GPS Solutions (2025) 29:187
https://doi.org/10.1007/s10291-025-01944-3

RESEARCH

Space-efficient vertical choke rings for geodetic-grade multipath mitigation in GNSS antennas

Veenu Tripathi[1] · Wahid Elmarissi[1] · Stefano Caizzone[1,2]

Received: 30 August 2024 / Accepted: 30 July 2025

Abstract

We present a novel design for a miniaturized choke ring structure, optimized for operation in the L5/E5a and L1/E1 frequency bands (1.176 and 1.575 GHz). The choke rings are vertically stacked and enable to achieve geodetic-grade multipath suppression while minimizing the planar footprint of the antenna. The measured performance of an antenna on the proposed choke rings (20 cm diameter) in the anechoic chamber has shown improved cross-polarization discrimination with front-to-back ratio > 22 dB. The developed structure is also compared to a canonical (horizontally stacked) choke ring structure and can achieve comparable or even better performance while having a significantly smaller footprint. This is also confirmed through GNSS field test results, where the residual multipath is obtained for the standalone antenna, the antenna on canonical choke rings and the antenna on the proposed choke rings, with clear improvements in terms of multipath suppression obtained with our proposed structure.

Keywords Antennas · Electromagnetics · Propagation · Multipaths · Interference suppression · GNSS measurements

Introduction

Satellite navigation plays a crucial role in a wide range of applications across various fields. Autonomous driving, aviation, maritime navigation, banking, agriculture are just a handful of domains that have greatly profited from the widespread accessibility of GNSS (Kaplan and Hegarty 2017). In the quest for precise positioning, all residual error sources have to be characterized and possibly minimized, as explained by Teunissen et al. (2017). Augmentation systems as well as PPP/RTK systems can strongly improve performance by estimating system errors, such as the ones generated at satellite or atmospheric level. The errors related to receiver hardware and environment are however more difficult to estimate and compensate through external systems and pose therefore limitations on the finally achievable performance. Antennas, as entry point of the GNSS signals into the receiving system, impact the positioning performance both through intrinsic errors (Caizzone et al. 2021a, b) as well as through their multipath susceptibility.

As a matter of fact, the radiation characteristics of GNSS antennas are not perfect, leading to the generation of back lobe radiation. This implies that the antenna receives signals not just from the intended direction but also from various other directions, including from the surface of the platform on which it is mounted. When signals from the GNSS satellite bounce off the platform surface and reach the antenna, they create a phenomenon called multipath (Smyrnaios et al. 2013). Multipath occurs when the antenna receives both the direct signal from the satellite and the reflected signals, resulting in multiple signal paths as shown in Fig. 1. Upon reaching the receiver antenna (Dielectric Resonator Antenna (DRA)), the reflected signals interfere with the direct signal, causing phase shifts and signal distortions and are one of the major remaining error sources in the GNSS error budget.

In order to minimize multipath from negative elevations, multipath-suppressing antennas with low backlobes are commonly utilized. The state-of-the-art technology for

✉ Veenu Tripathi
Veenu.Tripathi@dlr.de

Stefano Caizzone
Stefano.Caizzone@dlr.de

1 German Aerospace Center (DLR), Institute of Communications and Navigation, Oberpfaffenhofen, 82234 Wessling, Germany

2 Department of Electrical Engineering, School of Computation, Information and Technology, Chair of High-Frequency Engineering, Technical University of Munich, Munich, Germany

Published online: 14 August 2025

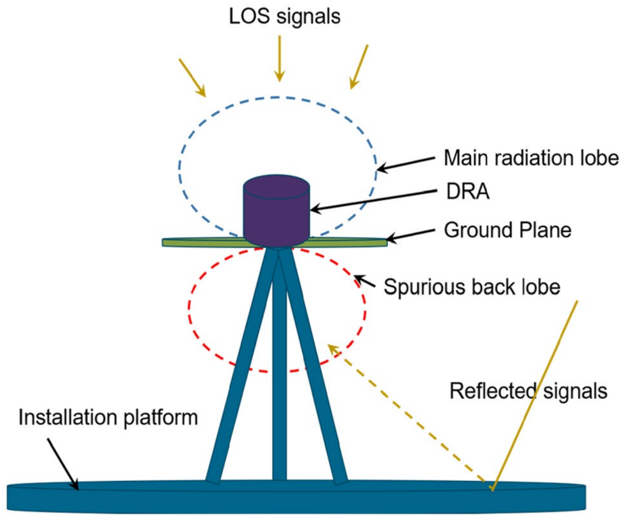


Fig. 1 Schematics for multipath generation due to installation platform

multipath mitigation is the choke ring antenna explained by Tranquilla et al. (1994). However, both the conventional Jet Propulsion Laboratory choke ring (Zhang and Schwieger 2017), which has multiple concentric metal rings stacked horizontally, and the '3D' choke ring (Bedford et al. 2009), which has concentric rings arranged in a conical shape, suffer from large volumes and weights. In an effort to minimize antenna size, substrate integrated choke rings has been proposed by Taghdisi et al. (2022) using commercially available FR4 laminates, which are glass-reinforced epoxy laminate material. Also, vertical choke ring consisting vertical cavities has been proposed by Lee et al. (2005), albeit sacrificing multipath rejection capability.

This paper tackles this concern by introducing a solution and detailing the design of multi-band miniaturized vertical choke rings aimed at mitigating multipath effects originating from the ground or mounting mast. Earlier research on this topic was outlined by Varma and Caizzone (2020), which proposed the use of metallic discs to establish multiple thin cavities for each frequency band. We have taken the original concept and fine-tuned the cavities to deliver good performance across both L1 and L5 frequency bands. Measured results of the GNSS antenna will be shown as well as a comparison between the cases without, with conventional and with vertical choke rings. Moreover, GNSS field tests clearly illustrate that the proposed choke rings achieve geodetic-grade multipath suppression.

The paper consists of six sections. The introduction is provided in Sect. "Introduction". Sect. "Proposed dual-band vertical choke rings design" provides the details about proposed vertical choke ring design. Comparative analysis of conventional horizontal choke rings is discussed in Sect. "Analysis with horizontally stacked choke rings". Sect. "Multipath suppression indicator (MPSI)" covers computation of multipath suppression indicator to quantitatively analyse the backlobe suppression by proposed antenna. GNSS field measurement results are discussed in Sect. "GNSS measurements" and finally, conclusions are drawn in Sect. 6.

Proposed dual-band vertical choke rings design

First, we discuss a new design of miniaturised choke rings. It incorporates a series of vertical choke rings that serve as cavities beneath the GNSS antenna. As an example, we have used a circularly polarized wide band dielectric resonator antenna (DRA), shown by Caizzone et al. (2018a, b), which is specifically engineered to receive signals across the entire GNSS frequency band and boasts a 10 cm diameter. Although the antenna performed very well in terms of cross-polarisation and pattern uniformity, it did not include any countermeasure against reflections from negative elevations. For this purpose, a choke ring design was added, which greatly reduces the gain of the antenna in the lower hemisphere which would lead to multipath mitigation from lower or negative elevation. These choke rings consist of metallic discs oriented parallel to the ground plane, as illustrated in Fig. 2, with a total height of approximately 7 cm and have a diameter of approximately 20 cm. These cylindrical rings serve as vertical cavities facilitating electromagnetic field cancellation through resonance, thereby generating standing waves. The underlying theory of this principle is elaborated well by Ida (1992).

Fundamentals and theory

The analogy between this transmission line model and the cylindrical cavity is studied in MIT Opensource. Ida (1992) also explained the transmission line model treatment of a metallic cavity. The quarter wave line exhibits both positive and negative-going waves. When the positive wave reflects off the short-circuit termination, it becomes a negative-going wave with a 180-degree phase shift. The voltages of the waves subtract at the termination and add at the input. The summation of the voltage waves creates standing wave pattern,

$$V(z,t) = V_0 \sin\left(-\frac{\pi z}{2l}\right)\exp(j\omega t), \tag{1}$$

where l denotes the transmission line length. Therefore, cavities with conductor lengths equal to quarter wavelengths would result in the voltages (or the electromagnetic currents) balancing themselves out and causing standing waves, hence blocking propagation of the (unwanted) waves.

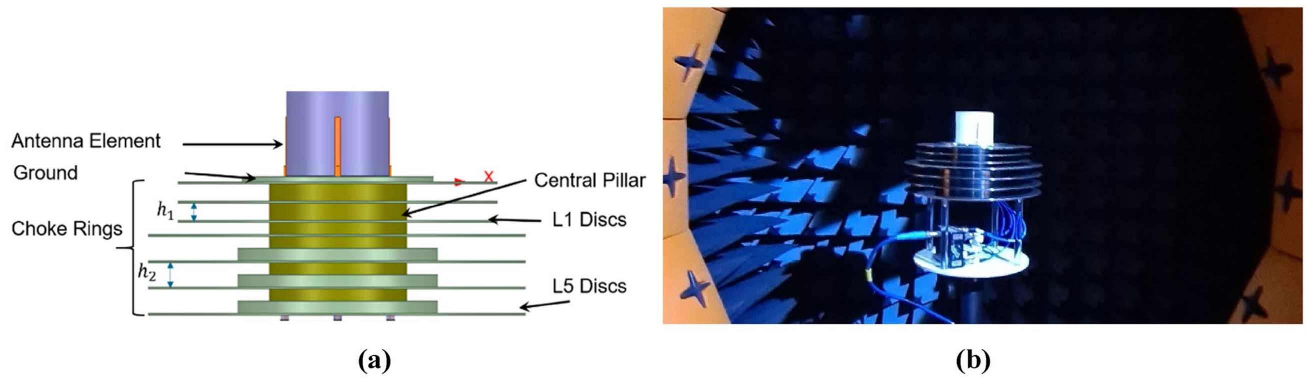


Fig. 2 DRA with proposed vertical choke rings. **a** Simulated model. **b** Measured antenna in Starlab

Design and analysis

The above-mentioned technique is used in designing the choke rings and are positioned beneath the ground plane. They are configured in two sets with distinct diameters, one set for the L5 band and another for the L1 band. Each pair of rings, or discs, forms a parallel cavity that is approximately one-quarter wavelength in length (around 43 mm for L1 and 63.5 mm for L5) from the central metallic pillar. The upper cavities are optimized for L1 band and lower ones for L5. The specific heights (h_1, h_2) between them have been optimized to minimize backlobe radiation. The lower L5 cavities are also interspersed with L1 cavities as shown in Fig. 2.

Backlobe radiation arises from spurious fields from the antenna, arising from surface waves propagating over the ground plane and eventually radiating at the ground edges. The designed structure aims at stopping the propagation of such unwanted field components. As a matter of fact, these spurious fields are compelled to traverse the quarter-wavelength discs in opposite directions after being reflected by the metallic pillar. As explained earlier and by Varma and Caizzone (2020), the electromagnetic currents flowing on the inner surface of these discs exhibit a counterbalancing effect, effectively mitigating their impact.

The vertical choke rings proposed are initially simulated and subsequently measured once mounted with the reference antenna element, as illustrated in Fig. 2. The simulations are performed using commercial software, i.e. Ansys HFSS (3D High Frequency Simulation Software). The simulated S parameter of the antenna with proposed choke rings are given in Fig. 3, which shows that it has good S11 (<-10 dB) over entire GNSS band. Measurements are carried out in the MVG Starlab measurement facility located at German Aerospace Center (DLR). Figures 4 and 5 present skyplot of the measured realized gain (RHCP and LHCP, both) outcomes for the L1 and L5 bands, respectively. The results are plotted in spherical coordinate system according to physics convention having zenith at $\theta = 0°$. The realized gain

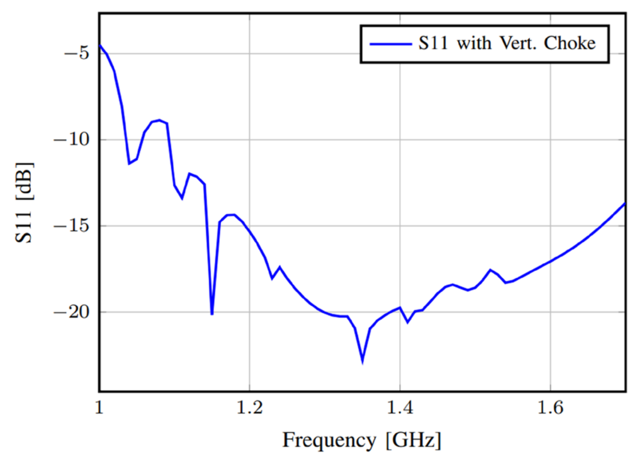


Fig. 3 S11 of DRA with proposed choke rings

results for $\phi = 0°$ cut are then compared with those of the standalone antenna ("without choke rings"), in Figs. 6 and 7. The difference in the simulation and measurements could come from the losses due to the discrete components used for feeding the antenna while measurement. Table 1 gives us the details about the performance of the antenna with and without vertical choke rings in terms of several parameters, i.e. realized gain, axial ratio and front-to-back ratio (FBR). The performance has been significantly increased after addition of proposed choke rings. Figure 8 also shows the comparison of FBR at zenith over the entire GNSS band.

Analysis with horizontally stacked choke rings

Leading GNSS choke ring antenna manufacturers like Ashtech, Leica, NovAtel, Topcon, and JAVAD typically position the choke ring around the radiating element. To compare the obtained performance with the one from commercial conventional choke rings, we have designed and

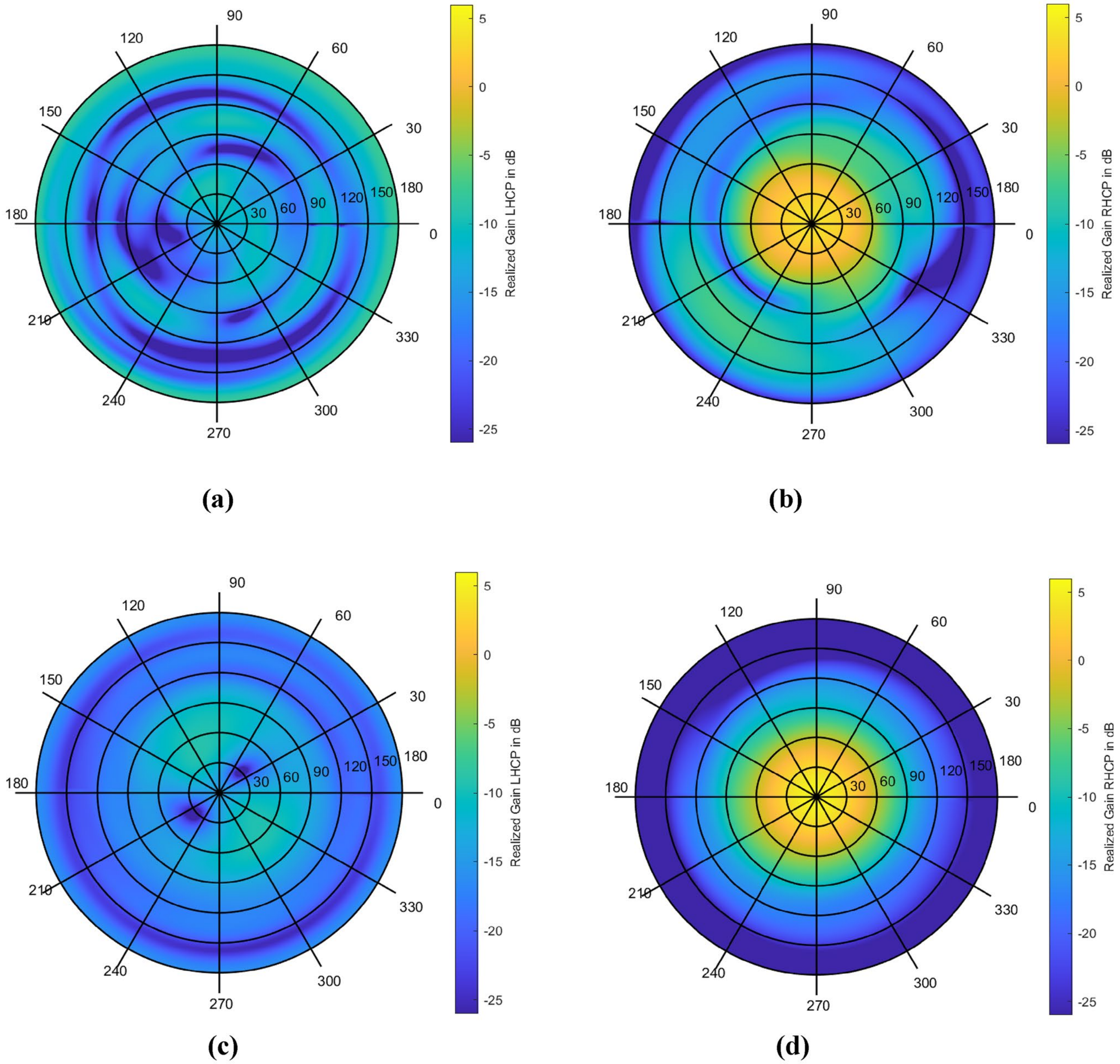


Fig. 4 Radiation pattern of DRA with/without proposed vertical choke rings at L1 central frequency. **a** LHCP Pattern (without). **b** RHCP Pattern (without). **c** LHCP Pattern (with). **d** RHCP Pattern (with)

manufactured comparable horizontally stacked choke rings (Caizzone et al. 2021b), as shown in Fig. 9.

The same antenna element, as mentioned in previous section, has been tested in both simulations and measurements with in-house developed horizontal choke rings. The size of the choke rings, i.e. 36 cm in diameter and 7.5 cm in height, is comparatively bigger and in par to the commercial standards. The obtained results from simulations and measurements at both L1 and L5 band center frequency are shown in Figs. 10 and 11, respectively. The results are also compared with measured results of the antenna without choke rings and we could see strong suppression in the backlobes of the antenna after adding big horizontal choke rings structure. The figures illustrate that the backlobe suppression achieved by the vertical choke rings although being strongly smaller and lighter, is comparable with the one of conventional (horizontal) choke ring structures, as depicted in Table 2.

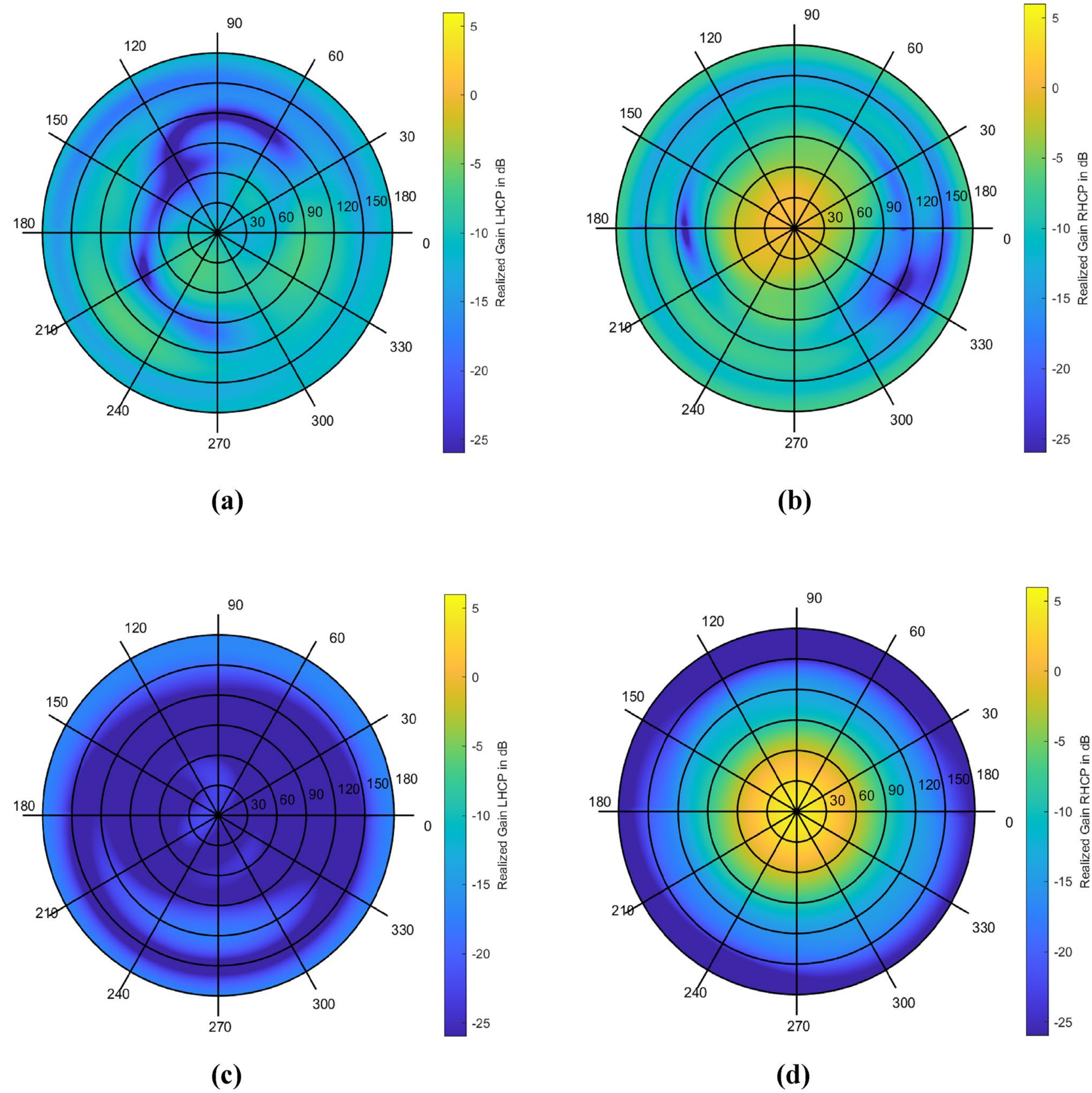


Fig. 5 Radiation pattern of DRA with/without proposed vertical choke rings at L5 central frequency. **a** LHCP Pattern (without). **b** RHCP Pattern (without). **c** LHCP Pattern (with). **d** RHCP Pattern (with)

Multipath suppression indicator (MPSI)

As examined by Caizzone et al. (2018b), the antenna's capacity to reject multipath signals stands out as a crucial factor indicating the overall performance of the system in the presence of various and distinct reflective sources. Various multipath suppression indicators have been established to enable the assessment of the antenna's standalone vulnerability to multipath in diverse reflection scenarios. Specifically, the indicator that prove valuable in this context is for reflections originating from lower elevations, such as terrain (referred to as $MPSI_{\{down\}}$). The indicator for specular multipath (i.e. smooth and flat reflectors, such as in tripod scenarios) is defined as.

$$MPSI_{\{down,spec\}} = \begin{cases} \log_{20}\left(-DUR_{\{tot,dB\}}\right) & ifDUR_{\{tot,db\}} < 0 \\ = 0 & ifDUR_{\{tot,db\}} > 0. \end{cases} \quad (2)$$

The Down-to-Up Ratio (DUR) is defined as

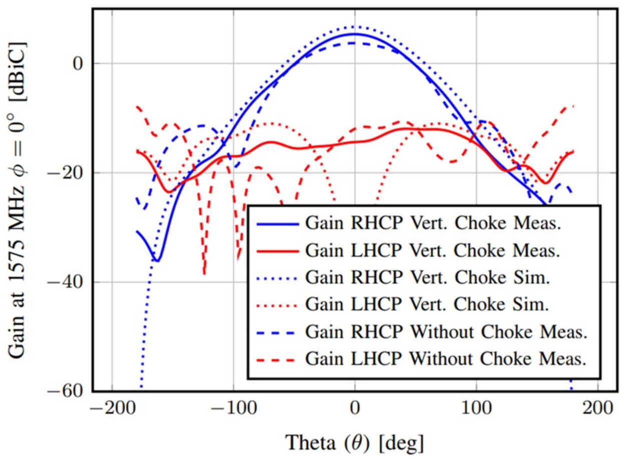


Fig. 6 Radiation pattern of DRA with or without proposed choke rings at L1 central frequency

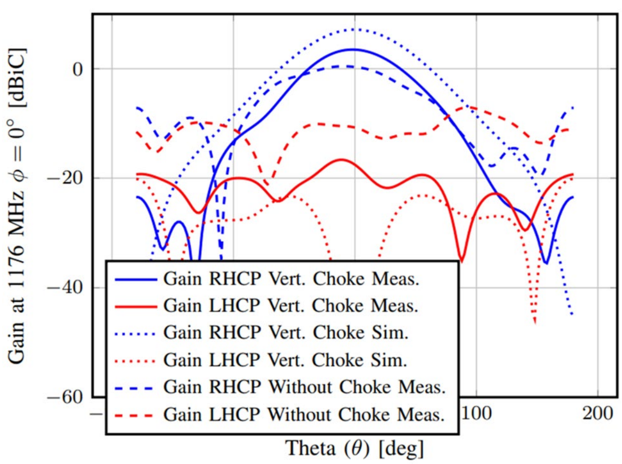


Fig. 7 Radiation pattern of DRA with or without proposed choke rings at L5 central frequency

Table 1 Antenna performance

Parameters	L1 Band		L5 Band	
	Without choke Rings	With choke rings	Without choke rings	With choke rings
Realized Gain (dB) @$\theta = 0°$	3.7	5.4	0.3	5
Axial Ratio (dB) @$\theta = 0°$	2.9	1.8	5	0.7
Axial Ratio (dB) @$\theta = 90°$	6.2	7.3	13.5	1.5
FBR (dB) @$\theta = 0°$	11.5	22	11.8	22.5

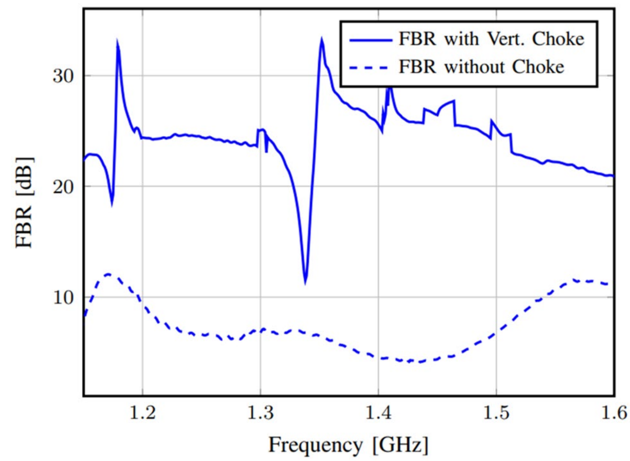


Fig. 8 Front-to-back Ratio of DRA with or without choke rings

$$DUR_{\{tot\}} = \frac{\left\{ \max\left(Gain_{\{TOT\}(\theta_M = -\theta_s, \phi_s)} \right) \right\}}{\left\{ Gain_{\{RHCP\}(\theta_s, \phi_s)} \right\}} \tag{3}$$

and considers the worst case of strongest multipath coming in any polarization from the specular direction of the line of sight (LOS) signal. Here, θ_s, ϕ_s are the elevation and azimuth of the incoming signal and θ_M, ϕ_M are the elevation and azimuth of the multipath. These indicators will then used in our analysis to evaluate the multipath suppression capability of the designed structures. Please note that a MPSI indicator close to 1 is related to a very good multipath suppression capability of the antenna, while a MPSI close to 0 expresses poor multipath suppression capability.

MPSI values are calculated for the antenna with and without choke rings and are depicted in the Figs. 12 and 13. The figures clearly show how the addition of the proposed choke rings improves the MPSI values for both L1 and L5 bands.

GNSS measurements

Additional validation of the antenna was conducted through GNSS field measurements, extending the assessment beyond the controlled environments of numerical simulations (such as Ansys HFSS) and antenna anechoic chambers (like MVG's Starlab). The developed antenna was tested in a real-life scenario, by placing it on a tripod at DLR campus with reflecting objects, like buildings, visible only for low elevations (apart from one reflection

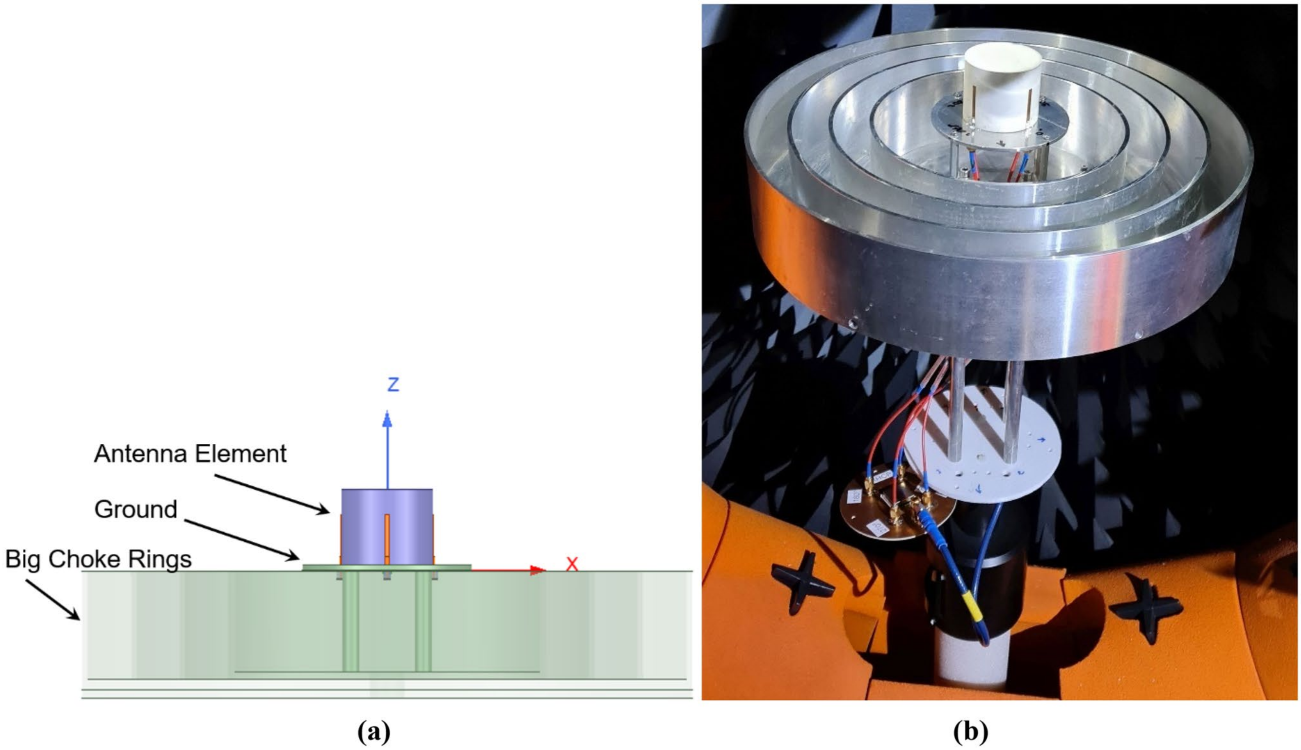


Fig. 9 DRA with horizontally stacked choke rings. **a** Simulated model. **b** Measured antenna in Starlab

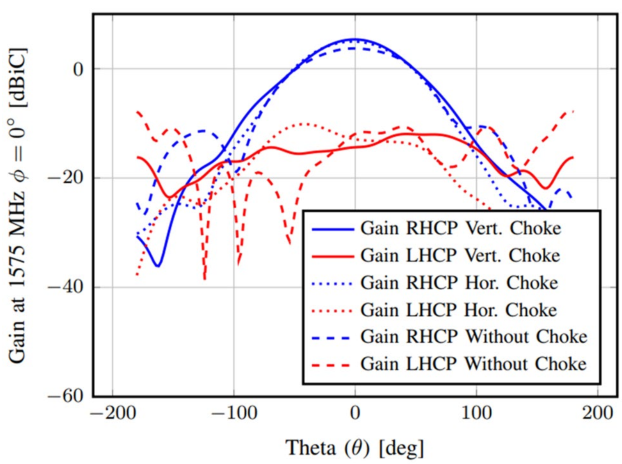


Fig. 10 Measured radiation pattern of DRA with or without choke rings at L1 central frequency

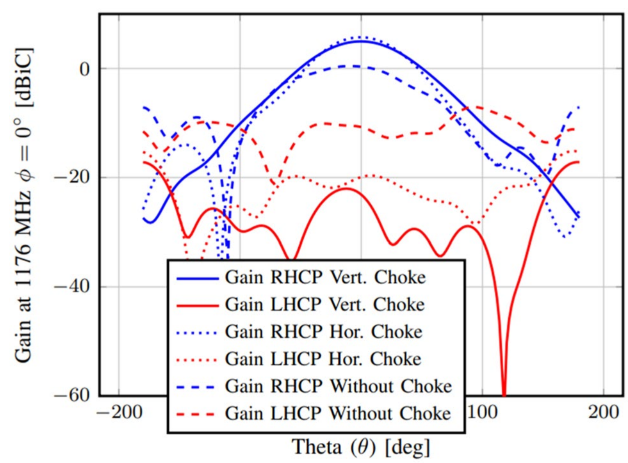


Fig. 11 Measured radiation pattern of DRA with or without choke rings at L5 central frequency

around 60° elevation due to the airport fence which is about 50 m from the ground) and hence having mostly specular reflection from terrain around the antenna. The measurement study spanned three days for all cases, i.e. the standalone antenna, the antenna fitted with horizontal choke rings and the antenna fitted with proposed choke rings, positioned at an installation height of 120 cm, as shown in Fig. 14. The antenna was connected to a Javad

Table 2 Size comparison between antenna with and without choke rings structures

Parameter	Antenna alone	With horizontally stacked choke rings	With proposed choke rings
Weight: (kg)	0.42	5.3	2.7
Diameter: (cm)	10	36	20

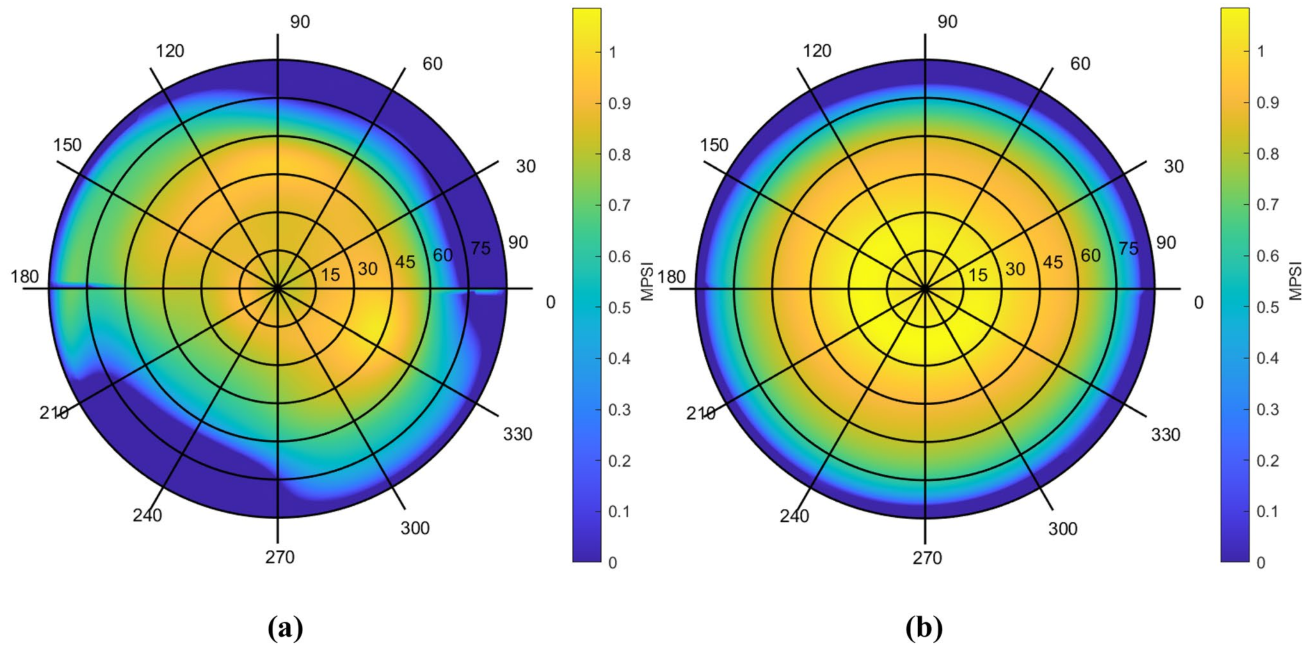


Fig. 12 $\theta = 0°$ at 1575 MHz. **a** Without choke rings. **b** With proposed choke rings

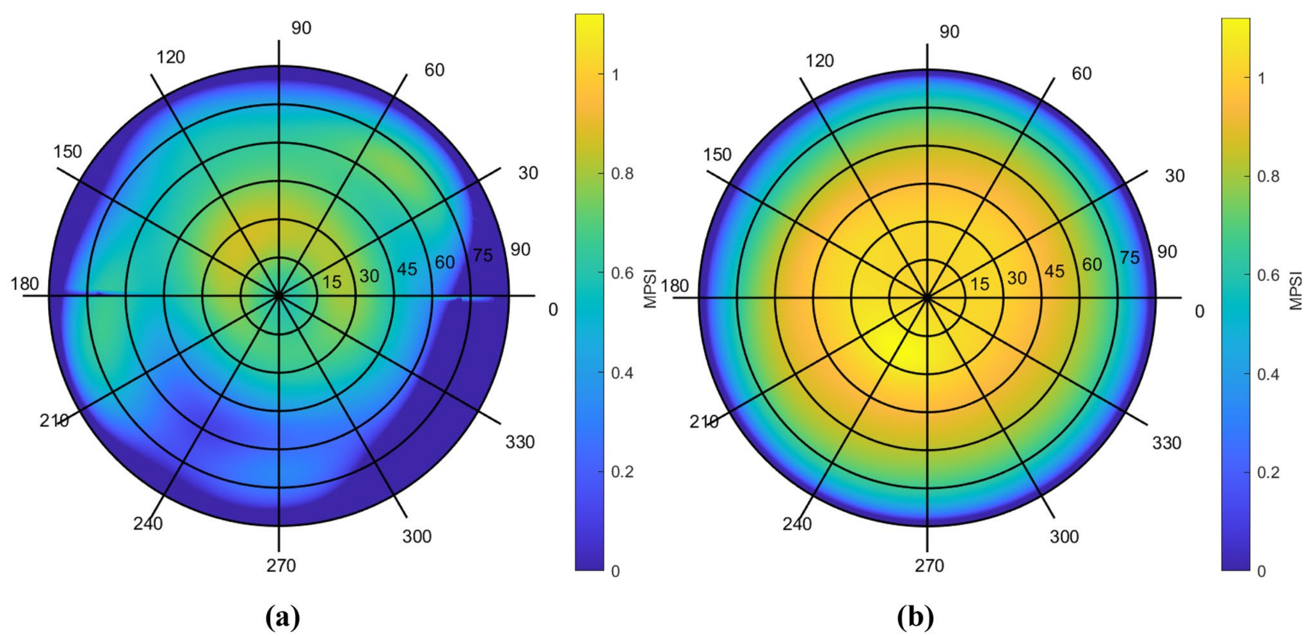


Fig. 13 $\theta = 0°$ at 1176 MHz. **a** Without choke rings. **b** With proposed choke rings

Delta receiver and GNSS measurements for all configurations were taken with the antenna in the same position and height above the ground in an open field, specifically during rain-free and partly cloudy 3-day periods.

The pseudorange multipath errors were then estimated using the code-minus-carrier (CMC) technique explained by Circiu et al. (2020), with a smoothing time of 100 s. The smoothed multipath errors for L1/E1 and L5/E5a for antenna alone, antenna with conventional horizontally stacked choke rings and antenna with proposed vertical choke rings are shown in Figs. 15, 16 and 17, respectively. It is important to emphasize that GNSS measurement outcomes are displayed with an inverted elevation axis, following the standard practice in the GNSS community. This means that the zenith

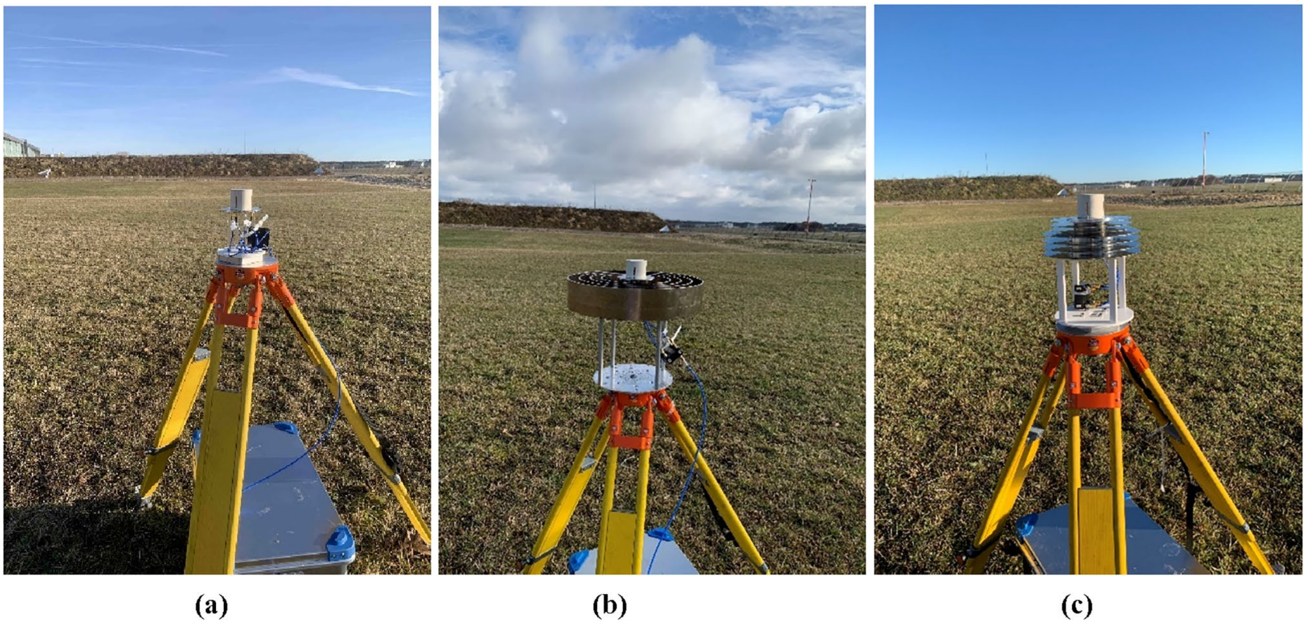


Fig. 14 GNSS field measurements of the antenna. **a** Without choke rings. **b** With big choke rings. **c** With proposed choke rings

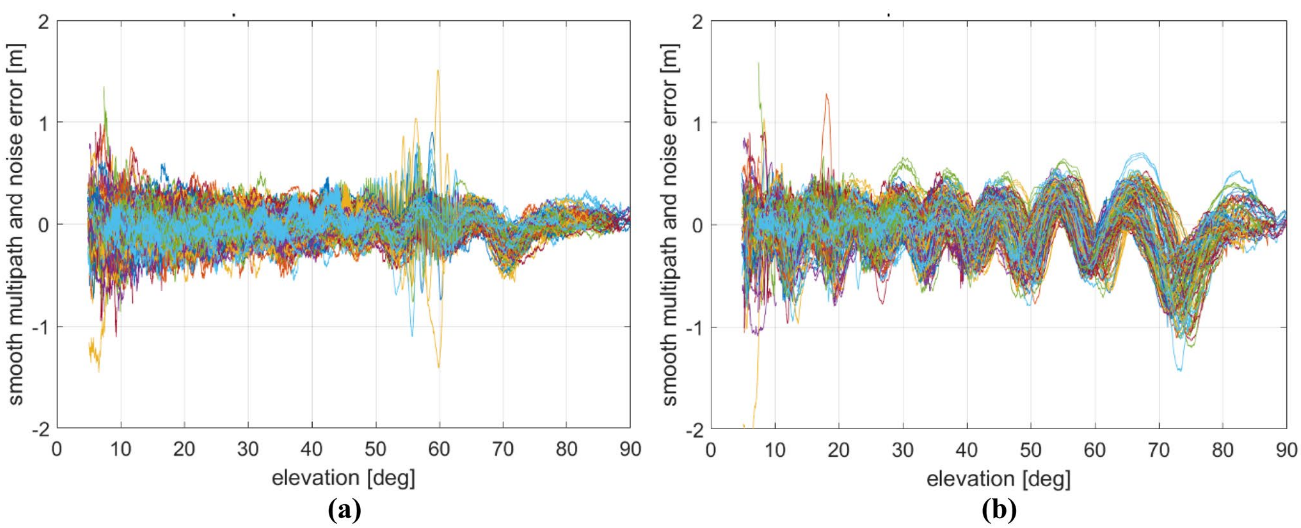


Fig. 15 Smoothed multipath estimate from GNSS data collected with the antenna without choke rings. **a** At L1/E1 band. **b** At L5/E5a band

of the antenna pattern, denoted as $\theta = 0°$, corresponds to an elevation of 90° in the GNSS measurements. Multipath errors typically peak near the horizon (0° elevation) and minimize towards the zenith (90° elevation). The figures clearly demonstrate that the proposed choke rings more effectively suppress multipath signals in both the L1 and L5 bands. In other words, the multipath error obtained with the proposed choke rings is reduced compared to antennas without choke rings or with horizontal choke rings.

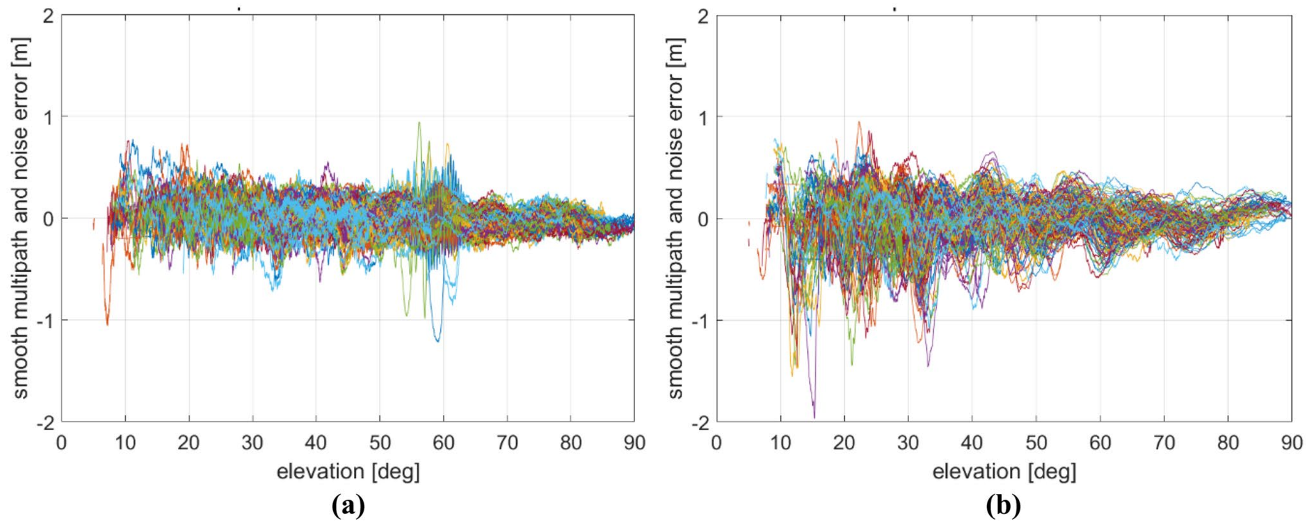


Fig. 16 Smoothed multipath estimate from GNSS data collected with the antenna with horizontally stacked choke rings. **a** At L1/E1 band. **b** At L5/E5a band

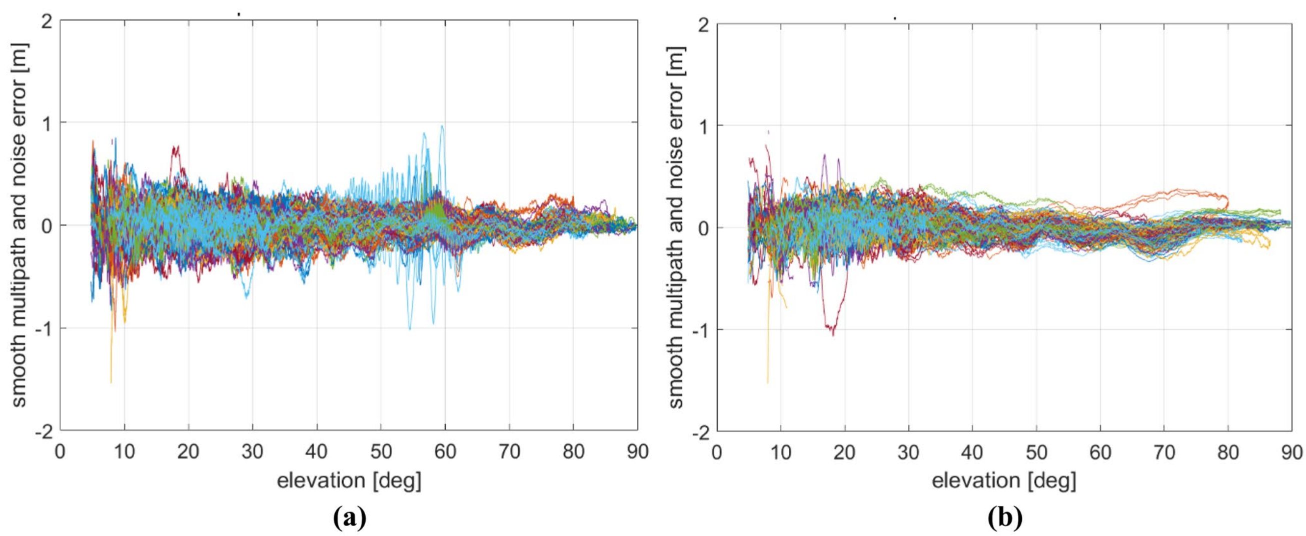


Fig. 17 Smoothed multipath estimate from GNSS data collected with the antenna with proposed choke rings. **a** At L1/E1 band. **b** At L5/E5a band

The standard deviation of the smoothed code-minus-carrier data (σ) containing multipath and noise combined is shown in Figs. 18 and 19 for GPS and Galileo constellation, respectively. A clear improvement of the multipath error (i.e. smaller multipath level) is visible for the antenna once mounted on the proposed vertical choke rings, with less oscillations and peaks (see Figs. 15, 16 and 17) with respect to the standalone antenna and even to the one mounted on horizontal choke rings. Table 3 succinctly summarizes the improvements in multipath suppression achieved by each configuration for elevations above 20 degrees. The improvement offered by the proposed vertical choke rings relative to the horizontal choke rings can be quantified using the following formulation:

$$\text{Improvement} = \frac{\left(\max\left(\sigma_{\{GPS,Galileo:Hor\}}\right) - \max\left(\sigma_{\{GPS,Galileo:Ver\}}\right)\right)}{\max\left(\sigma_{\{GPS,Galileo:Hor\}}\right)} \forall \text{ Elevation} > 20 \text{ deg.} \tag{4}$$

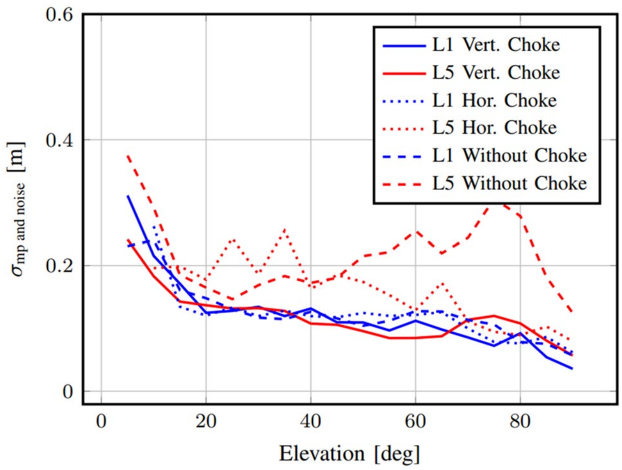


Fig. 18 Standard deviation of the smoothed multipath and noise combined for GPS Constellation

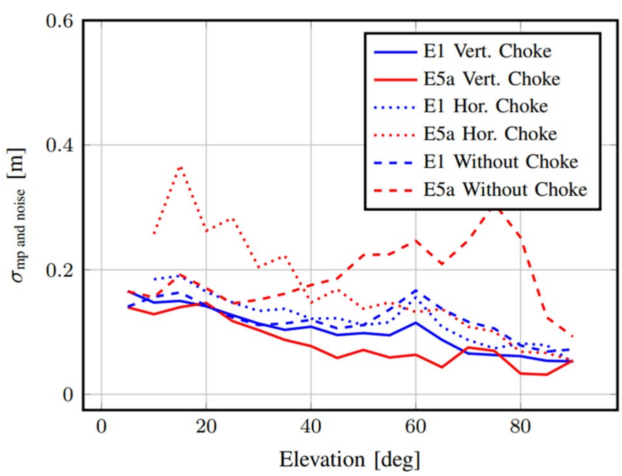


Fig. 19 Standard deviation of the smoothed multipath and noise combined for Galileo Constellation

Table 3 Multipath Suppression improvement between antenna with and without choke rings structures

Parameter	Proposed w.r.t. antenna alone (%)	Proposed w.r.t. horizontally stacked choke rings (%)	Horizontal w.r.t. antenna alone (%)
L1	20	14	6.6
L5	57	53	7.5

Conclusion

This paper has shown the design of multi-band miniaturized vertical choke rings, for use with high accuracy GNSS antennas. This technique provides high front-to-back ratio of around 22 dB and high MPSI values in the lower elevations which makes the antenna less exposed to ground reflections/multipaths. It allows minimizing the additional weight and size due to the choke ring structure, showing a reduction of 46% in weight and 44.5% in footprint with respect to a conventional horizontally-stacked choke ring. Real-time GNSS measurements also validate our approach by showing reduction in multipath errors at both L1 and L5 bands.

Author contributions Conceptualization, V.T. and S.C.; methodology, V.T. and S.C.; software, V.T.; hardware, W.E.; validation, V.T., W.E. and S.C. All authors have read and agreed to the published version of the manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL. No funds, grants, or other support was received.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors have no competing interests to declare that are relevant to the content of this article.

References

Bedford L., Brown N, Walford J (2009) New 3D four constellation high performance wideband choke ring antenna. In: Proceedings of the 2009 International technical meeting of the institute of navigation, Anaheim, CA, January 2009, pp. 829–835

Caizzone S, Schönfeldt M, Elmarissi W, Circiu M-S (2021a) Antennas as precise sensors for GNSS reference stations and high-performance PNT applications on Earth and in space. Sensors 21(12):4192. https://doi.org/10.3390/s21124192

Caizzone S, Circiu MS, Elmarissi W, Enneking C (2018) All-GNSSband DRA antenna for high-precision applications. In: 12th European conference on antennas and propagation (EuCAP 2018), pp. 1–4, London, UK, https://doi.org/10.1049/cp.2018.0902

Caizzone S, Circiu M-S, Elmarissi W, Enneking C, Felux M, Yinusa K (2018b) Multipath rejection capability analysis of GNSS antennas. In: Proc. of ION GNSS+ 2018 , Miami (USA), Sept., 33012/2018.16109

Caizzone S, Circiu M-S, Elmarissi W (2021b) GNSS Reconfigurable antenna design for multipath characterization. In: Proceedings of the 34th international technical meeting of the satellite division of the institute of navigation, ION GNSS+, Online, https://doi.org/10.33012/2021.18003

Circiu M, Caizzone S, Felux M, Enneking C, Rippl M, Meurer M (2020) Development of the dual-frequency dual-constellation airborne multipath models. Navigation. https://doi.org/10.1002/navi.344

Ida N (1992) Chapter: transmission lines, waveguides, and resonant cavities. In: Microwave NDT. Developments in electromagnetic theory and applications, vol 10. Springer, Dordrecht

Kaplan E, Hegarty C (2017) Understanding GPS/GNSS: principles & applications, 3rd ed., Artech

Lee Y, Ganguly S, Mittra R (2005) Multi-band L/sub 5/-capable GPS antenna with reduced backlobes. In: IEEE antennas and propagation society international symposium, pp. 438–441 Vol. 1A, Washington, DC, USA. MIT Opensource, https://web.mit.edu/22.09/ClassHandouts/Charged %20Particle %20Accel/CHAP12.PDF.

Smyrnaios M, Schön S, Liso M (2013) Multipath propagation, characterization and modeling in GNSS. InTech, https://doi.org/10.5772/54567

Taghdisi E, Ghaffarian MS, Mirzavand R (2022) Low-profile substrate integrated choke rings for GNSS multipath mitigation. IEEE Trans Antennas Propag 70(3):1706–1718. https://doi.org/10.1109/TAP.2021.3118809

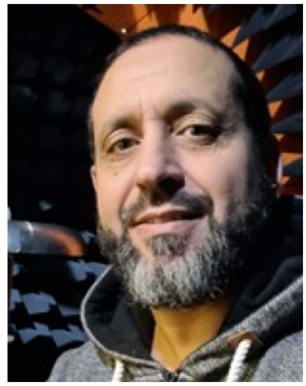
Teunissen PJG, Montenbruck O (2017) Handbook of global navigation satellite systems. Springer, Berlin/Heidelberg

Tranquilla JM, Carr JP, Al-Rizzo HM (1994) Analysis of a choke ring groundplane for multipath control in global positioning system (GPS) applications. In: IEEE transactions on antennas and propagation, 42(7) 905–911, https://doi.org/10.1109/8.299591

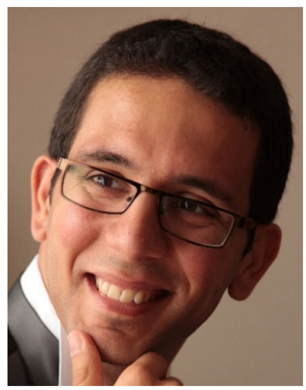
Varma S, Caizzone S (2020) Dual band GNSS antenna with high back lobe suppression. In: 2020 14th European conference on antennas and propagation (EuCAP), pp. 1–5, Copenhagen, Denmark, https://doi.org/10.23919/EuCAP48036.2020.9135668

Zhang L, Schwieger V (2018) Investigation of a L1-optimized choke ring ground plane for a low-cost GPS receiver-system. J Appl Geod 12(1):55–64. https://doi.org/10.1515/jag-2017-0026

Veenu Tripathi received B.Tech. in Electronics & Communication Engineering in 2012 from the Rajasthan Technical University, India, and M.Tech. in Electronics & Communication Engineering (specialization in RF and Microwaves) in 2014 from the Indian Institute of Technology Roorkee (IITR), India. In 2016, she started working as doctoral student with Antenna Group at the Institute of Communications and Navigation, German Aerospace Center (DLR), Oberpfaffenhofen and in 2020, obtained the PhD degree from Technical University of Munich, Germany. Since 2020 she has been working full time and her research interests include numerical techniques for microwave structures and conception and construction of new miniaturized antennas for satellite navigation, multipath suppression and installed performance evaluation.



Wahid Elmarissi received the B.Sc. in Physics from the University of Sciences “Mohammed V”, Rabat, Morocco, in 1992 and the Dipl. Ing. (FH) in electrical engineering from the University of Applied Sciences, Kiel, Germany, in 2003. In 2003, he joined the Institute of Communications and Navigation of the German Aerospace Center (DLR), where is responsible for measurement and manufacturing of antennas and antenna electronics.



Stefano Caizzone received the M.Sc. in Telecommunications Engineering and the Ph.D. degree in Geoinformation from the University of Rome “Tor Vergata”, Italy, in 2009 and 2015, respectively. Since 2010, he is with the Antenna group of the German Aerospace Center (DLR), where he has been responsible for the development of innovative miniaturized antennas. Since July 2020, he leads the Antenna Systems Group. His main research interests concern small antennas for satellite navigation, controlled radiation pattern antennas for robust satellite navigation and high-performance antenna design for precise satellite navigation, antenna arrays for satellite communication and installed performance analysis.