Impact of *In Situ* Radome Lightning Diverter Strips on Antenna Performance

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**Abstract**—Lightning diverter strips are commonly used to protect the antenna and sensitive equipment within an airborne radome. This article compares the impact of solid metallic and segmented diverter strips on the radiation properties of the enclosed antenna. Solid metallic and segmented diverter strips of different segment profiles, i.e., square, circular, and diamond, are considered. This article reports how the placement of diverters on the radome and their geometric detail affect the antenna parameters, namely reflection coefficient and far-field pattern. Furthermore, the surface electric field intensity on segmented diverter strips is analyzed for different shapes, sizes, and separations between the metallic segments.

**Index Terms**—Antennas, lightning, radomes.

I. INTRODUCTION

Antennas located within an aircraft nose and shielded by a dielectric radome are highly vulnerable to damage caused by lightning strike as this zone is likely to experience initial lightning attachments and first return strokes (Zone 1A) [1], [2]. It is, therefore, critical to integrate lightning protection on the radome surface in order to intercept lightning strikes and divert them to the airframe and away from the antenna. Lightning protection on the radome typically uses two types of diverter strips, namely solid metallic diverter strips and segmented diverter strips. Solid metallic diverter strips are made of solid bars of metal that are glued to the outside of the frame and provide a metal path for lightning current [1]–[4]. On the other hand, segmented diverter strips consist of a series of conductive segments fastened to a resistive material that is glued to the surface of the radome. Segmented diverters conduct lightning current by creating an ionizing channel in small gaps between metallic segments under a strong external field. A variety of segmented diverter strips are in use with segments that differ in the shape, size, and separation between them [3]. Most commonly used are diverters with circular, square, or diamond segments [3]. Typically, dimensions of segmented diverter strips that are used on radomes have widths less than 1 cm and metallic segments’ whole size is of the order of millimeters with the usual spacing between segments of the order of millimeters. An illustration of different types of segmented diverter strips is shown in Fig. 1. A geometrical model of a radome with a base radius of 0.4 m and a height of 0.45 m with eight 0.4 m-long segmented diverters is shown in Fig. 2(a) with a zoomed-in view of a segmented diverter strip on the radome surface shown in Fig. 2(b). The typical recommended spacing between diverter strips is 30–45 cm [3], [5].

An average aircraft is hit by a lightning once every 1000 h. The design challenge is that the presence of diverter strips needs to have a low impact on the antenna performance and at the same time provide adequate protection from lightning strikes. These, in essence, requirements can be fulfilled once an understanding is reached on how the geometry of diverter strips and their placement on the radome surface affect both the enclosed antenna and the lightning current conduction. The geometry of diverter strips, their length, spacing, and position need to be optimized in terms of lightning channel developments and at the same time ensure radar’s operability [6].

Understanding the physical mechanisms of the lightning current conduction and the impact that segmented diverter
geometry has on the breakdown voltage have mainly been explored using experimental measurements of lightning channels on either flat or realistic radomes [3], [4], [7]. Full-wave simulation analyses have been applied to simpler 2-D models of lightning channel ignition in segmented diverters [8], [9], while simplified 3-D simulation studies have been used to determine the streamer-leader development on radome diverter strips [6] and field distributions at the nose of the aircraft flying in thunderstorms [10]. These studies show that segmented diverters with larger metallic segments have lower breakdown voltages compared to those with smaller metallic segments but that smaller segments withstand higher current loads better [3]. The shape of the segments also affects the breakdown voltage, with diamond-type segments having lower breakdown voltages than circular or square segments [9]. Furthermore, the effectiveness of the protection afforded using segmented diverters significantly decreases with increased length of the segmented strip, with some studies also showing that segmented diverter strips have limited strike capability compared to metallic diverters that have multistrike capability [3]. In [10], the shielding effect of solid metallic and segmented strips on a spherical radome in the absence of an antenna was analyzed, and it was shown that solid diverter strips produce a shielding effect which increases with the number and the length of strips and that strong shielding causes undesirable field intensification at the front of the radome. This article shows that segmented diverter strips do not cause a shielding effect which indicates that there will be no interference with the antenna radiation field until the breakdown along the strip is established [10].

The lack of a more comprehensive and detailed study of the effect that diverter strips have on antenna radiation patterns is due to two main difficulties. First, in order to assess the impact of lightning protection on airborne antennas, broadband and fully coupled modeling of antenna–radome interactions on realistically sized geometries is required. This means that the antenna needs to be modeled in situ which requires full-wave computational algorithms that are capable of handling the multiscale nature of the problem, specifically the large scale of the radome and, at the same time, the small geometrical features of the antenna. Our recent work on modeling installed antennas using a full-wave time-domain method shows that antenna performance is significantly changed when installed in realistic environments and is affected by both near and far-field interactions [12], [13].

Second, and most importantly, CAD models of a radome with diverter strips are not readily available. Both the individual components, i.e., the radome and diverter strip, are defined in the Cartesian framework and it is impossible to generate a physically consistent geometry using constructive solid geometry (CSG) techniques without creating unphysical artifacts at the radome–diverter interface which are detrimental to the purposes of accurate electromagnetic (EM) analysis. However, the CSG approach can be replaced with the mean value coordinate (MVC) method that enables morphing of diverter strips onto the radome surface [14]–[17]. A step-by-step guide to the morphing of radome strips onto the radome surface is reported in [18] and will not be repeated in this article. An example of the radome geometry with diverter strips obtained using the MVC method is shown in Fig. 2.

The aim of this article is to conduct a detailed investigation, using a full-wave 3-D simulation tool, to assess the impact of diverter strips on in situ antenna performance. This will be done by considering different lengths and separations between diverters, different types of diverters (i.e., metallic or segmented), and the geometry detail of segmented diverter strips, i.e., the shape of conducting elements (square, circular, or diamond). Furthermore, the surface electric field distributions for different types of segmented diverter strip geometries are examined to assess their performance under the conditions of breakdown and lightning current conductions.

For this purpose, we use a time-domain numerical method based on tetrahedral mesh we refer to as the unstructured transmission line modelling (UTLM) method [19]. The main benefit of this method lies in the fact that it uses a tetrahedral mesh which requires fewer sample points to capture curved and multiscale geometries that are dominant in this scenario. Unstructured meshes are routinely used with finite-element (FE) methods [20] and have been developed for the finite-difference time domain (FDTD) [21]–[23]. However, the UTLM framework offers distinctly valuable features: a time-stepping algorithm that is obtained without approximations such as mass lumping; the electric and magnetic field samples are co-located in time and space and most importantly, the stability of a UTLM algorithm is provable a priori on a cell-by-cell basis without resorting to estimators such as the Courant condition. For large-scale simulations, this is a critical advantage as late time instability has never been observed with the UTLM. In the UTLM method, the tetrahedral mesh is seamlessly combined with a Cartesian mesh which is used to model large empty space regions without unduly compromising the computational efficiency or with the complexity of bespoke subgrid-ting techniques [24]. Being a time-domain method, the UTLM easily permits modeling of linear, dispersive, and nonlinear materials. Recent work has accounted for both electric and magnetic material losses [25], and the presence of carbon
fiber panels as embedded thin film layers between the mesh cells [26]. Finally, an important advancement in the development of the UTLM method is its ability to deal with multiscale features of practical problems by deploying complexity reduction techniques in which small computational cells are coalesced into larger entities to reduce both preprocessing time and run time [27]. The UTLM method is not discussed in detail in this article and supporting evidence for the accuracy and multiscale capability of the method, as well as its industrial deployment can be found in [19] and [24]–[27].

The rest of this article is organized as follows. Section II analyses the impact of solid metallic and segmented diverter strip parameters on antenna properties, Section III analyses the impact of the geometry of segmented diverter strips on the electric field distribution, and Section IV summarizes the main conclusions of this article.

II. IMPACT OF IN SITU RADOME DIVERTER STRIPS ON ANTENNA PERFORMANCE

In this section, the EM performance of the antenna inside a radome with lightning protection is analyzed. The lightning protection is assumed to consist of a number of diverter strips that are either all metallic or segmented diverter strips. Typical design parameters such as the length of diveters, the separation between diverter strips, and the shape of diverter segments, i.e., circular diamond or square, are considered.

The radome is considered to have an ogive profile described by the equation \( x^2 + y^2 = (2R/L)^2(L_p - z^p)^2/p \), where the \( z \) coordinate is defined along the axis of the radome, \( L \) indicates the length of the radome, \( R \) is the base radius, and the parameter \( p = 1.449 \) defines the radome profile. The radome base radius and length are fixed to be \( R = 0.4 \) m and \( L = 0.45 \) m, respectively. In all cases, the half-wave monolithic radome is made of a glass composite of thickness 24.4 mm and relative dielectric constant \( \varepsilon_r = 4.2 \) which is designed to operate at 3 GHz. The radome base is circular with a thickness of 5 mm. Radome material losses are neglected. A Vivaldi antenna operating at 3 GHz is placed inside the radome. The antenna is printed on a dielectric substrate with \( \varepsilon_r = 3 \) and is based upon [28]. The width, height, and thickness of the substrate are 40, 55, and 1.5 mm, respectively. The antenna is fed by a coaxial line whose inner radius is 0.375 mm and outer radius is 0.875 mm. The dielectric constant of coaxial insulator is \( \varepsilon_r = 2.25 \). The radome with in situ antenna as per given dimensions is shown in Fig. 3. Fig. 3 also shows the H-plane (\( \theta \)) and E-plane (\( \phi \)) definition.

Both types of diverter strips are considered, namely metallic and segmented diverter strips. The following diverter parameters are kept constant throughout this article.

1) The width of the solid metallic and segmented diverter strips is 1 cm.
2) The thickness of the solid metallic layer or metallic segments is taken to be 2 mm.
3) The metallic layer and metallic segments are placed on an insulating layer of 3 mm thickness and dielectric constant \( \varepsilon_r = 2 \).

As an illustration, the geometries of the segmented diverter strips with circular, diamond, and square segments are shown in Fig. 1 with separation between the segments of 0.5 mm. The diameter of circular segments is 5 mm and the diamond and square segments are of the same square shape but oriented differently with the side length of 3.54 mm. The length of the diverter is assumed to be that of a straight strip.

The whole problem is meshed with a hybrid mesh that is a combination of a 5 mm cubic mesh and a tetrahedral mesh. The antenna near field is meshed more finely with 1 mm hybrid mesh as described in [13]. The meshed radome with lightning protection is shown in Fig. 4(a) and the meshed detail of the diverter strip is shown in Fig. 4(b) demonstrating the hybrid cubic-tetrahedral and multiscale nature of the deployed mesh.

The antenna is excited with the fundamental TEM mode of the coaxial feed modulated by a time-domain pulse with 3 dB frequencies of 1.8 and 4.6 GHz. The fundamental TEM mode is obtained as an eigen solution of the discretized 2-D cross section of the coaxial cable [13], [29]. All simulations in this article are run on 60 processor cores of a commodity cluster for 2 million time steps. The threshold for forming cell clusters is 5 \( \mu m \) and the timestep is 0.018 ps [19]. As an example, the radome problem with 0.4 m-long metallic
diverter strips had 981,057 tetrahedra, 310,243 cuboids, and 181,581 clusters with the largest coalesced cluster having 63 cells. The overall simulation runtime was 7 h. In contrast, the radome with segmented diverters of 0.4 m in length had 1.2 million tetrahedra, 310,551 cuboids, and 189,544 clusters with the largest coalesced cluster having eight cells and an overall simulation runtime of 9.5 h.

Fig. 5 shows how the reflection coefficient of the antenna, $S_{11}$, is affected by the presence of radome lightning protection by comparing it with the reflection coefficient of the antenna inside the radome with no lightning protection. The segmented diverter strips with circular segments of 5 mm diameter and 1 mm spacing between segments are considered. In order to fit in with the recommended spacing between diverters of 30–45 cm [3], the radome is fit with a total of eight diverter strips separated by 31 cm at the radome base. Fig. 5 also compares the impact of diverter strips of different lengths, namely 0.15, 0.3, and 0.4 m.

Fig. 5(a) compares the $S_{11}$ of the antenna within a radome with and without solid metallic diverters of different lengths and Fig. 5(b) compares the antenna’s $S_{11}$ with and without segmented diverter strips of different lengths. Comparing Fig. 5(a) and (b), it can be seen that in both the cases of metallic and segmented diverter strips, the presence of diverters of various lengths does not significantly affect the reflection coefficient of the antenna. The only impact is the increase in reflection at the resonant frequency of 3 GHz by 6 dB for metallic diverters and by 5 dB for segmented diverters and, in both cases, a slight shifting of the resonant frequency to higher frequencies.

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Fig. 6 compares the impact of the separation of the metallic segments in segmented diverters on the antenna $S_{11}$ parameter. As in Fig. 5, eight segmented diverters of length 0.4 m are considered. Circular metallic segments of 5 mm diameter are considered with spacing between segments taken to be 1, 0.5, and 0.3 mm. Fig. 6 shows that reducing the separation between the metallic segments can affect the $S_{11}$ of antenna but has a higher impact at higher frequencies.

Fig. 7 compares the impact of the diverter strips on the 3-D radiation pattern. Antenna patterns are shown for the case of antenna enclosed in a radome with no lightning protection, Fig. 7(a), in a radome with eight solid metallic diverters, Fig. 7(b), and in a radome with segmented diverter with circular segments of 5 mm diameter and separation between segments of 1 mm, Fig. 7(c). All diverters are assumed to be 0.4 m in length. Fig. 7 shows that the metallic diverters...
have the highest impact on the radiation pattern, while this particular type of segmented diverters has relatively small impact on antenna radiation pattern. Comparing these results with those of [4], it can be seen that, although the antennas and radome are different, the impact of lightning protection on antenna radiation pattern is similar.

In order to clearly identify the impact of the diverter on the radiation pattern, the $H$-field and $E$-field radiation patterns will now be analyzed in more detail. A total of eight solid metallic or segmented diverters are placed on the radome and have a length of 0.4 m. Segmented diverter strips have circular segments of 5 mm diameter and 1 mm separation between segments, as in Fig. 5. Fig. 8(a) compares the $E$-plane radiation pattern and Fig. 8(b) compares the $H$-plane radiation pattern for antenna enclosed in a radome with no lightning protection, in a radome with metallic diverters, and in a radome with segmented diverters. Fig. 8 shows that metallic strips have a greater impact on the far-field pattern than the segmented diverter strips. Furthermore, comparing Fig. 8(a) and (b), it can be seen that the far-field radiation in the $E$-plane is more affected by the presence of lighting protection.

As the presence of solid metallic diverters impacts the far-field pattern more, Fig. 9 explores how the length of the solid metallic diverter strips affects the radiation pattern. Fig. 9 compares the radiation pattern of the antenna within a radome with no lightning protection (black dashed line) with an antenna within a radome with eight solid metallic diverter strips of lengths 0.15 (green), 0.3 (red), and 0.4 m (blue). Comparing Fig. 9(a) and (b), it can be seen that as the length of the strips is increased, the ripples in the $E$-plane far-field pattern are also increased.

Fig. 10(a) and (b) explores how the separation between diverter strips affects the far-field radiation pattern. Fig. 10(a) compares the $E$-plane far-field radiation pattern of antenna in a radome with no lightning protection (black dashed line) with an antenna enclosed with a radome with lightning protection consisting of 4 solid metallic strips (green line), 8 solid metallic strips (blue line), and 12 solid metallic strips (red line). Fig. 10(b) shows the same information but for segmented diverter strips. In all cases, the length of the strip is assumed to be 0.4 m. Fig. 10 shows that increasing the number of metallic strips, i.e., decreasing the separation between them, can significantly affect the radiation pattern in both planes. The recommended separation is 30–45 cm [3] and it can be seen that in the case of 12 strips where the separation at the base of the radome becomes 0.21 m, the overall radiation pattern is significantly affected by the presence of solid metallic strips.

Fig. 11(a) and (b) shows the same information but for segmented diverter strips with circular segments. The geometry of the segmented strips is the same as in Fig. 5, i.e., metallic segments are of 5 mm in diameter separated by 1 mm. Diverter strips are 0.4 m in length. Fig. 11 shows that similar to Fig. 10, the $E$-plane is more affected by the presence of segmented diverters but the impact is still much smaller when compared...
to the equivalent case of metallic diverters in Fig. 10. This result indicates that reducing separation between diverters is less critical in the case of segmented diverters strips than in the case of solid metallic strips.

Fig. 10. Comparison of the far field in (a) E-plane and (b) H-plane of an antenna placed inside a radome with no lightning protection (black dashed line) with an antenna within a radome with 4 metallic strips (green line), 8 metallic strips (blue line), and 12 metallic strips (red line).

Fig. 12 investigates how the separation between metallic segments affects the far-field radiation pattern of the radome antenna. The radome has eight segmented diverters with circular metallic segments of 5 mm in diameter and a strip length of 0.4 m. Three cases are considered, namely segmented diverters with separation between metallic segments of 1 (green), 0.5 (blue), and 0.3 mm (red). Fig. 12 shows that decreasing the separation between the segments results in increased disturbance of the antenna field pattern, specifically increasing the ripple in the E-plane and reducing the intensity in the main lobe in the H-plane. It can be argued that decreasing the segment separation is making the segmented diverter strip appear more like a metallic strip and for this purpose, Fig. 13 compares the effect of metallic diverter strips with segmented diverter strips with segment separation of 0.3 mm. A radome with eight diverters of 0.4 m in length is considered in both cases. Fig. 13 shows that the impact of these two types of diverters on the antenna far-field characteristic is very similar. In practice, segmented diverter strips have separations below 0.5 mm for good lightning protection [9] and this shows that the impact of segmented diverters on antenna radiation is not insignificant as stated in [4] and [10] and will depend upon the geometry detail of diverter strips.

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Having established how the separation of metallic segments in diverters affects antenna performance, we now consider the effect that the shape of the diverter segments has on antenna radiation and near field. Fig. 14 compares the far-field patterns of an antenna placed inside a radome with no lightning protection (black dashed line) with an antenna within a radome with 4 metallic strips (green line), 8 metallic strips (blue line), and 12 metallic strips (red line).
III. Impact of the Diverter Geometry on the Surface Electric Field Intensity

The performance of the diverter strips in the presence of the strong incoming field is investigated next. Examining the field intensity between segments permits an assessment of the sensitivity to breakdown. The structure analyzed consists of a segment of a diverter strip on which appropriate boundary conditions are applied.

Both Figs. 14 and 15 confirm that diverters with diamond segments would be a preferred choice for diverters as they interact least with the antenna radiation pattern and the reflection coefficient.
conditions (BCs) are applied. The schematic of the structure is given in Fig. 16(a) with open BCs specified at minimum and maximum positions against the $x$-direction and at the symmetry plane ($y = 0$) and matching BCs applied on other boundaries defined to be 10 mm away from the structure. The front and side view of the full problem meshed with a combination of tetrahedral and a global cubic 0.5 mm mesh with eight times finer mesh around the diverter structure is shown in Fig. 16(b). A zoomed-in view of the fine mesh around the segments is shown in Fig. 16(c).

All segmented diverters considered had a substrate thickness of 2 mm, a metal segment thickness of 2 mm, and a segment diameter of 5 mm. The separation between the segments was taken to be 0.3 mm. A diverter strip was subjected to a strong $x$-polarized Gaussian signal with a spectrum from 1 kHz to 300 MHz that propagates in the negative $z$-direction. Fig. 17 compares the surface electric field in the diverter segment for the circular, diamond, and square-shaped metallic segments. It can be seen that the maximum surface electric field in the case of a diamond segment is twice that for the case of the circular segment and larger than for the case of square segments indicating that the diamond segment shape will have an earlier breakdown. This is in agreement with the 2-D analysis of [9] where diamond-shaped elements had lower breakdown voltages compared to the square- and circular-shaped segments.

Fig. 18 compares the time waveform of the average $x$-directed surface electric field across the gap between the segments for each of the three diverter geometries. Fig. 18 shows that the diamond segments produce the largest peak surface field compared to square and circular elements.

Fig. 19 explores how the size and the separation between the metallic segments affect the surface electric field across the gap between the metallic segments. Diamond-shaped segments
diverter strips with separation between segments of 0.5 mm and greater have smaller effect on antenna than an equivalent metallic diverter strip, for practical values of separations of 0.3 mm, the segmented diverter strip has comparable effect on antenna far-field as the equivalent metallic diverter strip. Furthermore, the shape of the metallic segments in segmented diverters also affects how the antenna “sees” the radome lightning protection. The results show that diamond-shaped segments have the smallest impact on the antenna compared to diverters with circular and square segments even with practical separations of 0.3 mm. This article, thus, disagrees with conclusions of [4] and [10] that segmented diverter strips do not produce any visible shielding effects and concludes that the amount of shielding will strongly depend upon the actual geometry detail of the segmented strips. This article further analyzes the performance of the segmented diverter strips in the presence of the strong electrical field by analyzing surface current density on the strip. The results show that surface electric field between metallic segments is the strongest for the case of diamond-shaped segmented diverters and the weakest for the diverters with square metallic segments. The surface electric field between metallic segments increases with larger size of the metallic segments and with reduced separation between them. This new insight reinforces the importance of 3-D multiscale modeling in airborne radome design.

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