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Miniature antenna for GNSS satellite constellation reception

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Abstract

This paper presents the design, simulation, and real-world validation of a compact, dual-band, right-hand circularly polarized antenna for Global Navigation Satellite System (GNSS) applications. The antenna operates in the L1 (1575 MHz) and L5 (1176 MHz) bands, utilizing a stacked patch structure on low-cost FR4 substrates to achieve compactness and circular polarization. The design ensures axial ratio values below 3 dB, with peak gains of 2.59 dBi (L1) and -0.89 dBi (L5), while maintaining wide radiation coverage. Unlike many recent proposals based on Rogers substrates or complex geometries, our design focuses on cost-effectiveness and manufacturing simplicity. The prototype was validated using a Quectel LC29HAAMD GNSS receiver during the 2024 French National Microwaves Days (JNM), successfully acquiring over 40 satellites within 60 seconds in a real-world suburban environment. These results demonstrate the antenna's suitability for space-constrained and low-cost GNSS platforms in the "New Space" era.

Introduction

Global Navigation Satellite Systems (GNSS) play a fundamental role in modern positioning, navigation, and timing across both civilian and defense sectors [1],[2]. For many years, it has been demonstrated to be highly effective in trajectory definition and localization [1]. This capability is enabled by satellite constellations that facilitate the trilateration procedure, thereby enabling the user to receive precise measurements of their speed and geographic coordinates. A substantial array of phone applications exists that facilitate the identification of one's location, and these applications have attained a high degree of renown within the civil sphere. However, given their capacity to ensure both definition and trajectory guidance, as well as knowledge of strategic position, they emerge as indispensable instruments within the military context. The proliferation of multiple constellations, including GPS, Galileo, BeiDou-3, and GLONASS, has led to a surge in demand for compact, multi-band, and robust GNSS receivers. One of the critical challenges in receiver design lies in the antenna, which must offer dual-band operation (e.g., L1 and L5), right-hand circular polarization (RHCP), wide radiation coverage, and minimal size – all while remaining low-cost and tolerant to fabrication variations. Achieving this combination is non-trivial. Dual-band operation typically requires large radiating surfaces or complex feed structures, while circular polarization is sensitive to geometrical precision and substrate losses. These constraints are especially limiting in low-cost applications such as small satellites (CubeSats), UAVs, or IoT-enabled GNSS platforms. This assertion holds particular weight when considering the advent of new space. A substantial and pressing demand exists for cost-effective, miniature, and highly compact solutions. As a key component of the overall RF system, the search is on for a dual-band antenna with circular polarization that is both compact and cost-effective. Currently, the most suited technology available for this type of antenna is PCB (Printed Circuit Board) technology, which is inherently low profile, small, and very low cost, especially when combined with a low-cost substrate. A prominent difficulty in PCB design, especially within the purview of GNSS applications, lies in the development of designs that exhibit minimal substrate losses. In other words, a trade-off must be managed between antenna efficiency and compactness/price. This work prioritizes the cost-effectiveness aspect while maximizing the performance achievable within the specified topology.

Numerous antenna designs have been proposed as a solution to a low-cost, circularly polarized bi-band GNSS antenna. Classical solutions involve stacked patches on high-performance

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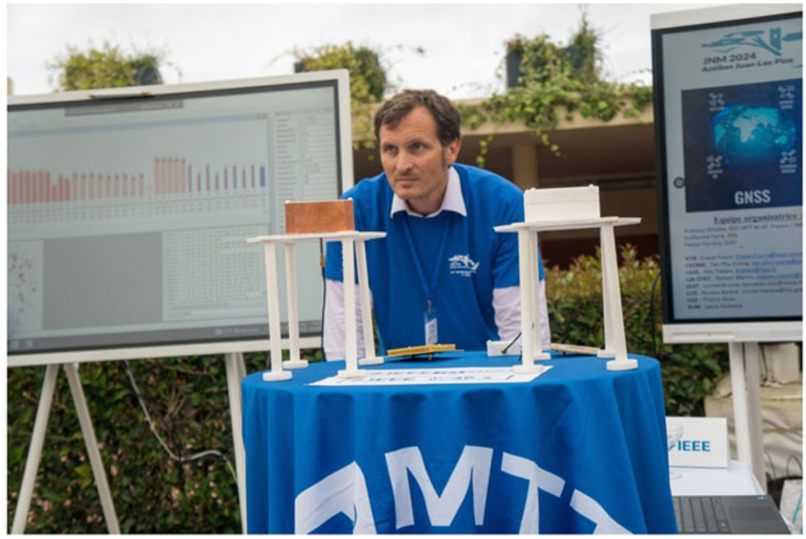

Figure 1. 1/2 final fight – antenna from CROMA PhD students (Grenoble) vs the antenna from the XLIM PhD student (Limoges).

substrates [3, 4], while others explore multi-element arrays [5], which are often unsuitable for wide-angle omnidirectional reception. More recent work includes dual-band CP antennas with advanced slot geometries such as V-shaped [7], eye-shaped [8], and sunlight-shaped [9] configurations. A hexaband slotted patch for GNSS and 5G is also reported in [10]

However, most of these approaches either lack experimental validation, require expensive materials (e.g., Rogers RO4003, Duroid), or involve manufacturing complexity. In this context, our work proposes a low-cost, dual-band RHCP antenna designed using two identical-height FR4 substrates. The antenna uses a stacked patch architecture with optimized geometry to ensure resonance at L1 and L5 while achieving an axial ratio of < 3 dB across both bands. Unlike prior work, the antenna was fabricated and validated in a real-world environment using a GNSS receiver and satellite tracking software.

Indeed, within the framework of the 23rd French National Microwaves Days (JNM) at Antibes (France) in 2024, a student contest was organized to highlight the best miniature receiving antenna for GNSS signals. The number of GNSS satellites discovered served as the criterion for determining the antenna's performance, in addition to its adherence to the prescribed requirements. A Quectel LC29HAAMD GNSS receiver and the QGNSS software, which can decode the NMEA frames from the GNSS module, were used to actually test the antenna. Over the course of 60 seconds, a full cold start measurement was conducted. The jury examined how many GNSS satellites were found within the 60-second period after it ended. The evening of the semi-finals and final took place at the Côte d'Azur racecourse in Cagnes-sur-Mer, as illustrated in Fig. 1 (semi-final). This paper presents the co-winning antenna, which is a stacked dual-band circularly polarized patch antenna. According to the constraints imposed by the contest organization, this antenna is fully passive, has a maximal size inferior or equal to 100 mm × 100 mm × 50 mm. The results confirm excellent acquisition performance, demonstrating the feasibility of low-cost, passive GNSS antennas compatible with emerging "New Space" requirements.

The paper is organized as follows. Section II examines the current state of the art in terms of the imposed parameters, while Section III provides a detailed description of the designed antenna and its performance. Section IV of this study presents an analysis of the design's tolerance robustness. Section V provides a state-of-the-art comparison, highlighting the advantages of the proposed antenna in terms of dimensions, cost, and real-world applicability. Finally, conclusions follow in Section VI.

Table 1. Specifications of the L-band GNSS reception antenna.

Parameters	Values	Units
Dimensions	100x100x50	mm
Frequency Bands L1	1559-1610	MHz
Frequency Bands L5	1164-1189	MHz
Polarization L1	RHCP	
Polarization L5	RHCP	

Antenna specifications for a GNSS reception application

A comprehensive examination of the state of the art was conducted to ascertain an antenna solution that would satisfy all pertinent specifications presented in Table 1. Several studies dedicated to the development of antennas that are compatible with the performance requirements of GNSS applications can be found in the state of the art [2]. The authors of this study elected to concentrate exclusively on solutions in planar PCB technology. Indeed, the solution's attributes, including its low profile, low cost, and versatility in terms of antenna performance, appear to make it the most suitable option in the context of a student competition. Moreover, the cost of a GNSS antenna is one of the most significant aspects of the design, particularly in the new space context [2].

The optimal antenna configuration must exhibit characteristics that are contradictory, including a wide radiation pattern ensuring spatial coverage and a substantial gain ensuring the link budget. Consequently, the authors opted to employ topologies that are optimized to address this trade-off. The majority of designs existing in the literature that are compatible with the specifications utilize patch antenna stacking methods. Indeed, the combination of two patches has been demonstrated to generate two distinct operating bands [3], [4]. Designs using antenna arrays, such as references [5], were not retained, since the final system is incompatible with

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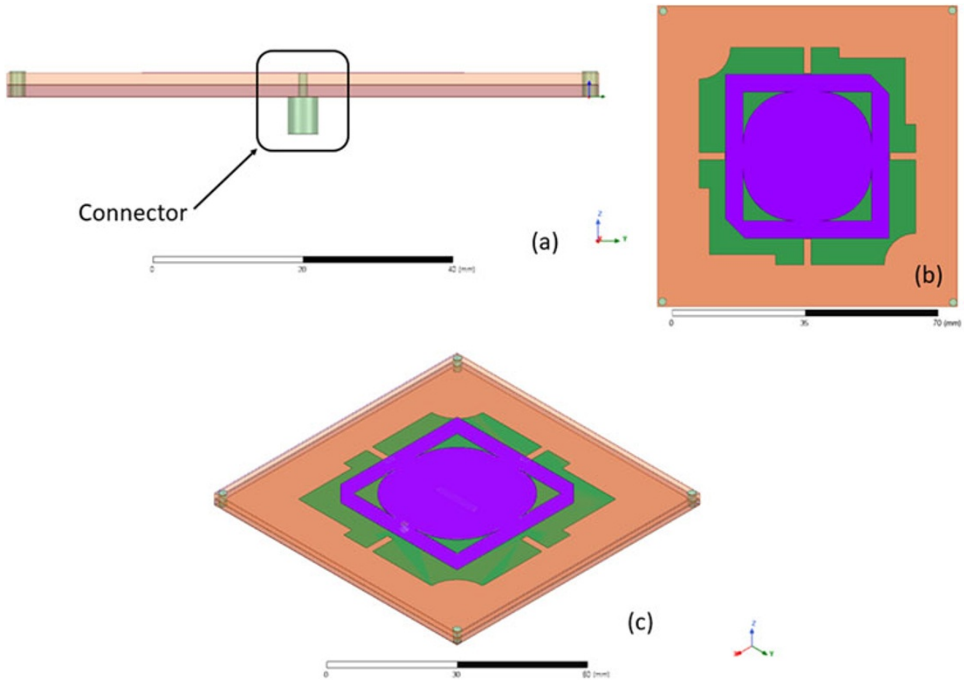

Figure 2. Simulated antenna with Ansys HFSS software, (a) side view, (b) top view, and (c) isometric view as proposed in [6].

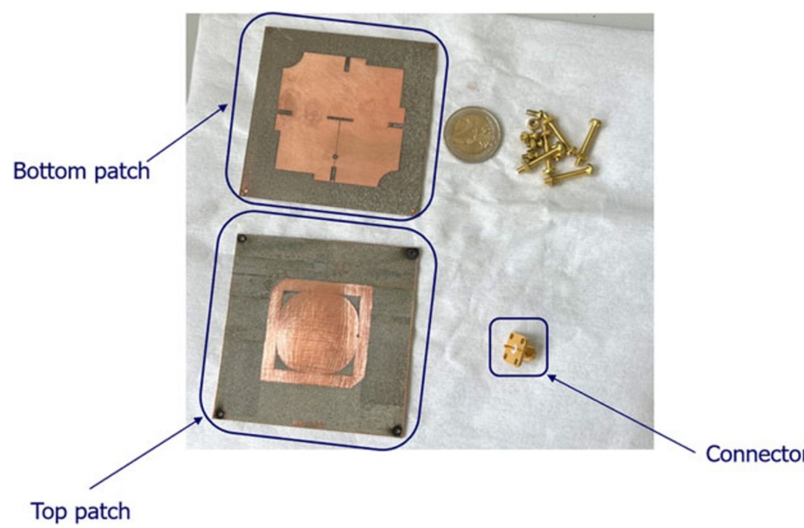

Figure 3. Different parts of the antenna, including the connector and screws used to adhere the two parts together

beamforming operation to cover the largest possible angular area. Finally, the design only simulated in the reference [6], which consists of a stacked patch antenna, was chosen for its compliance with the specifications, its radiation performance respecting the compromise between angular opening and gain, and its simplicity of design, specifically in relation to its feeding. As previously mentioned, [6] merely demonstrates simulations of the antenna design. This paper presents both the conception and the fabrication of the antenna, in addition to a practical validation of the antenna's performance in a real-world environment. The most crucial component was, above all, the substrate (FR4) that was utilized since it is a very accessible and affordable substrate that allows the antenna to be employed as a low-cost antenna that is compatible with new space. While [6] uses two distinct FR4 substrate heights, this work presents a design with the same height for both substrates, enhancing the concept's low-cost aspect.

Proposed antenna design

As mentioned previously, based on the simulated work available in [6], an antenna that meets the specifications imposed by the application was simulated (see Fig. 2) and fabricated (see Fig. 3) using an Enclosed Fiber Laser Marking Machine (50W fiber laser) [11] available in Lab-STICC UMR CNRS 6285.

The structure of the proposed dual-band circularly polarized (CP) microstrip antenna is illustrated in Fig. 2. It consists of two stacked radiating patches: an upper patch and a lower patch. Dual-band operation is achieved by placing the high-frequency patch above the low-frequency one. The process of miniaturization is accomplished through a conventional method involving the cutting of slots in the surface of the patch. This stacked dual-layer configuration enables independent tuning of each operating frequency, offering greater flexibility in the optimization process.

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Table 2. Geometric parameters

Parameter	W	W_1	W_2	W_3	W_4
Value (mm)	80	44.7	59	2	2.5
Parameter	W_5	W_6	t_3	t_4	t_6
Value (mm)	13.8	11.6	7	18.1	1.1
Parameter	c	r_0	r_1	h_1	h_2
Value (mm)	3.5	2.14	8.5	1.6	1.6

The upper patch is designed to operate at (L1 band) 1.57542 GHz, while the lower patch resonates at (L5 Band) 1.17645 GHz, with respective heights denoted as h_1 and h_2. To achieve size reduction, four vertical rectangular slits are etched into the lower patch, and four irregular triangular slots are incorporated into the upper patch. Additionally, a rectangular slot is introduced in the lower patch to enhance impedance matching for the single-feed CP antenna as explained in [6]. The antenna differs from [6] by the substrates' heights as explained previously, which leads to different geometric parameters. Note that a parametric study is presented in [6], where the impact of the height on the gain is highlighted.

The antenna was designed on a double FR4 substrate (thickness: 1.6 mm, dielectric constant ϵ_r: 4.4, and dielectric loss tangent: 0.02). In Fig. 3, the different parts of the antenna, including the connector and screws used to mount the two parts together, are presented. Note that the screws have been strategically positioned to avoid compromising electrical performance. The dimensions of the different values of the antenna (for the same variable as [6]) are presented in Table 2. As a reminder, our antenna uses two identical substrates of the same height (1.6 mm), whereas in [6], they use two substrates with different heights.

Figs. 4 and 5 show the surface current distributions at L1 and L5 frequencies, evaluated at various time phases, revealing a rotating vector field characteristic of RHCP. This behavior is enabled by the intentional design of the stacked patch geometry, which excites two orthogonal current modes with nearly identical amplitudes and a 90° phase shift. The simulated vector current patterns confirm the temporal rotation of the surface currents, resulting in RHCP radiation in the far field – fully aligned with the polarization requirements of GNSS applications.

Fig. 6 shows the co-polarized and cross-polarized realized gain of the proposed antenna at low frequency and high frequency 1.18 and 1.57 GHz, respectively. The shape of the radiation pattern is completely compatible with the expected diagram of a GNSS antenna, i.e., a wide aperture with a significant reduction in gain near the horizon to avoid certain interference effects near the horizon [2]. The cross-polarization remains significantly suppressed in all directions for the two bands. This confirms the polarization purity of the proposed antenna, which is essential to reject reflected multipath components in GNSS scenarios. The performance of the antenna in terms of radiation is completely consistent with the performance shown in simulation in ref [6]. However, the gain in the L1 band is significantly lower than the gain in the L5 band, which can be explained by the reduction in substrate height [6].

The simulated and measured S_{11} (dB) parameters are presented in Fig. 7, showing a good correlation and agreement with the specifications for the L1 and L5 bands.

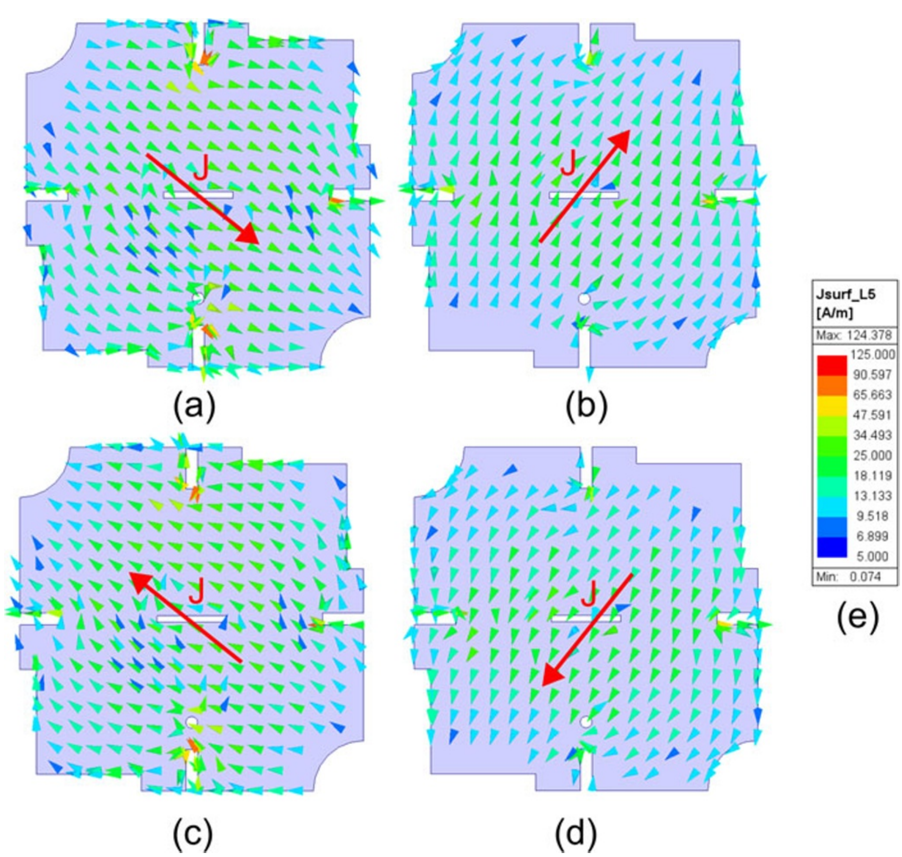

Figure 4. Simulated surface currents distribution at 1.176 GHz. (a) 0°. (b) 90°. (c) 180°. (d) 270°. (e) Colorbar.

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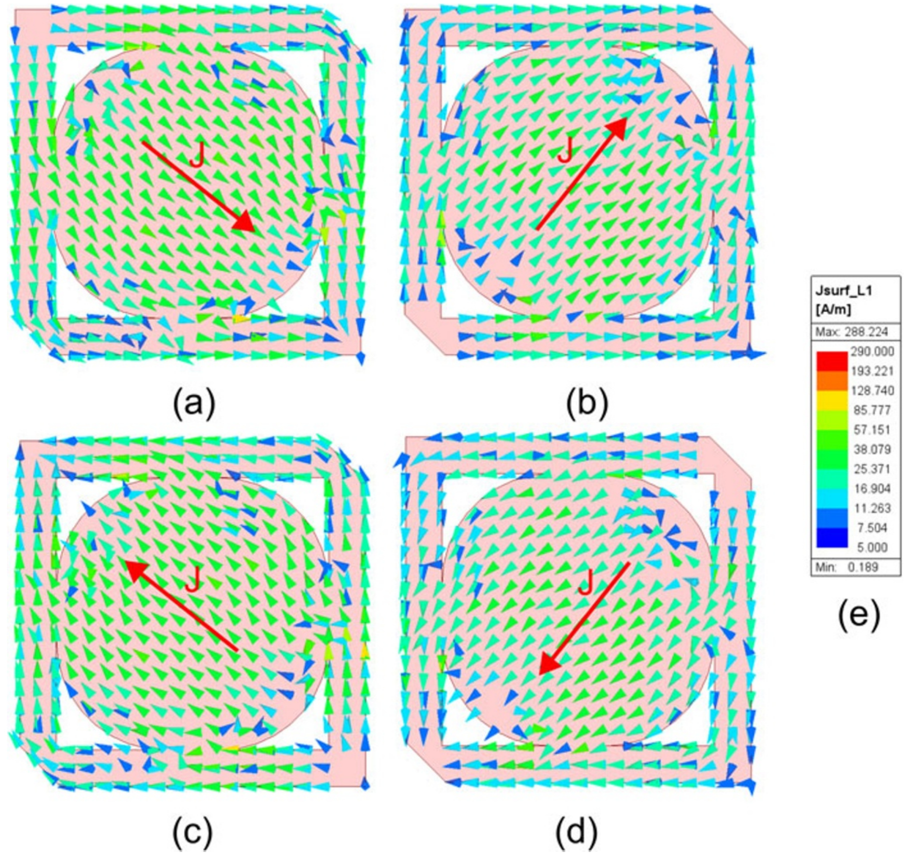

Figure 5. Simulated surface currents distribution at 1.575 GHz. (a) 0°. (b) 90°. (c) 180°. (d) 270°. (e) Colorbar.

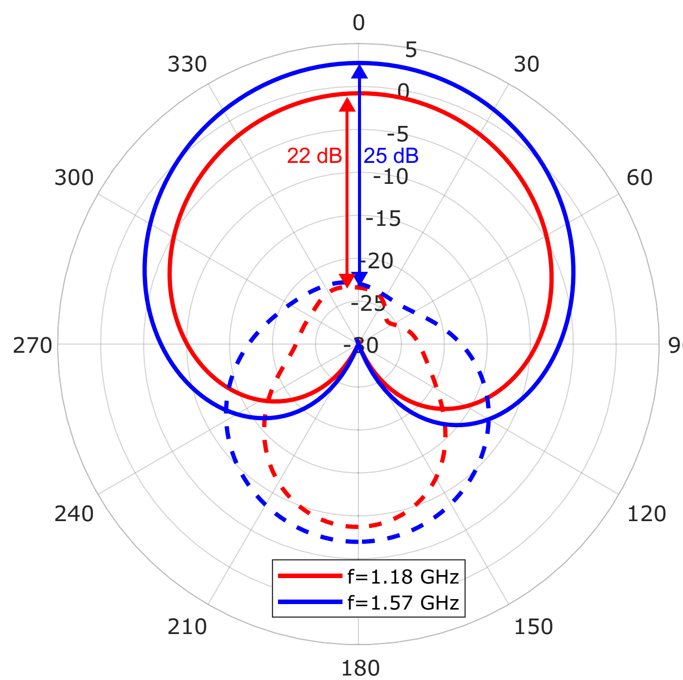

Figure 6. Simulated radiation pattern for $\phi = 0$ at the center frequency (continuous/dotted lines correspond respectively to co-polarization/cross-polarization).

Figure 8 illustrates the axial ratio as a function of the elevation angle, showing favorable circular polarization performance for both the L1 and L5 bands.

Finally, Fig. 9a) illustrates the simulated axial ratio as a function of frequency for both L1 and L5 bands. In both cases, the axial ratio remains below the critical 3 dB threshold, confirming the generation of RHCP. This behavior is maintained across the entire operating bandwidth, which is a key performance metric for GNSS reception. The smooth evolution of the axial ratio also demonstrates the stability of the stacked geometry and its

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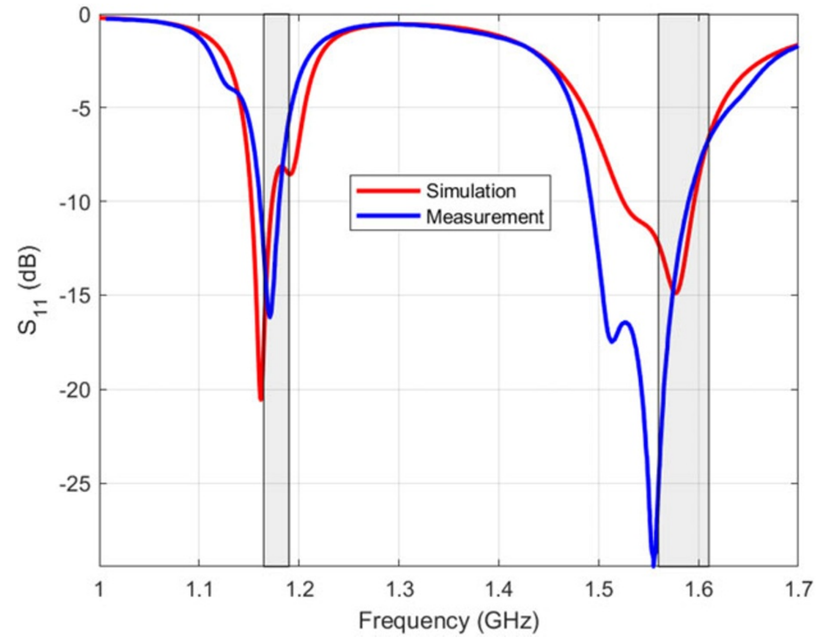

Figure 7. Comparison between simulated and measured return loss.

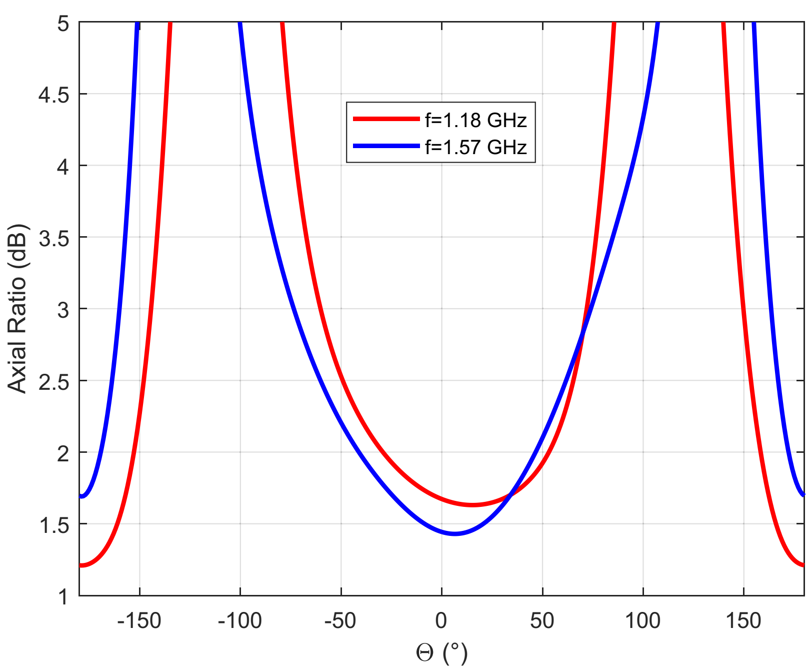

Figure 8. Simulated axial ratio (dB) as a function of the angle theta.

robustness to fabrication tolerances. Figure 9b) presents the simulated efficiency of the proposed antenna, reaching approximately 45% for the L1 band and 25% for the L5 band.

The antenna presented in this work meets the specifications imposed by the requirements. On the one hand, it is miniature and simple to manufacture, and on the other hand, thanks to the use of two stacked substrates, it is easy to achieve both dual-band characteristics (stacked patch) and RHCP polarization for the two operating frequency bands (L1 and L5), given the patch geometry, as illustrated in [6].

Ultimately, this simple, miniature, low-cost, and easily manufacturable antenna is fully aligned with the new space era.

Future work will explore integrating the proposed antenna into embedded platforms, extending it to tri-band operation (L1/L2/L5), and assessing performance under conformal configurations or additive manufacturing processes.

Study of substrate tolerance

The design of reference [6] has been constructed, measured, and tested. The results reveal that the design is well-suited to GNSS applications in terms of antenna performance.

It is a very basic and low-cost system that performs well even after reducing the first substrate height.

However, the design's tolerance to the substrate modification has not been investigated. In terms of dimension, the substrate height can vary by $\pm 10\%$. The variation of antenna performances with substrate height tolerance has been simulated with

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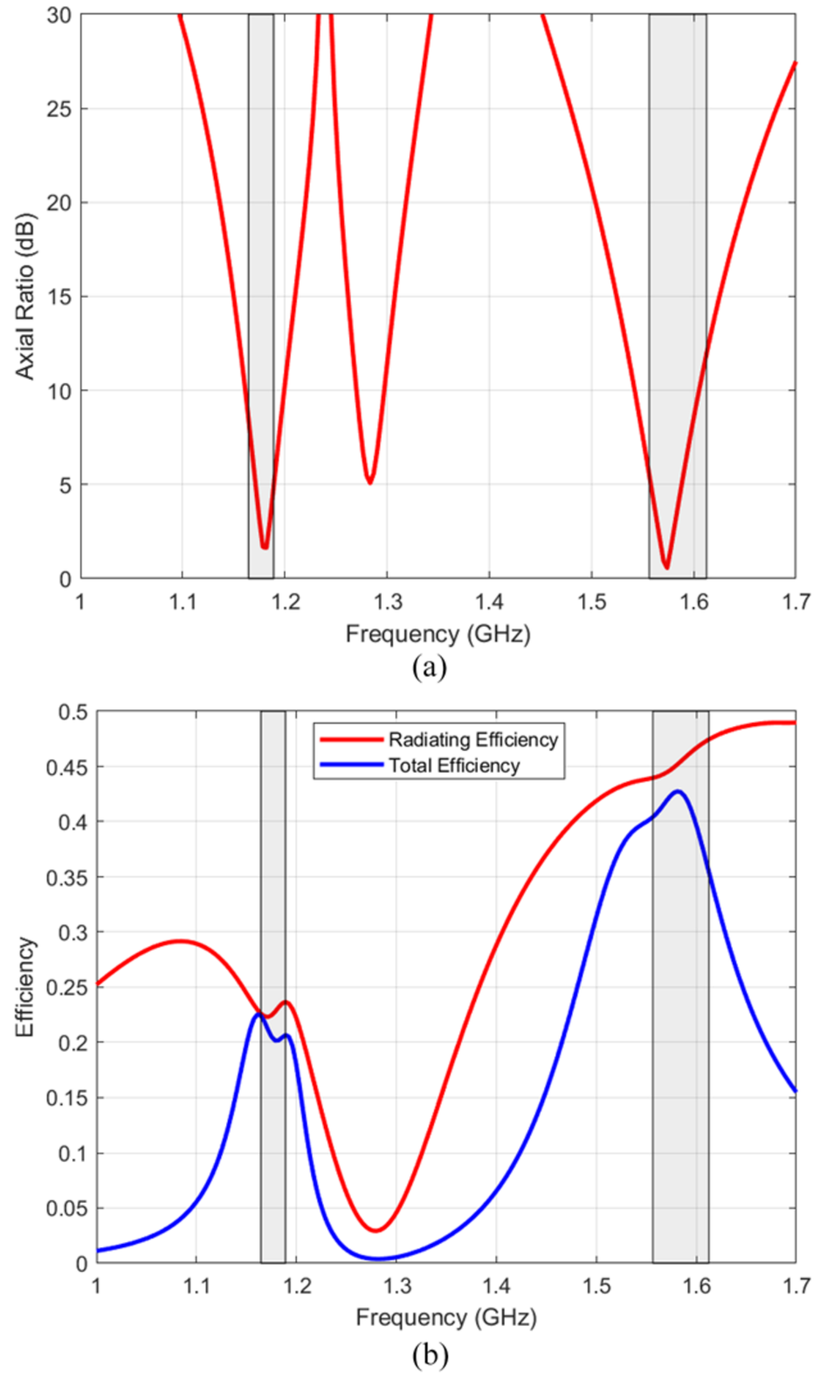

Figure 9. Performance over frequency. (a) Axial ratios ($\theta = 0; \phi = 0$). (b) Efficiencies.

two extreme cases: both substrate increases or reduces height by 10%.

Due to the variations, the return loss and radiation characteristics are impacted. However, the frequency corresponding to the lowest return loss level remains steady. Therefore, only S_{11} is presented in Fig. 10.

The L5-band is less sensitive than the L1-band, as the S_{11} minimum remains in the band in both tolerance cases. Even when L1-band adaptation changes to lower frequencies, the adaptation remains acceptable, and the overall operation is not compromised.

Comparison with existing designs

To highlight the advantages of the proposed antenna in terms of size, cost, and real-world applicability, a comparative analysis with several referenced GNSS antenna designs is presented in Table 3. The comparison considers key metrics such as physical dimensions, supported bands, gain, polarization, substrate, and whether the design was simulated or fabricated.

As shown, while some designs offer higher gain or wider bandwidths, they often rely on more complex structures or costly substrates such as Rogers or Duroid.

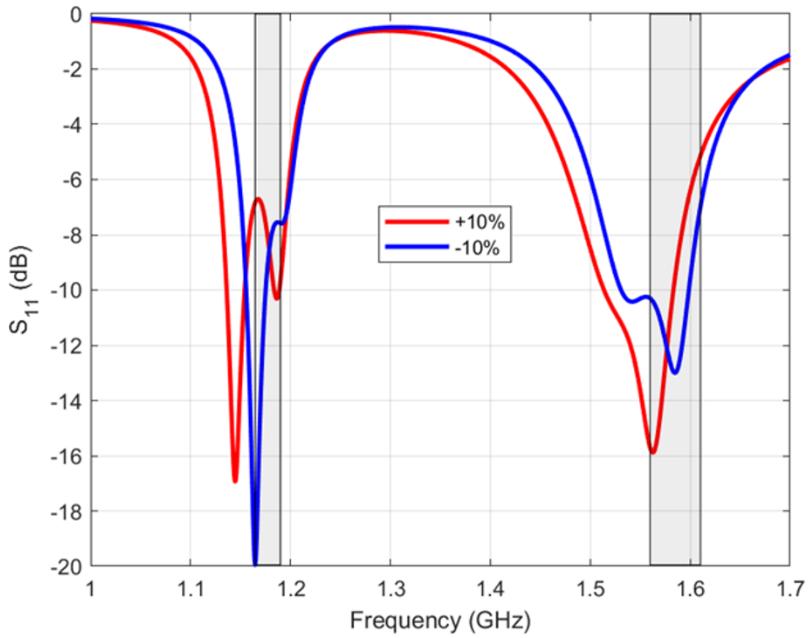

Figure 10. Evolution of return loss with substrate height tolerance.

Table 3. Comparison with existing GNSS antenna designs

Reference	Size	Bands	Gain (dBi)	CP	Substrate	Structure	Utilization
This Work	$80 \times 80 \times 3.2$ mm	L1/L5	2.59 / -0.89	RHCP	FR4	Stacked Patch	Real-world tested
Wang et al. (2009) [3]	$\sim 140 \times 140 \times 8.5$ mm	L1/L5	1.18 / 2.02	RHCP	F4B	Dual-Patch Stack	Fabricated
Anguera et al. (2003) [4]	$\sim 210 \times 180 \times 14$ mm	1.8-3.5GHz	8.7/8.9	RHCP	N/A	Multilayer Patch	Broad bandwidth
Maqsood et al. (2010) [5]	N/A	L1/L5	11	RHCP	Duroid RT 5880	Array (4 elements)	Requires beamforming
Wang and Zhang (2021) [6]	$80 \times 80 \times 4.6$ mm	L1/L5	2.84 / 1.23	RHCP	FR4 (dual height)	Stacked Patch	Simulated only
Awais et al. (2021) [7]	$100 \times 100 \times 3.2$ mm	L1/L5	2.5 / 4.4	RHCP	FR4	Stacked Patch, coplanar feed	Fabricated, low-cost
Sun et al. (2011) [8]	N/A	L1/L2	6 / 7	RHCP	FR4	Annular-ring Patch	Simulated only
Ding et al. (2014) [9]	N/A	L1/L5	5.2 / 3.5	RHCP	N/A	Aperture-Coupled Patch	Fabricated, dual-band

The proposed antenna (our work) demonstrates a unique combination of simplicity, cost-efficiency, and validated performance that differentiates it from existing designs. While many state-of-the-art GNSS antennas offer competitive performance in terms of gain or bandwidth, they often rely on complex geometries, costly high-frequency substrates such as Rogers or Duroid, or require advanced feeding networks and beamforming techniques.

In contrast, our antenna is fully passive, employs standard FR4 substrates, and maintains a compact form factor (80 mm $\times$ 80 mm $\times$ 3.2 mm) compatible with low-profile enclosures. Its dual-band behavior is achieved through a simple stacked patch configuration, eliminating the need for filters or external matching circuits. Most notably, this design has been tested and validated under real-world conditions winning, the JNM 2024 GNSS reception competition, confirming its readiness for practical deployment.

These characteristics make it particularly attractive for applications such as CubeSats, UAV-based navigation, and cost-constrained IoT GNSS receivers, where high performance, low cost, and ease of integration are equally critical. As the demand for scalable and autonomous navigation platforms grows, our antenna provides a balanced, manufacturable solution aligned with emerging "New Space" paradigms.

Conclusion

In this study, a compact, circularly polarized, bi-band antenna design is proposed, consisting of two stacked patch antennas with two FR4 substrates of the same height. The antenna has been meticulously designed to meet the established specifications for GNSS applications. The antenna's attributes, including its low profile,

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cost-effectiveness, straightforward design, robustness to manufacturing variations, and great performance, align seamlessly with new space technology trends and specifications.

A prototype was manufactured with a PCB laser engraver, and its performance was validated with a Quectel LC29HAAMD GNSS receiver and the QGNSS software during functional tests performed at the JNM'2024 antenna design contest.

Finally, the antenna won the competition (with approximately ten participating teams) tied with the team from the CROMA laboratory in Grenoble, detecting around 40 satellites in 60 seconds in real conditions in a suburban area.

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Conflict of interest. The authors declare they have no conflict of interest.

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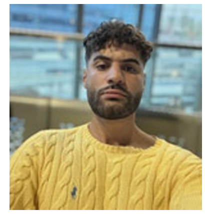

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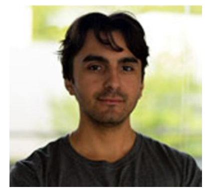

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Guillaume Ferre received the Ph.D. degree in the field of digital communications and signal processing from the Limoges University of Technology, in 2006. From 2006 to 2008, he was a Postdoctoral Researcher at the Limoges XLIM laboratory and then at the IMS laboratory in Bordeaux. Since 2022, he is a Full Professor at ENSEIRB-MATMECA, Engineering School of Bordeaux INP. After several administrative responsibilities in the Telecommunications Department of ENSEIRB-MATMECA, he is now the Director of Industrial Relations at ENSEIRB-MATMECA.He carries out his research activities within the IMS Laboratory in the "signal and image" team. These fields of research concern the circuits and systems for digital communications, whihc include:

- Signal processing and digital communications,
- Digital enhancement for wideband power amplifiers and time-interleaved analog-to-digital converters.

Guillaume Ferré is the author of more than 190 papers in international journals and conferences. He is also the author of 14 patents. He currently supervises 6 PhD students with a significant part of industrial research activities. He is a Member of several Technical Program Committees. He is the Principal Investigator (PI) of many national and international projects.

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