Chapter 2
Thunderstorms and Pre-lightning Electrostatics

Abstract Lightning flashes are preceded by the development of electrified thunderclouds and the electrostatic fields that are generated by the electric charges distributed inside the thundercloud. In this chapter we discuss the thundercloud and the theories that seek to explain the origin of the electrically charged thunderclouds. We review the importance of the pre-lightning flash electrostatic fields for lightning protection design, as well as the importance to structures of reducing electric field stress that leads to electric discharges, when electrically stressed by the thundercloud's electrostatic fields. The chapter presents the computation of electrostatic fields in the thundercloud environment, with specific reference to aircraft, which is treated as a floating electrode that moves inside the electrostatic fields of the thundercloud. The numerical results are only illustrative of the application of the techniques, and not final values for the structures considered. The flying, electrically floating aircraft presents a far more complex structure to the thundercloud electrostatic and dynamic lightning interaction than stationary ground structures, such as buildings and electric power substations. The technique developed may handle changes in the pitch and roll angles of the aircraft, or of any other object, in a thunderstorm environment. All the techniques developed for the aircraft may be readily applied to simpler ground structures as well.

2.1 Introduction

The physical nature of lightning is best described as a sudden flow of electrical charge within a cloud or from cloud to air (or to another thundercloud) or from a cloud to ground. That is, for a lightning discharge to happen, there should be an electric breakdown caused by high electric fields, resulting in a flow of electrical charges (i) within a cloud which is referred to as the intra-cloud (IC) flash, or (ii) between clouds which is known as the cloud to cloud (CC) flash, or (iii) from cloud-to-ground (CG) flash, and or (iv) from ground to cloud (or upward) flash, which is referred to as the GC flash. The direct and indirect effects of a lightning flash can adversely sever the operations of ground systems (e.g. an electric power gird) and airborne systems (e.g.

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the navigation and control systems of aircraft). Direct effects through lightning flash attachment on structures (e.g. an aircraft or a house) can result in physical damages ranging from puncture/splintering in non-metallic structure, holes and burns, arcing, vaporization, melting, or joule effects such as fire. Similarly, indirect or induced effects through resistive and electromagnetic couplings are capable of generating high voltages and currents within command, control, communication, and power circuits severing operations of mission critical systems if no protection and shielding mechanisms are applied.

It is useful to first examine the physics of the formation of thunderclouds within the troposphere, in particular the cumulonimbus clouds which are the major producer of electric storms. There are several reasons for this. The first and foremost reason is the proximity of these thunderclouds to the earth and the fact that thunderclouds are the most common source of lightning flashes. It t is important to acquire good knowledge of the electrical characteristics of the lightning-producing clouds, in order to model and determine conveniently the magnitude of the capacitance and the electric charges induced. In Fig. 2.1 is shown the distribution of electric charges inside a thundercloud. The electric charge structure is important when designing and protecting structures and electric systems against lightning strikes, both with reference to their geometry, placement, and the materials used. Moreover, knowledge of the thundercloud electric charge structures is important when imitating lightning strikes inside a high voltage laboratory for testing purposes.

The magnitudes of the electric charges are influenced by the size, structure, and topography of the clouds. That is, the electrical structure of the clouds can be conveniently modeled based on the Gaussian imaginary surface in order to determine the

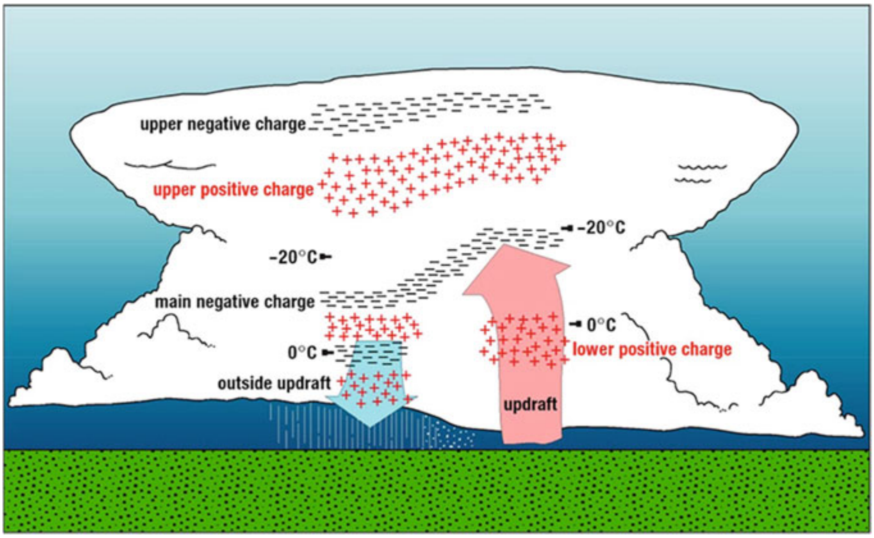


Fig. 2.1 Electric charge distribution in a thundercloud (Credit: NOAA, with permission)

capacitance and the induced electric charge of the thunderstorm clouds. This knowledge will become useful in electric circuit modeling, especially the (i) near-ground electrostatic perturbations, pre-breakdown of aircraft-thundercloud interaction and capacitance, and (ii) near-ground electrodynamics of aircraft interaction with lightning using capacitance determined for both metallic and non-metallic aircraft-body. Lightning is an atmospheric discharge of electricity. Lightning can occur in a thundercloud, volcanic eruptions, snow storm, and dust storms. In a typical thunderstorm of a negative CG flash, when the electric field in an electric charge-concentrated thundercloud exceeds the breakdown value, it will result in an impulsive transfer of electrostatic charge from the cloud base to the ground. The discharge takes place between two opposite charged regions, the base of a thundercloud which is of negative charge region, and the positive charges induced on the ground surface under the thundercloud. The discharge to ground can induce high current and electric potential through direct effects on a grounded structure, as well as on ungrounded structures such as an aircraft in flight. It can also be a source of electromagnetic pulses which cause indirect effects of lightning.

This chapter looks at pre-breakdown and electrostatic fields produced on structures (e.g. power line, aircraft or building housing sensitive electronics) under a thundercloud. In the case of a flying aircraft, the aircraft is a floating structure that is ungrounded and suspended in air between two electrically charged regions, the cloud and the ground. Since lightning strikes are not easily measureable, a predictive modeling is applied to model the pre-lightning discharges. A computational technique is applied based on three-dimensional (3D) dipole modeling of the pre-lightning strike and aircraft electrostatic environment. The 3D dipole model gives an accurate and succinct presentation of a lightning strike on a floating or ungrounded structures such as an aircraft in flight. The same computational technique presented in this chapter may be applied to electrostatic stress, for instance, on an outdoor, ground power substation under a thundercloud.

2.2 Formation of Thunderclouds

The classification of clouds is done using Latin cloud names based on physical appearances or shapes of the clouds. These classifications initially proposed centuries ago, are still used today with some modifications. The modern classification scheme is based on cloud shape and altitude. Generally the three main altitude classes are defined as low, mid-level, and high-level. From the three mentioned classes come the additional classifications based on the cloud types and combinations.

The cumulus clouds have several significant influences on life on earth: (i) they produce about 75% of the rain water that is much needed for survival on earth, (ii) they produce most of lightning flashes that contributes to the ozone layer build up through the ionization process, (iii) they are the sources of the fiercest winds on earth, the hurricane, the tornados, hailstorms, thunderstorms, and the squall lines, and (iv) the cumulonimbus clouds contribute to the overall earth's energy budget through the absorption via water vapor, and reflections of the sun's radiation through other particulates that exist within the clouds.

Cumulus clouds are also the major source of lightning flashes. Lightning is both destructive and needed for a healthy nature. The lightning flash (or electric discharge) contributes a relatively small portion to nitrogen fixation process where the gaseous nitrogen is converted into forms usable by living organisms. Moreover, the negative charges lowered by the lightning return stroke neutralizes the fair-weather buildup of positive charges on the surface of the earth.

The formation of the cumulus cloud sizes range from a relatively small portion of scattered clouds with no precipitations into the huge towering cumulonimbus (the rainstorm clouds). From the context of lightning cloud formation, the cumulus humilis is the first stage of thundercloud formation and then a significant transition into a deeper cumulus called the cumulus mediocris. The next stage of the development process reaching into a towering stage is the cumulus congestus, often termed the towering cumulus. The special feature of the cumulus congestus is a tall tower-like formation with a flat top called the anvil.

Cumulus clouds are necessary for lightning to form. Lightning can occur in a cumulonimbus with precipitation to ground, or with no precipitation to ground often referred to as dry thunderclouds. The lightning occurring in a dry thunderstorm is often the cause of bushfires. Conversely, there have been reported cases of lightning occurring with the absence of cumulonimbus clouds through sandstorm, snowstorm, and volcanic plumes. Figure 2.2 shows a lightning flash associated with volcanic plumes (Fig. 2.2a) and lightning causing a forest fire (Fig. 2.2b). The Lightning flash shown in Fig. 2.2a did not originate from a thundercloud. The lightning flash shown in Fig. 2.2b originated from a thundercloud.

(a) (b)

Fig. 2.2 **a** Lightning occurring within volcanic plumes. **b** Lightning strike causing a forest fire. (Credit: NASA, USA)

2.3 The Climatology of Lightning

2.3.1 *Cloud Electrification*

The physical mechanism behind the formation of cloud electrifications still remains debatable. The phenomenology resulting in electric discharges that cause lightning flashes is still a mystery. A number of theories have been proposed to explain the formation of cloud electrification process. However, it is difficult to deduce a definitive explanation due to the range of the distance scales between the micro-scale of the physical processes concerning the cloud hydrometeors (water particles) and the size of the thundercloud for the formation of electric charge distribution and clusters. A look at climatology of lightning will shed some light on the cloud electrification process. It is reported that clouds have to be 3–4 km thick before any electrification process takes place and the depth of the cloud is an influencing factor related to the electric charge and current intensities of lightning. Lightning is associated with convective activity. Cumulonimbus clouds are the largest form of convective cloud and typically produce lightning. Cumulonimbus clouds with lightning activity are generally referred to as thunderclouds. A brief discussion on the cloud electric charge formation and separation is given in the next section.

2.3.2 *Cloud Electric Charge Formation*

The process of electric charge buildup in thundercloud may be associated with moist air undergoing convection and precipitation resulting in the thundercloud. The convection process can lead to electric charge generation and separation in convective clouds. The presence of strong updrafts and the resulting development of precipitation are instrumental in the formation of an electric field of sufficient intensity for lightning discharge to take place.

There are two general theories that point to cloud electrification. These are the (i) inductive charging, and (ii) non-inductive charging processes. Each process is discussed in brief to shed some light on the mystery of cloud electrification process.

Inductive electric charging: This process will only induce cloud electrification in the presence of some pre-existing electric fields. The pre-existing electric fields that exist, apart from the fields generated by external sources in space such as solar storms and other cosmic radiation sources, will be the fair-weather field and other radiated fields on earth. The existence of a fair-weather field ensures that water particles suspended in the atmosphere in thunderclouds will become polarized.

The inductive charging mechanism is based on the ion capture theory of thunderstorm charge separation. It depends on ions being attached to frozen or liquid hydrometeors in the presence of an electric field, which makes the particles polarized. The lower side of the drop attracts the negative ions and repels the positive ions. In vertical, downward directed field (conventionally defined to be negative electric field), such polarization will cause an excess of positive charges to accumulate in the lower part of the particle, while negative charge will be located in the upper part. While the particle drops it will meet negatively and positively charged particles. Since the lower part is positively charged, negatively charged particles are attracted by the falling droplets, while positively charged particles are pushed away. As a result, the particle grows and becomes more negatively charged. This leads to a cloud with positively charged particles at the upper part and negatively charged particles at the bottom.

Non-inductive electric charging: This refers to those charging processes which are indifferent to the presence of an external electric field, and whose efficiency is not impacted by its strength. The two main mechanisms are: (i) the convection mechanism and (ii) the graupel-ice mechanism.

Non-inductive convection mechanism: This process is where the sources of positive and negative charges are considered to be external, that is, via fair-weather space charges, natural radioactivity near the land surface and cosmic rays near the top of the cloud. The positive electric charges near the ground are carried via warm air updrafts to the top of the growing cumulus. As a result, negative charges—produced by the cosmic rays at the top of the cloud—are attracted and attached to the cloud's boundary. Subsequent cooling and convective circulation result in downdrafts that are assumed to carry the negative charges down the side of the cloud towards the cloud's base. The positive space charges are ingested into the cloud. A negative screening layer forms around the cloud particles on the outside boundary, which moves down the sides towards the cloud base. Additional positive charges are further ingested at the base, and further negative charges flow to the upper cloud boundary to replace the loss of the screening layer charges that flowed to the cloud base along the sides. The lower accumulation of negative charges increases the electric field strength to a magnitude large enough to generate positive corona from ground objects. The corona becomes an additional source of positive charge that feeds into the cloud.

Non-convection graupel-ice mechanism: There is a general consensus that the non-inductive electric charge separation is the dominant mechanism by which thundercloud electric charge centers are formed. This mechanism does not need an external electric field to create a charge on a particle. This electric charge separation mechanism takes place during interactions of ice crystals and graupel particles in the presence of cloud drops. When the rising ice crystals collide with graupel (soft hail), the ice crystals become positively charged and the graupel becomes negatively charged. The updraft carries the positively charged ice crystals upward towards the top of the storm cloud. The larger and denser graupel is either suspended in the middle of the thunderstorm cloud or falls towards the lower part of the thundercloud. The upper part of the thunderstorm cloud becomes positively charged while the middle to lower part of the thunderstorm cloud becomes negatively charged.

Further, it is experimentally found that at certain liquid water content, cloud conditions, and temperature called the reversal temperature T_R, the graupel and ice crystal charge signs reverse. As a result, the smaller ice crystals become positively charged and carried to the upper regions while the larger graupel particles become negatively charged and descend relative to the smaller particles, after collision. Thus, the charge transfers during encounters of ice crystals and graupel will lead to the normal polarity usually found in the observations of terrestrial clouds.

These theories of inductive charging and non-inductive charging seem to be the two generally acceptable theories of cloud electrification despite no proven laboratory experimentations to date to justify these theories. Thus, the two theories remain debatable.

2.4 Negative Lightning Discharge Process

2.4.1 The Negative Lightning

As highlighted in Sect. 2.3, cloud electrification is simply a result of the buildup of electrostatic charges, of different polarities, within the cloud. A fundamental property of electric charge is the force that it exerts on other charges. An electric charge exercises a repelling force on another charge of the same sign as itself and attracts charge of the opposite sign. A region of forces called an electric field surrounds an electric charge. In a cloud-to-ground or negative flash, a positive charge is usually at the top of the cloud with negative charge in the base. There is a cluster of positive charges that resides at the base resulting in the tripole charge buildup. The electric field at the base of the cloud is of the order of 5×10^4 V/m[1]. However, for air to become ionized and gas electric discharge to initiate a leader in the pre-breakdown stage, the electric field intensity has to be above the critical electric field of about 3×10^6 V/m (3000 kV/m) for dry air at sea level and half this value at heights up to 6 km. However, at high altitudes, with reduced air density, the breakdown electric field may occur at 500 kV/m or 600 kV/m.

The negative lightning discharge process is discussed in relation to the cloud-to-ground lightning flash, since it comprises the majority of lightning flashes. Cloud to ground lightning flash makes up about 25% of the global lightning flashes and is referred as a high transient electrical discharge involving a thundercloud and ground. It includes many preliminary discharges or processes such as corona, stepped leader, streamers, inter-stroke process, dart (or dart stepped) leader, first and subsequent return strokes, and continuous current. Typically, a negative lightning flash to the ground may have more than one return stroke and other processes may occur prior to the first stroke, between consecutive strokes and after the last subsequent return stroke.

There are four major stages of a lightning flash. These are the pre-breakdown, the leader, the attachment process as it reaches an object on the ground, and the return stroke. The initial (first-stroke) leader is preceded by an in-cloud process called the preliminary breakdown. The details of mechanism of the preliminary breakdown process are not well known. However, it is believed that the preliminary breakdown process is attributed to the tripole vertical structure of the cloud charges that results in breakdown between the negative charge on the lower part of the cloud and a small pocket of positive charges that resides on that lower portion of the cloud. The formation of the clustered or a secondary small pole of positive charge, which occurs at the base of the thundercloud (see Fig. 2.1), is due to the warmer temperatures at the cloud base and the screening layer charge at the bottom of the cloud is ingested.

2.4.2 The Electric Discharge Process

The preliminary breakdown process generates a leader electric discharge channel which moves towards the ground. It starts as a slow-moving column of ionized air called the pilot streamer. After the pilot streamer has moved down by 30 m–50 m, a more intense discharge called the stepped leader takes place. Note that the 50 m long channel extensions occur rapidly in less than 1 microsecond duration. It takes about 60 ms for the stepped leader to travel a few kilometers from the cloud to near the ground. This corresponds to an average speed of 1×10^5 to 2×10^5 m/sec. Negative electric charge is carried from the main negative charge center and distributed along the length of the leader channel. Currents flowing in the leader channel range from hundreds of Amps to about 1000 Amps. The individual step, or extension of the leader channel, occurs in less than 1 microsecond.

The leader creates a conducting path between the negative cloud electric charge source region and ground. It distributes negative charge from the cloud source region along its path towards the ground. The quantity of positive electric charges residing on the earth's surface becomes even greater. These charges begin to migrate upward through buildings, trees, and tall structures. This upward rising positive charges - known as a **streamer**—approach the stepped leader in the air above the surface of the ground. The point where the leader and the streamer meet is the attachment point which paves way for the first return stroke. The first return stroke current measured at ground typically rises to an initial peak of about 30 kA in some microseconds and decays to half-peak value in some tens of microseconds. The return stroke effectively lowers to ground several Coulombs of electric charge originally deposited on the stepped leader channel including all the branches. It is possible for another leader to travel by the same channel that has been ionized by the stepped leader and the streamer. This leader is referred to as the dart leader which results in a subsequent return stroke. The time interval between the pre-breakdown and the subsequent return strokes could be about 62.5 ms.

The discussion so far has been based on the negative discharge leader from the cloud to ground which makes up about 25% of the global lightning. However, there can be positive leaders as well as a bipolar (both negative and positive) discharges from cloud to ground. Positive discharges make up about 10% of the cloud-to-ground flashes and account for the highest recorded lightning current of about 300 kA. Further, positive flashes usually comprise a single return stroke, compared to the negative lightning flash which produces two or more return strokes. Bipolar discharges of positive and negative polarities often occur in lightning flashes. The bipolar discharges may be divided into three types. The first is associated with polarity reversal in slowly varying (in milliseconds) current components such as those in continuous current components. The second type is characterized by the different polarities of the initial stage currents and the following return strokes. The third type involves return strokes of opposite polarities. Current of different polarities can follow the same ionized channel to ground. But these are initiated by clouds of different charge polarities. Current amplitude as high as 31 kA has been measured for the bipolar discharge.

2.5 Lightning-Aircraft Electrostatic Interactions

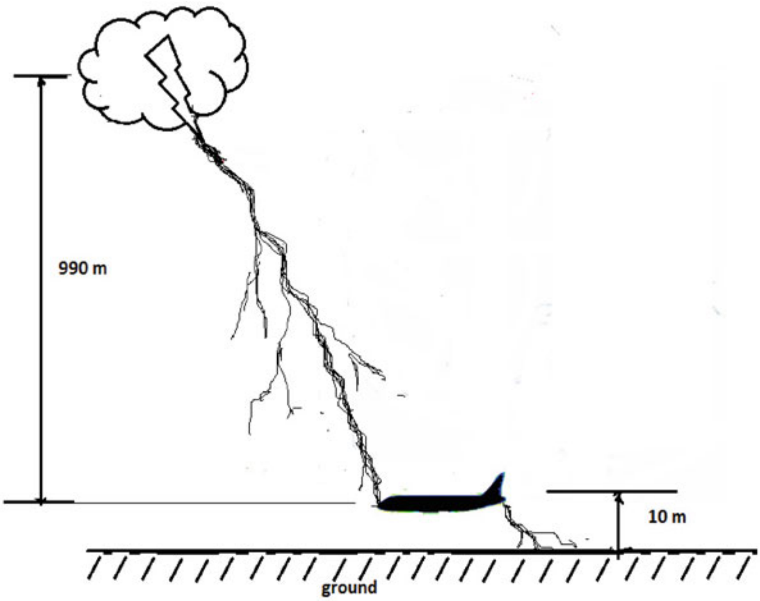
2.5.1 Two Types of Attachment Initiation

The aircraft-lightning attachments initiation are of two types. The first is the aircraft-triggered lightning flash and the second is the aircraft-intercepted lightning flash. The two attachment initiation processes are discussed separately in Sects. 2.5.2 and 2.5.3.

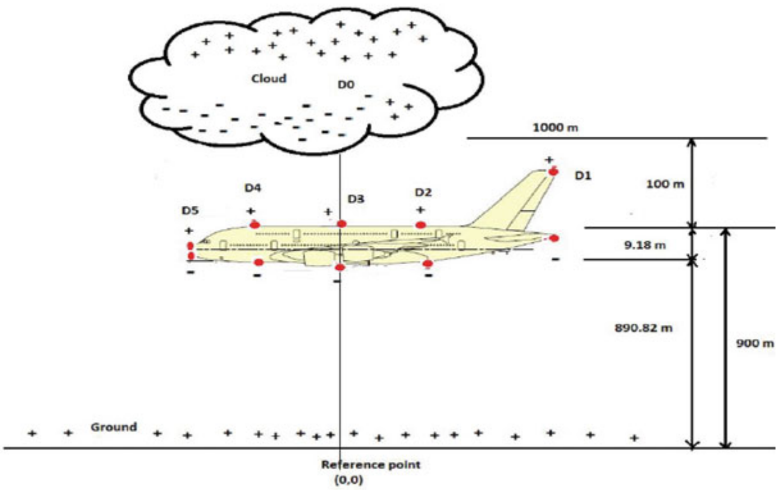
2.5.2 Aircraft-Triggered Lightning

An aircraft builds up electrostatic charges just by virtue of flying through the atmosphere as a result of friction or contact with electrified aerosols, dust, water vapor, and other atmospheric particulates. The aircraft lightning interactions begin when the aircraft approaches an electrified space or region of thundercloud formation. The entry of an aircraft into an ambient electric field can be regarded as a sudden introduction of a conductor into an electric field which intensifies the local electric fields around the conductor. This enhances the local electric field buildup. The electric field enhancement will reach a maximum along the aircraft extremities that are oriented towards the ambient fields. Typically, in an ambient field of 100 kV/m, the electric field at the radome could be enhanced to 1 MV/m 1000 kV/m); similarly at tail tips. The electric field at the wing tips could rise to 400 kV/m, and to 200 kV/m at the tips of the turbo engines.

The electric charging of the aircraft produces a potential gradient between it and its surroundings. When the potential gradient builds up to a sufficient level corona discharge results. The corona discharges occur at the extremities of the aircraft and initiate a bi-directional leader that connects the cloud electric charge center electrically to ground, through the aircraft. This is shown in Fig. 2.3a. Hence, there are two distinct phases to lightning-aircraft interaction. The first is the development of streamers and leader sets that develop at the field enhanced parts of the aircraft. The second phase is the high currents produced by the first and subsequent return strokes, once the leaders connect the aircraft to the cloud at one end, and to the ground at



(a)



(b)

Fig. 2.3 **a** Lightning strike to an aircraft. The thundercloud is connected to the ground through leaders at two attachment points on the aircraft (e.g. at radome and tail). **b** Pre-lightning scenario. A 2D polarized dipole along an aircraft (diagram not to scale) the other end. The second phase, therefore, induces the high energy transient current pulse, subsequent restrikes, and the long duration of the slow currents.

2.5.3 Aircraft Intercepted Lightning

An aircraft can also be exposed to a naturally occurring lightning strike. A naturally occurring lightning strike begins with a leader generated from the cloud base (for a cloud-to-ground lightning strike) and propagates downwards to ground. It may be intercepted by an approaching aircraft, in that the aircraft flies straight into an existing lightning leader. The electric field of the approaching leader intensifies about the aircraft extremities and emanates a leader connecting the naturally approaching lightning leader. Simultaneously, an additional leader emanates from other aircraft extremities connecting the ground (for a cloud-to-ground flash). The point on the aircraft that connects to the leader becomes the attachment point while that on the aircraft extremities which connects the aircraft to ground becomes the exit point (see Fig. 2.3a). The occurrence of aircraft intercepting lightning is very rare compared to that of aircraft triggered lightning incidence.

2.6 Probability of Lightning Strike to Aircraft

2.6.1 Factors Affecting Probability

The probability of an aircraft being struck by lightning depends on three influential factors. These include aircraft size, aircraft flight profile, and geographic area of operations.

2.6.2 Probability Dependence on Aircraft Size

There is a high lightning strike rate probability for large aircraft. This is due to the fact that a large aircraft entering an intense region of thunderstorm electric field would significantly modify the intensities of the field allowing lightning leader formation at a lower ambient electric field than it would be if there were no aircraft.

2.6.3 Probability Dependence on Flight Profile

The flight profile is another influential factor that increases the probability of lightning strike rate to an aircraft. That is, a lightning strike to an aircraft is a function of both the aircraft flight profile and the thunderstorm formation altitudes. Aircraft at a low altitude either in ascending or descending phases have an increased probability of being struck by lightning. It is further stated that aircraft flying short haul between closely situated cities flying mostly at low altitudes stand a higher chance of being struck by lightning. About 63% of lightning strikes to aircraft observed (based on 2700 lightning strikes to aircraft for the period 2002–2009) occurred during aircraft descent while 35% occurred in the ascending stage. Only about 2% of lightning strikes to an aircraft occurred at the cruising stage. The high percentage of strikes occurring during descent could be attributed to the fact that aircraft in flight over long distances on reaching their destinations when encountering a thunderstorm, would have limited fuel supply to reroute to other airports in proximity. Thus, there is no alternative to landing under the thundercloud. Further, there are certain policy restrictions limiting flights, for example, international flights, being allowed to land at certain airports only; e.g. at large international airports). In such circumstances an aircraft would inevitably have to land at the point of destination. Further, aircraft on the ground is usually delayed, and not allowed to take off, if a thunderstorm is hovering over the airport. Such are the probable reasons for the high percentage of lightning strikes to aircraft during descent compared to those while ascending.

2.6.4 Probability Dependence on Geographic Area of Operations

Thunderstorm formation is unevenly distributed with high frequency of lightning strikes occurring along the equatorial regions. Lightning activity is more continental than oceanic, with continental updrafts at 50 m/s producing more thunderclouds compared to the 10 m/s updrafts over the ocean. Moreover, intense lightning activity is seen to prefer dry climates (e.g. Africa) rather than wet climates (e.g. South America), although both regions may be close to the earth's equator. Surface temperature is seen to be a key to driving lightning activity. The average of lightning return stroke current peak is about 30 kA for land, while oceanic lightning strikes have current peaks exceeding 30 kA, since the attachment point on the sea surface has a much smaller resistance than attachment point resistance to land.

2.7 Thundercloud Induced Electrostatic Charges

For aircraft triggered lightning, the return stroke current is induced at the point where the upward leader from the aircraft extremity meets the downward cloud leader. Since an aircraft is in flight with no form of grounding, the aircraft leader is bi-directional, connecting the cloud charge electrically to ground via the downward leader. The stroke point where the first return stroke current originates can be either at the ground or on the surface of the aircraft. An aircraft-triggered lightning flash may be considered using the dipole theory and the corona discharge mechanism. For a cloud-to-ground negative flash, the charged cloud center and the charge on the ground can be represented by a dipole with the cloud monopole being negative and ground monopole positive. The electric field lines prior to breakdown emanate from the positive charge sinking at the negative charge forming uniform fields that can be estimated from:

$$E(-) = E(+) = \frac{Q}{4\pi\varepsilon_0\left(H^2 + r^2\right)}, \tag{2.1}$$

where E is the electric field, Q is the cloud electric charge, which can be determined from the cloud capacitance modeled on the Gaussian surface of the cloud voltage; ε_0 is the permittivity of free space, H is the height of the center of the charged cloud from the ground, and r is the radial distance of, say, a ground observation point from the charged cloud center. The electric field produced by the negative electric charge of the thunder cloud, E(–), is equal to the electric field produced by the positive electric charge image, E(+).

The electric field does not remain uniform when lightning discharge occurs in the presence of an aircraft as it enters the region between the two electric charges of the charged dipole. An aircraft entering a charged region would become electrically polarized. The electric charge build up on the aircraft surface would correspond to the polarities of both the ground charge and the cloud center. For a negatively charged cloud center, the charge on the top surface of the aircraft would be positive while that on the belly of the aircraft surface would be negative. The earth electric charge will be positive. This forms dipoles on the aircraft surfaces. Figure 2.3b shows the dipoles shown in small shaded circles (in red) on the top surface and on the belly of the aircraft. The electric fields will be large on the extremities of the aircraft with values estimated to be 100 times the ambient electric field. The high electric fields at the extremities can far exceed the ambient fields, causing a corona breakdown in the surrounding air producing a bi-directional leader that connects from one end of the aircraft to the cloud (or the stepped leader descending from the cloud) and the other end to the ground. When contact is made with the cloud stepped leader, a high-current discharge is generated that gives rise to the luminous brightness that is seen during lightning strikes known as the first return stroke current, a rapidly traveling (at 10^8 m/s) current (and intense light) pulse.

The high lightning current discharge travels from the lightning strike point to the charged cloud interlinking the two oppositely charged regions, thus neutralizing electric charges. The strike point can be located at an aircraft extremity such as the radome, wingtip, tail cones, or engines, and the stroke connects the aircraft to cloud and ground; or the strike point can be on the earth connecting the cloud charge through the aircraft to the earth strike point. The point at which a leader originates on the aircraft surface is referred to as the entry point or the attachment point. The point along the aircraft extremities where the leader propagates towards the ground is called the exit point.

After the return stroke, the lightning flash may end, if the thundercloud electric charge has mostly been lowered to the ground by the return stroke and the continuing current that flows immediately following it. That means that there is not enough electric charge left inside the thundercloud electric charge center to initiate another leader stroke electric discharge. But most negative flashes lead to three or four subsequent leader-return strokes—some even more than 15 subsequent strokes. During this time since the aircraft is moving, the subsequent strokes occur at different points on the aircraft body (producing multiple punctures) with the attached lightning channel being dragged along the aircraft surface. This is, for obvious reasons, called the swept stroke. Thus, if enough electric charge is available in the thundercloud to produce another lightning flash, a continuous leader called a dart leader moves down the return stroke channel from the previous stroke, depositing negative charge along its length. Dart leaders generally deposit less electric charge than stepped leaders. Thus subsequent lightning flashes generally lower less electric charge to the aircraft and to ground and have smaller return stroke currents than the first return strokes.

2.8 Pre-lightning Flash Electrostatics of Thunderstorms: Analysis

2.8.1 The Electrostatic Fields

The lightning flash involves rapidly changing, dynamic electromagnetic fields. However, before the generation of the leader and return strokes, the electromagnetic phenomena are static, that is, largely not changing in time. In this case, there are no magnetic fields, since the electric charges are largely stationary. The static electric field is of great interest to the engineering designer in two respects. First, it is the electrostatic field stress on ground and airborne objects that triggers initial electric discharges on the objects. The electric discharges are initiated at points where the electric (that is, electrostatic) field is large. Hence in all good design practice, the designer seeks to reduce the electric fields generated on objects by the nearby thundercloud which carries large amounts of static electric charges. These thundercloud electric charges generate the large electrostatic fields. Secondly, where the electrostatic fields induce large electric charges on objects and electronic circuits, local electrostatic discharges (ESD) and insulation breakdown may be initiated, causing the equipment and system to malfunction or breakdown. ESD is a major cause of concern to the microelectronic industry, with the use of microelectronic equipment and circuits (e.g. in digital signal processors, digital controllers, and networking), their use being widespread in airborne and ground systems, including critical mission, military, and medical operating systems. Scientists too are interested in the electrostatic phenomena associated with the thundercloud, since the electrostatic fields initiate the initial electric breakdown processes including the streamers, corona and the leader stroke. We explore the electrostatics of the thundercloud by considering the complex situation of an aircraft in the vicinity of a thundercloud.

2.8.2 Aircraft and Electric Dipole Placements

A study of the lightning induced electric field on an aircraft between thundercloud and ground either parked or in cruising, ascending, or descending flight mode is simulated using the dipole method and the cloud charge structure mechanism. The cloud charge is calculated based on the Gaussian spherical surface of the cloud electric charge center, while the charges on an aircraft are computed using the dipole method. The charge on the ground attains the same magnitude as the cloud charge but with opposite polarity, usually a positive polarity (for negative cloud-to-ground lightning flash). For an aircraft traveling below a charged cloud and ground, the totality of charges on its body is electrically neutral. That is, with equal distribution of mono poles of opposite polarities with separation distances equivalent to the aircraft geometry and component/body separation distances. For example, the separation distance of a dipole on the fuselage is simply the diameter of the fuselage separating the mono pole on the underbelly from the top surface of the fuselage whereas a dipole on the wing tip is separated by the thickness of the wing tips or the height of the winglets or sharklets on the wingtips. Thus, modeling an aircraft surface charges using the electric dipoles gives a succinct representation of the charge build up based on the aircraft geometry for the purpose of calculating the electric fields, the aircraft potential, and the capacitance. The electric dipole has charge separation distance d and charges $+q$ and $-q$. The method makes use of elementary theory of electrostatic induction on the distribution of charges within an object that occurs as a reaction to the presence of a nearby charge cluster (Hoole and Hoole, 1996). The analogy is applied to an aircraft as it goes through a charged electric storm causing migration of polarized charges on the surface with positive charges on the top for a negative cloud flash.

In order to model accurately the dipole on an aircraft, accurate dimensions of the aircraft airframe have to be used. In this case study, the A380 Airbus was modeled to assess the pre-breakdown electrostatic charges. Using the known geometry and dimensions of the aircraft, dipoles are placed on the surface as illustrated in Fig. 2.4a and b.

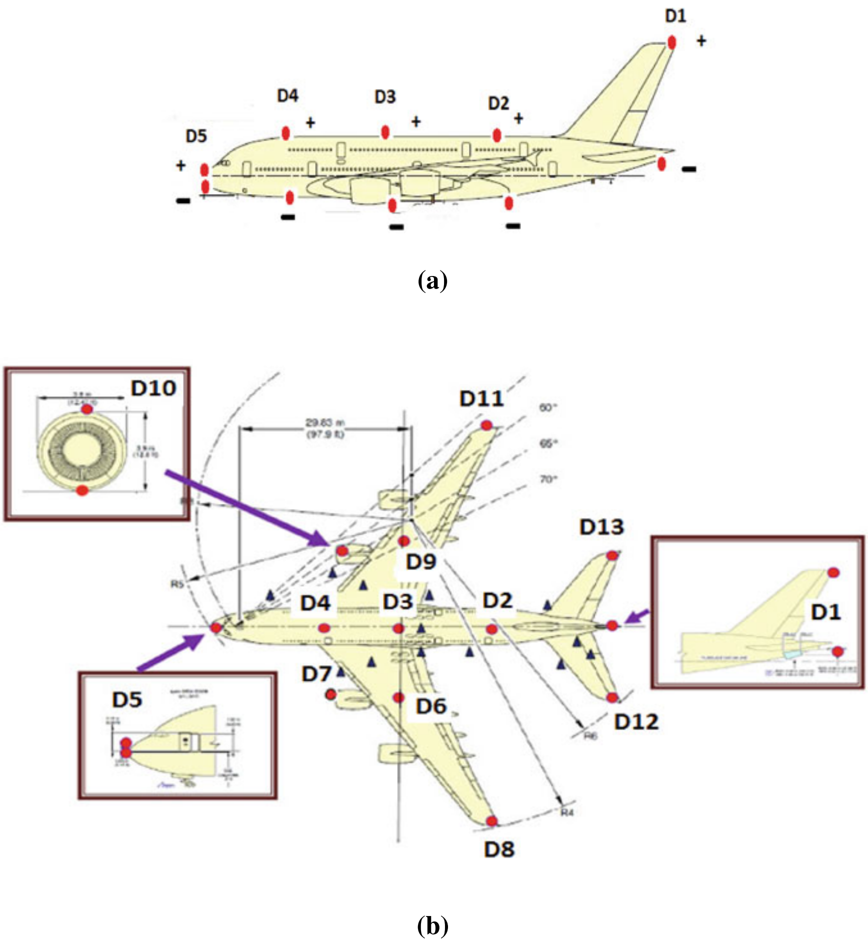


Fig. 2.4 An illustration of airbus A380 aircraft 3-dimensional 3D) dipole arrangements **a** dipoles along fuselage, rudder, and radome, and **b** dipoles along the wings and engines

There has been extensive research carried out by NASA and other research organizations to categorize and understand the electrical environment surrounding the thundercloud by either flying aircraft close to the electrified clouds and sometimes right into them. Amongst the aircraft used is the NASA Global Hawk aircraft which is mounted with instruments to measure and record electric fields, magnetic fields, electric currents, and voltages induced on the body of the aircraft as well as the internal electrical wiring of the aircraft that connects the communication, control, command, and power system of the aircraft. However, such research activity is expensive and is limited by the aircaraft sizes and payload capacity, and the size of the thunderclouds the aircraft flies into. The 3D dipole method has the advantage that it can give an analysis of the pre-breakdown stage (the electrostatic buildup) as well as the breakdown stage (the electrodynamics stage) of any aircraft in a lightning environment with different electric charge structures. The dipole method proposed allows for all kinds of aircraft to be tested and studied in a variety of positions and inclinations with respect to the electric charge centers inside the cloud, before the aircraft is struck by lightning which is the electrostatic stage of the aircraft-thunderstorm interaction. The dipole electric charges are placed on the aircraft surface, and once these electric charges are computed using the technique outlined in Sect. 2.7, the electric fields around the aircraft surface are easily determined, helping also electrically to zone better the aircraft body for structure reinforcement, optimizing the geometry against electric stress, protection measures and where to (and where not to) place sensitive electrical and electronic equipment inside the aircraft. The 3D dipole computational test-bed offers huge advantages in being able to test the whole aircraft with every detail of its body included under a realistically modeled thundercloud with electric charge centers that may be situated in complex arrangements. Both large commercial aircraft as well as smaller military aircraft, and large electric power substations as well as a single, isolated house, may be studied. Hence, more accurate zoning may be done with reference to the probability of lightning strike to different surface areas of say the aircraft or substation or house, which in turn will determine the areas to be most protected against lightning and on how to layout electrical and communication circuits with sensitive electronic navigational, communication and control equipment, as well as the electric power systems apparatus from earth electric power grids to aircraft electric power grids.

2.8.3 Determining the Electric Charges Induced on an Aircraft and the Electric Fields Generated Around an Aircraft Body

The 3D dipole model is used to calculate the aircraft voltage, the electric charge on the surface of the aircraft, and the electric field produced by these charges using Eqs. (2.2)–(2.7). The aircraft surface voltage is given by.

$$V_A = k \cdot q_{AD} \cdot \left(\frac{1}{r_+} - \frac{1}{r_-} \right), \tag{2.2}$$

where k is a constant, q_{AD} is the aircraft dipole charge, V_A, is the aircraft voltage. r_+ and r_- are the distances from the positive and negative mono poles and their images to a selected point on the aircraft surface.

Note that in (2.2), V_A and q_{AD} are unknown terms. The only known terms in the equation are the distances from the dipole to a selected coordinate or point on the surface of the aircraft and the separation distances of the mono poles which is placed according to the aircraft geometry, and the altitude of the aircraft, and the dipole mirror images (replacing the earth). Thus, since the aircraft is at an equipotential surface, the aircraft voltage V_A is the same at all points which makes the coupled equations easier to compute. The cloud charge is computed from the cloud capacitance using a given cloud charge diameter, for instance, 200 m. The cloud potential is taken to be -50 MV for a negative flash. The cloud geometry is assumed to be that of a spherical Gaussian surface.

The aircraft surface electric charge calculation makes use of the coefficients of potential of the electric dipole charges and their mirror images on the ground with reference to a selected observation point on the surface of the aircraft. Since the aircraft geometry is in 3D, three-dimensional distances (x, y, z) are used as defined in (2.3). That is, for a particular point, say p_1, on the aircraft surface, the distance from the center of a dipole to the point p_1 on the surface of the aircraft is given by (2.3). The angle between the midpoint of the dipole and the point p_1 is given by (2.4), with the angle measured with reference to an infinite, perfectly conducting plane, which is the ground plane. A similar equation is used in the calculation for the image dipole charges below an infinite ground plane. The electric dipole charges and their image charges are assigned different variables names in the equations.

$$dis\left(x_{p1},\ y_{p1},\ z_{p1}, k\right) = \sqrt{\left(x_{p1} - x_k\right)^2 + \left(y_{p1} - y_k\right)^2 + \left(z_{p1} - z_k\right)^2} \tag{2.3}$$

$$\theta_{p1}\left(x_{p1},\ y_{p1},\ z_{p1}\right) = \left[\cos^{-1}\left(\frac{\left(y_{p1} - y_k\right)}{dis\left(x_{p1}, y_{p1}, z_{p1}, k\right)}\right)\right], \tag{2.4}$$

where *dis* stands for the distance between centre of a dipole and an observation point on the surface of the aircraft, and θ is the angle subtended by the monopole and the observation point *p1* with respect to the ground plane. The general term for the coefficients of potential for the dipole charge is.

$$q_{ADCoeff} = \left(\frac{1}{dis\left(x_{p1}, y_{p1}, z_{p1}, k\right)}\right) - \left(\frac{1}{dis\left(x_{p1}, y_{p1},\ z_{p1}, k\right)}\right) + \\ + \left(\frac{1}{dis\left(x_{p1},\ y_{p1},\ z_{p1}, l\right)}\right) - \left(\frac{1}{dis\left(x_{p1},\ y_{p1},\ z_{p1}, l\right)}\right) \tag{2.5}$$

where $q_{ADcoeff}$ is the coefficient of the charge due to the dipole *k* on the surface of the aircraft and its image *l* within the earth. Note that q_{AD} is the dipole charge. Moreover, $q_{ADcoeff}$ is the coefficient of the dipole charge and its image, which are functions of the distance between the dipole charge and its image. The electric charge induced on the surface of the aircraft by the cloud electric charge and the other electric charges on the aircraft surface is given by

$$Q_n = \left(\frac{1}{q_{AD_{Coeffn}}}\right)\left((4 \cdot \pi \cdot \epsilon_0 \cdot V_A) - \begin{pmatrix} q_{AD_{Coeff1}} Q_1 + q_{AD_{Coeff2}} Q_2 + q_{AD_{Coeff3}} Q_3 + \ldots \\ \ldots + q_{AD} coeff_{\,n-1} Q_{n-1} \end{pmatrix}\right). \tag{2.6}$$

The equation for the aircraft voltage V_A at any point p on the aircraft surface due to n number of dipole charges is

$$\begin{aligned} q_{AD_{Coeff1}} Q_1 + q_{AD_{Coeff2}} Q_2 + q_{AD_{Coeff3}} Q_3 + \\ \ldots + q_{AD_{Coeff\,n}} Q_n = 4 \cdot \pi \cdot \varepsilon_0 \cdot V_A \end{aligned} \tag{2.7}$$

Rearranging (2.7), the charge Q_n (which becomes the subject of the equation) is given by (2.6). The variable Q_n is then substituted in the equation set for voltage for the next point p_2 in order to eliminate the Q_n. The next charge variable Q_{n-1} is defined and substituted in the equation set for voltage due to the next point p_2. The procedure is repeated for $(n + 1)$ points where n is the total number of dipoles that make up the aircraft dipoles. This is simply the process of solving a set of linear equations by the substitution method. The final equation is a single matrix equation comprising the charge coefficients and the aircraft voltage V_A. The aircraft voltage V_A is the only unknown term in the single matrix equation. This aircraft voltage is computed from the charge coefficients and finally the charges and the electric fields are determined.

A software test-bed was developed to calculate the charges and the electric fields at different points along the aircraft bodies for aircraft at various altitudes and at various distances from the charged cloud center. The results tabulated in Tables 2.1, 2.2, 2.3, 2.4, 2.5 are for the airbus A380 aircraft at various altitudes and distances from the charged cloud.

2.8.4 Analysis of the Airbus A380 Aircraft Results

Tables 2.1 and 2.5 show the results for the computed voltages, electric charges, and electric field strength for the Airbus A380 surface at various altitudes and distances from the charged cloud. The results indicate the areas with the highest electric fields exceeding the breakdown electric fields of 400 kV/m which have a high probability of triggering lightning flash. The breakdown electric fields primarily appear at the aircraft extremities at an average ambient aircraft electric field of about 75 kV/m. The electric field build up at these extremities that exceed the breakdown fields can cause the ionization of the surrounding air thus initiating an upward stepped leader capable of triggering a lightning strike. It is observed that areas of high electric fields include the radome, the wing tips and the middle parts of the wings, and the stabilizers.

Table 2.1 shows the results for an A380 airbus at an altitude of 800 m, that is, at 200 m directly below the charged cloud of −50MV for a negative flash to the

Table 2.1 Electric charges and electric fields for an airbus A380 at an altitude of 800 m directly below a charged cloud at 1000 m altitude

Computed Aircraft Voltage V_A: -2.172×10^7 V			
Dipole location and dipole number	Dipole charge (C/m)	Electric field (V/m)	Comment
Rudder tip	4.416×10^{-3}	2.412×10^5	
Mid-fuselage	3.013×10^{-6}	1.363×10^5	
Radome	1.999×10^{-4}	7.986×10^7	[a]Above Breakdown E-field
Mid-left wing	3.623×10^{-5}	3.514×10^5	
Left wing engine	6.406×10^{-5}	1.276×10^5	
Tip left wing	1.81×10^{-3}	1.252×10^7	[a]Above Breakdown E-field
Mid-right wing	4.875×10^{-5}	4.495×10^5	[a]Within breakdown
Right wing engine	7.489×10^{-5}	1.288×10^5	
Tip right wing	1.63×10^{-3}	1.127×10^7	[a]Above Breakdown E-field
Left stabilizer tip	2.877×10^{-3}	2.873×10^8	[a]Above Breakdown E-field (become possible entry point)
Right stabilizer tip	2.801×10^{-3}	2.798×10^8	[a]Above Breakdown E-field

[a]At high altitude with reduced air density, the breakdown electric field may be as high as 400 kV/m

ground. The aircraft electrostatic potential computed is –21.72 MV resulting in high electric charges and electric fields on the aircraft surface. The dipole electric fields calculated along the A380 aircraft show very high electric fields at the tip of the horizontal stabilizers, the tips of the wings, and at the radome. These electric fields exceeded the specified breakdown electric fields of 400 kV/m. The two extremities with the highest electric fields are most likely to initiate bi-directional leaders towards the charged cloud center to trigger a lightning flash connecting through the other extremities to ground. The left stabilizer is most likely to become the lightning entry point and the right stabilizer to be the exit point. However, with the aircraft moving with respect to the cloud, there is the possibility of a swept stroke path that can develop along the aircraft fuselage. The swept path can either be through the radome or the tips of either wing to ground These two extremities of the wings, like the radome, carry large electric charges and have high electric fields.

It is noted from Table 2.1 that the values of the electric charges and the electric field distribution along the aircraft surface are not symmetrically identical. This is attributed to the non-uniformity of the aircraft geometry and the distribution of points selected along the surface that are used in (2.2)–(2.6) to calculate the coefficients of the charges. This accounts for the slight variations in values of the electric fields and the charges. The electric fields at a point on an aircraft surface will be the vector sum of the collection of the electric fields due to the other dipole charges, the cloud charge, and the image charges. Thus, the slight variations observed in the values of the electric charges and the electric fields calculated.

Table 2.2 shows a similar trend for an aircraft at 500 m altitude with the charged cloud at 1000 m altitude, that is, 500 m directly above the aircraft. The extremities of high electric fields are the two horizontal stabilizers and the radome. The swept path for the lightning flash will be along the stabilizers and the radome. However, with the electrically charged cloud and the aircraft moving, the capacitance, and the charges may vary thus producing changes in the electric fields at the other extremities. The most likely swept path would be along the stabilizers through the fuselage and radome to ground. One of the stabilizer tips becomes CHECK the entry point while the radome becomes the lightning exit point as defined in normative zoning standards.

Further, Table 3.3 shows the results for an aircraft at an altitude of 800 m but at 1000 m distance away from the charged cloud. The charged cloud is at an altitude of 1000 m. The results show the build up of charges initiating very large electric fields at the horizontal stabilizers and the wing tips exceeding the breakdown electric fields of 400 kV/m. The possible entry point is most likely the left horizontal stabilizer. The swept lightning channel will be along the fuselage through the wing tips to ground.

Table 2.2 Electric charges and electric fields for an airbus A380 at an altitude of 500 m directly below a charged cloud at1000 m altitude

Computed Voltage V_A: -6.642×10^6 V			
Dipole location and number	Dipole charge (C/m)	Electric field (V/m)	[a]Comment
Rudder	3.007×10^{-4}	2.501×10^4	
Mid-fuselage	1.423×10^{-7}	2.045×10^4	
Radome	1.31×10^{-5}	1.309×10^6	Above Breakdown E-field
Mid-left wing	2.233×10^{-6}	2.838×10^4	
Left wing engine	3.72×10^{-6}	1.99×10^4	
Tip left wing	1.124×10^{-4}	7.781×10^5	Within breakdown
Mid-right wing	3.316×10^{-6}	3.591×10^4	
Right wing engine	4.335×10^{-6}	1.993×10^4	
Tip right wing	1.003×10^{-4}	6.941×10^5	Within breakdown
Left horizontal stabilizer tip	1.941×10^{-4}	1.939×10^7	Above Breakdown E-field (becomes entry point)
Right horizontal stabilizer tip	1.892×10^{-4}	1.89×10^7	Above Breakdown E-field

[a]At high altitude with reduced air density, the breakdown electric field may be as high as 400 kV/m

2.8.5 Zoning

The results given in Tables 2.4 and 2.5 show the electric fields at the aircraft extremities for the A380 airbus at an altitude of 800 m, but at a distance of 5 km and 50 km from the charged cloud, respectively. The electric field reaches 900 kV/m for the A380 aircraft at a distance of 5 km from the charged cloud center which exceeds the breakdown electric field. This field is capable of initiating a step leader when the aircraft moves close enough to the charged cloud. However, at a distance of 50 km, the electric fields are drastically reduced. This observation shows a distance of 50 km from a charged cloud is a safe distance to fly the aircraft.

The results in Tables 2.1, 2.1, 2.2, 2.3, 2.4, 2.5 were compared with the current practice in zoning of aircraft surfaces and geometrical shapes. The zones identify areas of high probability of lightning attachment depending on the electrostatic field enhancement due to electric charge build up in these areas. Moreover, there are other zones to which the probability of lightning attachment being swept from an original attachment point is high. It is also observed that the swept stroke path would occur along the extremities where large electric field build up occurs. That is, the lightning flash will be swept from one extremity with large electric field along the aircraft body to the other extremity with a large electric field, and discharge to the ground. Further, it is observed that the values obtained in the results may be used to identify and more accurately classify the zones during the aircraft design stages, including for lightning protection design. The electric field enhanced regions include the rudder, the stabilizers, the radome, and the wing tips. Further, the results show a safer distance for large aircraft such as the airbus A380 is about 50 km from the thundercloud, to avoid the generation of electric discharges. Fly by wire and non-metallic body aircraft designers are interested in the enhanced electric field areas of the aircraft body in order to divide the aircraft body into zones where threatening electric field enhancements and lightning strikes are highly probable, and zones with minimum probability of strikes. These are the regions to be avoided when placing mission critical navigational and control systems as well as microelectronic equipment. The severe cloud-to-cloud lightning strikes in which aircraft may get engaged is the most severe threat to navigational, microelectronic, and measurement systems.

2.8.6 A F16 Military Aircraft Flying Between Two Charged Centers

2.8.6.1 F16 Electric charge Model

Figure 2.5 shows the scenario under study where an F16 military aircraft is flying between two oppositely charged electric charge cells (or electric cloud centers). Since the aircraft is positioned inflight, and horizontal and between two electrically charged

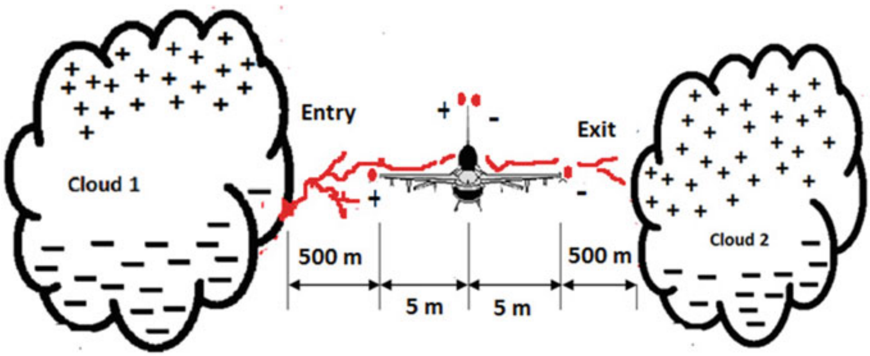


Fig. 2.5 An F16 military aircraft positioned between two charged clouds (Not to scale)

centers, or electric clouds, the dipoles are aligned horizontally with positive electric charges accumulating close to the negatively charged Cloud 1 and the negative charges positioned towards that of the positively charged Cloud 2. The tip of the aircraft wings is at a distance of 500 m from the charged clouds (on both sides). The F16 military aircraft is at an altitude of 1000 m just at level with the two 1000 m altitude cloud cells.

In Fig. 2.5, the electric cloud diameters are taken to be 200 m for Cloud 1 and 200 m for Cloud 2. The voltages are assumed to be −50 MV and +50 MV for Cloud 1 and Cloud 2 respectively. The F16 military aircraft is assumed to be at level between the two electric cloud cells of positive (Cloud 2) and negative (Cloud 1) electric charges. The cloud electric charges are calculated using spherical Gaussian surfaces. The capacitance and electric charge of Cloud 1 are calculated to be 1.11212×10^{-8} Farads and −0.556 Coulombs respectively. Similarly, the capacitance and the electric charge of Cloud 2 are calculated to be 1.11212×10^{-8} Farads and +0.556 Coulombs. From the horizontal placements of the dipoles as shown in Fig. 2.5, the positive monopoles are aligned horizontally towards the negative electric cloud cell (Cloud 1). Similarly, the negative monopoles are aligned horizontally towards the positive electric cloud cell (Cloud 2). The electric charges on the F16 military aircraft are then calculated from the dipole moment and the aircraft voltage. Finally, the electric fields are determined from the calculated dipole charges. Tables 2.1, 2.2, 2.3, 2.4, 2.5, 2.6 show the results for aircraft voltage V_A and the charges for dipoles on an aircraft surface with aircraft at various altitudes and separation distances from the two charged cloud cells.

2.8.6.2 Analysis of the F16 Military Fighter Aircraft Results

The results in Table 2.6 through Table 2.8 show the electric potential, the electric charges, and the electric fields for the F16 military aircraft flying between two separate electric cloud cells of opposite polarities (positive and negative voltages polarities).

Table 2.6 shows the results when the F16 military aircraft is flying between two electric cloud cells of -50 MV and + 50 MV. The separation distances from the aircraft wings to the two charged cloud cells are each 500 m from the two wings tips as shown in Figs. 2.5 and 2.6. The aircraft potential is 7.742×10^6 V. The electric fields are large at the extremities, the rudder tip, the wing tips, mid fuselage, and the nose boom (a slender metal extension projecting from the nose of the aircraft). The values of the fields are in the range of 10^7–10^9 V/m. The values are extremely high. In practice, these high values would never be reached as the breakdown would have occurred at 400 kV/m for ionization of air to occur. That is, the electric field would have reached a breakdown value before the aircraft reached the altitude to trigger lightning flash. Thus, flying between the separation distance of 500 m between the two electrically charged cloud cell centers is extremely dangerous for an F16 military.

Similarly, from Table 2.7, the potential for an F16 military aircraft at 1000 m altitude with the wing tips at a distance of 5000 m from the two charged cloud cells is 7.316×10^4 V. The high electric field occurred at the rudder tip and the nose boom. The values exceed the breakdown electric field of 4×10^5 V/m (or even lower) at higher altitudes. In practice, the breakdown down electric field would have occurred before reaching these two high values shown in Table 3.7. That is, the breakdown electric field would have probably occurred at electric fields exceeding the high altitude breakdown electric field of400 kV/m. Thus, for an F16 military aircraft within close proximity of a charged electric cloud cell at the potential of -50 MV with a separation distance of 5000 m, the electric field can build up towards the breakdown value.

2.9 Electrostatic Fields of Pre-lightning Thundercloud Environment

The results in Tables 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7 were compared with the current practice in zoning of aircraft surfaces and geometrical shapes. The zones identify areas of high probability of lightning attachment depending on the electrostatic field enhancement due to electric charge build up in these areas. Moreover there are other zones to which the probability of lightning attachment being swept from an original attachment point is high. The values obtained may be used to identify and more accurately classify the zones during the aircraft design stages, including lightning protection design. The electric field enhanced regions include the rudder, the stabilizers, the radome, and the wing tips for an airbus A380. Similarly, for an F16 military aircraft flying horizontally between two charged electric cloud cells, the accurately identified zones of high electric fields reaching breakdown are mainly the rudder and the nose boom.

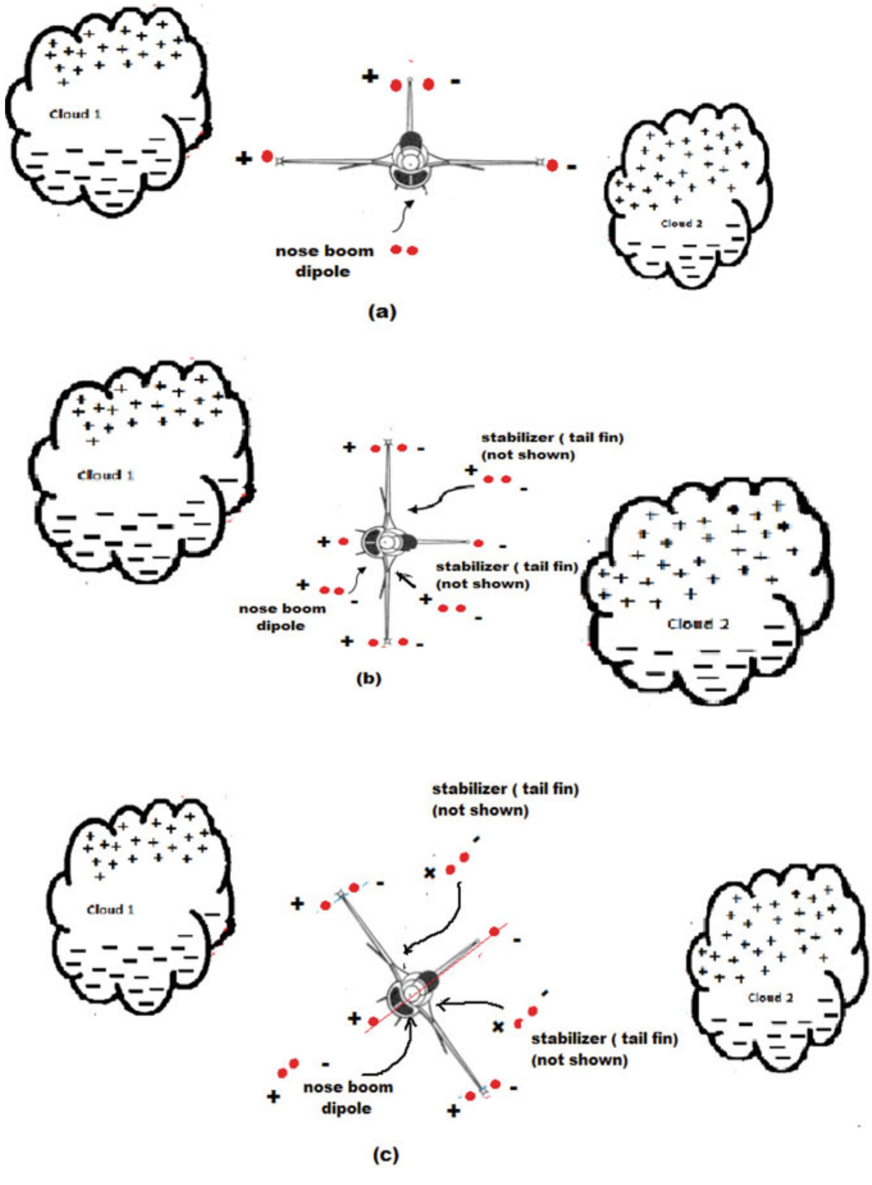


Fig. 2.6 Different roll angle orientations of the F16 military aircraft and dipole alignments **a** horizontal position, **b** vertical position, and **c** positioned at an angle

Table 2.3 Electric charges and electric fields for an airbus A380 at 800 m altitude but 1000 m away from a charged cloud at 1000 m altitude

Computed Voltage V_A: -2.821×10^6 V			
Dipole location and number	Dipole charge (C/m)	Electric field (V/m)	[a]Comment
Rudder tip	1.668×10^{-3}	7.566×10^4	
Mid-fuselage	2.603×10^{-6}	2.121×10^4	
Radome	2.178×10^{-5}	2.176×10^6	Nearing breakdown E-field
Mid-left wing	8.067×10^{-6}	7.536×10^4	
Left wing engine	1.818×10^{-5}	1.611×10^4	
Tip left wing	4.799×10^{-4}	3.32×10^6	Above Breakdown E-field
Mid-right wing	4.025×10^{-5}	3.625×10^5	
Right wing engine	1.652×10^{-5}	1.558×10^4	
Tip right wing	6.179×10^{-4}	4.274×10^6	Above Breakdown E-field
Left horizontal stabilizer tip	1.155×10^{-3}	1.153×10^8	Above Breakdown E-field (high probability of entry point)
Right horizontal stabilizer tip	1.114×10^{-3}	1.113×10^8	Above Breakdown E-field

[a]At high altitude with reduced air density, the breakdown electric field may be as high as 400 kV/m

Table 2.4 Electric charges and electric fields for an airbus A380 at 800 m altitude but 5000 m away from a charged cloud at 1000 m altitude

Computed Voltage V_A: -6.12×10^4 V		
Dipole location and number	Dipole charge (C)	Dipole electric field (V/m)
Rudder tip	1.36×10^{-5}	669.296
Mid-fuselage	2.048×10^{-8}	314.979
Radome	1.552×10^{-7}	1.551×10^4
Mid-left wing	6.684×10^{-8}	676.392
Left wing engine	1.396×10^{-7}	294.147
Tip left wing	3.684×10^{-6}	2.549×10^4
Mid-right wing	3.238×10^{-7}	2.928×10^3
Right wing engine	1.357×10^{-7}	292.391
Tip right wing	4.795×10^{-6}	3.317×10^4
Left horizontal stabilizer tip	9.401×10^{-6}	[a]9.39×10^5
Right horizontal stabilizer tip	9.072×10^{-6}	[a]9.061×10^5

[a]Exceeds breakdown field of 400 kV/m

Table 2.5 Electric charges and electric fields for an airbus A380 at 800 m altitude but 50,000 m from a charged cloud at 1000 m altitude

Computed Voltage V_A: −64.31 V		
Dipole location and number	Dipole charge (C/m) WHY PER M?	Electric field (V/m)
Rudder tip	1.603×10^{-9}	2.822
Mid-fuselage	2.374×10^{-12}	2.826
Radome	1.717×10^{-11}	3.309
Mid-left wing	7.927×10^{-12}	2.827
Left wing engine	1.601×10^{-11}	2.827
Tip left wing	4.215×10^{-10}	4.059
Mid-right wing	3.791×10^{-11}	2.846
Right wing engine	1.434×10^{-11}	2.827
Tip right wing	5.517×10^{-10}	4.748
Left stabilizer tip	1.107×10^{-9}	110.60
Right stabilizer tip	1.068×10^{-9}	106.75

Table 2.6 Dipole charges and electric fields for F16 military aircraft at 1000 m in altitude at level with two charged cloud cells of 500 m apart

Cloud altitude: 1000 m F16 military aircraft altitude: 1000 m and 500 m away from the two charged clouds Computed Voltage V_A: 7.742×10^6 V		
Dipole location	Dipole charge (C)	Dipole electric field (V/m)
Rudder tip	0.04196	5.175×10^9 (above breakdown field)
Fin	4.48925×10^{-4}	5.28×10^7 (above breakdown field)
Mid-fuselage back	7.3322×10^{-4}	3.211×10^7 (above breakdown field)
Wing	3.641×10^{-3}	1.4×10^7 (above breakdown field)
Mid-fuselage front	1.4639×10^{-3}	6.741×10^7 (above breakdown field)
Nose boom	0.07924	1.781×10^{10} (above breakdown field) High probability of strike point

Fly by wire and non-metallic body aircraft designers are interested in the enhanced electric field areas of the aircraft body in order to divide it into zones of protection. The highly probable zones are zones with threatening electric field enhancements and probable lightning strikes and zones with less enhancements of electric fields have minimum probability of strikes. The high strike risk regions are to be avoided

Table 2.7 Dipole charges and electric fields for F16 military aircraft at 1000 m altitude at level with two charged cloud cells and 5000 m from the center of two charged cloud cells

Cloud altitude: 1000 m F16 military aircraft altitude: 1000 m but 5000 m from cloud charge centers Computed voltage V_A: 7.316×10^4 V		
Dipole location	Dipole charge (C)	Dipole electric field (V/m)
Rudder tip	3.965×10^{-4}	4.89×10^7 (above breakdown field)
Fin	4.242×10^{-6}	4.998×10^5 (above breakdown field)
Mid-fuselage back	6.929×10^{-6}	3.048×10^5
Wing	3.441×10^{-5}	1.353×10^5
Mid-fuselage front	1.3833×10^{-5}	6.377×10^5 (above breakdown field)
Nose boom	7.488×10^{-4}	1.683×10^8 (above breakdown field) High probability of strike point

when placing mission critical navigational and control systems as well as microelectronic equipment. The severe cloud-to-cloud lightning strikes in which an aircraft becomes a part of the lightning flash path is the most severe threat to navigational, microelectronic, and measurement systems.

Finally, presentation of the 3D dipole modeling of electric charges and electric field computations agrees with the norm that electric fields are highest at the extremities or sharp edges. These are situations where high electric fields exist on the surface of a body when the monopole charges that make up these dipoles on the surface have the least separation distances, and large electrically induced charges will appear on the surface of the aircraft. However, if the aircraft body is oriented differently, as when the military aircraft changes its roll angles, this will alter the dipole orientation, and thus the electric field distributions over the aircraft surface. In the results for Fig. 2.6, the F16 military aircraft is horizontally positioned between two charged cloud cells of opposite polarities. The electric field is highest at the nose boom and the tip of the rudder (vertical stabilizer). However, if the F16 military aircraft possesses the flexibility to maneuver its position inflight in different aerobatic orientations as shown in Fig. 2.6b and c, the dipole separation distance would vary. In Fig. 2.6b, the wing tips, the horizontal stabilizers, and the nose boom would have the highest electric fields. For Fig. 2.6c the wing tips, the horizontal stabilizers, and the nose boom would have the highest enhanced electric field induced. The electrostatics computation method we have presented enables the computation of electric potential, electric charge and electric fields at any one of these positions.

2.10 Electrostatic Computation and Evaluation: A Computer-Based Tool

This chapter is presented a reliable approach to calculating the prestrike electrostatic charges and electric fields build up on an aircraft using the 3D dipole method. The method may be used for any structure, whether airborne or ground, to determine a critical understanding of the thundercloud electric threat posed and how to design and to protect to minimize damaging engagement with the pre-lightning electrostatic fields and initiating a lightning flash. The computational tool based on the equations presented in this chapter was developed to handle the thundercloud electrostatic environment, and to evaluate the electric charges induced on the surface of an aircraft and the electric fields produced over any structure by the thundercloud electric charge centers. Using the knowledge of both the electrostatic charges induced and the electrostatic fields generated, it is possible to form zones over the aircraft body to indicate areas of high risk to lightning strike. These are the areas in which microelectronic, navigation, and instrumentation equipment will be subject to high electrostatic stress possibly leading to local electrostatic discharges (ESD). Regions of aircraft structure which may be classified as high-risk zones include the radome, the mid-left and mid-right wing areas as well as the aircraft wing edges in the case of airbus A380. For the F16 military aircraft, the orientation of the aircraft while maneuvering highlights the changing regions of threat including the wing tips, the horizontal stabilizers, and the nose boom depending on the orientation of the aircraft with respect to ground. It was found that even when the aircraft is flying well away from the thundercloud, some zones may still experience large electrostatic stress. The technique reported herein may also be used to study how each zone may dynamically change in experiencing electrostatic stress as the aircraft changes its pitch or roll angles, or when a swept lightning stroke moves over the body of the aircraft.

2.11 Personal Lightning Safety

For purposes of personal safety the following are prudential rules to adopt and follow:

1. When there are lightning flashes in the neighborhood, avoid outdoor activities. Stay indoors. Postpone outdoor events when there is thunderstorm activity in the neighborhood.
2. When you are having a group activity, and you should hear thunder, ask everyone either to go indoors or get into vehicles. Do so immediately. Stay in until 30 min after hearing the last thunder clap.
3. Do not use wired telephones during thunderstorms. Avoid taking showers when there is a thunderstorm. Water is a good conductor, in case the house gets struck by lightning.
4. If you are caught outdoors in a thunderstorm as a group, spread out so that you reduce the chance of multiple causalities if lightning should strike the group.

5. Stay away from tall, isolated objects such as trees, towers, or utility poles. Stay away from metal conductors such as metal fences and wires.
6. Tents, front porches, picnic shelters, or any covering without metallic covering, wiring, or plumbing are not safe.
7. If someone is struck, give CPR if you are trained. Call emergency. If available, use an Automatic External Defibrillator.
8. Lightning usually strikes outside the area of heavy rainfall and can strike up to 30 km from where there is rainfall. Lightning strikes occur before rainfall, as well as after.
9. Do everything to avoid becoming a victim to lightning. It can cause permanent disabilities to the body and mind.

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