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An Airborne VHF Printed Monopole Antenna for Platform Constrained Applications

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Abstract—Major challenges faced by airborne VHF monopole antennas are to achieve wideband characteristics in permissible antenna height and to find the apt location for mounting, so as to satisfy sufficient ground plane around its feed point. The increased applications of electromagnetic spectrum result in a large number of antennas competing in the limited space available on platform. The asymmetries and curved surfaces on the platform as well as the limited size of the available ground plane may result in an insufficient ground plane for these antennas on platform. The deficient ground plane can deteriorate the radiation characteristics of antenna. Printed monopole antenna, which does not require a backing ground plane, can overcome this deficiency, as the ground planes of these antennas are implemented in the same plane as that of the radiating element. This paper proposes a wideband printed monopole VHF antenna for airborne applications which simultaneously achieves reduced height and reduced ground plane on platform. The antenna has a size of $0.1045\lambda \times 0.1272\lambda \times 0.072\lambda$, where λ is the free space wavelength at lowest frequency of operation, and it achieves a $3:1$ VSWR bandwidth of 38%. The radiation characteristics and size of the proposed antenna are comparable to the conventional airborne blade monopole antenna with the added advantage of requiring minimal ground plane to mount on.

1. INTRODUCTION

Aircraft antennas are subjected to strict electrical and mechanical constraints. The shape and size of these antennas are restricted by the physical length, width and height of the aircraft, and it is further restricted by the environment and aircraft operations. Further, applications such as communication, navigation, telemetry, electronic warfare demand wideband antennas with omnidirectional radiation coverage in azimuth and near azimuth planes with linear polarization. Hence, owing to their simple planar structures, omnidirectional radiation characteristics and wide impedance bandwidth, blade monopole antennas are the most preferred antennas in airborne communication systems [1].

It is well known that the ground planes of monopole antennas play a vital role in determining antenna radiation characteristics [2]. Airborne monopole antennas utilize the skin of the airborne platform as its ground plane. The task of finding a suitable mounting location on platform is difficult when many systems are competing in limited surface area. The space constraints in the specific mounting location for the monopole antenna on the airborne platform result in insufficient ground planes for these antennas on platform. This deteriorates radiation performance of an antenna [3]. The asymmetries and curved surfaces on the platform as well as limited size of the available ground plane influence the performance of a monopole antenna significantly. Also nowadays, the skin of the airborne platform is made up of a mixture of composite materials whose conductivity may not be fairly good. Composite materials are used for aircraft skin owing to their weight savings over aluminium parts with high strength

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and corrosion resistance. Just as a non-infinite ground plane can affect the antenna performance, ground planes with non-infinite conductivity can move antenna operation away from ideal behavior. Hence, monopole antennas with reduced ground plane are a requirement for airborne applications.

Monopole antennas with reduced ground plane [4, 5] are not suitable for airborne applications as they achieve this characteristic by modifying the ground plane geometry.

The monopole antenna that does not require a backing ground plane was first presented in 1997. In 1997, Johnson and Rahmat-Samii introduced a tab monopole (Printed monopole), with the monopole patch and ground plane printed on the same plane of the substrate, which overcomes the disadvantage of planar monopoles requiring backing ground plane [6]. Various configurations of printed monopole antennas were studied in the following several years, mainly on the geometries of the monopole and ground plane. The wideband characteristics of printed monopole antennas were explored widely for UWB applications [7]. Only very few printed monopole antennas have been reported in VHF/UHF band [8–13]. The printed monopole antennas that exhibit wideband characteristics in VHF/UHF band are listed in [11–13]. However, these antennas [11–13] are not suitable for airborne applications due to their larger size ($\sim 0.3\lambda$, where λ is the free space wavelength at the lowest frequency of operation). The major constraint in designing an airborne printed monopole antenna in VHF/UHF band is achieving compactness and wide bandwidth simultaneously, along with sufficient gain.

This paper proposes a printed monopole antenna in VHF band that simultaneously realizes both compactness and wideband characteristics. To optimize the performance, several techniques are combined: patch meandering, ground meandering, patch top loading, ground top loading, and R-L loading. The performance of this antenna is presented in terms of bandwidth, gain, and radiation pattern by HFSS simulation as well as measurements. The radiation characteristics of the antenna mounted on a large ground plane are also evaluated for establishing reduced ground plane effect. An empirical relation is also derived to calculate the resonant frequency of this structure and is presented. The derived equation is validated for different sets of dimensions and different substrates.

2. ANTENNA EVOLUTION AND PROPOSED GEOMETRY

2.1. Design Evolution

The evolution of the antenna is shown in Fig. 1. A simple printed strip monopole antenna (Fig. 1(a)) is chosen as the reference antenna [14]. For airborne communications, compact height is a major concern. Hence height reduction methods have to be employed on reference antenna. Decreasing the height of the monopole radiator shifts the resonant frequency to higher side, and the radiation resistance of the antenna at the intended frequency band decreases. This can be compensated by top loading. Top loading the antenna increases the length of surface current path within the reduced antenna dimension

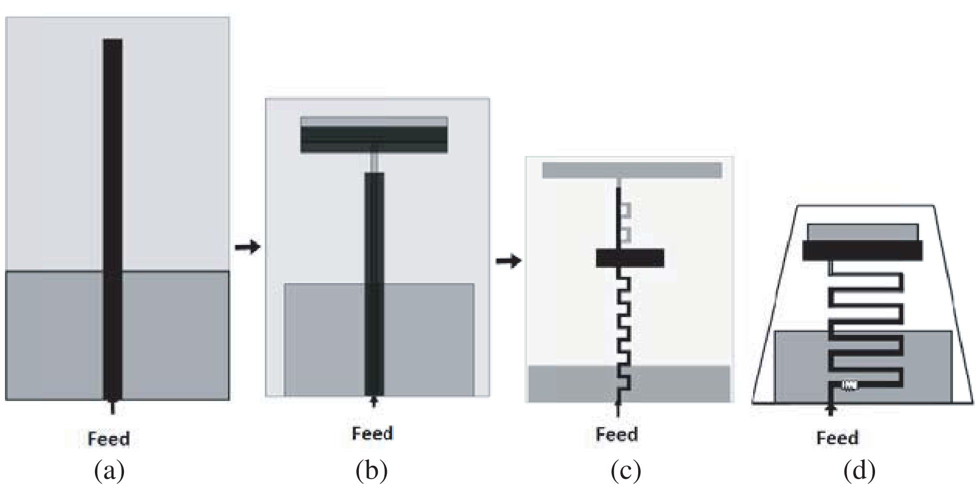


Figure 1. Antenna evolution.

and thus decreases the resonant frequency. Hence, top loading was introduced in the radiator to reduce the height of reference antenna. As the size of the monopole antenna decreases, ground plane size plays a role in determining resonant frequency and bandwidth. In order to increase the bandwidth, a strip and a top loading were introduced in the ground plane, and the patch top loading was gap coupled to the radiating strip for improved impedance matching. Thus, the height of the reference antenna is reduced by implementing top loading in the radiating patch and ground plane as shown in Fig. 1(b) (Antenna 1). Then meandering of the radiating strip and ground plane is introduced to further decrease the antenna height (Fig. 1(c)) (Antenna 2). Meandering the patch increases the path over which the surface current flows, and that eventually results in lowering of the resonant frequency. The resonant frequency of a meander line antenna is decided by the physical dimensions of the meander lines, on the basis of height, width, number of folds, and overall length of the meander structure [15]. Finally, the horizontal length of the meander line is increased, and resistor-inductor loading is introduced to achieve a compact wideband printed monopole antenna (Fig. 1(d)) (Antenna 3). The dark area in the figure shows the radiating patch, and the grey area shows the ground patch at the bottom.

FR4 epoxy ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$ and thickness 0.16 cm) was used as the substrate for the antenna design. The width of the substrate was chosen to be less than 30 cm for all archetypes. The VSWR plots of these antennas are shown in Fig. 2. A comparison on the height reduction and VSWR bandwidth of these antennas are given in Table 1.

Table 1. Comparison on the height reduction and bandwidth of antennas in evolution process.

	Reference antenna	Antenna 1	Antenna 2	Antenna 3
Total height in cm	70	52	40	23
Height reduction in %	-	25	42	67
3 : 1 VSWR bandwidth (%)	22	27	24.5	33

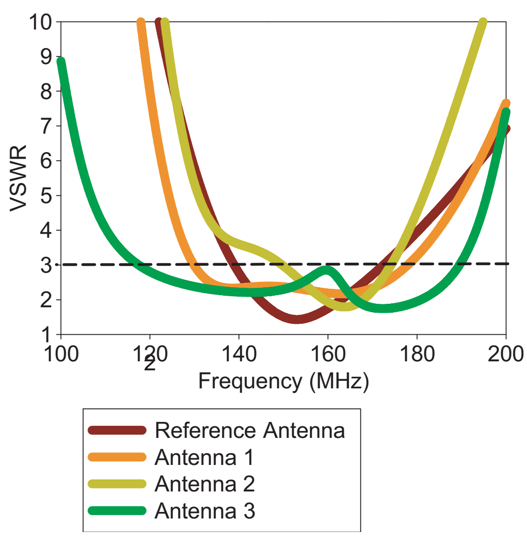
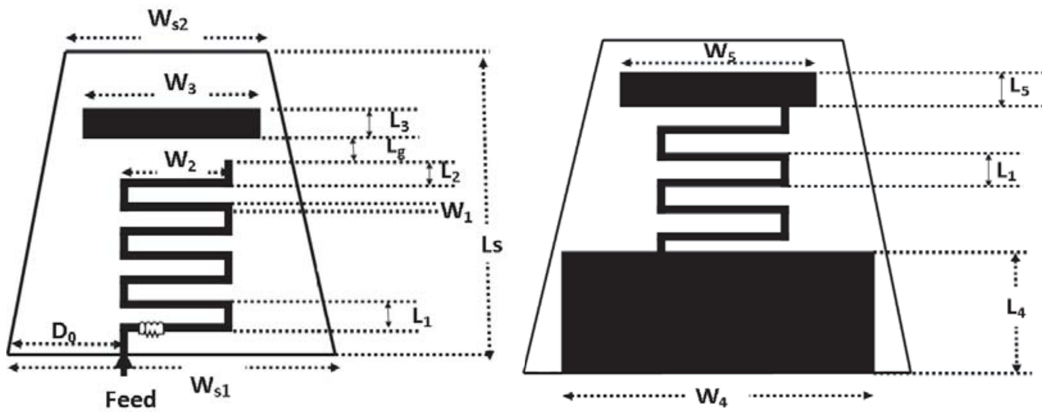


Figure 2. VSWR of antennas in the evolution process.

2.2. Design of the Proposed Antenna

The schematic of the proposed antenna is shown in Figs. 3(a)–(b). The substrate used is FR4 glass epoxy of dielectric constant $\varepsilon_r = 4.4$ and thickness 0.16 cm. The dimensions of the geometry are outlined in Table 2.



(a) (b)

Figure 3. Structure of proposed antenna; (a) Radiating patch. (b) Ground patch.

Table 2. Dimensional details.

Parameters	L_s	W_{s1}	W_{s2}	D_0	L_1	W_1	L_2	W_2
Value (cm)	23	28	17.5	9.5	2.5	0.5	2	10
Parameters	L_3	W_3	L_g	L_4	W_4	L_5	W_5	
Value (cm)	2.5	14	1.5	9	23.2	2	15	

The radiating patch of the antenna consists of meander line structure and a top loading structure. The top loading structure is gap coupled to meander line for improved impedance matching. On ground plane, meander structure is incorporated along with the partial rectangular ground plane, symmetric with that of the meander line on the radiating patch for improved impedance matching. Top loading structure is also incorporated in ground plane for achieving frequency reduction.

Wideband characteristic is achieved by R-L loading. A parallel combination of lumped inductor of 200 nH and resistor of 15 Ω is connected in series to the radiating patch. The values of inductor and resistor are optimized by simulations using HFSS. A tradeoff between impedance bandwidth of the antenna and gain was considered while choosing the resistor value.

The antenna was designed in an aerodynamic shape so as to reduce air drag. A 50 Ω TNC connector is used to excite the antenna. An aluminium base plate of dimensions 0.5 cm $\times$ 28 cm $\times$ 8 cm was used for mounting the antenna. It holds the connector and acts as an interface between antenna and the mounting platform. A photograph of the fabricated antenna is shown in Fig. 4.

3. SURFACE CURRENT DISTRIBUTION

The simulated surface current distribution on the radiating patch as well as on the ground plane of the antenna at center frequency 160 MHz is shown in Figs. 5(a)–(b), respectively. It can be observed that surface current distribution shows a variation slightly greater than one half wavelength along the radiating patch at resonant frequency. The distribution of current on top loading of radiating patch is uniform. The ground plane meandering and ground top loading can be considered as a coupled line as its current is the image component of that on the radiation element.

4. MEASURED RESULTS

The performance of the antenna was evaluated using Keysight Technologies E5071C ENA Vector Network Analyzer. At first, the antenna was tested for its VSWR characteristics without any additional ground plane. The antenna was then mounted perpendicularly on a 120 cm (4 ft) diameter circular

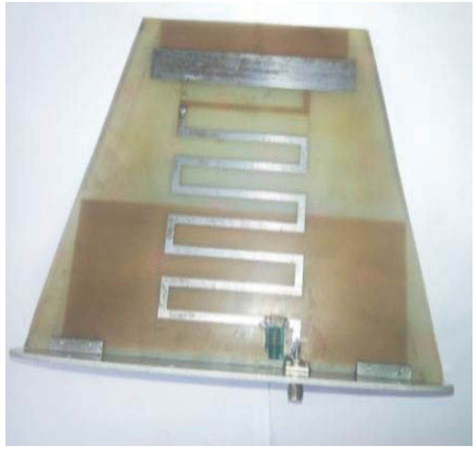


Figure 4. Photograph of fabricated antenna.

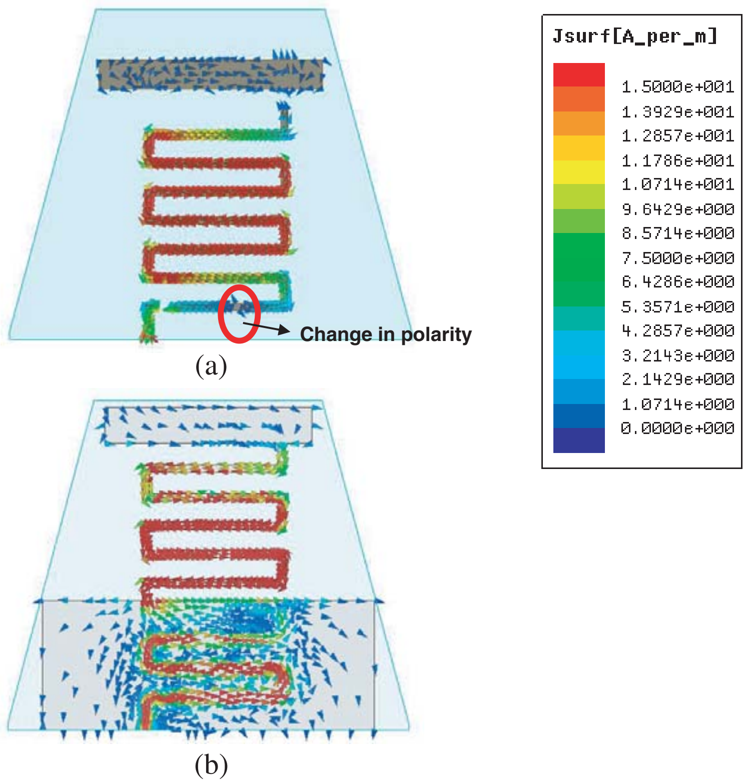


Figure 5. Simulated current distribution on (a) radiating patch, (b) ground patch.

ground plane, and the VSWR was measured. The measured VSWR is found less than 3 ($S_{11} < -6$ dB) over the referred frequency band in both the cases, although the presence of ground plane shows a slight shift in the frequency band towards lower side as shown in Fig. 6. The effect of mounting ground plane on the printed monopole antenna is much less than a conventional planar monopole antenna.

The measured gains of the antenna with and without mounting ground plane are shown in Fig. 7 and compared with a conventional airborne blade monopole antenna [16] and a basic printed strip monopole antenna (Reference antenna in Fig. 1). The presence of large ground plane increases the gain in the lower frequency region due to improved impedance matching.

The antenna was tested for its far field radiation characteristics in an open field. The normalized

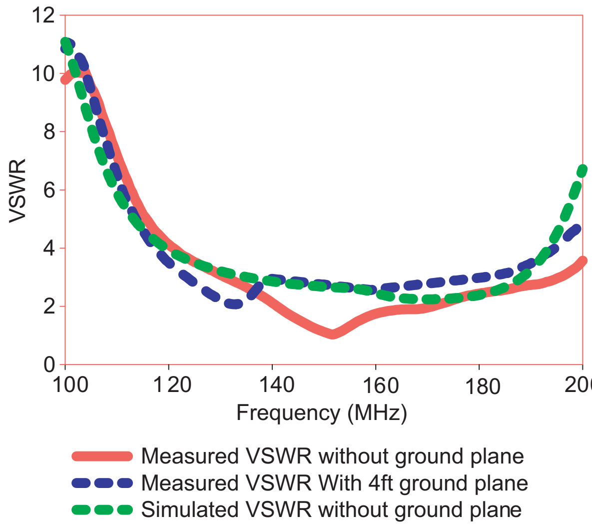


Figure 6. Measured VSWR with and without ground plane.

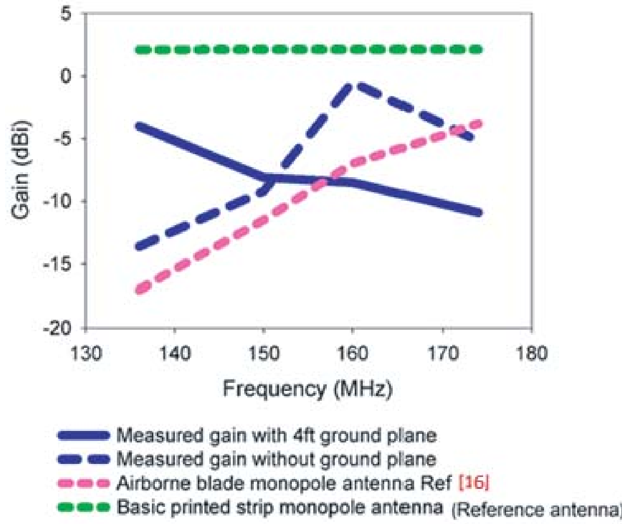
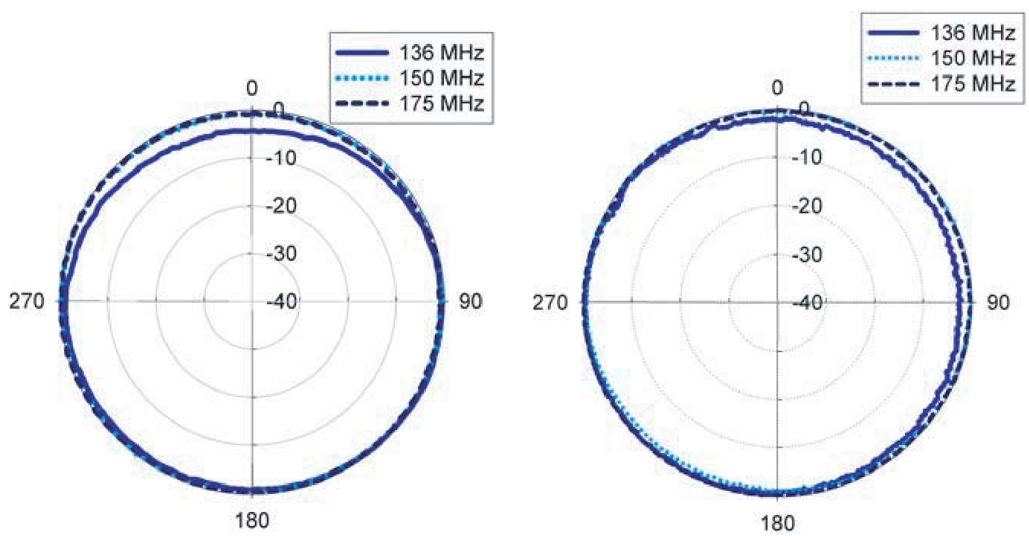


Figure 7. Measured gain.



(a) (b)

Figure 8. (a) Azimuth pattern with 4 ft ground plane. (b) Azimuth pattern without ground plane.

H plane radiation patterns of the antenna with and without mounting ground plane at 136, 150 and 175 MHz are illustrated in Figs. 8(a) and (b), respectively. It can be seen that the H plane radiation pattern of the proposed antenna is nearly omnidirectional at all frequencies.

The measured, normalized E plane radiation patterns of the antenna with and without mounting ground plane at 136, 150 and 175 MHz are illustrated in Figs. 9(a) and (b), respectively. The elevation pattern at the higher side of the frequency band resembles a "figure-eight" pattern, and at lower frequency side, it is slightly distorted. The null depth of the elevation pattern is improved in the presence of large mounting ground plane.

A comparison of the proposed antenna was carried out with the airborne blade monopole antenna reported in literature [16] operating in the band of 135 MHz–175 MHz and is tabulated in Table 3. It is obvious from the table that the performance of the antenna is comparable to the conventional airborne blade monopole antennas operating in VHF band with the added advantage of requiring minimal ground plane to mount on.

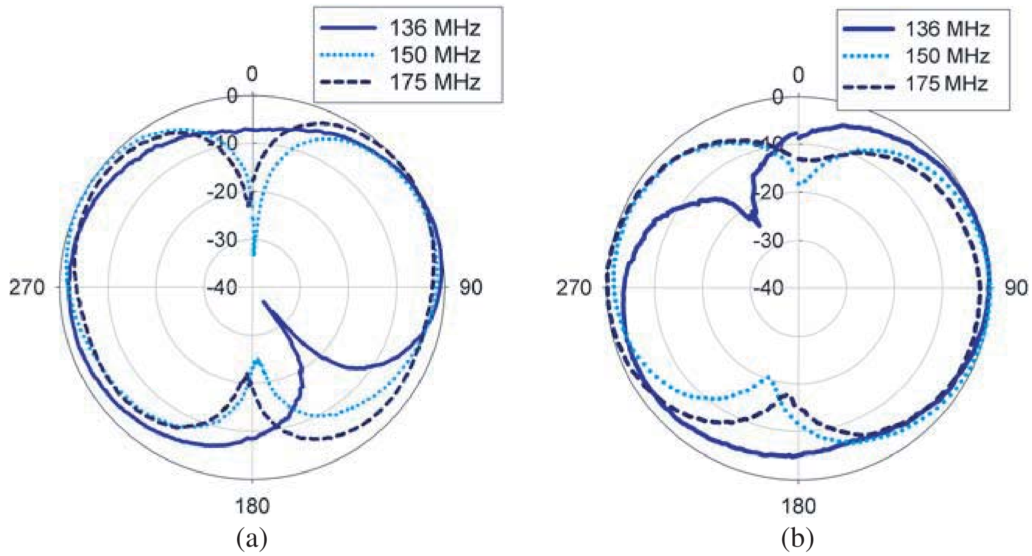


Figure 9. (a) Elevation pattern with 4 ft ground plane. (b) Elevation pattern without ground plane.

Table 3. Comparison of the antenna with the airborne antenna in literature.

Characteristics	**RL Loaded Meandered Toploaded Printed Monopole Antenna**	**Airborne blade monopole antenna Ref. [16]**
Height	23 cm	18.8 cm
Ground plane size	Antenna base plate (0.5 cm × 29 cm × 8 cm)	120 cm diameter around the feed
3 : 1 VSWR bandwidth	130–190 MHz	135–175 MHz
Minimum gain over the frequency band	−14 dBi	−17 dBi
Radiation pattern	Omnidirectional	Omnidirectional

5. DESIGN EQUATION FOR RESONANT FREQUENCY CALCULATION

The design equations for the resonant frequency of an antenna structure can be derived based on the parametric studies and surface current analysis.

To derive the resonant frequency of the proposed antenna, a two-step procedure was adopted. First the relation between the resonant frequency and geometrical parameters of conventional printed meander line structure alone (Fig. 10) is derived. Then the relation for resonant frequency calculation of the proposed antenna is derived by incorporating the effect of meander line and other dimensional parameters of the antenna.

From deep parametric study conducted on the meander line structure it was inferred that the effective electrical length of this antenna depends on number of turns N, length of the meander segment L_1, width of horizontal segment W_2, width of the meander line W_1, and the total length of the antenna $L = N \times L_1$. The equation for calculating the effective length due to the basic meander line structure (L_m) in terms of geometrical parameters is derived as

$$L_m = 0.5 + 0.017W_2 + 0.05N + 0.004L + 0.045W_1 + 0.02NW_2 \ldots \quad (1)$$

Since the contribution of meander line employed in the radiating patch has significant effect on the resonant frequency of RL loaded meandered top loaded printed monopole antenna, Equation (1)

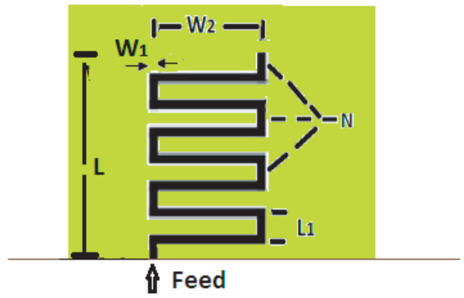


Figure 10. Structure of meander line antenna.

is used in the derivation of the design equation of this antenna. The notation L_M is used to denote the effective length due to meander line structure on radiating patch. The resonant frequency of the proposed antenna is further varied by dimensions L_4, W_4, L_5, and W_5. It is also varied marginally by dimensions L_3, W_3 and L_g. The resonant frequency of the antenna is also slightly varied by the meander line on the ground patch. The notation L_G is used for denoting the effective length due to the meander line on the ground patch and is calculated from Equation (1).

Thus, the effective length of the proposed antenna in terms of geometrical parameters is estimated by the relation

$$L_{eff} = \frac{1}{3}\left(3L_M + 1.3W_4 + 3.5L_5 + 0.8W_5 - 6L_4 + 0.52L_3 - 0.3W_3 + 0.52L_g + 0.001L_G\right)\ldots. \quad (2)$$

It is observed from the surface current distribution (Fig. 5) that the effective electrical length of the antenna corresponds to half wavelength at resonant frequency. It is reported in the literature that resonant frequency variation of the printed monopole antenna with substrate dielectric constant is not by a factor of $\sqrt{\varepsilon_r}$ but by a factor closer to unity. Hence, variable k is used to denote the effect of effective permittivity of the substrate [17].

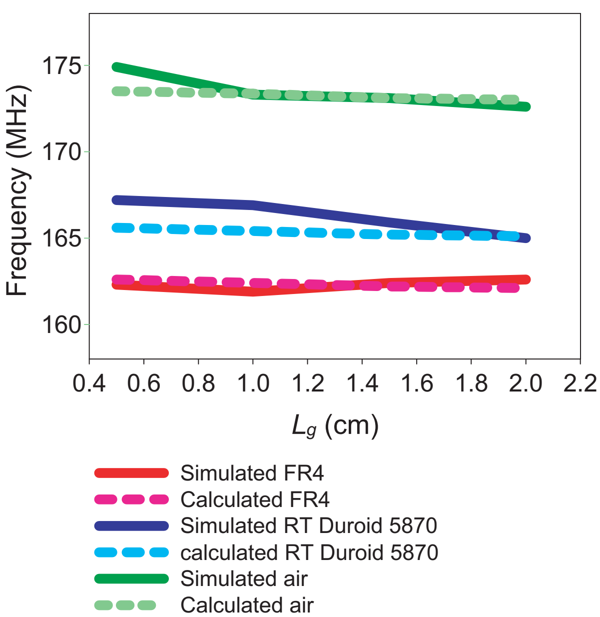


Figure 11. Comparison between theoretical and simulated result for various L_g values ($h = 0.16$ cm; $L_5 = 2$ cm; $L_3 = 2.5$ cm; $W_3 = 14$ cm; $L_4 = 9$ cm; $W_4 = 23.2$ cm; $W_5 = 15$ cm).

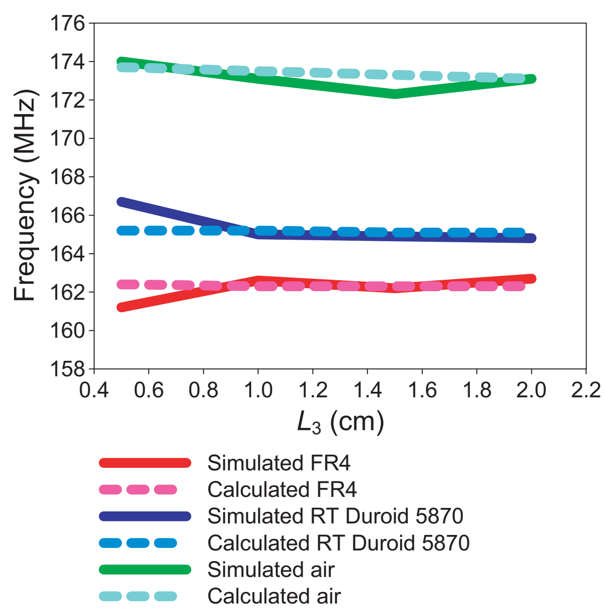


Figure 12. Comparison between theoretical and simulated result for various L_3 values ($h = 0.16$ cm; $L_5 = 2$ cm; $L_g = 1.5$ cm; $W_3 = 14$ cm; $L_4 = 9$ cm; $W_4 = 23.2$ cm; $W_5 = 15$ cm).

Accordingly, resonant frequency of the proposed antenna is calculated from the relation,

$$fr = \frac{c}{\lambda} = \frac{c}{2 \times L_{eff} \times \sqrt{\varepsilon_r}} = \frac{c}{2 \times L_{eff} \times k} \dots \tag{3}$$

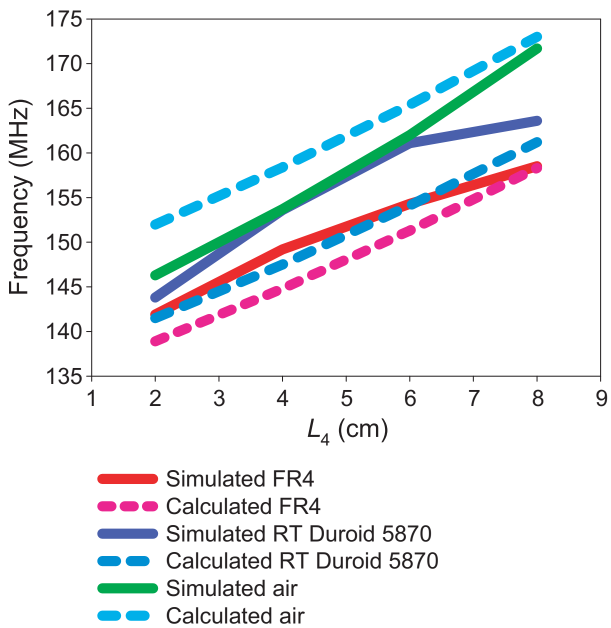


Figure 13. Comparison between theoretical and simulated result for various L_4 values ($h = 0.16\,\text{cm}$; $L_5 = 2\,\text{cm}$; $L_g = 1.5\,\text{cm}$; $W_3 = 14\,\text{cm}$; $L_3 = 2.5\,\text{cm}$; $W_4 = 23.2\,\text{cm}$; $W_5 = 15\,\text{cm}$).

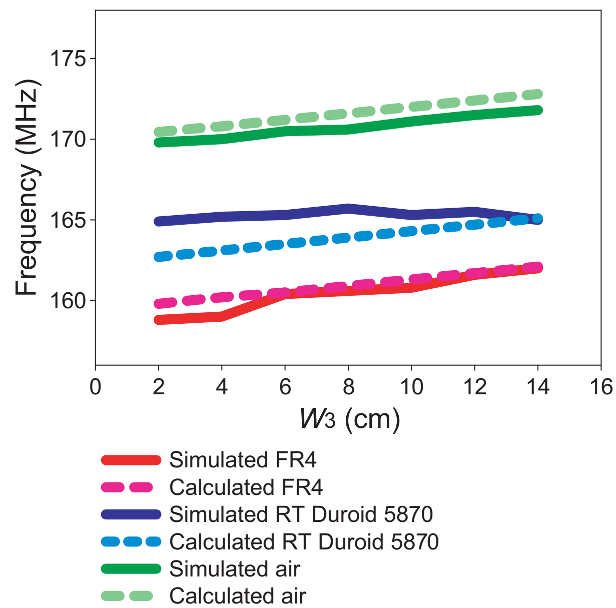


Figure 14. Comparison between theoretical and simulated result for various W_3 values ($h = 0.16\,\text{cm}$; $L_5 = 2\,\text{cm}$; $L_g = 1.5\,\text{cm}$; $L_3 = 2.5\,\text{cm}$; $L_4 = 9\,\text{cm}$; $W_4 = 23.2\,\text{cm}$; $W_5 = 15\,\text{cm}$).

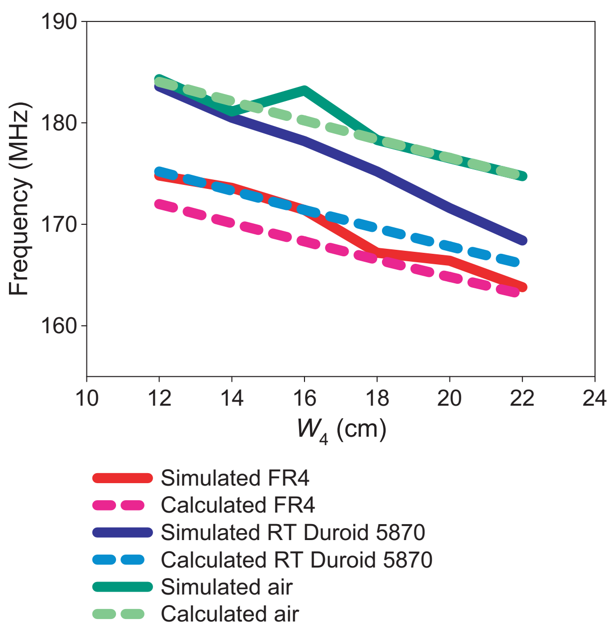


Figure 15. Comparison between theoretical and simulated result for various W_4 values ($h = 0.16\,\text{cm}$; $L_5 = 2\,\text{cm}$; $L_g = 1.5\,\text{cm}$; $L_3 = 2.5\,\text{cm}$; $L_4 = 9\,\text{cm}$; $W_3 = 14\,\text{cm}$; $W_5 = 15\,\text{cm}$).

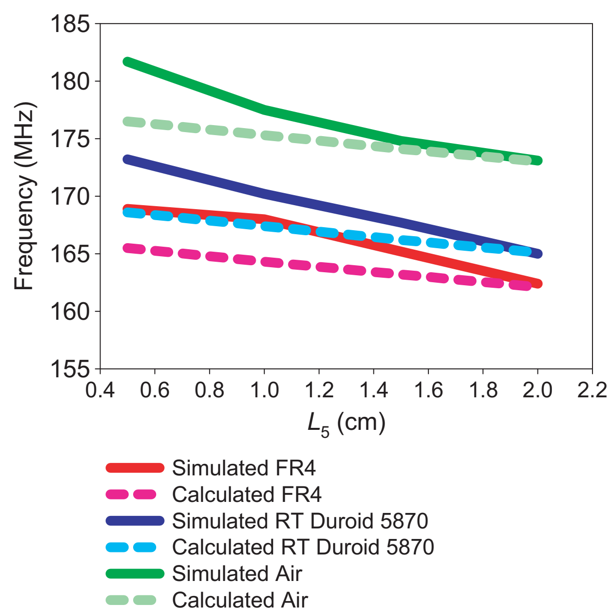


Figure 16. Comparison between theoretical and simulated result for various L_5 values ($h = 0.16\,\text{cm}$; $W_3 = 14\,\text{cm}$; $L_g = 1.5\,\text{cm}$; $L_3 = 2.5\,\text{cm}$; $L_4 = 9\,\text{cm}$; $W_4 = 23.2\,\text{cm}$; $W_5 = 15\,\text{cm}$).

6. VALIDATION OF DESIGN EQUATION

For examining the validity of these conclusions, the antenna was designed for various dimensional values and simulated using HFSS software. In order to establish the influence brought by each parameter, the methodology followed is varying one parameter over a range keeping all other parameters fixed. The design was simulated for different substrates also — FR4 epoxy ($\varepsilon_r = 4.4$), RT Duroid 5870 ($\varepsilon_r = 2.3$) and air ($\varepsilon_r = 1.0006$) were selected for this purpose. The value of k that corresponds to effective dielectric constant of FR4 is determined as 1.1 and that of RT Duroid 5870 as 1.08. The value of k for air is 1.

Figures 11–17 depict the comparison between simulated and calculated resonant frequencies for different sets of dimensional parameters. The % error calculated between the simulated and calculated results is less than 5% for all cases.

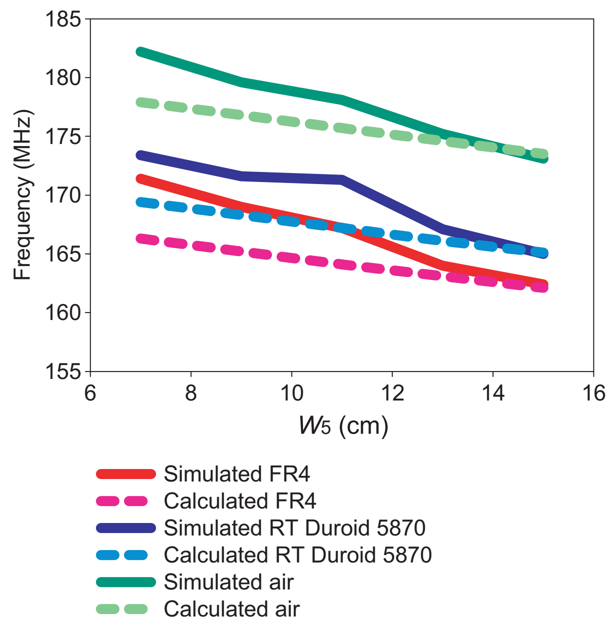


Figure 17. Comparison between theoretical and simulated result for various W_5 values ($h = 0.16$ cm; $L_5 = 2$ cm; $L_g = 1.5$ cm; $L_3 = 2.5$ cm; $L_4 = 9$ cm; $W_4 = 23.2$ cm; $W_3 = 14$ cm).

7. CONCLUSION

A compact wideband printed monopole antenna operating in VHF band has been developed for platform constrained airborne applications. The antenna achieves a $3:1$ VSWR bandwidth of 38%, and the gain of the antenna varies from -14 dBi to -1.5 dBi within the band. It achieves a height reduction of 63% compared to a conventional quarter wave monopole antenna and 67% compared to a basic printed strip monopole antenna. The overall height of the antenna is 0.1λ at the lowest frequency of operation. The proposed VHF monopole antenna requires nil or minimal ground plane on the platform. The radiation characteristics are measured with antenna alone as well as with antenna mounted on $\lambda/2$ diameter ground plane and are presented. Empirical equation to calculate the resonant frequency of the antenna was derived in terms of its geometrical parameters and validated for different substrates and different sets of dimensions.

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