the stroke multiplicity which is higher than any other published work.

‘Which of the three engineering return stroke models (TLM, MTLL, MTLE), best reproduce radiated lightning electric field peaks measured within the 2-10 km range for upward lightning in Johannesburg, South Africa?’

The transmission line (TL), modified transmission line linear (MTLL) and the modified transmission line exponential (MTLE) models were used to simulate the remote electric field at 2 km and 6 km. The simulations were compared to the measured vertical electric field at these distances. All the models showed linear agreement when comparing the modelled and measured initial peak values. Better agreement was seen for all the models at 6 km compared to 2 km. Listed below are the observations regarding each model

TL Simple with the least absolute difference from the measured initial values. The linear agreement was lower compared to the other models. TL models only simulate the peak value and not the overall wave-shape.

MTLL Showed some details of the overall wave-shape but performed slightly better overall than TL but slightly worse than the MTLE model.

MTLE Initial peak value is consistently less than the measured value. Greatest linear agreement between the measured peak value and the simulated value (i.e offset by a scaling factor). The wave-shape is most identical to what is expected and when compared to the measured electric field.

8.1 Future work

This work especially the answer to part one of the research question can be used in future studies of the characteristics of upward lightning in the Johannesburg region. The characteristics observed over the 2020-2021 lightning season should be included in a long-term study to determine the characteristics for the region with greater confidence.

The tower’s characteristic response should also be investigated with respect to the effect it has on the remote electric field. The fluctuations were shown to be high frequency in nature and would therefore be more prominent in the radiative field (do to the derivative nature of the radiative field). This is of particular interest to lightning detection systems as they tend to use detection from sensors that are further away to estimate the current. These measurements were shown to be predominantly comprised of the radiative field.

There are many models available that model the remote electric field, for example finite difference time domain based models. This work could be used as a comparison to evaluate the performance of these additional models.

This is the second collection of upward lightning measurements, after Eriksson, in South Africa. The installation of a current measurement at the Hillbrow tower is expected to be completed by the end of 2022. In this work it was noted that several lightning events had dual tower interactions (lightning to both towers in the same flash). The new measurements could be used in conjunction with this work to investigate the electric fields produced when there is two towers involved in a single flash.

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Appendix A Electric field

The flat plate sensor can be modelled as a capacitor and the measurement can be modelled as a capacitive divider. A change in the vertical electric field produces a change in the voltage across the flat plate antenna. A capacitor has the effect of differentiating the input signal, hence the use of an integrator.

The integrator circuit is designed to introduce a gain factor and to negate the differential effect that the flat plate antenna has. The circuit used for the design is based on the work of Kohlmann et al. [94]. The circuit design is presented in figure A.1.

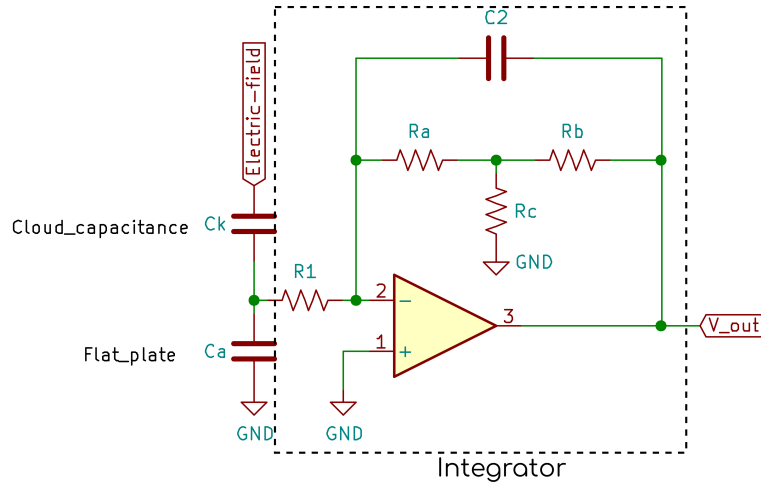


Figure A.1: Schematic of the equivalent circuit for the measurement unit. The integrator is indicated by the dotted line, C_a corresponds to the capacitance of the flat plate antenna. C_k represents the effective capacitance between the clouds and the plate.

The flat plate capacitor has a radius of 12.5cm and a gap of 1.0cm. The design produces a system that has a gain factor of $43 \left[\frac{mV}{V/m} \right]$. Figure 3.5 shows the equipment that is used to make the vertical electric field measurements. The output is recorded using a Texas Instruments PCI N-611 measurement board, that allows for sampling at 5MHz. The software records and creates 1 second files that are GPS timestamped.

The bandwidth for the circuit was measured in the laboratory and conforms to the design, with a pass-band between 1Khz to 1Mhz and a roll-off of 6dB. This circuit design has been used alongside and evaluated with flat plate sensors [2, 30, 38, 95–99].

The time constant selected is 0.5 ms, for any parts of the waveform that had duration much less than this the measured value accurately reproduces the real change. For parts of the disturbance that continue for a longer period (such as slower continuing current) distortion is expected to occur. This can be corrected for, as is demonstrated in

Appendix B Return-strokes used

This appendix shows all the current and electric field measurements used, alongside the simulated data used. For each figure the first sub-figure shows the current and simulated current. The second sub-figure shows the electric field at the 2 km measurement point. The third sub-figure show the 6 km measurement point. For clarity in seeing the waveforms the y-axis of the electric field measurements are *not* kept the same for the 2 km and 6 km measurements. The time indicated on the x-axis of each of the graphs indicate the time in milliseconds from the time of the first measurement for the event. For example, the point with an x-value of 2271 was measured 2271 milliseconds after the initial electric field measurement. Figure B.1 shows the full measurement from the flash observed on 05 October 2020 at 14:40:33, this flash is referred to as flash A. Figure fig:rsfull2 shows the full measurement from the flash observed on 31 October 2020 at 17:06:52, this flash is referred to as flash B.

B.1 Flash A

This section shows the full current and electric field measurements and simulations for the flash on 05 October 2020 at 14:40:33 in figure B.1, referred to as flash A. In figures B.2 to B.12 the zoomed-in sections of the individual pulses and return strokes that were used in this work are shown.

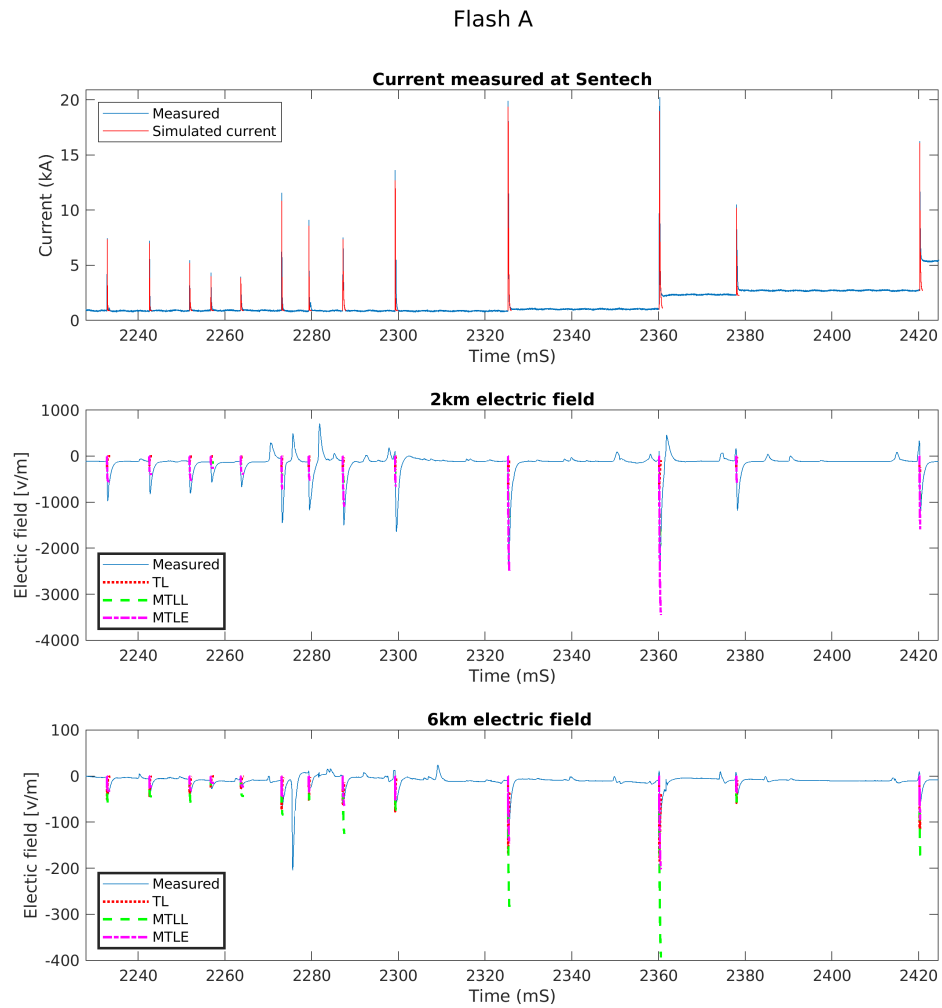


Figure B.1: Graph showing measured and simulated current and electric fields for the full flash on 05 October 2020 at 14:40:33.

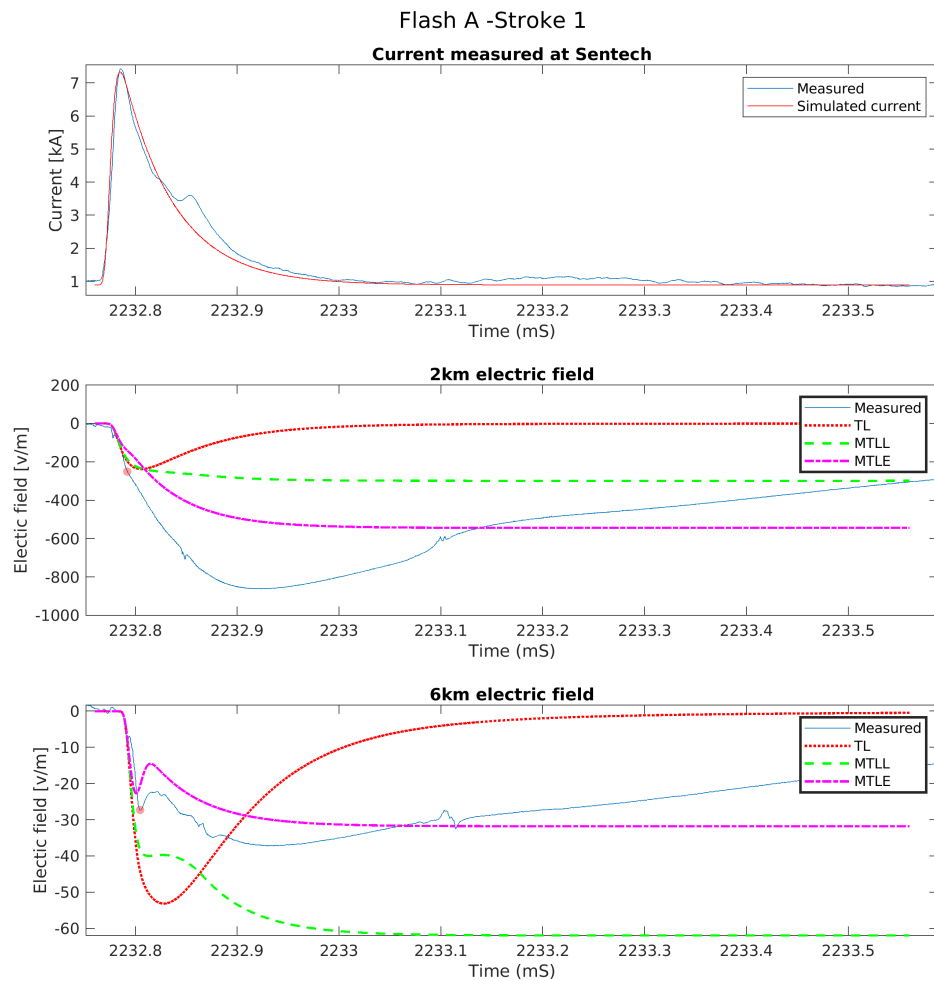


Figure B.2: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke A of the full flash on 05 October 2020 at 14:40:33.

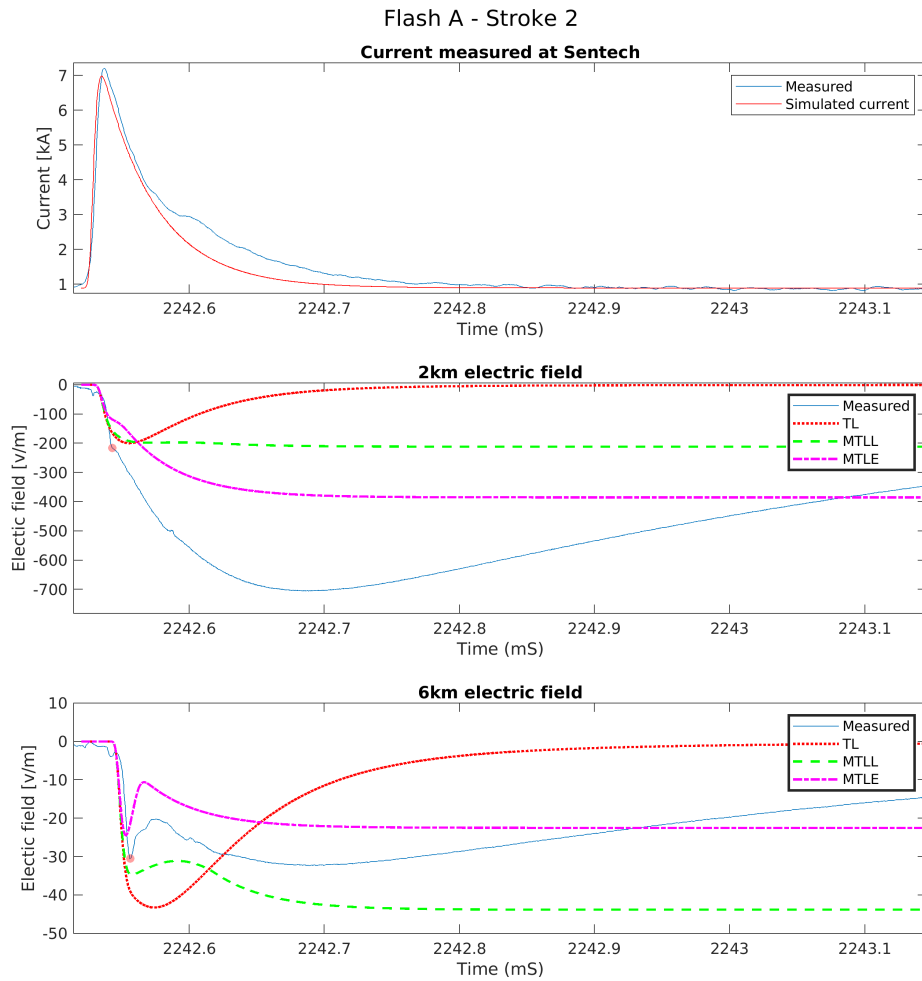


Figure B.3: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke B of the full flash on 05 October 2020 at 14:40:33.

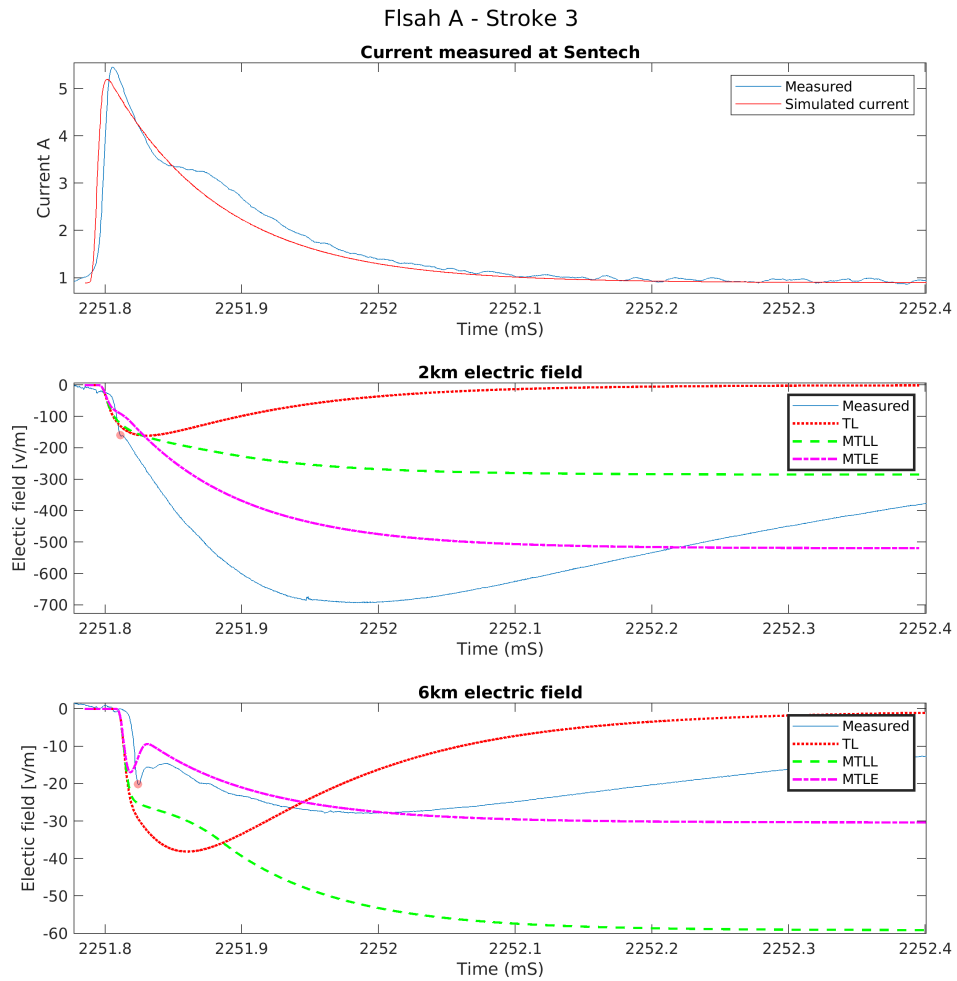


Figure B.4: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke C of the full flash on 05 October 2020 at 14:40:33.

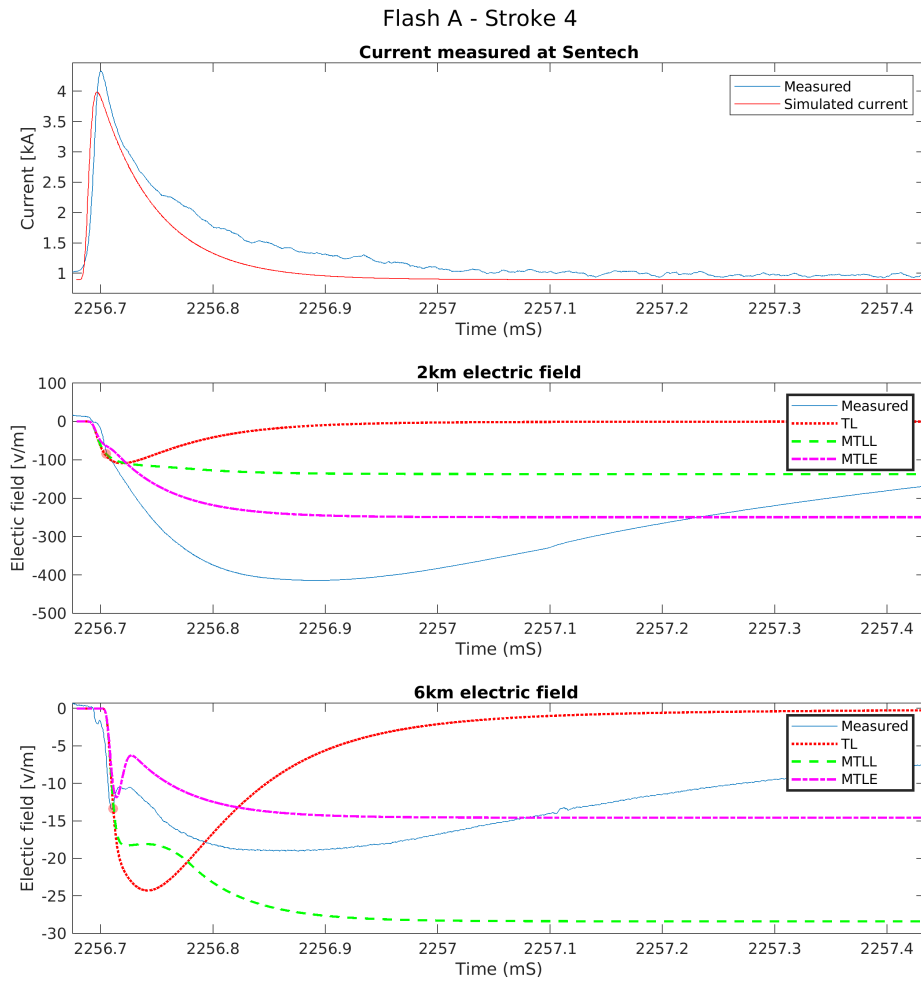


Figure B.5: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke D of the full flash on 05 October 2020 at 14:40:33.

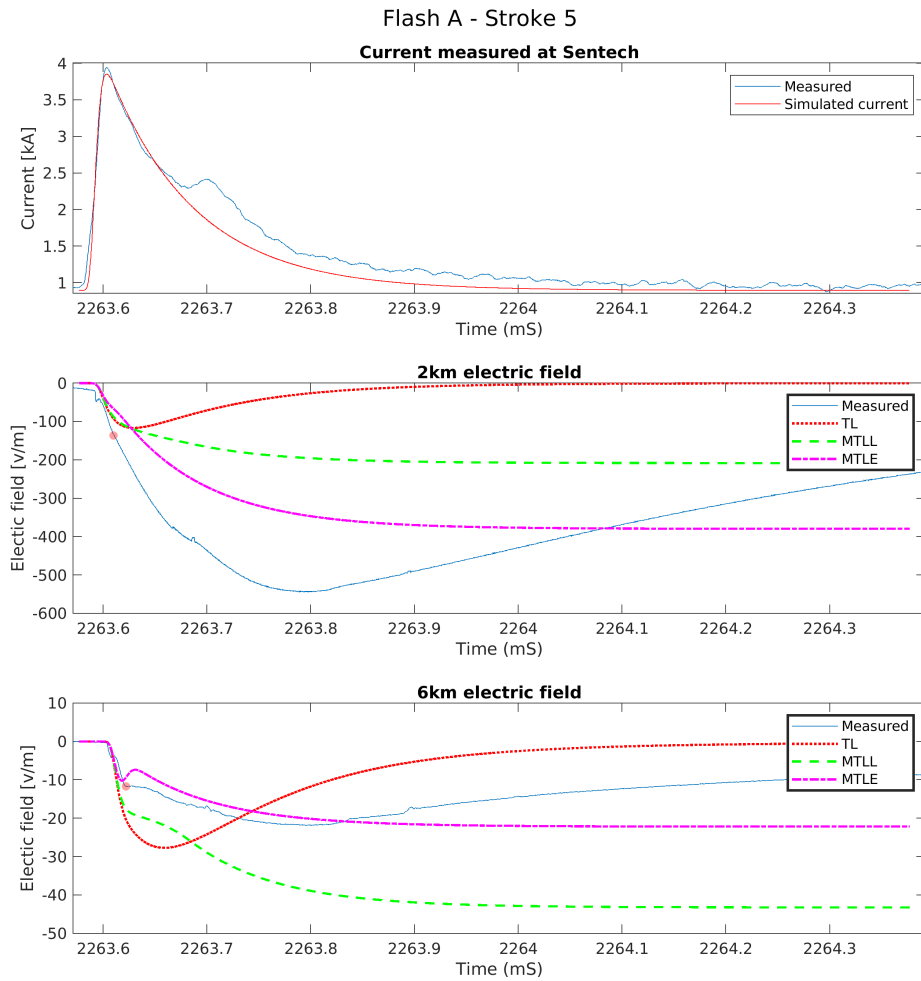


Figure B.6: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke E of the full flash on 05 October 2020 at 14:40:33.

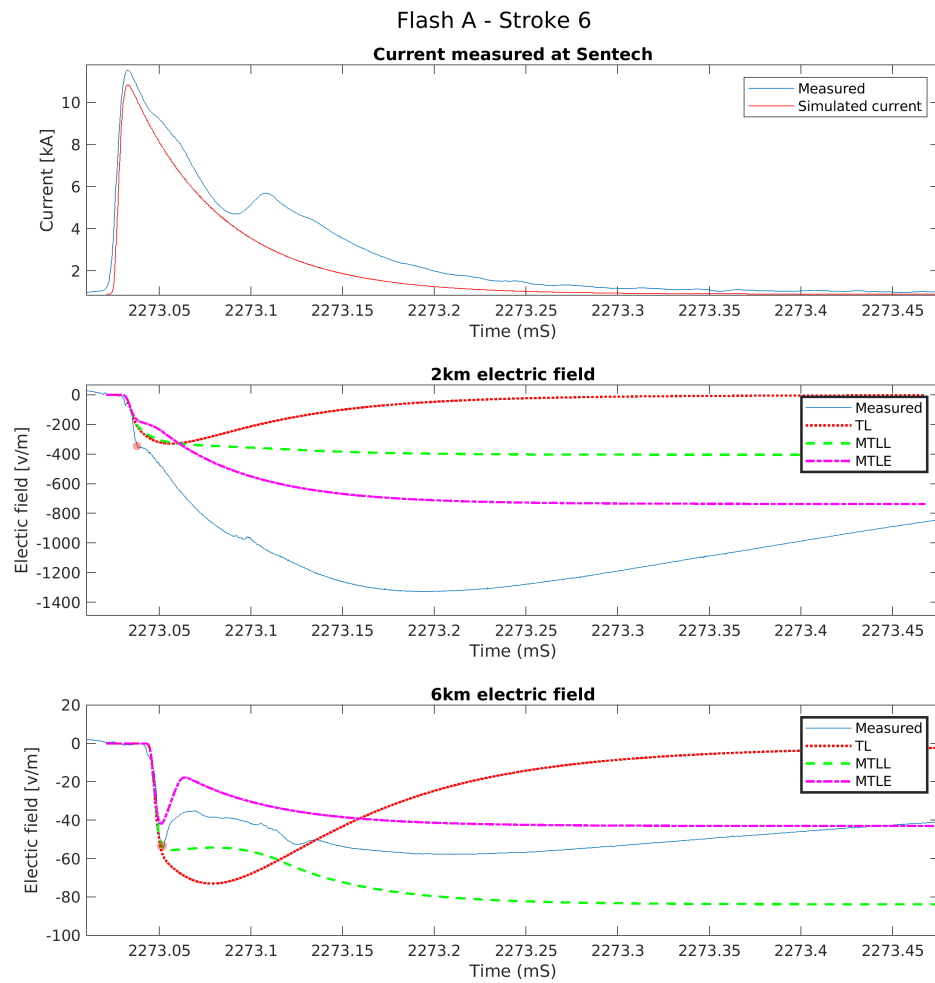


Figure B.7: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke F of the full flash on 05 October 2020 at 14:40:33.

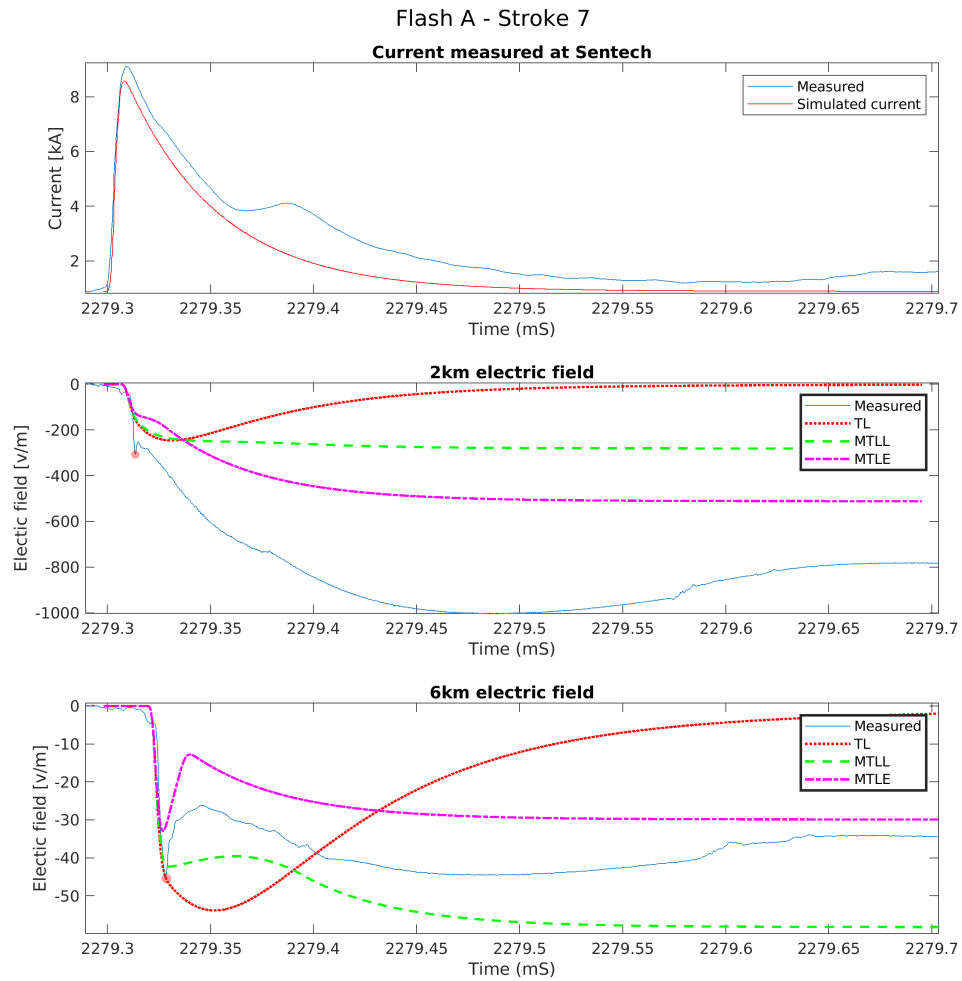


Figure B.8: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke G of the full flash on 05 October 2020 at 14:40:33.

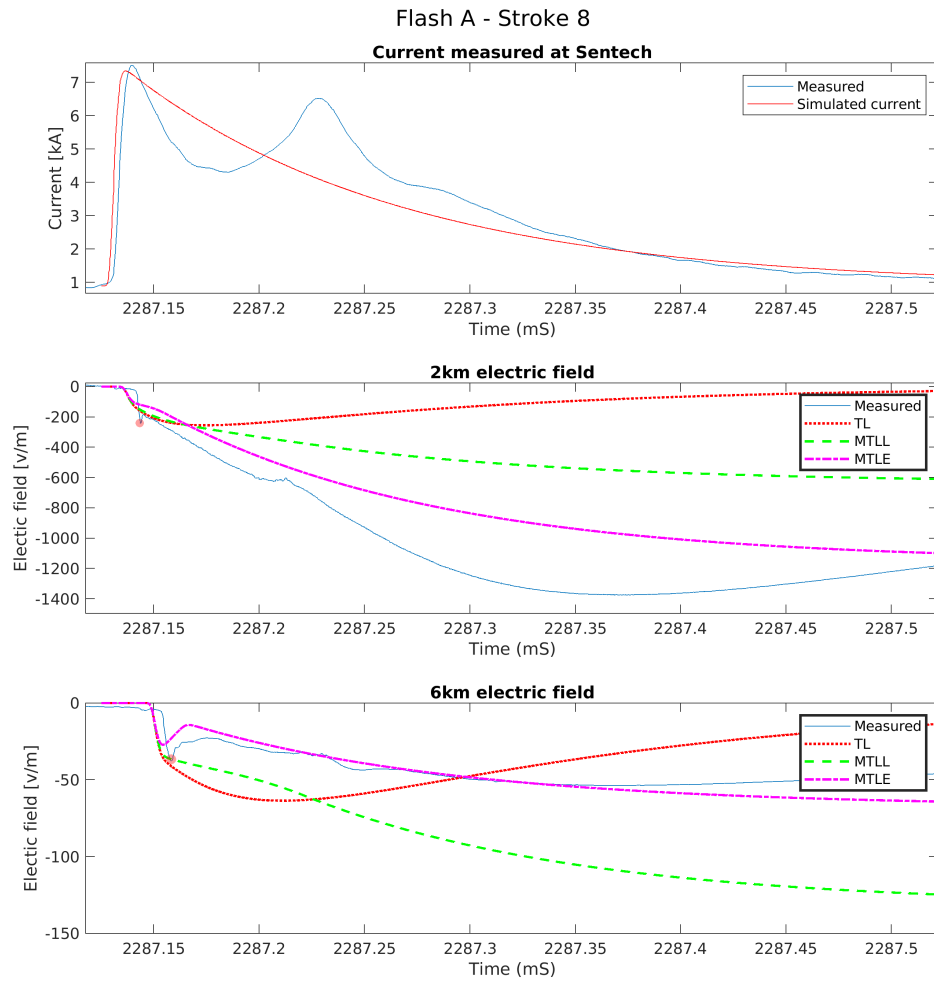


Figure B.9: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke H of the full flash on 05 October 2020 at 14:40:33.

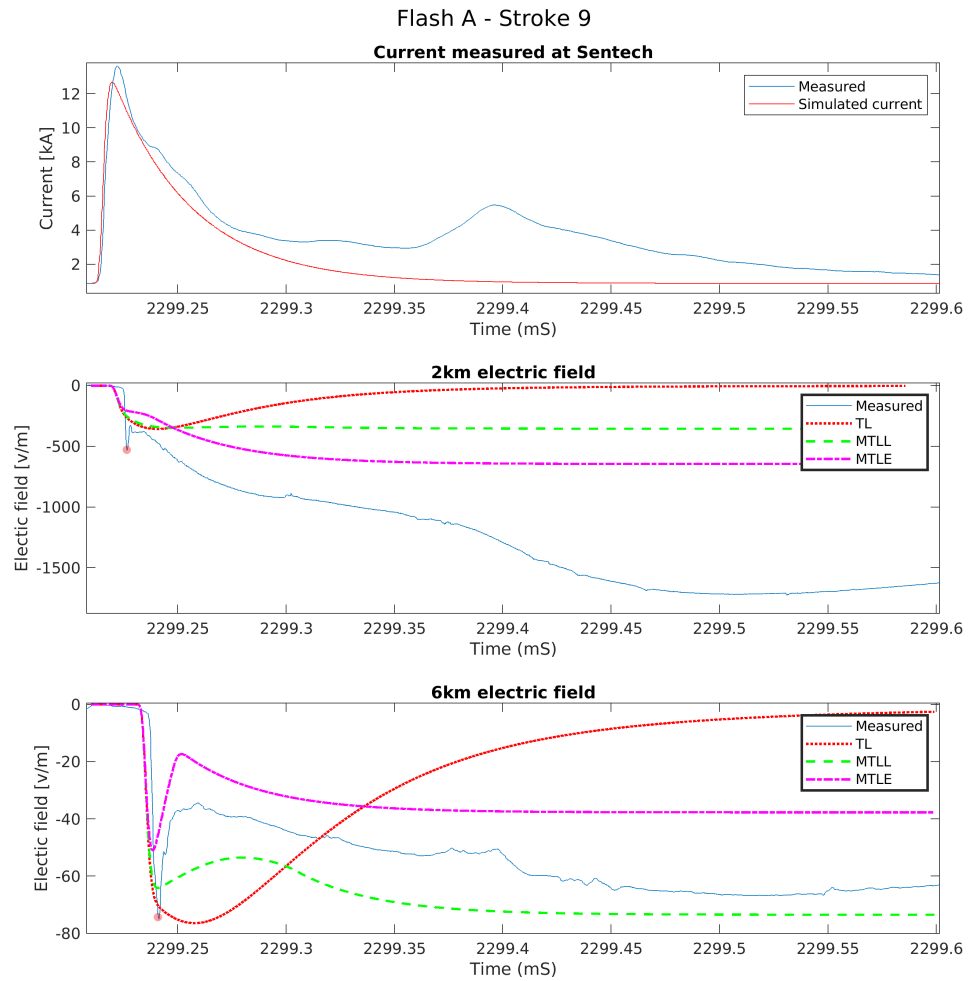


Figure B.10: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke I of the full flash on 05 October 2020 at 14:40:33.

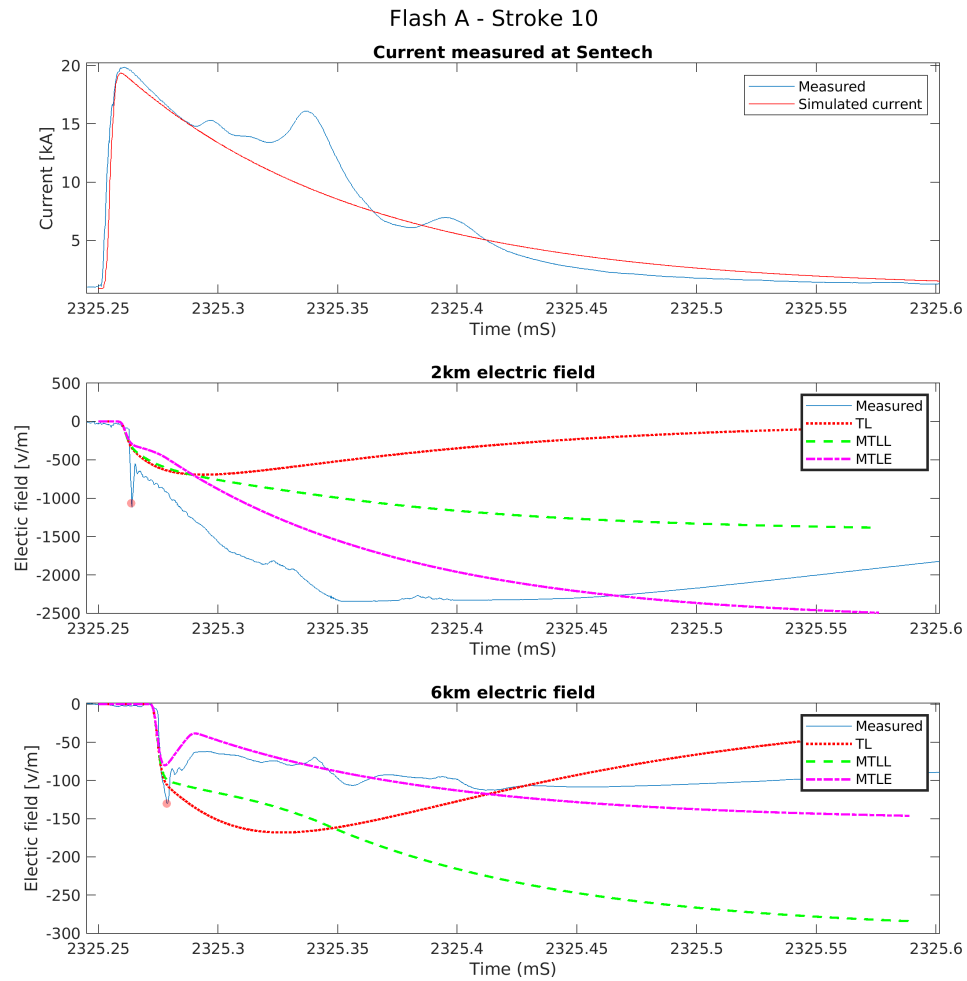


Figure B.11: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke J of the full flash on 05 October 2020 at 14:40:33.

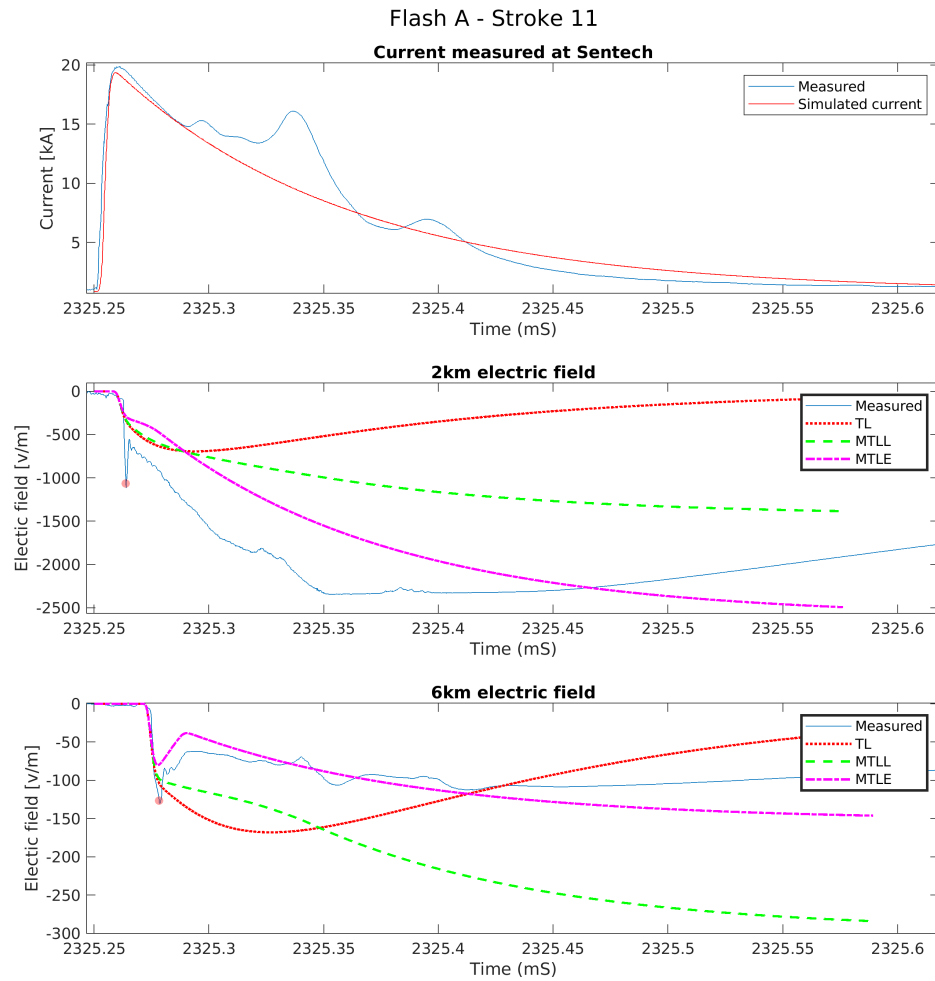


Figure B.12: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke K of the full flash on 05 October 2020 at 14:40:33.

B.2 Flash B

This section shows the full current and electric field measurements and simulations in figure B.13 for the event on 31 October 2020 at 17:06:52, referred to as flash B. In figures B.14 to B.33 the zoomed-in sections of the individual pulses and return strokes that were used in this work are shown.

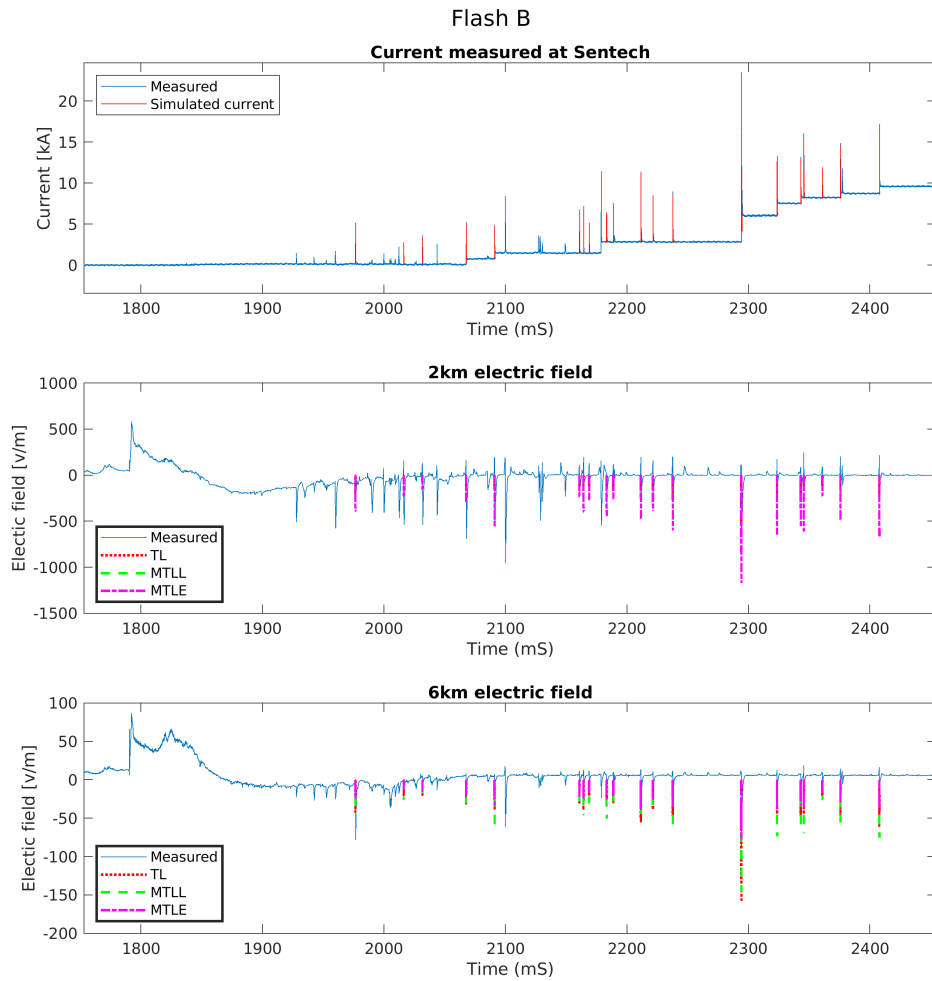


Figure B.13: Graph showing measured and simulated current and electric fields for the full flash on 31 October 2020 at 17:06:52.

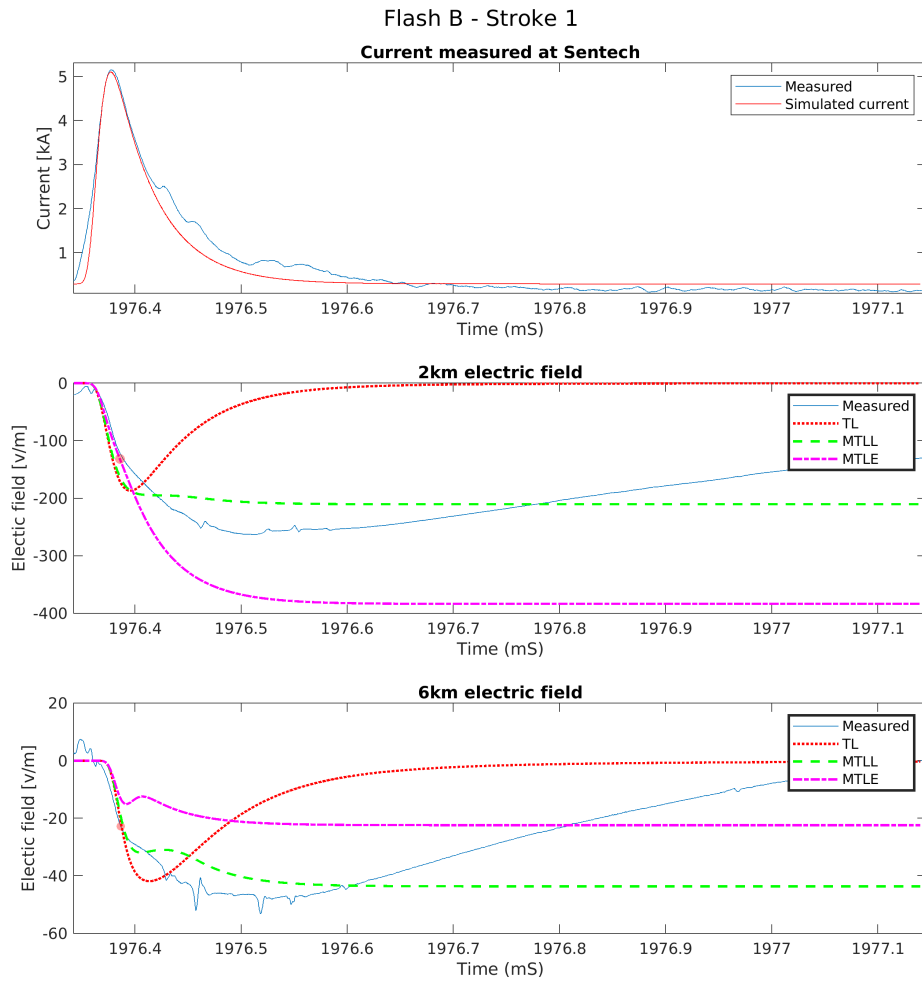


Figure B.14: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke A of the full flash on 31 October 2020 at 17:06:52

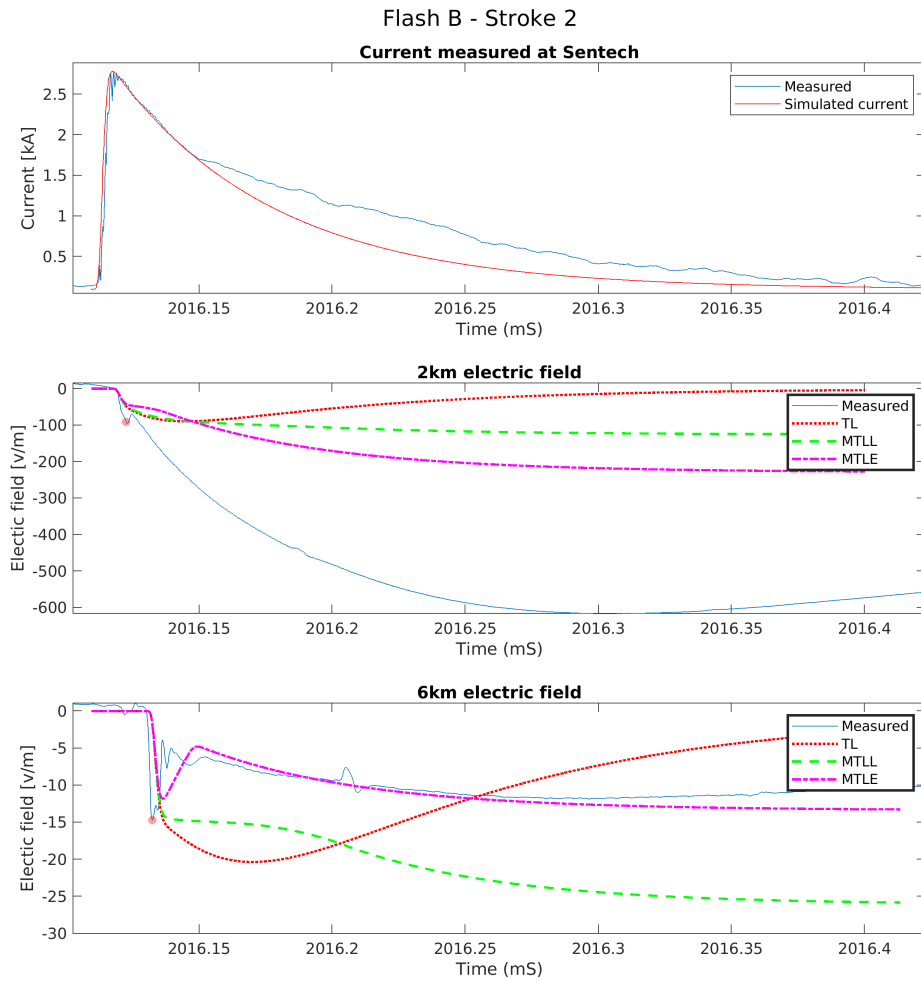


Figure B.15: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke B of the full flash on 31 October 2020 at 17:06:52

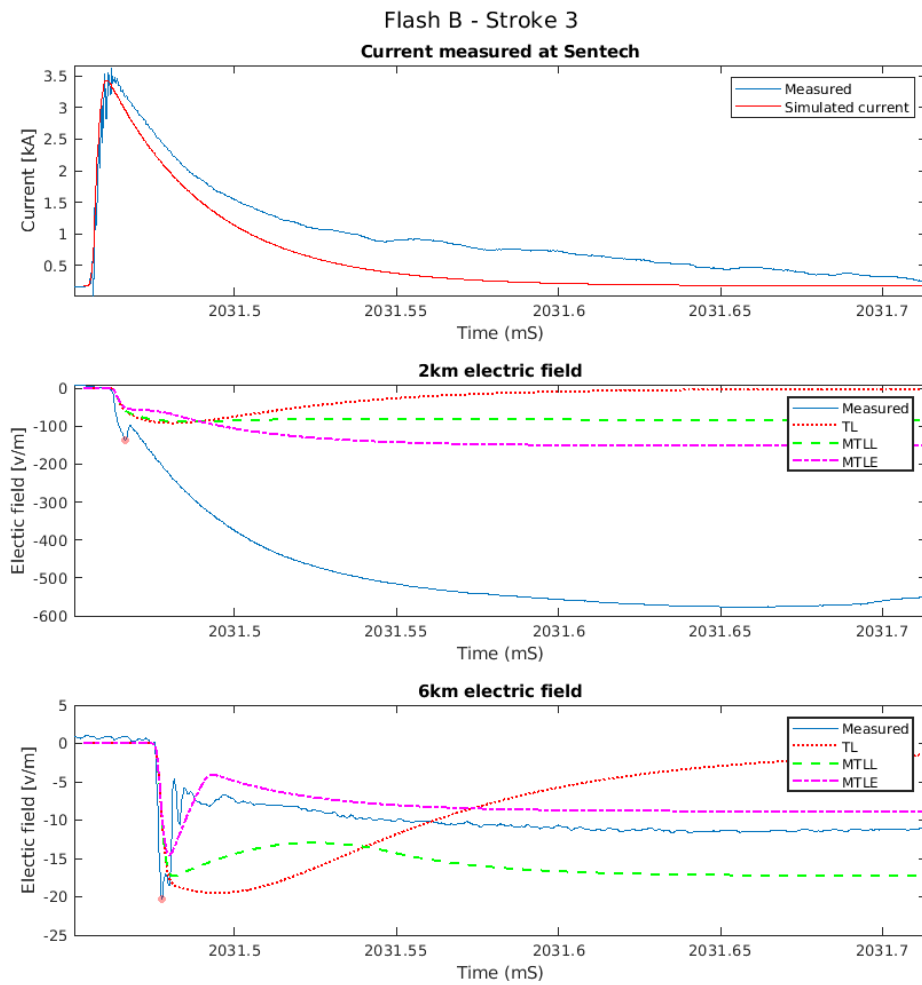


Figure B.16: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke C of the full flash on 31 October 2020 at 17:06:52

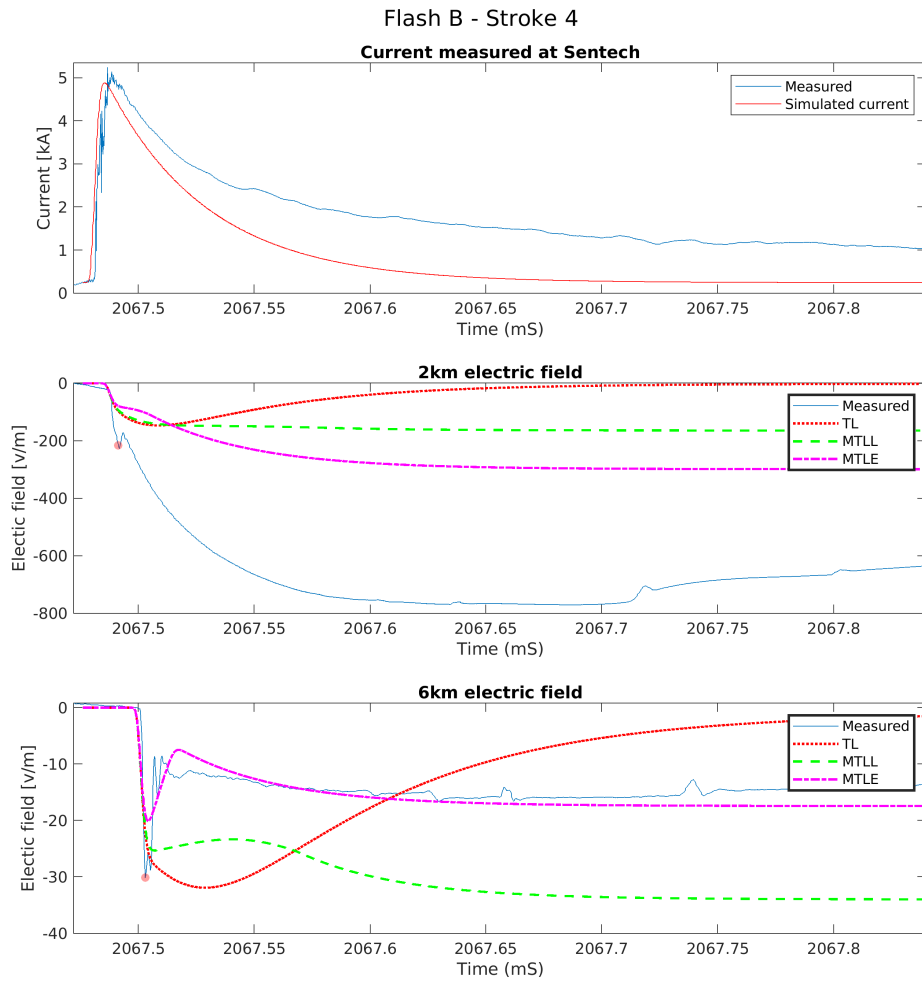


Figure B.17: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke D of the full flash on 31 October 2020 at 17:06:52

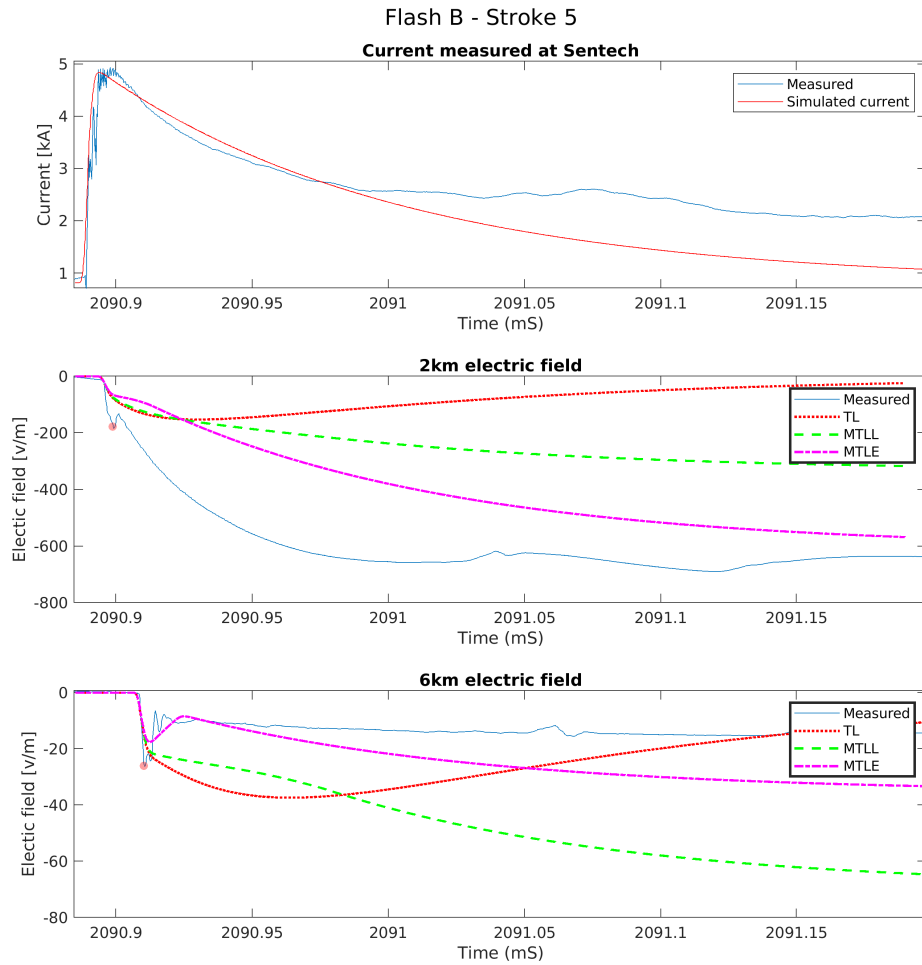


Figure B.18: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke E of the full flash on 31 October 2020 at 17:06:52

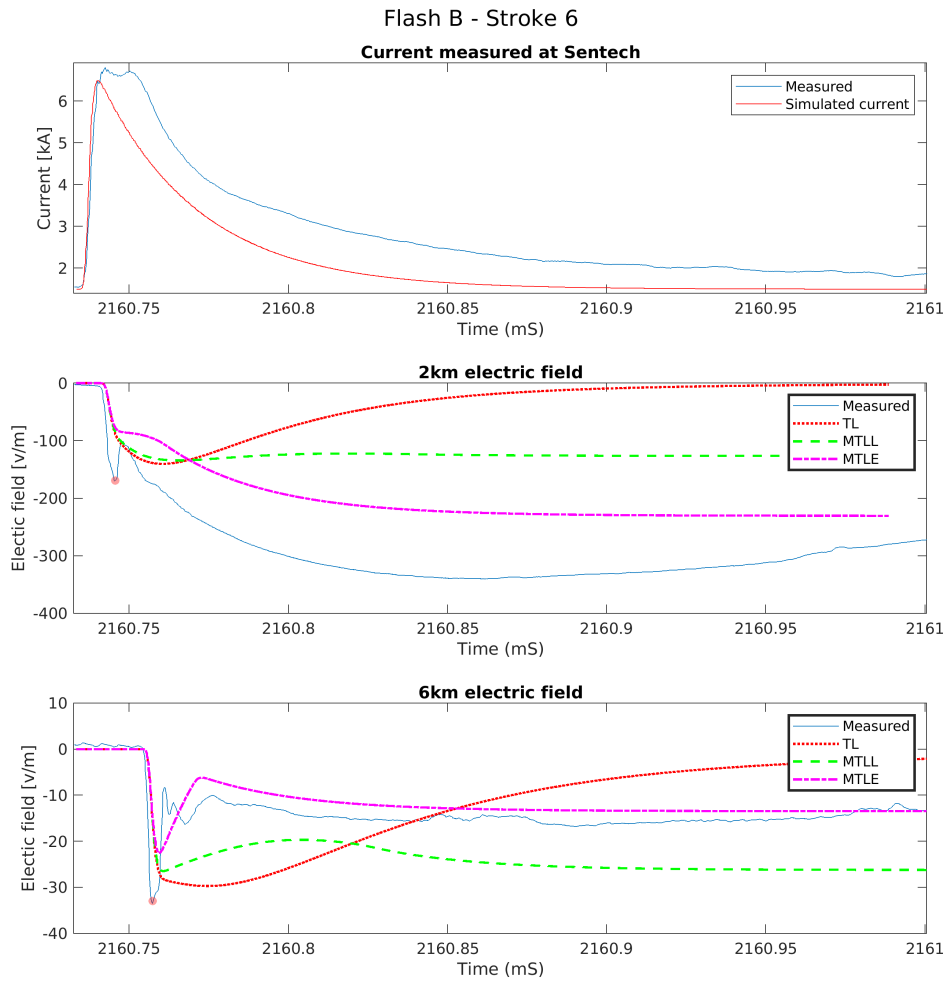


Figure B.19: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke F of the full flash on 31 October 2020 at 17:06:52

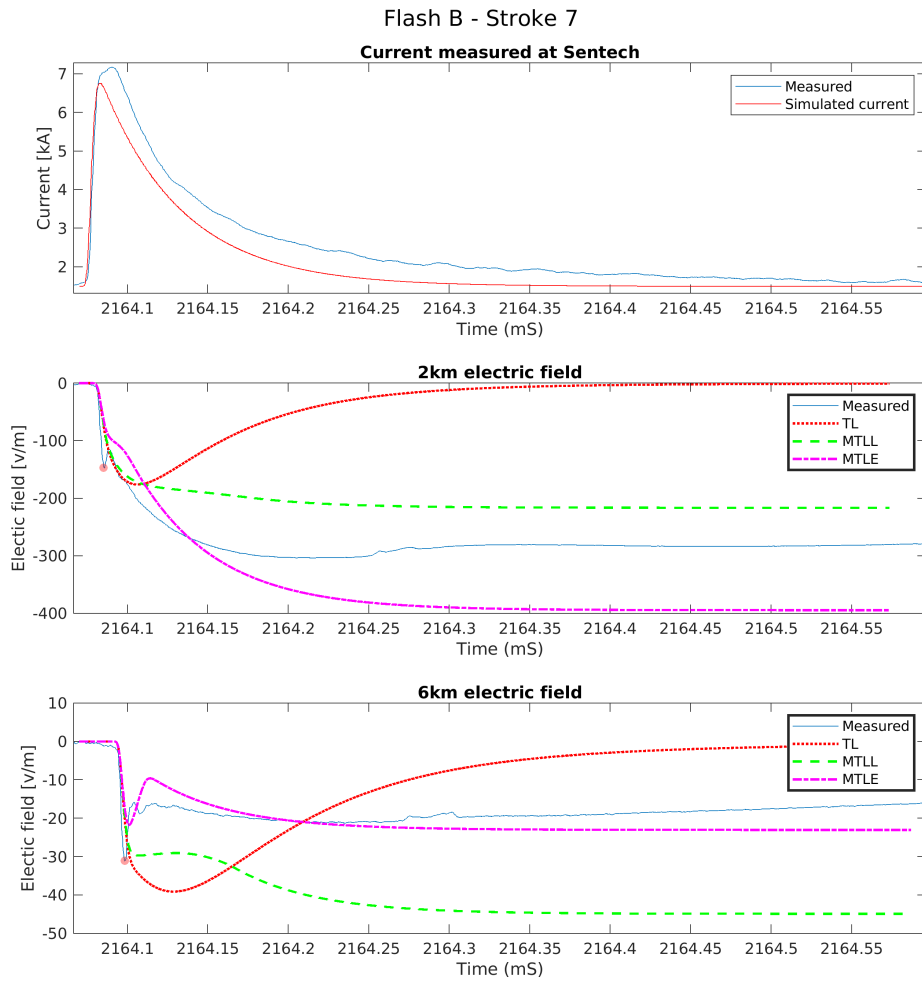


Figure B.20: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke G of the full flash on 31 October 2020 at 17:06:52

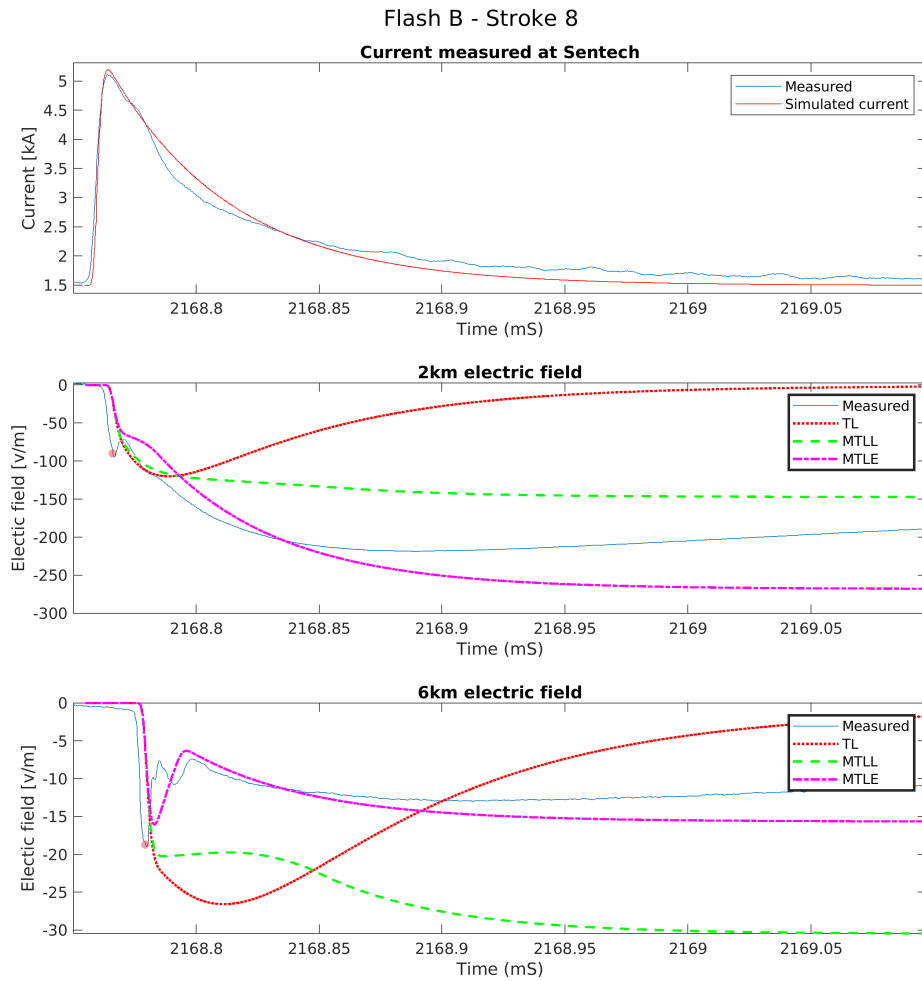


Figure B.21: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke H of the full flash on 31 October 2020 at 17:06:52

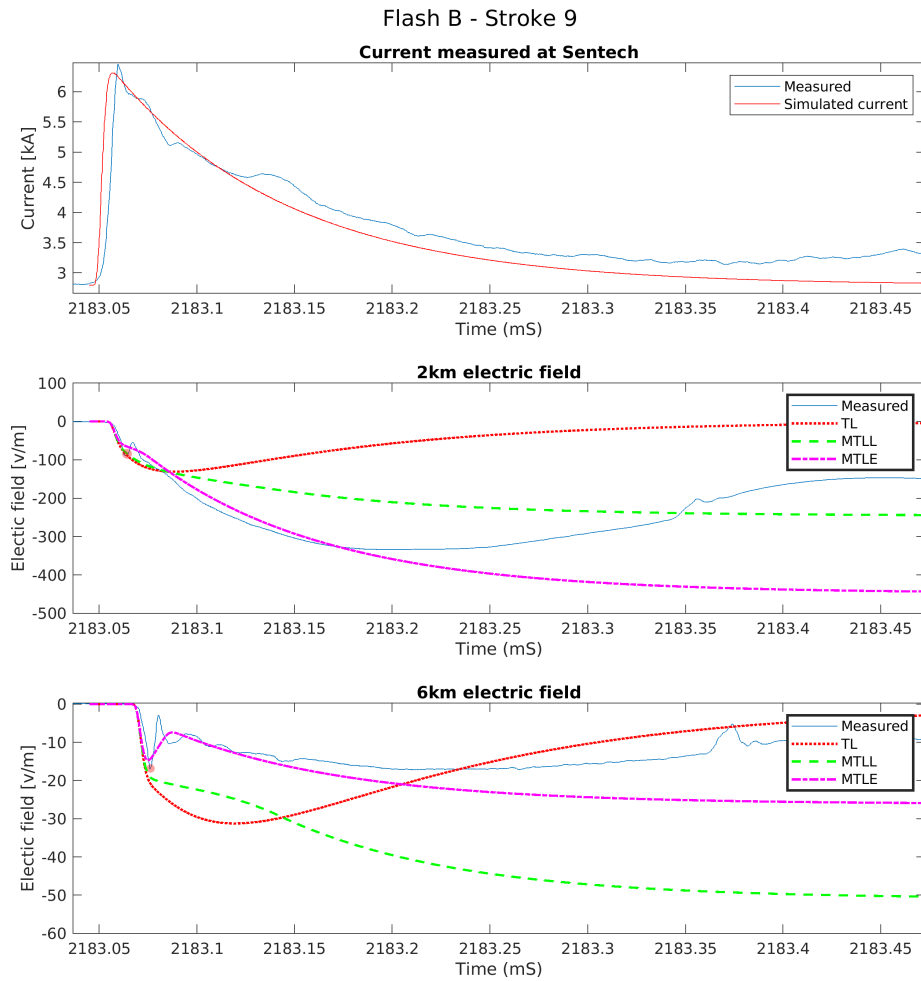


Figure B.22: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke I of the full flash on 31 October 2020 at 17:06:52

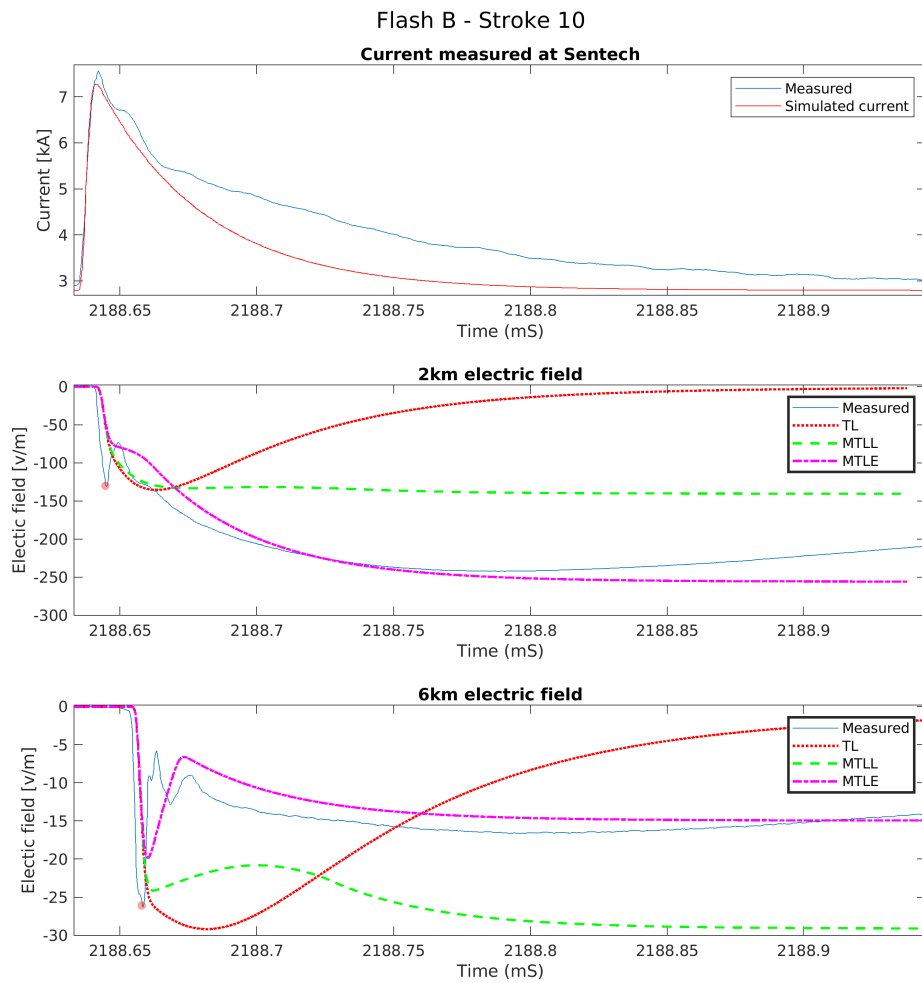


Figure B.23: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke J of the full flash on 31 October 2020 at 17:06:52

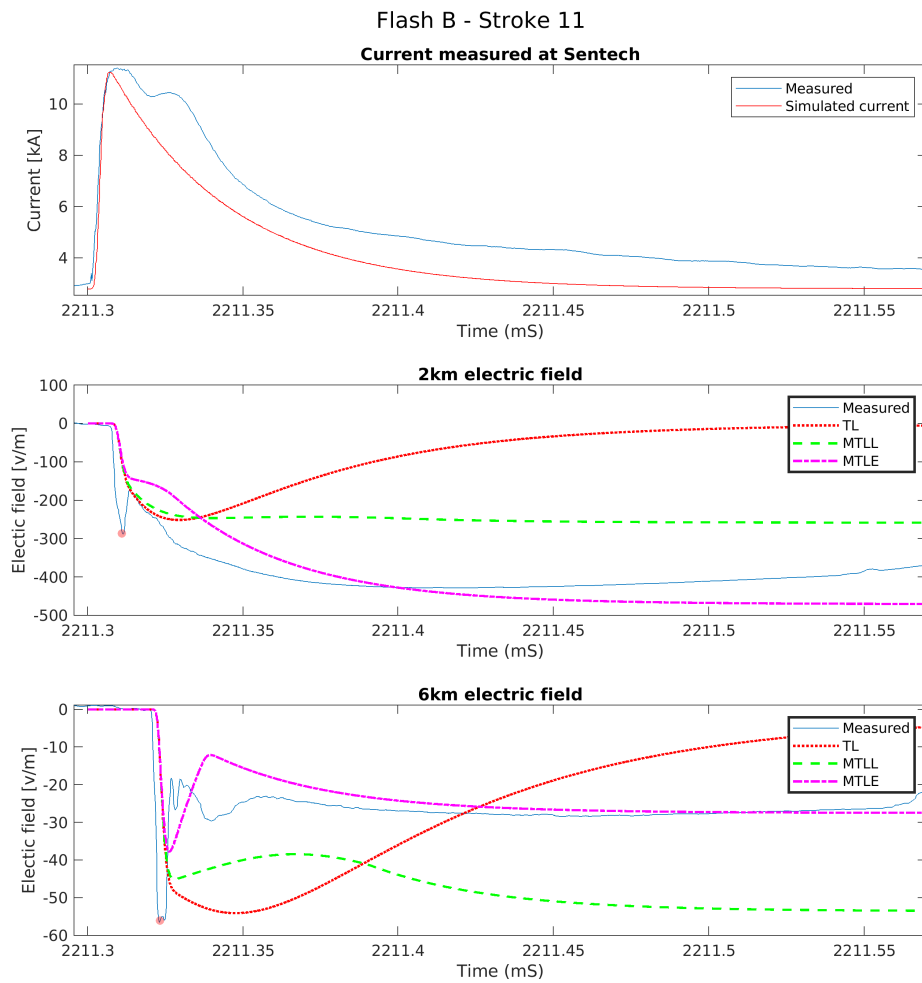


Figure B.24: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke K of the full flash on 31 October 2020 at 17:06:52

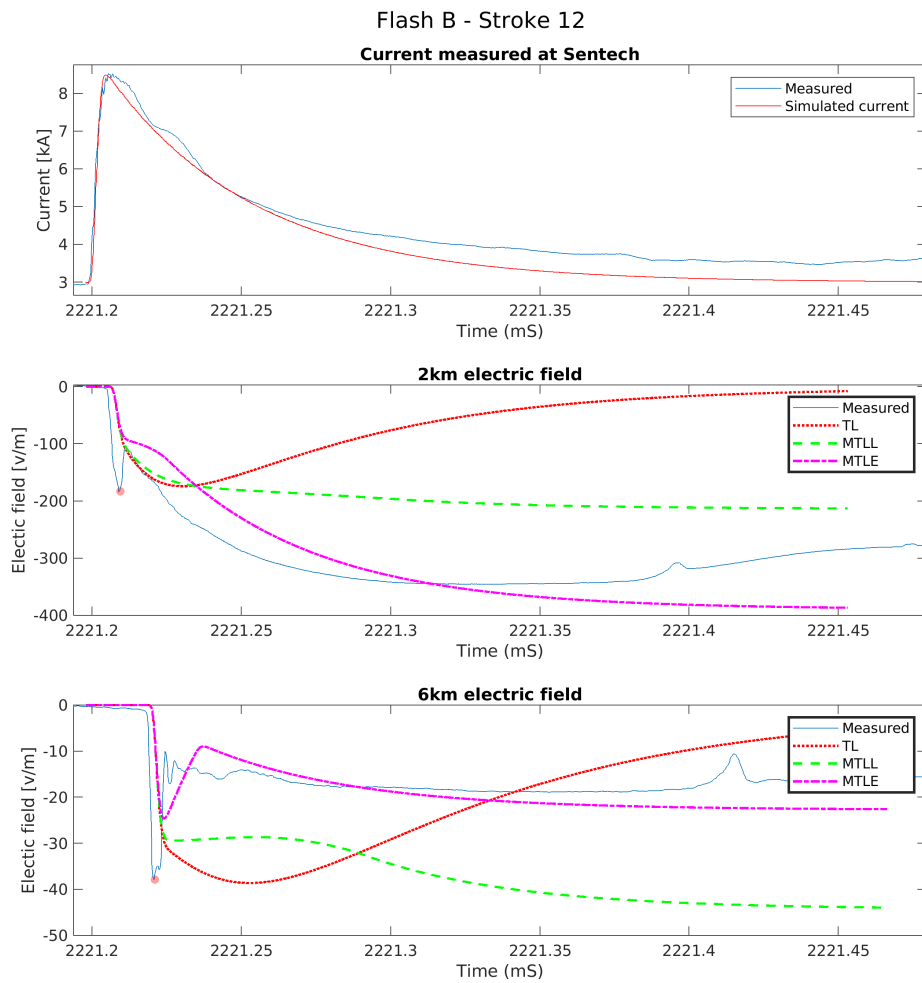


Figure B.25: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke L of the full flash on 31 October 2020 at 17:06:52

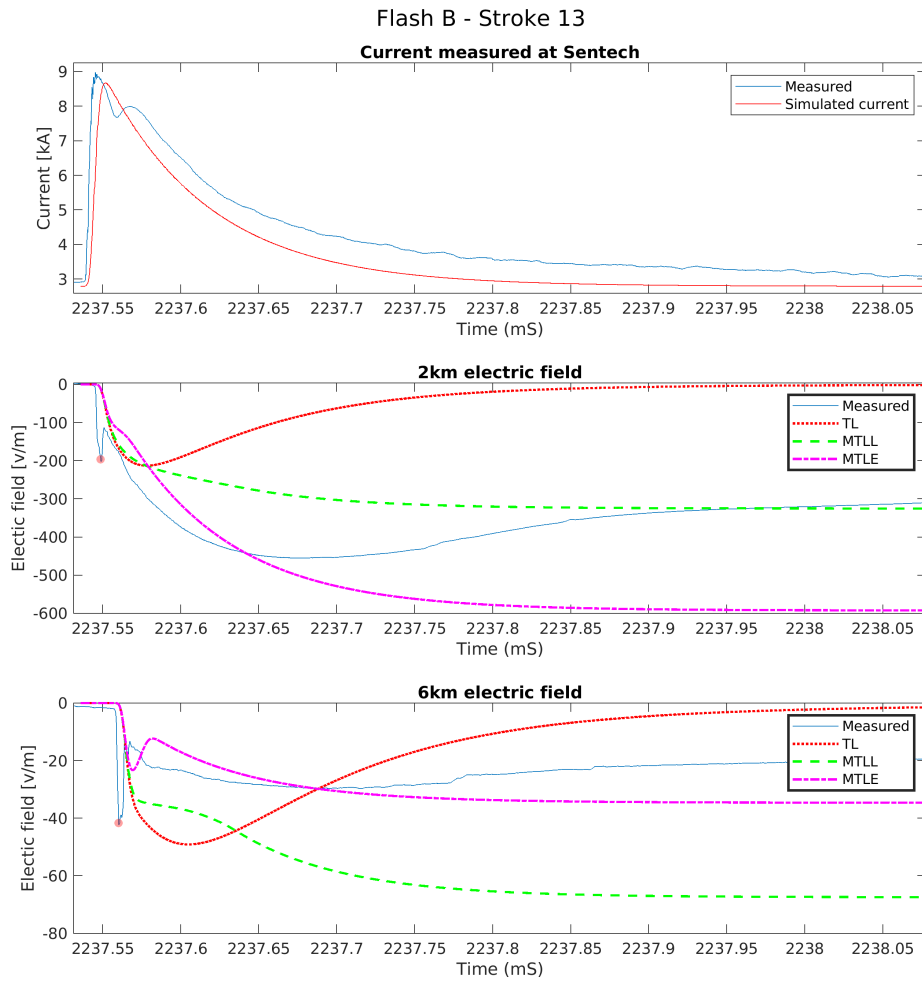


Figure B.26: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke M of the full flash on 31 October 2020 at 17:06:52

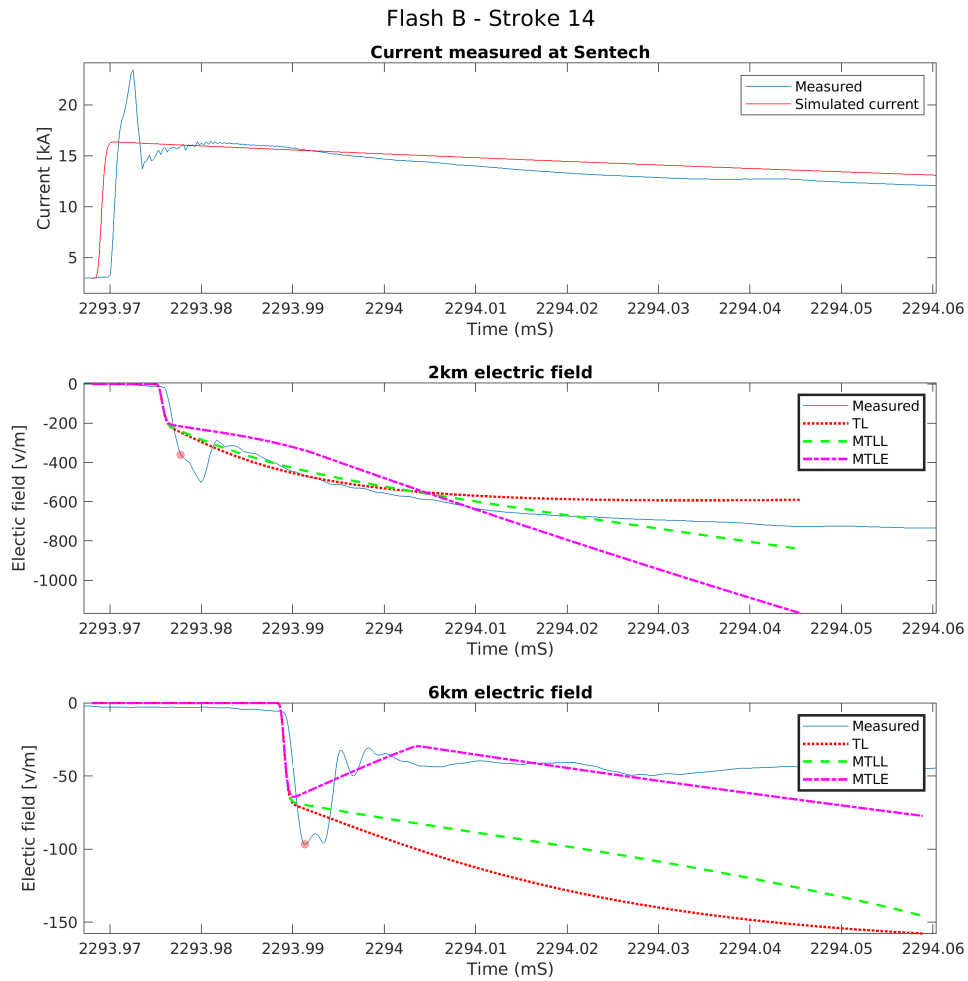


Figure B.27: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke N of the full flash on 31 October 2020 at 17:06:52

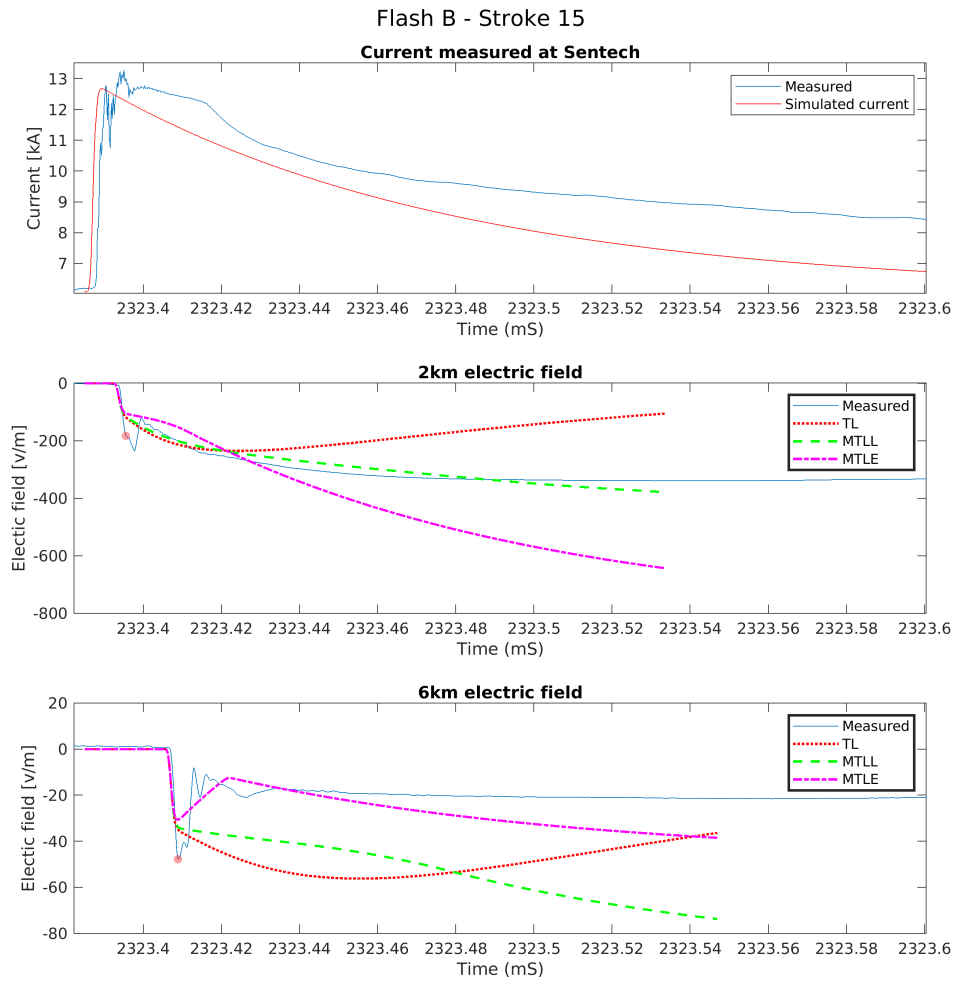


Figure B.28: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke O of the full flash on 31 October 2020 at 17:06:52

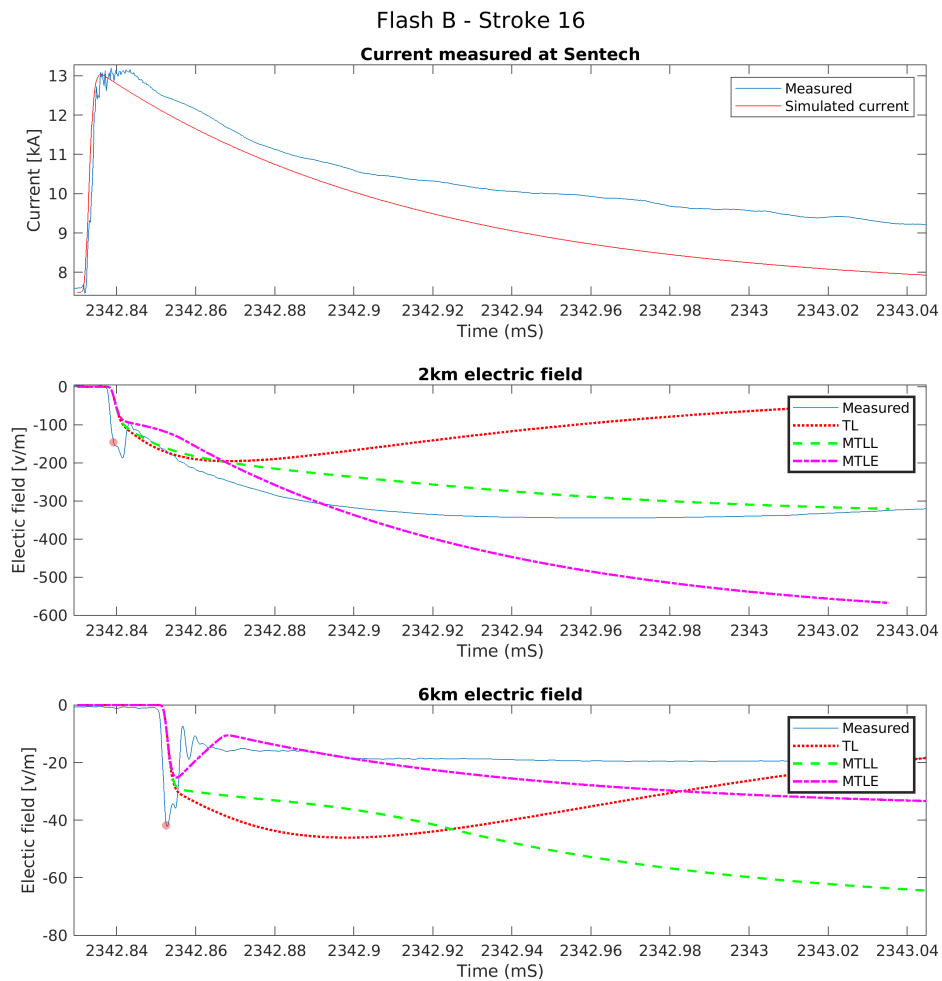


Figure B.29: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke P of the full flash on 31 October 2020 at 17:06:52

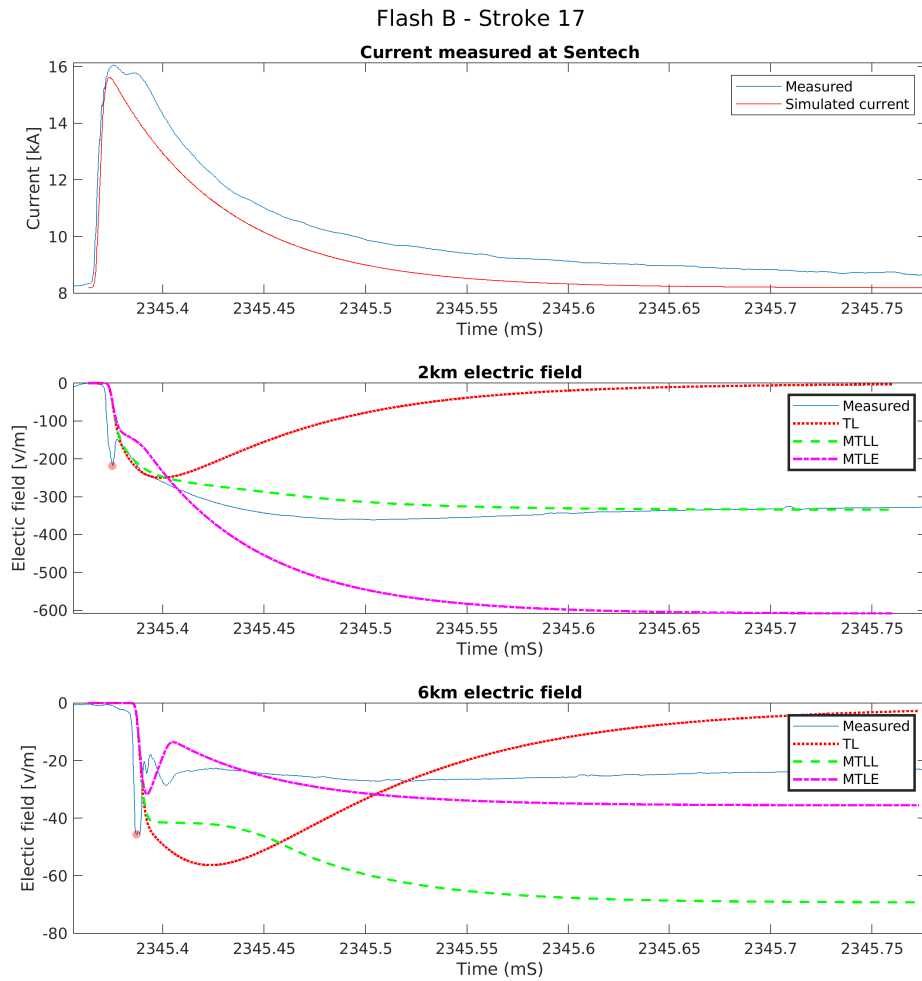


Figure B.30: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke Q of the full flash on 31 October 2020 at 17:06:52

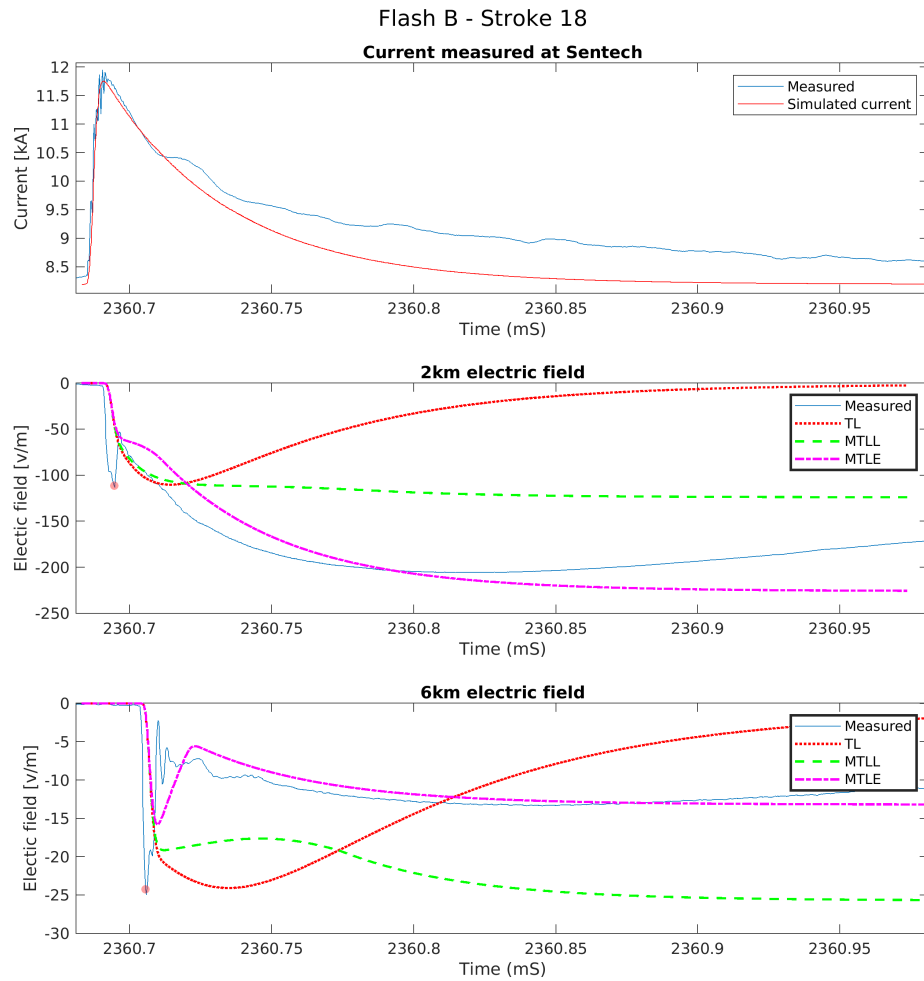


Figure B.31: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke R of the full flash on 31 October 2020 at 17:06:52

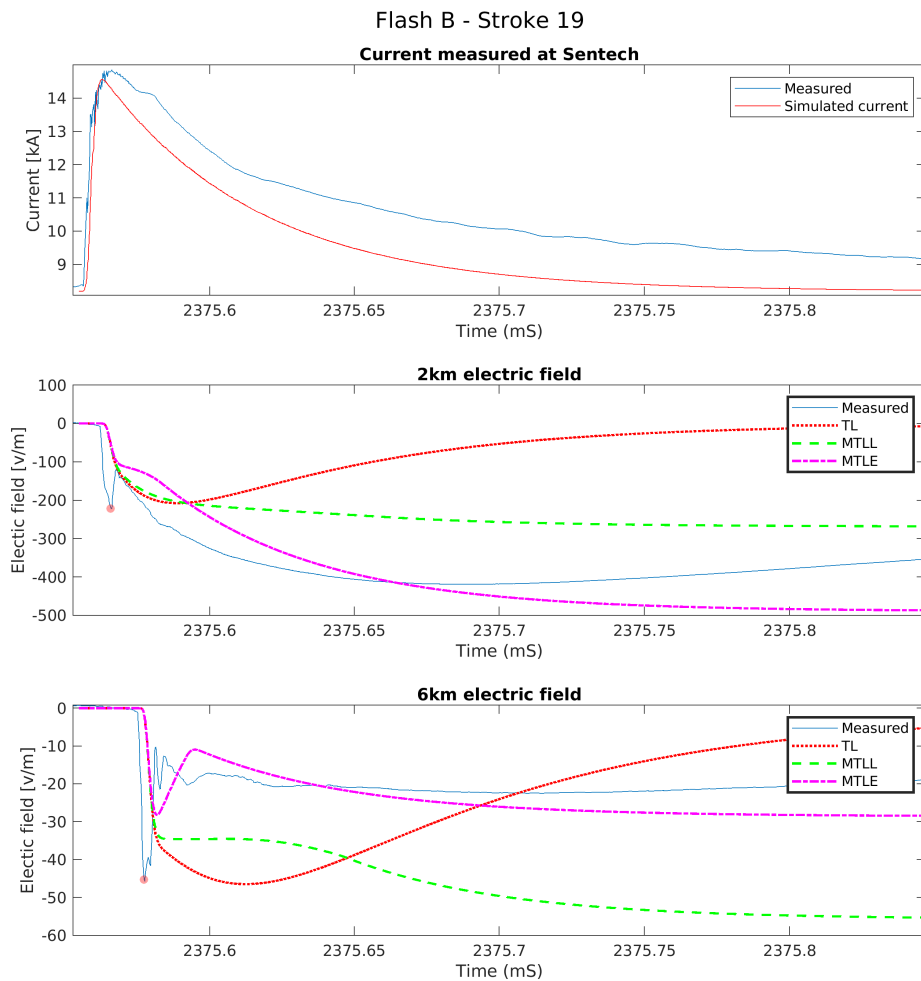


Figure B.32: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke S of the full flash on 31 October 2020 at 17:06:52

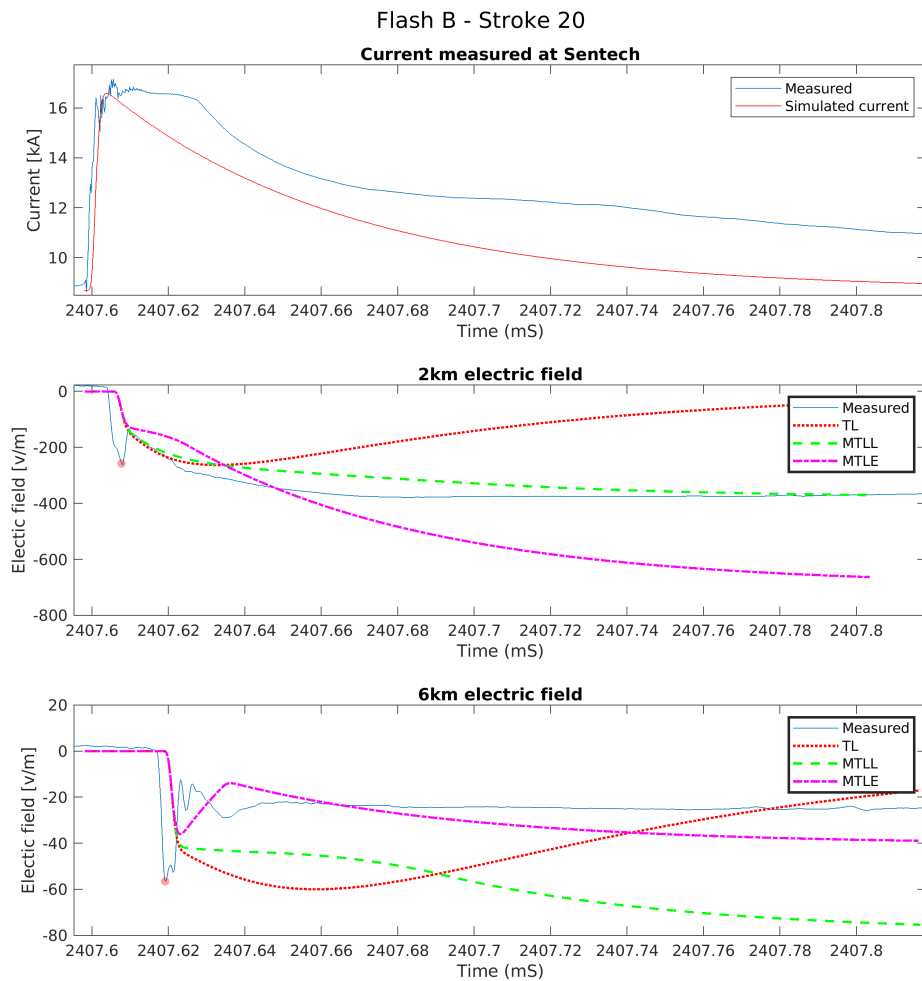


Figure B.33: Graph showing a zoomed in section for the measured and simulated current and electric fields for return stroke T of the full flash on 31 October 2020 at 17:06:52

Appendix C ICLP publications

This appendix contains the conference articles submitted during my dissertation.

First lightning current measurements to the Sentech tower, South Africa

Jason R Smit, Hugh GP Hunt, Carina Schumann
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School of Electrical and Information Engineering
The University of The Witwatersrand
Johannesburg, South Africa
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Abstract—The current measurements from the Sentech tower for the 2020-2021 rain season are presented. The tower is a cylindrical concrete radio broadcast tower, situated on the highveld plateau in Johannesburg, South Africa. The season produced 43 distinguishable lightning current measurements, 186 return strokes, 30 ICC fast pulses and 7 ICC_{Only} events. The return stroke multiplicity for the season is 6.41. The return stroke median current is 7.51 kA while the ICC pulses had a median peak of 3.75 kA. The median charge transfer for a lightning event with return strokes is 41.36C, while it is 35.51C for ICC_P events and 26.08C for ICC_{Only} events.

Return stroke, Upward lightning, ICC, ICC pulses, Sentech tower

I. INTRODUCTION

Tall towers have historically provided a unique opportunity to study the electrical current that flows during lightning events due to the frequency with which they are struck by lightning compared to other ‘standard’ sized structures [1]. However, the effect of the tower height can affect the nature of the lightning phenomenon, most clearly in the initiation of upward leaders. The first such instrumented towers go back to the Empire State building, along with Mount San Salvatore and the CSIR Tower in South Africa - particularly noteworthy as the first instrumented tower to be specifically erected for the purpose of lightning measurements and, not being a hugely tall structure, had many downward lightning events [2-4]. Subsequently, other towers have been instrumented around the world. A similarly installation to the CSIR tower was installed in Minas Gerais, Brazil at Morro do Cachimbo and the Peissenberg, Gaisberg and Santis Tower in Europe (Germany, Austria, and Switzerland respectively) have been instrumented as well as the CN tower in Canada and the Tokyo SkyTree in Japan [5-10]. More recently, wind turbines in the north of Japan have been instrumented [11]. In this work, we look at the first results of the latest instrumented tower - the Sentech tower in Johannesburg, South Africa. The tower was first instrumented in October 2020 just in time for the South African thunderstorm season and forms the key measurement in the

Johannesburg Lightning Research Laboratory. This is the first set of current measurements to be made in South Africa since Eriksson and the CSIR tower installation.

II. INSTRUMENTATION

A. Location of measurement

The Sentech tower is in Johannesburg, South Africa (26.1925oS, 28.0067oE). Fig. 1 shows a top-down view of Johannesburg indicating the location of the Sentech tower (shown and circled in red). The Hillbrow Tower, another tall communications tower in Johannesburg is indicated in blue. Johannesburg is on the highveld plateau of the interior of South Africa and is approximately 1700m above sea level. The topology and local weather produce thunderstorms between the months in November and April. The Sentech tower is a concrete tower that is 237m tall.

B. Current measurement

The measurement of the lightning current is done using a DEHN detect system [12]. The system has two Rogowski coils set with different gain sensitivities. The first coil is set with a high gain and is used to measure currents between -2 and 2 kA and is primarily used to detect and measure slow initial continuing currents (ICC). The second coil is set with a low gain and can measure current in the range of -250 to 250 kA and is used to measure the peak (impulse) currents of ICC pulses and return strokes.

The system has a maximum response of 40 kA/μs. The coils are sampled at 4 MHz each and have the pre-trigger set to 0.5 with a recording time of 1 second each. The pre-trigger was changed to 0.4 half-way through the season as it was noted that the reduced value was better suited to the duration of the events measured. Fig. 2 shows a measurement made on 12 December 2020 at 20:57:10 UTC. Both the ICC (high gain) and impulse (low gain) measurements are shown for the same event in figure 2(a) and (b) respectively.

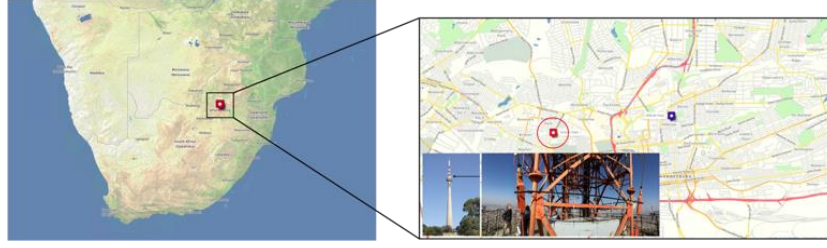


Figure 1. Image showing the location of the Sentech tower, South Africa

III. METHODOLOGY

The following section describes how the current waveforms measured over the 2020-2021 Johannesburg thunderstorm season were analysed. Some measurement artefacts present needed to be addressed in post-processing and this is also described here.

A. Current analysis

Figure 2 also shows how the waveforms are analysed and categorised. The categories used are as they have been used by Diendorfer et al. [7] and by Michishita et al. [11]. ICC is used to refer to the initial continuing current that is associated with the initiation of an upward event. ICC_P refers to events where there are pulses (ICC fast pulses) that exceed 2 kA superimposed on initial continuing current, but there are no return stroke following the ICC. ICC_{RS} refers to events where the ICC is followed by one or more return strokes exceeding 2 kA. An ICC_{only} event has no current pulses more than 2 kA. Unknown events are events that cannot be classified.

B. Data post-processing considerations

For some measurements, it was also noted that the waveform contained an offset from the zero value after ICC or a return stroke. This occurs due to the circuit compensation, where the zero value drifts during the measurement due to either significantly fast or slow rise times and is only present in cases with these extreme rise values. To compensate for this offset, a linear trigonometric correction is applied. An example of the offsets is represented alongside a corrected waveform in fig. 3. (a)-(b) respectively. The presence of reflections or oscillations on the front of high peak current events was noted in the measurements. Fig. 4 shows an example of this with the raw measured data plotted in blue. This is likely due to the height/characteristic frequency of the tower and has been seen in similar cases such as those seen by Heidler et al. and Romero et al. [14, 15]. To reduce the effect of the oscillations on the measurements such that peak current comparisons with other towers could be made, a ten-point moving average filter is applied to the waveforms, as indicated by the red line in the figure. For all the statistics, the filtered waveforms were used.

IV. RESULTS

For the lightning season 2020-2021 (November 2020 - April 2021) there were 57 recorded measurements to the Sentech Tower. Of the recorded events, 43 measurements could be distinguished as lightning attachments to the tower. A summary of the flashes is presented in table I. All recorded flashes were negative (negative cloud charge centres).

TABLE I. MEDIAN AND GEOMETRIC MEAN OF PEAK CURRENTS FOR DIFFERENT EVENTS

Event type	No of flashes	Number of fast pulses	Current Peak [kA]	
			Median	GM
ICC _{RS}	26	257	7,51	7,69
ICC _P	6	30	3,75	3,96
Total	32	287	-	-

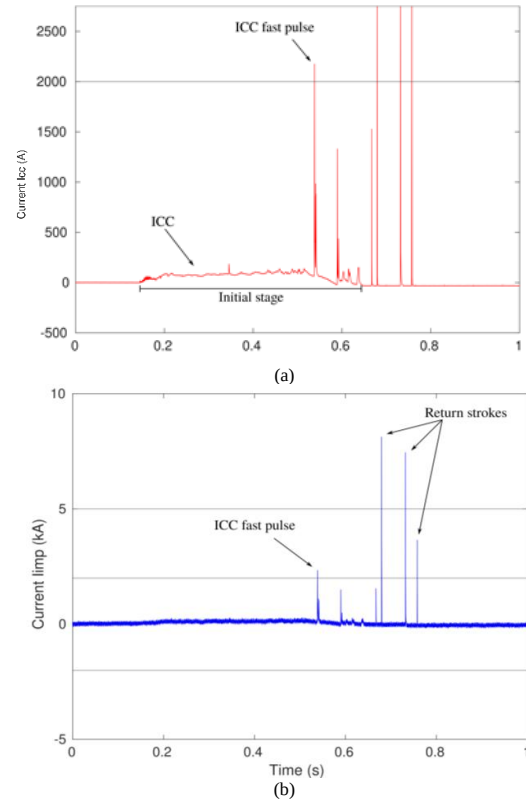


Figure 2. A lightning current measurement made at the Sentech Tower, Johannesburg, South Africa on 12 December 2020 at 20:57:10 UTC. (a) shows the high gain channel, used for measuring slow initial continuing current (b) shows the low gain channel, used for measuring the peak impulse currents.

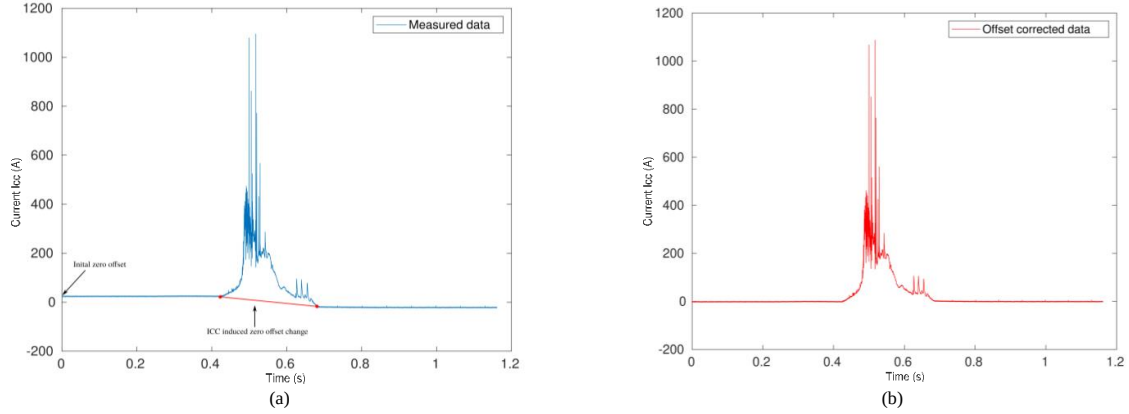


Figure 3. Example of current offset artefact (a) ICC with negative offset and (b) waveform after offset correction.

The analysis of the pulses (ICC_P and ICC_{RS}) is presented in table II. Of the 42 (downward excluded) events, 25 (59.52 %) have return strokes following the ICC (ICC_{RS}). This amount far exceeds the 13% in Japan [11] and the 30% seen at the Gaisberg Tower in Austria [7]. Only 7 (16.67 %) events had fast pulses (ICC_P) superimposed on the ICC and did not have return strokes following the ICC. This percentage is lower than the 41% seen in Japan and the 22% seen at Gaisberg. However, the amount is clearly reduced due to the much higher percentage of ICC_{RS} . ICC events without any fast pulse or return strokes (ICC_{only}) amounted to 10 (23.81 %).

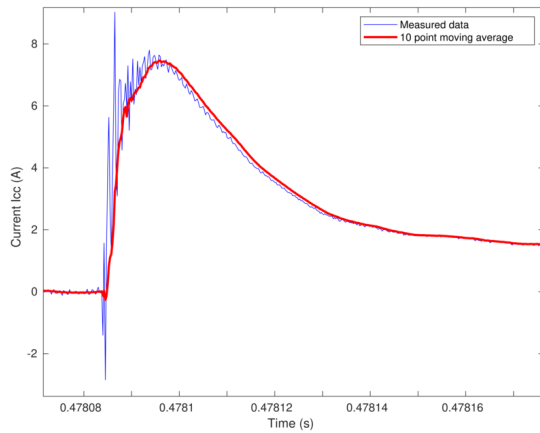


Figure 4. A peak current measurement made from an event on the 31st of October 2020 at 15:58:48 UTC. The blue plot shows the measured data, where oscillations due to the tower height can be seen. The red plot shows the implemented ten point moving average filter.

A. Multiplicity

For the 29 ICC_{RS} flashes, there were a total of 186 return strokes and an average multiplicity of 6.41. This value is higher than the observed values in Brazil (2.0), at the CN Tower (2.4), in the United States (3.4), at the Japanese Wind Turbines (3.5), the Beijing meteorological tower (4.3), at the Gaisberg Tower

(4.4), and even when compared to the winter only flashes for the Gaisberg Tower (4.8) [11, 13-18]. An overview of the multiplicity is presented in fig. 5. It is worth noting that there were 6 (20.69 %) flashes that had a multiplicity above 10. The multiplicity of the fast pulses (ICC_P) was less than that of the return strokes (ICC_{RS}), as well as the range of multiplicity values. This contrasts with Michishita et al., who showed a greater range in multiplicity of the fast pulses when compared with the multiplicity of the return strokes but a similar average multiplicity between the two [11].

TABLE II. SUMMARY OF THE CURRENTS MEASURED AT THE SENTECH TOWER, JOHANNESBURG (2020-2021)

Event Type	Flashes (Events)	Pulses and strokes
ICC_{RS}	26	257 (186 _{RS} , 71 _P)
ICC_P	7	30
ICC_{only}	9	0
Downward RS	1	1
Unknown	13	11
Total	56	299

B. Inter-stroke intervals

The inter-stroke duration distribution is presented in fig. 6. It is noted that the distribution is similar to that seen by Diendorfer et al., although within a smaller range. The geometric mean inter-stroke interval is 15.30 ms (median: 17.32 ms) which is comparable to the values seen by Diendorfer et al. and Michishita et al. [7, 11]. The histogram in fig. 7 shows the time between ICC fast pulses. The distribution is similar to that of the inter-stroke distribution however this is for fewer events (115 vs. 175). The geometric mean between pulses is 13.7 ms (median: 15.67 ms) and hence is less than that seen for the time between return strokes. This result is similar to, but not as pronounced, as seen by Michishita et al. With the range of time intervals also being greater for the fast pulses compared to the inter-stroke value for the return strokes.

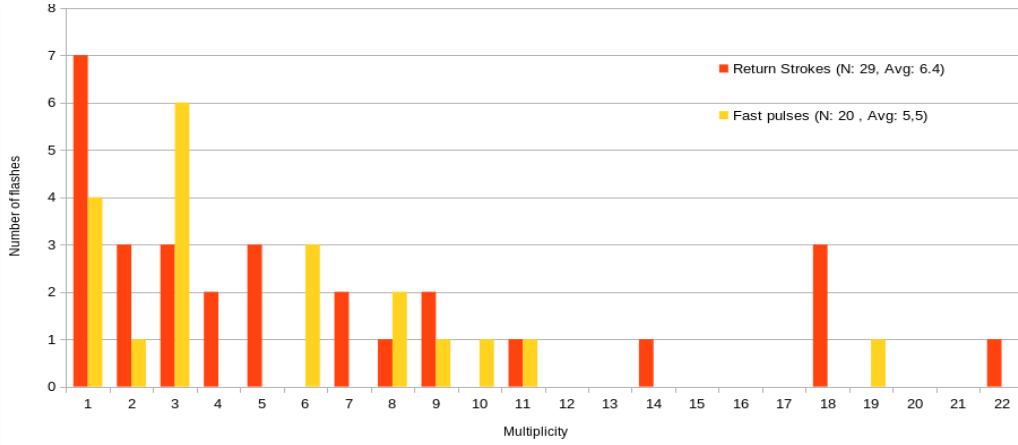


Figure 5. Multiplicity of ICCRS and ICCP cases.

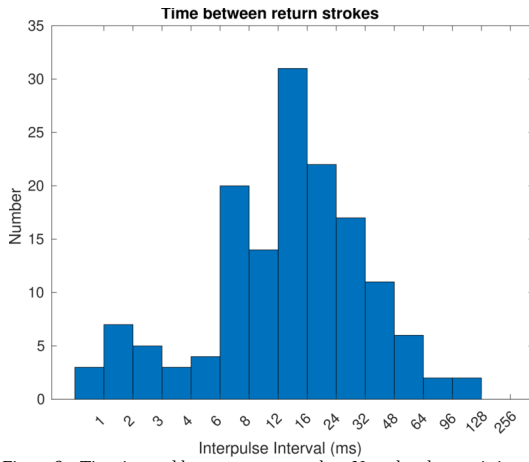


Figure 6. Time interval between return strokes. Note that the x-axis is presented in the log base 2 scale.

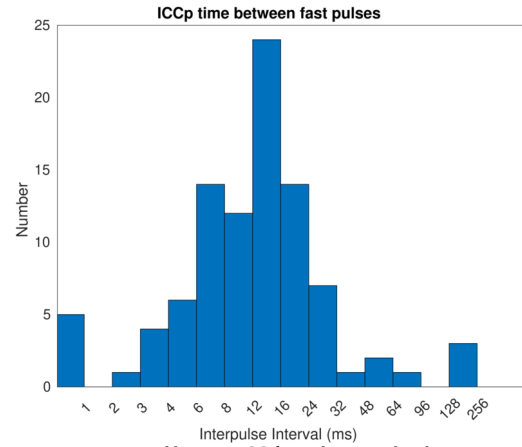


Figure 7. Time interval between ICC fast pulse. Note that the x-axis is presented in the log base 2 scale.

C. Peak Currents

The cumulative probability of the peak currents of the ICCRS return strokes is presented in fig. 8. The probability distribution shows a near-linear log-normal relation as seen by Romero et al and Diendorfer et al. [7, 15]. The highest recorded peak current for the period was 34.56 kA. The same analysis was performed for the fast pulses superimposed on the ICCP cases. The cumulative probability is presented in fig. 9. This again shows a near linear log-normal distribution however the gradient is far steeper with 99.9% of fast ICC pulses being below 8 kA. The highest peak current measure was 25.18 kA for the fast ICC pulses. Similar was seen by Michishita et al.

D. Charge transfer

The total charge transfer for each event was determined by numerically integrating the current waveforms after offset correction was completed. The results are presented in table III. The charge transfer for return stroke events is comparable to the values that were seen at the Gaisberg Tower and slightly higher than those seen by Michishita et al. [7, 11]. However,

the charge transfer for ICCOnly and ICCP is comparable to values measured by Michishita et al.

V. DISCUSSION

The most distinct characteristic noted in this analysis is the average multiplicity of the events in which return strokes followed the initial continuing current – this is significantly higher than many other instrumented towers around the world. Also of distinction, is the large number of measurements (43) made in just a single season.

The reasons for this need to be explored and may be related to the specific characteristics of Johannesburg – as noted already, the altitude of the region is 1700 m above sea level and typically has -10°C isotherms in the range approximately 6000 m. This is well above the height of the tower. The high sampling rate (4 Mhz) could also lead to increased ability to distinguish return strokes although, some events have durations more than 1 second, meaning it is possible some return strokes have also been missed. The amount of data is limited and some of the data may be skewed due to the limited number of storms

recorded. However, the high return stroke currents as well as flash multiplicity was seen across all days.

Of further research interest, is the second tower in the region – Hillbrow/Telkom Tower. It is noted that the towers are sometimes struck simultaneously, and further analysis should distinguish these current measurements from cases where just the Sentech Tower is struck.

TABLE III. TABLE COMPARING THE CHARGE TRANSFER BETWEEN DIFFERENT STUDIES

Study	Charge transfer (C)					
	ICCP		ICCP		ICCRS	
	GM	Median	GM	Median	GM	Median
Sentech 2021 (this study)	23.41	26.08	29.31	35.51	34.49	41.36
Michishita et al [2]	24.50	25.30	38.60	36.90	29.30	38.80
Gaisberg [1]	-	-	-	-	41.00	44.00

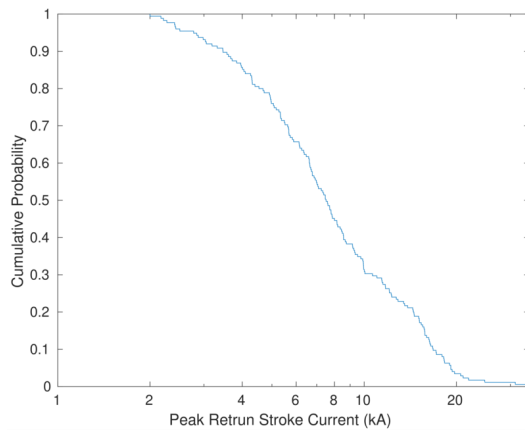


Figure 8. Peak current distribution of upward initiated lightning for the Sentech tower 2020-2021

VI. CONCLUSION

The current measurements from the Sentech Tower for the 2020-2021 rain season are presented. The season produced, 186 return strokes, 30 ICC fast pulses and 7 ICCOnly events. The return stroke median current and median ICC fast pulse peak currents are comparable to the values seen in literature at 7.51 kA and 3.75 kA, respectively. The median charge transfer also agrees with literature for return strokes this is 41.36C, while it is 35.51C for ICCP events and 26.08C for ICCOnly events. The return stroke multiplicity however is higher for the Sentech Tower than elsewhere for the season the value is 6.41.

ACKNOWLEDGMENT

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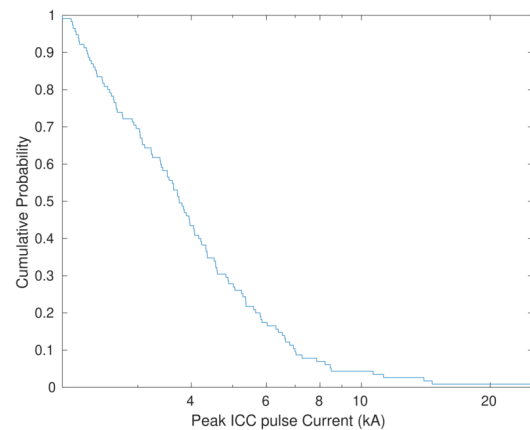


Figure 9. Peak ICC pulse current distribution of upward initiated lightning for the Sentech tower 2020-2021

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Metric collection on semantically segmented high-speed lightning footage with machine learning

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Abstract—An investigation of the accuracy of a system using semantic segmentation in determining the number of individual strokes, direction of leaders and strike points for high-speed lightning footage. The paper uses a pre-trained DeepLabv3+ network, chosen to allow for the lowest computer requirements, where the last layers of the model are retrained on lightning footage. The network produces semantic segmented images where each pixel has a numerical label which are evaluated to count strokes. Regions of interest are created per strike and used to reduce noise. The system has a stroke detection efficiency of 70.1%, direction accuracy of 80% and a strike point accuracy of 89.5% when evaluated on 15 videos.

Keywords—Lightning, stroke, machine learning, MATLAB, Region of interest, DeepLabV3+, high-speed video

I. INTRODUCTION

Modern high-speed cameras allow us to view the different physical processes of lightning. The processes of interest include upwards (ground to cloud), downwards (cloud to ground) and inter-cloud (cloud to cloud) based on the movement of the initial leader [1–3]. Each of these categories can be further categorised by the polarity of the charge carriers.

High-speed video footage is essential to the study of lightning due rapid propagation speed and the number of different elements that take place within a microsecond. At present lightning events are recorded using specialised video equipment allowing for saving 1 second segments of footage.

This footage requires sorting to extract frames of interest and manual recording of metrics. This work requires manually viewing and extraction of the metrics on a per frame basis. To reduce the burden on a researcher this paper investigates modifications of the system developed by Smit et al. [4] in aiding the process of lightning classification as done by [5, 6].

Using high-speed footage as input the system attempts to detect and record the frame information about strokes, number strike points as well as to determine the direction. The basis of the system is a semantic segmentation network that labels pixels on a per image basis. The output images are used and evaluated in sequence to extract the required information.

High speed videos of lightning allow for the study of the formation of lightning [7, 8], speed and formation of leaders [7–10], the structural differences between different types of lightning [5, 7, 10, 11], the dependence of storm specific conditions [11] and studying a channel's influence on additional strokes [5, 13]. The use of high-speed footage has been particularly useful in the study of processes that are not visible below 10 000 frames per second [7]. These events included return stroke analysis [13], recoil leaders [10] and evaluating flash duration [5, 8, 10, 15]. High speed footage is further used in verifying lightning location systems [16]. This is possible due to the correlation between the luminosity of a channel and the continuous current [17]. It is also currently being used to study physical phenomena such as space stems [18] among other uses.

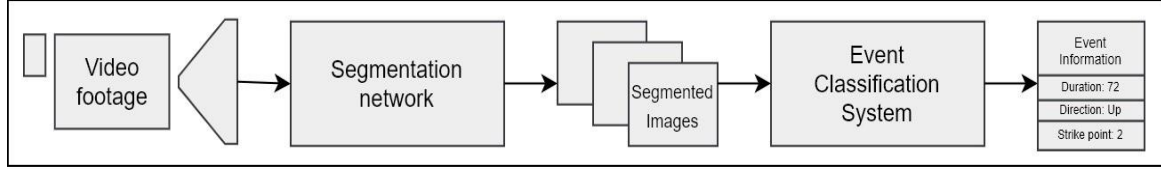


Figure 1. Simplistic representation of the system sub-components

Machine learning has seen major improvements in accuracy, number of learnable variables and speed as the network topologies improved [19]. Machine learning is applied in several fields of study [20–22], however most of the prior work is focused on low speed (less than 1000 frames per second) footage. Machine learning has been applied to the field of lightning [23–25], while this application focused on lightning prediction and weather pattern effects. The system produced by Smit et al. [4] tried to determine whether machine learning could be used to segment lightning. The work showed that high-speed footage cannot be processed in large chunks due to the memory requirements. It is therefore important to perform segmentation on individual images. The paper also showed that using a sequence of segmented images it is possible to extract some information about the overall event.

II. SYSTEM OVERVIEW

The system is designed with the aim to run on a local system without requiring cloud computing/supercomputer. This requires that the overall system is effective in the use of the available resources (RAM, CPU and GPU). The design does not require a dedicated GPU. The system design requires a trained semantic segmentation network. The network selected is DeepLabv3+, where the last layers have been stripped and retrained on labelled ground truth data (labelled by the author) using the data from Warner et al. [5].

The system uses the semantic segmentation network to classify on a per image basis. The output of this classification is used to classify overall events by tracking the lightning frames in sequence. A simplified system diagram is presented in Fig. 1. All footage used is recorded using a Phantom v310 high-speed camera, with the frame rate set between 10 000 and 23 000 frames per second.

A. Semantic segmentation network

The semantic segmentation network is based on Deeplabv3, as described by Chen et al [26], where the final layers are stripped and re-trained. To reduce the weight that blank (no lightning) frames have on the segmentation network, most empty frames are removed except those that immediately surround an event. Removal of empty frames has a further benefit of reducing the number of frames to train on. For each video, ground truth masks are required that provide an expected pixel value for the input sequences. These are created using compositing software where slow-moving aspects of a sequence's masks are created once for an entire sequence as they remain the same throughout. The remaining labels are created in a procedural fashion on a per frame basis. The sequences are split into training, test, and validation in the ratio 75:15:15 and the system then trains on the provided data. The

segmentation network produces images where each pixel value is replaced by a numerical value from 1-6. An example of the output is presented in Fig. 2, where the colour mask is added to emphasize the different values. Note that the *lightning* label is used for both leaders and established channels as these are indistinguishable in a still frame. *Stroke* is used from any flash or brightness which is normally associated with a return stroke. *Ground* is used to label the *ground* and background buildings. *Other* is used for occluding structure in the foreground such as a lightning rod, rain drops, etc. *Sky* is the label for the sky and *Cloud* is the label for clouds.

B. Sequence classification

For a sequence of images, the system programmatically goes through each output image and evaluates the labels within the images. The sequences are separated into sub-events where a sub-event is *lightning* surrounded by 'empty' frames or the start/end of the footage. To avoid noise being recorded as lightning events a threshold of pixels is set to 1% of the total pixels. The system attempts to compensate for poor classification from the segmentation by having a buffer of three frames. For the detection of strokes, the system attempts to find a frame that has greater than 5% of the pixels that are labelled as *stroke*, and groups consecutive frames that have this label. In this case the overall candidate event is labelled an attachment event. For each stroke cluster the first frame number is recorded as well as the number of frames that have the stroke label. If there are further groups of *stroke* labels that occur without the *lightning* label disappearing these strokes are recorded as part of the initial lightning event, as this represents M-components. The details of these stroke events are recorded just as the initial stroke is recorded. The events which do not have a frame with a stroke are labelled attempted leaders.

C. Region of interest

To remove noise when finding the direction and determining strike points, it becomes convenient to create regions of interest. For an event that contains a stroke, the frame following a group of stroke frames is used if it contains the *lightning* label. This frame is selected as this frame most likely contains an established channel. For the case where there is no stroke (attempted leaders), the full frame is used instead. The region of interest is a bounding box that surrounds the lightning channel in this frame, as this channel would be used by the leader. The region of interest is a bounding box in the standard MATLAB format. The return value is a matrix of the form: (left, top, width, height). Where *left* is the x-value of the left edge of the bounding box, *top* is the y-value of the topmost part portion, *width* and *height* are the number of pixels in the x and y direction, respectively.

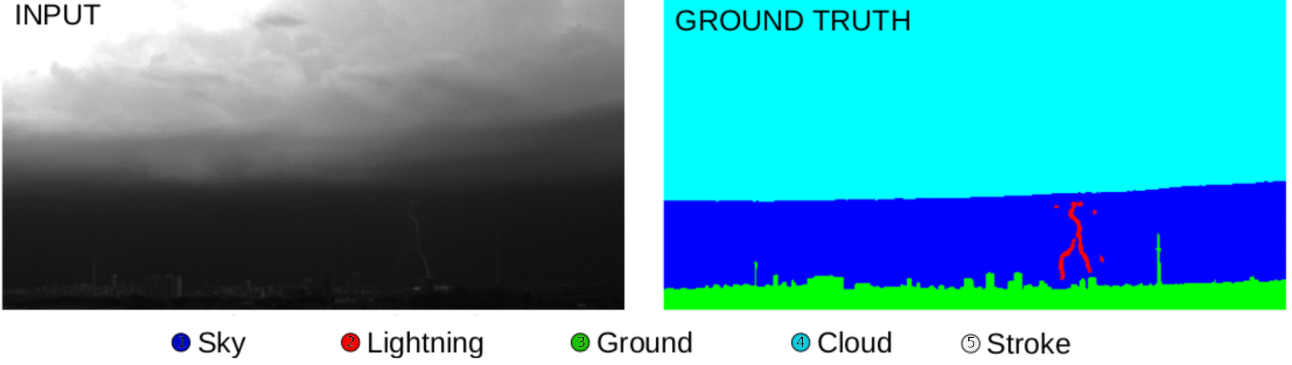


Figure 2. Example image showing the expected output and the labels used by the system

D. Direction determination

The region of interest is used to set all pixels outside the region to a zero value. This reduces the affect that noise has on the determination of the direction of a stroke. Using the MATLAB implementation of the clustering algorithm DBSCAN [27] the system clusters the pixels and tracks the changes of the centroids of these pixels over the frames. The resultant Y (vertical) value of the vector is then evaluated to determine the direction of the leader.

E. Strike point detection

From each strike, the region of interest is compared to prior strike points. If the region of interest around the lightning pixels is the same or is contained within another region, it is immediately proposed as the same region/channel. For the case where the subsequent strike's region of interest does not neatly overlap the region of interest is compared by (1).

This formula places greater weight on the similarity of the placement of the bounding box than the size of the bounding box. Images that have a similarity greater than 0.95 are proposed as the same. The proposed channels have their region of interests compared using the structural similarity function in MATLAB (ssim). If the value is greater than 99% the strike point is deemed to be the same point. For the cases where the bounding box around the channel does not match closely or the lightning is dissimilar a new strike point is assigned in numerical order.

F. System output

The output of the system is four folders. One folder is the *pixelLabel* folder that contains the direct output of the semantic

$$\frac{1}{6} \left(2 \left| 1 - \frac{\text{left}_{\text{old}}}{\text{left}_{\text{new}}} \right| + \left| 1 - \frac{\text{width}_{\text{old}}}{\text{width}_{\text{new}}} \right| + 2 \left| 1 - \frac{\text{top}_{\text{old}}}{\text{top}_{\text{new}}} \right| + \left| 1 - \frac{\text{height}_{\text{old}}}{\text{height}_{\text{new}}} \right| \right) \quad (1)$$

segmentation network. These are images with each pixel labelled from 1-5 indicating the classification of the pixels. The folder *output* contains the images where colours have been used to replace the numerical values which allow for easier

identification of events by a user, as is done in Fig. 2. An *overlay* folder is produced that has the input images overlaid on the output images allowing a user to validate or use the masks as a guide to classification. The final folder, named *analysis*, has four files each containing metrics about the system. The resultant analysis of the lightning is a MATLAB table saved as *events.mat*. The table provides the results of the complete system predictions, and the output takes the form presented in Tab. II. It should be noted that the strike point will only have a similarity value if the strike point is determined to be the same as a prior strike point. If a *stroke* occurs without the *lightning* disappearing this stroke is added to the struct of the initial strike, with all the accompanying information. This could therefore be used as a method to detect large M-components.

III. PERFORMANCE EVALUATION METHODOLOGY

The system is compared to ground truth data created as captured by Schumann et al. [6]. The result is a spreadsheet that details information about all lightning events within the videos. The spreadsheets contain the time that each stroke occurs. The direction of the leader, numerical strike point and the duration of a stroke. Using this information, labels are created for the videos and the ground-truth observations can be used to evaluate the stroke detection, strike points and direction information.

A. Semantic segmentation methodology

To ensure that the segmentation system performs as required, the system is to be validated using labelled test data that has not been seen by the system. The data used for evaluation is the 'validation' sequences that were split during the training phase as mentioned in Section 2-A.

B. Metric methodology

For each video, the strokes can be compared directly to the information presented in the spreadsheets. Here the frame and the embedded timestamp can be compared to the recorded ground-truth time of an event to determine if a stroke is recorded at the same time. The direction accuracy can be compared to the information in the ground-truth data, since each stroke has a direction associated and recorded alongside the event. Finally, for each video and each stroke, the

TABLE I. TABLE SHOWING THE OUTPUT METRICS PRODUCED BY THE SYSTEM

Heading	Description
Start:	The frame number where the first lightning is detected
Duration:	The number of frames that have lightning
Type:	Labels the event as attachment or attempted leaders
Strokes:	A struct that can have multiple rows of the form [First frame with stroke, frame duration]
Direction:	The direction of the initial leader can be Up, Down or Unknown
Region of interest:	Has a bounding box value of the form [left, top, width, height]
Strike point:	A struct of the form [numerical number of strike point, similarity value]

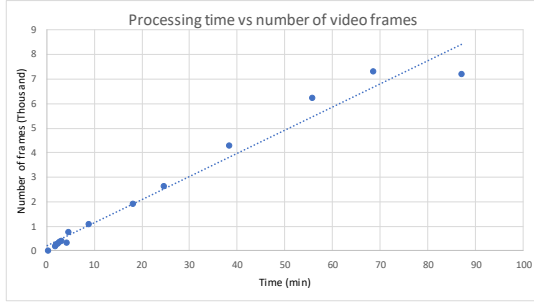


Figure 3. Graph showing the time trend for videos of different sizes.

spreadsheet assigns a strike point number just as the program does. Accuracy of the system can be evaluated by comparing the number of strike points assigned and that the strike points change to a new number for each new strike point. It is also useful to evaluate the accuracy of the strokes and M-components presented. This is done manually by looking at the frame number for each presented classification and determining if that event was correctly classified.

IV. RESULTS

A. Semantic segmentation

The ground truth values provided by Schumann et al. [6] are used to create masks and evaluate the performance of the system in the event classification. The performance of the network is presented in Tab. 1.

B. System processing speed

The system can perform segmentation on several videos with different numbers of frames. The results of the processing time are presented in Fig. 3 it is evident that the performance is linearly dependent on the number of frames within a video. This is due to the write speed of the hard drive since each frame is resized to fit the semantic segmentation network size requirements and write operations cannot be performed in parallel.

C. System overall performance

The frame information can be extracted from the times recorded by Schumann et al. [6]. Since the resolution of the recorded times is rounded to the nearest 1 ms and the frame rate produces a resolution of 0.04 ms, each event frame can be within 11 frames of the recorded time. This could lead to errors in the evaluation of the candidate frame. The real frame is compared to the candidate frame produced by the system. For this investigation, the time of the first proposed stroke is

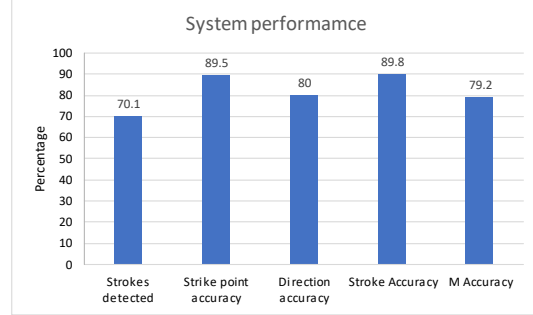


Figure 4. System evaluation result using 15 videos

compared with the ground-truth stroke time to determine the accuracy of the proposed stroke frame. The rest of the strokes for an event are only considered when evaluating the accuracy. The direction is compared for each proposed event to the actual direction of the leader. Finally, for each video the performance of the strike point analysis is evaluated on a per video basis. The system performance was evaluated using 15 different videos with varying lengths and perspectives. The result of the system performance is presented in Fig. 4. From the testing dataset videos there were 77 strokes in total of which 23 were not detected. Of those, the majority of missed strokes were from a single video which had part of the frame over-exposed due to sunlight. This made it difficult for the system to distinguish *stroke* from other *lightning*. It was further noted that some strokes were part of another stroke due to lightning being erroneously detected in all frames between stroke frames. The system made two errors in strike point detection by assigning new strike points to identical channels. The system incorrectly classifies new strike points if the first strike points produce a very small region of interest while subsequent strikes have larger regions of interest.

The system had a direction classification of 80 percent, however only one of the videos was an upwards event. The system had difficulty with strokes that had a short frame duration as these strokes were most susceptible to noise due to each frame having a larger contribution to the ultimate prediction. By evaluating the output table and comparing it to the ground truth data, using the first entry in the stroke struct as a stroke and the subsequent 'strokes' as M-component events. The system has an accuracy of 89.8 percent for labelling an overall event when compared to the event labels assigned by Schumann et al [6]. This mirrors the network metrics for the stroke accuracy presented in Fig. 4. The lower accuracy for M-events is due to the semantic segmentation system erroneously labelling some bright channels as a stroke.

V. DISCUSSION

A. Semantic segmentation

The networks, regardless of network type, label more pixels than required (very broadly fit to the regions) as discussed in [4]. This lack of granularity reduces the application of semantic segmentation in determining the polarity of lightning as well as the exact point of attachment.

B. Portability

Training occurs once on the machine learning system and allows for a deployable machine learning application that is computationally efficient. Since the *trained* system does not require large computational resources (such as a GPU or high-end CPU), it could be deployed in varying regions. The trained network could be reused (not requiring re-training) except for labels related to the particular region of interest. These labels would include the ground and/or other labels specific to the field of view for the region. The time it takes to process a full-length video of 1 second at 23 000 frames per second during testing was approximately 1 hour. This time can be reduced greatly by reducing the number of frames required to evaluate by trimming the video prior to introduction into the system. Furthermore, it is advised to use a solid-state drive as opposed to a standard hard drive to allow for a reduction of the impact of read/write times, but this is not a requirement. The system automatically uses any GPU that the system has and would also benefit from a better performing GPU while performing the semantic segmentation but also does not require a GPU.

C. Limitations

The test data is limited to 15 videos and further testing should be conducted to improve the accuracy of the results. The test data should include several upward events to evaluate the direction detection. From the testing and manual evaluation, noisy outputs from the segmentation network cause a lot of erroneous classifications. Threshold of pixels reduces the amount of false detection being labelled as a lightning event, but faint channels are then not classified properly. This results in the end time of events being incorrect, which prevents the accurate evaluation of strike end time. It further prevents the detection of faint forming channels which cause the direction finding to malfunction. This occurs as the channel brightens as the leader nears the ground [7]. The segmentation initially recognises the bottom part of the leader, and the following frames give the appearance that the leader propagated upwards. The system is limited to work on a single video at a time. This may reduce the user experience where a user has filmed several videos. The system should have the ability to automatically process the batch of videos reducing the user interaction. This functionally can be added by changing the user interface of the system without requiring changes to the core system.

The application is designed to work on individual videos which have been exported to tif sequences, which loses some of the embedded information. This requires a pre-processing step for each video that is recorded which should be automated. The Phantom cine format is well documented and there are MATLAB tools available. The toolkit can thus be used to

create an import function that removes the requirement of the tif sequences. This would remove large parts of the read/writes that take place improving the overall performance and would allow for preservation of the embedded frame information such as exposure values, time, etc.

Although rare, the system is not designed to deal with multiple strike points in a single frame as it assumes a single strike point. The system also incorrectly assumes that regions of interest that are not similar in size and not the same. From the region of interest, one could determine the lowest point (cluster of pixels) that have the lightning label. This could be used to make a better prediction of strike point and may distinguish between strike points which are geographically very similar.

For training of the segmentation network, a large variety of training footage was used. The dataset was organised in train, test, validate where the split is in a 75:15:10 ratio. With the same ratio across day/night footage. By inspecting the footage, it becomes apparent that the footage from daytime and nighttime have different aspects that need to be considered. For instance, the day footage does not have a large contrast between the background and the lightning, while it is completely the opposite for evening footage. Furthermore, daytime footage has a greater importance in understanding the ground and background during non-stroke frames. This seems to suggest that it may be advantageous to train two systems which specialise in daytime and night-time footage, respectively. This would further create the advantage of reducing the dynamic range across the sequences and may allow for better performance on the *lightning* label prediction.

D. Further research

The system does not perform well for detecting M-components due to using a semantic segmentation network on a per image basis. This procedure does not allow for detection of events that are not markedly different from other events, where most M-components in isolation would look like a channel. The only way to accurately track M-components is by looking at luminance changes across frames per video. The luminance values could be plotted and would follow a similar sketch of the pattern of electric radiation presented on page 165 of Cooray et al. [7]. Machine learning could then be used to evaluate the outputs and identify M-components. This method could be used in conjunction with the current system to improve overall accuracy while maintaining the benefits of the current system (strike points and direction finding).

VI. CONCLUSIONS

The use of a per image semantic segmentation networks on high-speed video footage allows for extracting metrics from a recorded lightning event. The performance of a system that evaluates video on a per frame basis is limited to the performance of the system in use. The system developed does not correctly classify all events; however, research is required to determine what effect different training on the segmentation networks would produce. The overall system can detect the difference between different strike points within a given video with high accuracy except where the initial region of interest

for a channel is very small. The system requires testing on additional videos to get evaluation results with a higher degree of confidence and on even more varied data, for example Upward-events.

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