7 (2): 171-177 (2023)

Journal of Aviation

https://dergipark.org.tr/en/pub/jav

e-ISSN 2587-1676

Design and Simulation of a Conformal Micro-Strip Patch Antenna at GNSS L1/ E1 Frequency Band

Betül Yılmaz[1*]

[1*]Mersin University, Electrical-Electronics Engineering Department, 33343, Yenişehir, Mersin, Türkiye. (betuly@mersin.edu.tr).

Article Info

Received: 11 January 2023
Revised: 27 April 2023
Accepted: 03 May 2023
Published Online: 22 June 2023

Keywords:
Conformal Antenna
U-Slot Patch Antenna
GNSS Application
L1 frequency Band
Unmanned Aerial Vehicles

Corresponding Author: *Betül Yılmaz*

RESEARCH ARTICLE

https://doi.org/10.30518/jav.1232589

Abstract

In this paper, we have designed a conformal U-slot type micro-strip (µ-strip) patch antenna to be used in L1 frequency band. First, a primary design of flat, rectangular U-slot µ-strip patch antenna is designed around the center frequency of L1 band that is 1575.42 MHz. Then, this design has been converted to a conformal type such that it can be used cylindrical platforms such as missiles. The primary design of conformal U-slot µ-strip patch antenna has been optimized for the L1, E1 frequency band between 1563 MHz and 1587 MHz, and 1559 MHz and 1591 MHz; respectively. Then, antenna parameters such as operation bandwidth and the radiation pattern were reported based on the optimized simulation results for this stand-alone conformal antenna. Finally, this antenna has been positioned on a missile model and the antenna simulation is repeated to validate the effectiveness and the usability of this antenna on a realistic platform and the scenario. The real-physics antenna simulation of the final optimized conformal U-slot type µ-strip patch antenna mounted on the missile model has shown that this antenna is effectively operation between 1.5442 and 1.6077 GHz such that it can conveniently be used for Global Navigation Satellite System (GNSS) applications of L1 and E1 band.

1. Introduction

For the last decade, the use of conformal antennas has been gaining a lot of interest thanks to emerging many applications of missile, unmanned air vehicles (UAVs), and similar platforms (Balderas et al., 2019; Obeidat et al., 2009; Pradhan et al., 2022; Chen et al., 2017; Khalil et al., 2019; Morton et al., 2006). The foremost necessity of using conformal antennas comes from the aerodynamic requirements of these platforms such that any antenna that has to be mounted on such platforms will almost no effect of their flight dynamics on contrary to linear antennas such as dipole or monopole (Ozdemir et al.; 1997). µ-strip patch antennas; at this point of view, has the great advantage of being easily produced with conformal features when compared to any other type of antennas. Therefore, it is common to use such planar type of antennas on these kind of platforms (Gaetano et al., 2012; Mondal et al., 2014; Nikolaou et al., 2006).

Among widely used µ-strip patch antennas, the U-shaped one has the attractive feature of having wider frequency bandwidth compared to rectangular µ-strip patch antenna. Many researchers have put significant effort in understanding the physics behind the resonant frequency and radiation characteristics of U-slot µ-strip patch antenna (Tong 2005, Bhattacharjee et al., 2013; Rani et al., 2010; Mishra et al., 2015; Mitha et al., 2018). Tong has given the required formulations for the antenna dimensions based on the common antenna parameters such as effective dielectric constant, resonant frequency and the bandwidth for the broadband planar U-slot µ-strip patch antenna (Tong 2005). Bhattacharjee et al. have given a planar U-slot µ-strip patch antenna design for Wireless LAN applications at 2.45GHz (Bhattacharjee et al., 2013). Rani and Dawre have presented a similar design of the same antenna; but this time for satellite communication frequencies between 4 GHz and 6 GHz by applying Genetic algorithm for the optimization of the antenna gain (Rani et al., 2010). All of these studies were for planar type U-slot µ-strip patch antennas. There are very few studies that uses conformal designs of U-slot µ-strip patch antennas that were reported in the literature (Mishra et al., 2015; Mitha et al., 2018): Mishra and Gupta have proposed a four-stage U-slot µ-strip patch antenna to achieve dual band operation around 6.7 and 7.3 GHz (Mishra et al., 2015). Mitha and Pour have designed conformal wideband U-slot µ-strip patch antenna for X-band of frequencies (Mitha et al., 2018).

In this study, we present a unique conformal U-slot µ-strip patch antenna specially designed to be used GNSS L1/ E1 usages including the frequency band of 1559 MHz -1591 MHz. The other main goal of this study is to use the final design on a realistic platform such as a missile and also assess the performance characteristics. The structure of the paper is as follows: In the next section, a general theory of planar, rectangular U-slot µ-strip patch antenna is reviewed. In Sect. III, the numerical design of the rectangular U-slot µ-strip patch antenna is achieved for the GNSS L1/ E1 frequencies by the help of antenna simulation and analysis tool of CST Studio

Suite 3D (CST Studio Suite 2023). In Sect. IV; first, the conformal version of the antenna that was designed in the previous section is attained; and afterwards, the associated antenna analysis study for the conformal version of the antenna is presented. Next, the final, optimized conformal U-slot µ-strip patch design is put on a realistic missile model and the antenna performance of the whole geometry is investigated and reported. The last section is dedicated to the discussions and the concluding remarks.

2. Review of U-Slot µ-Strip Patch Antenna

A typical geometry of the U-slot rectangular patch antenna is shown in Fig. 1a. The key dimension parameters are marked on the antenna geometry in this figure. First, we review the theory behind the U-slot rectangular patch antenna so that we can use this theoretical primary design to be used for the design of conformal U-slot µ-strip patch antenna.

2.1. Design Equations for rectangular U-slot µ-strip patch antenna

The design dimensions of the U-slot µ-strip patch antenna are based on the desired center frequency; f_c and the frequency bandwidth; $B = f_H - f_L$ of the antenna. Here, f_H and f_L stand for higher and lower frequencies of the -10 dB bandwidth of the antenna.

If the dielectric constant of the patch's substrate material is ε_r and the thickness of the substrate is h, then the width of conducting patch of the designed antenna can be obtained as follows (Bhattacharjee et al., 2013);

$$W = \frac{c_0}{2f_c}\sqrt{\frac{2}{\varepsilon_r + 1}}. \tag{1}$$

where c_0 is the velocity of the light in free-space. Then, the effective dielectric constant can be approximately calculated via (Bhattacharjee et al., 2013);

$$\varepsilon_{r,eff} = 0.5(\varepsilon_r + 1) + 0.5(\varepsilon_r - 1)\left[1 + 12\frac{h}{W}\right]^{-1/2} \tag{2}$$

The actual length of patch is obtained by regarding of the effective length $L_{eff} = c_0/(2f_c\sqrt{\varepsilon_{r,eff}})$ and the length extension on each end by a distance Δ_L which is given by (Rani et al., 2010):

$$L = L_{eff} - 2\Delta_L \tag{3}$$

where Δ_L, so called the scattering length, can be calculated via (Rani et al., 2010);

$$\Delta_L = 0.412h\frac{\left(\frac{W}{h} + 0.264\right)\left(\varepsilon_{r,eff} + 0.3\right)}{\left(\frac{W}{h} + 0.8\right)\left(\varepsilon_{r,eff} - 0.258\right)} \tag{4}$$

For the rectangular U-slot µ-strip patch antennas, the design procedure proposed in (Bhattacharjee et al., 2013; Rani et al., 2010) can be incorporated to achieve an initial design.

The parallel arms of the U-shaped slot are also parallel to the length side of the patch. L_s and W_s are horizontal and vertical widths of U-slot arms, respectively. Nominal values for the initial values of L_s and W_s can be initially appointed as (Tong 2005, Bhattacharjee et al., 2013; Rani et al., 2010; Weigand et al., 2003)

$$L_s = \frac{\lambda_c}{60} \qquad W_s = \frac{\lambda_c}{60} \tag{5}$$

where λ_c is the center wavelength. Then, the slot width W_i can be calculated by (Tong 2005, Weigand et al., 2003);

$$W_i = \frac{c_0}{f_L {\varepsilon_{r,eff}}^{1/2}} - 2\left(L_{eff} - L_s\right) \tag{6}$$

where the length of the slot L_i is selected such that it should satisfy the inequalities of

$$\frac{L_i}{W} \geq 0.3 \qquad \frac{L_i}{W_i} \geq 0.75. \tag{7}$$

As the last rectangular U-slot µ-strip patch antenna, the slot spacing from edge can be approximated as (Tong 2005, Weigand et al., 2003);

$$S_s \approx L - L_s + 2\Delta_{L-L_s-S_s} - \frac{1}{\sqrt{\varepsilon_{eff(pp)}}}\left(\frac{c_0}{f_H} - (2L_i + W_i)\right) \tag{8}$$

where

$$\varepsilon_{eff}(pp) = 0.5\left((\varepsilon_r + 1) + \frac{(\varepsilon_r - 1)}{\left(1 + \frac{12h}{W_i - 2W_s}\right)^{1/2}}\right) \tag{9}$$

and

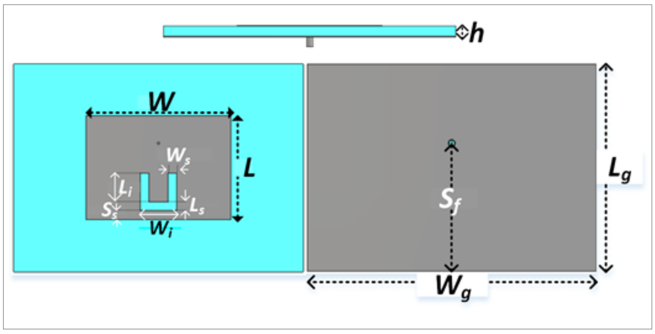
$$2\Delta_{L-L_s-S_s} = 0.824h\frac{\left(\varepsilon_{eff(pp)} + 0.3\right)\left(\frac{W_i - 2W_s}{h} + 0.262\right)}{\left(\varepsilon_{eff(pp)} - 0.258\right)\left(\frac{W_i - 2W_s}{h} + 0.813\right)} \tag{10}$$

3. Design and Simulation of Rectangular U-slot µ-strip patch antenna

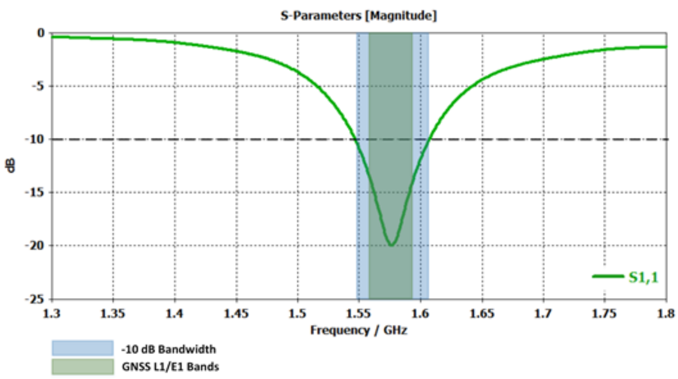
Based on the formulations that have listed in Sect. II, we have started with a preliminary design of the rectangular U-slot µ-strip patch antenna by the help of CST Studio Suite 3D antenna design and analysis tool (CST Studio Suite 2023). For the substrate the commercially available and widely used substrate material of high-density polyethylene (HDPE) (Khouaja et al., 2021) whose dielectric constant is 2.4 with a substrate thickness of 1.5 mm was selected. The thickness of the copper material was 100 µm. The feeding of the antenna was accomplished via a coaxial feed that has a nominal characteristic impedance of 50**Ω.**

The initial design parameters were calculated by using the formulas given in equations between (1) and (10) and, then the optimization toolbox of CST has been utilized to make the design around the center frequency of the L1 band. The design of the rectangular U-slot µ-strip patch antenna has been finalized as given in Fig. 1a. The optimized and final parameters of the designed rectangular U-slot μ-strip patch antenna are listed in the middle column of Table I.

Simulation results for the final designed rectangular U-slot μ-strip patch antenna are reported in Fig.1 and Fig.2. The reflection coefficient (S_{11}) plot of the designed antenna is given in Fig 1b in which we can see that the antenna provides S_{11} performances at least -10 dB for the frequencies between 1.5466 and 1.6070 GHz. Therefore, one can easily observe that the antenna's operational bandwidth covers the frequency bands of GNSS L1/E1. The radiation pattern simulation results for the designed antenna are shared in Fig. 2. First, the three-dimensional (3D) radiation pattern of the antenna is depicted in Fig. 2a. By looking at the radiation pattern of the antenna, it is observed that the antenna's radiation direction is almost towards to upper hemisphere that is very suitable with the GNSS L1/ E1 applications such as using it as an GPS receiver antenna. A more detailed analysis of the radiation pattern of the designed antenna is given in Fig. 2b and 2c using the two-dimensional (2D) radiation pattern plots in dB scale. The 2D E-plane ($\phi = 0°$) and H-plane ($\phi = 90°$) patterns are plotted with respect to different θ angles as plotted in Fig. 2b and Fig. 2c, respectively. These patterns clearly show that this antenna is well directive towards zenith (z) direction with a gain of 8.1 dB. The half-power beam width (HPBW) values of 65.5° and 80.4° for the E-plane ($\phi = 0°$) and H-plane ($\phi = 90°$) patterns are achieved, respectively. Based on these analyses, we can easily conclude that this antenna can be conveniently used for GPS applications with good fidelity as the most of the pattern locates at the upper hemisphere of the antenna.

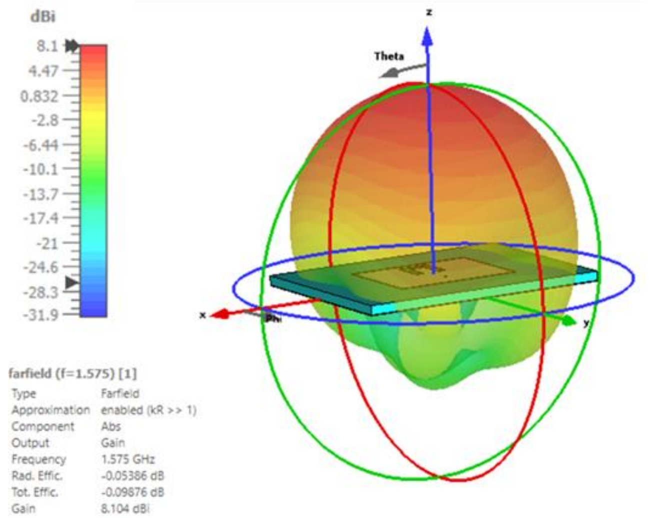


(a)

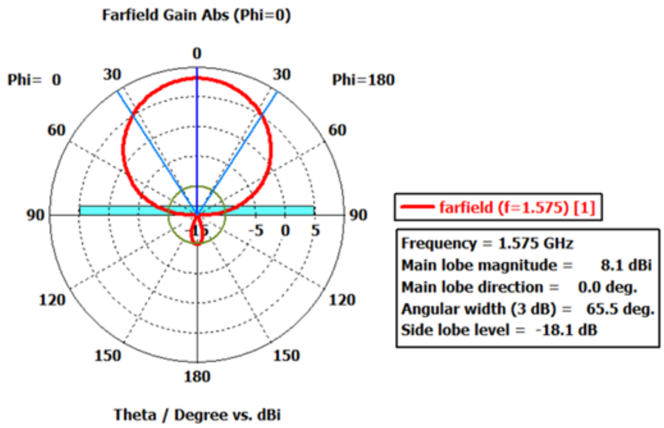


(b)

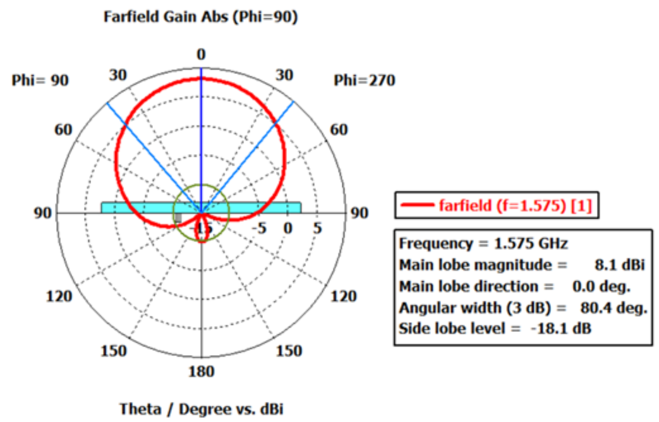
Figure 1. (a) The geometry, and (b) reflection coefficient (S11) simulation result for the designed U-slot rectangular patch antenna



(a)



(b)



(c)

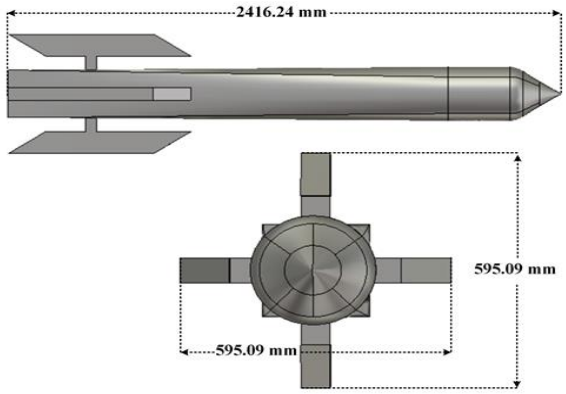
Figure 2. Radiation pattern of the designed U-slot rectangular patch antenna: (a) 3D pattern, (b) 2D E-plane (θ) pattern at $\phi = 0°$, and (c) 2D H-plane (θ) pattern at $\phi = 90°$

4. Design and Simulation of Conformal U-Slot μ-Strip Patch Antenna

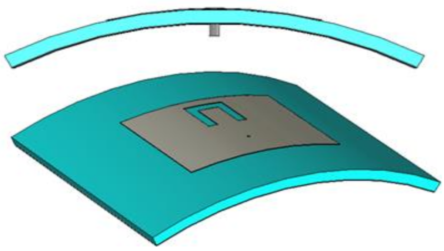
4.1. Conformal U-Slot μ-Strip Patch Antenna: Stand Alone

After completing the rectangular, flat design of U-slot rectangular patch antenna, its conformal version is tried by the help of CST. For the conformal version of this antenna, a missile model whose CAD in Fig. 3a was considered to be able to bend the antenna accordingly. This missile has the size of $2.4\ m \times 0.6\ m \times 0.6\ m$.

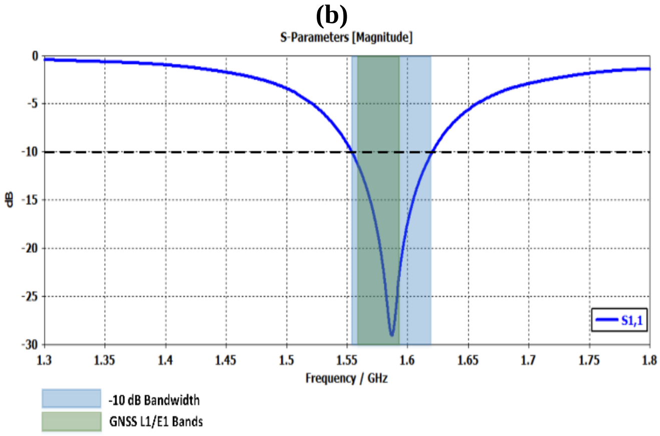
Using the bending tool of the CST, the designed rectangular U-slot μ-strip patch antenna has been bent as depicted in Fig. 3b. Then, this antenna has been optimized to be able to such that the antenna dimensions are finalized as listed along the last column of Table I. The simulation of this optimized, final conformal U-slot μ-strip patch antenna was accomplished by the help of CST software. The reflection coefficient performance is drawn with respect to frequency as shared in Fig. 3c. By examining this figure, it is obvious that the -10 dB bandwidth of this conformal antenna is 67 MHz ranging from 1.553 and 1.620 GHz that obviously covers the whole GNSS L1/E1 frequency band as illustrated in Fig. 3c.



(a)



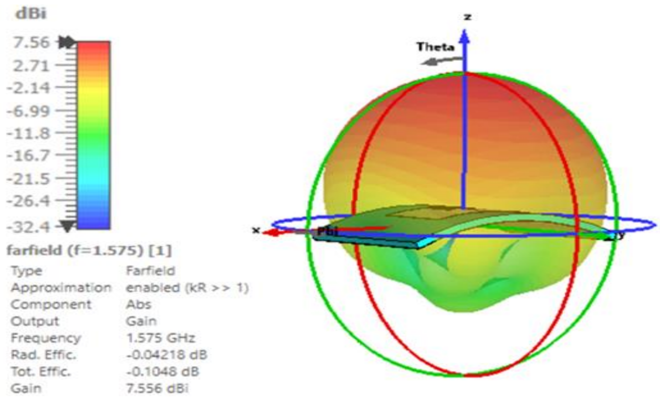
(b)



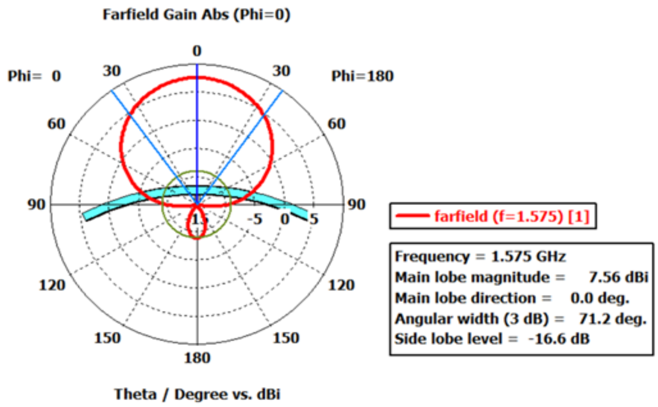
(c)

Figure 3. The missile model that the antenna to be put on, (b) the designed conformal antenna after CST optimization, (c) reflection coefficient (S_{11}) simulation result for the designed U-slot conformal patch antenna

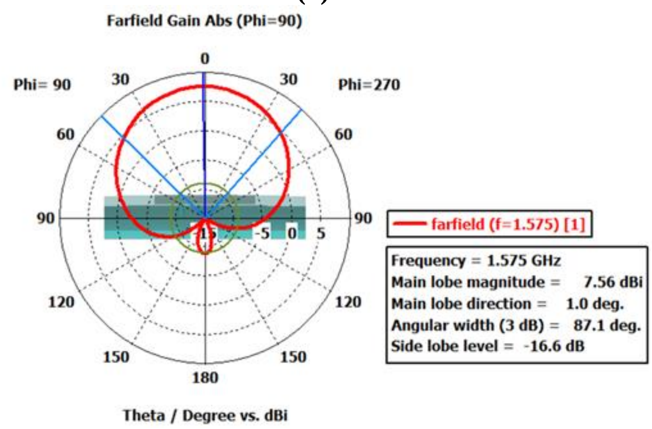
The radiation pattern simulation results for the designed conformal U-slot μ-strip patch antenna are given in Fig. 4. First, the 3D radiation pattern of the antenna is depicted in Fig. 4a. As expected, the directivity of the conformal antenna which was 8.1 dB is a little bit decreased when compared to that of rectangular antenna since the effective antenna aperture has also been reduced. However, the antenna's radiation direction is again almost towards to upper hemisphere that is well appropriate with the GNSS L1/ E1 usages. A supplementary comprehensive analysis of the radiation pattern of the designed conformal antenna is shared in Fig. 4b and 4c via 2D radiation pattern plots. The 2D E-plane ($\phi = 0°$) and H-plane ($\phi = 90°$) patterns are plotted with respect to different θ angles as given in Fig. 4b and Fig. 4c, respectively. These patterns evidently demonstrate that this antenna is healthy directive towards upward direction with a gain of 7.56 dB. The -3B beamwidth performances for E-plane ($\phi = 0°$) and H-plane ($\phi = 90°$) radiation patterns were obtained as 71.2° and 87.1°, respectively. Therefore, these figures successfully claim that this antenna can be suitably used for GNSS L1/ E1 applications.



(a)



(b)



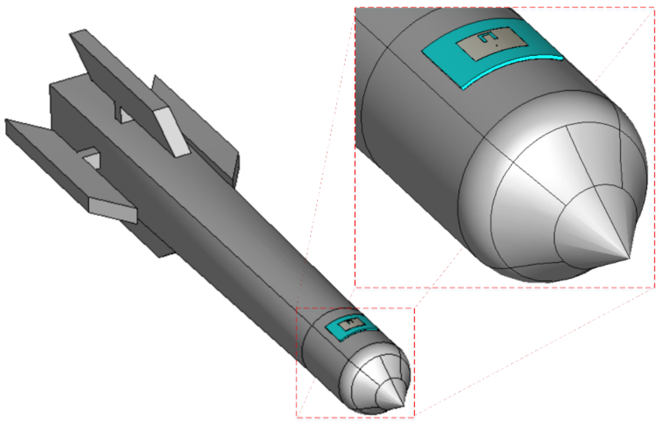
(c)

Figure 4. Radiation pattern of the designed conformal U-slot patch antenna: (a) 3D pattern, (b) 2D E-plane (θ) pattern at $\phi = 0°$, and (c) 2D H-plane (θ) pattern at $\phi = 90°$

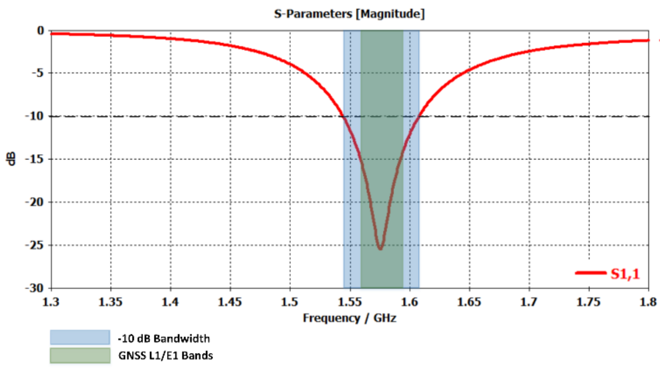
4.2. Conformal U-Slot µ-Strip Patch Antenna on a Missile Model

Once the conformal U-slot µ-strip patch antenna design, optimization and simulation has been completed, it is mounted on the missile model as illustrated in Fig. 5a. To do that, the aluminum model has been cut from the region where the antenna was mounted such that the coax feeding is now located in the inner side of the model.

Next, the CST simulation of conformal antenna mounted on the missile model has been completed with the designed antenna dimensions finalized in the previous subsection. Achieved antenna parameters are given in order. First, the reflection coefficient result was obtained as given in Fig. 5b. It is clear from the figure that the -10 dB bandwidth of conformal U-slot µ-strip patch antenna mounted on the missile model is 64 MHz ranging from 1.544 and 1.608 GHz. We observe a loss of 3 MHz bandwidth that does not affect the usage of designed antenna for the GNSS L1/E1 applications since the antenna still covers the frequency range between 1559 MHz and 1591 MHz.



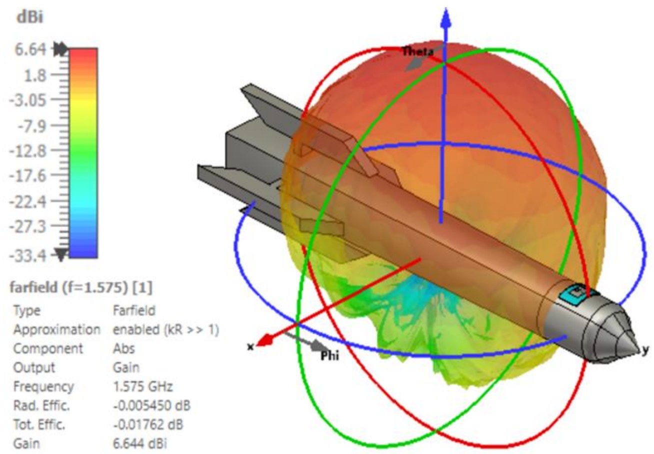
(a)



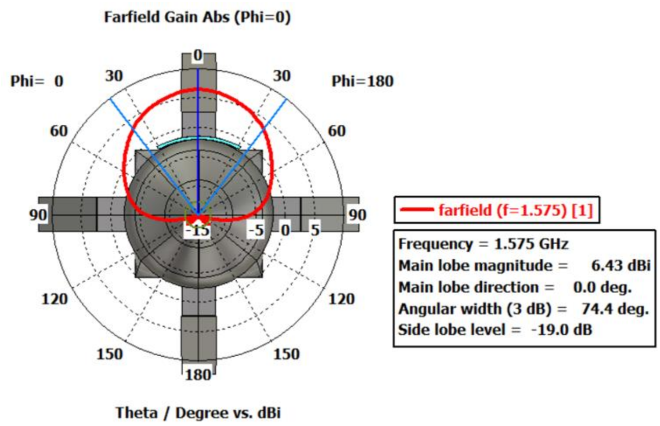
(b)

Figure 5. The conformal antenna mounted on the missile model, (b) S_{11} simulation result for the conformal antenna mounted on the model

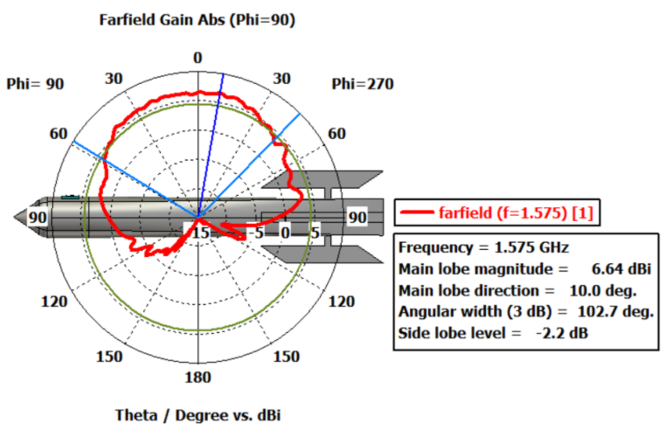
Obtained results for the radiation pattern simulation of the designed conformal U-slot µ-strip patch antenna mounted on the missile model are depicted in Fig. 6. First, the 3D radiation pattern of the antenna is depicted in Fig. 6a. By looking at the radiation pattern of the antenna, the pattern is again upward directed suitable for the GNSS L1/ E1 applications. The gain of the antenna together with the missile model is found as 6.64 dB that is approximately 0.95 dB lower than that of stand-alone antenna case. Therefore, the effect of the missile platform to the antenna gain is less than 1 dB. 2D E-plane ($\phi = 0°$) and H-plane ($\phi = 90°$) antenna radiation patterns are depicted in Fig. 6b and Fig. 6c, respectively. The HPBW results for E-plane ($\phi = 0°$) and H-plane ($\phi = 90°$) radiation patterns were obtained as 74.4° and 102.7°, respectively. Therefore, the main lobes patterns were a little bit widened with a small decreased amount of gain as expected. Based on these frequency bandwidth and radiation pattern analyses, it can be deduced that our conformal U-shaped µ-strip patch antenna can be reliably used GNSS L1/E1 practices.



(a)



(b)



(c)

Figure 6. Radiation pattern of the designed conformal U-slot patch antenna on top of the missile model: (a) 3D pattern, (b) 2D E-plane (θ) pattern at $\phi = 0°$, and (c) 2D H-plane (θ) pattern at $\phi = 90°$

Table 1. Design parameters of rectangular/conformal u-slot μ-strip patch antenna

Design Parameters		Rectangular U-slot μ-strip Patch Antenna (mm)	Conformal U-slot μ-strip Patch Antenna (mm)
Patch width	W	77.15	79.09
Patch length	L	55.8	55.03
Ground width	W_g	154.3	157.84
Ground length	L_g	111.6	110.05
Feed inset from edge	S_f	69.24	68.28
Slot width	W_i	19.6	20.09
Slot length	L_i	20.05	19.77
Slot spacing from edge	S_s	5.14	5.07
Slot thickness (horizontal, vertical)	L_s, W_s	$W_s = L_s = 4.59$	$W_s = 4.71, L_s = 4.53$
Substrate thickness	h	1.5	1.5

5. Conclusion

In this paper, we have designed a special conformal U-slot μ-strip patch antenna to be used in the L1/E1 frequency band 1563 MHz-1587 MHz and 1559 MHz-1591 MHz, respectively. The dimensions for the rectangular version of the antenna were calculated using theoretical formulas that were specially developed for rectangular U-slot μ-strip patch antenna. Then CST software has been utilized using these initial, calculated values of the dimensions to be used during the optimization. Once the rectangular version of the antenna was finalized, its conformal version was designed and optimized thanks to the CST optimization tool. The antenna parameters were reported such that they are in good agreement with the requirements of GNSS L1/E1 applications such as GPS. Finally, the optimized conformal U-slot μ-strip patch antenna was put on a metal missile model and its performance was checked. It has been seen from the CST simulation results that the final, optimized antenna has slightly less operational frequency bandwidth compared to that of stand-alone conformal antenna. Such a small reduction of 3 MHz is acceptable and does not exceeds the extremes of GNSS L1/E1 frequency bands. Hence, this antenna can be conveniently and reliably used for the goal range of frequencies with achieving the radiation pattern requirements. This is because of the fact that the operational frequency band of final, optimized conformal antenna ranges from 1544 MHz to 1608 MHz; whereas, the GNSS L1/E1 frequency band is actually inside this band; i.e., from 1559 MHz and 1591 MHz.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

References

Balderas, L.I., Reyna, A., Panduro, M.A., Del Rio, C. and Gutiérrez, A.R. (2019). Low-Profile Conformal UWB Antenna for UAV Applications. IEEE Access, 7, 127486-127494.

Bhattacharjee, P., Hanumante, V. and Roy, S. (2013). Design of U-Slot Rectangular Patch Antenna for Wireless LAN at 2.45GHz. 9th International Conference on Microwaves, Antenna, Propagation and Remote Sensing 11th – 14th December, Jodhpur, INDIA, 132-135.

Chen, C. and Zheng, H. (2017). Design of a dual-band conformal antenna on a cone surface for missile-borne. In Proceedings of the 2017 Sixth Asia-Pacific Conference on Antennas and Propagation (APCAP), 16–19 October 2017, Xi'an, China, 1–3.

CST Studio Suite, https://www.3ds.com/products-services/simulia/products/cst-studio-suite/ last verified: 07/01/2023.

Gaetano, D., Ammann, M.J., McEvoy, P., John, M., Keating, L. and Horgan, F. (2012). Proximity study of a conformal UWB directional antenna on water pipe. Microw. Opt. Technol. Lett., 54(8), 1982-1986.

Khalil, H., Rafique, U., Ahmed, M.M., Rahman, S. and Nazar, W. (2019). A Comparative Study of Conformal Antenna Arrays for Aerodynamic Applications. In Proceedings of the 2019 Photonics & Electromagnetics Research Symposium—Fall (PIERS—Fall), 17–20 December 2019, Xiamen, China, 3211–3217.

Khouaja, A., Koubaa, A. and Daly, H.B. (2021). Dielectric properties and thermal stability of cellulose high-density polyethylene bio-based composites. Industrial Crops and Products, 171, 113928.

Mishra, P. and Gupta, P. (2015). Compact U-Slotted Dual Band Conformal Microstrip Antenna. International Journal of Engineering Research & Technology (IJERT), 4(12),167-171.

Mitha, T. and Pour, M. (2018). Conformal Wideband Microstrip Patch Antennas on Cylindrical Platforms. Progress in Electromagnetics Research Letters, 80, 1-6.

Mondal, S. and Sarkar, P.P. (2014). Design of an ultrawideband conformal metal antenna. Microw. Opt. Technol. Lett., 56(2), 430-434.

Morton, T.E. and Pasala, K.M. (2006). Performance analysis of conformal conical arrays for airborne vehicles. IEEE Trans. Aerosp. Electron. Syst., 42(3), 876–890.

Nikolaou, S., Ponchak, G.E., Papapolymerou, J. and Tentzeris, M.M. (2006). Conformal double exponentially tapered slot antenna (DETSA) on LCP for UWB applications. IEEE Trans. Antennas Propag., 54(6), 1663-1669.

Obeidat, K., Rojas, R.G. and Raines B. (2009). Design of antenna conformal to V-shaped tail of UAV based on the method of Characteristic Modes. 2009 3rd European Conference on Antennas and Propagation, 23-27 March 2009, Berlin, Germany, 2493-2496.

Ozdemir, C. and Ling, H. (1997). Joint time-frequency interpretation of scattering phenomenology in dielectric-coated wires. IEEE Transactions on Antennas and Propagation, 45(8), 1259-1264.

Pradhan, S. and Gupta, B. (2022). High-Gain Dual-Mode Cylindrical Rectangular Patch Antenna for Airborne Applications. IEEE Transactions on Aerospace and Electronic Systems, 58(5), 4168-4179.

Rani, A. and Dawre, R.K. (2010). Design and Analysis of Rectangular and U slotted Patch for Satellite Communication. International Journal of Computer Applications, 12(7), 36-40.

Tong, C.H.M. (2005). System Study and Design of Broad-band U-slot Microstrip Patch Antennas for Aperstructures and Oppurtunistic Arrays. Master Thesis, Naval Postgraduate School, Monterey, California, 1-109.

Weigand, S., Huff, G.H., Pan, K.H. and Bernhard, J.T. (2003). Analysis and design of broad-band single-layer rectangular U-slot microstrip patch antennas. IEEE Transactions on Antennas and Propagation, 51(3), 457-468.

Cite this article: Yilmaz, B. (2023). Design and Simulation of a Conformal Micro-Strip Patch Antenna at GNSS L1/ E1 Frequency Band. Journal of Aviation, 7(2), 171-177.