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A CRITICAL EVALUATION AND ANALYSIS OF METHODS OF DETERMINING THE NUMBER OF TIMES THAT LIGHTNING WILL STRIKE A STRUCTURE

Sphiwe Hamilton Ngqungqa

A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfillment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 2005

DECLARATION

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

_____

(Signature of candidate)

_____day of_____(year)_____

A REVIEW OF THE INFLUENCE OF HEIGHT ON THE INCIDENCE OF POSITIVE UPWARD LEADERS FROM TALL STRUCTURES

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Abstract: The primary objective of this paper is to present results regarding data obtained from Eskom's Lightning Positioning and Tracking System (LPATS) and is a continuation of the work presented at the two SAUPEC Conferences in Pretoria and Stellenbosch [1, 2]. LPATS provides some useful information regarding the lightning field measurements around the Brixton and Hillbrow Towers, in Johannesburg, for the two seasons of June 2001 to June 2003. The results suggest that there is a significant increase in apparent ground flash density in the vicinity of the towers when compared to the surrounding areas. The observation of mean current values in the order of -20kA suggests that the increased contribution of upward flashes to the total incidence of flashes in tall structures should lead to a decrease in measured current amplitudes.

Keywords: Tall structures, current amplitude, critical height

1. Introduction

Engineers and scientists have done a great deal of work to build an adequate knowledge base of the engineering parameters of the lightning ground flash. These parameters are imperative to an electrical engineer concerned with lightning protection problems, whether these relate to power transmission, systems for distribution, telecommunication installations or buildings or structures. The most important of these parameters are the peak current amplitude (including its probability of distribution) and the characteristics of the current waveform, an understanding of which forms the basis for lightning protection.

Tall structures have always been spots of significant lightning activity. Most of these structures or high towers (exceeding 60m in height) are primarily associated with different types of radio towers.

The main objective of this paper is to present the final results obtained from Eskom's Lightning Positioning and Tracking System (LPATS) regarding lightning strikes to two tall structures, namely the Brixton and Hillbrow towers in Johannesburg, South Africa.

2. Background: Upward Leaders

For the purpose of protection system design, it is imperative to understand what happens in the final stages of lightning propagation in determining the final point of strike on the earth's surface. The objective of the protection system is to ensure that the lightning terminates on a part of the protection system connected to ground rather than on some sensitive part of the building or structure. All the standards in current use are specifically designed for structures less than 60m tall [3]. Consequently, lightning protection for tall structures and buildings is not regulated by the currently available standards.

Fundamentally, lightning is a manifestation of a very large electric discharge and spark [4]. Lightning discharges to earth are usually initiated at the fringe of a negative centre [5]. Lightning manifests itself in various forms, namely, flash to ground, cloud to cloud flash, cloud to air flash, ball lightning and hot lightning [5]. The final stage of lightning (cloud to ground) involves the initiation from some part of the structure on the ground of a positively charged channel that propagates upwards (the upward leader) and finally intercepts the downward propagating negatively charged channel (downward leader) [5]. For the interception of the two leaders to occur, certain criteria must be met with regards to the relative velocities of their leader tips. The relative velocities of the two leader tips depend on the magnitude of the linear charge density along the stepped leader (in C/m), which in turn is related to the peak lightning current [6]. Thus upward leaders initiated from a structure are able to intercept downward leaders in the vicinity of the structure and hence result in the lightning stroke terminating on the structure, thereby increasing the incidence of lightning strikes to the structure.

3. Structure Height vs. Equivalent Height

In general, it may be noted that in much of the discussions and papers published, the height of a structure has been adopted as a variable parameter for analysis. Eriksson et al had suggested that this is a gross simplification since it is really the shape of the structure or a dimensional relationship that is the more important consideration [7]. In reality, the influence of a structure upon the lightning striking mechanism is determined by the degree to which the electrostatic field in the vicinity of a charged leader (or thundercloud field) is intensified by the presence of the structure. This in turn, according to Eriksson, is a function of the shape of the structure rather than its height alone and, as has been shown in the case of tall masts or chimneys, the shape of a structure may be expressed in terms of the ratio between the height of the structure and the structure's equivalent radius, H/R, the so called "slenderness ratio" [7].

A number of previous measurement exercises around the world have not taken the latter considerations into account and one is thus compelled to consider height alone as a base parameter for comparative analysis. There may be some justification for this, in that the slenderness ratios (i.e. values of H/R) for practical structures may be of somewhat similar orders of magnitude [8]. In certain instances, however, such as structures on prominent mountains, it is necessary to introduce the concept of "effective height". The apparent elevation from the surrounding area enhances the relative field intensification on the top of the structure in comparison to any other structures in the same vicinity. The work of Anderson et al [7] indicates that in a given uniform electrostatic field, the intensification at a structure top will be enhanced by a factor of 1.6 for an increase in slenderness ratio (H/R) over the range 100 to 210 [8].

Popolansky and Eriksson produced results which suggest a decreasing trend in median current amplitude with increasing

height, for all flashes [8]. However, the data does not distinguish between the upward and downward flashes.

4. Previous Research

In 1972, the Council for Scientific and Industrial Research (CSIR), initiated a research programme to study, mainly, the direct measurement of parameters of the lightning discharge that are of prime importance to electrical engineers [8]. The CSIR research programme included the following aspects [9]:

a) Direct measurement of the current waveform characteristics of strokes during flashes to structures – including current amplitudes, maximum rates of rise, polarity, charge transfer, etc. This involved the development of indirect techniques for such measurements and includes a study of the features of the high-speed electric field changes associated with ground flashes.
b) A study of the striking process during discharges to structures and the influence of structures upon this process. An essential feature of this aspect is the study and measurement of lightning strike distance and lightning peak current amplitude.

The study was conducted on a 60m mast. The mast was of triangular aluminium lattice sections raised upon insulators at the base and supported by fully insulating stays. In the event of a lightning flash, this design would confine lightning current to the body of the mast itself and allow the current to be measured at the base of the mast during its passage across the insulated base section into the earth. The main objective was to obtain data involving the more common downward discharge, rather than the upward flash [8].

Eriksson presented the first preliminary data in 1977 [8]. The data indicates that just more than half of flashes to the mast have been of negative polarity (about 52%) and have progressed in the downward direction. The influence of the mast as far as distortion or intensification of the electrostatic field is concerned, is not so extreme as to result in high incidence of the so-called "unnatural" upward flashes. Of the total flashes, more than 70% of which correspond to a downward direction of progression. Based on the common practice to approximate current amplitude distributions by the lognormal distribution [10], Eriksson obtained median current amplitude of 41kA versus 30 and 28kA by Berger and Popolansky, respectively [8]. Berger's results were based on a larger number of flashes than Eriksson's, whereas Eriksson's results are based on the downward negative flashes only. Also, the median peak current amplitude for all negative flashes to the research mast (including both upward and downward flashes) is 25kA [8].

The data obtained after fifteen years of running the CSIR research mast reinforces earlier research that for a 60m mast, the lightning incidence on the structure is still largely of downward type [8], which agrees with Eriksson's findings. Furthermore, by assuming lognormal distribution of the measured data, a peak current amplitude of 33kA is obtained and is comparable to Cigre's 30kA for downward flashes [11].

4.1 Relative Incidence of Upward Flashes from Tall Structures

In order to determine the annual incidence of flashes to tall structures, Eriksson produced the following table regarding the relative incidence of upward flashes from tall structures [1, 8], as can be seen in Table 1:

Table 1: Relative Incidence of Upward Flashes

Source	Structure Height in m	Relative frequency of occurrence of upward flashes
LPATS	5	2%
LPATS	17	3%
Pierce	150	23%
	200	50%
	300	80%
	400	91%
McCann	110	8%
	180	24%
	400	96%
Berger	350	84%
Gorin	540	92%
Garbagnati	500	98%
LPATS	*582*	*85%*

The figure below, Figure 1, is obtained by plotting the results obtained in Table 1, above:

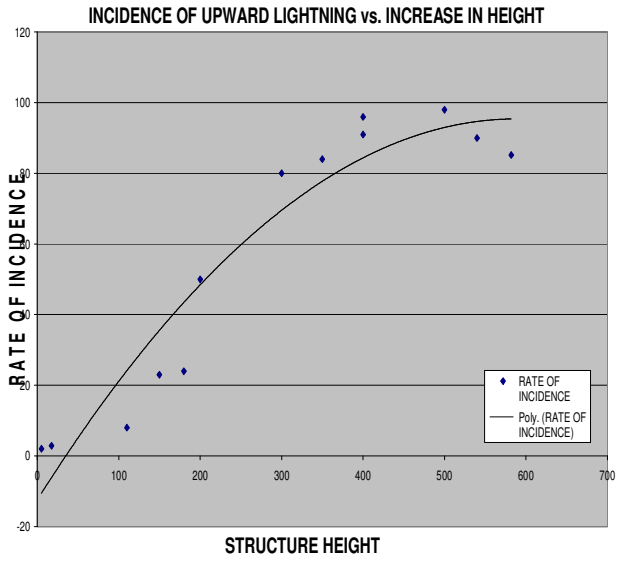


Figure 1: Relative Incidence of Upward Flashes

- There is sufficient data to indicate that an increase in structure height results in a corresponding increase in incidence of upward leaders.
- The data suggests that structures having heights below 100m will not normally experience upward flashes. Similarly, structures having heights greater than and/or equal to 400m will always display upward flashes [1,2]. However, it is not strictly correct to compare using the height alone.
- It would seem, from the available data, that there is a critical height beyond which the incidence of upward flashes from tall structures would tend to decrease. That height is in the range of 500 to 600m, even though more data may be required to verify that range.
- From Figure 1, the data indicates that, for structures in excess of 500m, will tend to experience an apparent saturation in the incidence of upward flashes.

4.2 The effect of structure height to the electric field

Rachidi et al performed an analysis of the electric and magnetic fields radiated by lightning, the first and subsequent return strokes to high towers, particularly the Toronto CN Tower (about 553m tall) [13]. The analysis was done by utilizing measurements of lightning electromagnetic fields, from which lightning currents are inferred by means adopting some empirical or theoretical relations [13]. The measurements were taken 2km away from the tower. The results show that:

- The peak magnetic field associated with tower strokes is about 2 times (for the first stroke) to 3 times (for the subsequent stroke) as large as that corresponding to return strokes initiated at ground level
- Both the electric and magnetic fields are most affected by the presence of the tower
- The tower's electric field (tower is 553m tall) has a dominant effect on the electromagnetic field at 2km [13].

Diendorfer presented similar results as well [14]. He shows that the influence of a tall structure on the lightning mechanism is caused by the increase of the electrostatic field. Also, he shows that, similar to artificially triggered lightning, tall structures favour the initiation of an upward leader (ground to cloud). In many cases in a lightning channel established by an upward leader, a number of downward subsequent strokes (cloud to ground) are observed [14].

5. LPATS

The lightning positioning and tracking system (LPATS) has been in use in South Africa since 1993 [15]. The system sensors were upgraded in 1999, providing sufficient location accuracy in the range of 500m to 1km [16].

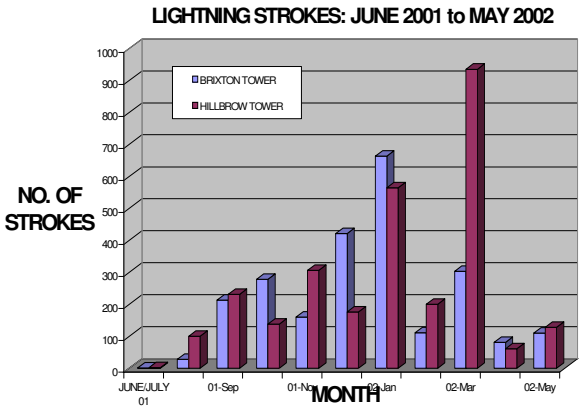
LPATS was used to determine the incidence of lightning flashes to the surrounding tall structures, namely, the Brixton and Hillbrow towers for two seasons, namely, from June 2001 to May 2002 and from June 2002 to June 2003. The Hillbrow tower is 5.2 km north east of the Brixton tower. The physical height of the Brixton Tower is 250m high and the Hillbrow Tower is about 220m high.
The system uses six magnetic sensors (forming a hexagon) situated mainly in the Gauteng, Limpopo, Mpumalanga, KwaZulu-Natal and the Free State areas since these are areas of high lightning activity [15, 16]. For system operation, a minimum of three sensors is required to run the system since only three signals are required for triangulation and detection. The detection efficiency of LPATS is higher inside the hexagon, about 98%, and slightly lower outside the hexagonal area of the sensors. For both seasons, the system availability was found to be more than 95%. The Brixton and Hillbrow Towers are located within the hexagonal area of the system sensors.

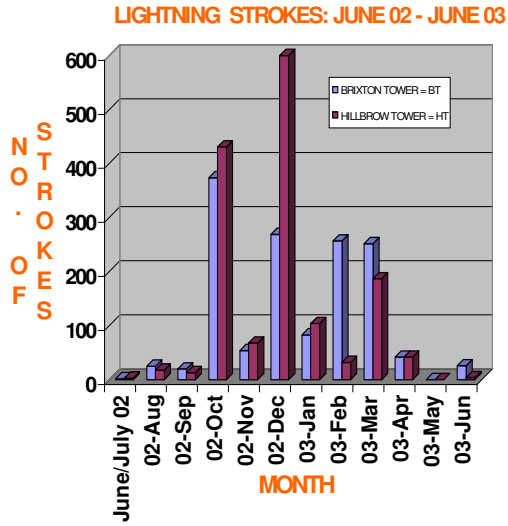
5.1 Preliminary Results

The Lightning Positioning and Tracking System provides information about the location (latitude/ longitude), the peak current and subsequent strokes for lightning activity in South Africa. For all ground striking flashes, the accuracy of LPATS was designed to be in the range of a few hundred meters to a kilometer [16]. For practical purposes, this level of accuracy is adequate for analysis and comparison.

All strokes in the vicinity of the tower (defined by the radius $0 < R < 2.5$ km) are assumed to be terminating on and/or in the vicinity of each tower. This is a reasonable assumption considering that the accuracy of LPATS covers a range of a few hundred metres to a kilometre and the distance of 2.5km is within the measuring accuracy of LPATS. Also, the two towers are 5.2 km apart, so any strikes beyond 2.5 km would be considered outside the vicinity of the respective tower. The radius of $2.5 < R < 10$ km defines the area far or away from the towers.

In evaluating the local ground flash density for both the Brixton and Hillbrow towers, it is interesting to note the lightning activity in the vicinity of the two towers as shown by figures 2 and 3 below:





Figures 2 & 3: Lightning strokes in vicinity of tower

The figures above indicate the number of strokes experienced by the Brixton Tower (BT) as well as the Hillbrow Tower (HT) for the two seasons of June 2001 to May 2002 and June 2002 to June 2003. The figures indicate a significant increase in the incidence of strokes between the months of October and March as expected since it is typically the lightning season in South Africa. A higher incidence of strokes is experienced during the months of December for both seasons.

However, it is also interesting to note that both towers experience a very similar pattern of incidence of strokes, though March 2002 and December 2002 represent some deviations of exceptionally high incidence of strokes for the Hillbrow Tower. This may be explained by the fact that both towers are about the same height and are relatively placed within the same area, within 5.2 km of each other. Furthermore, it was also determined that there is an appreciable increase in local flash density compared to the surrounding areas, as shown by tables 2 and 3 below:

Table 2: Flash Density Change: June 2001 – May 2002

	STROKES		FLASH DENSITY (flashes/km^2/year)	
	R < 2.5	2.5 < R < 10	R < 2.5	2.5 < R < 10
BT	293	2076	2.71	1.28
HT	329	2512	3.05	1.55

Table 3: Flash Density Change: June 2002 – June 2003

	STROKES		FLASH DENSITY (flashes/km^2/year)	
	R < 2.5	2.5 < R < 10	R < 2.5	2.5 < R < 10
BT	144	1260	1.33	0.78
HT	186	1316	1.72	0.81

NOTE: BT = Brixton tower & HT = Hillbrow tower

The results indicate that in the vicinity of the two towers, there is an increase in the flash density, with each tower experiencing direct strokes of 293 and 329 for the Brixton and Hillbrow towers, respectively, for the year June 2001 to May 2002. According to Diendorfer, structures of similar height and construction to the Brixton and Hillbrow Towers experience lightning flashes with stroke multiplicity in the range of 4.5 to 6.5 [14]. Since both towers are relatively very high, an average of 5.5 strokes per flash is assumed for the Brixton and Hillbrow towers. Consequently, from Tables 3, it is clear that the BT and HT towers would experience direct strikes of 26 and 34 flashes per annum, respectively. These values are in the same order as those obtained by using Eriksson's equations and IEC Standards [3, 17, 18], which predict the direct strikes to be 54 for BT and 42 for HT, though the predicted value for BT is twice that obtained from LPATS.

From Tables 2, it can be seen that a much higher incidence of strokes was experienced for the season of June 2001 to May 2002. Hence the BT and HT towers would experience direct strikes of 53 and 60 flashes per annum, respectively. These values are in the same order and slightly higher than those obtained by using Eriksson's equations and IEC Standards, as previously stated.

Subsequently, the flash densities for the circular areas (enclosed by the radii $0 < R < 2.5$km and $2.5 < R < 10$km) are determined. From Table 2, the flash densities (flashes per square kilometer per year) are found to be 2.71 and 3.05 in the vicinity of BT and HT, respectively. The flash density values for the area far from the towers are 1.28 and 1.55 for BT and HT, respectively. Table 3 presents a similar set of results to Table 2 for the season of June 2002 to June 2003. These values of flash density are considered to be uniform within the respective areas respective for which they are determined. These results suggest that the flash density in the vicinity of the tower is twice that far away from the tower.

5.2 The effect of structure height to direct strikes from LPATS

The number of direct strikes observed by the technical staff from the BT and HT is actually much higher than those obtained from LPATS and from Erickson's equations. The values for direct strikes from LPATS and Eriksson's equations were obtained without considering the effect of equivalent height of the respective towers, which plays a very important role in the incidence of lightning strikes to the towers. Though Erickson's equations have been largely used for heights in the range of 20 to 500m, assuming an "equivalent or effective height" of 400m for both the BT and HT will help determine the number of direct strikes that both towers are likely to experience. This seems reasonable when considering that both towers are situated on elevated or hilly areas in comparison to the surrounding areas. Using Eriksson's equations [17], the value of predicted direct strikes to the towers is 142, which is in the order of the actual direct strikes observed to the towers.

5.3 Mean Current Distribution

All strokes experienced by the tower consist of both the first and subsequent strokes, for both polarities. Current data considers the effects of both types of strokes on the mean current on both the BT and HT, though there is higher incidence of negative flashes compared to positive flashes.

In order to determine the trend of the median current with change in distance, the values of the mean current were determined for each area around the towers, as defined by the radii of $0 < R < 2.5$ km and $2.5 < R < 10$ km, respectively. The tables below, Table 4 and 5, show the

mean current distribution in the vicinity of the towers and far from the towers.

Table 4: Mean Current Distribution: June 2001 to May 2002

	BRIXTON TOWER	**HILLBROW TOWER**
MEAN CURRENT 0 < R < 2.5	**-22kA**	**-21kA**
MEAN CURRENT 2.5 < R < 10	**-27kA**	**-26kA**
MAX URRENT STROKE	**-243kA**	**-175kA**
MIN CURRENT STROKE	**+5kA**	**-4kA**

Table 5: Mean Current Distribution: June 2002 to June 2003

	BRIXTON TOWER	**HILLBROW TOWER**
MEAN CURRENT 0 < R < 2.5	**-26kA**	**-22kA**
MEAN CURRENT 2.5 < R < 10	**-23kA**	**-25kA**
MAX URRENT STROKE	**-243kA**	**-175kA**
MIN CURRENT STROKE	**+5kA**	**-4kA**

- From the tables, it can be deduced that both towers seem7s to have similar patterns of current distribution throughout the entire seasons of June 2001 to May 2002 and June 2002 to June 2003. The mean current values are of the same order for both towers.
- Both tables above do indicate that there are slight differences in the mean current in the vicinity of the tower and away from the tower.
- From the above tables, it is observed that there is an apparent decrease in the median current (of all flashes) from the vicinity of the tower to away from the tower, though Table 5 shows a slight deviance (for the Hillbrow Tower) from the general results obtained.
- From Table 4, the value of the mean current in the vicinity of the towers is in the order of –20kA and the value of the mean current far from the towers is in the order of –25kA to about 30kA.

Further analysis of current distribution can be achieved by separately comparing the first and subsequent strokes on both towers and that is outside the scope of this paper.

6. Discussion

- LPATS data seems to indicate that there is a significant increase in ground flash density in the vicinity of the towers. This confirms the triggering effect of tall structures due to upward flashes
- The increased contribution of upward flashes to the total incidence of flashes in tall structures further leads to a decrease in measured current amplitudes (for all flashes) with increasing structure height.
- The observation of mean current values in the order of -20kA seems to consolidate that notion.
- The adoption, by Uman et al [10], of median peak current amplitude of the order of -40kA for flashes to flat country seems plausible.
- The high multiplicity of flashes to tall structures in the vicinity of the structure suggests that a relatively small electric field would be required (as compared to ground) to initiate an upward leader from the top of the

structure and hence a high incidence of upward leaders from tall structures.

7. Conclusion

- The evaluation of the ground flash density in the vicinity of the Brixton and Hillbrow Towers shows a significant increase to the local flash density, which confirms the triggering effect of tall structures

- It further confirms that careful analysis of LPATS data can lead to meaningful results being obtained and that LPATS can be used as a tool to assist in better understanding the effects of lightning on tall structures.

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9. References

[1] Ngqungqa S.H., Jandrell I.R., Britten A.C. : "A preliminary review of the influence of height on the incidence of upward leaders from tall structures", SAUPEC, University of the Pretoria, Pretoria, 2003

[2] Ngqungqa S.H., Jandrell I.R., Britten A.C. : "A review of the influence of height on the incidence of upward leaders from tall structures: Some preliminary results", SAUPEC, University of Stellenbosch, Stellenbosch, 2004

[3] SABS IEC 61024-1-1 (1993): "The Protection of structures against Lightning: Part 1: General Principles: Section 1: Guide A – Selection of Protection Levels for lightning protection systems", IEC, 1993

[4] Kuffel, E., Zaengl, W.S., Kuffel, J.: "High Voltage Engineering", Butterworth-Heinemann, 2000

[5] Lewis, W. W.: "The Protection of Transmission Lines against Lightning", G. E. Series, 1950

[6] Marshall, J. L.: "Lightning Protection", John Wiley & Sons, 1973

[7] Anderson, R.B., Eriksson, A.J., Kroninger, H.: "Lightning and tall structures – some preliminary observations", 4th Int. Conf on Gas Discharges, IEE Conf Publications No 143, September 1976

[8] Eriksson, A.J.: "Lightning and tall structures", Trans. SAIEE, Volume 69, Pt 8, pp238 - 252, August 1978

[9] Malan, D.J.: "The Physics of Lightning", University of the Witwatersrand, Johannesburg, 1963

[10] Uman, M.A., McLain, D.K., Fischer, R.J., and Krider, E.P.: " Currents in Florida lightning return strokes", J Geophysics Res, Vol 78, No. 18, pp. 3 530 – 3 537, June 1973

[11] Geldenhuys, H.J., Eriksson, A.J., Bourn, G.W.: "Fifteen Years' Data of Lightning Current Measurements on a 60m Mast", Trans. SAIEE, pp. 98 – 103, September 1989

[12] Eriksson, A.J.: "Reply to Discussion on paper "Lightning and tall structures"", Trans. SAIEE, Volume 70, No. 5, May 1979

[13] Rachidi, F., Janischewskyj, W., Hussein, A.M., Nucci, C.A., Guerrieri, S., Chang, J.S.: "Electromagnetic fields radiated by lightning return strokes to high towers", ICLP, pp 23 – 28, September 1998

[14] Diendorfer, G., Schulz, W.: "Lightning incidence to elevated objects on mountains", 24th ICLP, pp 173–175, Sept. 1998

[15] Redelinghuys, M.G.: "Consideration of the optimization of Transmission Lines using data from a Lightning Position and Tracking System (LPATS)", School of Electrical and Information Engineering, University of the Witwatersrand, Johannesburg, 1996

[16] LPATS, Eskom Transmission Centre, Simmerpan, Germiston, Johannesburg, 2003

[17] Eriksson, A.J.: "The incidence of lightning strikes to power lines", IEEE Trans. On Power Delivery, Vol. PWRD-2, No. 3, July 1987

[18] Jandrell, I.R., Van Coller, J.M., Nixon, K.J.: "Earthing and Lightning Protection", Revision 1.0, University of Witwatersrand, Johannesburg, 2002

ABSTRACT

The primary objective of this research work was to review current and previous data regarding the influence of height on the incidence of upward lightning on tall structures around the world. The research involved the reviewing of available data, field measurements and laboratory experiments as well as evaluating data obtained from the Lightning Positioning and Tracking System (LPATS) regarding the Brixton and Hillbrow Towers in Johannesburg. The evidence obtained so far suggests that there is a significant increase in the incidence of upward leaders from tall structures with increase in structure height. This increase seems to be significant for structures over 100m and above. The data suggests that structures having heights below 100m will not normally experience upward flashes. Hence the occurrence of upward leaders for structures in the range of 10 to 60m is relatively very small. Furthermore, a structure's geometry has been observed to have the ability to modify the electric field intensity in the vicinity of the structure. The evaluation of the ground flash density in the vicinity of the Brixton and Hillbrow Towers shows a significant increase to the local flash density, which seems to suggests the triggering effect of tall structures. This further confirms that careful analysis of LPATS data can lead to meaningful results being obtained and that LPATS can be used as a tool to assist in better understanding the effects of lightning on tall structures. However, more research is required to correlate LPATS data with strikes to local tall structures of varying slenderness ratios as well as determine the saturation effect with increasing structure height.

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"...that I may know Him..."

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1. INTRODUCTION

Engineers and scientists have done a great deal of work to build an adequate knowledge base of the engineering parameters of the lightning ground flash. These parameters are imperative to an electrical engineer concerned with lightning protection problems, whether these relate to power transmission, distribution systems, telecommunication installations or buildings or structures. The most important of these parameters are the peak current amplitude (including its probability of distribution) and the characteristics of the current waveform, an understanding of which forms the basis for lightning protection.

The primary objective of this research was to review and evaluate available data used to determine the number of times a tall structure will be subjected to lightning strokes. That includes, among other things, a consideration of the general questions relating lightning and tall structures – with a specific consideration of the possible influence of tall structures on the frequency and amplitude distributions of lightning currents on such structures. However, specific emphasis is placed on the initiation of positive upward flashes from tall structures.

This research began by focusing on the physics of lightning which is fundamental in the understanding of the lightning phenomenon. Furthermore, the understanding of the lightning current waveform is a key element in understanding the flow of charge and its measurement from a lightning strike. A brief overview of the standards is meant to highlight a general exclusion of the tall structures from the regulated environment of electrical protection of structures. The initiation of upward lightning from tall structures is also compared to the initiation of downward lightning from the clouds to ground. This is achieved by reviewing data from the CSIR research mast and data from around the world. Furthermore, data from the Lightning Position and Tracking System (LPATS) is used to determine the influence of tall structures on the initiation of upward lightning from such structures.

2. THE PHYSICS OF LIGHTNING

The physics of lightning forms the basis for the understanding of the lightning phenomenon. Several theories have been advanced to explain the accumulation and discharge of electrostatic charge or static electricity in clouds. Among the best known are Simpson's breaking-drop theory, the Elster and Geitel influence theory as well as Wilson's ionization theory [1]. Franklin made the first experiments of major contribution towards the understanding of lightning in the middle of the eighteenth century. Wilson, of cloud-chamber fame, can be regarded as the father of contemporary thinking about the physical mechanisms of lightning [2]. The arrival of high-speed photography, the oscilloscope and radar has enabled much research and progress towards the knowledge and understanding of lightning. In addition to making measurements from ground (sometimes from the top of mountains) more recently, satellites have been employed by scientists, engineers and meteorologists to further studies involving lightning and its effects.

Broadly speaking, it is generally accepted that the accumulation of electricity in the clouds takes place in the presence of ionized air, moisture in the atmosphere and upward air currents [1]. It has been observed that in the upper regions of the cloud or in the Antarctic the impact of ice may produce a separation of electricity in a manner similar to that which occurs by the breaking of raindrops. Another generally accepted notion is that electrification by the action of solar and ultraviolet rays on ice crystals in the upper regions of clouds is also a possibility [1, 2].

It is also generally observed and accepted that the lower portion of the cloud is usually predominantly negative and the upper part predominantly positive, with a region of mixed charge at a level in which the temperature lies between 0°C and -20°C [2]. Some researchers have discovered that in the tropical regions of the earth, this region of separation occurs at a much higher altitude than in the temperate regions. Some researchers believe that an important mechanism in the accumulation of charges is the transition of water to ice in certain portions of the clouds (See Appendix B for more details on the thundercloud mechanisms).

Further measurements were also conducted on discharge currents from vertical antenna. Discharge currents (cloud-field currents) from a vertical antenna have been recorded up to approximately 500 microamperes [1]. Potential gradients at the earth's surface due to storm clouds have been recorded up to approximately 300kV per meter, as compared to the potential gradient due to the normal earth field, of the order of 100V per meter.

Fundamentally, lightning is considered to be a manifestation of a very large electric discharge and spark [3]. Typically, the negative discharge center of the

thundercloud may be located anywhere between 500m and 10 000m above ground. Lightning discharges to earth are usually initiated at the tip of a negative center [3]. Lightning manifests itself in various forms, namely:

- Flash to ground
- Cloud to cloud flash
- Ball lightning and
- Hot lightning

Only the most usual and common form of the discharge from cloud to ground will be considered in this report, i.e. flash to ground type and ground to cloud type of lightning.

2.1 The Global Electrical System

According to Marshall, a widely accepted view of the global electrical system is that the earth and the lower ionosphere are two highly conductive surfaces separated by an imperfect insulating atmosphere [2]. Furthermore, for comparative purposes, Marshall uses the analogy of a large condenser with some leakage. Observations show that, over fair-weather areas, there is a downward transfer of positive charge, which tends to reduce the positive potential of the ionosphere and to neutralize the negative charge on the earth.

Also, within the global electrical system, lightning discharges transfer positive charge upward at a rate sufficient to sustain a balanced dynamic system. That is, the regular current flow between the positively charged ionosphere and the negatively charged earth is controlled and maintained by global thunderstorm activity. It has been observed that the values of steady fair weather potential gradient and air-earth current closely follow the thunderstorm diurnal variation curve [2], as depicted by Marshall (see Appendix A for details).

It has also been recorded that solar flares (i.e. unsteady shine, flicker flashes or burns) produce increases in the steady electrical field and current flow between the ionosphere and earth. Accordingly, increased lightning discharges can be expected after such solar outbursts [2]. However, these are not common occurrences, particularly in southern Africa. The ionosphere is the layer within the height range of 50 to 75 km above the surface of the earth. Observations show that over the earth's surface, as many as two thousand thunderstorms are continually in existence [2]. According to measurements, active thunderstorms discharge (by lightning) at an average rate of about 20 Coulombs every 10 seconds, which is equivalent to approximately to 2A of steady current [2]. Furthermore, as the average global air-earth current is in the order of 1500A, this would indicate the existence of 700 to 800 active thunderstorms (and even more if minor storms are included). The steady electrical field is about 3V/cm near ground level under fair-

weather conditions. Marshall noted that during thunderstorm development, the electrical field can rise to 500 or 600V/cm beneath the thunderstorm and to much higher values near level or below a stepped leader. The total steady potential between ionosphere and earth is estimated at 300kV. From this and the total steady current of about 1500A, the resistance of the atmosphere is estimated to be 200Ω.

2.2 The Thundercloud

The existence of the lightning phenomenon brings into focus the physical understanding of the thunderstorm cloud. Generally, the thunderstorm cloud maybe regarded as a charge-separation mechanism or an electric generator satisfying the "need" of the global system. This notion stems from the general finding that thunderstorms generate charges (lightning flashes) that help "regulate" the global electrical system (For a more detailed understanding of the thunderstorm characteristics, see Appendix B).

There are four major theories that are generally accepted and used to explain the principal processes of thundercloud electrification. The table below, Table 1, gives a summary and validity of such theories [4].

Table 1: Nature of Lightning Processes

Description/ Reference	Process	Assessment/Validity
Selective ion capture; Wilson	Natural radiation ionizes air molecules. Earth's electric field induces charge separation within raindrop. Underside of droplet captures negative ions. Upwardly moving air current sweeps positive ions past water droplet.	Explains polarity of cloud; also of sign and magnitude of charge on rain. Process occurs too slowly to account for most of charge in a mature cell.
Frictional Impact; Simpson and Scrase	Collisions of ice particles leave ice negatively charged and air molecules positively charged.	Based on charge/ice correlations in clouds. Little experimental data.
Freezing of aqueous solutions; Reynold's et al	Potential difference develops at a liquid-solid boundary. Glazed hailstone with adhering water makes a collision. Dislodged water carries away positive	Experimentally verified for natural rain. However, hard hail is not always produced.

	charge.	
Temperature gradients in ice; Latham and Mason	Concentration of H^+ and OH^- ions decreases rapidly with falling temperature. Because mobility varies with type of ion, separation of charges occurs. Ice ruptures before thermal equilibrium becomes established.	Charge separation has been verified. Calculations show that this process can produce the quantity of charge found in mature thundercloud.

The counter-flow of air in the developing thundercloud carries a positive charge upward and a negative charge downward. This positioning of the charges is sometimes referred to as bipolar or dipole charge [2]. In addition to the main charge centers, negative in the lower parts of the thundercloud and positive in the upper parts of the cloud, pockets of opposite charge accumulate below the lower main charge center and above the upper charge center. That is, a negative layer of charge gathers at the top of the cloud and a positive one at the base.

A normal thundercloud will comprise several "cells" or dipoles of charge. The whole cloud may have lateral dimensions of several kilometers. Recently, sufficient evidence, obtained by meteorologists, strongly indicates that the base of a cloud may be 1 or 2 kilometers above ground and its top 10 to 14 kilometers above ground.

2.3 Lightning Flash

The lightning discharge to ground has a tree-like structure, thereby leading to the term "branch" in much of its description. To simplify the description of the lightning discharge to ground, only those terms that have common usage over the whole field of gas discharges have been used quite extensively.

The word "flash" means a sudden burst of flame or light [4]. The public of most countries, especially those in the tropics, has seen numerous examples of the lightning flash. Through photographic and satellite observations, engineers and scientists have obtained information that enables this short-lived event to be subdivided as follows:

a) Initial discharge
b) Mature Stage
c) The Leader
d) Return Strokes

The completely conducting discharge from cloud-to-ground (main discharge) is often referred to as a stroke. The flash comprises mechanisms that occur in a common ionized channel.

2.3.1 Initial discharge

Observations, based on electromagnetic radiation and electrostatics, show that discharges occur within the cloud for an appreciable time (i.e. 100ms) before the stepped leader is seen [4]. Even though there is some uncertainty about their exact location, there is sufficient evidence to prove that such discharges do exist.

2.3.2 Mature Stage

As the charge separation proceeds in the cloud cell, the potential difference between the concentrations of charge increases and the potential drop across any vertical unit distance of the charged mass similarly increases. After an appreciable while (20 min or so) of the charge generation process, the cloud will have reached a mature stage, charged to a point where a discharge will be initiated [3].

2.3.3 The Leader

There are several varieties of lightning discharge and of these, the dominant cloud-to-earth type is the most dominant in terms of frequency of occurrence. The channel to earth is first established by a stepped discharge called a leader or leader stroke. The initiation of the leader might be due to the downward movement of negative charge outside an up-drift in the core.

2.3.4 Return Stroke

It is the return stroke that has destructive effects and therefore arouses our concern about protection. It can be regarded as an intense positive current from ground or as the lowering of negative charge to ground [2]. Its purpose is to neutralize the opposite charges between cloud and earth. After the first return stroke, it is usual for another region of the cloud to provide sufficient charge for a second stroke or several more, separated by intervals of 10 to 20msec. This return discharge of one stroke or succession of strokes is called a flash.

2.3.5 The Dart Leader

After the first return stroke, there is usually enough charge in the higher region of the cloud to initiate another leader. Usually this leader follows the path taken by the previous stroke. Owing to the remnant ionization of the path, the leader darts to earth directly in about 1ms. Hence, it is called a dart leader. The interval between

the first return stroke and the dart leader is about 70ms, on average [2] and thereafter successive dart leaders and their return strokes may recur at 40 to 50ms intervals. Three or four return strokes along the same path are common. There are as many as ten return strokes in about 10% of lightning flashes [2]. If a dart leader is too long delayed, due probably to the slowness of charge build-up in the cloud, the path ionization diminishes and the next leader will "step" its way downward, but at a higher velocity and with shorter steps than the original stepped leader.

Whereas the velocity of the stepped leader is in the range of 0.01 to 0.7% of the velocity of light, the dart leader's velocity is between 0.13 and 10% of the speed of light [2]. For more details on the lightning flash (see Appendix C).

2.4 Analogy with Spark Breakdown in Air

There are similarities between the processes of an electrical spark across an air gap to that of a cloud-to-ground lightning discharge. The characteristics of the air-gap breakdown are helpful in explaining the lightning discharge [2, 5]. When a sufficiently high voltage is applied across a volume of insulating gas (such as reasonably dry air), the gas breaks down and electrons are released. Above a certain voltage an ionization wave, called a streamer, proceeds from the highly stressed positive electrode towards the cathode, branching out along the way and extending into the gas where the electrical field stress is relatively less. If the applied voltage is high enough, the vigorous streamer or streamers reach the cathode with a high potential wave front. As the wave front reaches the cathode, the temporary local electrical field stimulates the electron emission and the negative streamers from the cathode are produced. These negative streamers greatly increase the density of ionization in the channel, which yields a "backstroke" or discharge across the gas from cathode to anode [2, 3]. For longer gas paths or air gaps, the streamers from the anode might be incapable of reaching the cathode. In this case, a number of secondary channels will develop at the anode and proceed toward the cathode. The resulting increased ionization of the gas can become dense enough to produce breakdown of the gap and a spark discharge.

2.5 Negative Downward Lightning

From observations and measurements, the majority of lightning strokes terminating on low structures on the ground are of the negative downward type [6, 7]. The structures that are less than 60m in height are considered to be low or common structures, according to the standards [8, 9, 10, 11, 12].

In this case, a channel of negative charge propagates from a negative charge region in the thundercloud towards the positively charged ground.

There are four types of cloud-to-ground lightning discharges that can occur [7], namely:

1. Negative downward
2. Positive downward
3. Positive upward
4. Negative upward

See Appendix E for the pictorial representation of the cloud-to-ground lightning.

Jandrell et al depict the most usual and common form of the discharge from cloud to ground (negative downward) as shown below:

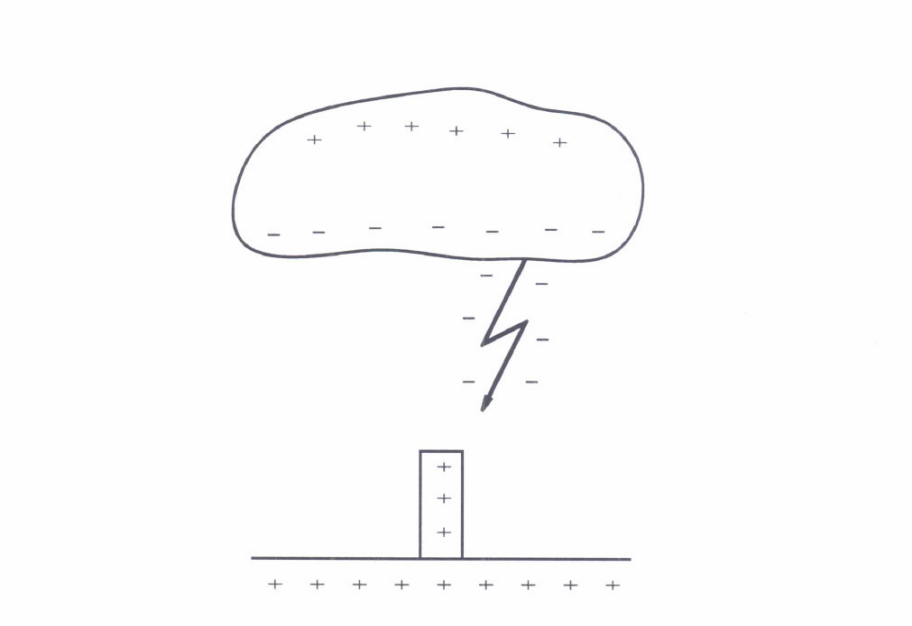


Figure 1: Negative downward lightning [7]

It's been observed and measured that lightning strokes from cloud to ground account for about 10% of lightning discharges [7]. Over 90% of the cloud to ground flashes are negatively charged, at low altitudes [13]. The majority of discharges during thunderstorms take place between clouds. Discharges within clouds often provide general illumination.

2.6 The Final Stage

For the rationale of lightning protection system design, it is crucial to understand what happens in the final stages of lightning transmission in determining the final point of strike on the earth's surface. The objective of the protection system is to

ensure that lightning terminates on a lightning rod or similar structure to ground rather than on some more sensitive part of the building or structure.

The final stage of lightning involves the initiation from a lightning rod or similar structure on the ground of a positively charged channel that spreads upwards (the upward leader) and finally intercepts the downward propagating negatively charged channel (the downward or stepped leader).

For the interception of the two leaders to occur, certain criteria must be met with regards to the relative velocities of their leader tips. The relative velocities of the two leader tips depend on the magnitude of the linear charge density along the stepped leader (in Coulombs per meter leader length), which in turn is related to the peak lightning current [7]. Thus upward leaders initiated from a structure are able to intercept downward leaders in the vicinity of the structure and hence result in the lightning stroke terminating on the structure, thereby increasing the incidence of lightning strikes to the structure (See Appendix E).

From the standards, the ability of a structure to attract adjacent downward leaders is described in terms of the attractive radius or attractive area of the structure [7, 8-12]. According to Jandrell et al, after the interception of the downward leader by the upward leader, an ionized channel of high conductivity is established between the cloud and the ground through which charge equalization between the channel charge and the ground occurs [7]. This charge equalization involves the flow of current down the lightning channel through the structure and into the ground (as depicted by Jandrell) as shown by figure below:

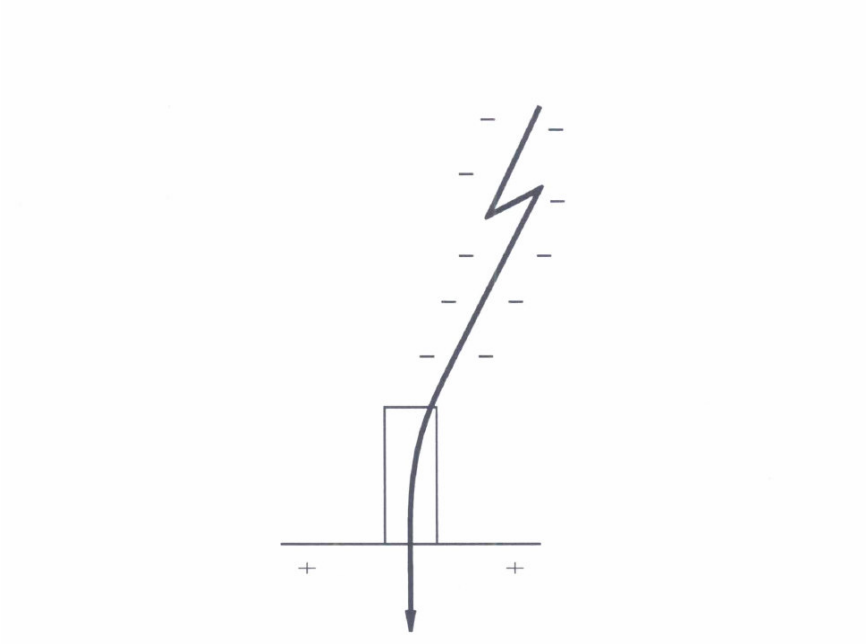


Figure 2: Lightning termination on a structure [7]

3. THE LIGHTNING CURRENT WAVEFORM

It has been established that the lightning current is a function of or proportional to the magnitude of the linear charge density along the stepped leader (in Coulombs per meter leader length) [7]. Hence, a basic understanding of the lightning current waveform is essential for understanding the flow of charge and its measurement from a lightning strike. The flow of charge during a lightning stroke is best described in terms of the associated current magnitude, by defining a suitable current waveform that closely approximates the actual lightning current.

For illustrative purposes, a wide variety of lightning current waveforms actually measured is approximated by a unipolar waveform known as the double exponential waveform, according to the standards [8-12] (see Appendix D).

There are three main criteria used in defining the lightning waveform, namely:

- The Peak current amplitude
- The rate of rise
- The time taken to reach crest and the time taken to reach half life.

3.1 The Peak Lightning Current

A lightning flash generally consists of a number of individual current surges (strokes) of similar form or shape, [7, 8-12, 13]. The first stroke within a flash usually has the largest peak current (typically three times that of subsequent strokes). Consequently, when describing the peak current of a flash we usually imply that of the first stroke.

Due to the large variance in magnitude of the peak lightning currents, a probability factor is used to define peak currents, i.e. the probability of the peak current exceeding a particular value [7, 8-12]. According to SABS IEC 61024-1-1 (1993), assuming lognormal distributions based on years of collecting statistical data and measurements, the important values are:

- 98% of first strokes have peak currents larger than 4kA
- 80% of the first strokes have a peak current exceeding 20kA
- The probability of first stroke peak currents exceeding 90kA is 5%
- Interestingly, there is a 5% probability that the peak current of a positive stroke will exceed 250kA

The figure below is a graphical representation of the above-mentioned values:

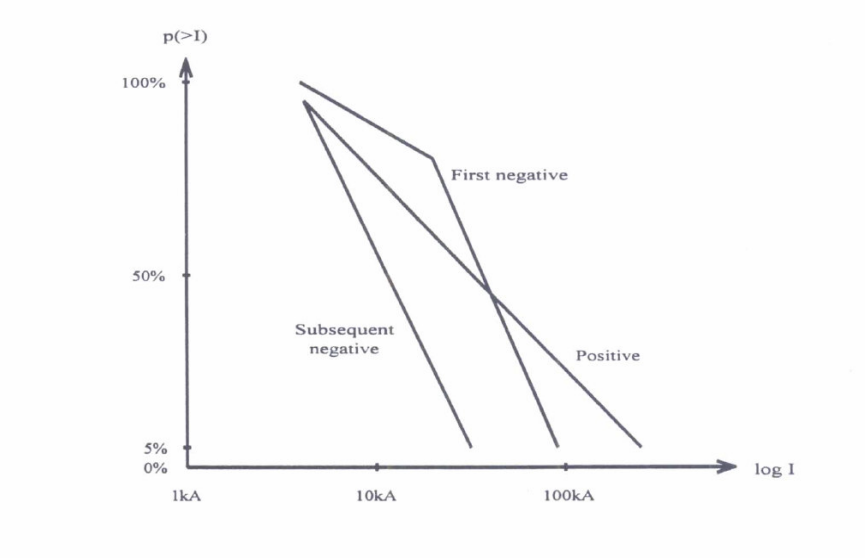


Figure 3: Cumulative Frequency of Current [9]

For a common structure, the value of the peak current is important for calculating the attractive radius of a structure, the volt drops across resistive components of lightning protection systems and for calculating induced voltages due to adjacent lightning strikes

3.2 The rate of rise of the Lightning Current

Subsequent strokes within a lightning flash usually exhibit higher rates of rise of current. However, since their peak values are lower, the rate of rise of the first stroke is generally more important. Therefore by rate of rise of lightning current, reference is made to the first stroke of the flash [7, 8-12].

Once again, the rate of rise of the lightning current has a large scatter and is described in terms of a probability factor, i.e. the probability of the rate of rise of lightning current, di/dt, exceeding a particular value. See Appendix D for more details.

Thus the probability of the maximum rate of rise of the current of a first negative stroke exceeding 9.1 kA/μs is 95% or 95% of first strokes have a peak value of current exceeding 9.1 kA/μs.

There is some evidence that the rate of rise of current at a high tower is less than in the open country as from a high tower it is almost certain than an upward positive leader will rise, probably slowly, to meet the downward leader , whereas over flat

ground, the downward leader travels (with increased speed) almost to ground [13]. According to Allibone, the rate of rise of subsequent strokes is unlikely to be influenced by the height of the ground termination of the flash and it is this rate of rise which we should be concerned with, particularly in transmission line management [13].

The rate of rise of the current is important when calculating volt drops across inductive components of lightning protection systems and for calculating induced voltages due to adjacent lightning strikes.

3.3 The duration of the lightning current waveform

The lightning current waveform is described in terms of the time to crest and the time to half value, so that a 10/350μs waveform has a time to crest of 10μs and a time to half value of 350μs.

For negative downward strokes, typical current waveforms are:

- First stroke: 5.5/75 μs
- Subsequent strokes: 1.1/32 μs

From SABS IEC 61024-1-1 (1993), the values for the time to crest and the time to half life values are given, as shown in Appendix D.

3.4 The Direction taken by a flash

The effect of nearby conductors and buildings, towers, etc., on the direction taken by a flash to ground towards the end of its journey is of great importance. If there is any tendency to "attract", then the number of flashes per annum to a building of specified area will exceed the number of flashes to be expected over that area of open country [13].

There are many records of lightning flashes striking remarkably near to towers. However, very little photographic evidence is available from which velocities of the leader can be measured [13]. The Brixton TV Tower (± 250m) or the Moscow TV Tower (537m) might be expected to behave like the Empire State Building, discharging up to approaching clouds. Over a period of seven years [13], 75 leaders did rise up from the top of the tower (Moscow Tower) but 14 strokes descended to ground within a radius of 500m and one struck the ground only 125m from the base. Seven strokes struck the side of the mast at distances from 5 to 215m below the top. Photographic evidence has shown that these flashes have

arrived along almost horizontal paths and had thus probably come from cloud centers displaced from the tower axis [13].

According to Allibone, similar observations have been made in the laboratory, by applying a million-volt impulse to a rod/rod-on-plane gap consisting of a "tower" of height H and a small protuberance of height H/10 both standing on the plane with the tower adjusted sideways so that, with minimum impulses applied, all sparks terminate on the tower [13, 14]. The upward and downward leaders show just where the junction has occurred. When a 20% over-voltage is applied, most sparks now terminate on the plane or on the short projection (protuberance).

To arrive at the "attractive" power of a rod, mast tower or building standing perpendicular to ground, the field-strength must be considered at the ground as the leader approaches. The higher the electrical field strength, the greater the current in the flash [13, 14].

4. LIGHTNING PROTECTION STANDARDS

For the purpose of lightning protection system design, it is important to capture what actually takes place in the final stages of lightning propagation. This is essential for determining the final point of strike or interception on the earth's surface. The primary objective of the protection system is to ensure that the lightning strike terminates on a part of the protection system connected to ground rather than on some sensitive part of the building, structure or equipment. A thorough knowledge and understanding of lightning parameters forms the basis of any protection system. Lightning parameters have been derived and formulated statistically from experiments and data that have usually been obtained from measurements taken on high towers or objects [8, 9, 10, 11, 12]. All the standards in current use are specifically designed for structures, which are less than 60m tall and considered to be common structures [8-12]. Common structures, according to SABC IEC 1024-1-1, are structures that are used for ordinary purposes, whether commercial, farming, institutional or residential. That is, structures higher than 60m are not considered. Another type of structures covered by the standards is the special structures, which are divided into four categories, namely:

1. Structures with confined danger
2. Structures dangerous to their surroundings
3. Structures dangerous to social and physical environments
4. Miscellaneous structures

Future standards are envisaged to provide additional information on lightning protection for non-common (miscellaneous) structures, such as:

- Tall structures
- Tents, camping sites and sports fields
- Temporary installations
- Structures under construction

Consequently, lightning protection for tall structures and buildings is not regulated by the current available standards. However, a lightning protection system of special design might be considered for these structures. Essentially, these require special attention in order to adequately protect them, including people and equipment which may be used in such structures.

5. BACKGROUND: UPWARD LIGHTNING

A lot of research has been performed on tall structures around the world. A great deal of the work about upward lightning was performed (through experimental investigations) by Berger, who recorded the lightning currents for nearly 30 years at a tower on the Monte San Salvatore near Lugano, in Switzerland [15, 16]. Positive lightning currents were also measured in Italy [17], Czechoslovakia [18], and Japan [19, 20]. The observations of positive flashes in winter thunderstorms in Japan showed the highest current amplitudes and charges. However, winter lightning on the sea coast of Japan was found to have some unusual characteristics [21]. From the electric field observations, it was shown that the ratio of the positive lightning is much higher than that of summer. At the same time, transmission line due to the winter lightning were unpredictable by means of conventional theories [21]. Also, observations of upward lightning from tall structures, closely associated with winter lightning, were made [22].

In the past, the electric fields of positive flashes were recorded in many countries [16, 22]. Nevertheless, the electric field characteristics of positive flashes are less well-known as compared to negative lightning flashes. A laboratory experiment by Orlov et al affirms a general understanding that the upward leader would occur nearest to the tip of the highly charged cloud above it [23]. Implicitly, that means positive upward leaders would be ejected from the structure if and when the field is sufficient enough to do so. Heidler et al recorded the electric fields of very near positive flashes in the distance range up to some kilometers from 1995 to 1997 [16]. The average distance was about 4km. The electric fields of positive lightning were measured in near thunderstorms over Munich. It was found that the positive strokes are typically succeeded by continuing currents lasting either less than 10ms or longer than 20ms [16]. Normally, the positive flashes had only one return stroke. Nevertheless, several multiple positive flashes were measured, showing one subsequent return stroke after a typical time interval of 100ms. The charge of the positive strokes was estimated from the electrostatic field change due to the total lightning discharge. A maximal charge of about 100C seems to be a realistic upper limit for the impulse currents of positive lightning.

5.1 Variations of the Leader and Stroke

From mountain peaks or very tall structures, such as the Empire State Building, a positive leader channel may start from the peak due to the intense concentration of positive charge accumulated there, forced by the strong electrical field. When this leader reaches the cloud, the charge there remains diffuse in the volume of water

droplets, with the result that there is no sudden increase in current but a comparatively gradual current flow of modest amplitude. However, any subsequent strokes return to the common pattern of a down-going dart leader and a high current return stroke. The positive leader carries a heavier current than a negative leader (up to 250kA) [9]. See Appendix D, for comparison purposes.

Occasionally there is a lightning stroke between a positively charged cloud and ground. For this kind of stroke, there can be an upward negatively charged leader followed by a positive current stroke from the cloud or a downward positively charged leader followed by an upward negative current stroke.

Positive leaders advance without stepping in most cases and at a higher velocity than negative leaders [2]. In negative ground-to-cloud strokes, the leader also advances upwardly in steps. The junction point with a positive streamer from the cloud occurs at a considerable height above ground. At high ground altitude, the junction has been observed at 1000 to 1800 m above a tower struck by lightning.

6. LIGHTNING INCIDENCE TO TALL STRUCTURES - FIELD MEASUREMENTS

6.1 Results from the CSIR Research Mast

In 1972, the Council for Scientific and Industrial Research (CSIR), initiated a research programme to study, mainly, the direct measurement of parameters of the lightning discharge that are of prime importance to electrical engineers [24]. The CSIR research programme included the following aspects:

c) Direct measurement of the current waveform characteristics of strokes during flashes to structures – including current amplitudes, maximum rates of rise, polarity, charge transfer, etc. This involved the development of indirect techniques for such measurements and includes a study of the features of the high-speed electric field changes associated with ground flashes.

d) A study of the striking process during discharges to structures and the influence of structures upon this process. An essential feature of this aspect is the study and measurement of lightning strike distance and lightning peak current amplitude.

The automated station was situated on the CSIR campus, about 10km east of Pretoria. The station comprised a 60m mast and two adjacent huts that housed the associated automatic power supply and instrumentations systems. The station was located upon a ridge about 80m higher than the surrounding terrain, situated at an altitude of about 1400m above sea level. The mast was of triangular aluminium lattice sections raised upon insulators at the base and supported by fully insulating stays. In the event of a lightning flash, this design would confine lightning current to the body of the mast itself and allow the current to be measured at the base of the mast during its passage across the insulated base section into the earth. The main objective was to obtain data involving the more common downward discharge, rather than the upward flash [24].

Eriksson presented the first preliminary data in 1977 [24]. A total of 25 flashes occurred in the intervening five lightning seasons, giving a mean annual incidence of five flashes per year. Of these 25 flashes, 36% occurred in the month of November, the monthly flash incidence for the remaining seven months of the season being 9%.

Table 2: Flashes recorded on the CSIR Research Mast

Total number of flashes recorded (1972 – 1977)	**25**
Mean number of flashes per year	5
Number of flashes on which current measurements were obtained	15
Total number of strokes recorded during the measured flashes	22
Incidence of observed downward flashes	52%
Incidence of observed upward flashes	20%
Observed ratio of downward/upward flashes	2,6:1
Observed incidence of negative flashes	60%
Observed incidence of positive flashes	0
Median Current for first negative downward strokes	41kA
Median Current for all negative flashes	25kA

The data indicates that just more than half of flashes to the mast have been of negative polarity (about 52%) and have progressed in the downward direction. The influence of the mast as far as distortion or intensification of the electrostatic field is concerned, is not so extreme as to result in high incidence of the so-called "unnatural" upward flashes. Also, the data shows that, current measurements were made on a total of 15 flashes. Of the 15 flashes, 11 correspond to a downward direction of progression. Based on the common practice to approximate current amplitude distributions by the lognormal distribution [25], Eriksson obtained a median current amplitude of 41kA.

The data obtained after fifteen years of running the CSIR research mast is very comparable and similar to that first obtained in the first five years of running the mast [26]. The table below, Table 3, indicates that for a 60m mast, the lightning incidence on the structure is still largely of downward type [26], which agrees with Eriksson's findings [24]. Furthermore, by assuming log-normal distribution of the measured data, a peak current amplitude of 33kA is obtained (which is comparable to Cigre's 30kA) for downward flashes [26].

Table 3: CSIR Research Mast data after 15 years

Total number of flashes recorded	**66**
Mean number of flashes per year	4.33
Total number of downward flashes	29
Total number of upward flashes	21
Ratio of downward/upward flashes	1.38:1
Annual mean flash density	6.4

6.2 Relative Incidence of Upward and Downward Flashes on Elevated Structures

Eriksson produced the following table regarding the relative incidence of upward flashes from tall structures [24] in order to determine the annual incidence of flashes to tall structures, as can be seen in Table 4, below:

Table 4: The relative incidence of upward flashes from tall structures [24]

Source	**Structure Height in m**	**Relative frequency of occurrence of upward flashes**
Pierce	150	23%
	200	50%
	300	80%
	400	91%
McCann	110	8%
	180	24%
	400	96%
Berger	350	84%
Gorin	540	92%
Garbagnati	500	98%

The figure below, Figure 4, was obtained by plotting the results obtained in Table 4, above:

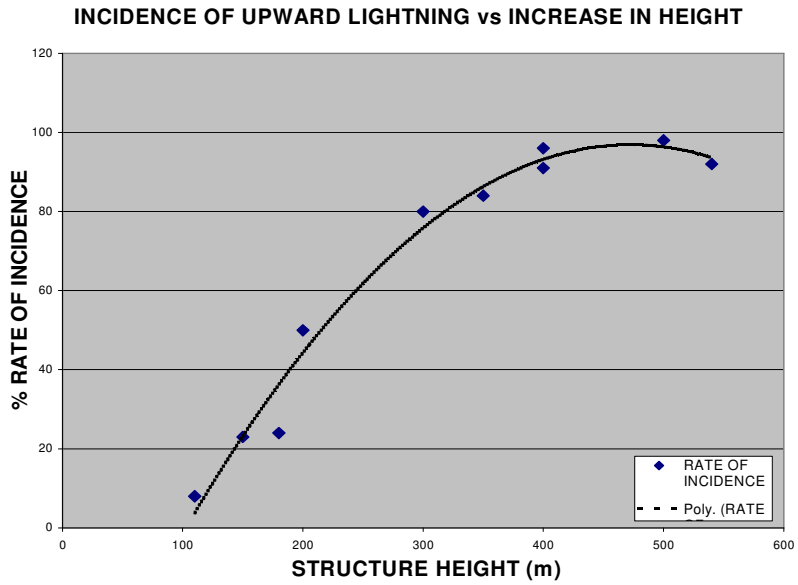


Figure 4: Frequency of incidence of upward lightning vs. Height

- The data suggests that structures having heights below 100m will not normally experience upward flashes. Similarly, structures having heights greater than and/or equal to 400m will always display upward flashes. However, it is not strictly correct to compare using the height alone.
- It would seem, from the available data, that there is a critical height beyond which the incidence of upward flashes from tall structures would tend to saturate and begin to decrease. That height is in the range of 500 to 600m, even though more data may be required to verify that range more accurately.
- From Figure 4, the data indicates that, for structures in excess of 500m, will tend to experience an apparent saturation in the incidence of upward flashes.
- The table below, Table 5, is based on Stringfellow's review and analysis of Eriksson's data, as presented in [24]. Stringfellow's data is an improvement on Eriksson's data which was based on the normalization based on keraunic values instead of the more reliable ground flash density [27]:

Table 5: Incidence of flashes on tall structures [27]

Source	N_g Derived annual regional ground flash density per km^2	Structure height in m	Annual frequency of recorded flashes	Annual frequency of flashes normalized to N_g = 1,0
Popolansky	0,76	25	0,08	0,11
		35	0,07	0,09
		45	0,08	0,11
		55	0,10	0,13
		65	0,13	0,16
		75	0,15	0,20
		85	0,18	0,24
		95	0,17	0,22
		115	0,28	0,36
		540	34,2	45,0
Muller-Hillebrand	0,68	28	0,05	0,08
		50	0,06	0,09
		65	0,12	0,17
		107	0,13	0,19
		107	0,75	1,10
		170	0,75	1,10
		370	8,53	12,5
Szpor et al	0,51	24	0,02	0,03
		37	0,03	0,06
		53	0,02	0,04
		80	0,13	0,26
		130	0,29	0,57
		225	1,56	3.06
Beck	3.00	24	0,19	0,06

		31	0,11	0,04
		31	0,28	0,09
		60	0,21	0,07
		60	0,49	0,16
		70	0,56	0,19
		90	0,91	0,30
		105	0,38	0,13
		110	1,81	0,60
		170	2,24	0,75
		340	37,3	12,4
McCann	3,00	400	23,8	7,93
Anderson and Jenner	5,00	20	0,15	0,03
Eriksson	7,00*	148	5,50	0,79
Berger	5,50*	350	58	10,5

- The data seems to indicate a significant increase in the annual frequency of flashes for structures in excess of 100m
- The data suggests that structures having heights below 100m will not normally experience upward flashes, while structures having heights greater than 400m will virtually always display upward flashes. There are a number of possible explanations for this phenomenon. The data also seems to indicate that there is a critical height at which the number of upward leaders tends to decrease with increase in structure height [27]. One possible explanation is that it may be due to over-saturation where the electric field cannot support any further ejection of upward leaders from the structure. Alternatively, there may be enough upward leaders to cause inter and intra cloud discharges, resulting in a drop in the electric field strength, which would mean the field intensity is not adequate enough to release upward leaders.

6.3 Structure Height – Effective Height

In general, it may be noted that in much of the discussions and papers published, the height of a structure has been adopted as a variable parameter for analysis.

Eriksson et al had suggested that this is a gross simplification since it is really the shape of the structure or a dimensional relationship that is the more important consideration [25]. In reality, the influence of a structure upon the lightning striking mechanism is determined by the degree to which the electrostatic field in the vicinity of a charged leader (or thundercloud field) is intensified by the presence of the structure. This, in turn, is a function of the shape of the structure rather than its height alone and, as has been shown in the case of tall masts or chimneys, the shape of a structure may be expressed in terms of the ratio of the height of the structure and the structure's equivalent radius, H/R , the so called "slenderness ratio" [28].

A number of previous measurement exercises around the world have not taken the latter considerations into account and one is thus compelled to consider height alone as a base parameter for comparative analysis. There may be some justification for this, in that the slenderness ratios (i.e. values of H/R) for practical structures may be of somewhat similar orders of magnitude [24]. In certain instances, however, such as structures on prominent mountains, it is necessary to introduce the concept of "effective height". The apparent elevation from the surrounding areas enhances the relative field intensification on the top of the structure in comparison to any structures in the same vicinity. For example, the research mast was 60m tall on top of a hill 80m above the surrounding area, was given an effective height of 148m [24]. The work of Anderson et al [28] indicates that in a given uniform electrostatic field, the intensification at a structure top will be enhanced by a factor of 1.6 for an increase in slenderness ratio (H/R) over the range 100 to 210 [24], when to compared to open or flat country [29].

6.4 The Effect of Structure Height on the Electric Field

The knowledge of lightning current parameters comes from either direct measurements using, for example, high towers which are instrumented or from utilizing measurements of lightning electromagnetic fields from which lightning currents are inferred by adopting some empirical or theoretical relations [30, 31, 32, 33]. Experimental observations and theoretical investigations have shown that the presence of an elevated strike object or a tall tower could affect substantially lightning currents and their radiated electromagnetic fields [30].

A better knowledge and understanding of lightning electromagnetic fields is essential for an efficient insulation design of electric power networks and telecommunication systems [34, 35, 36]. Rachidi et al performed an analysis of the electric and magnetic fields radiated by the lightning first stroke and subsequent return strokes to high towers, particularly the Toronto CN Tower, which is approximately 553m tall [30]. In the analysis, two channel-base current waveshapes, corresponding respectively to typical first and subsequent return strokes, are utilized. Using the Modified Transmission Line (MTL) model, which

was modified to take into account the presence of an elevated strike object [34], radiated electric and magnetic field waveforms were computed and analyzed. The effect of the presence of the tower on the magnitude and shape of the magnetic field was investigated.

The results obtained by Rachidi et al show that both for first and subsequent return strokes, the presence of the tower results in a significant increase in the electromagnetic field peak [30]. For the subsequent return stroke, however, the effect of the tower is much more appreciable. Also, the results show that the peak magnetic field associated with tower strokes is about two times (for the first stroke) to three times (for the subsequent stroke) as large as that corresponding to return strokes initiated at ground level [30].

Diendorfer et al presented similar results as well for the Toronto CN Tower [37, 38]. He shows that the influence of a tall structure on the lightning mechanism is caused by the increase of the electrostatic field. Also, he shows that, similar to artificially triggered lightning, tall structures tend to favour the initiation of an upward leader (ground to cloud). In many cases in a lightning channel established by an upward leader, a number of downward subsequent strokes (cloud to ground) are observed [37].

6.5 The influence of Structure Height upon Current Amplitude Distributions

Recently there has been a lot of published data relating the results of field measurements of lightning current peak current amplitudes to structure height. Popolansky presented preliminary data, based on an analysis of measurements in tall chimneys having various heights, together with data from three other field measurement programmes [24]. Together with measurements recorded with magnetic links on 120m tall radio masts in South Africa, Eriksson produced results [24], as shown in Table 6, which suggest a decreasing trend in median current amplitude with increasing height, for all flashes. However, the data does not distinguish between the upward and downward flashes.

Table 6: Current amplitude distribution vs. structure height [24]

Source	Structure height in m	Median Current Amplitude in kA for all negative flashes
Popolansky[11]	22-55	34.6
	55-65	29.7
	65-85	22.9
	85-140	16.3
Anderson[11]	20	40.0
Hagenguth et al[11]	400	10.0
Eriksson[11]	120	24.3

The available data regarding values of lightning current strikes to flat country are those presented by Uman, which indicate a median current of 37kA to open country [28, 29]. Apparently, a value of the order of 40kA for first downward strokes is indicated.

6.5.1 Results from the CN Tower

Rachidi et al considered the Toronto CN Tower as an elevated strike object characterized by a height of 553m above ground [30]. The tower is modeled as a single, uniform and lossless transmission line (model A as presented by Rusan et al [35]. However, it has been shown that for a more accurate representation of the tower, three or four transmission line sections in cascade are to be considered [39]. The reflection coefficients at the bottom and at the top of the tower are assumed to be 0.48 and – 0.5, respectively. These values have been derived analyzing the fine structure of the lightning return stroke current measured at 474m above ground level [30, 35].

Furthermore, a great deal of research work was conducted by Janischewskyj et al on the Canadian Tower in Toronto [39-45]. Janischewskyj et al show that, by using a modified transmission model, the tower gives almost as twice as large a contribution to the total magnetic field as the lightning channel itself [39]. Also, the calculated magnetic field magnitudes were found to be close to the observed values, in the order of 1.1 to 1.16, respectively. This further affirms the enhancing effect of the tower on the field in the vicinity of the tower itself.

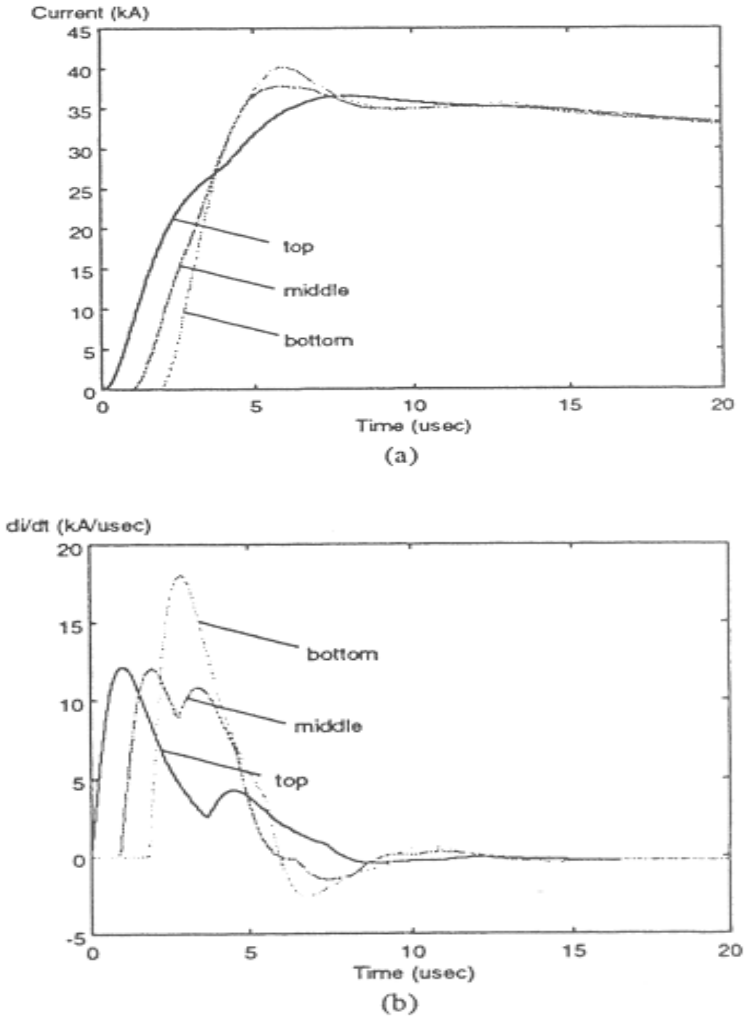
Many other researchers have performed laboratory experiments and field measurements as well as developed models that provide more insight and

understanding in the initiation and characteristics of the upward leader [46, 47, 48, 49, 50, 51, 52]. A lot of progress has been made in that regard.

6.5.2 Current measurements along the tower

The waveforms for current and current derivative evaluated at the top of the tower (553m), the middle (276.5) and the base of the tower (0m), starting from the typical first return stroke current presented in figure 1 below, as injected current at the top of the object [34] and taking into account reflections at its two extremities.

The figures below show the current and current derivative waveforms, respectively:



Figures 5 (a) & (b): Current and current derivative along the strike object for a typical first return stroke [30]

It can be seen that moving towards the ground, the current experiences a higher peak value and a faster rise time due to the contribution of the reflected wave at the ground level [30].

The figure below presents similar results, using the typical subsequent return stroke current. It can be seen that in the case of subsequent strokes both the current and the current-time derivative are more significantly affected by the presence of the tower [30].

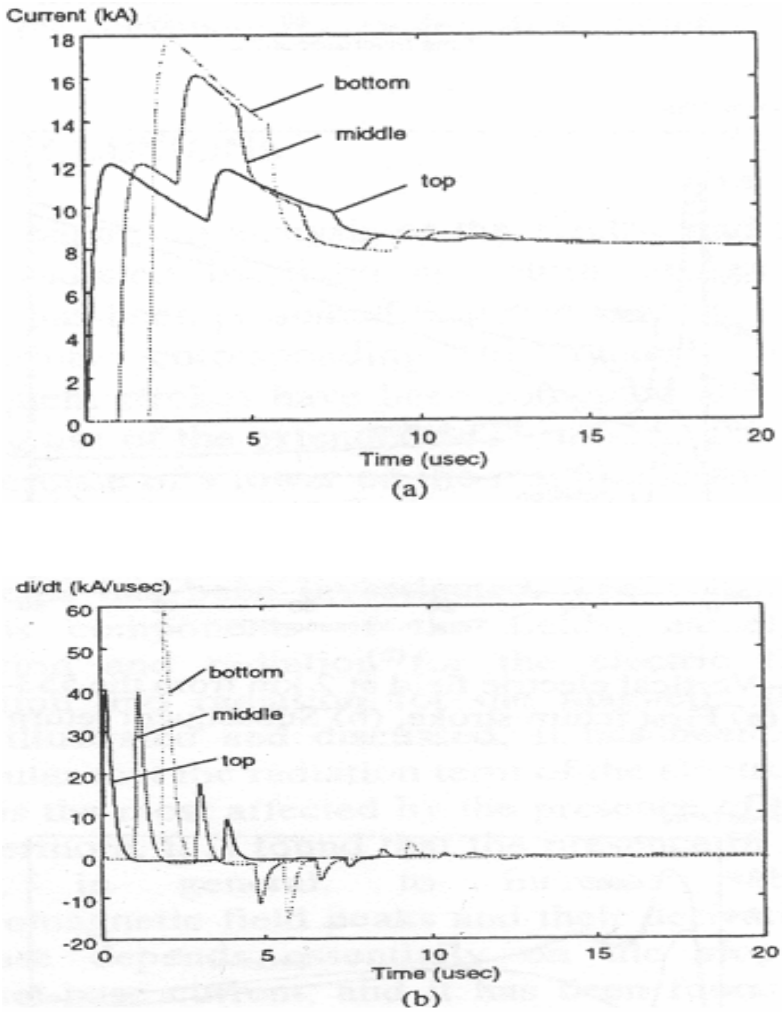


Figure 6 (a) & (b): Current and current derivative along the strike object for a typical subsequent return stroke [30]

7. DATA FROM LPATS

7.1 Background: LPATS

The advent of lightning location systems has ushered lightning research into a new era. These systems have the ability to detect huge quantities of lightning data over a considerable area. As a country of high lightning activity, South Africa has been studying lightning characteristics for many years [24, 25, 26, 27, 28, 53].

The Lightning Position and Tracking System (LPATS) has been in use in South Africa since 1993 [53]. Global Atmospherics Inc., an American company based in Florida, developed the system and was installed by Eskom early in 1993. When LPATS started off, two on-line customers were connected to the system. By the end of 1996 there were four external customers and seven on-line Eskom customers using the system.

Currently, there are ten user groups within Eskom using the system off-line for fault-investigations. Numerous insurance companies also use these services in the investigation of lightning-related insurance claims. During May 1996 a functional process was formed to support the growing customer base and to manage the system.

The system was regarded as very vital for the progression of lightning research in South Africa. The system provides information about the location (latitude/ longitude), the peak current and subsequent strokes for lightning, ground flash density and time of day of occurrence [53].

7.2 System Components

The system consists of the following components [54]:

1. Six lightning receivers, which are responsible for lightning stroke detection. The receivers are located in Gauteng, Mpumalanga, KwaZulu Natal, Free State, North West and Limpopo.

2. Central Analyzer, which processes all lightning data and calculates stroke location.

3. VIS (Visual Information System), which is the user interface for easy access to lightning data. There is an on-line version available that operates on a real-time basis and an off-line version that works on archived data and that is used for fault analysis.

4. Communication media: The receivers are connected to the central analyzer via ESKOM leased lines. The connection from the VIS to the central system could be either ESKOM leased line or a data casting connection via the SABC. Off-line data is obtained via the ESKOM LAN/WAN network.

5. GPS Satellite, which is used to ensure that all system clocks are synchronized and system timing is accurate.

7.3 System Operation

- A lightning stroke generates an electromagnetic signal which radiates outward from the source and is detected by the lightning receivers.

- The remote receivers receive the lightning waveform and attach a time stamp to the stroke, corresponding to the peak of the wave. The receivers also record the stroke amplitude, polarity and whether the event is a cloud or a ground stroke.

- This information is then transmitted to the Central Analyzer for processing.

- The Central Analyzer receives the reports from all the stations and uses this data to calculate the stroke location, using a "time of arrival" method. Once the stroke location has been determined a complete report of each lightning stroke is compiled.

- The report from the Central Analyzer is sent to the Video Information System for access by the user. As the data is displayed it is archived so that it can be accessed at a later time.

- In order to ensure that all data is accurate the timing of the system has to be exceptionally precise. GPS satellites are used to synchronize system clocks to achieve accuracy within 1 millisecond.

7.4 System Applications

A few of the LPATS applications are:

1. It is used by control centers as an early warning aid.

2. It is used by an external customer to monitor storm activity near Eskom lines. In case of storms, the customer can switch over to their resources and

isolate themselves from Eskom. This can reduce dips and outages and make a tremendous saving for the customer.

3. It is used in fault investigations to verify or determine lightning as the cause of the faults.

4. It is used to provide an accurate database for the determining of key lightning parameters for electrical insulation and protection design and prediction of lightning failure of systems (e.g. lightning ground flash density)

5. It is used as a forecasting aid to the South-African Weather Bureau in Pretoria

7.5 System Performance

System performance is specified in terms of locational accuracy and detection efficiency.

7.5.1 Location Accuracy

This gives an indication of the distance deviation (in kilometres) that an LPATS recorded stroke can have from the physical strike point on the ground. Theoretically, strokes that occur within the area surrounded by the remote receivers will have a very low deviation (i.e. as little as 500m deviation from the real strike point) while strokes occurring far from the receivers show a much greater distance deviation (up to 32km) [54].

For practical purposes, this level of accuracy is adequate for analysis and comparison.

7.5.2 Detection Efficiency

This gives the percentage of total number of strokes that LPATS will detect. Once again it can be seen that the system's best response occurs within the area surrounded by the receivers. Up to 90% of all lightning strokes will be detected by LPATS in this area.

7.5.3 Other Factors

The system performance can also be influenced by a number of factors like:

a) The total number of lightning receivers operational at any given time**.** If a remote receiver is not operational or the communication link between the receiver and the central system is down or unstable then both the locational accuracy and the detection efficiency of the system will be affected.

b) The status of the communications between the remote receivers and the central analyzer and the central analyzer and the VIS users. If any communication link is unstable (due to local noise etc.) then there will be data loss. This situation is especially severe when this occurs between the central analyzer and the user. Many strikes may be lost due to poor communications.

The system performance is a very critical parameter and must be considered when evaluating lightning data. The locational accuracy and detection efficiency plots must always be considered and the user must be aware of the other possible factors which could affect a particular data set.

7.5.4 Current System Performance

During the measurement of the lightning strokes for the seasons of June 2001 to June 2003, the system was fully operational and all six magnetic sensors (forming a hexagon) were in full use. The sensors are situated mainly in the Gauteng and Mpumalanga areas since these are areas of high lightning activity. A minimum of three sensors is required to run the system since only three signals are required for triangulation and detection.

The detection efficiency of the system was found to be higher inside the hexagon, about 98%, and slightly lower outside the hexagonal area formed by the sensors [54]. For the seasons of June 2001 to June 2003, the system availability was found to be more than 95%.

8. RESULTS FROM LPATS

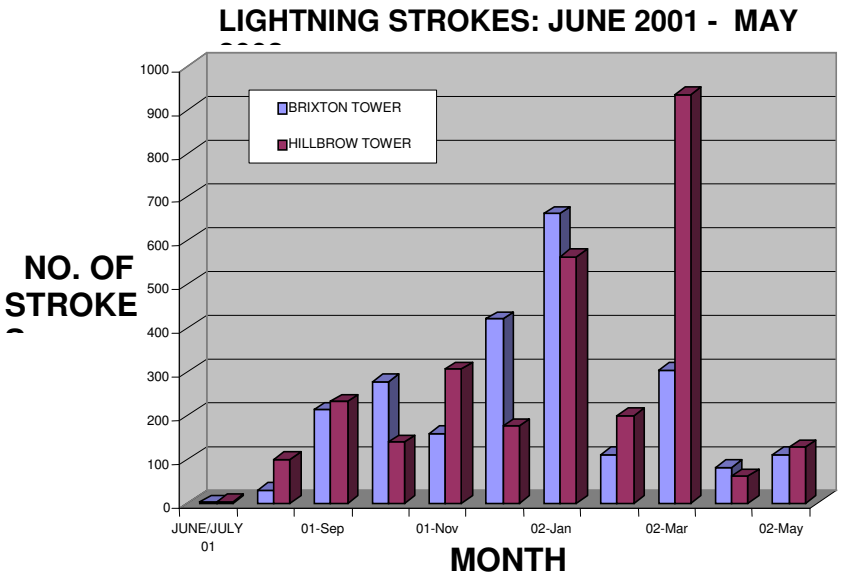
LPATS provides information about the location (latitude/ longitude), the peak current and subsequent strokes for lightning activity in South Africa. For all ground striking flashes, the accuracy of LPATS was designed to be in the range of a few hundred meters to a kilometre [53, 54]. For practical purposes, this level of accuracy is adequate for analysis and comparison.

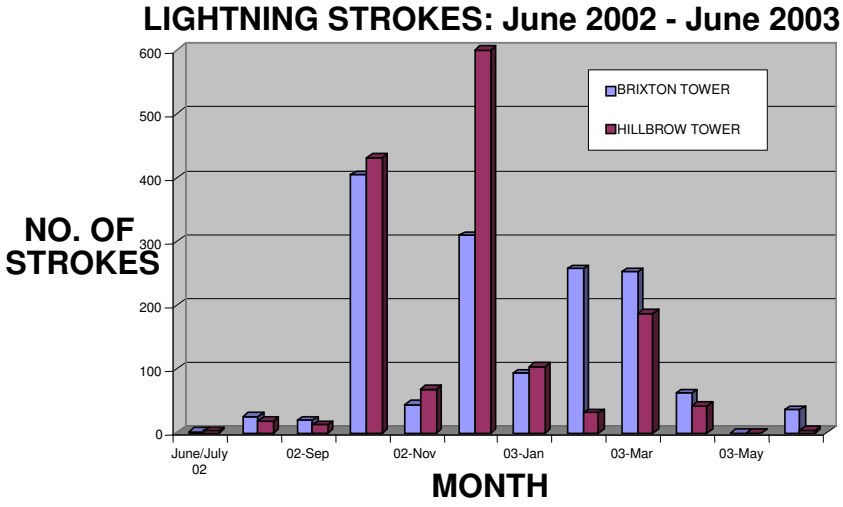
All strokes in the vicinity of each tower, defined by the radius $0 < R < 2.5$ km, are assumed to be terminating on each tower. Hence we refer to "apparent" ground flash density in the vicinity of each tower, recognizing that the flashes within this area are initiated by the presence by each tower. This is a reasonable assumption considering that the accuracy of LPATS covers a range of a few hundred metres to a kilometre and the distance of 2.5km is within the measuring accuracy of LPATS. Also, as the two towers are 5.2 km apart, any strikes beyond 2.5 km would be considered outside the vicinity of the respective tower. The radius of $2.5 < R < 10$ km defines the area far away from the towers.

The first sets of results obtained from LPATS were presented at the SAUPEC Conferences held in Pretoria and Stellenbosch, respectively [55, 56].

8.1 Lightning Activity

In evaluating the apparent ground flash density for both the Brixton and Hillbrow Towers, it is interesting to note the lightning activity in the vicinity of the two towers as shown by figures 7 and 8 below:





Figures 7 & 8: Lightning strokes in vicinity of each tower

The figures above indicate the number of strokes experienced by the Brixton Tower (BT) as well as the Hillbrow Tower (HT) for the two seasons June 2001 to May 2002 and June 2002 to June 2003. The figures show a significant increase in the incidence of strokes between the months of October and March as expected since it is typically the lightning season in South Africa. A higher incidence of strokes is experienced during the months of December for both seasons.

However, it is also interesting to note that both towers experience a very similar pattern of incidence of strokes, though March 2002 and December 2002 represent some deviations of exceptionally high incidence of strokes for the Hillbrow Tower.

8.2 Apparent Flash Density

Furthermore, the LPATS data suggests that there is an appreciable increase in apparent flash density in the vicinity of each tower compared to the surrounding areas for both seasons, as shown by Table 7 below:

Table 7: Flash Density Change: June 2001 – June 2003

	STRIKES		FLASH DENSITY (flashes/km^2/year)	
	R < 2.5 km	2.5 < R < 10 km	R < 2.5 km	2.5 < R < 10 km
Brixton Tower	219	1921	11.15	6.51
Hillbrow Tower	258	2014	13.13	6.84

NOTE: BT = Brixton tower & HT = Hillbrow tower

Table 7 gives an average of the results obtained for the two seasons to give a more realistic picture of what happens in reality. From Table 7, the results indicate that in the vicinity of each tower, there is an increase in the apparent flash density, with each tower experiencing an average of direct strikes of 219 and 258 for the Brixton and Hillbrow towers, respectively, for the both seasons. From figures 18 and 19, it is worth noting that the rate of lightning activity was much lower for the season of June 2002 to June 2003 season. The results obtained for the flash density away from each tower are similar to those obtained from the standards [8-12]. The results are 6.51 and 6.84 flashes per square kilometer per annum, for the Brixton and Hillbrow Towers, respectively, when considering the vicinity away from the tower. This compares favourably with the value of 7 flashes per square kilometer per annum for the Johannesburg area [8-12].

The flash densities in the vicinity of the towers are found to be 11.13 and 13.13 flashes per square kilometer per annum for the Brixton and Hillbrow Towers, respectively. This shows a minimum increase of 42% in the apparent flash density. These results (for both seasons) suggest that there is a significant increase in flash density in the vicinity of the tower.

According to Diendorfer, these values are similar to values obtained for tall structures with the same height [37]. These values are more than four times those obtained by using Eriksson's equations and IEC Standards [8-12, 53, 54], which predict the direct strikes to be 54 for BT and 42 for HT. However, Eriksson's equations are mainly used for downward lightning [2, 14, 24, 26, 29].

8.3 The effect of structure height to direct strikes from LPATS

The number of direct strikes observed by the technical staff from the BT and HT is actually much higher than those obtained from Eriksson's equations [24] and similar to those obtained from LPATS. Hypothetically, upward lightning accounts for the remaining three-quarters of strikes from each tower.

The values for direct strikes from Eriksson's equations were obtained without considering the effect of equivalent height of the respective towers, which plays a very important role in the incidence of lightning strikes to the towers. Hence for any accurate analysis, an "effective height" for both the BT and HT will help determine the number of direct strikes that both towers are likely to experience. This seems reasonable when considering that both towers are situated on elevated or hilly areas in comparison to the surrounding areas, though the Hillbrow Tower is situated in an area highly populated with tall buildings.

8.4 Median Current Distribution

All strokes experienced by the towers consist of both the first and subsequent strokes, for both the negative and positive polarities. Current data considers the effects of both types of strokes on the mean current on both the BT and HT, though there is higher incidence of negative flashes compared to positive flashes.

In order to determine the trend of the median current with change in distance, the values of the mean current were determined for each area around the towers, as defined by the radii of $0 < R < 2.5$ km and $2.5 < R < 10$ km, respectively.

The tables below, Tables 8 and 9, show the mean current distribution in the vicinity of the towers and far away from the towers.

Table 8: Mean Current Distribution: June 2001 - May 2002

	BRIXTON TOWER	HILLBROW TOWER
MEDIAN CURRENT 0 < R < 2.5 km	-22kA	-21kA
MEDIAN CURRENT 2.5 < R < 10 km	-27kA	-26kA
MAX CURRENT STROKE	-225kA	-168kA
MIN CURRENT STROKE	-5kA	-5kA

Table 9: Mean Current Distribution: June 2002 - June 2003

	BRIXTON TOWER	HILLBROW TOWER
MEDIAN CURRENT 0 < R < 2.5 km	-26kA	-22kA
MEDIAN CURRENT 2.5 < R < 10 km	-23kA	-25kA
MAX CURRENT STROKE	-243kA	-175kA
MIN CURRENT STROKE	+5kA	-4kA

- From the tables above, it can be deduced that both towers seem to have similar patterns of current distribution throughout the entire seasons of June 2001 to May 2002 and June 2002 to June 2003. The mean current values are of the same order for both towers.
- Both tables above do indicate that there are slight differences in the mean current in the vicinity of the tower and away from the tower.
- From the above tables, it is observed that there is an apparent decrease in the median current (of all flashes) from the vicinity of the tower to away from the tower, though Table 9 shows a slight deviance (for the Hillbrow Tower) from the general results obtained.
- From Table 8, the value of the mean current in the vicinity of the towers is in the order of –20kA and the value of the mean current far from the towers is in the order of –25kA to about 30kA.

9. DISCUSSION

1. The data from the CSIR 60m research mast shows that most of the lightning was of the downward type. The peak amplitude distributions of all upward strikes on the mast have been shown to be significantly lower than those of downward strikes. This suggests that a relatively lower field may be required to launch an upward leader to a downward leader, with increase in structure height.

2. Median peak current amplitudes appear to decrease with increase in height. Further research on the mast shows that a peak current amplitude of 33kA is comparable to 30kA of Cigre, due to the increase in upward leaders' incidence on the structure.

3. There is sufficient data to indicate that an increase in structure height results in a corresponding increase in incidence of upward leaders. This increase seems to be significant for structures over 100m [26]. The change in the occurrence of upward leaders for structures in the range of 10 to 60m is relatively very small.

4. A structure's height alone cannot be used as a parameter in determining the lightning strikes to that structure, but its geometry. The slenderness ratio (H/R) may indicate a structure's ability to modify the intensity of the electric field in the vicinity of the structure.

5. For practical purposes, tall structures must be protected against downward lightning. However, the high incidence of upward leaders with increased structure height requires a review of the protection techniques for tall structures.

10. CONCLUSION

The evidence obtained so far suggests that there is a significant increase in the incidence of upward leaders from tall structures with increase in structure height. This increase seems to be significant for structures over 100m [26] and above. The data suggests that structures having heights below 100m will not normally experience upward flashes. Hence the occurrence of upward leaders for structures in the range of 10 to 60m is relatively very small.

Furthermore, the increased contribution of upward flashes to the total incidence of flashes in tall structures should lead to a decrease in measured current amplitudes (for all flashes) with increasing structure height. The adoption of median peak current amplitude of the order of 40 to 45kA for flashes to flat country is indicated [29], though more data is required in this regard.

In addition, the evaluation of the ground flash density in the vicinity of the Brixton and Hillbrow Towers shows a significant increase to the local flash density, which suggests the triggering effect of tall structures. This further confirms that careful analysis of LPATS data can lead to meaningful results being obtained and that LPATS can be used as a tool to assist in better understanding the effects of lightning on tall structures. However, more research is required to correlate LPATS data with strikes to local tall structures of varying slenderness ratios as well as determine the saturation effect with increasing structure height.

More research is required to determine the influence of the structure dimensions to the striking process and the resulting relationship between the incidence of lightning flashes and the height of the structure

11. RECOMMENDATIONS FOR FUTURE WORK

- Further analysis of current distribution can be achieved by separately comparing the first and subsequent strokes on both towers but that is outside the scope of this paper.

- For more reliable results from the LPATS, a minimum five-year period of the analysis of lightning strikes would be sufficient enough to reveal a more realistic pattern of lightning performance of the Hillbrow and Brixton Towers. This is based on the observation that there is a constant change in climatic conditions which, in turn, affects lightning activity and hence the lightning behaviour of the structures and towers being studied.

APPENDIX A:The thunderstorm diurnal variation curves

The thunderstorm diurnal variation curve:

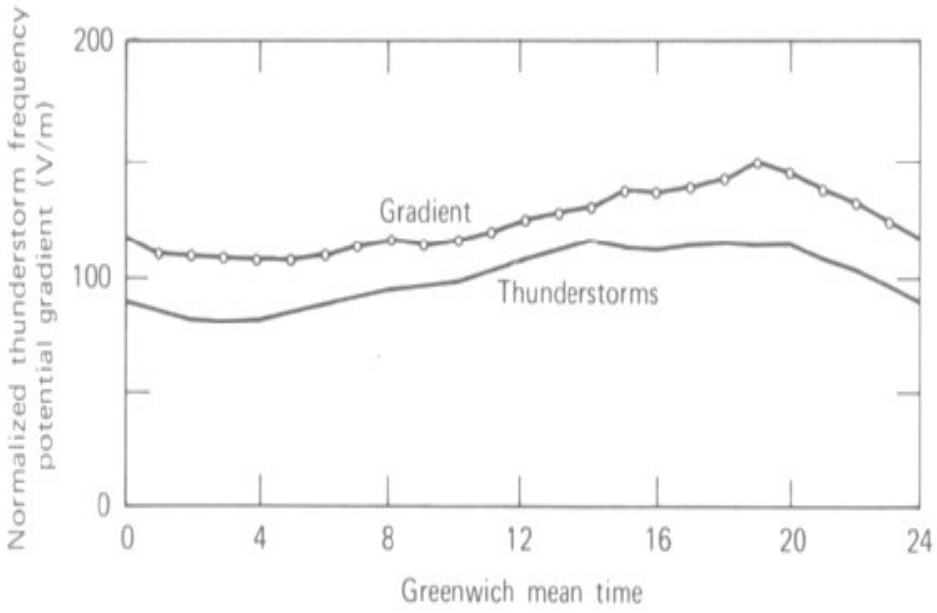


Figure 1: Diurnal variation of potential gradient and thunderstorm frequency (plotted by Whipple) [2]

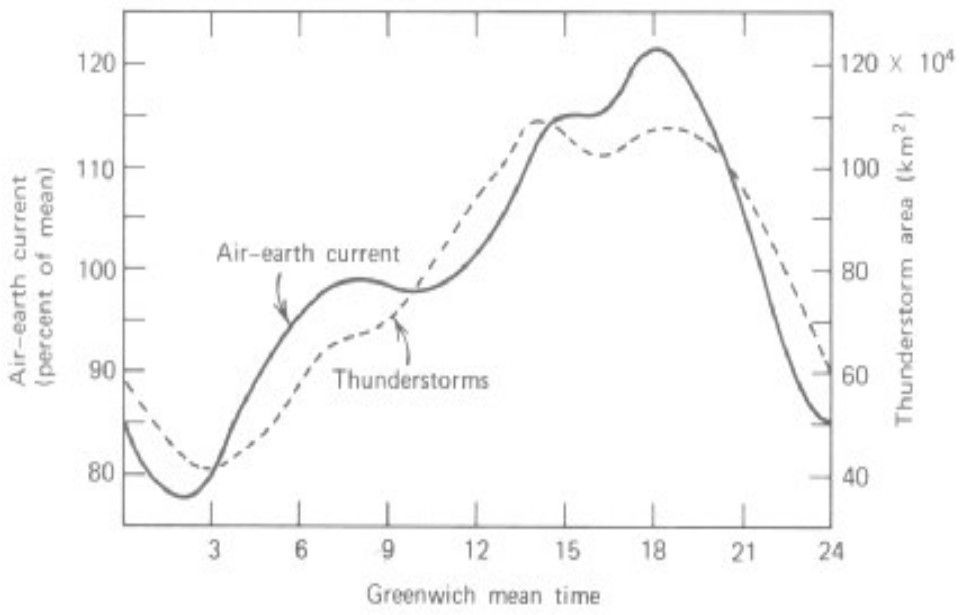


Figure 2: Diurnal variation of thunderstorm area (Whipple) and fair-weather air-earth conduction current at Mauna Loa Observatory [2].

APPENDIX B: Thunderstorms and the Thundercloud

The thunderstorm is, mechanically and thermodynamically, a creation of the troposphere in which the temperature decreases with height sufficiently for clouds to build upward buoyantly. These "cumulus" clouds are initiated by the condensation of water vapour in excess of equilibrium values, into cloud droplets about 10μm in diameter. These droplets might freeze into ice crystals. With or without freezing these droplets aggregate to form precipitation particles whose individual mass is a million times that of the constituent cloud droplets. These precipitation particles are raindrops, snowflakes, graupel (low-density mixture of cloud droplets and air) and, least frequently, hail, which has 10 to 100 times more individual mass than the other particles. Raindrops are sometimes melted snowflakes or graupel rather than the first phase or aggregation of cloud droplets. Cumulus clouds can develop one way or another, depending on the degree of the "ice" phase. Cumulus clouds can develop into cumulonimbus clouds, which produce rain showers or complexes of rain showers. However, not all rain showers become thunderstorms or parts thereof.

In the thermodynamic aspects, the phenomenon of supercooling strongly influences the mechanics and electrical properties of rain showers. The thermal properties of water are also a fundamental factor [2]. Water will not freeze, until it reaches –40°C, unless it contains some site on a solid surface from which the crystalline pattern of ice can develop outward. Most water, unless highly purified, does contain solids with sites on them. The sites are also given the name "nuclei". The greater the number of nuclei, the higher the temperature at which the particle is effective in producing freezing. The rise in temperature is proportional to the exponential increase in the number of nuclei. Every raindrop and cloud droplet is a separate sample requiring its own nucleus if it is to freeze. A raindrop contains enough nuclei to have an effective freezing temperature in the range of -15 to -25°C. However, raindrops seldom get this cold. Cloud droplets, possessing fewer nuclei, are seldom active (freezing) at temperatures warmer than -30°C and many of them would have to reach -40°C before freezing. Unlike larger samples of water, such as those in containers or ponds, which freeze at 1 or 2°C below the nominal freezing point, the cloud droplets require supercooling to freeze. Conversely, to freeze the droplets supercooling must occur and the freezing process occurs (when it does) over a wide range of temperatures within the cloud and therefore over a wide range of heights.

Cloud droplets and ice crystals fall through still air at speeds of less than 0.3m/sec; snowflakes fall at 1m/sec and raindrops fall at 5 to 10m/sec [2]. Cumulus clouds are in vertical circulation and contain more or less concentrated updrafts and downdrafts with velocities of 30m/sec or greater. When the updraft velocity is greater than the fall speed of the raindrops, it is possible for the raindrops to ascend as they grow and to be stored aloft in considerable concentrations, which

may reach values of mass such as to neutralize the buoyancy and so turn the updraft into a downdraft.

Cumulus cloud growth may start with warm moist air rising from the surface and cooling (because of expansion), then mixing with less moist surrounding air that has been at a height of several kilometers for a period of hours. Clouds are mixtures of air with different histories and include mixtures of a variety of "hydrometeors" (i.e., particles of solid or liquid water). The mixing activity continues through the few-hours lifetime of the cloud or storm. There are a number of postulations that have been put forward to explain the generation of an electrical charge in a thunderstorm. Hence there are also various ways in which the elements of a rain shower may possibly achieve the charge separation that eventually results in lightning. The charge separation is related to the supercooling and in some cases the freezing of droplets as well as the disposition of charge concentration in a mature thundercloud (which is due, in some part, the vertical circulation – updrafts and downdrafts). The figure below illustrates the particle flow in relation to temperature and height:

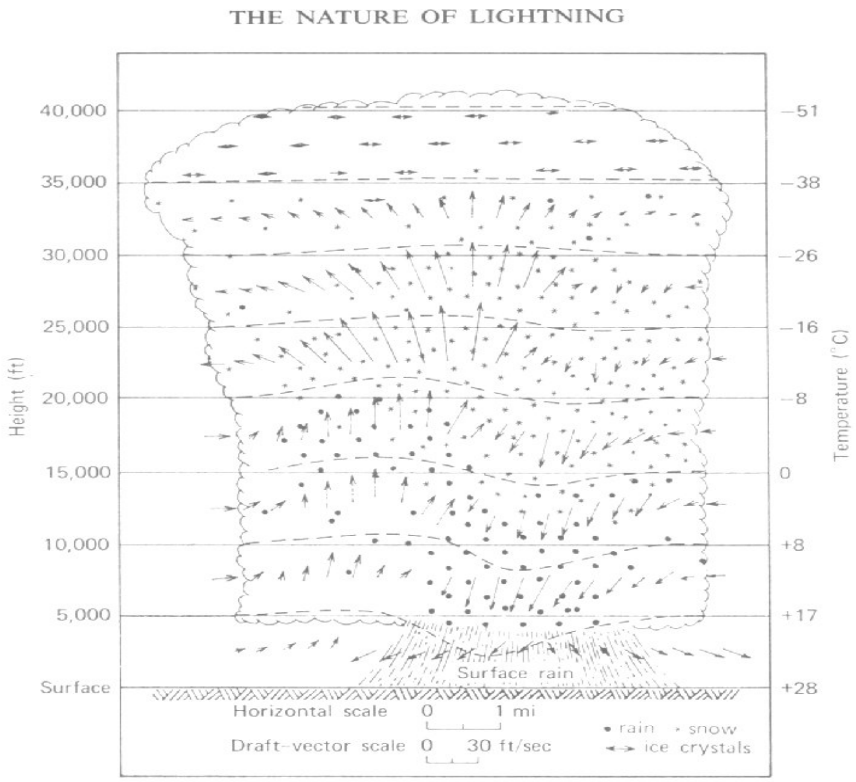


Figure 1: An idealized cross section through a thunderstorm cell in its mature stage [2]
KEY: • rain, ∗ snow, ↔ ice crystals. After Golde

APPENDIX C: The Lightning Phenomenon

1. Initial Discharge

Observations, based on electromagnetic radiation and electrostatics, show that discharges occur within the cloud for an appreciable time (i.e. 100ms) before the stepped leader is seen [4]. Even though there is some uncertainty about their exact location, there is sufficient evidence to prove that such discharges do exist. Further, from general reasoning, it is concluded that some form of precursor process must take place in order to interconnect the vast number of charges within a thundercloud.

Whatever the mechanism of production, the resultant charge must reside on ice and/or water particles. Substantial evidence shows that the bottom of the negatively charged ion region is 1 to 2 km above the base of the cloud. As both this intermediate zone and the lower part of the negatively charged region are at a temperature above zero centigrade, large water drops must be present. Although the production of discharges by distorted water drops in an electric field has been postulated - a good mathematical treatment is provided by Griffiths and Phelps – some aspects require a little clarification.

In a uniform DC field, a droplet of undistorted radius r (mm) becomes unstable when the field exceeds the value E_c (V/m) as given by:

$$E_c \approx 5 \times 10^6 \sqrt{(s/r)} \qquad (1)$$

Where s is the surface tension of the water in air; e.g. for r = 2mm and s = 7×10^{-2} N/m, $E_c \cong 1$ MV. As the droplet distorts, the field increases in the air at its tip. The corresponding enhancement factor is obtained by considering the droplet to be a prolate spheroid; this field increases by at least an order of magnitude for sharply pointed shapes [4].

The unperturbed field E, due to the charges on all the droplets, is obtained from coulomb's Law as:

$$E = \sum Q/4\pi\in_o R^2 \qquad (2)$$

Where $\in_o$ is the permittivity of free space, Q is the quantity of the charge on a particular water droplet and $|R|$ is the distance from that droplet to the point in space under consideration.

For the air to become substantially ionized, a large avalanche of electrons needs to be created; Using Meek's criterion [5] for the streamer – i.e. a luminous streak of discharge, then:

$$\int (\alpha - \eta)\, dx = 20 \qquad (3)$$

…integrating between 0 and x

where α (m^{-1}) is Townsend's electron multiplication coefficient, η(m^{-1}) is the electron molecule attachment coefficient and x (m) is the length of the avalanche in the direction of the electric field. Complicating features arise because $(\alpha - \eta)/N$ is a strong function both of E/N – where N(m^{-3}) is the number density of the air molecules – and the humidity of the air. For dry air:

$$\alpha - \eta \approx 10^{-19} N \exp -4 \times 10^{-19}\, N/E \qquad (4)$$

whilst this value of $(\alpha - \eta)$ is reduced about ten-fold when the air is saturated with water molecules.

Another feature to note, is that N is a function of both pressure p and absolute temperature T and so, according to the kinetic theory of gases:

$$N = p/kT \qquad (5)$$

Where k is Boltzman's constant. Further, p varies with altitude H, given by the relationship:

$$p = p_o \exp. - mgH/GT \qquad (6)$$

where p_o is the pressure at sea level, m is the mass of the air molecule, g is the acceleration of free fall and G is the universal constant of gases. For example, equations (5) and (6) show that there is approximately 40% decrease in N in going from sea level and temperature 30°C to the cloud at 4.5km and temperature 0°C.

This substantial reduction in air density means that breakdown in the cloud occurs at a much lower value of field than that in air at sea level [4]. For example, Paschen's curve shows that the uniform field value at a height of 4.5km is approximately 2MV/m (cf. 3MV/m at sea level). By using some experimental findings for the water-triggered breakdown of a uniform field gap as investigated by Swift [6], it is estimated that a discharge could be initiated by a large droplet (e.g. 5mm radius) for a field as low as 0.5 MV/m. This postulate seems plausible as the field within a thundercloud can have peak values that lie within the range 0.1 to 0.8 MV/m [4]. Once a streamer forms, discharges probably propagate from water drop to water drop, thereby producing both a path to the base of the cloud and plasma that interlinks much charge.

2. The Mature Stage

As the charge separation proceeds in the cloud cell, the potential difference between the concentrations of charge increases and the potential drop across any vertical unit distance of the charged mass similarly increases. After an appreciable while – 20 min or so – of charge generation process, the cloud will have reached a mature stage, charged to a point where a discharge will be initiated [2]. The temperature at the main negative charge center will be about -5°C and at the auxiliary pocket of the positive charge below it, about 0°C. The main positive charge center in the upper cloud will be about 15°C colder than its negative charge center. At the mature stage, the total potential difference between the main charge centers will be 10^8 to 10^9 V and the total stored charge several hundred coulombs. Only a part of the total charge is released by lightning to earth, as there are both inter-cloud and intra-cloud discharges as well. The situation at the mature thundercloud stage is depicted in figure 4:

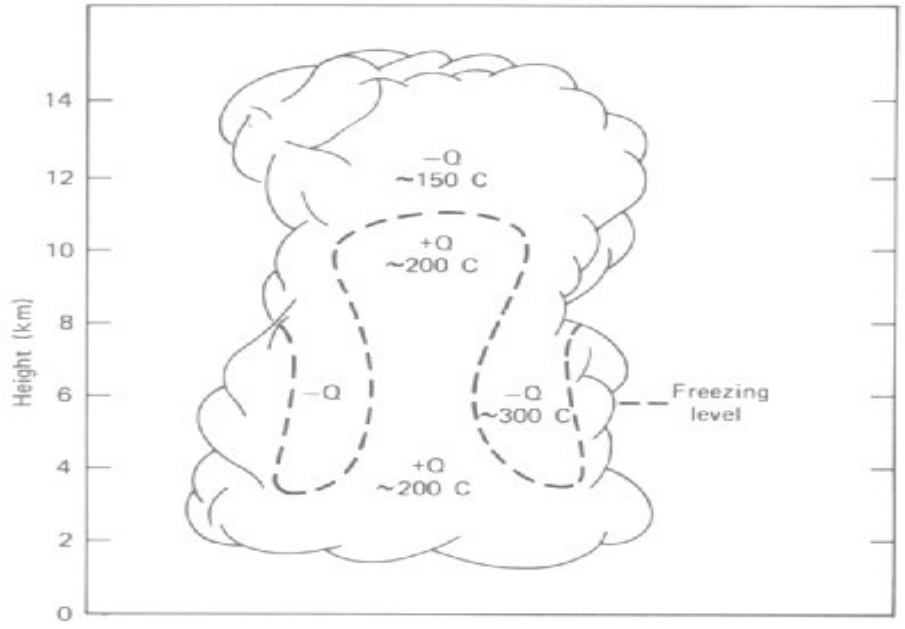


Figure 1: Estimated charge distribution in a mature thundercloud.
After Phillips [2]

3. The Leader

There are several varieties of lightning discharge and of these, the dominant cloud-to-earth type will be described in detail. The channel to earth is first established by a stepped discharge called a leader or leader stroke. The initiation of the leader

might be due to the downward movement of negative charge outside an up-drift in the core. Positively charged moisture particles are drawn into this flow, which in turn attracts more negatively particles in a funneling action that, under the influence of the strong electrical field, eventually forces a negative streamer out of the base of the cloud into the air. Another possible mechanism is the breakdown between elongated, polarized water droplets at the cloud base caused by the high potential field or a discharge between the negative-charge mass in the lower cloud and the positive pocket of charge below it.

Once in the air, the negative streamer advances in steps, seeking areas of positive space charge. It may probe into several branch paths but stop after a short distance in favour of the main channel, which presents more positive charge [2]. The average speed of the stepped leader is about 10^5 m/sec, or one thousandth of the speed of light. Each step of the leader advances its tip a distance of 10 to 200 m and these spurts are separated by time intervals of 40 to 100 μsec [2]. The tip of the leader bears a corona fringe and at the completion of each step a pulse of current shoots back toward the cloud. The leader deposits a small portion of the cloud charge along its length, which is neutralized by space charge. The developmental stages of a leader are shown below:

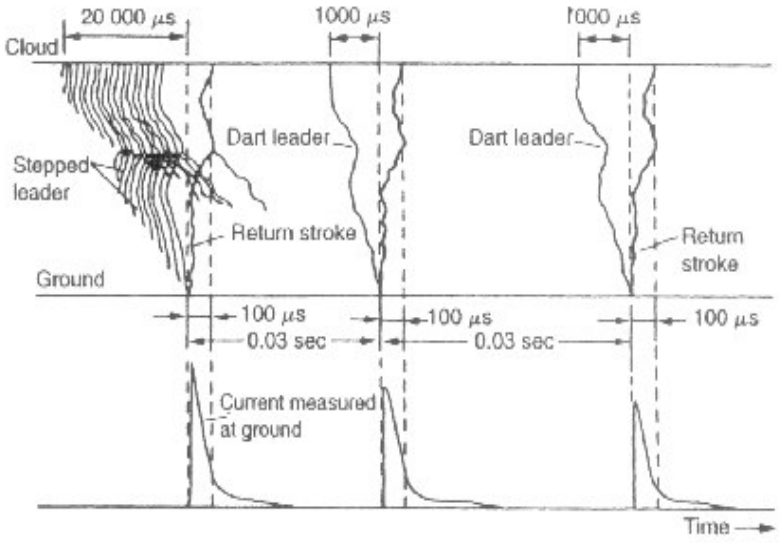


Figure 2: The developmental stages of a lightning flash [3]

While the leader channel is developing, there is a displacement current between the charged cloud and ground caused by the high potential difference. This current is supplemented by point discharges from earth objects, such as buildings, towers, trees or even blades of tall grass. At some instant, the concentration of such discharges can constitute an arc that flows upward to meet the leader tip at 20 to

70 m above ground, depending on the existing field potential. The point at which the two channels meet is called the point of strike and is the start of the return stroke. The stepped leader takes about 20ms to reach the earth and the return stroke takes about 100μs to flash from earth to cloud. It is within the last 100m of ground or of an object thereon that the point of strike is determined. The higher the electrical potential between cloud and ground, the higher will be the striking point. Also, the stronger the electrical field, the less likely is the leader to deviate from the vertical as it nears the earth. The area within which a strike may be expected near a tall earthed object is accordingly dependent on the electrical field strength and this makes it difficult to predict the "safety zone" afforded by a tall object.

The "dead-end" branch paths that the stepped leader may have probed feed positive space charge into the return stroke channel, which assumes the potential of the cloud at the instant of strike. These branch paths or "forks" glow from the heavy current and give rise to then term "forked lightning".

4. Return Stroke

It is the return stroke that has destructive effects and therefore arouses our concern about protection. It can be regarded as an intense positive current from ground or as the lowering of negative charge to ground [2]. Its purpose is to neutralize the opposite charges between cloud and earth. After the first return stroke, it is usual for another region of the cloud to provide sufficient charge for a second stroke or several more, separated by intervals of 10 to 20msec. This return discharge of one stroke or succession of strokes is called a flash. The current in a stroke averages about 20kA, but in exceptionally intense storms can exceed 100kA. The average charge released per flash is about 25C.

The return stroke current heats the path instantly to temperatures of 15 000 to 20 000°C, making the air luminous and causing the explosive air expansion that we hear as thunder. Each return stroke is a unidirectional current pulse that rises to a crest value in a few microseconds and then decays over a period of several tens or hundreds of microseconds.

The strike point near the earth depends on the strength of the potential gradient below the leader channel and the distribution of space charge in the atmosphere, so that it is not only high objects and elevations alone that receive strikes but also plains, lakes or even a valley between mountains. At the instant before a return stroke of the usual kind there is an intense electrical field, with the ground positive and the atmosphere above negative. Immediately after the stroke, there is a reversal of field, with the ground becoming negative with respect to a positive space above. This reversal may be explained by the existence of a comparatively large distributed positive charge within the lower portions of the storm cloud.

A strong wind can displace succeeding strokes laterally, making them appear as a wide band known as ribbon lightning. Some discharges from clouds do not reach the ground. Strokes within clouds often provide general illumination, known as sheet lightning. Sometimes “bead” or “chain” lightning is observed, caused by an intense stepped leader, neutralizing space charge with a high current at each step. Another variety called ball lightning has been observed in the form of a luminous ball moving laterally near the earth, after a nearby lightning discharge.

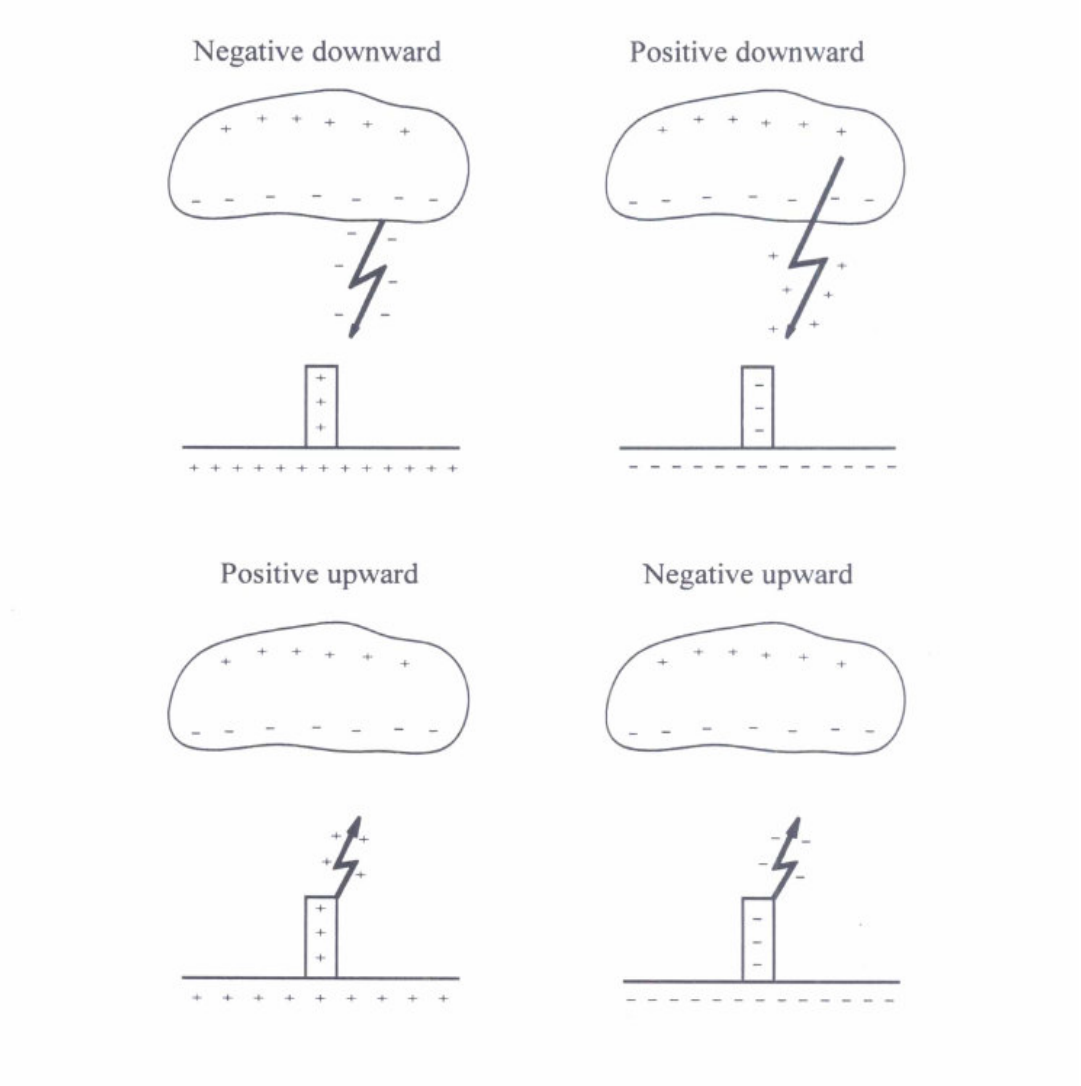


Figure 3: Illustration of Cloud- to-ground discharges [7]

APPENDIX D: Lightning Current Waveform

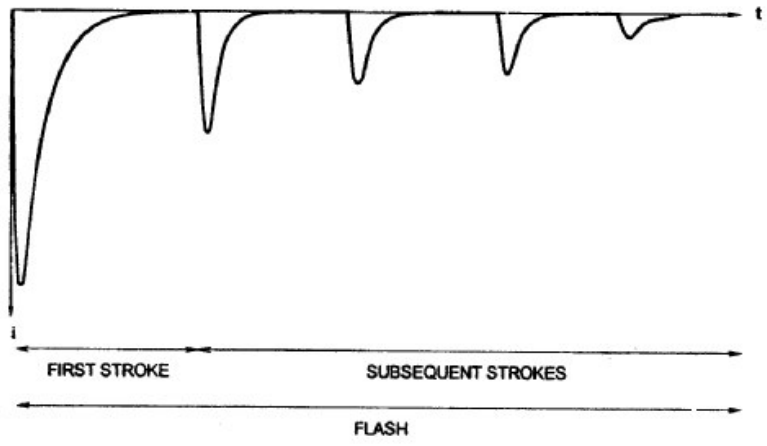


Figure 1: A Lightning Flash [8-12]

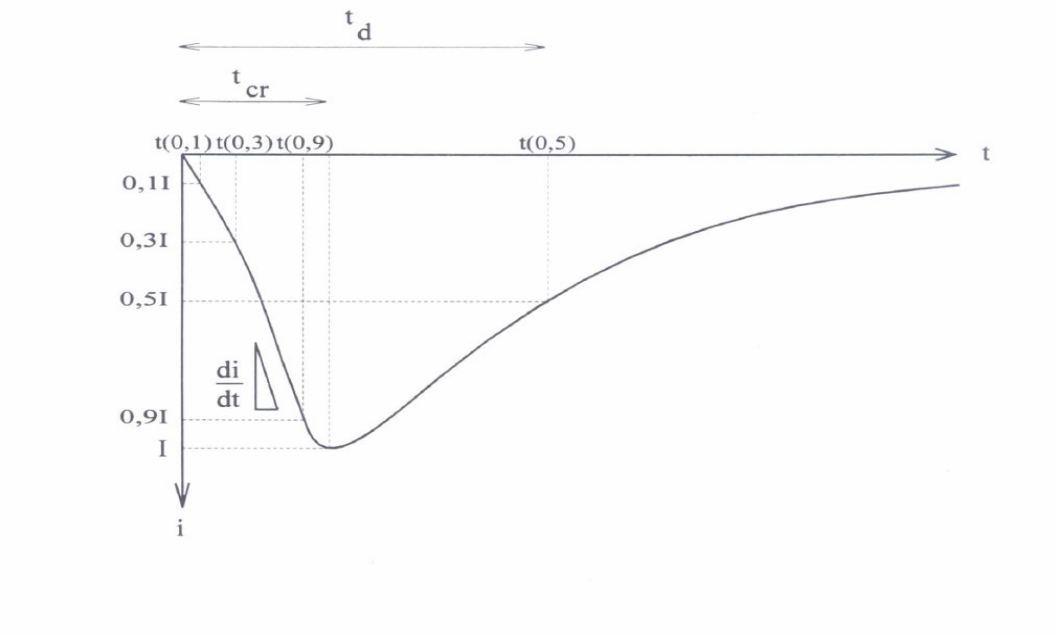


Figure 2: Standard Current Waveform

From the graph:

where I = peak current, kA
di/dt = rate of rise of current in kA/μs
$(di/dt)_{max}$ = maximum rate of rise

- Average slope between the 10% and 90% points on the wavefront:

$$(di/dt)_{10\%/90\%} = \frac{(0.9I - 0.1I)}{(0.9t - 0.1t)}$$

- Average slope between the 30% and 90% points on the wavefront

$$(di/dt)_{10\%/90\%} = \frac{(0.9I - 0.3I)}{(0.9t - 0.3t)}$$

t_{cr} = time to crest, in μs
t_d = time to half value on tail, in μs

1. Peak Current

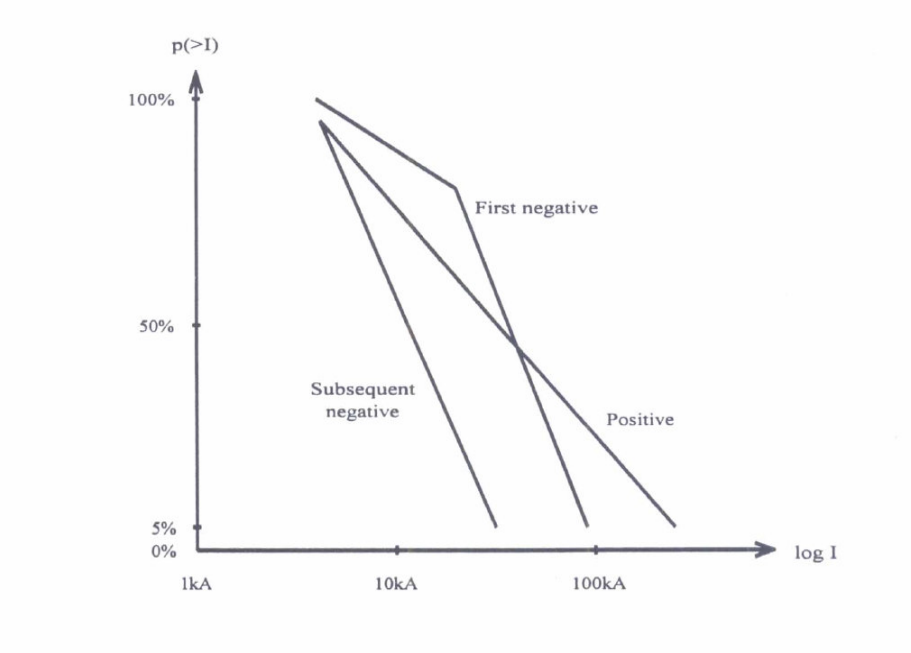


Figure 3: Cumulative Frequency of Current

2. Rate of Rise

Table 1: Cumulative Frequency of rate of rise

First negative strokes	Cumulative Frequency		
	95%	**50%**	**5%**
Maximum Rate of rise	**9.1kA/µs**	**24 kA/µs**	**65 kA/µs**
Average steepness			
Between 30% & 90%	**2.6 kA/µs**	**7.2 kA/µs**	**20 kA/µs**
Between 10% & 90%	**1.7 kA/µs**	**5 kA/µs**	**14 kA/µs**

Subsequent negative strokes	Cumulative Frequency		
	95%	**50%**	**5%**
Maximum Rate of rise	**10kA/µs**	**40 kA/µs**	**162kA/µs**
Average steepness			
Between 30% & 90%	**4.1 kA/µs**	**20 kA/µs**	**99 kA/µs**
Between 10% & 90%	**3.3 kA/µs**	**15 kA/µs**	**72 kA/µs**

Positive strokes	Cumulative Frequency		
	95%	**50%**	**5%**
Maximum Rate of rise	**0.2 kA/µs**	**2.4 kA/µs**	**32 kA/µs**

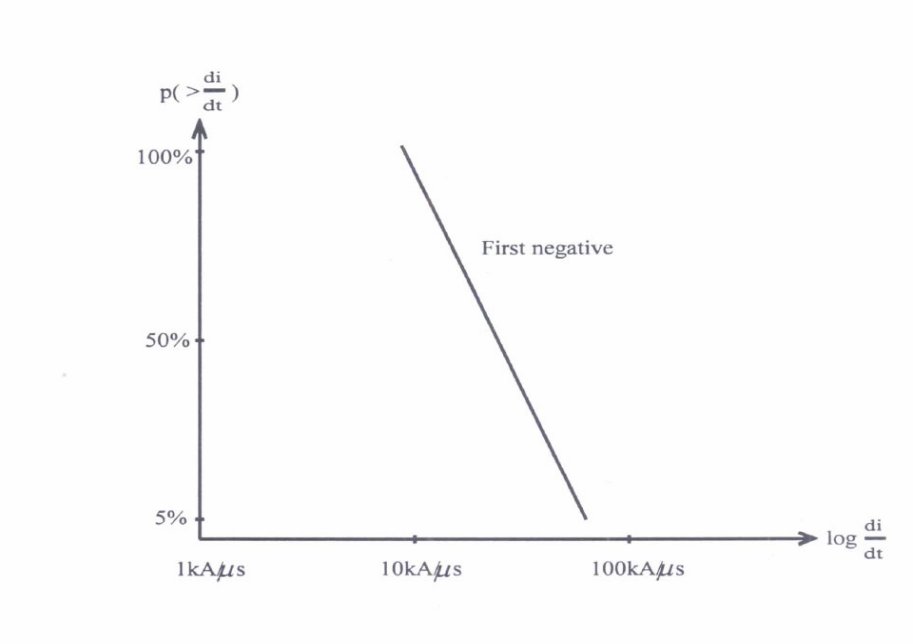


Figure 4: Cumulative Frequency of rate of rise

3. Time to crest and time to half life

Table 2: Cumulative Frequency of total rise time (assuming lognormal distributions)

First negative strokes	Cumulative Frequency		
	95%	**50%**	**5%**
Total rise time	**1.8μs**	**5.5μs**	**18μs**
Rise time			
Between 30% & 90%	**1.5μs**	**3.8μs**	**10μs**
Between 10% & 90%	**2.2μs**	**5.6μs**	**14μs**

Subsequent negative strokes	Cumulative Frequency		
	95%	**50%**	**5%**
Total rise time	**0.2μs**	**1.1μs**	**4.5μs**
Rise time			
Between 30% & 90%	**0.1μs**	**0.6μs**	**3.0μs**
Between 10% & 90%	**0.2μs**	**0.8μs**	**3.5μs**

Positive strokes	Cumulative	Frequency	
	95%	**50%**	**5%**
Total rise time	**3.5μs**	**22μs**	**2000μs**

Also, the values for t_d from SABS IEC 61024-1-1 (1993) are:

Table 3: Cumulative Frequency of time to crest and time to half life

	Cumulative	Frequency	
	95%	**50%**	**5%**
First negative strokes	**30μs**	**75μs**	**200μs**
Subsequent strokes	**6.5μs**	**32μs**	**140μs**
Positive stroke	**25μs**	**200μs**	**2000μs**

These values should be compared with the standard waveforms used for testing electrical equipment (for induced effects):

- 1.2/50μs (voltages – good test of the impulse withstand capability of insulation of equipment)
- 8/20μs (current – waveform is representative of actual induced surges)

Extended lightning current waveforms are also experienced (the lightning current can have a tail (< 1000Amps) that extends for hundreds of milliseconds). This type of lightning is known as hot lightning and is associated with the ignition of fires.

4. The Measurement of the Current in the flash

A number of methods have been used to measure current in a lightning flash [9], namely by:

1. Using Fusing wires
2. The pinching of a metal tube by its self-created magnetic force (pinch-effect force)
3. Magnetizing of basalt rock, developed nowadays into the magnetizing of small steel laminations or wires, so called magnetic links,
4. The klydonograph which records photographically the corona discharge from a point onto a photo-plate and from the diameter of the Lichtenberg figure so recorded, the voltage and thus the current, in a shunt can be recorded and

5. The cathode-ray oscillograph

The magnetic link and other methods can only record the maximum value of the currents in the flash – but in general that is most critical for engineering use and has been used all over the world on transmission lines and recording stations or towers to record the current flowing into earth and phase conductors. The towers are usually limited to 30m.

Using oscillographic techniques, it was established that lightning currents are unidirectional as opposed to oscillatory [13].

5. The velocities of the different strokes

The velocities of negative leader strokes can be derived from field-change measurements and high-speed photography. Their velocities have a very wide range. From a number of experiments performed so far, it does show that velocities are proportional to the amount of charge carried by the clouds that discharge to ground. This can be proven by laboratory experiments, which show that leader stroke velocities increase sharply with over-voltages [13]. As charges accumulate in the cloud, they are likely to produce, at the region from where the leader to ground eventually starts, a voltage higher than the minimum needed to discharge to ground and thus drive it down faster than at minimum speed [13].

APPENDIX E: Cloud-to-ground Lightning

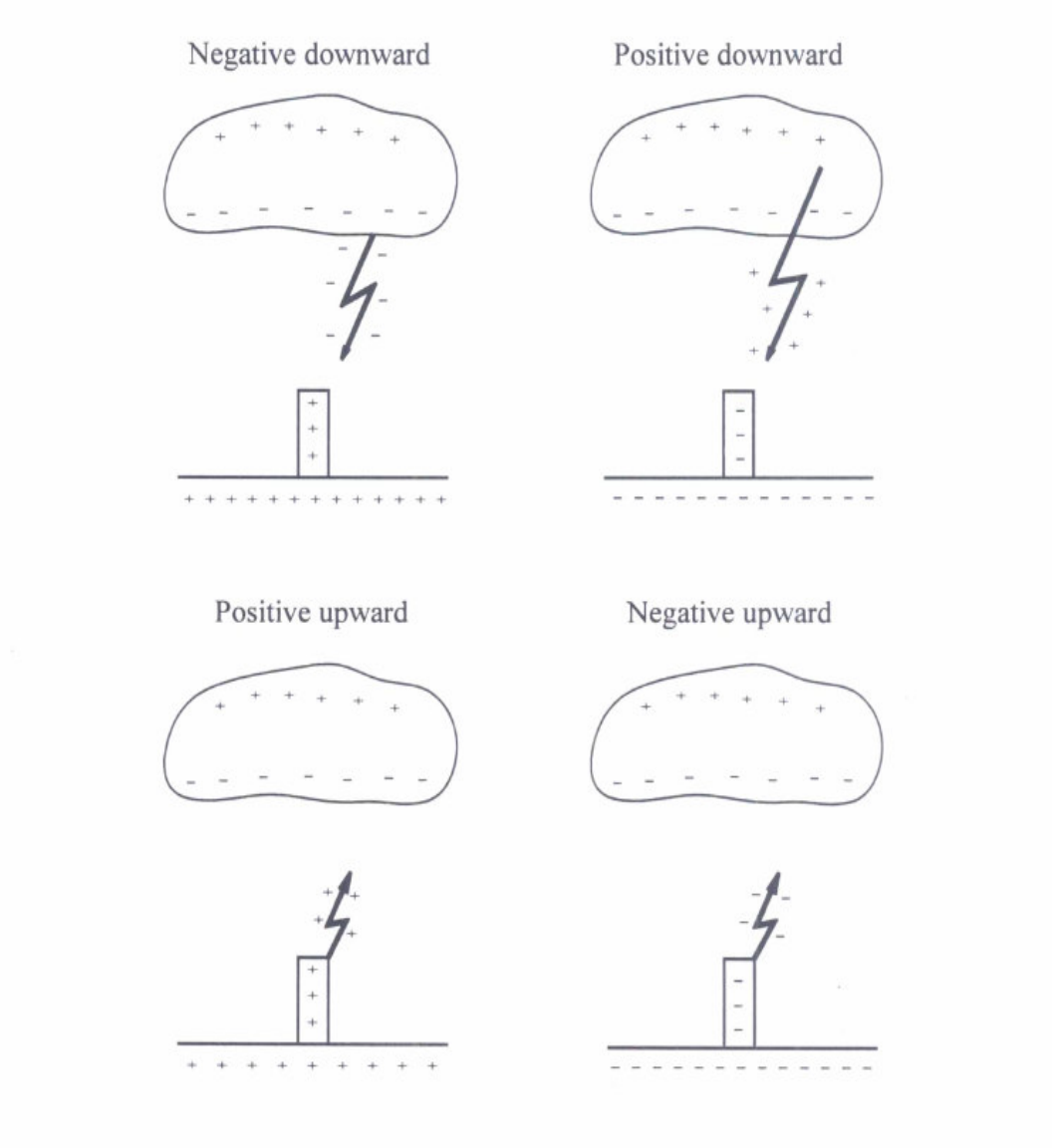


Figure 1: Cloud to ground Lightning [7]

There are four types of cloud-to-ground lightning discharges that can occur [7], namely:

5. Negative Downward
6. Positive Downward
7. Positive Upward
8. Negative Upward

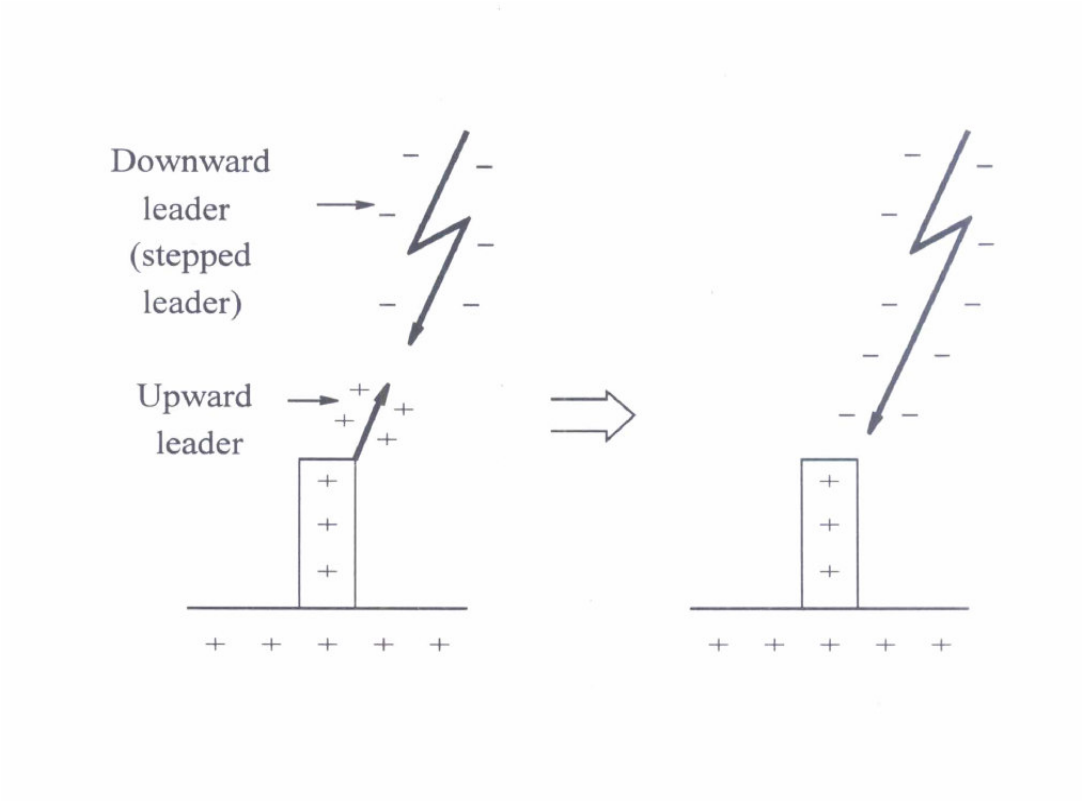


Figure 3 (a): Lightning termination on a structure [7]

REFERENCES

[1] Lewis, W. W., The Protection of Transmission Lines against Lightning, G. E. Series, 1950

[2] Marshall, J. L., Lightning Protection, John Wiley & Sons, 1973

[3] Kuffel, E., Zaengl, W.S., Kuffel, J., High Voltage Engineering, Butterworth-Heinemann, 2000

[4] Swift, D., Lightning Discharge: A Critical Review of Data and Theories, University of the Witwatersrand, Johannesburg,

[5] Meek, J.M., Physics Review, Revision 57, pp. 722 – 728, 1940

[6] Swift, D.A., Fourth International Symposium on High Voltage Engineering, Athens, Paper

[7] Jandrell, I.R., Nixon, K. J., Van Coller, J.M., Earthing and Lightning Protection Revision 1.0, University of the Witwatersrand, Johannesburg, 2002

[8] SABS IEC 1024-1: "Protection of structures against Lightning: Part 1: General Principles, IEC, 1990

[9] SABS IEC 61024-1-1: "Protection of structures against Lightning: Part 1: General Principles: Section 1: Guide A – Selection of Protection Levels for lightning protection systems", IEC, 1993

[10] SABS IEC 61024-1-2: "Protection of structures against Lightning: Part 1-2: General Principles: Guide B – Design, installation, maintenance and inspection of lightning protection systems, IEC, 1998

[11] SABS IEC 1312-1: "Protection against lightning electromagnetic impulse, Part 1: General Principles, IEC, 1995

[12] SABS IEC 0313: "The Protection of structures against Lightning, IEC, 1999

[13] Allibone, T.E., A review of lightning as a natural phenomenon, pp. 1.1.1 to 1.1.15, ERA Report no. 87-0328

[14] Malan, D. J., The physics of Lightning, University of the Witwatersrand, Johannesburg, 1963

[15] Berger, K, Anderson R.B., Kroninger, H., Parameters of lightning flashes, Electra 41, pp. 23 – 37, 1975

[16] Heidler, F., Drumm, F., Hopf, C., Electric fields of positive earth flashes in near thunderstorms, ICLP, pp. 42 – 47, September 1998

[17] Garbagnatti, E., Marioni, F., LoPiparo, G., Parameters of lightning currents. Interpretation of the results obtained in Italy. 16th ICLP, Budapest, report R-1.03, 1981

[18] Popolansky, F., Lightning current measurement on high objects in Czechoslovakia, 20th ICLP, Interlaken, report 1.3, 1990

[19] Goto, Y., Narita, K., Komuro, No., Honma, N., Current waveform measurement of Winter lightning struck an isolated tower, 20th ICLP, Interlaken, report 1.9, 1990

[20] Miyake, K., Suzuki, T., Shinjou, K., Characteristics of winter lightning currents on Japan sea coast, IEEE Transactions on power Delivery, Vol. 7, No. 3, pp. 1450 – 1456, 1992

[21] Ishii, M., Shimizu, K., Hojo, J., Shinjo, K., Termination of Multiple-stroke flashes observed by electromagnetic field, ICLP, pp. 11 – 16, September 1998

[22] Shindo, T., Asakawa, A., Yokota, T., Sakai, T., Characteristics of lightning strokes to a high stack in winter season in Japan, ICLP, pp. 54 – 59, September 1998

[23] Orlov, A.V., Syssoev, V.S., Temnikov, A.G., Vereshchagin, I.P., Investigation of the probability of upward leaders generation on electrode system situated in the electric field of a charged aerosol cloud, ICLP, pp. 66 – 71, September 1998

[24] Eriksson, A. J., Lightning and Tall structures, Trans. SAIEE, Volume 69, pt. 8, pp 238-252, Aug 1978

[25] Anderson, R.B., Eriksson, A.J., Kroninger, H, Lightning and tall structures – some preliminary observations, 4th Int. Conf on Gas Discharges, IEE Conf Publications No 143, September 1976

[26] Geldenhuys, H. J., Eriksson, A.J., Bourn, G.W., Fifteen years of data of lightning Current Measurements on a 60m Mast, Trans. SAIEE, pp 98-103, September 1989

[27] Eriksson, A.J., A Reply to Discussion on paper: "Lightning and tall structures", Trans. SAIEE, Volume 70, No. 5, May 1979

[28] Anderson, R.B., Eriksson, A.J., A Summary of Lightning Parameters for Engineering Applications, Cigre Ish. Paper no. 33-06, pp. 1 – 12, Aug-Sept. 1980

[29] Uman, M.A., McLain, D.K., Fischer, R.J., and Krider, E.P., Currents in Florida lightning return strokes, J Geophys Res, Vol 78, No. 18, pp. 3 530 – 3 537, June 1973

[30] Rachidi, F., Janischewskyj, W., Hussein, A.M., Nucci, C.A., Guerrieri, S., Chang, J.S., "Electromagnetic fields radiated by lightning return strokes to high towers", ICLP, pp 23 – 28, September 1998

[31] Willett, J.C., Bailey, J.C., Idone, V.P., Orville, R.E., Eybert-Berard, Barret, L., "Submicrosecond intercomparison of radiation fields and currents in triggered lightning return strokes based on the "transmission-line model"", J. of Geophys. Res., Vol. 94, pp13275 – 13286, 1989

[32] Rakov, V.A., Thotaphillil, R., Uman, M.A., "On the emperical formula OF Willet et al relating lightning return stroke peak current and peak electric field", J. of Geophys. Res., Vol. 97, No. D11, pp11527-11533, July 1992

[33] Rachidi, R., Thotaphillil, R., "Determination of lightning currents from far electromagnetic fields", J. of Geophys. Res., Vol. 98, No. D10, pp18315-185321, October 1993

[34] Guerrieri, S., Heidler, F., Nucci, C.A., Rachidi, F., Rubenstein, M., "Extension of the two return stroke models to consider the influence of elevated strike objects on the lightning return stroke current and the radiated electric field", Rome Int. Conference on EMC, Sept. 1996

[35] Rusan, R., Janischewskyj, W., Hussein, A.M., Chang, J.S., Comparison of measured and computed electromagnetic fields radiated from lightning strikes to the Toronto CN Tower", ICLP, Florence, Italy, pp. 297-303, September 1996

[36] Guerrieri, S., Nucci, C.A., Rachidi, F., Rubenstein, M., "On the influence of elevated strike objects on directly measured and indirectly estimated lightning currents", presented at IEEE PES Summer Meeting, Berlin July 1997

[37] Diendorfer, G., Schulz, W., Lightning incidence to elevated objects on mountains, 24th ICLP, pp 173–175, Sept. 1998

[38] Diendorfer, G., Schulz, W., Fuchs, F., Comparison of correlated data from the Austrian Lightning System and measured lightning currents at the Peissenberg Tower,, 24th ICLP, pp 168 - 172, Sept. 1998

[39] Janischewskyj, W., Hussein, A.M., Shostak, V., Propagation of lightning current within the CN Tower, International Cigre Colloquium on Insulation Co-ordination, Toronto, paper 33-2.10, September 1997

[40] Janischewskyj, W., Shostak, V., Hussein, A.M., Comparison of lightning electromagnetic field characteristics of first and subsequent return strokes to a tall tower: 1. Magnetic field ICLP, pp 245 – 250, September 1998

[41] Janischewskyj, W., Hussein, A.M., Wiacek, M., Chang, J.S., "Details of Canadian National Tower flashes utilizing a Digital high-speed camera", ICLP, pp 101 – 106, September 1998

[42] Abdel-Rahman, M., Janischewskyj, W., Hussein, Rachidi, F., Chang, J.S., "Statistical analysis of magnetic fields due to CN Tower multi-stroke flashes", ICLP, pp 107 – 112, September 1998

[43] Hussein, A.M., Janischewskyj, W., Mileswki, M., Shostak, V., Chang, J.S., Chisholm, W., Return stroke current waveform parameters of lightning to the CN Tower (1991 – 2001), ICLP, pp. 161 – 166, September 2002

[44] Bermudez, J.L., Rachidi, F., Janischewskyj, W., Hussein, A.M., Shostak, V., Rubinstein, M., Nucci, C.A., Chang, J.S., Joe, P., Nyffeler, M., Simultaneous measurements of electromagnetic fields at two distances and of current associated with lightning return strokes to the CN Tower, ICLP, pp. 155 – 160, September 2002

[45] Shostak, V., Janischewskyj, W., Hussein, A.M., Chang, J.S., Modelling of electromagnetic field associated with lightning return strokes to a complex tall tower, ICLP, pp. 167 – 172, September 2002

[46] Miki, M., Shindo, T., Rakov, V.A., Uman, M.A., Rambo, K.J., Schnetzer, G.H., Diendorfer, G., Mair, M., Heidler, F., Zischank, W., Thottapillil, R., Wang, D., Characterization of the initial stage of upward-initiated lightning, ICLP, pp. 14 – 19, September 2002

[47] D'Alessandro, F., Kossmann, C.J., Gaivoronsky, A.S., Ovsyannikov, A.G., Investigation of upward leader initiation in the high voltage laboratory, ICLP, pp. 259 – 264, September 2002

[48] Diendorfer, G., Mair, M., Schulz, w., Detailed brightness versus lightning current amplitude correlation of flashes to the Gaisberg Tower, ICLP, pp. 8 – 13, September 2002

[49] Rachidi, F., Bermudez, J.L., Rubinstein, M., Statistical evaluation of lightning current parameters from remote electromagnetic field measurements, ICLP, pp. 96 – 99, September 2002

[50] Wada, A., Asakawa, A., Shindo, Luminous phenomenon during upward leader development – lightning observational results at 200m high chimney, ICLP, pp. 3 – 7, September 2002

[51] Barański, P., Some properties of multiple stroke cloud-to-ground discharges in thunderstorms near Warsaw, ICLP, pp. 24 - 26, September 2002

[52] Fuchs, F., On the transient behaviour of the telecommunication tower at the Mountain Hoher Peissenberg, ICLP, pp. 36 - 41, September 1998

[53] Redelinghuys, M.G., Consideration of the optimization of Transmission Lines using data from a Lightning Position and Tracking System (LPATS), School of Electrical and Information Engineering, University of the Witwatersrand, Johannesburg, 1996

[54] LPATS, Eskom Transmission Centre, Simmerpan, Germiston, Johannesburg, 2003

[55] Ngqungqa S.H., Jandrell I.R., Britten A.C. : “A preliminary review of the influence of height on the incidence of upward leaders from tall structures”, SAUPEC, University of the Pretoria, Pretoria, 2003

[56] Ngqungqa S.H., Jandrell I.R., Britten A.C. : “A review of the influence of height on the incidence of upward leaders from tall structures: Some preliminary results”, SAUPEC, University of Stellenbosch, Stellenbosch, 2004