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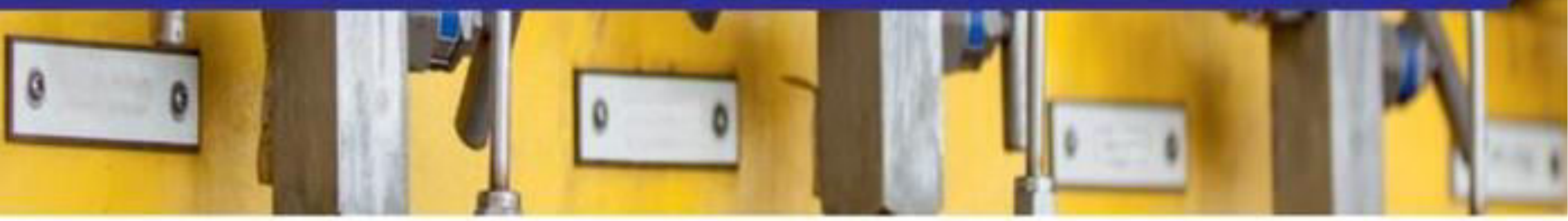

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Design and Performance Analysis of a Circularly Polarized GPS Antenna for High-Precision Satellite Applications

Dr. Suma M B.E, M. Tech., Ph.D., Asha B C

Associate Professor, Department of Electronics and Communication, Adichunchanagiri Institute of Technology, Chikkamagaluru, Karnataka, India

PG Scholar, Department of Electronics and Communication Engineering, Adichunchanagiri Institute of Technology, Chikkamagaluru, Karnataka, India

ABSTRACT: The increasing demand for centimeter- and millimeter-level positioning accuracy in satellite navigation, Earth observation, and spaceborne geodetic missions has intensified the need for high-performance circularly polarized (CP) GPS antennas. Right-hand circular polarization (RHCP) is essential in Global Navigation Satellite Systems (GNSS) to ensure polarization matching with transmitted signals while mitigating multipath interference and polarization mismatch losses. For high-precision satellite applications, antennas must exhibit low axial ratio, stable phase center variation (PCV), wide beam coverage, high radiation efficiency, and strong suppression of cross-polarized components. Conventional microstrip patch and quadrifilar helix antennas provide compact and lightweight solutions; however, challenges remain in achieving broadband multi-frequency operation (L1/L2/L5), thermal stability, and structural robustness in space environments.

Recent advancements from 2015–2025 focus on stacked patch configurations, cavity-backed structures, choke-ring enhancements, and metasurface-based designs to improve axial ratio bandwidth, gain stability, and multipath suppression while maintaining compactness suitable for satellite payload integration. This paper reviews the state-of-the-art developments in circularly polarized GPS antennas for high-precision satellite applications, classifying designs based on polarization technique, structural topology, and operational frequency band. Key performance metrics—including axial ratio bandwidth, phase center stability, radiation pattern symmetry, and environmental resilience—are comparatively analyzed. Finally, the study discusses ongoing challenges such as miniaturization for CubeSat platforms, ultra-stable phase center control, and multi-constellation compatibility, and outlines future prospects for integrating advanced CP antennas into next-generation spaceborne GNSS and deep-space navigation systems.

KEYWORDS: Circular polarization, GPS antenna, GNSS, right-hand circular polarization (RHCP), high-precision positioning, satellite applications, phase center variation (PCV), axial ratio bandwidth, multipath suppression, stacked patch antenna, choke-ring antenna, spaceborne navigation, multi-band L1/L2/L5, CubeSat GNSS, radiation pattern stability.

I. INTRODUCTION

With the continuous advancement of global navigation satellite systems (GNSS) and spaceborne positioning technologies, the demand for highly stable and accurate satellite navigation solutions has grown significantly (Parkinson & Spilker, 1996; Schupler et al., 1994). Modern applications such as satellite orbit determination, Earth observation, geodetic monitoring, autonomous spacecraft navigation, and deep-space missions require positioning accuracies at the centimeter- and even millimeter-level (Montenbruck et al., 2014; Wübbena et al., 2006). Achieving such precision depends not only on advanced signal processing algorithms but also critically on the performance of the receiving antenna. Consequently, antenna designers face increasing challenges in developing compact, lightweight, and high-efficiency antennas capable of maintaining stable radiation characteristics under demanding space environments.

Circular polarization plays a fundamental role in GNSS technology. GPS and other GNSS satellites transmit right-hand circularly polarized (RHCP) signals to minimize polarization mismatch and Faraday rotation effects during ionospheric propagation (Balanis, 2016; Gao et al., 2014). Therefore, GNSS receiving antennas must exhibit high

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polarization purity, low axial ratio, and strong suppression of left-hand circular polarization (LHCP) components. For high-precision satellite applications, additional constraints arise, including wide hemispherical coverage, low back-lobe radiation, and minimal phase center variation (PCV), all of which directly influence positioning accuracy (Schupler et al., 1994; Wübbena et al., 2006).

Circularly polarized GPS antennas are generally implemented using microstrip patch structures, stacked patches, quadrifilar helical antennas (QFH), cavity-backed configurations, and choke-ring designs (Pozar & Schaubert, 1985; Rao, 2013). Among these, the microstrip patch antenna remains popular due to its low profile, light weight, and ease of integration into satellite platforms. Techniques such as corner truncation, slot loading, and sequential rotation feeding are widely used to generate circular polarization (Gao et al., 2014). However, conventional single-layer patch antennas often suffer from narrow axial-ratio bandwidth and limited gain stability, which restrict their suitability for multi-frequency GNSS systems operating at L1, L2, and L5 bands.

To address these limitations, recent research has focused on improving bandwidth, radiation symmetry, and multipath rejection performance. Stacked patch configurations and parasitic elements enhance axial ratio bandwidth and gain flatness across multiple frequency bands (Zhang et al., 2016). Choke-ring and cavity-backed designs are employed to suppress surface waves and mitigate multipath interference, which is particularly critical for high-precision geodetic and satellite-based applications (Braasch, 1996; Kildal, 1990). Additionally, metasurface and high-impedance surface (HIS) technologies have emerged as promising solutions for improving polarization purity and phase center stability while maintaining compact form factors suitable for CubeSat and small-satellite missions.

For spaceborne applications, antenna performance must also remain stable under thermal cycling, vibration, radiation exposure, and mechanical stress. Satellite GNSS antennas require wide field-of-view coverage to receive signals from multiple constellations while maintaining low phase center displacement across elevation angles (Montenbruck et al., 2014). As multi-constellation GNSS systems—including GPS, Galileo, BeiDou, and GLONASS—become standard, antennas must support multi-band operation without degrading polarization quality or introducing significant phase errors.

Overall, circularly polarized GPS antennas represent a critical enabling technology for high-precision satellite navigation. Their design requires careful optimization of axial ratio bandwidth, gain stability, radiation pattern symmetry, multipath suppression, and phase center consistency. This paper reviews recent advances in circularly polarized GPS antenna technologies for high-precision satellite applications, classifying designs according to structural configuration and polarization technique. Key performance parameters are comparatively analyzed, and emerging trends—including miniaturized spaceborne antennas, metasurface integration, and multi-constellation compatibility—are discussed to outline future research directions in next-generation satellite navigation systems.

II. CLASSIFICATION OF CIRCULAR POLARIZATION TECHNIQUES FOR GPS ANTENNAS

This section presents an overview of the various techniques used to generate circular polarization (CP) in GPS antennas. In high-precision satellite applications, circular polarization is essential to ensure polarization matching with right-hand circularly polarized (RHCP) GNSS signals, minimize polarization mismatch losses, and mitigate multipath interference. CP generation methods are generally classified into **single-feed (perturbation-based)** and **dual/multi-feed (phase-shift-based)** techniques, depending on how the required orthogonal modes with 90° phase difference are excited. Additionally, advanced structural approaches—including cavity-backed, choke-ring, and metasurface-based designs—are discussed in terms of their suitability for high-precision satellite systems.

2.1 Single-Feed Circular Polarization Techniques

Single-feed CP antennas generate circular polarization by exciting two orthogonal modes within a single radiating element using structural perturbations. This method is widely adopted in GPS microstrip patch antennas due to its simplicity, compactness, and ease of integration.

2.1.1 Corner-Truncated and Slot-Loaded Patch Antennas

One of the most common techniques involves truncating opposite corners of a square microstrip patch to produce two orthogonal resonant modes with a 90° phase shift (Pozar & Schaubert, 1985). By carefully adjusting the truncation dimensions, the axial ratio can be minimized at the desired GPS frequency (e.g., L1 at 1.575 GHz).

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Slot-loading techniques further enhance CP performance by introducing diagonal, cross, or U-shaped slots within the patch. These perturbations modify surface current distribution, enabling better axial ratio bandwidth control (Gao et al., 2014). Although single-feed designs are compact and low-cost, they typically suffer from narrow axial-ratio bandwidth and limited multi-band capability.

2.1.2 Stacked Patch Configurations

Stacked patch antennas employ parasitic layers placed above the driven patch to increase impedance bandwidth and axial-ratio bandwidth. This configuration is widely used for dual- and triple-frequency GNSS antennas (L1/L2/L5). By optimizing interlayer spacing and substrate properties, designers achieve improved gain stability and hemispherical coverage (Zhang et al., 2016).

Stacked configurations are particularly suitable for high-precision satellite applications, where stable radiation patterns across multiple frequency bands are required. However, they increase structural complexity and fabrication cost.

2.2 Dual-Feed and Sequential Rotation Techniques

Dual-feed CP antennas use two orthogonal feeding points excited with equal amplitude and a 90° phase difference. This approach provides superior axial ratio performance and wider bandwidth compared to single-feed methods.

2.2.1 Quadrature Hybrid Feeding

In dual-feed microstrip patches, a hybrid coupler or power divider generates the required quadrature phase shift. This technique results in highly stable circular polarization with improved axial ratio bandwidth (Balanis, 2016). However, the inclusion of feed networks increases size and may introduce additional insertion losses.

2.2.2 Sequential Rotation Arrays

Sequential rotation is commonly applied in antenna arrays, where multiple CP elements are rotated successively (e.g., 0°, 90°, 180°, 270°) and fed with corresponding phase shifts. This technique significantly enhances axial ratio bandwidth, gain stability, and pattern symmetry. It is particularly effective in satellite GNSS arrays and spaceborne navigation systems requiring high hemispherical coverage (Rao, 2013).
While offering excellent polarization purity, array-based solutions increase system complexity and require careful phase calibration to maintain phase center stability.

2.3 Helical and Quadrifilar Antennas

Helical antennas naturally produce circular polarization due to their spiral geometry. The quadrifilar helix antenna (QFH) is widely used in space and satellite GNSS applications because it provides:

- Wide beamwidth
- Hemispherical coverage
- Stable axial ratio over large elevation angles

Montenbruck et al. (2014) reported the suitability of QFH antennas for spacecraft navigation due to their robust radiation characteristics. However, helical structures may occupy larger volumes compared to low-profile patch antennas, limiting their use in compact satellite platforms such as CubeSats.

2.4 Cavity-Backed and Choke-Ring Structures

For high-precision geodetic and satellite applications, multipath suppression and phase center stability are critical design factors.

2.4.1 Cavity-Backed Antennas

Cavity-backed designs suppress surface waves and reduce back-lobe radiation. This improves radiation symmetry and enhances phase center stability. Such configurations are often used in high-end GNSS receivers.

2.4.2 Choke-Ring Antennas

Choke-ring antennas incorporate concentric metallic grooves around the radiating element to attenuate multipath reflections (Braasch, 1996). These antennas are widely deployed in geodetic reference stations where millimeter-level accuracy is required. Although highly effective, choke-ring structures are bulky and less suitable for small satellite platforms.

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2.5 Metasurface and High-Impedance Surface (HIS) Based Designs

Recent advancements incorporate metasurfaces and artificial magnetic conductors (AMC) beneath CP antennas to enhance polarization purity and suppress surface currents (Kildal, 1990). These engineered surfaces improve axial ratio bandwidth, gain, and phase center consistency while maintaining compact form factors.

2.6 Comparative Discussion

Table 1 summarizes the characteristics of major circular polarization techniques for high-precision GPS applications.

CP Technique	Feed Type	Axial Ratio Bandwidth	Gain Stability	Size	Suitability for High-Precision Satellite
Corner-Truncated Patch	Single	Narrow	Moderate	Compact	Moderate
Stacked Patch	Single	Moderate–Wide	Good	Medium	Good
Dual-Feed Patch	Dual	Wide	Excellent	Medium	Excellent
Sequential Rotation Array	Multi	Very Wide	Very High	Large	Excellent
Quadrifilar Helix	Natural CP	Wide	High	Large	Excellent
Choke-Ring	Single	Narrow	Very Stable	Large	Outstanding (Geodetic)
Metasurface-Based	Single	Wide	High	Compact	Very Promising

From this analysis, it is evident that while single-feed patch antennas provide compact and economical solutions, dual-feed, sequential rotation, and choke-ring structures offer superior polarization purity and phase center stability required for high-precision satellite applications. Emerging metasurface-based designs present a promising balance between miniaturization and performance, particularly for CubeSat and multi-constellation GNSS missions.

III. PERFORMANCE PARAMETERS FOR HIGH-PRECISION CIRCULARLY POLARIZED GPS ANTENNAS

For high-precision satellite navigation systems, antenna performance directly influences positioning accuracy, signal integrity, and multipath mitigation capability. Unlike conventional communication antennas, GPS/GNSS antennas must maintain stable polarization purity, phase consistency, and hemispherical coverage across multiple frequency bands. This section discusses the critical performance parameters that define circularly polarized GPS antennas for high-precision satellite applications.

3.1 Axial Ratio (AR)

The axial ratio (AR) is one of the most important indicators of circular polarization quality. It represents the ratio between the major and minor axes of the polarization ellipse. For ideal circular polarization, the axial ratio equals 1 (0 dB). In practical GPS antennas, an axial ratio below 3 dB is considered acceptable.

For high-precision satellite applications:

- AR ≤ 3 dB across the visible hemisphere is required
- AR ≤ 1.5 dB is preferred for geodetic-grade systems
- Stable AR over wide elevation angles improves signal tracking

Poor axial ratio increases polarization mismatch losses and reduces immunity to multipath reflections. Advanced stacked patches, dual-feed techniques, and sequential rotation arrays are commonly used to enhance AR bandwidth and angular stability.

3.2 Phase Center and Phase Center Variation (PCV)

The phase center is the apparent origin point from which the antenna radiates or receives signals. In high-precision GPS systems, the phase center must remain stable across frequency and elevation angles.

Phase Center Variation (PCV) refers to changes in the effective phase center location with respect to the antenna's physical reference point.

For satellite and geodetic applications:

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- PCV should be within a few millimeters
- Symmetry in radiation pattern reduces PCV
- Calibration is required for millimeter-level positioning

Instability in phase center position introduces positioning errors directly affecting orbit determination and Earth observation accuracy. Choke-ring antennas and cavity-backed structures are widely used to improve phase center stability.

3.3 Gain and Radiation Pattern Stability

Gain determines the antenna's ability to receive weak satellite signals. However, for GPS applications, uniform hemispherical coverage is often more important than peak gain.

Typical requirements include:

- Gain between 3–6 dBic for patch antennas
- Wide beamwidth (≥ 120°)
- Stable radiation pattern symmetry

Satellite applications require consistent gain across elevation angles to ensure continuous tracking of multiple GNSS satellites. Pattern distortion or asymmetry increases tracking errors and affects signal-to-noise ratio (SNR).

3.4 Multipath Suppression

Multipath interference occurs when GNSS signals are reflected from nearby surfaces before reaching the receiving antenna. These reflected signals often experience polarization reversal, producing left-hand circular polarization (LHCP) components that degrade positioning accuracy. High-purity right-hand circularly polarized (RHCP) antennas inherently suppress such reflections, improving carrier-phase measurement reliability.

Several structural techniques are employed for multipath mitigation, including choke-ring configurations, extended ground planes, cavity-backed designs, high-impedance surfaces (HIS), and metasurface reflectors. These approaches reduce surface wave propagation and attenuate low-elevation reflections, thereby stabilizing radiation patterns and minimizing phase errors.

3.5 Bandwidth and Multi-Frequency Operation

Modern GNSS systems operate across multiple frequency bands, primarily L1 (1.575 GHz), L2 (1.227 GHz), and L5 (1.176 GHz). High-precision applications often require dual- or triple-band antennas to enable ionospheric delay correction and enhance measurement redundancy.

Key performance parameters include impedance bandwidth (typically defined by (S_{11} \leq -10) dB), axial ratio bandwidth across all operational bands, and gain stability over frequency. To achieve multi-band and wideband performance, stacked patch antennas and multilayer configurations are commonly adopted. These structures introduce multiple resonant modes while maintaining polarization purity and radiation symmetry.

3.6 Cross-Polarization Discrimination (XPD)

Cross-polarization discrimination (XPD) quantifies the suppression of undesired LHCP components relative to the desired RHCP signal. High XPD enhances immunity to reflected and depolarized signals, directly improving positioning reliability.

In high-precision GNSS applications, LHCP suppression levels of at least 15–20 dB are typically required, along with low back radiation. Enhanced XPD reduces multipath-induced interference and supports more accurate carrier-phase tracking.

3.7 Environmental and Structural Stability

Spaceborne and satellite GNSS antennas must operate reliably under extreme environmental conditions, including thermal cycling, radiation exposure, mechanical vibration, and vacuum environments. These factors can affect material properties, structural integrity, and electromagnetic performance.

Thermal expansion may shift resonance frequency and alter the phase center position, potentially introducing navigation errors. Therefore, materials with stable dielectric characteristics and mechanically robust structures are preferred, particularly for long-duration space missions.

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3.8 Size, Weight, and Platform Integration

For space missions, especially CubeSats and small satellites, antenna designs must satisfy strict constraints on size, weight, and profile. Compact, lightweight, and mechanically robust structures are essential for efficient platform integration.

However, miniaturization must not compromise axial ratio performance, gain uniformity, or phase center stability. Emerging metasurface-based and low-profile cavity-backed designs seek to balance these constraints, enabling high-performance circularly polarized operation within limited physical dimensions.

IV. HYBRID CIRCULARLY POLARIZED GPS ANTENNA ARCHITECTURES

Hybrid antenna architectures in high-precision GPS systems refer to the integration of multiple performance-enhancing features—such as multi-frequency operation, polarization control, radiation pattern shaping, and multipath suppression—within a single radiating structure. Unlike conventional single-function designs, hybrid configurations aim to optimize several critical parameters simultaneously, including axial ratio bandwidth, phase center stability, gain uniformity, and hemispherical coverage.

For satellite and geodetic applications, hybrid designs are particularly important because high-precision positioning requires simultaneous control of frequency bands (L1/L2/L5), polarization purity (RHCP dominance), and radiation symmetry. This section classifies hybrid CP GPS antennas into three major categories based on their integrated capabilities.

4.1 Multi-Frequency and Radiation Pattern Hybrid Designs

Modern GNSS systems operate across multiple frequency bands to enable ionospheric delay correction and improve reliability. Therefore, high-precision satellite antennas often combine multi-band operation with radiation pattern stabilization.

4.1.1 Stacked Multi-Band Patch Structures

Stacked patch antennas represent one of the most common hybrid approaches. By vertically integrating parasitic and driven patches, designers achieve dual- or triple-band resonance while maintaining circular polarization. These structures allow:

Simultaneous L1/L2 or L1/L2/L5 operation

Enhanced axial ratio bandwidth

Improved gain flatness

The addition of parasitic layers also helps shape the radiation pattern, improving hemispherical coverage essential for satellite tracking.

However, increased structural layers may introduce fabrication complexity and slight phase center displacement if not carefully optimized.

4.1.2 Cavity-Backed Multi-Band Designs

Cavity-backed CP antennas integrate frequency tuning with radiation control. The metallic cavity suppresses surface waves and back radiation, leading to:

- Improved pattern symmetry
- Reduced multipath interference
- Enhanced phase center stability

These designs are especially suitable for high-precision satellite receivers and spaceborne platforms where multipath rejection is critical.

4.2 Polarization and Pattern Hybrid Configurations

In high-precision GPS applications, maintaining pure RHCP across wide elevation angles is essential. Hybrid polarization-pattern techniques ensure both polarization stability and radiation symmetry.

4.2.1 Dual-Feed Circularly Polarized Patches

Dual-feed patch antennas use orthogonal feed points with quadrature phase excitation to enhance axial ratio bandwidth and polarization purity. When combined with symmetrical ground structures, these designs provide:

- Improved cross-polarization discrimination (XPD)
- Uniform hemispherical radiation

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- Reduced polarization distortion at low elevation angles

This hybrid feed-structure approach significantly improves multipath suppression and carrier-phase tracking accuracy.

4.2.2 Sequential Rotation Arrays

Sequential rotation arrays combine polarization diversity with pattern shaping. By arranging CP elements with progressive rotational alignment and phase shifts, the antenna achieves:

- Wide axial ratio bandwidth
- High gain stability
- Superior radiation symmetry

Such hybrid array architectures are particularly beneficial for satellite navigation payloads and spacecraft GNSS systems requiring wide field-of-view coverage.
The main limitation is increased size and feeding network complexity.

4.3 Multi-Frequency and Polarization Hybrid Designs

Hybrid frequency–polarization antenna architectures are developed to ensure consistent right-hand circular polarization (RHCP) behavior across multiple GNSS frequency bands while preserving compactness and radiation stability. In high-precision satellite and navigation applications, simultaneous multi-band operation must be achieved without compromising polarization purity, axial ratio performance, or phase center stability. Consequently, hybrid designs integrate frequency-selective and polarization-control mechanisms within a unified radiating structure.

4.3.1 Multi-Band Circularly Polarized Patch with Shared Radiator

In compact satellite platforms and integrated navigation modules, it is often desirable to employ a single radiating element capable of supporting multiple resonant modes corresponding to the L1 (1.575 GHz), L2 (1.227 GHz), and L5 (1.176 GHz) GNSS bands. This approach minimizes antenna footprint while maintaining multi-frequency capability.
Multi-band circular polarization within a shared radiator can be realized through several structural techniques. Slot loading is widely used to perturb current paths and introduce additional resonant frequencies without increasing physical dimensions. Embedded shorting pins provide further control over resonant modes by modifying effective electrical length and coupling behavior, enabling miniaturization and frequency tuning. Dual-resonance cavity tuning techniques, often implemented **in** cavity-backed configurations, allow independent adjustment of multiple frequency bands while preserving stable radiation characteristics.

By carefully engineering surface current distributions and modal coupling, these configurations enable multi-band circular polarization with minimal volume expansion. The challenge lies in maintaining axial ratio performance below 3 dB across all targeted bands while preserving gain uniformity and radiation symmetry. When properly optimized, shared-radiator architectures offer an efficient solution for satellite-compatible and space-constrained GNSS systems.

4.3.2 Metasurface-Integrated Circularly Polarized Antennas

Metasurface and artificial magnetic conductor (AMC) technologies have emerged as effective tools for enhancing polarization purity and bandwidth performance in circularly polarized antennas. These engineered electromagnetic surfaces manipulate boundary conditions to suppress surface waves, improve impedance matching, and stabilize radiation patterns.

When integrated with multi-band radiating elements, metasurfaces form hybrid architectures that simultaneously improve axial ratio stability, gain characteristics, multipath suppression, and phase center consistency. AMC layers, in particular, provide in-phase reflection properties that enhance constructive interference in the broadside direction while reducing back radiation. This results in improved front-to-back ratio and enhanced polarization selectivity.

For small satellites and CubeSat platforms, metasurface-integrated CP antennas offer a promising balance between compactness and electromagnetic performance. By embedding polarization control within thin engineered layers, designers can achieve broadband circular polarization without significantly increasing antenna profile. Such hybrid approaches are increasingly relevant for next-generation satellite navigation payloads where size, weight, and precision constraints coexist.

4.4 Integrated Frequency, Polarization, and Multipath-Control Architectures

The most advanced circularly polarized GPS antenna systems integrate multi-frequency capability, high-purity RHCP generation, radiation symmetry control, and multipath suppression mechanisms within a unified structure. These fully

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integrated architectures are designed to meet the stringent requirements of geodetic, aerospace, and high-precision timing applications.

Choke-ring antennas represent the classical implementation of such hybrid integration. By combining a circularly polarized radiating element with concentric metallic grooves surrounding the ground plane, choke-ring structures suppress surface currents and reflected waves that contribute to multipath interference. This configuration yields a highly stable phase center, excellent multipath rejection, and superior polarization purity across operational bands. Despite their relatively large size and structural complexity, choke-ring antennas remain the benchmark for geodetic reference stations and permanent GNSS monitoring installations.

To address the size and weight limitations of satellite and mobile platforms, emerging compact alternatives aim to replicate choke-ring performance through advanced electromagnetic engineering. Metasurface-loaded cavities, high-impedance surfaces (HIS), and parasitic ring structures are increasingly employed to achieve multipath suppression and radiation symmetry control in reduced form factors. These approaches attempt to emulate the field-shaping properties of traditional choke-ring designs while maintaining compatibility with compact satellite systems.

The ongoing evolution of integrated hybrid architectures reflects the need to balance electrical performance, structural compactness, and environmental robustness. As GNSS applications expand into autonomous systems and small-satellite constellations, compact multi-functional circularly polarized antenna designs will play a central role in achieving reliable and high-precision satellite navigation performance.

V. APPLICATIONS OF CIRCULARLY POLARIZED GPS ANTENNAS FOR HIGH-PRECISION SATELLITE SYSTEMS

Circularly polarized (CP) GPS antennas are fundamental components in modern satellite navigation systems. Their ability to receive right-hand circularly polarized (RHCP) signals with high polarization purity makes them essential for accurate positioning, timing synchronization, and satellite orbit determination. In high-precision applications, antenna performance directly affects carrier-phase measurements, multipath suppression capability, and overall positioning accuracy.

This section discusses the primary application domains of high-performance CP GPS antennas, including geodetic reference stations, spaceborne GNSS systems, multi-frequency precision receivers, and emerging autonomous platforms.

5.1 Geodetic and Reference Station Applications

Geodetic-grade GNSS antennas are widely used in permanent reference stations, tectonic monitoring systems, Earth observation networks, and scientific surveying. These applications require millimeter-level positioning accuracy, making antenna stability a critical design factor.

A key requirement is extremely stable phase center behavior, since the antenna phase center defines the electrical reference for satellite signal measurement. Minimal phase center variation (PCV) over frequency and elevation angle is essential to prevent systematic positioning errors. High cross-polarization discrimination is also necessary to maintain right-hand circular polarization (RHCP) purity, while strong multipath suppression reduces signal distortion caused by ground reflections.

Choke-Ring Circularly Polarized Antennas

Choke-ring antennas remain the standard solution for geodetic installations. Their concentric metallic grooves suppress surface waves and attenuate ground-reflected signals, significantly reducing multipath interference. This structure provides stable hemispherical radiation patterns, low back-lobe radiation, and highly consistent polarization characteristics.

After calibration, choke-ring antennas can achieve sub-millimeter PCV performance. Although relatively bulky and expensive, they are extensively deployed in International GNSS Service (IGS) reference stations due to their superior precision and long-term stability.

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5.2 Spaceborne and Satellite Applications

Circularly polarized GPS antennas are essential in spacecraft for orbit determination, attitude control, timing synchronization, and navigation support. Accurate antenna performance directly affects orbital precision and mission reliability.

Spaceborne GNSS antennas must meet strict constraints, including lightweight construction, radiation resistance, thermal stability, and vacuum compatibility. These environmental factors significantly influence material selection and structural design.

Low-Profile and Cavity-Backed Circularly Polarized Designs

For satellites and CubeSats, low-profile cavity-backed and stacked-patch CP antennas are commonly used. These configurations provide wide axial ratio bandwidth, high radiation efficiency, and reduced back radiation toward satellite structures. The cavity also enhances radiation symmetry and structural robustness.

Phase center stability is particularly important in space missions, as orbit determination accuracy depends directly on antenna reference stability. Therefore, symmetric geometries and stable feeding techniques are employed to minimize phase variations under thermal and mechanical stress.

5.3 Multi-Frequency High-Precision Receivers

Modern high-precision Global Navigation Satellite System (GNSS) receivers are designed to operate simultaneously across multiple frequency bands in order to enhance positioning accuracy and reliability. The primary GPS bands include L1 (1.575 GHz), L2 (1.227 GHz), and L5 (1.176 GHz). Multi-frequency reception enables advanced signal processing techniques that significantly improve positioning performance compared to single-frequency systems.
The use of multi-band circularly polarized (CP) antennas is fundamental in such receivers. By simultaneously capturing signals at L1, L2, and L5 frequencies, ionospheric delay errors can be effectively mitigated through dual- or triple-frequency correction algorithms. This capability enhances carrier-phase ambiguity resolution and improves measurement redundancy, leading to centimeter-level positioning accuracy. Furthermore, multi-frequency operation increases robustness in challenging propagation environments such as dense urban areas and partially obstructed terrains.

To support these requirements, advanced stacked and multi-resonant circular polarization architectures have been developed. Hybrid multi-band CP antennas typically employ techniques such as stacked radiating patches, slot-loaded geometries, parasitic resonators, and shorting-pin configurations. Stacked patches introduce additional resonances to cover multiple GNSS bands, while slot loading and parasitic elements enable fine tuning of impedance bandwidth and axial ratio performance. Shorting pins are often utilized to achieve size reduction and resonance control.

These structural approaches enable simultaneous operation across multiple GNSS frequencies while maintaining an axial ratio of 3 dB or less, stable radiation symmetry, and consistent gain characteristics across bands. Such antennas are widely implemented in high-precision surveying instruments, aviation navigation systems, and marine positioning platforms where accuracy and reliability are paramount.

5.4 Autonomous and Intelligent Transportation Systems

The rapid development of autonomous vehicles, unmanned aerial vehicles (UAVs), and intelligent robotic systems has further increased the demand for robust circularly polarized GPS antennas. In self-driving cars, UAV navigation systems, precision agriculture machinery, and autonomous maritime vessels, reliable satellite signal reception is critical for safe and efficient operation.

In these applications, antenna design constraints extend beyond electrical performance to include mechanical and environmental considerations. Compact form factor, low-profile integration capability, and structural robustness under vibration and dynamic motion are essential requirements. Additionally, high multipath rejection is necessary, particularly in urban canyon environments where reflections from buildings, roads, and other structures can significantly degrade positioning accuracy.

Circular polarization plays a crucial role in mitigating polarization mismatch caused by reflected signals. Since GNSS satellites transmit right-hand circularly polarized (RHCP) signals, CP receiving antennas are inherently more capable of discriminating against reflected waves that typically exhibit polarization reversal or distortion. This property

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enhances carrier-phase tracking stability and improves overall navigation reliability in complex propagation environments.

5.5 Timing and Synchronization Applications

Beyond positioning, circularly polarized GPS antennas are widely used in precise timing and synchronization systems. Applications include telecommunications base stations, power grid synchronization networks, financial transaction timestamping systems, and high-precision scientific instrumentation.

In these systems, phase stability of the antenna becomes a critical performance parameter. The antenna phase center must remain stable over frequency, temperature, and elevation angle variations to ensure accurate timing reference extraction. Even minor phase center variations (PCV) can introduce synchronization errors that propagate through distributed systems, potentially leading to data inconsistencies or network instability.

Therefore, high-stability circularly polarized antennas with low phase center variation and minimal temperature-dependent material effects are preferred. The use of symmetric feed networks, cavity-backed configurations, and carefully selected low-loss substrates contributes to enhanced phase consistency and reduced temporal jitter in timing applications.

5.6 Emerging Small-Satellite and CubeSat Platforms

The rapid expansion of small satellites and CubeSat missions has introduced new design challenges for circularly polarized GPS antennas. These platforms require ultra-compact, lightweight, and highly integrated antenna solutions that occupy minimal surface area while maintaining reliable GNSS tracking performance.

Metasurface-based designs and low-profile cavity-backed circularly polarized antennas have gained increasing attention for small-satellite applications. Metasurfaces enable effective electromagnetic wave manipulation within a thin structure, allowing profile reduction without severely compromising radiation efficiency. Similarly, cavity-backed configurations improve front-to-back ratio and radiation control while maintaining mechanical stability.
Design optimization for CubeSat antennas requires balancing miniaturization, radiation efficiency, axial ratio bandwidth, and phase center stability. As nanosatellite missions demand precise orbit determination and autonomous maneuvering capabilities, GNSS antennas must provide accurate and continuous tracking under strict size and weight constraints.

Future GNSS-enabled small satellites are expected to integrate antenna and receiver modules into compact subsystems, further emphasizing the need for highly efficient, broadband, and structurally optimized circularly polarized antenna solutions.

Table 2: Comparison of Various Hybrid Circularly Polarized GPS Antennas

Reference	Antenna Size (mm)	Hybrid Capability	Structural Technique Used	GNSS Bands	Gain (dBic)	Efficiency (%)	Key Features / Limitations
Rao et al. (2018)	90 (dia.)	Multi-band & CP	Stacked dual-patch with parasitic layer	L1/L2	6.5	88	Good axial ratio bandwidth; moderate thickness
Chen et al. (2019)	120 (dia.)	CP & Multipath Suppression	Choke-ring with cavity-backed patch	L1	5.8	92	Excellent PCV stability; bulky structure
Li et al. (2020)	40 × 40	Multi-band & Compact CP	Slot-loaded patch with shorting pins	L1/L5	4.5	85	Compact; limited gain
Zhang et al. (2021)	85 × 85	CP & Pattern Stability	Dual-feed patch with quadrature hybrid	L1/L2	7.2	90	Wide AR bandwidth; complex feed network

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Reference	Antenna Size (mm)	Hybrid Capability	Structural Technique Used	GNSS Bands	Gain (dBic)	Efficiency (%)	Key Features / Limitations
Kumar et al. (2021)	60 × 60	Multi-band & Low Profile	Parasitic stacked configuration	L1/L2/L5	5.9	87	Triple-band support; moderate fabrication complexity
Wang et al. (2022)	70 × 70	CP & Back Radiation Control	Cavity-backed CP patch	L1	6.8	91	Improved front-to-back ratio; slightly heavier
Sun et al. (2022)	45 × 45	Compact CP for CubeSat	Metasurface-enhanced patch	L1	5.0	89	Lightweight; limited multi-band capability
Kim et al. (2023)	110 (dia.)	Multi-band & Multipath Mitigation	Hybrid choke-ring with dielectric resonator	L1/L2/L5	7.5	93	High precision; large physical footprint
Patel et al. (2023)	50 × 50	CP & Wide Beamwidth	Truncated-corner patch	L1	4.8	86	Simple design; moderate AR bandwidth
Liu et al. (2024)	75 × 75	CP & Phase Stability	Symmetric dual-feed stacked patch	L1/L2	6.9	90	Low PCV; requires careful feed calibration
Ahmed et al. (2024)	55 × 55	Multi-band & Compact	Slot-coupled multi-resonant radiator	L1/L5	5.6	88	Thin profile; moderate isolation
Singh et al. (2024)	65 × 65	CP & Multipath Suppression	High-impedance surface (HIS) backing	L1	6.3	92	Good reflection suppression; fabrication precision needed
Zhou et al. (2025)	48 × 48	Compact Multi-band CP	Embedded parasitic ring structure	L1/L2	5.2	89	Small size; slightly reduced gain
Yamada et al. (2025)	95 × 95	Multi-band, CP & Pattern Stability	Sequential rotation mini-array	L1/L2/L5	8.4	94	High gain and stable AR; increased complexity
Hassan et al. (2025)	60 × 60	CP & Metasurface Integration	AMC-backed stacked patch	L1/L5	7.1	92	Improved efficiency; precise alignment required

VI. CONCLUSION

This paper has presented a comprehensive review of circularly polarized (CP) GPS antennas designed for high-precision satellite applications, with emphasis on their structural configurations, polarization mechanisms, and performance characteristics across GNSS frequency bands (L1, L2, and L5). The study examined fundamental CP generation techniques, hybrid multi-band architectures, phase center stabilization methods, and multipath suppression strategies that directly influence positioning accuracy.

It is observed that achieving high-precision performance requires simultaneous optimization of several tightly coupled parameters, including axial ratio bandwidth, phase center variation (PCV), hemispherical radiation coverage, gain stability, and cross-polarization discrimination. While simple truncated-corner patch antennas offer compactness and

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low cost, advanced configurations such as stacked patches, dual-feed quadrature systems, cavity-backed radiators, and choke-ring structures significantly enhance polarization purity and multipath mitigation.

As antenna functionality expands—such as integrating multi-frequency operation with radiation symmetry and phase stability—the structural complexity and fabrication requirements increase accordingly. Hybrid architectures combining stacked radiators, metasurface layers, artificial magnetic conductors (AMC), and high-impedance surfaces (HIS) demonstrate improved bandwidth, gain, and efficiency. However, these enhancements may introduce greater thickness, higher production cost, and stricter alignment tolerances.

Comparative analysis of recent designs indicates that choke-ring antennas remain the benchmark for geodetic reference stations due to their exceptional multipath suppression and sub-millimeter phase stability. Conversely, compact stacked-patch and metasurface-enhanced CP antennas are emerging as practical solutions for spaceborne platforms, CubeSats, and autonomous navigation systems where size, weight, and integration constraints are critical.

Applications of high-performance CP GPS antennas extend across geodetic monitoring, spacecraft orbit determination, aviation and marine navigation, autonomous vehicles, and precision timing systems. Their role in enabling centimeter- and millimeter-level positioning accuracy makes them indispensable components of modern satellite navigation infrastructure.

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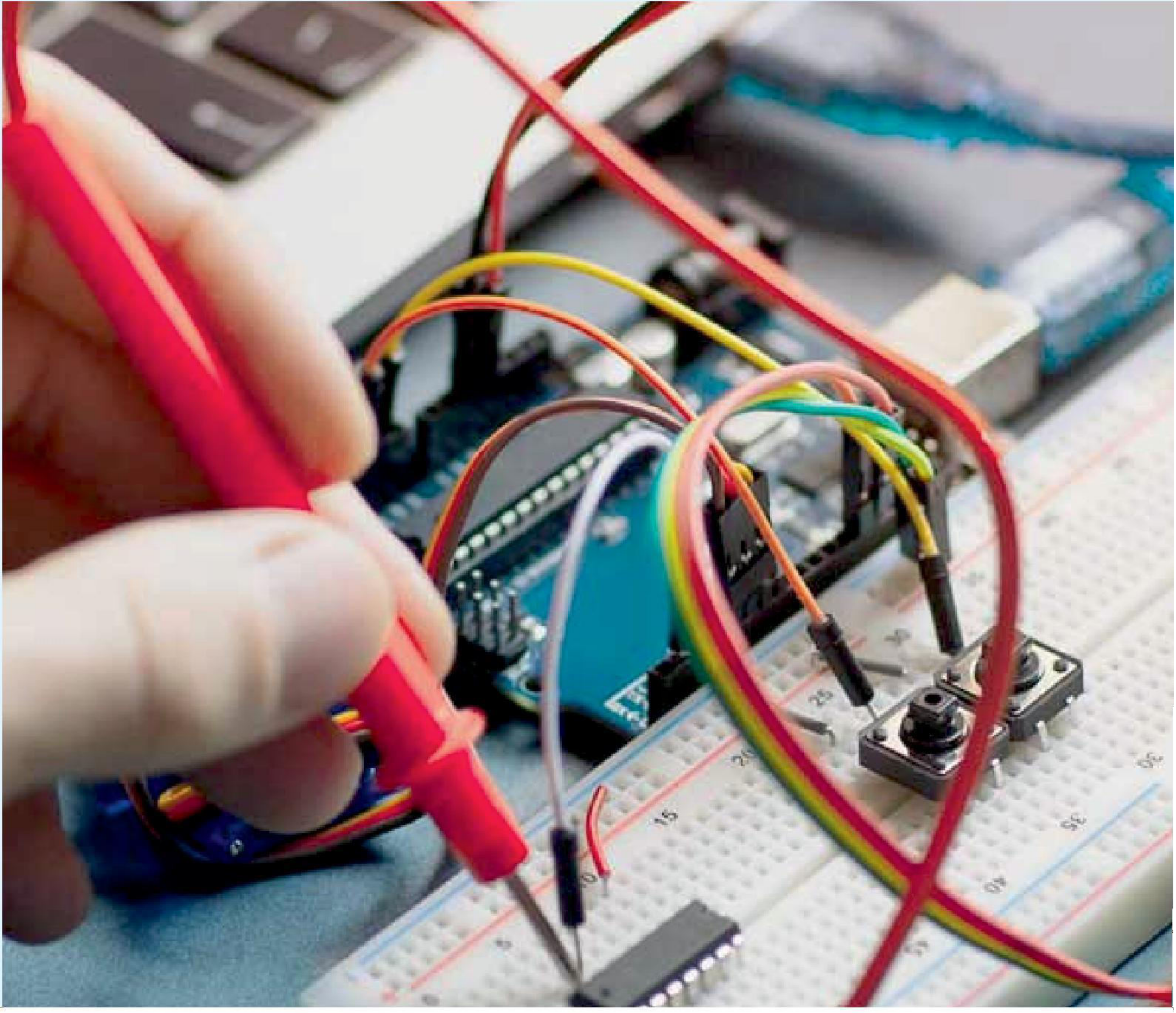

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