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ARTICLE

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ENVIRONMENTAL EFFECTS ON DIFFERENT TYPES OF RADOMES

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Radomes are important in various domains of engineering and science, as it offers protection to the electronic devices used for different types of communication, from adverse environmental factors. Considering the extended period of usage, exposure to adverse weather conditions has significant impact on radomes. This paper reviews the types of radomes, the effect of various environmental factors on them and the mitigation strategies for these effects. In addition, the paper also discusses the maintenance of different types of radomes to protect antenna and other components. Further, it provides an overview of two important effects viz., rainfall and lightning, on ground and airborne radomes, respectively. Results of simulations studies are also presented.

Keywords: *Radome, environmental effect, mitigation, rainfall, lightning, current flow, antenna gain*

Introduction

A radome is a protective cover that shields radar antennas or other sensitive equipment from various environmental factors allowing radar signals or other electromagnetic waves to pass through with minimal distortion. It is a specialized enclosure designed to protect radar systems from adverse weather conditions due to wind, rainfall, icing, temperature, lightning and other potentially damaging factors without affecting their functionality. By protecting from severe weather events through offering a strong barrier, radomes contribute to the enhancement of their lifespan and minimize the maintenance costs.

Radomes must shield the radar equipment while allowing radar signals through with minimum loss. Careful material selection and design considerations are needed to guarantee that the radome does not impede the radar system's functionality. Radomes are essential for safeguarding and improving the functionality of radar systems for different purposes. Radomes can also have additional features like heating systems to avoid ice accumulation, lightning protection strips to guard against electrical damage, and mechanisms for upkeep and inspection[1]. Some radomes feature integrated power generation and communication systems, including solar panels, battery storage and satellite communication links.

Radomes come in various shapes and sizes, and are made up of different materials, depending on the specific requirements of the antenna system. It can range from simple spherical or cylindrical structures to more complex designs tailored to the specific antenna shape and size. Usually, materials like fiberglass, composite materials, or fabrics coated with certain compounds that are transparent to radar waves are employed in the manufacturing of the radomes.

Based on the placement of the radomes, there are mainly three types of radomes, ground-based radome, ship

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radome and airborne radome. A brief description of each of them is presented in the following sections.

Ground-based Radome: Ground-based radomes (Fig. 1) are designed to shield radar antennas installed on the ground from the atmospheric effects while preserving the optimal radar performance. These radomes are employed in a variety of applications such as military defence, air traffic control, weather monitoring, and surveillance. Ground based radomes are in various shapes and sizes, but it features a dome-shaped or cylindrical design to guard the radar antenna. The structural stability and durability are designed to endure a variety of adverse weather conditions.

Installing ground-based radomes involves placing them on concrete pads or foundations, which offer a stable base for the construction. The radome may need to be anchored to the ground during installation to protect it from high winds and other environmental factors. Radome's design includes access doors or panels that enable service, maintenance, and inspection of the radar equipment. It also ensures the safety of sensitive components.

Climate control systems and ventilation may be added to keep optimal operating conditions and avoid moisture build up inside the radome. These systems help in controlling humidity and temperature, ensuring that radar equipment functions reliably under all-weather circumstances. In order to protect against electrical damage from lightning strikes, ground-based radomes are generally equipped with lightning protection systems. Lightning rods, grounding conductors, and surge suppressors are common components of these systems, designed to divert electrical currents safely away from the radar equipment.

Regular maintenance is essential for ensuring the continued effectiveness of ground-based radomes. Inspecting the structural integrity, cleaning the exterior surfaces, examining the seals and gaskets for any signs of wear or damage, and conducting necessary upkeep on the ventilation and climate control systems are some of the regular maintenance measures.

Ground-based radomes are designed to operate across various frequency bands, each offering unique advantages and applications. Various frequency bands in operation are given below.

S-band (1 to 2 GHz): This band is used in radar systems for various purposes including air traffic control, weather monitoring, surveillance, and navigation. The S-band offers advantages such as moderate atmospheric attenuation, reasonable antenna sizes and good compromise between range and resolution in radar applications. In satellite communication, it provides a balance between atmospheric losses and antenna size, making it suitable for various applications.

C-band (4 to 8 GHz): The C-band is favoured for ground-based radomes due to its relatively low atmospheric attenuation. This means that radar signals experience less signal loss due to factors such as rain, snow, and atmospheric moisture. Additionally, antennas operating in the C-band have reasonable sizes, making them practical for various ground-based applications. Moreover, C-band equipment is often more affordable compared to higher frequency bands. This radar offers a good compromise between range, resolution, and atmospheric attenuation, making it suitable for long-range surveillance and tracking. C-band frequencies have advantages such as better penetration through adverse weather conditions like rain and clouds compared to higher frequency bands like Ku-band and Ka-band, making them suitable for applications where reliability is crucial.

X-band (8 to 12 GHz): X-band radar systems are widely used in both military and civilian applications due to their ability to provide high resolution and accuracy. X-band satellite communication is utilized for high-data-rate applications such as military communications, remote sensing, and broadband internet services. However, they are more susceptible to atmospheric attenuation, especially in adverse weather conditions, than lower frequency bands like C-band[2].

Ku-band (12 to 18 GHz), K-band (18 to 26.5 GHz) and Ka-band (26.5 to 40 GHz): These bands offer higher resolution and increased data transmission capabilities than the C-band. Signals in these bands have more degradation due to rain, fog, and atmospheric gases. Additionally, antennas operating in these bands tend to be smaller, but more expensive to deploy and maintain. In K-band, the middle frequency, ~22.4 GHz, is absorbed by water vapour in the atmosphere. Therefore, these frequency bands have high atmospheric attenuation which makes it applicable mainly for short range applications.

The most widely used band for ground-based radomes is the C-band (4 to 8 GHz). The popularity of the C-band is attributed to several factors, including its balance between atmospheric attenuation, antenna size, and cost effectiveness. The choice of frequency band for ground-based radomes depends on the specific requirements of the application, balancing factors such as resolution, signal

Fig. 1: Ground based radome (Courtesy: https://www.tcn.al/tcn/wp-content/uploads/2018/10/radome-1024x683.jpg)

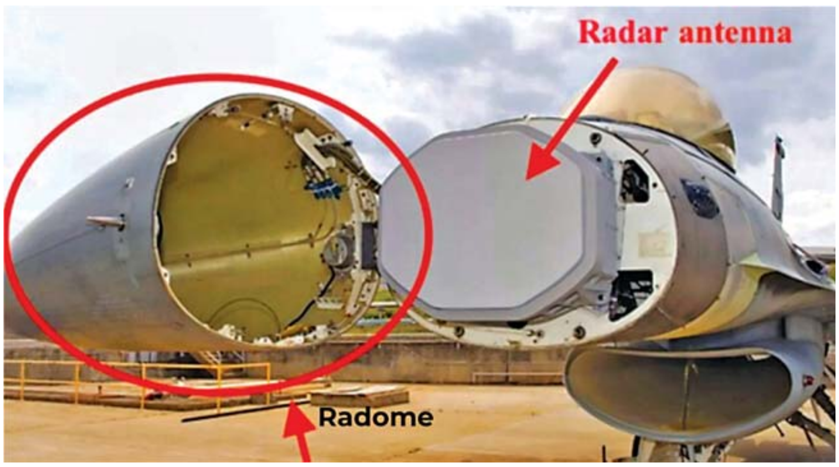

Fig. 2: Aircraft radome (Courtesy: https://orbitshub.com/decoding-the-importance-of-radome-in-aircraft-design/1)

integrity, equipment size, and cost. The higher frequency bands have more attenuation compared to the lower frequency bands.

Airborne Radome: Airborne radomes are specific protective coverings designed to house aircraft radar antennas and reduce aerodynamic interference which are essential to the operation and performance of airborne radar systems. The lifting condition of the aircraft is easily achieved with weight reduction. To reduce the weight of the aircraft, lightweight yet sturdy materials like fiberglass, composites, or specially coated fabrics are used to design airborne radomes. These materials are selected because they will not add excessive weight to the aircraft while withstanding exposure to atmospheric conditions and high aircraft speeds.

Radar transparency is one of the most important features of aerial radomes. Radars in military aircraft should be accurate in detecting, tracking, and identifying other aircraft, ground vehicles, and ships, which is essential for situational awareness and threat detection. The radomes must permit least

Fig. 3: Ship radome (Courtesy: https://tos.org/oceanography/article/deployment-of-the-sea-pol-c-band-polarimetric-radar-to-spurs-2)

Fig. 4: Ground radomes exposed to environmental effects (https://www.justdial.com/jdmart/Visakhapatnam/Doppler-Weather-Radar-Station—Beach-Road/0891PX891-X891-170605215203-R8D7_BZDET/catalogue/photos?nid=12021772&current_selection=3&current_section=player&selected_tab=0)

amount of distortion or attenuation to radar signals. Radar transparency is achieved by using specialized materials and coatings that sufficiently shield the enclosed radar antenna.

During the development, significant engineering is required to ensure structural integrity, aerodynamic efficiency, and radar transparency. The shape of airborne radomes is carefully designed to minimize aerodynamic drag and maintain the overall performance of the aircraft [3]. Streamlined domes, cones, or teardrop designs are standard forms that lower turbulence and air resistance. Along with these considerations, airborne radome design also considers compatibility with the aircraft's fuselage, attachment mechanisms, and airflow patterns. Depending on the particular needs of the radar system and the aircraft platform, airborne radomes are usually mounted outside the aircraft, either on the nose, fuselage, or wings. Fig. 2 shows the radome of a defence aircraft mounted at the nose.

Airborne radomes in military applications can be equipped with stealth technology to reduce radar reflections. Stealth radomes represent a significant advancement in military technology, engineered specifically to mitigate radar reflections. These structures are designed to minimize radar cross-section, thereby increasing the stealth capabilities of military installations or aircraft. Employing specialized materials and intricate shapes, stealth radomes effectively scatter or absorb radar waves, thus making it more difficult to detect.

Airborne radomes must be regularly maintained and inspected, just like any other aircraft component, to guarantee their continuing dependability and efficiency. Cleaning, checking for wear or damage, and replacing or repairing damaged parts are examples of maintenance procedures. Airborne radomes are available in various configurations to suit different aircraft platforms and radar system types. Some air-borne radomes are designed specifically as weather radar, surveillance radar, synthetic aperture radar (SAR), etc., each with unique requirements for performance, size, and installation.

Ship Radome: Specialized enclosures installed on ships to protect radar antennas are called ship radomes. It preserves radar systems and ensures optimal efficiency in challenging sea conditions. Ship radomes are made of robust components such as composite materials, metal alloys, and fiberglass that are resistant to the adverse conditions of the marine environment and exposure to saltwater, strong winds, and rough seas. These materials have been selected according to their strength, resistance to corrosion, and capacity to preserve structural integrity in the face of dynamic loading.

Ship radomes are available in various forms and arrangements, contingent upon the specifications of the radar system and the design of the ship (Fig. 3). Common forms include conical, cylinder, and dome shapes for structural stability and aerodynamic effectiveness. Ship radome designs also consider compatibility with the superstructure of the vessel, installation location, and antenna size[4]. Ship radomes, like those in aircraft, maintain radar transparency in order to allow radar signals through with less distortion or attenuation. Radar transparency is achieved using specialized materials and coatings that protect the enclosed radar antenna.

Additionally, to maximize radar performance and reduce signal loss, ship radomes may incorporate features like radome windows or apertures. Depending on the design of the ship and the requirements of the radar system, ship radomes are usually positioned outside the vessel, either on the deck, mast, or superstructure. Securing the installation to the ship's structure, aligning the radar antenna precisely, and integrating it with the navigation and communication systems are all necessary steps in the installation procedure. To ensure correct installation and operation, ship radomes may include cable conduits, mounting brackets, and weather seals.

To ensure sustained performance and dependability, regular inspections and maintenance are necessary. Cleaning, preventing corrosion, checking for wear or damage, and replacing or repairing items are some examples of tasks related to maintenance. Ship radomes can also be designed to blend in perfectly with the vessel's profile to improve overall concealment and reduce visual detection. It can support several kinds of radar systems for numerous maritime applications each with different needs for performance, coverage, and detecting capabilities such as navigation, surveillance, weather monitoring and defence.

Environmental Effects

Different environmental phenomenon can significantly impact radomes in different ways, during operation. The temperature fluctuations ranging from extreme cold to extreme heat can induce expansion and contraction of materials, potentially resulting in structural issues like cracking or delamination.

Moisture accumulation on radome surfaces during precipitation can lead to performance degradation of radar systems and facilitate the growth of mold or mildew.

Prolonged exposure to intense ultraviolet (UV) radiation from the sun can cause degradation of radome materials, leading to yellowing, brittleness, or loss of transparency over time.

Additionally, the risk of bird strikes during flight poses a threat to radome integrity, with potential damage affecting both structure and radar performance. While radomes are engineered to withstand lightning strikes, the radome remains susceptible to surface damage and alterations in electrical properties, which may impact radar functionality. In the case of airborne radomes, high-speed winds encountered during flight exert significant forces on the radome structure, necessitating careful design and aerodynamic considerations to ensure resilience against deformation or damage. Understanding and addressing these environmental challenges are vital for maintaining the reliability and effectiveness of radomes.

Effects of Environmental Factors:

- **Humidity and Precipitation:** The moisture accumulation on radome surfaces increases the possibility of structural damage and performance degradation. Excessive moisture can damage the radome's internal radar systems and enhance the growth of mildew on its surface, which reduces the transparency and functionality of the radar[5]. Therefore, in order to minimize the negative effects of humidity and preserve the best possible radar performance, regular inspection and cleaning procedures are essential. High humidity levels can increase the absorption and scattering of radar signals as they pass through the radome material. This can lead to signal attenuation, reducing the effectiveness of the radar system. In the case of ground radomes and ship radomes, humidity levels inside the radome can lead to condensation forming on the interior surface, particularly if there is a temperature differential between the inside and outside of the radome. Condensation can interfere with radar signals and may also cause corrosion or other damage to the electronic components inside the radome.

- **Temperature:** Temperature significantly impacts radomes due to the materials used in their construction and their exposure to varied environmental conditions. Radomes are exposed to a wide range of temperatures, from low to high temperatures in direct sunlight. These temperature fluctuations can cause the material of radomes to expand and contract, leading to dimensional changes and stress within the structure. Repeated thermal cycling may result in fatigue, deformation, and distortion of the radome. Additionally, temperature differences can affect the mechanical properties of the radome material; at low temperatures it may become more brittle while at high temperatures it may soften or deform, compromising its structural integrity and electromagnetic transparency. Hence, selecting appropriate materials for radomes that can maintain mechanical strength and dimensional stability over a broad temperature range is crucial.

- **Wind:** Strong winds can exert dynamic pressures and aerodynamic forces on the radome, causing deformation, vibration, or even structural failure; if not properly addressed. Wind loads encountered during aircraft flight exert significant forces on the radome structure, presenting various challenges and considerations. The aerodynamic design of the radome must effectively manage these forces to ensure structural integrity and optimal performance. Proper design attentions, such as aerodynamic shaping and structural reinforcement are crucial to mitigate the effects of disastrous winds and maintain the aerodynamic profile. Aerodynamic testing and analysis are conducted to assess the radome performance under different wind conditions and ensure compliance with safety and performance standards.

- **Turbulence:** Turbulent airflow around a radome can exert mechanical stress on the structure. This stress may result from wind gusts, turbulent eddies, or vortex shedding. The fluctuating forces acting on the radome can induce vibrations, oscillations, or dynamic loads, potentially leading to structural fatigue and deformation. Turbulence can generate pressure differentials, lift, and drag forces. These aerodynamic forces can affect the stability and balance of the radome. High-speed airflow can create localized pressure variations, which may cause suction or lift forces on the radome. Turbulence plays an important role in the case of airborne radomes.

  Turbulence-induced vibrations excite the natural frequencies of the radome structure, resulting in dynamic responses such as resonance or flutter. Resonant vibrations can amplify mechanical stresses. Proper damping, vibration isolation, and aerodynamic shaping are necessary to mitigate dynamic response effects in turbulent conditions.

Turbulence can intensify the effect of environmental factors such as rain, hail, or airborne debris, which can cause abrasion, erosion, or impact damage to the radome surface. Turbulent airflow can accelerate the ingress of moisture, dust, or pollutants into the radome interior, potentially compromising the functionality of radar equipment and electronic components.

- **UV Exposure**: UV exposure coming from the sun can degrade the radomes over time, leading to yellowing, brittleness and loss of transparency. Airborne radomes at high altitudes are exposed to intense UV radiation, which accelerates material degradation. Protective coatings and UV-resistant materials are commonly used to mitigate UV-induced damage and preserve the structural integrity and electromagnetic transparency of radome.
- **Chemical Exposure**: Chemical exposure can accelerate material degradation and compromise the effectiveness of the radome in protecting radar equipment. Radomes installed in industrial or coastal areas may be exposed to corrosive chemicals, saltwater, pollutants, and airborne contaminants. Certain chemicals can cause surface damage to radome materials, such as etching or pitting. This damage may reduce the transparency of the radome material, affecting radar signal transmission, or creating weak points that could lead to structural failure over time. Chemical residues or contaminants on the surface of the radome can interfere with radar signals, leading to signal attenuation, distortion, or other performance issues. This interference can impact the accuracy and reliability of the radar system housed within the radome.
- **Biological Growth**: Biological growth, such as the accumulation of algae, moss, lichens, or other organic matter, can have several negative effects on radomes. It can cause signal attenuation, leading to reduced radar performance. The presence of organic material can absorb, scatter, or reflect radar waves, resulting in degraded signal strength and reduced radar coverage[6]. Organic growth on the radome surface can cause signal distortion by altering the propagation characteristics of radar waves. This can result in inaccurate target detection, false returns, and reduced radar resolution.

Regular cleaning and maintenance may be required to remove biological growth from the radome surface. This can increase operational costs especially in remote or inaccessible locations. Biological growth on the radome surface can detract from the aesthetic appearance of the structure, particularly in urban or highly visible locations. In some cases, biological growth can penetrate the surface of the radome and cause structural damage over time. This can compromise the integrity of the radome and necessitate costly repairs or replacements.

Mitigation Strategies for Environmental Effects on Radomes: It is essential to address the impacts of adverse environmental conditions on radomes and other components properly, whenever necessary. Factors such as temperature fluctuations, atmospheric pressure and aerodynamic forces are significant challenges to these components. To effectively address these challenges, engineers have developed various mitigation strategies designed to increase the durability and efficiency of radomes.

Two of the main mitigation methods are careful selection of materials and the use of protective coatings. Radomes, which are typically made of materials such as fiberglass or carbon fibre, can degrade when exposed to environmental factors. To combat this, engineers choose materials that are more resistant to corrosion and UV radiation. In addition, the application of protective coatings such as epoxy resins improves weather resistance and extends the life of protective domes.

Another important strategy is the implementation of thermal management systems. Extreme temperature fluctuations can stress radar dome materials and cause structural damage. Thermal management systems, including passive insulation and active heating/cooling mechanisms, help to regulate interior temperatures. This minimizes thermal stress and ensures optimal performance in various environmental conditions.

In addition, aerodynamic design considerations play a key role in reducing the effects of environmental forces on canopies. High-speed and turbulent airflow can place significant aerodynamic stress on airborne radomes. Advanced aerodynamic design techniques, such as antenna shape optimization and vortex generator integration, reduce drag and the effects of aerodynamic forces.

Routine inspection, maintenance and repair are equally important as design considerations. Regular inspections allow engineers to identify and repair any damage or malfunction quickly. Maintenance, such as cleaning and reapplying protective coatings, will reduce the effects of environmental exposure. Rapid repair of identified damage prevents further degradation and maintains structural integrity. By carefully selecting materials, implementing thermal management systems, considering aerodynamic design, and performing regular maintenance, engineers can improve the durability of radomes to ensure continued performance and safety of the antenna.

Simulations followed by experimental methods are important for selection and optimization. Some of these methods are discussed below.

- Materials selection: Choosing durable and weather-resistant materials (such as advanced composites or UV-stabilized polymers) to design light domes can improve environmental resistance and extend antenna life.
- Coatings and treatments: The application of protective coatings and surface treatments or anti-Corrosion solutions can help mitigate UV radiation, effects of chemical exposure and biological growth of radar material. These treatments can improve durability and maintain signal transparency.
- Design optimization: By optimizing radar design features such as aerodynamics, drainage systems, and ventilation, the accumulation of moisture, debris, and biological contaminants can be minimized. Appropriate design considerations can improve environmental tolerance and reduce maintenance requirements.
- Protective coatings: Special coatings are applied to the radar surface to repel water, prevent biological growth, and minimize the effects of solar radiation.
- Structural design improvements: Improvements in the design of protective domes, which include aerodynamic shapes or stronger construction materials, to sustain strong winds and snowfall.
- Heating systems: Heating systems are applied to prevent snow and ice accumulation, especially in cold climates.
- Signal correction algorithms: Development of algorithms to correct signal attenuation or distortion caused by environmental factors. This may include advanced data processing techniques to filter out noise and distortion.
- Routine maintenance and calibration: Establish routine maintenance procedures to check and repair physical damage and recalibrate the radar system as needed.
- Environmental monitoring: Using sensors to monitor the environmental conditions around the radar and adjust radar settings or signal processing methods accordingly.
- Research and testing: Continuous research and testing for efficient understanding of the effect of various environmental factors on radome performance and developing more effective repair methods.

Simulation analysis plays an important role in mitigation studies due to the limitation of cost and time for experimental studies. Using suitable simulation software, mitigation method for specific radomes can be narrowed down which can be tested experimentally for further verification to suit practical application.

Effects of Rainfall and Lightning

Two major effects, the effect of rainfall and lightning are discussed in the following sections. Preliminary simulation studies conducted on wet ground based radomes with different materials and lightning strikes on airborne radomes are also included.

Effects of Rainfall on Ground Based Radomes: Rainfall can have several effects on radomes. These effects can impact the structural integrity, radar transparency, and overall performance of the radome Fig. 4 shows a radome affected by continuous rainfall and without proper maintenance. Various effects of rainfall on radomes are listed below.

- **Material Degradation:** Steel and aluminium components used in radome structures are especially susceptible to corrosion from rainwater. Regular moisture exposure can cause rust, which compromises the structural integrity of radome. The use of composite materials in radome construction may expose them to water penetration, which could cause material separation and layer delamination. The adhesive bonding between composite layers can weaken due to water penetration, compromising the radome's structural stability.
- **Water Ingress**: Rainwater ingress into the radome's interior may be possible due to poorly sealed joints

or broken surfaces. Water entry can cause internal component corrosion, electrical shorts, and equipment damage[7]. Gaskets, seals, and caulking are examples of sealing mechanisms to stop leaks and preserve the radome's waterproof integrity. Rainwater accumulation on the surface of radomes can cause pooling, particularly if its surfaces are flat or have a low slope. Water accumulation can put additional strain and weight on the radome structure, which could lead to deformation or collapse.

- **Impact on Radar Performance**: Radar performance can be lowered and signals may be attenuated when rainwater droplets on the radome's surface, scatter and absorb radar waves. Water droplets have the potential to cause interference and noise in radar measurements, which can compromise tracking and detection precision and dependability. Radar signals can be refracted and distorted by traveling through the radomes covered with rainfall. This can lead to reduced target resolution, false returns, and signal distortion, especially during intense rain or storms. The effect will be more for the radomes at higher frequency bands.
- **Structural Effects**: Wind-driven rain may apply extra pressure to the radome surface, raising the risk of leaks, surface damage, and structural collapse. Radome structures need to be built with the right reinforcing and anchoring systems to withstand the mechanical forces brought on by wind and rain. Wind-induced forces and the weight of accumulated rainwater might cause dynamic loading on the radome structure. This could affect the radome's structural integrity and long-term dependability by causing fatigue, vibration, and resonance effects.

Radomes are generally optimized to reduce transmission loss and prevent signal variations caused by radome seams. Hydrophobic materials are used to minimize the extra attenuation that can occur when the surface becomes wet. Michael Frech have analysed wet radome impacts on dualpol moments and found that differential Reflectivity, ZDR has large impact, demanding a corrrection of ZDR. The other dualpol moments were weakly affected by wet radome when study of the cases with moderate precipitation and intense precipitation were done[8]. They mentioned that the bias may be higher than +0.8 dB.

Merceret and Ward[9] had shown that attenuation due to rainfall is less than 1 dB at S and C bands for light rainfall events and it is not dependent on the radome type. The attenuation increases with the rainfall rates and for S-band it is less than 1 dB for a rainrate of 100 mm/hr, while for C-Band the attenuation may be around 5 dB for 50 mm/hr rainfall rate.

Simulation studies on effect of the wet radomes on antenna performance were conducted. The study is conducted using different materials such as PTFE (Polytetrafluoroethylene), DuPont, Ultem etc. The antenna gain for the radomes using these materials are shown in fig. 5a, 5b and 5c. Protective coatings, thermal management and other design optimization can also be effectively done by using simulations in HFSS software.

Effects of Lightning: Lightning can seriously affect the structure of radomes, especially aircraft radomes. When lightning strikes the radome, the high electrical energy can cause several forms of damage[10]. The intense heat generated by the lightning can melt or burn the radome material, leading to surface burning, formation of bubbles and peeling of layers within the radome material or painting. The mechanical force of the lightning strike can cause structural deformation, cracking, and fragmentation of the radome material (Fig. 6 a).

Additionally, the electrical discharge can erode the surface of the radome, resulting in pitting, surface roughness, and material ablation (typically manufactured using composite materials). These effects can compromise the structural integrity, aerodynamic performance, and electromagnetic transparency of the radome, potentially affecting the radar system's functionality and the safety of the aircraft. To mitigate these risks, aircraft manufacturers incorporate lightning protection systems into radome designs, including conductive materials and grounding systems, and implement regular inspection and maintenance procedures to detect and address any lightning-related damage properly. The effects of lightning on radomes are

- **Direct Strikes**: A direct lightning strike to a radome can cause immediate and severe damage. The intense heat generated by the lightning bolt can melt or vaporize radome materials, resulting in localized melting, charring, or burning of the surface. The force of the lightning strike can also cause physical damage to the radome structure, such as punctures, cracks, or fractures. These structural defects compromise the integrity of the

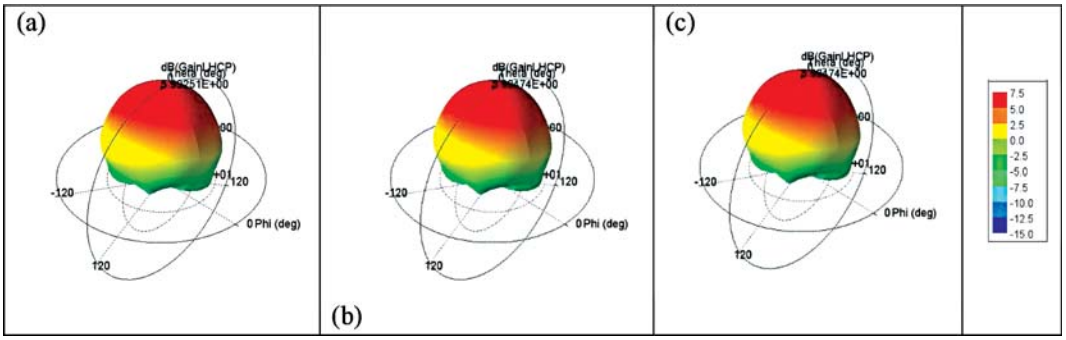

Fig. 5: (a), (b) and (c): The gain plots for PTFE, DuPont and Ultem radome materials, respectively.

Fig. 6(a): Damages caused by lightning strike on aircraft (Courtesy: https://www.theatlantic.com & http://www.chinaaviationdaily.com/news/44/44306.html)

Fig. 6 (b): The wreckage of flight 1492 (https://en.wikipedia.org/wiki/Aeroflot_Flight_1492#/media/File: Aeroflot_Flight_1492_wreckage.png)

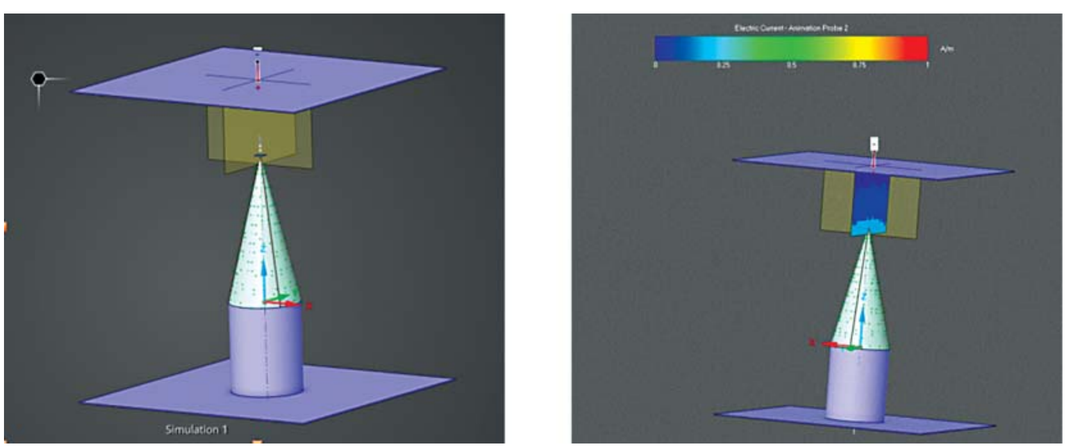

Fig. 7a: Simulation model and **7b:** Path of the current flow

radome, potentially exposing the enclosed equipment to further damage from environmental elements.

- **Indirect Effects**: Even if a radome is not directly struck by lightning, nearby strikes can induce transient electrical currents and electromagnetic fields in the structure. These induced currents can flow through conductive components within the radome, such as metallic mounting brackets or reinforcement structures, leading to electrical arcing, heating, or component failure. Electromagnetic fields induced by lightning can also interfere with sensitive electronic equipment housed within the radome, causing malfunctions, signal distortion, or data corruption. The electromagnetic pulse (EMP) generated by lightning can induce voltage spikes in electrical circuits, damaging semiconductor devices and other electronic components.

- **Fire Risk**: The heat generated by a lightning strike in the radar dome can ignite a fire hazard on the dome or in the surrounding environment. If the radar contains combustible materials such as insulation, wiring or equipment housings, a fire caused by lightning can spread rapidly, causing extensive damage to the radar dome and potentially endangering personnel or nearby structures. Fire suppression systems can be installed in protective domes to reduce the risk of fire in the event of a lightning strike. These systems may include automatic fire detection and extinguishing mechanisms such as sprinklers, fire extinguishers or inert gas flooding systems.

Fig. 6b shows the wreckage of Russian aircraft - flight 1492 (Sukhoi Superjet 100 aircraft) on 5th May, 2019. The flight was struck by lightning when it was climbing out. The aircraft suffered an electrical failure and did an emergency landing at the nearest airport. While landing, it bounced and the touch down was hard, which caused collapsing of the landing gear, spillng of fuel out of the wings, and a fire eruption. The fire affected the rear of the aircraft, killing 41 of the 78 people on board. The lightning strike caused primary radio failiure and the autopilot system became inoperative, creating a diffficult situation. This tragic incident underscores the importance of advanced lightning protection in aviation and ensuring that critical systems remain operational and that aircraft can withstand such natural phenomena without compromising safety.

Solid or segmented lightning diverter strips are used to protect the radomes from lightning. The diverter strips should be designed in such a way that it can withstand a current of 200 kA . Use of segmented strips are advised for better electromagnetic performance[11].

It is very difficult to study the effects of lightning on aircraft through experiments, as it attracts high costs to do the tests repeatedly. Further, these are destructive tests too. Due to these problems, simulation plays an important role in the lightning studies. Using simulation, we can design an effective lightning protection scheme in the form of lightning protection strips, meshing, etc., for handle the heat and transient current during lightning. Signal interference of these strips can also be studied and the optimal position, number, size and material of a lightning protection strip for a particular aircraft/radome can be designed. Based on these simulations, the best design can be selected followed by sufficient experimental support to install on the aircraft. Fig. 7a and b represent a simulation model created in EMA 3D software to study lightning strikes and the path of the current flow, respectively.

Summary

The paper gives an overview about three types of radomes and the environmental effects on them. Severe damages may occur to the aircrafts, if radomes containing the navigation equipment are exposed to hostile nature and natural phenomena. The exposure for a longer period affect the performance of the radome and in turn the antenna inside in a negative manner. In order to safeguard radomes various maintenance and mitigation measures are taken at appropriate intervals. Simulation studies play a major role in the development phase of these radomes for addressing the possible damages caused by the environmental impact, to manufacture a safe aircraft, cost effectively.

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