Deutscher Luft- und Raumfahrtkongress 2017
DocumentID: 450139

FFS: LIGHTNING STRIKE PROTECTION OF RADOMES – AN OVERVIEW

C. Karch[*]
Airbus Defence and Space GmbH, 81663 Munich, Germany

M. Calomfirescu, M. Rothenhäusler, C. Brand, and H. Meister
Airbus Defence and Space – Military Aircraft, 85077 Manching, Germany

Abstract

In order to function correctly, all aerials including radar or satcom antennas need to be electrically external to metallic aircraft skin. However, antennas have an unacceptable aerodynamic shape and have to be protected from airflow forces by an EM-transparent structure. EM-transparent structures / radomes are constructed from dielectric material, offering no EM screening of the aerial to the external electric fields associated with lightning or atmospheric storm conditions. The antenna metallic structure presents a major electrical stress raiser and is a preferred target for a lightning strike.

Whilst designing a radome, the primary considerations are mechanical strength, thermal, weight and radar transmission properties that are not fully compatible with high dielectric strength and lightning strike protection abilities. Additionally a lightning protection system has to be designed, which prevents lightning flashes from puncturing the radome structure and from damaging the antenna-receiver system. However, the lightning protection system should not have a significant impact on the antenna pattern.

It is yet generally not possible to quantify all the lightning strike protection factors sufficiently accurate to have full confidence in any numerical prediction of the radome performance under lightning strike. High voltage testing that reproduces the lightning phase of the *bidirectional leader* development is therefore essential. The necessary experimental procedures needed for a lightning protection design of a generic satcom radome for a typical future MALE UAV are discussed in detail.

1. INTRODUCTION

On average every commercial airliner gets struck by lightning at least once per year. Thus, the test and design criteria of a new aircraft are becoming important, since the aircraft safety is increasingly dependent on fail-safe electronic equipment. Moreover, the lightning strike protection (LSP) for less-conductive carbon fibre composites or nonconductive fibreglass is more critical than that for metallic airframe structures [1].

According to statistics an airplane is struck by lightning on average every 1,000 to 3,000 flight hours. For commercial aircraft, that is equivalent to one lightning strike per year. The aircraft must be able to withstand such a strike without failure of critical electronic equipment and/or without any impairment of flight characteristics [2].

In-flight experiments have shown that there are two types of aircraft lightning strikes. The most frequent case (90% of events) is lightning triggered by the intrusion of an aircraft in a region with an intense electrostatic field [3]. The electric breakdown of air at normal conditions occurs is about 3 MV/m. This value depends on air density of and decreases with increasing height. The electric fields in thunderclouds are generally much less than electric breakdown values. An aircraft located in a thundercloud electrical field will, however, become polarized and the field values at the aircraft surface will become large where the surface curvature is high enough such as wing tips, pitot tubes, nose tips, rimes of nacelles etc., see Fig. 1. The mechanism for lightning initiation by aircraft is often explained by *bidirectional leader* theory, which describes this process as a positive leader starting from the aircraft in the direction of the ambient electric field; followed a few milliseconds later by a negative leader developing in the opposite direction [4]. The less frequent case is the direct interception of an approaching lightning leader.

A special attention has to be paid to aircraft's radomes that contain weather radar or other flight instruments. In order to function properly a radar cannot be contained within a conductive enclosure. Instead, lightning diverter strips applied along the outer surface of the radome shall protect this area. These strips can consist of solid metal bars or a series of closely spaced buttons of conductive material. In many ways, diverter strips function like a lightning rod.

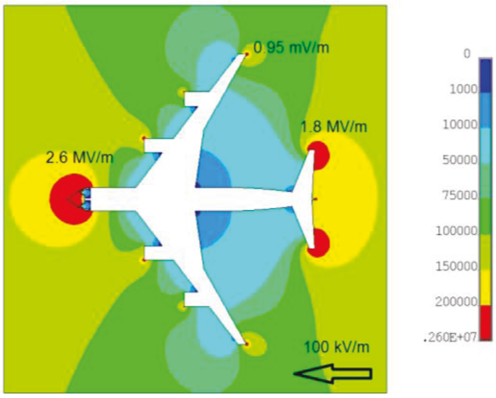

Fig. 1: 2D electrostatic field around an aircraft in a 100 kV/m ambient electric field.

---

[*] Corresponding author: christian.karch@airbus.com

In Fig. 2 the enhancement of the ambient electric field is presented around the radome area (a detail from Fig. 1). It is clearly shown, that the dielectric radome structure cannot shield the external electric field. A partial shielding effect is here caused by the solid diverter strips only.

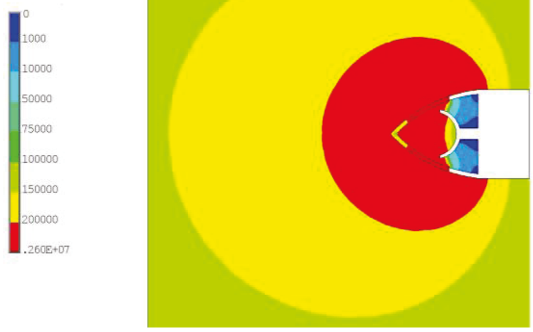

Fig. 2: 2D electrostatic field around the radome area in a 100 kV/m ambient electric field.

2. LIGHTNING PROTECTION DESIGN

A typical future MALE UAV configuration possesses a wideband antenna for a satellite communication [5]. As an example the Talarion UAV concept is shown in Fig. 3. This antenna has to be protected against all environmental impacts by a dielectric radome structure. The impact of the protecting structure on the satellite antenna radiation patterns should be as small as possible. This means that a lightning protection system has to be designed, which on the one hand prevents lightning flashes from puncturing the radome structure and from damaging the antenna-receiver system. On the other hand the lightning protection system should not impact the antenna pattern significantly. In the following the necessary steps for a lightning protection design of dielectric aerials / radome structures are discussed using some selected results obtained for a generic satcom radome for a typical future MALE UAV. A comprehensive view of the FFS generic satcom radome project is given in reference [6].

Fig. 3: Talarion UAV (Mock-up) [5].

The property of a radome to resist potential lightning stresses and to avoid mechanical thermo-mechanical damage by lightning loads depends on the constructive design of the protection system (diverter strip types, arrangement of strips), on the dielectric strength of the radome structure, on antenna features (geometry, size, position, tilt mechanism) and on the mechanical design of the radome wall structure.

It should be noted that the mechanical design[1] of the radome wall structure

- solid (monolithic); generally made of resins incorporating reinforcements such as chopped glass fibers,
- sandwich; consisting of alternating high-density (high relative dielectric constant) and low-density (low relative dielectric constant) materials

is closely correlated with EM design[2], since the antenna performance is altered by radome effects that include:

- boresight error and boresight error slope,
- antenna sidelobe levels increase,
- depolarization and/or cross-polarization,
- antenna voltage standing wave ratio increase,
- and finally insertion losses.

Usually, the radome structure and the antenna features are predetermined before lightning strike protection design is done (according to the requirements mentioned above). Thus, subsequently the diverter strip type and the strip arrangement have to be designed taking into account the lightning protection and low antenna impact performance requirements.

2.1. Diverter Strips

Solid diverter strips are usually used for commercial aircraft radome applications. Solid diverter strip shield immediately the antenna from external electric fields. Thus, the electric field strength is reduced at the antenna site and the probability of streamer-leader transition from the antenna is lowered as well. Typically 6 to 12 strips are placed on the radome surface. The cross sectional area depends on the material used and is determined by the lightning current load (usually designed for 1A aircraft zone). The surface of the solid diverter strips can be painted. The strips are fastened through radome structure with screws, see Fig. 4. Solid strips have a multistrike capability and might be installed inside the radome.

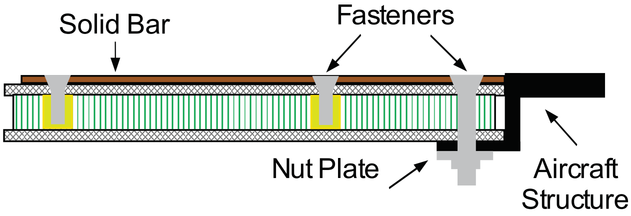

Fig. 4: Scheme of solid diverter strip design.

However, the impact of solid diverter strip arrangement on the antenna radiation patterns is definitely larger than that of segmented diverter strips. Thus, for applications where the additional impact of the lightning protection system on the antenna radiation pattern is critical segmented diverter strips are preferred. The segmented diverters vary in several features: shape, size and distance of the metallic buttons and strip material properties as well. The segmented strips are adhered to the surface of the radome and have a limited multistrike capability only. The

---

[1] The aeromechanical (elastic and strength moduli and hardness) and environmental requirements (water absorption, rain & particle erosion) are the binding guidelines for the mechanical design.

[2] The relative dielectric constant and the loss tangent of the materials used as well as their operational frequency dependence impact the EM design. In addition the dielectric strength / the breakdown voltage of the radome wall structure influence the protective effectiveness of all lightning protection measures.

scheme of the segmented diverter strip design is shown in Fig. 5. It should be noted that larger segments have lower breakdown voltages, but smaller segments usually withstand high current loads better. The early designs had resistive strip on backside that tied segments together electrically and grounded segments to aircraft. Meanwhile, the resistive strip on backside is not used, since it impedes the plasma ignition of the strip; the lack of resistance does not affect the p-static performance of the strip. The typical spacing between segmented diverters is about 30 to 45 cm at the radome mounting ring. In any case segments are not to be painted. Moreover, the operation of segmented diverter strips is strongly influenced by external environmental conditions (water, ice, rain erosion, …) [7].

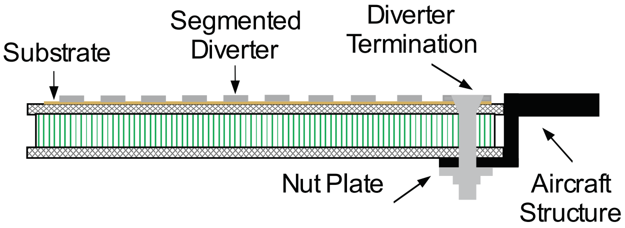

Fig. 5: Scheme of segmented diverter strip design.

Segmented diverter strips shield the antenna only when ionized plasma effected by an applied external electric field is formed above diverter strips. Thus, a *complete plasma ignition* is crucial for an effective lightning protection. The mechanism of the ionization and plasma formation above a segmented diverter strip is schematically shown in Fig. 6.

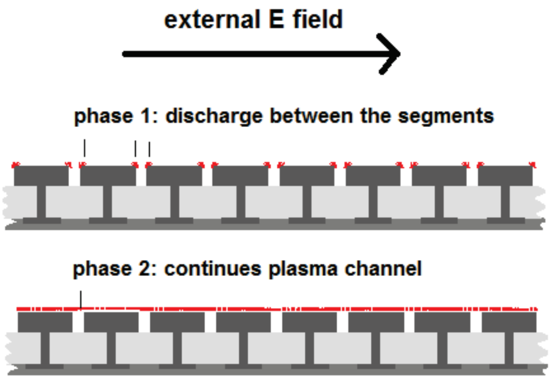

Fig. 6: Ionization and plasma formation mechanism.

The first step of the lightning protection concept is a proper selection of the diverter strip type. Two criteria are decisive for the selection:

- the required minimum impact on the antenna performance,
- the highest possible protection effectiveness for the identified maximum diverter strips length.

The first criterion is related to the EM transparency of the strip.[3] For the antenna-radome configuration considered the maximum size for the buttons should be about 1.2 mm. The second criterion takes into account that the protection effectiveness of segmented strips decreases significantly with increasing length.

Two different types of segmented diverter strips have been considered. The diameter of the cylindrical buttons of the first diverter type is about 0.76 mm. The data of the ignition voltage and ignition characteristics of this diverter type are not provided by the supplier. However, it can be assumed, that the ignition voltage of this diverter is significantly higher than those of a second type with button's diameter of about 1.52 mm [8]. The front and the rear side of both diverter strips are shown in Fig. 7.

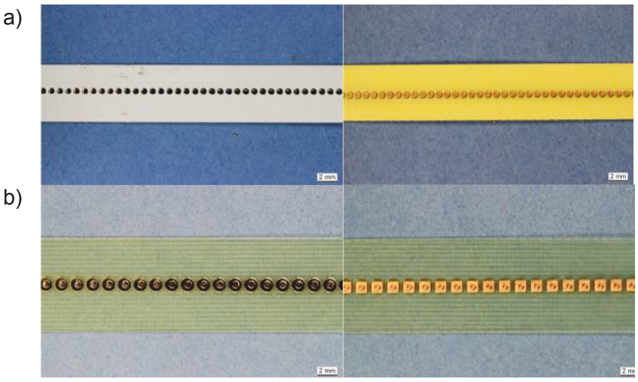

Fig. 7: Top and bottom view of diverter types considered.

The primary method to assess the protective effectiveness of segmented diverters is the characterization of their ignition voltage as a function of diverter length. The setup to measure the ignition voltage is shown in Fig. 8.

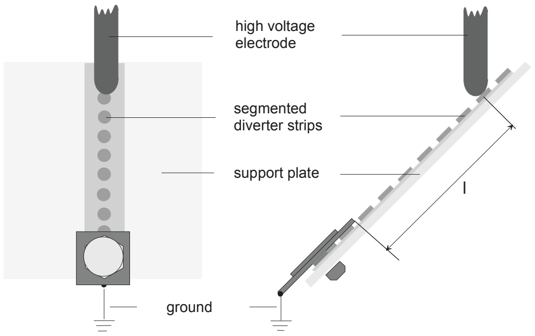

Fig. 8: Scheme of HV ignition measurement setup.

The measurements are performed with two different high voltage waveforms A and D [9].:

- aging effects caused by repeated high voltage and/or high current loads,
- polarity and rate of rise of the high voltage pulse,
- shape, size of buttons, rear side resistance coating,
- strip length, and finally
- environmental conditions.

The diverter strip which has been selected for the application given, do not show any aging effects by high voltage loads, at least up to few shots.

The mean ignition voltage of the strips is plotted in Fig. 9 as a function of strip length for both polarities. The ignition voltage increases roughly with increasing strip length. The mean electrical field needed to ignite a plasma channel above the segmented strip is approximately 1 (0.75) kV/cm for the high voltage waveform A (D) for a strip length below 100 cm.

---

[3] If the transmission loss has to be limited by 0.1 dB, the maximum dimension of the buttons must be smaller than 1/8 λ_0, where λ_0 represents the electric free field wave length of the highest operating antenna / radar frequency.

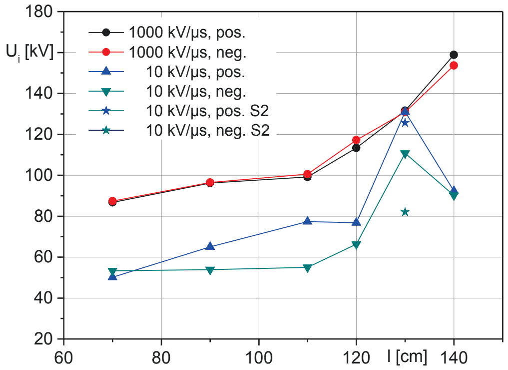

Fig. 9: Mean ignition voltage U_i of strips with button diameter of 1.52 mm as a function of strip length.

2.2. Breakdown voltage of radome structure

The breakdown voltage characterizes the lightning protective effectiveness of the radome wall structure. The radome structure considered here is an A – sandwich with variable core thickness (taper). The taper is used to optimize the reflection/transmission properties of the radome structure (the local electrical impedance matching to relevant angles of incidence).

The measurement of the breakdown voltage is performed on the basis of international standards IEC 60243-1 and IEC 60243-3 [11], [12]. In addition, the ED-84 and SAE ARP5412 standards are considered as well [9]. For these measurements the HV wave form B 1.2/40 µs is taken into account. The experimental setup at the University of the German Federal Arm Forces Munich is shown in Fig. 10.

Fig. 10: HV – test setup with pulse generator, measuring divider and testing rack with DUT [13].

The experimental results are summarized in table below. The values presented are averaged above both polarities.

A	B	D
114	89	85

Table 1: Mean breakdown voltages of an A – sandwich for different HV wave forms (polarity-independent).

These data indicate that the breakdown voltage decrease with decreasing rate of rise of the wave form. The values start with about 114 kV for wave form A, via nearly 90 kV for wave form B and descend to about 85 kV for wave form D.

2.3. Pre-Estimation of maximum strip length and spacing

A first estimation of the maximum allowable strip length is based on the comparison of the ignition voltage of diverters with the breakdown voltage of the radome wall. All geometrical effects, which might arise from the impact of the antenna and/or the wall curvature, are neglected. This procedure is considered as being conservative; the radome structure is punctured, if the ignition voltage of the strip is higher than breakdown voltage of the structure.

The ignition voltage of the strip of type button size 0.76 mm exceeds considerably breakdown values of 100 kV for a strip length of about 70 cm [14]. In case of the strip of type button size 1.52 mm- the breakdown voltage for HV A is about 114 kV, for HV B 89, and for the slow HV D about 85 kV. Consequently, 85 cm can be considered as the lower limit value for the length of this diverter strip type.

2.4. HV tests of radome-structure antenna system

In order to minimize the impact of the lightning protection system on the antenna performance, the potential margin concerning the length of the diverter strips should be on one's best assessment. Therefore, an experimental test setup is used, which takes the impact of the metallic antenna platform into account. The chapter 2.4.1 deals with this setup and with the results based hereon. The following chapter 2.4.2 treats the admissible distance between diverter strips.

2.4.1. Admissible length of diverter strips

The estimation of the maximally admissible length of the diverter strip based on the comparison of their ignition voltage with the breakdown voltage of the radome structure can be considered as conservative. This procedure corresponds to a situation, where the antenna is in direct contact with the inner radome surface. The real positive distance between antenna and radome surface requires an additional voltage drop, which is responsible for the breakdown of the corresponding air gap. If the distances between antenna and radome as well as the respective core thicknesses are known, it is possible to determine the acceptable strip length more accurately. A draft, which illustrates the testing configuration in detail, is presented in Fig. 11.

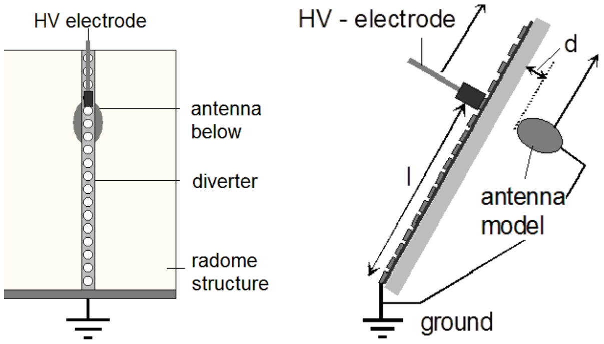

Fig. 11: Measurement setup for admissible diverter length.

In some sense this setup can be considered as a modification of test setup C [10], which is used to determine the admissible maximum distance between two strips. The procedure starts with a small length l of the electric arc between HV- and grounding electrode. For this length no puncture of the structure is expected. Then, the position of the HV – electrode is changed such that the length of the arc, which must be ignited, is increased. The antenna mock-up is relocated in the same way as the electrode in order to maintain the specified relative position of electrode and antenna. This procedure is repeated as long as a first puncture of the radome structure occurs. The last position without electrical breakdown of the structure determines the maximum acceptable length of the diverter strips.The typical wave shapes of HV waveforms A and D are plotted in Fig. 12 and Fig. 13, respectively.

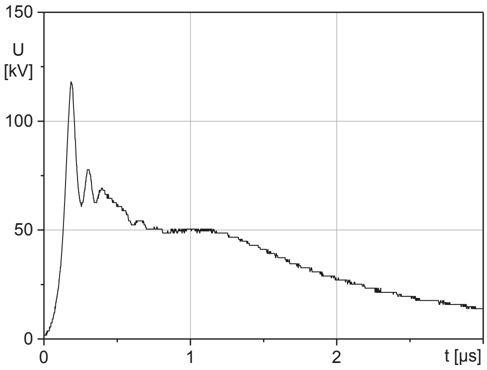

Fig. 12: Typical shape of recorded HV waveform A.

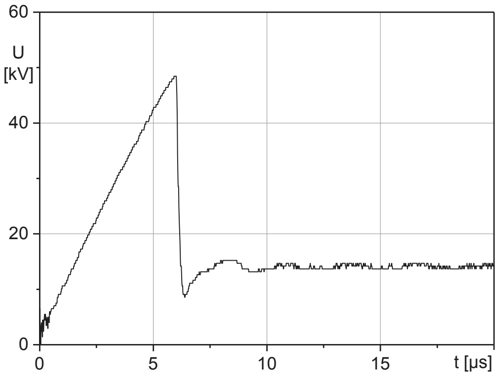

Fig. 13: Typical shape of recorded HV waveform D.

The corresponding recordings showing the ignition of the plasma channel above the segmented diverter strips are shown in Fig. 14.

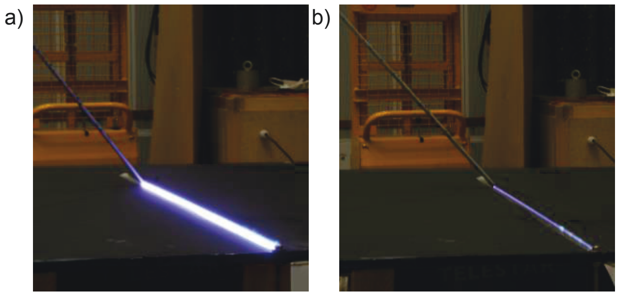

Fig. 14: Typical recording of the plasma ignition caused by the HV wave form A (a) and D (b) with a nominal slope of 1000 and 10 kV/µs, respectively.

None of these tests with HV waveform A and D with both polarities and segmented diverter strip length up to 100 cm resulted in a puncture of the sandwich panel followed by a discharge to the antenna mock-up. Thus, these results demonstrate that segmented diverter strips of type buttons 1.52 mm may be applied on the satcom-radome configuration with a length of about 100 cm.

2.4.2. Maximum spacing of diverter strips

Experience has shown that diverter spacing determined from development tests as illustrated in Fig. 15 have proved to be successful in subsequent final verification tests of radomes, employing similar diverter spacing.

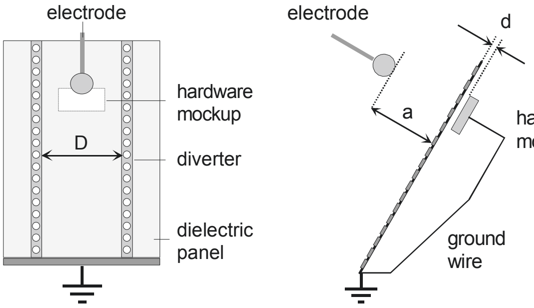

Fig. 15: Test setup C according to EUROCAE WG 31, ED 105 [10]

This test setup is most appropriate for developmental tests to evaluate skin panel constructions and diverter strip configurations. The radome panel is placed on two wooden supports. Two segmented diverter strips are fixed on the panel by double-sided adhesive tape in a distance D. The injection electrode, an aluminium rod with approximately 10 mm diameter, is adjusted in a height a (equal D) midway above the diverter strips. The procedure starts with a small spacing D. For this spacing no puncture of the structure will occur. Then, the spacing is increased and the position of the HV – electrode is changed as well. The antenna mock-up is relocated in the same way as the electrode in order to maintain the specified relative position of electrode, diverter strips, and antenna. This procedure is repeated as long as a first puncture of the radome structure occurs. Each test arrangement is intended to result in initiation of electrical activity, such as corona and streamering, at the test object (and not at the external electrode) as it occurs in flight just before a lightning strike attachment. A typical skin panel is about 1 m square, although other sizes and shapes would be acceptable, sufficient to accommodate a full scale arrangement of protection devices. Coatings like skin materials, surface finishes and paints should be applied. The diverters should be as long as they would be in the aircraft installation. A mockup of any conductive items behind the protective surface should be placed at an appropriate position behind the skin at the distance "d". The protection devices are normally at facility ground potential and the electrode is at high potential. In order to apply a realistic test condition, experience has shown that the electrode should be positioned midway between the diverter strips, as in the example of Fig. 16, where the discharge path occurs between the electrode to and along both diverters. It should be noted that in most cases the discharge path appears between the electrode and one of the diverter strips.

It is shown that positive polarity for both HV waveform is the critical one. In case of negative polarity diverter spacing of 60 cm and more is possible. On the other hand the most critical case is the HV waveform D with negative polarity discharge, where puncture occurs for diverter spacing of more than 50 cm, see Fig. 17.

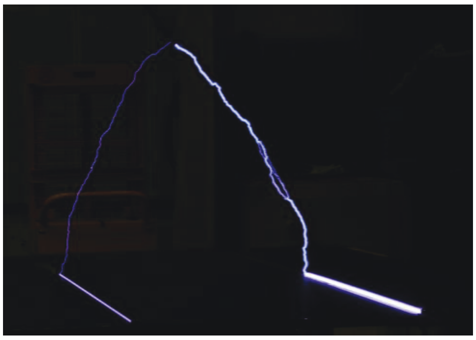

Fig. 16: Plasma channel from the electrode directly to and along both diverters.

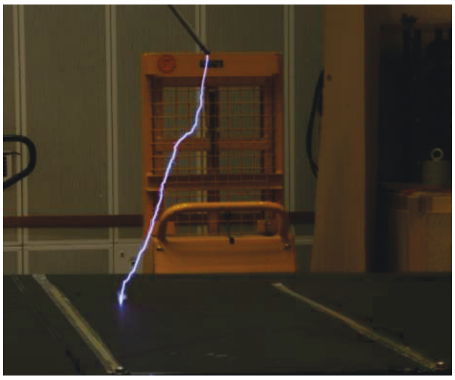

Fig. 17: Plasma channel from electrode to antenna through the radome panel (HV waveform D with positive polarity).

The damage on the front and rear side of the radome panel caused by dielectric puncture is shown in Fig. 18.

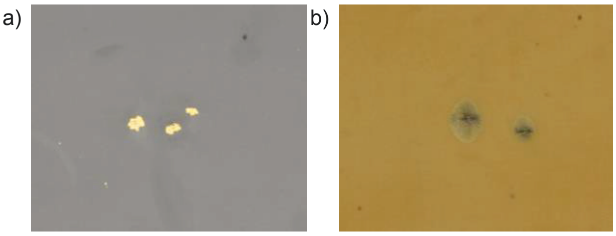

Fig. 18: View on the front (a) and rear side (b) of a punctured radome panel.

2.5. Summary and Outlook

The electric field strength inside a dielectric radome is not attenuated significantly by the radome wall structure itself. Consequently, the radome does not produce any significant electromagnetic screening effects even if an anti-static paint is applied. Thus, in order to avoid the inception of a discharge from the radar/ antenna inside the radome, solid or segmented lightning diverter strips are usually used to produce either the necessary electromagnetic shielding effect and/or to trigger the streamer-leader from the tip of the diverter strips.

There are few general guidelines that should be followed when designing lightning diverters on electrically non-conducting aircraft structures [2], [14]. Based upon the findings discussed above and the general guidelines available a lightning protection system can be designed for the given generic radome [5]. It should be noted that several lightning protection design options are possible:

- Some manufactures forgo lightning protection measures for small radome structures / small UAVs.
- There are some minimalist approaches where the direct neighborhood of the radar / antenna is protected only.
- There are hybrid protection systems consisting of solid and segmented diverter strips that on the one hand provide a sufficient level of safety and on the other hand minimize the impact on the antenna radiation patterns.
- For commercial aircraft applications solid diverter strips are generally used for weather radars, as they provide the highest level of safety against lightning strikes. However, the impact effects of this design option on the antenna patterns may be too high for some other applications.

In addition there are many factors influencing the structural and electric radome performance under lightning strike conditions which cannot be tested on small coupon samples. Therefore, either numerical 3D modelling and simulations or further high voltage and high current tests using full-scale test objects are compulsory [15], [16].

After a final design concept has been compiled, the following tasks on a full-scale radome sample are to be performed:

- the current carrying capability and adequacy of grounding concept tests,
- tests for a successful completion of the initial leader attachment using a full-scale radome sample, and finally
- tests for a successful completion of the swept channel attachment on a full-scale radome sample (for radomes with surface areas in the Zone 1A as well as 1C, and / or 2A and 2B).

The initial leader attachment tests are mandatory for certification purposes. The European standard, ED-105A [10] describes the initial leader attachment test, in order to localize possible lightning leader attachment points on full size structures, in order to localize flashover or puncture paths, along or through dielectric surfaces, and / or in order to assess the performance of protection devices, such as radome diverter strips. The test object should be a full-scale production hardware or a representative prototype. Any paint finishes should be included to ensure realistic development of corona and streamering from conducting elements. Electrically conducting objects, such as antenna elements and lights which are normally enclosed by the radome should be represented within the test object. This can be accomplished by actual devices or geometrically correct mock-ups with coating of sufficient electrical conductivity. If the conducting objects may be oriented in several positions, those that represent worst cases should be represented in the test. Other conductors such as mounting fasteners, frames, hinges and latches must also be represented.

There are two test arrangements, designated Setup A or B, that can be used for tests on complete production or prototype test objects like radomes. Exemplarily, the arrangement of Setup A is illustrated in Fig. 19 for a typical nose radome configuration.

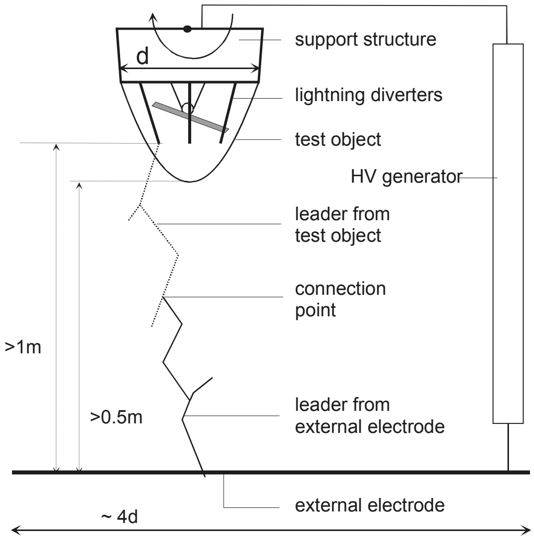

Fig. 19: Initial leader attachment test setup A.

The test object is elevated above an external electrode, which is a large area ground (metallic) plane placed on the facility floor. The dimensions of the ground plane and spacing between the test specimen and the ground plane depend upon the size of the test object, as indicated in Fig. 19. Connections of the streamers should occur in the air away from the test object, as illustrated in Fig. 19. The test object should normally be tested with two or more orientations, to represent electric field directions that this part of the aircraft may experience in flight.

The Voltage waveform D as defined in ED-84 [9] should be applied for Test Setups A and B, since this is most representative of the electric field at an aircraft extremity during an initial leader attachment. The test voltage should be applied at both polarities. It is recommended that two discharges in each polarity are applied in each test object or electrode orientation. The detailed test procedure and data recording can be found in the European standard ED-105A and reference [17].

A hybrid lightning protection system consisting of solid and segmented diverter strips is currently being developed by Airbus Defence and Space GmbH. The basis for the design of the hybrid lightning protection system are the experimentally obtained results for the dielectric breakdown of the generic satcom radome structure as well as for the maximum length and spacing of the investigated segmented diverter strips. The full-scale radome prototype designed by Airbus Defence and Space – Military Aircraft [5] is going to be manufactured by an external global player in the field of high-quality and sophisticated composite materials. The necessary current carrying capability tests on representative coupons are going to be performed in an external high-voltage laboratory. Finally, the efficiency of the lightning protection system on a full-scale generic satcom radome prototype will be tested in an external high-voltage laboratory.

3. REFERENCES

[1] C. Karch and C. Metzner, *Lightning Protection of Carbon Fibre Reinforced Plastics – An Overview*, Proceedings of ICLP 2016, Estoril, Portugal, 2016, DOI: 10.1109/ICLP.2016.7791441,

[2] J.A. Plumer, and R.A. Perala, *Lightning Protection of Aircraft*, Lightning Technologies Inc., (2nd edition), 2014

[3] M.A. Uman and V.A. Rakov, *The interaction of lightning with airborne vehicles*, Progress in Aerospace Sciences, Vol. 39, pp. 61-81, 2003

[4] V. Mazur and J.P. Moreau, *Aircraft-triggered lightning: processes following strike initiation that affect aircraft*, J. Aircr., Vol. 29, pp. 575-580, 1992

[5] Leitkonzept Fortschrittliche Flugzeugstrukturen – FFS, Airbus Defence & Space - Military Aircraft, Rechliner Straße, 85077 Manching, Germany

[6] C. Brand and H. Meister, *FFS - Zur Entwicklung vogelschlaggefährdeter, multi-bandfähiger Radome für zukünftige UAVs*, DLRK Congress 2017

[7] C. Karch, *Lightning Protection of WB – SATCOM Radom, Impact of Environmental Condition on Segmented Diverter Strips,* Airbus, TX3RP1620011, 2016

[8] D. Wilmot, 16572 Burke Ln, Huntington Beach, CA 92647 http://lightningdiversion.com/home/

[9] EUROCAE ED-84, *Aircraft Lightning Environment and Related Test Waveforms*, European Organisation for Civil Aviation Equipment, Paris 1997, SAE ARP5412-Revision, "Aircraft Lightning Environment and Related Test Waveforms," SAE Aerospace, 2005

[10] EUROCAE WG 31, *Aircraft Lightning Test Methods.* Eurocae ED-105, Revision 2013

[11] IEC: *Electrical strength of insulating materials – Test methods – Part 1: Test at power frequencies*, IEC 60243-1, 1998

[12] IEC: *Electrical strength of insulating materials – Test methods – Part 3: Additional requirements for 1,2/50 µs impulse tests*, IEC 60243-3, 2001

[13] Chair for High Voltage Technique and Lightning Research, Universität der Bundeswehr München

[14] C. Karch and W. Wulbrand, *Lightning Protection of WB – SATCOM Radome - Maximum Length and Distance of Diverter Strips – Final Report*, Airbus, TX3RP1620081, 2016

[15] C. Karch *et al.*, *An approach to determining radome diverter strip geometry,* ICOLSE 2001, Aerospace North America SAE International 2001

[16] C.J. Hardwick. *et al.*, *Joint Programme on Improving Lightning and Static Protection of Radomes*, Culham Electromagnetics and Lightning Limited, CUL/LT-0036, Culham, 2001

[17] C. Karch, *Lightning Strike Test Requirements for UAV MALE Radome*, TX3RP1720492-Technical Report, Munich, 2017