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16. Abstract

A new Ku-band antenna system has been developed to support passive positioning and navigation (PPN) using Ku-band signals of opportunity (SoOP) transmitted by low Earth orbit (LEO) satellites. The compact seven-element antenna is low-cost and easy to fabricate. Its radiation pattern is optimized to provide stable signal-to-noise ratio (SNR) across most of the sky above 25° elevation, enabling longer and more consistent PPN operation without requiring active beam-steering to track rapidly moving LEO satellites. The pattern also suppresses low-elevation reception to reduce interference from terrestrial sources. The design can be readily scaled for use with different LEO constellations and frequency bands. This report describes the design methodology, operating principles, fabrication process, and measurement validation of the antenna system.

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Final Report: Ku-Band Array Antenna for Using LEO Satellite Signals in PNT

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Abstract

A new Ku-band antenna system has been developed to support passive positioning and navigation (PPN) using Ku-band signals of opportunity (SoOP) transmitted by low Earth orbit (LEO) satellites. The compact seven-element antenna is low-cost and easy to fabricate. Its radiation pattern is optimized to provide stable signal-to-noise ratio (SNR) across most of the sky above 25° elevation, enabling longer and more consistent PPN operation without requiring active beam-steering to track rapidly moving LEO satellites. The pattern also suppresses low-elevation reception to reduce interference from terrestrial sources. The design can be readily scaled for use with different LEO constellations and frequency bands. This report describes the design methodology, operating principles, fabrication process, and measurement validation of the antenna system.

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This work was financially supported in part by the U.S. Department of Transportation under Grant 69A3552348327 for the CARMEN+ University Transportation Center.

Executive Summary

This semi-annual report documents the progress of the Ku-Band Array Antenna for Using LEO Satellite Signals in PNT project, led by Dr. Chi-Chih Chen, Research Associate Professor in the Department of Electrical and Computer Engineering at The Ohio State University. The project operates under Grant No. 69A3552348327 and is funded through the CARMEN+ University Transportation Center. The performance period spans August 1, 2024 to December 31, 2025.

A novel cost-effective Ku-band antenna system was developed to enable passive positioning and navigation (PPN) using signals of opportunity (SoOP) transmitted by low Earth orbit (LEO) communication satellites. The rapid growth of Ku-band LEO constellations such as Starlink and OneWeb underscores the importance of compact, power-efficient ground antennas capable of maintaining stable signal-to-noise ratio (SNR) without active electronic beam steering. The proposed design directly addresses this need through an innovative combination of antenna geometry, pattern shaping, and manufacturing simplicity.

Traditional high-gain phased arrays can track fast-moving LEO satellites but are bulky, expensive, and power-hungry, often requiring thousands of active elements and tens of watts of continuous power. In contrast, the presented system introduces a 7-element circularly-polarized helical antenna array—six tilted side elements surrounding a broad-beam top element—mounted on a corrugated ground plate and a raised central tower. This arrangement produces a carefully engineered elevation-dependent gain profile, providing high gain at mid-sky angles where LEO satellites spend most of their time, while intentionally suppressing gain near the horizon to reject terrestrial interference. The array covers the 10.7–12.7 GHz Ku-band downlink and maintains stable SNR for elevation angles above 30°, enabling robust PPN operation without dynamic steering.

The antenna's geometry—including 7 tapered helix elements mounted above an optimized corrugated ground plate—was developed to compensate for the variations in satellite-to-user distance such that stable SNR can be achieved regardless of the position of LEO satellites. Simulations show that this approach produces the desired gain slope in the elevation pattern, with side elements peaking near 60° and the top element covering the zenith region. Fabricated prototypes were tested in The Ohio State University ElectroScience Laboratory Compact Range. While the measured gain patterns demonstrate the intended wideband, hemispherical coverage, the results revealed some gain reductions relative to simulations. Further investigation identified the cause as the dielectric loss of an epoxy material applied at the base of the helical wires for mechanical reinforcement. Updated simulations incorporating the epoxy's measured dielectric properties confirmed this explanation and aligned well with the observed performance.

Overall, this work validates a compact, low-SWaP, mechanically simple antenna solution tailored for LEO-based PPN applications. The design successfully shapes the elevation gain pattern to mitigate LEO propagation loss variation and demonstrates reliable Ku-band performance. Although prototype measurements were impacted by lossy epoxy, the underlying design principles remain sound and scalable to other frequency bands and LEO constellations. This approach offers a practical pathway toward enabling ubiquitous PPN capability without reliance on GNSS or complex phased array technology.

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Abstract

A novel Ku-band antenna system has been developed to support passive positioning and navigation (PPN) using Ku-band signals of opportunity (SoOP) transmitted by low Earth orbit (LEO) satellites. This compact, low-cost, seven-element antenna is straightforward to fabricate and features an optimized gain pattern designed to maintain a stable signal-to-noise ratio (SNR) across most of the sky above 25° elevation. This enables longer and more reliable PPN operation without the need for active beam-steering to track fast-moving LEO satellites. The antenna pattern also suppresses low-elevation reception to minimize interference from terrestrial emitters. In addition, the design can be easily scaled for compatibility with different LEO constellations and frequency bands. This report describes the antenna design methodology, operating principles, fabrication process, and measurement validation.

Introduction

There has been an increasing interest in positioning and navigation using SoOP transmitted from LEO satellites, as an alternative to GPS and GNSS signals [1]-[4]. Ku-band (10.7-12.7 GHz) is commonly used for downlink signals by many LEO satellites like Starlink [5] and Oneweb [6]. This is mainly because of the FCC spectrum allocation under 47 CFR Part 25 [7] which specifies 11.7-12.2 GHz range for space-to-Earth transmissions, as well as 12.2-12.7 for Direct Broadcast Satellite (DBS) service. The received LEO satellite's signal strength on earth surface is much stronger than GPS/GNSS signals due to higher transmitting powers and shorter distances to earth. However, LEO communication satellites have much faster angular velocities and wider satellite-to-user distance variations with time. This results in rapid signal strength variations [8] if high-gain antenna is used without beam steering and simultaneous tracking of multiple satellites to derive the position and time. On the other hand, although using lower gain antennas can have broader sky coverage all the time, this leads to lower SNR which produces greater positioning errors.

The current phase array technology can achieve high gain with multiple beam steering capability [9]-[12]. However, this approach is bulky, costly, and often consumes a lot of power. For example, a commercial phase array with 30 dB gain (state-of-the-art LEO satellite antennas) could have as many as 1,000 active elements and could consume more than 75 watts constantly. For multiple beam steering, one must digitize the signal received by various antenna elements and control the magnitude and phase of individual digitized signals to generate multiple scannable beams, leading complex receiver electronics. Therefore, a more economic compact LEO receiving antenna for general positioning and navigation is needed.

To achieve constant SNR of LEO satellites from $\theta=0^o$ at zenith to a desired minimum satellite angle of say $q=70^o$, the ideal antenna needs to have an elevation pattern whose gain increases as the satellite angle decreases to compensate for the higher propagation loss associated with the longer satellite distance. For instance, the antenna gain should be 7.43 dB higher at 20^o of elevation compared to its gain at zenith for a satellite in the 550 km orbit, as illustrated in Figure 1. In addition, the antenna gain should be as low as possible near horizon for rejecting land-based interferences. The antenna gain also needs to be sufficiently high for receiving LEO satellite signals. Kozhaya et al. demonstrated successful reception of the Starlink satellites' OFDM beacons (10.7-12.7 GHz) using a 14.8 dB horn antenna and a LNB with 50 dB conversion gain.

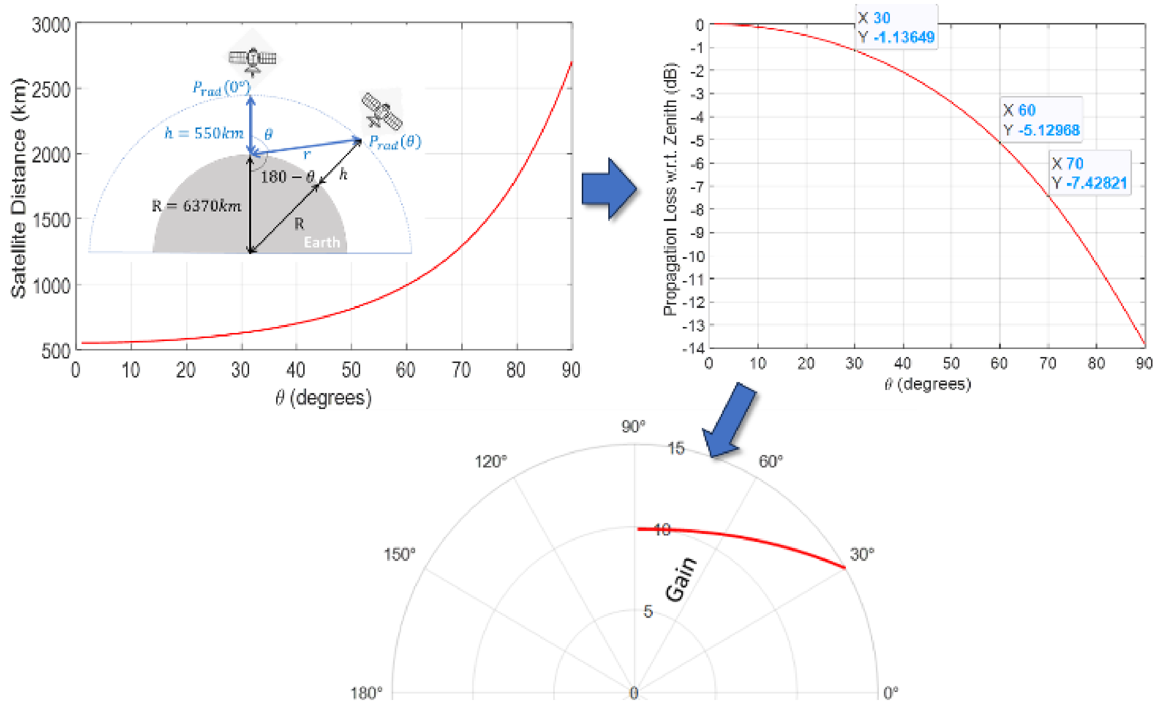


Figure 1: Predicted propagation loss (top right) and ideal elevation gain pattern (bottom) to achieve constant received power from a isotropic radiation source in 550 km orbit at different elevation angles.

The antenna design objectives of the proposed Ku-band LEO receiving antenna include (1) inexpensive and low size weight and power (SWaP), (2) circular-polarization property (3) optimized gain patterns for providing constant SNR of the received LEO satellite signals across the sky, complete sky coverage, and high rejection to ground interferences. Commercial off-the-shelf (COTS) antennas suffer from poor SNR in most of the sky region due to the satellites' spotlight transmitting patterns and the large distance variations of LEO satellites, resulting in frequent signal loss and higher vulnerability against interferences.

Design Descriptions

Figure 2 shows the overall geometry of the proposed 7 elements helical antenna system [13][14] mounted on a raised tower above a corrugated ground plate for receiving LEO signals from 1.7 GHz to 12.7 GHz with stable SNR above 30^o elevation angle. The overall height and diameter of this antenna system are 83mm and 272mm, respectively. The six side elements jointly provide 360o of azimuthal coverage. The base of each side helical antenna is positioned 22.5mm above the ground and tilted 40^o above horizon to provide a shaped elevation pattern coverage from θ=30^o to θ=70^o from 10.7 GHz to 12.7 GHz.

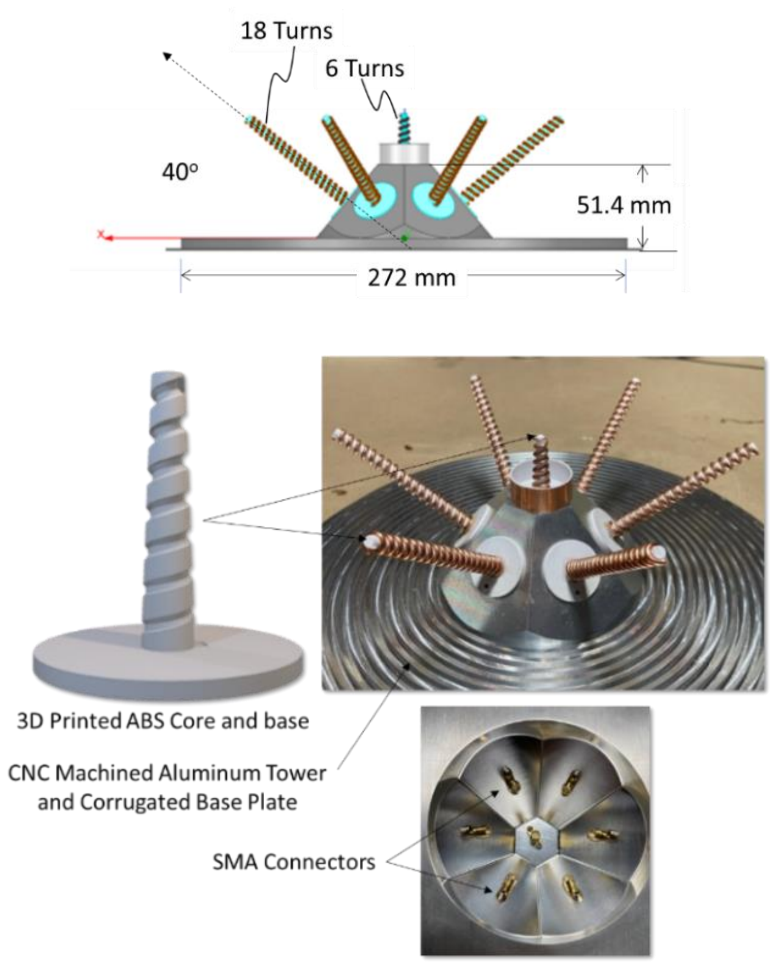


Figure 2: Fabricated prototype of the novel 7-helix antenna system for receiving LEO satellite signals in Ku band.

The geometry of the corrugated rings was optimized to produce minimum gain at horizon in the forward direction around 11.7 GHz, as depicted in the upper right corner of Figure 3. It is well known that a corrugated surface produces a high-impedance surface which suppresses vertically polarized creeping waves. The low gain pattern at low elevation angles helps reject land-based interferences. Figure 4 compares the simulated elevation patterns of a single side element mounted on a flat conducting disk and on a corrugated disk of the same diameter. It shows that the corrugated surface case (dashed line) produces lower gain at low elevation angles. This corrugated ground disk was CNC machined out of a solid aluminum block.

A. Side Element Design

Each of the six RHCP helical antennas on the sides is made of 18 turns of 2mm dia. copper wire wound around an 3D printed ABS plastic core. The diameter of the helix measured from the center of wires linearly decreases from $0.9\lambda_0$ at its base to $0.6\lambda_0$ at its tip. λ_0 corresponds to the free-space wavelength at 11.7 GHz. The diameter of the ABS core is 85% of that of the helix. The pitch angle of the helical wire is fixed at 9^o. The ABS core is also attached to a wider ABS base plate for better mounting strength without impacting the performance. The number of turns was chosen to produce a gain level close to 15 dBic around $\theta=60^o$ and 10 dBic around $\theta=30^o$, as shown in Figure 5. Each side helical antenna is tilted upwards

40° from horizon to produce a gain peak around 60° in the presence of corrugated rings. The base of each side helix is mounted on the side face of the center tower at an optimal height where lowest sidelobe is achieved. The height and width of the tower were kept to minimal to minimize overall antenna dimensions without causing mutual coupling between adjacent helical elements. The bottom end of each helical wire is soldered to the center conductor of a SMA connector mounted below the center tower, as seen in the bottom right picture of Figure 2.

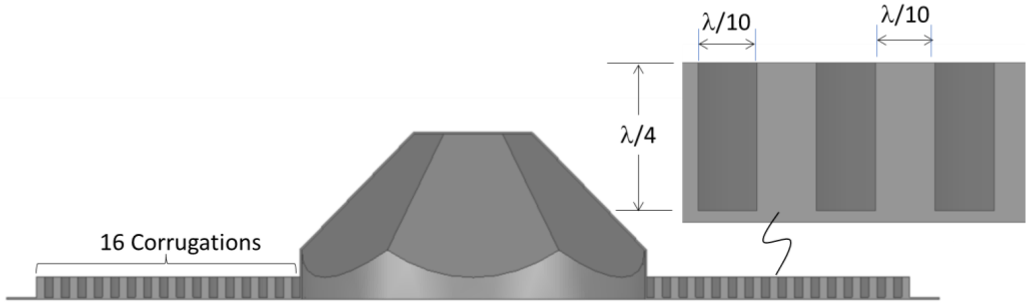


Figure 3: Corrugated conducting plate design for suppressing ground waves.

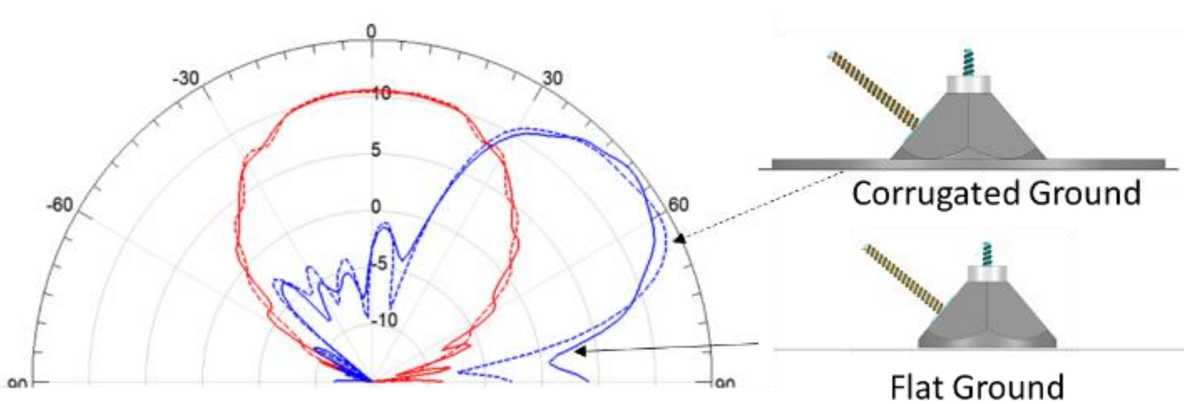


Figure 4: The simulated elevation pattern of the side element at 11.7 GHz shows reduced gain at low elevation angles.

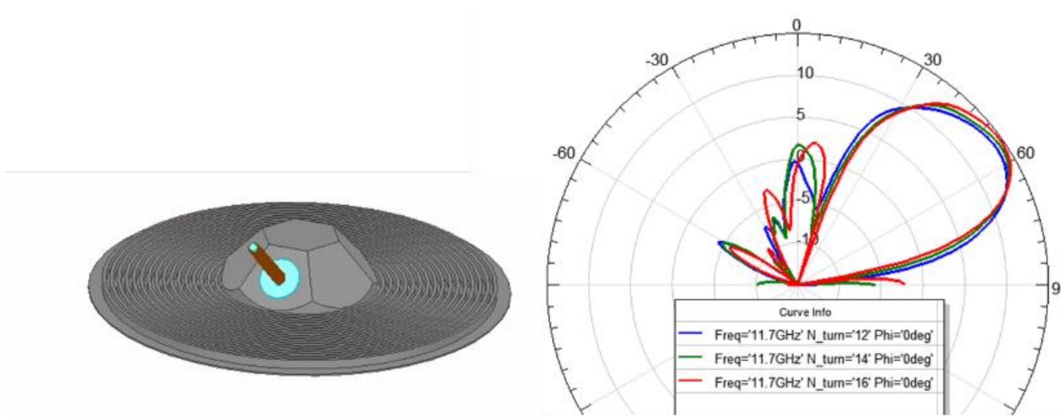


Figure 5: The effect of the number of turns on the elevation pattern of the side element.

B. Top Element Design

The top RHCP helical antenna has broader patterns and is responsible for receiving LEO satellite signals at higher elevation angles from $\theta=0^o$ to $\theta=30^o$. The helical wire is also made of a 2 mm in diameter. copper wire wound around an ABS plastic core. The diameter of the helix from center of wires linearly decreases from 0.84 λ_0 at its base to 0.5 λ_0 at its tip. λ_0 corresponds to the free-space wavelength at 11.7 GHz. The diameter of the ABS plastic core is 85% of that of the helix. The pitch angle of the helix is fixed at 9^o. The ABS core is also attached to a wider ABS base plate for stronger mounting strength without impacting antenna performance. The number of turns was chosen to produce a gain of approximately 10 dBic at zenith. A circular conducting wall with a height of 0.48 λ_0 is added at its base for reducing sidelobes, especially at horizon, and producing smooth broad patterns, as demonstrated in Figure 6. Figure 7 plots the simulated gain patterns of all 7 elements in the upper hemisphere with zenith being and the center of the graph. The radial axis corresponds to the q angle with $\theta=90^o$ being at the outmost rim. The azimuthal realized gain patterns of the six side elements at 11.7 GHz for (a) $\theta=60^o$, (b) $\theta=50^o$, and (c) $\theta=40^o$. These results demonstrate stable sectoral gain patterns from the side elements and 360 degrees coverage from the 6 side elements.

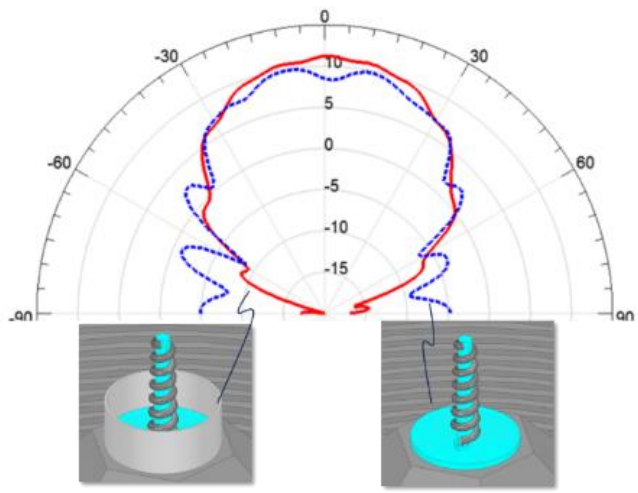


Figure 6: Comparison of elevation patterns of the top element at 11.7 GHz with and without a short conducting wall around its base.

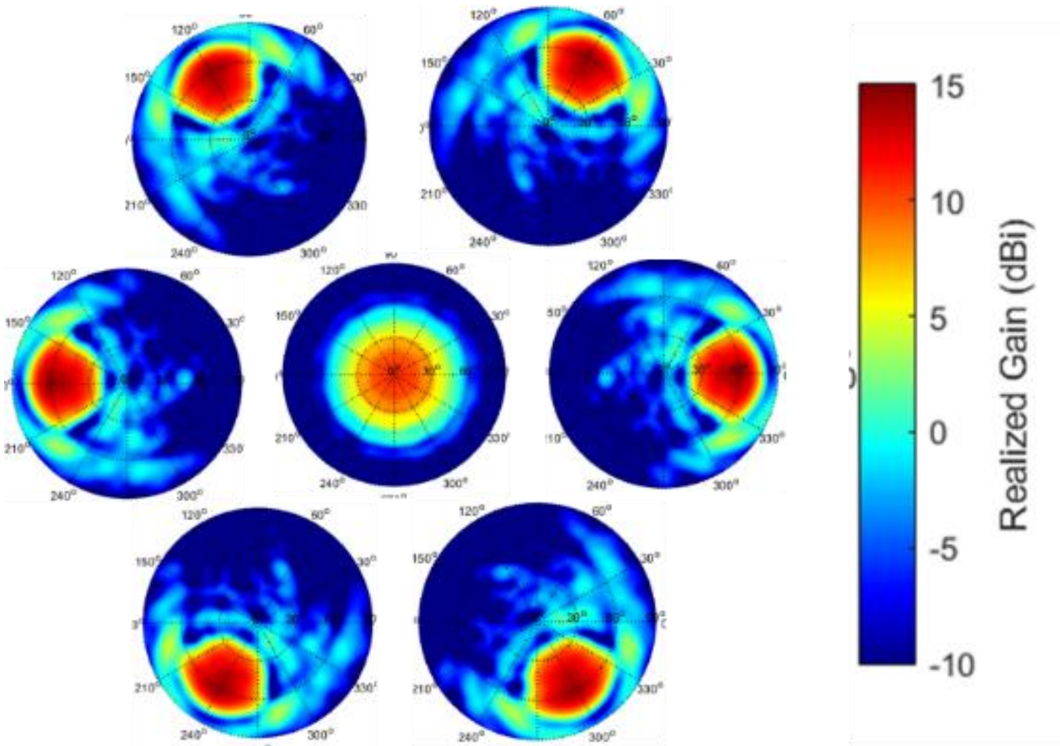
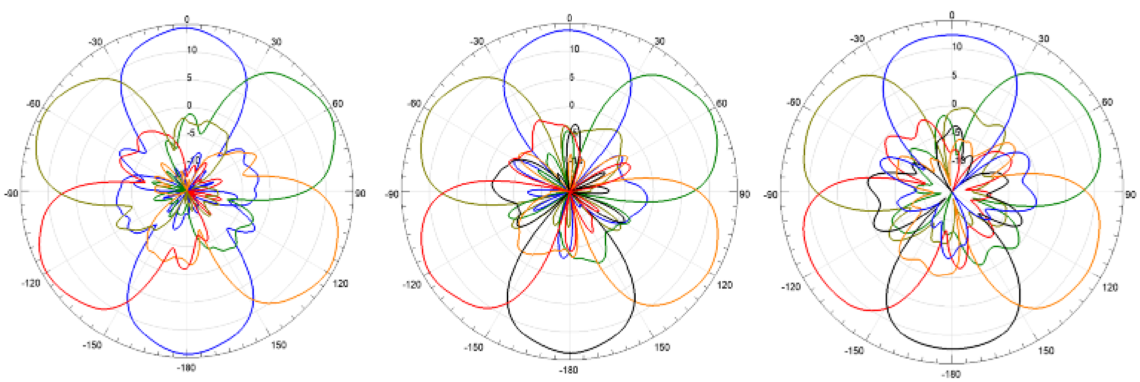


Figure 7: Simulated 3-D realized gain pattern of the upper hemisphere of each of the seven antenna elements at 11.7 GHz. Zenith is at the center of the plot. The radial axis corresponds to elevation angle from zenith (θ =0o) to horizon (θ=90o) at the outer rim.



(a) θ=60° (b) θ=50° (c) θ=40°

Figure 8: Simulated azimuthal realized gain patterns of the six side elements at 11.7 GHz for (a) θ =60°, (b) θ =50°, and (c) θ =40°.

Measurements Validation

The gain patterns of the fabricated prototype were measured inside the OSU ElectroScience Laboratory's Compact Range. The measured reflection coefficients of the six side elements are compared with the simulation data (dashed line) in Figure 9. It is observed that elements 2, 3, 4, and 6 have a reflection level higher than -10 dB below 12.1 GHz and the measured results are all higher than the simulated values. Note that the mismatch loss for these reflection coefficients of -10 dB at 11.7 GHz is 0.32 dB which is 0.25

dB higher than the 0.07 dB for the simulated reflection coefficient of -18dB. Figure 10 compares the simulated boresight (θ = -60°) gain versus frequency of the side helical element with the measured data of six side elements. These results demonstrate the wide bandwidth property in the desired frequency range. However, the measured gain level is lower than the simulated value by approximately 3 dB at 10.7 GHz and increases to 5 dB at 12.7 GHz. The cause of this will be explained shortly.

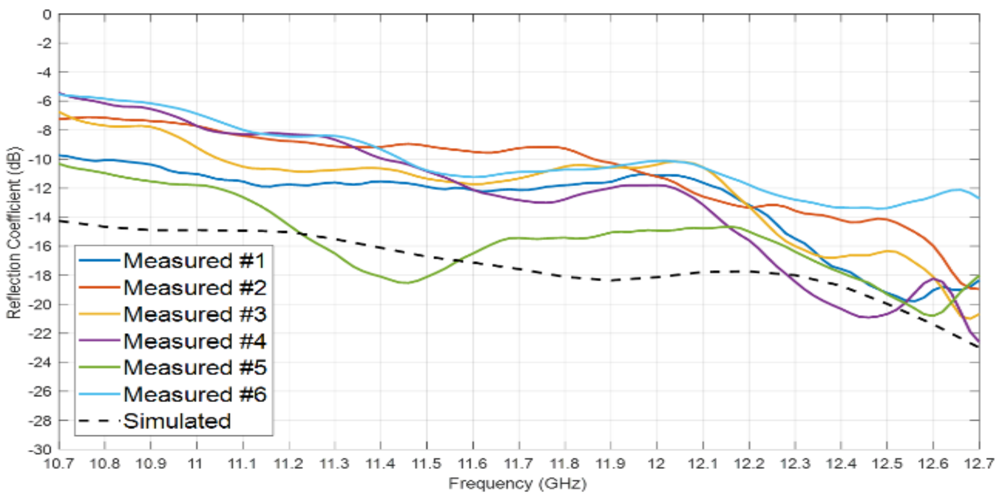


Figure 9: Comparing the simulated reflection coefficients of the side helical antenna with the measured results of six side helical elements.

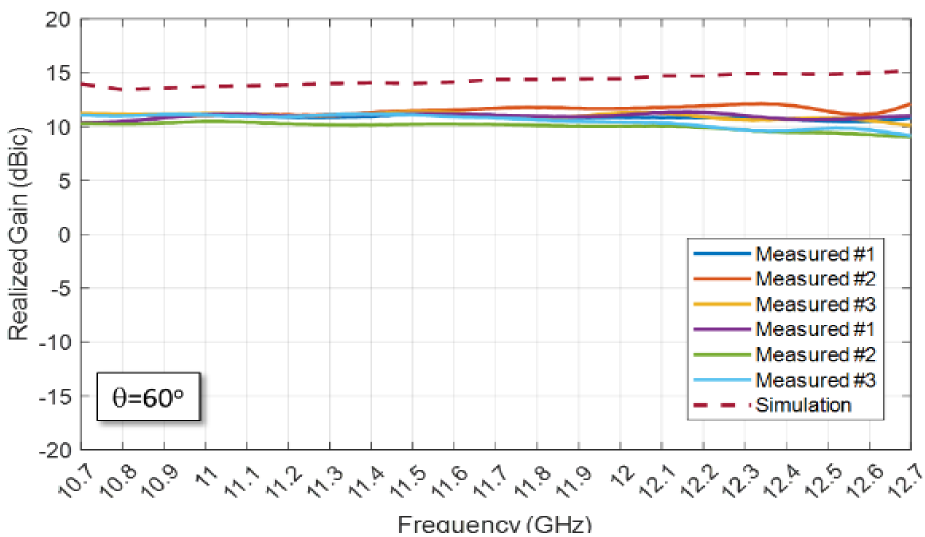


Figure 10: Comparing the simulated boresight gain versus frequency of the side helical element with the measured gain of six side elements.

Figure 11 compares the measured and simulated realize gain patterns at 11.7 GHz in the elevation plane (left) and azimuthal plane at θ =-60o (right) for one of the side elements. Both plots show lower measured gain is lower than the simulated values by about 2.5dB. The pattern of the side element also loses the specially designed sloped gain pattern which should peaks around θ =-60o. This happens to the measured gain patterns of all six side elements, as shown in Figure 12. Similar lower measured gain levels are also observed in the top element, as shown in Figure 13.

Further investigation on the lower measured gain values revealed the cause to be related to the epoxy applied at the base of each helical antenna for stronger mechanical strength. This kind of epoxy was found to have a dielectric constant of around 3.4 and loss tangent of approximately 0.01.The new simulated gain patterns and gain vs. frequency performance with epoxy added are compared with measured data in Figure 14 with good agreements. The slight difference between them is likely caused by the additional 0.25dB mismatch loss discussed in Figure 9.

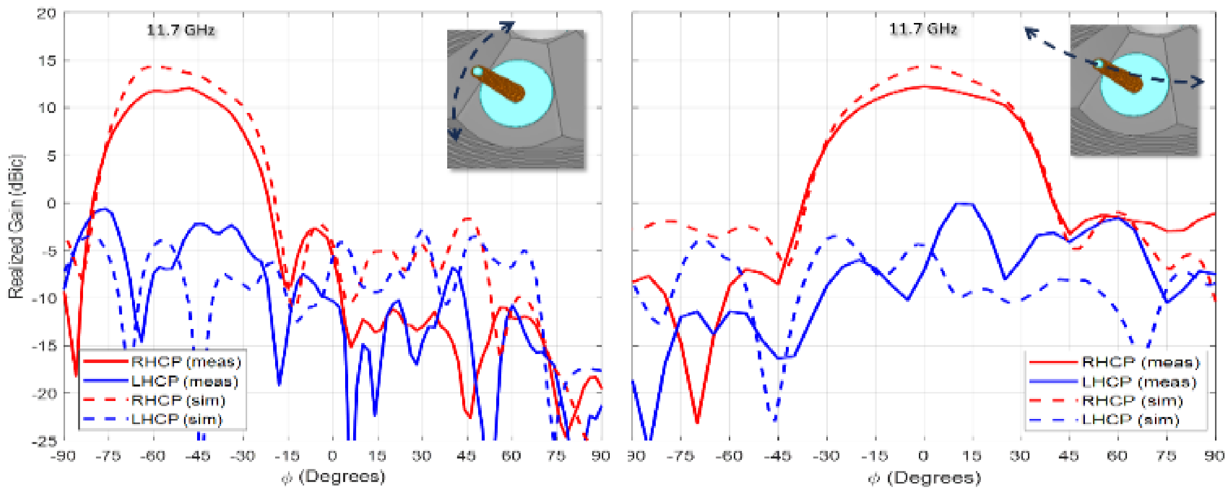


Figure 11: Comparing the simulated and measured realized gain patterns of the side helical antenna in its principal elevation and azimuthal planes.

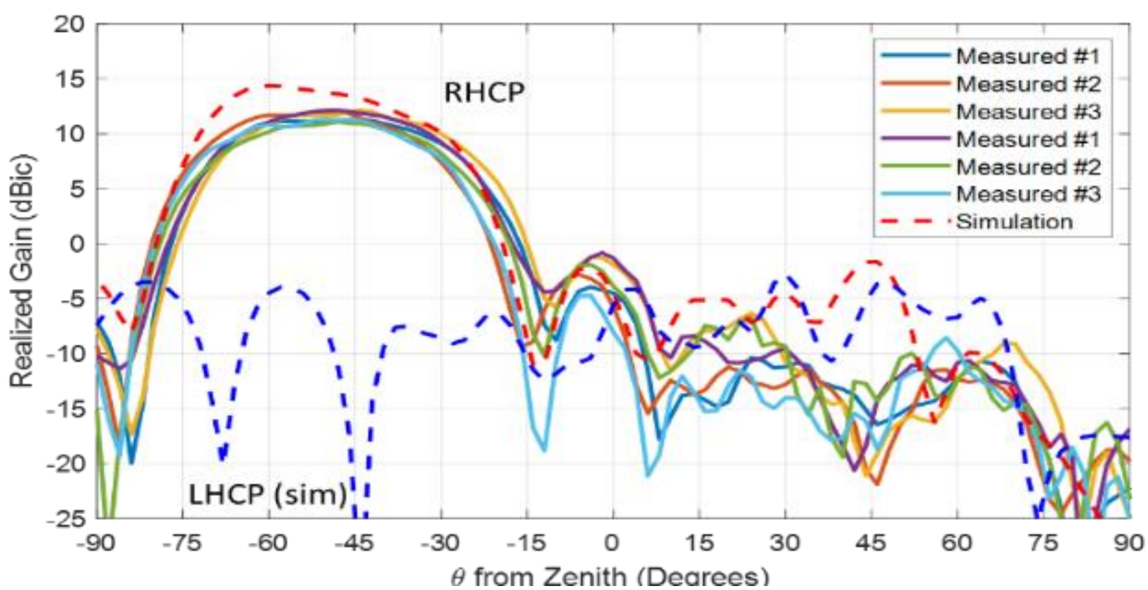


Figure 12: Comparing the simulated elevation gain pattern of the side helical antenna with the measured gain patterns from all six side elements.

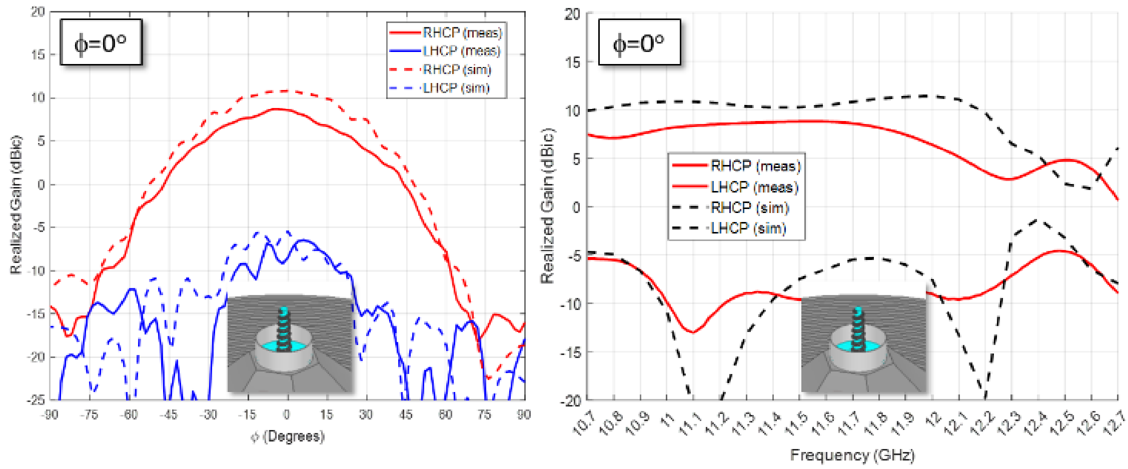


Figure 13: Comparing the simulated and measured elevation gain pattern and gain vs. frequency performance of the top helical antenna element.

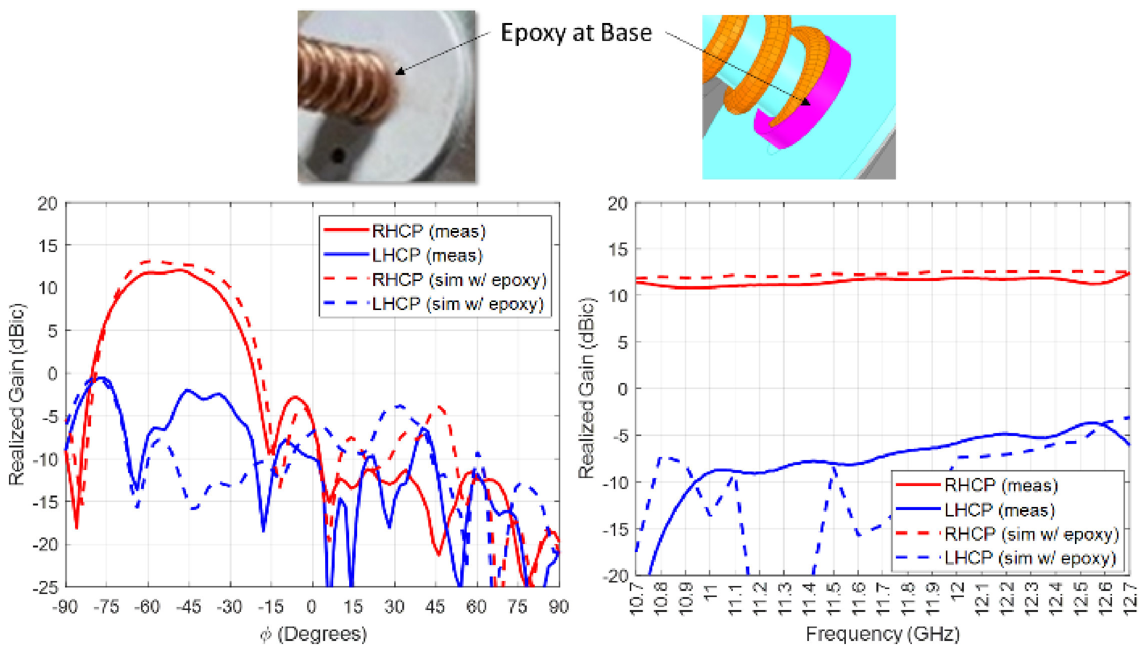


Figure 14: Comparing the simulated and measured elevation gain pattern and gain vs. frequency performance of a side element. Epoxy material was added in the simulation model.

Conclusions

A 7-element helical antenna assembly design concept was demonstrated for receiving LEO satellite communication signals for position and navigation for with a stable SNR over the sky area above 30o degrees of elevation. The combination of high-gain helix, raised tower, and corrugated ground surface allowed one to shape the elevation pattern to compensate for the different propagation loss associated with different LEO satellite angles. The predicted pattern and frequency performance were examined via prototype measurements. Unfortunately, the relatively lossy epoxy applied to secure the base of helical element cause the measured results to deviate away from the predicted values.

Acknowledgement

This work was financially supported in part by the U.S. Department of Transportation under Grant 69A3552348327 for the CARMEN+ University Transportation Center.

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