
ANALYSIS OF LIGHTNING PROTECTION RELIABILITY OF AN AIRCRAFT WHEN STRUCK BY LIGHTNING SURGES

Ibeni, C.; Ahiakwo, C. O.; Idoniboyeobu, D.C & Braide, S. L
Department of Electrical Engineering,
Rivers State University,
P. M. B. 5080, Port Harcourt, Nigeria.

ABSTRACT

The activities of lightning incidence occurrence daily, monthly, annually have recorded an extreme destructive impact particularly to the study zone (Omuagwa International Airport Port Harcourt, Rivers State, Nigeria) under investigation. These constraints have made the airline operators to efficiently plan to schedule flight especially in the rainy season. This research is aimed at employing reliability technique in order to estimate and predict lightning parameters including (shape or slope, scale or characteristics life and location parameters) that takes into considerations the lightning flashes thunder storms density prediction of the lightning-surges behaviour using weibull probability density functions in conjunction with the application of simple least-square techniques to determine the parameters of weibull distribution for purpose of directing aircraft zone for navigation in the event of probable uncertainties. Following records of data set the occurrence of lightning strikes occurs mostly during the presence of lightning thunder-storm under investigation which are normally influenced by natural phenomenon of vegetation, Rivers (surrounded by the study zone), temperature (heated up over time collected rivers water) these relationships are key determinants for the precipitation of rain and lightning thunder strike.

Keywords: Lightening, Strike, Aircraft, Weibull Distribution, Probability Values

INTRODUCTION

The phenomenon of lightning is one of the most destructive forces in nature that occurs on an average of about 8 million times a day causing extreme conditions to safety (Sun *et al.*, 2015). Lightning is a massive spark that results from the development of millions of volts between clouds or between a cloud and the earth. When lightning occurs, it is accompanied by an average current of 30,000 amperes and electric potential of several million kilovolts delivered within 100 microseconds (Mitchard, Jamoshid, Clark Carr & Haddad, 2016). With such a high degree of current and voltage, a lightning impact of less than a square centimeter could result in a powerful electromagnetic pulse that is capable of disrupting and destroying electrical and electronic systems.

While the effect of lightning is felt in virtually all electrical and electronic systems, its effect on an ascending or descending aircraft is most feared due to the conducting properties of aircraft structures (Mitchard *et al.*, 2016). It is on record that an average of one lightning strike is expected for each 3,000 hours of flight for commercial aircraft with a minimum of one lightning strike in a year (Mitchard *et al.*, 2016) as cited by (Lee & Collins, 2017a). When an ascending or descending aircraft is struck by lightning, induced currents and voltages on structures generate system upset. While most structures and modes of transport are designed to withstand lightning strikes with little adverse effect by the use of a variety of techniques that rely on creating a path to ground to safely divert lightning currents, the same cannot be said for aircraft. This is because aircrafts present a distinct set of design challenges, as it is difficult to establish a direct path to ground for an aircraft while ascending or descending.

Furthermore, even if a direct path is established for an ascending or descending aircraft when there is lightning, there is the fear that the aircraft itself can initiate a conductive surface between the cloud and the Earth. More so, recent techniques in the design of aircraft increased its vulnerability to lightning strikes and bringing about newer challenges in the protection of aircraft. Rimal and Faba, (2017) are of the opinion that there is need to develop new ways that can accurately indicate the induced effect of lightning strike on aircraft arriving at or leaving the airport. This is because over the years full numerical simulation with accurate digital model of the aircraft considering its different structural materials have been elusive. The induced voltages in electrical and electronic circuits are increased due to the need for the consideration of such factors as diffusion process, aperture coupling as well as its effect on future aircraft which is more complex in internal architecture (Rimal & Faba, 2017).

With the risk analysis of electromagnetic and environmental effect of lightning on aircraft being a major concern to the aviation industry, efforts have continued relentless at finding a lasting solution to reduce to the barest minimum, the damaging effect of lightning (Lee & Collins 2017b). The electromagnetic energy coupling system that could have adverse effects on aircraft have been summed into three major components namely the electromagnetic energy source, the electromagnetic energy transfer path and the electromagnetic energy receptor (Lee & Collins, 2017b).

Lightning protection reliability is an important aspect of every operations of the aviation industry particularly to the aircraft flight engagement that seriously requires accurate design for the occurrence of lightning strike on the view to assure the safety of the aircraft system, lives and properties etc. Since there is no control in the natural occurrence of lightning strike incidence to respective geographical locations and seasons, thus there is strong need for mitigation techniques and prediction of daily, monthly and annual thunder lightning flames occurrence that may result into loss of lives etc.

Essentially, the high risk of danger due to lightning strike uncontrollably necessitate minimizing the critical touch voltage in the operating circumstance of the lighting arrestor and diverters. This means that an explicit and detail predictions analysis strategies of flash density for geographical zone particularly to the study case (Umuogba International Airport) are conducted on daily, monthly and annual basis on the view to effectively play, monitor, control the operations of the schedule time and periods.

MATERIALS AND METHODS

Formulation of Well Bull – Distribution Parameters

Probability theory and statistics, the weillull distribution are a continuous probability distribution. The two parameters Weibulldistribution estimation is given as;

$$f(v) = \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} \ell \left[-\left(\frac{v}{c}\right)^k \right] \quad (1)$$

where, shape or slope = k

the value ℓ is given as;

scale parameter = c

$\ell = 2.718$

β = shape or slope

δ = scale

$f(v)$ = consider a weillull distribution function to predict V for example, mathematically as;

or

$$f(v) = 1 - \ell \left[-\left(\frac{v}{c}\right)^k \right] \quad (2)$$

$$F(t) = \left(\frac{\beta}{\alpha}\right)^{\beta-1} \rho \left(\frac{t}{\alpha}\right)^{\beta} \quad (3)$$

where:

$$\alpha = \ell - \left[\frac{c}{m} \right] \quad (4)$$

$$c = \frac{\sum_{i=1}^N y_i}{N} - m \frac{\sum_{i=1}^N x_i}{N} \quad (5)$$

$$\beta = m = \frac{\sum_{i=1}^N x_i y_i - \sum_{i=1}^N x_i \sum_{i=1}^N y_i}{\sum_{i=1}^N x_i^2 - \frac{\left[\sum_{i=1}^N x_i \right]^2}{N}} \quad (6)$$

$$\beta = m = \frac{\sum_{i=1}^N x_i y_i - \sum_{i=1}^N x_i \sum_{i=1}^N y_i}{\sum_{i=1}^N x_i^2 - \frac{\left[\sum_{i=1}^N x_i \right]^2}{N}} \quad (7)$$

$$MTBF = \alpha \Gamma \left(1 + \frac{1}{\beta} \right) \quad (8)$$

Case 1: Determination of number of Lightning days, Cloud to Ground (CG) for Prediction of Lively Occurrence

$$\text{Number of lightning days (CG)} = \frac{\text{Total number of thunder storm day}}{n} \quad (9)$$

Case 2: Determination of Flash due to Groundflash Density (GFD)

According to Anderson, the expression of ground flash density as a function of thunder day (T_α) or Keraunic level or thunder hour (T_h) are given as;

The ground flash density (n_g):

$$n_g = 0.04 T_\alpha^{1.25} \text{ flashes km}^2/\text{year} \quad (10)$$

and

$$n_g = 0.054 T_h^{1.1} \text{ flashes km}^2/\text{year} \quad (11)$$

Optimal Estimation of Weibull Distribution Parameter for Lighting Flash Density

The rate of failure and Mean Time Between Failure (MTBF) are considered as the key parameters of reliability analysis technique which are estimated using Weibull distribution function. Since Weibull distribution has the capacity to model, analyse failure rates, forecasting failures in modeling of failures and system process. The distributions are features by three parameters of shape (β) or slope, scale (α) and location (η) respectively. The least square technique is used for the estimation of weibull distribution parameters. Following the provision technique in the estimation of weibull parameters, the average rating method are also used through statistical data regarding to frequency and number of failure according to the equation;

$$Fi = \frac{i-0.3}{(N+0.4)} \quad (12)$$

Where;

Fi : average rank of occurring

i : failure of occurrence

For each individual component i , is adjusted rank of age of failed component N – total ranking number of component.

The Weibull parameters (β, α and η) are determined using the equation of a straight line (least square method), as:

$$y_i = m x_i + c \quad (13)$$

Where

$$\alpha_i = I_n(ti) \quad (14)$$

Where ti is independent age (year) of failed component in rank i .

$$\text{Thus, } y_i = \ln \ln \left[\frac{1}{1 - Fi} \right] \quad (15)$$

Essentially from least square techniques, the major components of weibull distribution are estimated the Weibull shape parameter as given,

$$\beta = m = \frac{\sum_{i=1}^N x_i y_i - \sum_{i=1}^N x_i \sum_{i=1}^N y_i}{\sum_{i=1}^N x_i^2 - \left[\sum_{i=1}^N x_i \right]^2} \quad (16)$$

$$\sum_{i=1}^N x_i^2 - \frac{\left[\sum_{i=1}^N N_i \right]}{N} \quad (17)$$

Similarly the intercept (C) is characterized as

$$C = \frac{\sum_{i=1}^N y_i}{N} - m \frac{\sum_{i=1}^N x_i}{N} \quad (18)$$

The life or scale Weibull parameters (α) can be determined as;

$$\alpha = \rho^{-\left[\frac{C}{m} \right]} \quad (19)$$

The Weibull probability distribution function (t) shows probability of failure in certain time (t) given as:

$$F(t) = \left(\frac{\beta}{\alpha} \right) \left(\frac{t}{\alpha} \right)^{\beta-1} \rho \left(\frac{t}{\alpha} \right) \quad (20)$$

The boundary condition for Weibull parameter given as;

$$\begin{aligned} \alpha &> 0 \\ \beta &> 0 \\ 0 &\leq t < \infty \end{aligned} \quad (21)$$

Thus, the cumulative distribution function $F(t)$ shows the probability of failure with respect to time (t) is presented as;

$$F(t) = 1 - e^{-\left(\frac{t}{m} \right)^\beta} \quad (22)$$

Boundary conditions are:

$$\begin{aligned} \alpha &> 0 \\ \beta &> 0 \\ 0 &\leq t < \infty \end{aligned} \quad (23)$$

The reliability function $R(t)$ will show probability of remaining intact till the time (t) and the rates of failure $\lambda(t)$ are presented as:

$$R(t) = 1 - F(t) = \rho - \left(\frac{t}{m} \right)^\beta \quad (24)$$

And ;

$$\lambda(t) = \frac{f(t)}{R(t)} = \left(\frac{\beta}{\alpha} \right) \left(\frac{t}{\alpha} \right)^{\beta-1} \quad (25)$$

The shape parameter β affects the shape distribution curve. Therefore the shape parameter was changed, the curve of $f(t)$ varies in different shapes. Essentially for example the curve turns to exponential distributions when $\beta = 1$, similarly it will resemble the raylight distribution when $\beta = 2$ and evidently represents normal distribution when $\beta = 3.5$ respectively. That is failure rate is decreasing while $\beta < 1$, it means components is its early failure. Also the failure rate is constant when $\beta = 1$ the component experiences occasional failures. Essentially the failure rate will be increasing when $\beta > 1$ than the component in the loss failure condition.

Mean and Standard Deviations of Weibull Distribution

The Weibull distributions are defined in terms of shape and scale parameters given as;

$$\mu = \alpha \Gamma \left(1 + \frac{1}{\beta} \right) \quad (26)$$

Similarly,

$$\mu^2 = \alpha^2 \left[\Gamma\left(1 + \frac{2}{\beta}\right) - \Gamma^2\left(1 + \frac{1}{\beta}\right) \right] \quad (27)$$

Where,

$\Gamma(\cdot)$: represents gamma functions, which could be estimated.

Hence,

$$\Gamma = \sqrt{2\pi} t^{(t-0.5)} \rho^{-t} \left(1 + \frac{1}{12t}\right) \quad (28)$$

RESULTS AND DISCUSSION

Case A: The figure 1 shows the plot of the failure rate of lightning occurrence against time. It is observed that the failure rate of lightning occurrence is increasing with time. It was also observed that the slope of the failure rate of the lightning occurrence curve decreases as the scale-parameter increases.

Following to the distribution in figure 2 that shows the 3D contour plot. The plot represent and shows values of the estimates of the three-parameter weibull distribution which vary along the contour axes. It is observed that moving from the bottom of the contour to the top, the value of the scale and shape parameters can be observed increasing gradually while the values of the location parameter is affected. That is the activities of lightning occurrences decreases with varying location and zone due to natural attraction of vegetation and river water around.

From Figure 3 the probability of failure of occurrence of lightning over time are presented. It is observed that the probability line is seen curved inward (concave down) while the adjusted (shifted) probability line is observed to be linear. The slope of the probability plot is decreasing at the beginning until it gets to the end of the plot.

Figure 4 shows a visualization that reliability was initially very high at the beginning but over time, it is seen to be decreasing. This means that of the activities of the rainy season in the study area gradually move to the dry season, the likelihood of lightning thunderstorm also reduces, which is one of the principal components of lightning occurrence, due to geographical location, season etc. Thus there will be gradual drop in reliability.

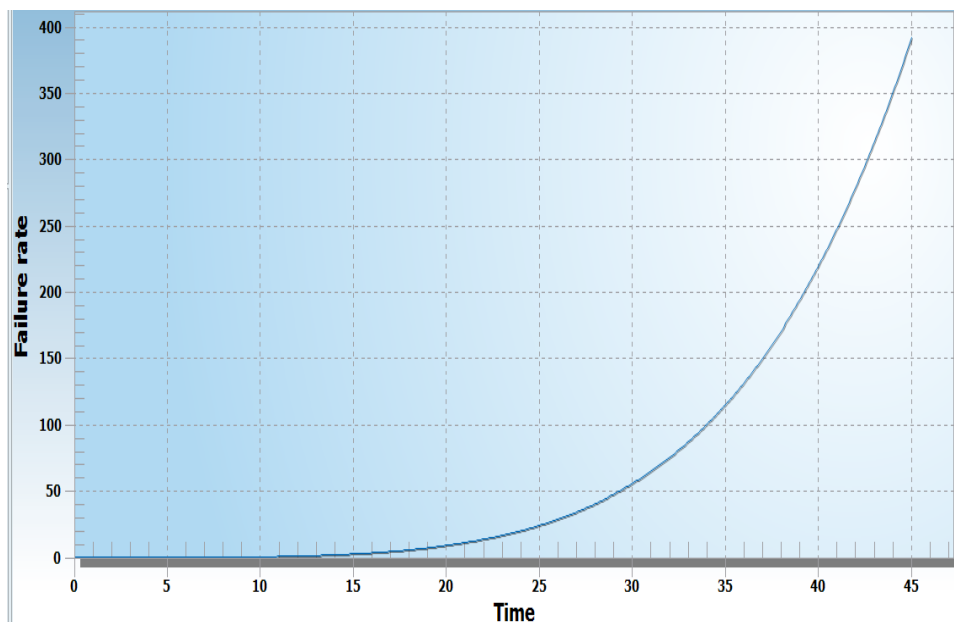


Figure 1: Failure rate of lightning in occurrence against time

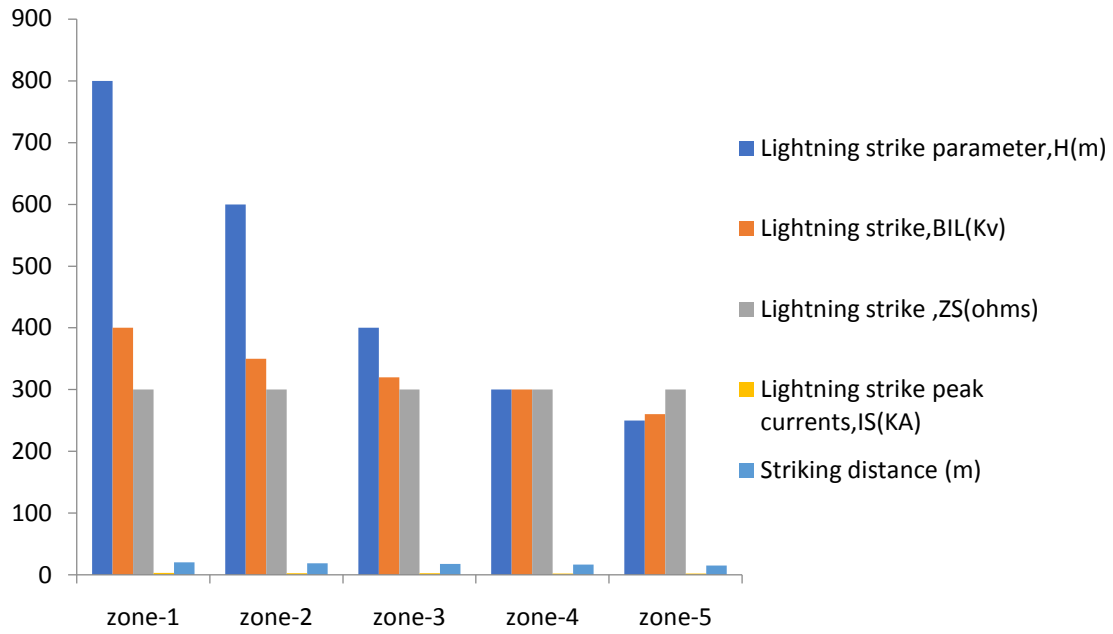


Figure 2: Composite lightning parameters with zones of occurrence

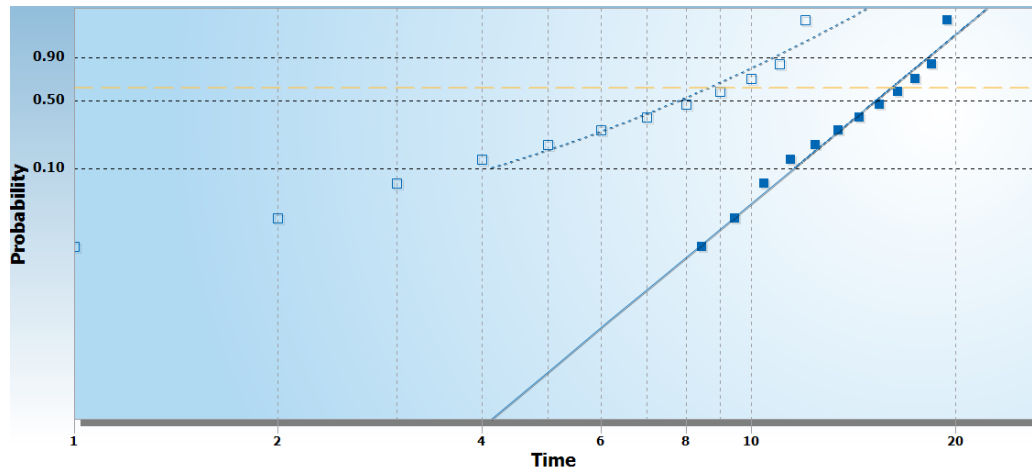


Figure 3: Probability of lightning versus time, blity with time

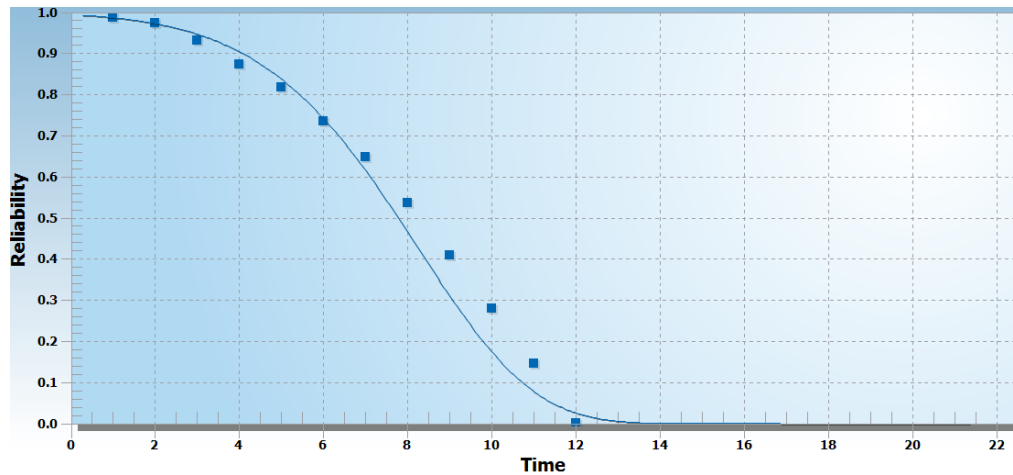


Figure 4: Reliability with time

Case B: Unreliability with Time

Figure 5 shows the presentation of unreliability with time, the occurrence of lightning incidence are not feasible at most case especially during rainy season that might attract lightning occurrence. The unreliability plots show the activities of lightning that is not duly observed during dry season.

The figure 6 shows the probability distribution function (PDF) versus time. From the plot, the probability density function (PDF) is observed increasing steadily up to a certain time, $t =$ shows, but from this point further a sharp decrease in the probability density functions, that is the activities of rainfall increases from a point to a point of decrease, where the tendency or likelihood of thunder storm becomes minimal.

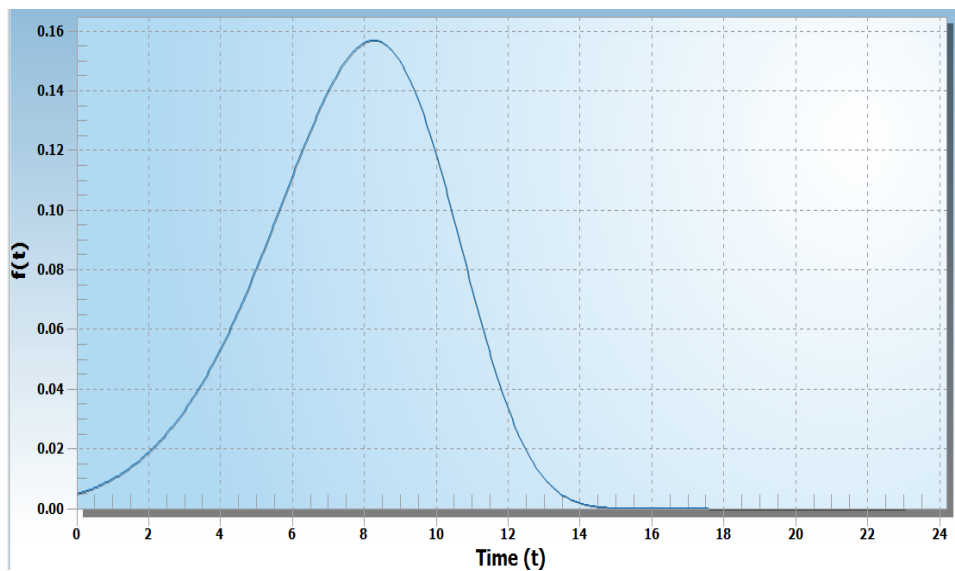


Figure 6: Probability distribution function (pdf) versus time

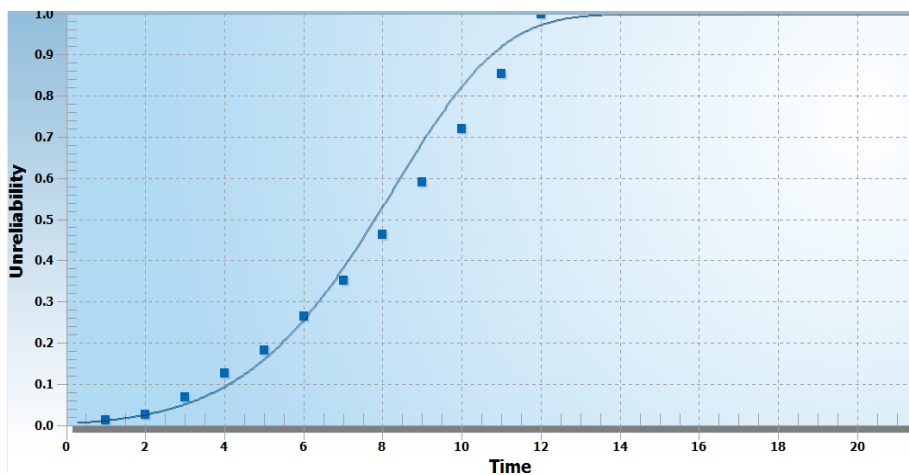


Figure 5: Unrelia

CONCLUSION

The lightning occurrence due to adverse condition of thunderstorm in the study area (Omagwa International Airport) has reached to the point of major concern to predict and estimate lightning strike parameters particularly to enable designers to put strong

consideration to lightning protection equipment, aircraft for commercial flight operations, going to the national and international standard of national agency of space and administration (NASA) and space meteorologist which are based on lightning current measurement, lightning strike distance, lightning strike peak currents etc.

This research work has considered the determination of total manager of flashes for 2010-2020, flashes due to cloud to ground, 122 for the year 2010, 100 for the year 2011, 97 for the year 2012, 112 for the year 2013 up to the year 2020 respectively. This study also adopted optimal estimation of weibull parameters of shape or slope, scale or life characteristics and location parameter at the point of latitude, this is in order to provide predictive program of commercial flight activities for improved aviation industry operation and engagement, significantly the data obtained from the study case, NASA, meteorological space technology centre are input data to estimate the principal components weibull probability density function, that is the shape ($\beta = 2.2246$) scale ($\alpha = 3.8472$) location ($\eta = 0.2773$). The lighting activities during daily monthly and annually measurement of thunderstorm are due to rating event which are used to determine the cloud to ground flash densities by the predictive technique of probability density function of time. This shows that the location understudy following to the calculated values of flash densities of Omuagwa international air-port aviation industry is a thunderstorm/rainy prone-zone which is one of the major parameter for the determination of lightning strike probable to aircraft structure lightning strike. The yearly calculated values of flashes within the zones have strong forces of attraction of rainy season.

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