A|R|J
Amrit Research Journal April 2024, Vol. 4, Issue 2, 11-17

ISSN: 2738-9553
RESEARCH ARTICLE

Possibility of Lightning Strike to Surface-Mounted Antennas on Aircraft

Soumyadeep Chowdhury[1*], Sayantan Das[1], Udaya Kumar[1]

[1]Department of Electrical Engineering, Indian Institute of Science Bengaluru, Bengaluru, India

**E-mail: soumyadeepc@iisc.ac.in*

(Received: July 17, 2023, Received in revised form: February 4, 2024, Accepted: February 4, 2024, Available Online)

DOI: https://doi.org/10.3126/arj.v4i2.65538

Highlights

- The present work investigates on the likelihood of lightning attachment on surface mounted antennas on the aircraft considering a simplified aircraft model.
- It is seen that the field intensification at the antenna tip is highly localized, which is not adequate enough to support a stable propagation of connecting electrical leader.
- Unlike other airplane extremities antenna tips can't be considered as possible initial attachment point.
- The mode of attachment for any given ambient field remains unaffected by the surface mounted antennas.

Abstract

Lightning is considered a significant electromagnetic hazard for airplanes. One of the initial stages in developing lightning protection systems for airplane involves determining potential areas where lightning may strike and attach to the airplane. The most common mode of attachment to the airplane, known as the airplane-initiated mode, is caused by airplane-initiated bipolar leaders. Previous research has indicated that airplane components, such as the nosecone, wingtips, and stabilizer tips, play a crucial role in the commencement of connecting leaders. Apart from these, other extremities formed by the surface-mounted antennas are also present on the airplane. These antennas are typically 40-50 cm tall, providing sharp protrusions where significant field intensification can occur under the influence of the ambient field. Lightning attachment to the antenna subjects it to high rate of rise of current and large variation in local electric field. Moreover, the initial attachment can result in local intense heating and consequential damage. Therefore, it is crucial to investigate how these surface-mounted antennas are vulnerable to attachment compared to other airplane extremities. The current investigation aims to measure the likelihood of lightning striking antennas on airplane.

Keywords: *Lightning, Attachment, Antennas, Airplane*

Introduction

Lightning is an intricate and momentary occurrence with a spatial span reaching several kilometers. Lightning flashes present a potential danger to both life and property. [1].

Lightning poses a significant electromagnetic threat to airplane and hence is a serious concern for the aviation industry. Field data suggests that, on average, an airplane experiences lightning strikes approximately once or twice a year. A commercial airplane encounters a lightning strike approximately once every 1000 hours of flying, roughly translating to one strike per year.

The repercussions of lightning strikes on airplane can range from minor issues like burn marks and local deformations to more

[*]*Corresponding author*

severe outcomes such as damage to tanks containing the fuel, the risk arising out of explosion of an amalgamation of air and the fuel and the destruction of electronic circuit components of the airplane. In the pursuit of lighter and more robust designs, modern airplane increasingly incorporate composite materials like fiberglass and carbon fiber. Despite their superior strength-to-mass ratio, these materials exhibit poor conductivity, potentially leading to damage of their outer structure and heightened field penetration in the core regions when subjected to lightning strikes. Additionally, the extensive integration of fragile electronic instruments in airplane further amplifies the vulnerability to lightning-related risks.

As per the National Oceanic and Atmospheric Administration, lightning bolts incur a cost of around 2 billion USD for air carriers, not including costs for repair. Consequently, the integration of lightning mitigation strategies has become an essential component of contemporary aviation technology design. There are two mechanisms by which a lightning strike can happen. In the first scenario, there are bi-directional leaders emerging from the airplane within the very intense surrounding electric field generated by the cloud and the stepped electrical discharge (leader). This category of lightning, initiated by airplane, constitutes almost 90% of the documented cases to date [2]. The second, less frequent occurrence is when the airplane comes into contact with a descending lightning leader from the cloud. In most recorded instances of airplane lightning incidents, the positive discharge (leader) typically precedes the development of the negative discharge (leader). After the positive discharge extends over a few meters, the negative discharge emerges from the point where negative field is maximum [3]. As both positive as well as negative discharges manifest, the bi-polar leader discharge steadily intensifies until it bridges the space between the descending stepped discharge and the upward discharge.

Research in the field of bipolar discharge from floating objects within laboratory gaps is well-documented in the literature. In 1995, Rizk proposed an analytical model [4] to investigate the flashover of extended gaps in dedicated high voltage laboratories [5, 8] involving a conductor which is electrically floating subjected to a switching surge. Subsequently, Castellani et al. reported empirical data on discharges from an object which is electrically floating positioned in a plane-plane gap which is around 10-11m long [5,6]. More recent work by Gao et al. [7] reported flashover voltages for a 2 m gap amidst electrically ungrounded cylindrical rods.

The chronological sequence of occurrences involved with the onset of lightning discharge from airplane is firmly established and broadly accepted. Nevertheless, owing to the intricacies involved in the physics behind the inception and propagation of the discharge, there is a scarcity of literature on the simulation of such discharges from airplane. Das et.al has developed a model [8] which is capable of simulating bipolar leader discharges. The modeling of airplane-incepted leader discharges entails simulating both positive and negative leader discharges. To achieve this, appropriate models for simulating these discharges from the airplane have been adopted from existing literature on laboratory experiments. For precise field computation, the Surface Charge Simulation Method (SCSM) has been utilized in [8], along with sub-modeling, which employs the Charge Simulation Method (CSM).

Earlier investigations [8,11,12] have demonstrated that in the mode of lightning incepted by airplane, the potential initial attachment points are primarily limited to the extreme ends of the airplane, including the vertical fins, nose cone, wingtips, and similar areas. Apart from these, other extremities formed by the surface-mounted antennas are also present on the airplane. These antennas are typically 40-50 cm tall [14], providing sharp protrusions where significant field intensification may occur under the influence of the ambient field. Initial lightning attachment leads to a very high rate of rise of current and large variation in local electric field. Moreover, the arc established during the initial attachment can have a damaging effect on the surface of the airplane due to intense heating. However, it should also be noted that even without initial attachment, the antenna can still get involved in re-attachment as the lightning channel sweeps backward on the airplane surface. Although the same is not guaranteed. Therefore, it is crucial to investigate how these surface-mounted antennas are vulnerable to attachment compared to other airplane extremities. Hence, in the present work an attempt has been made to quantify this vulnerability using a model for airplane-initiated bipolar leader discharges. [8]

Details of Airplane Model and Antenna Model Used

Airplane Model used

The focus of the current study is on a widebody passenger tri-jet manufactured by McDonnell Douglas in 1970 in the United States, known as the DC-10. This airplane, with a length of 55.55 m and a wingspan of 47.35 m (Fig. 1), has been selected for investigation. The exterior skin of the airplane model is segregated into 11,000 surface elements which are triangular in shape through the use of Mesh Lab software.

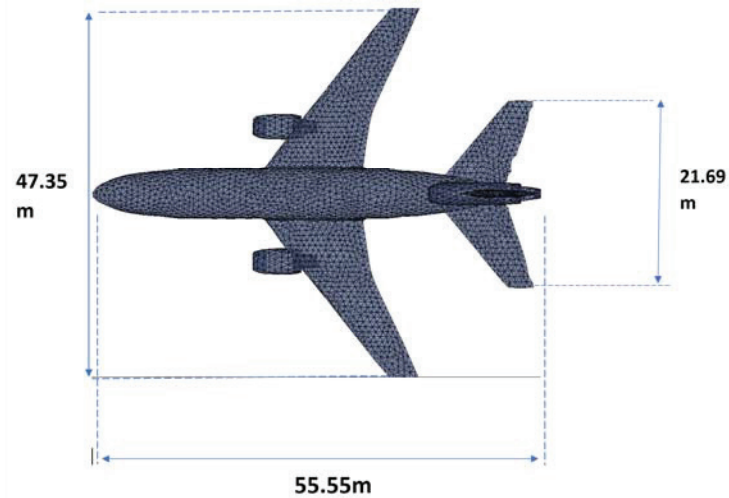

Fig. 1. Dimensions of the DC-10 airplane model

Antenna Used

A surface-mounted VHF antenna of dimensions 41.91cm x 7.06cm x 40.64cm is considered. [14]. The shape and the dimensions of the antenna considered in the present work is shown in Fig. 2. The dimensions of the surface mounted VHF antenna are relatively small and hence it is discretized into 44 quadrilateral surface elements (Fig. 2). The antenna should be at the same floating potential as the airplane. For the purpose of analysis, the antenna is placed at two preferred positions, one at the middle of the fuselage of the airplane and the other at the cockpit of the airplane.

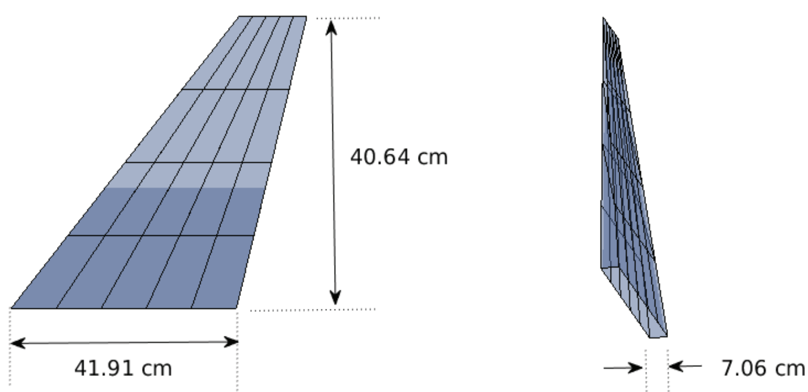

Fig.2 . Dimension of the antenna considered as mentioned in [14]

Methodology

Field Computation

When airplanes are struck by lightning, it is a result of the interaction between storm clouds and the descent of electrical leaders. Hence, it becomes crucial to conduct field computations in the vicinity of the airplane. The depicted downward progressing leader is conceived as a vertically aligned conduit with a distributed charge along its length, adhering to the model presented by Cooray et al. [9]. The leader discharge model employed in this study demands precise computation of the surrounding electric field. To achieve this, it is imperative to consider the ambient field generated by both the thundercloud and the lightning leader when calculating the electric field around the airplane.

The existing challenge can be characterized as an open geometry issue. Consequently, to compute the electric field, we employ a boundary-centric computational technique known as the Surface Charge Simulation Method (SCSM).. In order to enhance the precision of field computation near the airplane's sharp edges and corners, which are the most likely points for leader inception, a combination of sub-modelling and SCSM is utilized.

Fig. 3 illustrates the equipotential lines around the antenna due to a downward approaching electrical leader of 50kA anticipated return stroke current. A comprehensive description of the technique employed for field calculation is provided in [8].

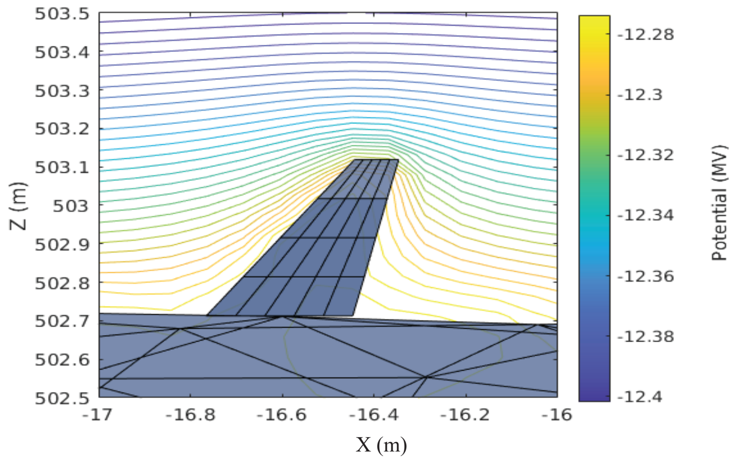

Fig. 3. Equipotentials around the antenna positioned on the cockpit under the influence of a downward progressing leader of 50 kA anticipated return stroke current, placed 100 m above the antenna

Identification of Attachment Initiated by the Airplane

As explained previously, this method of connection encompasses noteworthy instances of electrical leader phenomenon originating from the airplane. Hence, the process of identifying airplane-initiated attachment necessitated the creation of models for both positive and negative electrical leader discharges stemming from the airplane. A framework for describing the inception and advancement of bipolar discharges originating from an airplane is formulated in [8]. To model positive leader discharges within gaps in the high voltage laboratories and positive upward electrical discharges from electrically grounded entities, Becerra et al. introduced a simplified physical model [9]. This specific model [9] is utilized to simulate the emergence and progression of positive discharges originating from the airplane. However, to simulate negative leader discharges initiated by the airplane, a physical model (originally developed and validated by Rakov et al.) [9] for negative discharges within gaps in laboratories is employed.

As discussed in [8], it becomes evident that, in contrast to laboratory gaps, an airplane in flight cannot maintain a unipolar leader. The stable growth of these leaders, whether positive or negative, which are instigated by the airplane, hinges upon the interdependence they establish with each other.

Identification of Attachment Intercepted by the Airplane

In scenarios involving attachment intercepted by the airplane, the area where streamers develop along the downward progressing leader directly spans the space between the airplane (or the streamer initiated by the airplane) and the tip of the leader. As a result, in this mode of attachment, the progression of the leader is determined by evaluating the mean electric field intensity (Eavg) present between the head of the downward progressing electrical leader and the airplane. When observing a specific location of the downward progressing leader, if the Eavg surpasses a crucial threshold of 500 kV/m (measured at a temperature of 20°C and pressure of 1 ATM), the requisite condition for direct streamer connection is satisfied (as indicated by equation 1).

$$E_{avg} = \frac{V_{leadertip} - V_{aircraft}}{D} \geq 500\ kV/m \qquad (1)$$

where, $V_{leadertip}$ and $V_{aircraft}$ refer to the respective potentials of the leader head and the airplane. D represents the smallest distance between the airplane and the downward progressing leader tip.It's important to highlight that unlike grounded objects and electrodes present in the laboratories, the electric potential of an airplane (referred to as $V_{aircraft}$) is not constant due to its electrically floating nature. Due to the presence of a downward progressing leader, the electric potential of the airplane becomes a significant fraction of the electric potential at the head of the downward progressing leader [13-14].

Consequently, in order to establish the attachment with the airplane, the $V_{aircraft}$ in equation (1) needs to be recomputed for every step of progression of the downward electrical stepped leader.

Procedure

The airplane is regarded as maintaining a consistent altitude of 500 meters above the ground. Two different positions of the antenna are considered. For the first case, the antenna is positioned on the cockpit (referred to as position-1), and for the second case, it is placed the middle of the fuselage top surface of the airplane (referred to as position-2) as shown in Fig. 4. The lightning leader is descended vertically exactly above the antenna. Given that 90% of lightning strike to the earth exhibits negative polarity, this study exclusively considers the negative downward-progressing leader. 10, 30, 50 kA anticipated return stroke currents of the downward progressing leader are considered. For the two positions of the antenna, it is checked whether the antenna can incept a stable positive leader discharge or not before attachment (of any mode) happens to any other point on airplane.

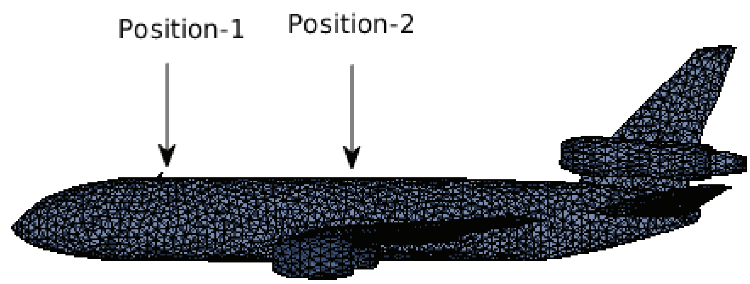

Fig. 4. Antenna locations on airplane considered

In an earlier work [13], the lower limit of anticipated return stroke current below which attachments are mostly attributed to airplane-intercepted mode is determined.

In the current study, a comparable analysis has been conducted to explore the influence of surface-mounted antennas on the critical stroke current.

Results and Discussion

Fig. 5 shows inception and elongation of upward positive leader from the antenna tip (at position-1 as per Fig. 4) for 10, 30 and 50 kA anticipated return stroke currents of the downward progressing leader. In the same, the variation of the normalized potential difference between the airplane and the downward progressing leader tip (ΔV_{norm}) with leader descent is shown. (ΔV_{norm}) is defined as Eqn 2.

$$\Delta V_{norm} = \frac{V_{leader\ tip} - V_{aircraft}}{V_{leader\ tip}} \qquad (2)$$

where, is the potential at the downward progressing leader tip and is the potential of the airplane. It's important to highlight that, since a flying airplane is electrically floating, its potential undergoes changes as the lightning leader descends. Therefore, in equation. (2) is a function of downward progressing leader position.

It can be seen from Fig. 5 for 10, 30 and 50 kA current, the upward leader attains length of 7.8 cm, 8 cm, and 13 cm respectively before streamer mode of bridging takes place (equation (1)). Earlier work shows that to ensure a stable bipolar leader propagation connecting leader should attain length of a few tens of meters [8]. Therefore, these small upward leaders from antenna are

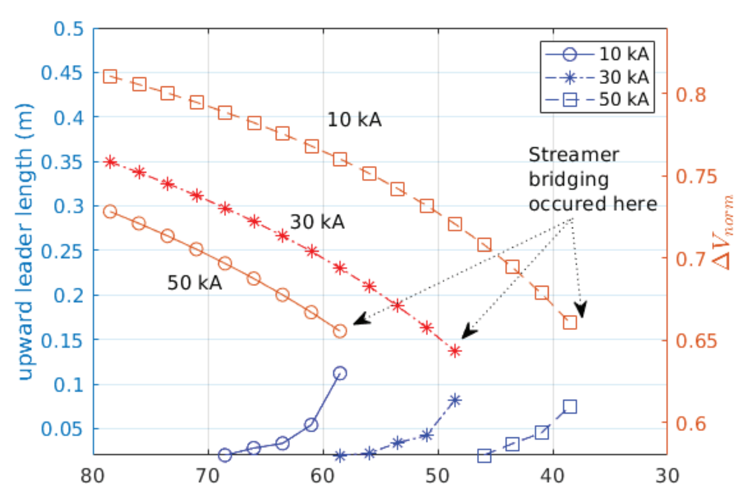

Fig. 4. Growth of the upward positive leader (left Y-axis in blue color) from the tip of the antenna placed at position-1 as the lightning leader descends. Variation (right Y axis in red color) with the decreasing gap.

not sufficient to establish a stable leader discharge. As a result, for all the stroke currents, attachment occurs through airplane-intercepted mode.

The unsuccessful inception of upward leader from antenna can be explained from Fig. 6. It shows potential distribution along the discharge axis from the antenna tip under the influence of downward progressing leader of anticipated return stroke current of 50 kA and 60 m above the antenna. It can be seen from Fig. 6 that the field intensification is highly localized, i.e., only confined within a few centimeters of the antenna tip. In other words, the field intensity weakens quickly in space. However, for stable leader propagation, field strength is required for a larger spatial extent. Therefore, in this case, the leader gets incepted from the antenna but gets choked after 13 cm leading to unsuccessful upward leader propagation.

A similar phenomenon is observed when the antenna is placed at position-2 (Fig. 4). The modes of attachment and associated upward leader length for the two different antenna positions are tabulated in Table. 1. The antenna fails to incept a stable positive upward leader discharge for this case also. For this antenna position, leader inception from antenna gets even more difficult as compared to the antenna position 1. At 10 kA stroke current of the downward progressing leader, the antenna can't even incept a positive upward leader (Table 1). It should also be noted that at 50 kA stroke current, vertical stabilizer launches a longer upward leader compared to the antenna. Therefore, the chance of attachment to vertical stabilizer is higher than the antenna.

In a previous study [13], it was demonstrated that when the anticipated return stroke current is below 15 kA, the attachment is primarily influenced by the airplane-intercepted mode. In the current investigation, a similar exercise has been carried out in the presence of surface mounted antenna. It is seen that the lower limit of stroke current below which all attachment occur with airplane-intercepted mode remains unimpacted. Antenna can't incept stable connecting leader; thus, the mode of attachment remains the same irrespective of its presence.

Table 3. Modes of attachment and upward leader lengths for two different antenna positions

Anticipated stroke current (kA)	Mode of attachment	
	Antenna position-1	**Antenna position-2**
10	Airplane-intercepted (leader length from antenna – 7.8 cm)	Intercepted (leader length – No inception)
30	Airplane-intercepted (leader length from antenna – 8 cm)	Airplane-intercepted (leader length – 5.5 cm)
50	Airplane-intercepted (leader length from antenna – 13 cm)	Airplane-intercepted (leader length from antenna- 8 cm, leader length from vertical stabilizer – 1.03 m)

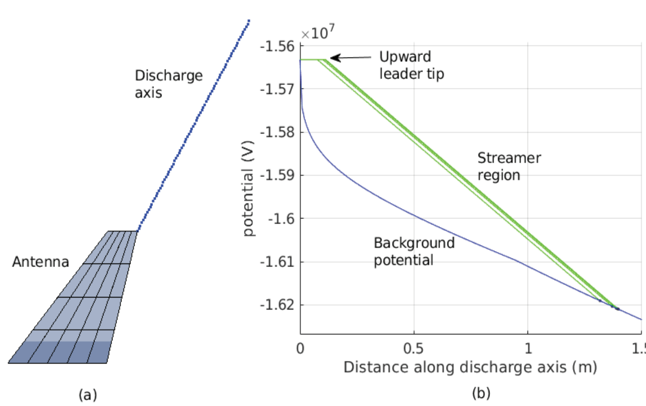

Fig. 6. Potential distribution along the discharge axis from antenna placed at position-1. (a) Antenna and discharge axis from its tip, (b) potential distribution along the discharge axis before and during the upward discharge propagation

Summary

Field data suggests that most of the lightning bolts are caused by airplane initiated connecting electrical leaders which elongates a few tens to hundreds of meters leading to attachment. Earlier studies have shown that airplane geometries such as nosecone, wingtips, stabilizer tips play a significant role in the inception of the connecting electrical leaders. Apart from these extremities, surface mounted antennas provide additional sharp protrusions on airplane. The present work investigated the impact of the antenna on the attachment. Two different positions of the antenna are considered on the airplane surface, one at the middle of the fuselage and the other on the cockpit of the airplane. Both the cases are studied separately, and it is seen that the field intensification at the antenna tip is highly localized, which is not adequate enough to support a stable propagation of connecting electrical leader. Thus, antenna can't establish a stable connecting leader propagation. Therefore, unlike other airplane extremities antenna tips can't be considered as possible initial attachment point. It is also found that the mode of attachment for any given ambient field remains unaffected by the surface mounted antennas.

References

1. R. L. Holle, "Some aspects of global lightning impacts," 2014 International Conference on Lightning Protection (ICLP), Shanghai.
2. P. Lalande, A. Bondiou-Clergerie, and P. Laroche, "Analysis of available in-flight measurements of lightning strikes to airplane," SAE Technical Paper, Tech. Rep., 1999.
3. Mazur, V. A physical model of lightning inception on airplane in thunderstorms. J. Geophys. Res. Atmos. 1989, 94, 3326–3340
4. Rizk, F.A. Effect of floating conducting objects on critical switching impulse breakdown of air insulation. IEEE Trans. Power Deliv. 1995, 10, 1360–1370.
5. Castellani, A.; Bondiou-Clergerie, A.; Lalande, P.; Bonamy, A.; Gallimberti, I. Laboratory study of the bi-leader process from an electrically floating conductor. I. General results. IEE Proc.-Sci. Meas. Technol. 1998, 145, 185–192
6. Castellani, A.; Bondiou-Clergerie, A.; Lalande, P.; Bonamy, A.; Gallimberti, I. Laboratory study of the bi-leader process from an electrically floating conductor. Part 2: Bi-leader properties. IEE Proc.-Sci. Meas. Technol. 1998, 145, 193–199.
7. Gao, J.; Wang, L.; Wu, S.; Xie, C.; Tan, Q.; Ma, G.; Tueraili, H.; Song, B. Effect of a floating conductor on discharge characteristics of a long air gap under switching impulse. J. Electrost. 2021, 114, 103629.
8. S. Das and U. Kumar, "Modeling of Bi-Polar Leader Inception and Propagation from Flying Airplane Prior to a Lightning Strike," Atmosphere, vol. 13, no. 6, p. 943, Jun. 2022, doi: 10.3390/atmos13060943
9. Becerra, M.; Cooray, V. A simplified physical model to determine the lightning upward connecting leader inception. IEEE Trans. Power Deliv. 2006, 21, 897–908
10. Guo, Z.; Li, Q.; Bretas, A.; Rakov, V.A. A simplified physical model of negative leader in long sparks. Electr. Power Syst. Res. 2019, 176, 105955
11. U. Kumar and V. Cooray, "Limitations of RSM in Zoning of Airplanes," Asia-Pasific International Conference on Lightning, 2018.
12. S. Das and U. Kumar, "Comparative analysis for inception of positive connecting leader from a cruising and grounded airplane," in 2022 36th International Conference on Lightning Protection (ICLP), 2022, pp. 1–5.
13. S. Das and U. Kumar, "Modes of lightning attachment to airplane at different stroke currents and relative positions of descending lightning leader," 2023 12th Asia-Pacific International Conference on Lightning (APL), Langkawi, Malaysia, 2023, pp. 1-6, doi: 10.1109/APL57308.2023.10182199.
14. "VHF Communication Antennas" 214.320.9770 Dallas Avionics 800.527.2581. https://www.dallasavionics.com/edo/edo.pdf