GNSS Antenna Technologies: A Critical Review of Design, Performance, and Emerging Directions for Resilient Positioning, Navigation, and Timing

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ABSTRACT

Global Navigation Satellite Systems (GNSS) now underpin a wide range of positioning, navigation, and timing (PNT) applications, from autonomous vehicles and precision agriculture to critical infrastructure timing and geodetic monitoring. The antenna remains a performance-limiting component in these systems: it determines how effectively satellite signals are captured, how well multipath and interference are suppressed, and how stable the phase reference is for high-precision measurements. This review provides a critical assessment of GNSS antenna technologies, covering established designs (patch, helical, choke ring, chip, stacked, dipole, and array antennas) alongside their operating principles, performance trade-offs, and application suitability. Key performance parameters, including gain, bandwidth, axial ratio, polarization purity, impedance matching, phase centre stability, and group delay, are examined with attention to their practical influence on positioning accuracy. The review also addresses frequency band support across GPS, GLONASS, Galileo, BeiDou, QZSS, and NavIC constellations, and maps antenna requirements against current and forthcoming signal modernisation efforts. Importantly, the paper situates GNSS antenna design within the broader context of emerging challenges and opportunities: the growing threat of intentional jamming and spoofing, the development of controlled reception pattern antennas (CRPAs) for interference mitigation, the integration of GNSS with low Earth orbit (LEO) PNT augmentation layers, the convergence of satellite navigation with 5G/6G non-terrestrial networks, and the demand for compact, wearable, and reconfigurable antenna solutions. The review identifies specific gaps in current research and outlines directions for antenna designs capable of meeting the requirements of next-generation resilient PNT architectures.

Keywords: GNSS antenna; controlled reception pattern antenna (CRPA); resilient positioning; phase center stability

INTRODUCTION

Global Navigation Satellite Systems (GNSS) provide the backbone for modern positioning, navigation, and timing services. Four global constellations are now operational: the United States GPS, Russia's GLONASS, the European Union's Galileo (which reached full operational capability in 2024), and China's BeiDou-3 (Maciejewska and Maciuk, 2025). Regional systems, notably Japan's Quasi-Zenith Satellite System (QZSS) and India's NavIC, further augment coverage over their respective service areas. Together, these constellations

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make more than 130 satellites available to a modern multi-constellation receiver, a substantial improvement over the single-constellation era (Ahmed et al., 2025).

The antenna is the first element in the GNSS signal chain, and its design has a disproportionate effect on overall system performance. A poorly designed or poorly matched antenna degrades signal-to-noise ratio, introduces phase centre variations that propagate directly into positioning errors, and fails to suppress multipath reflections or interference (Raj and Mandal, 2025). Conversely, a well-designed antenna can improve positioning accuracy, enable reception across multiple frequency bands and constellations, and provide resilience against signal degradation. These considerations are not merely academic. As GNSS-dependent applications expand into safety-critical domains (autonomous driving, aviation, and maritime operations), and as the electromagnetic environment grows more hostile (with documented increases in both intentional jamming and spoofing incidents across multiple regions), the demands placed on GNSS antennas are intensifying (Calian GNSS, 2025; NovAtel, 2025).

Several parallel developments are reshaping what is expected of a GNSS antenna. First, constellation modernisation is adding new signals and frequencies. GPS III satellites carry the L1C civil signal, Galileo's High Accuracy Service (HAS) delivers approximately 20 cm horizontal accuracy, and Galileo Second Generation (G2) satellites are scheduled for initial launches around 2027 with improved antennas and inter-satellite links. These developments require antennas with wider bandwidth and stable multi-frequency performance. Second, the growing vulnerability of GNSS to radio-frequency interference has driven interest in controlled reception pattern antennas (CRPAs) and adaptive array processing for civilian applications, a domain previously confined to the military sector. Third, the emergence of Low Earth Orbit PNT (LEO-PNT) as a complementary navigation layer, exemplified by ESA's Celeste LEO-PNT demonstration satellites launched in March 2026, introduces new antenna requirements including reception of signals from rapidly moving, low-altitude satellites. Fourth, the convergence of satellite navigation with 5G and forthcoming 6G non-terrestrial networks (NTN) is creating demand for antenna solutions that can support both communication and positioning functions (De Gaudenzi et al., 2025).

Despite these developments, much of the existing literature on GNSS antennas remains descriptive, cataloguing antenna types and their general characteristics without critically assessing their suitability for the evolving PNT landscape. This review aims to address that gap. It provides a structured evaluation of established GNSS antenna technologies, analyses the performance parameters that determine positioning quality, surveys frequency band support across current and planned constellations, and examines the application domains where different antenna designs are deployed. Critically, it also assesses emerging antenna technologies and design paradigms driven by the need for resilient, multi-source PNT in an increasingly contested electromagnetic environment.

Types Of GNSS Antennas

GNSS antennas can be broadly categorized by their physical structure, operating principle, and intended application. The principal types discussed in the literature and deployed in practice include patch, helical, choke ring, chip, stacked, dipole, and array antennas. Each involves different design trade-offs between size, cost, performance, and complexity. This section examines each type, with attention to their operating mechanisms, strengths, limitations, and the applications for which they are best suited.

Patch Antennas

Patch antennas are the most widely deployed GNSS antenna type, owing to their low profile, ease of manufacture, and straightforward integration into consumer and industrial platforms. A typical GNSS patch antenna consists of a metallic radiating element mounted on a dielectric substrate above a ground plane as shown in figure 1. The radiating element is dimensioned to resonate at the desired GNSS frequency, and the feed arrangement (probe feed, aperture coupling, or proximity coupling) is configured to excite two orthogonal modes with a 90-degree phase offset, producing the right-hand circular polarization (RHCP) required for GNSS signal reception (Mishra et al., 2024).

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The radiation pattern of a single-layer patch antenna is broadly hemispherical, with maximum gain near the zenith, which aligns well with the overhead distribution of GNSS satellites. Typical gain values for commercial GNSS patch antennas range from 3 to 7 dBi, depending on substrate material, ground plane dimensions, and whether an active low-noise amplifier (LNA) is integrated. The compact form factor makes patch antennas suitable for smartphones, tablets, vehicle-mounted receivers, unmanned aerial vehicles (UAVs), and wearable devices (Wang et al., 2025).

However, single-layer patch antennas have inherent bandwidth limitations, typically covering only a single GNSS frequency band (for example, L1 at 1575.42 MHz). This restricts their use in applications requiring multi-frequency reception for ionospheric error correction. Multipath rejection is also modest compared to more specialized designs, because the ground plane is usually too small to effectively suppress low-elevation reflected signals. For applications where cost, size, and weight are the primary constraints, and where single-frequency, metre-level accuracy is acceptable, the patch antenna remains the default choice.

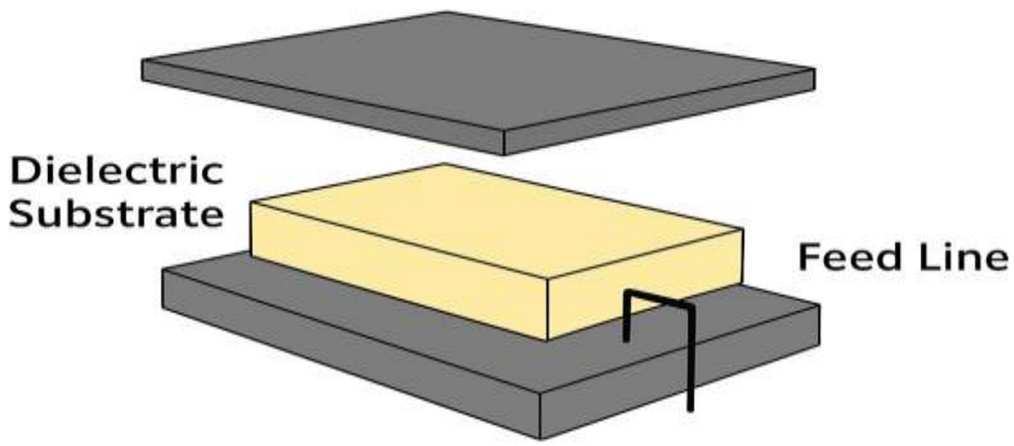

Figure 1: A Patch GNSS Antenna (Mishra *et al.,* 2024).

Helical Antennas

Helical antennas consist of a conducting wire wound in a helix above a ground plane as shown in figure 2. For GNSS applications, they typically operate in axial mode, where the helix circumference is approximately one wavelength, producing a directional beam with inherent circular polarization (Cheng et al., 2023). This natural circular polarization is an advantage: unlike patch antennas, which require specific feed arrangements to achieve RHCP, helical antennas produce circular polarization as a consequence of their geometry.

The axial-mode helical antenna offers several performance benefits for GNSS. Its beamwidth is wide enough to receive signals across a broad range of elevation angles, while its directional gain is higher than that of a simple patch. The polarization purity (indicated by a low axial ratio) tends to be maintained over a wide angular range, which helps reduce multipath errors from reflected signals that arrive with reversed polarization. Multi-turn helical designs can achieve gain values of 10 dBi or more, making them suitable for surveying, aviation, and precision navigation where signal quality is important.

The main drawback of helical antennas is their physical profile. They extend vertically above the ground plane, making them less suitable for applications where a flush or low-profile installation is required. Quadrifilar helix antennas (QHAs) offer a compact variant and have found use in handheld GNSS receivers and, more recently, in LEO-PNT satellite payloads, where Anywaves has developed deployable QHA antennas for ESA's Celeste demonstration mission operating in L-band (Anywaves, 2025). For terrestrial applications requiring compactness alongside good circular polarization, the QHA represents a useful compromise between performance and size.

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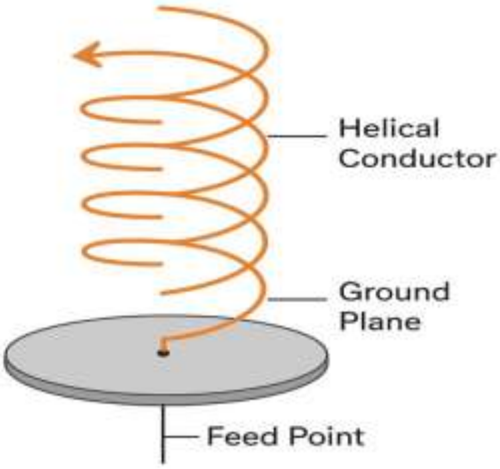

Figure 2: A Helix GNSS Antenna (Cheng *et al.,* 2023)

Choke Ring Antennas

Choke ring antennas are the reference standard for high-precision GNSS applications where multipath suppression and phase centre stability are non-negotiable requirements. The design consists of a central radiating element (typically a patch or dipole feed) surrounded by concentric metallic rings, each approximately a quarter-wavelength deep at the operating frequency as shown in figure 3 (Taghdisi et al., 2021). These rings act as corrugated surfaces that attenuate surface waves propagating along the ground plane, thereby reducing the antenna's sensitivity to signals arriving from low elevation angles, where multipath reflections are most prevalent.

The result is a sharp roll-off in the antenna's gain pattern below approximately 10 degrees elevation, which effectively filters out ground-reflected signals while maintaining good reception of direct satellite signals at higher elevations. Phase centre variations (PCVs) in choke ring antennas are typically small and well-characterised, making them suitable for geodetic networks, continuously operating reference stations (CORS), and scientific applications where millimetre-level positioning is required (Cao et al., 2020).

The principal limitations of choke ring antennas are their size and weight. A multi-frequency choke ring antenna can measure 30 cm or more in diameter and weigh several kilograms. This makes them impractical for mobile, airborne, or consumer applications. Substrate-integrated choke ring designs have been proposed as a more compact alternative, reducing the overall footprint while retaining some of the multipath suppression characteristics (Taghdisi et al., 2021). Cost is also a factor: choke ring antennas are significantly more expensive than patch or helical alternatives, limiting their use to applications where performance justifies the investment.

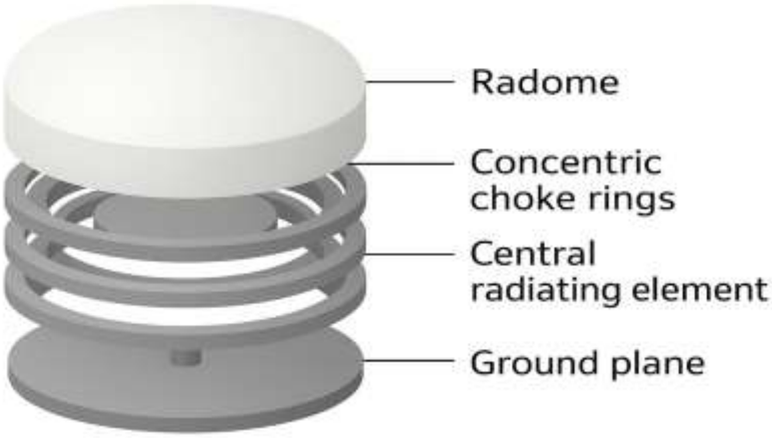

Figure 3: A Choke ring GNSS Antenna (Taghdisi *et al.,* 2021)

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Chip Antennas

Chip antennas are miniature ceramic-based antennas designed for integration onto printed circuit boards (PCBs) in space-constrained devices. They consist of a metallic radiating element deposited on a high-dielectric-constant ceramic substrate as shown in figure 4, which allows the antenna to be physically much smaller than the free-space wavelength at GNSS frequencies (Abd Rahman et al., 2022). Typical chip antennas for GNSS measure only a few millimetres on each side.

The small size comes at a performance cost. Chip antennas generally exhibit lower gain (often below 0 dBi before any LNA), narrower bandwidth, and less effective circular polarization compared to patch or helical designs. Their radiation pattern is also more dependent on the PCB ground plane geometry, which means that performance can vary significantly depending on the host device's layout. Multipath rejection is minimal.

Despite these limitations, chip antennas are the dominant choice for Internet of Things (IoT) sensors, asset trackers, wearable devices, and other applications where physical size, power consumption, and unit cost are the primary design drivers. In these contexts, absolute positioning accuracy is often secondary to the ability to obtain a position fix reliably in a small form factor. As dual-frequency GNSS chipsets (supporting L1 and L5 simultaneously) become standard in mass-market devices, the demand for chip antennas capable of covering both bands is growing, though achieving adequate bandwidth and efficiency across two separated bands in such a small element remains a design challenge.

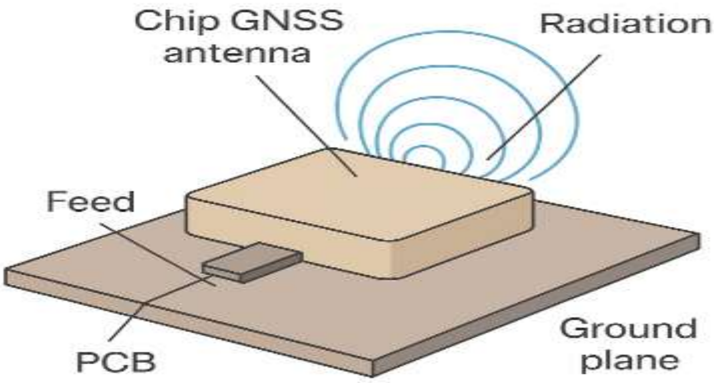

Figure 4: A Chip GNSS Antenna (Abd Rahman *et al.,* 2022)

Stacked Patch Antennas

Stacked patch antennas address the bandwidth limitation of single-layer patches by introducing one or more additional radiating layers separated by dielectric substrates. The lower (driven) patch is directly fed, while the upper (parasitic) patches couple electromagnetically, each resonating at a slightly different frequency. The combined response produces a wider operating bandwidth than any single layer could achieve alone, making stacked designs suitable for multi-frequency GNSS reception (Kiris, 2024).

A well-designed stacked patch antenna can cover two or three GNSS frequency bands (for example, L1/E1 and L5/E5a) within a single compact structure. This is particularly relevant for modern receivers that exploit dual-frequency measurements to correct for ionospheric delay, a capability that significantly improves positioning accuracy. Stacked designs are used in high-precision GNSS receivers, geodetic surveying instruments, UAV navigation systems, and precision agriculture equipment.

Dipole-Based Antennas

Standard dipole antennas consist of two conductive elements fed at the centre. In their basic form, they produce linearly polarized radiation, which is inherently mismatched with the RHCP signals transmitted by GNSS satellites. This polarization mismatch results in a 3 dB signal loss even under ideal conditions, and

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worsens when multipath reflections (which tend to be left-hand circularly polarized after a single reflection) are present (Sheikh et al., 2025).

To make dipole structures compatible with GNSS, modifications are applied. Crossed dipoles, in which two orthogonal dipole elements are fed with a 90-degree phase difference, produce circular polarization. Quadrifilar helical antennas can be understood as a helical extension of the crossed-dipole concept. Turnstile antennas, another crossed-dipole variant, are used in some GNSS reference station designs.

In practice, modified dipole antennas are used where simplicity, light weight, and omnidirectional coverage in the horizontal plane are advantageous, for example, in low-cost navigation receivers, maritime applications, and some IoT deployments. Their performance in terms of multipath rejection and phase centre stability is generally inferior to patch, helical, or choke ring designs, limiting their use in precision applications.

Array Antennas

Array antennas consist of multiple antenna elements arranged in a defined spatial configuration, typically linear, circular, or planar. By controlling the amplitude and phase of signals at each element, the array's composite radiation pattern can be shaped electronically: beams can be steered toward satellites of interest, and nulls can be placed in the direction of interference sources, all without any physical movement (BniLam et al., 2023).

For GNSS applications, the most significant variant is the controlled reception pattern antenna (CRPA), which combines a multi-element antenna array with adaptive beamforming algorithms. CRPAs were originally developed for military applications to protect GPS receivers against intentional jamming. The antenna array spatially filters incoming signals, maintaining gain toward desired satellite signals while suppressing jamming or spoofing signals that arrive from different directions. Recent systems such as NovAtel's RoDAR have demonstrated 15 to 25 dB of additional jamming resistance compared to single-antenna receivers, alongside spoofing detection capabilities across multiple GNSS bands (NovAtel, 2025). Calian GNSS has introduced compact CRPA designs with in-band null-forming for civilian critical infrastructure and defense applications (Calian GNSS, 2025).

Comparative Summary of GNSS Antenna Types

Table 1 provides a comparative overview of the principal GNSS antenna types discussed above, summarizing their typical characteristics, advantages, limitations, and primary application domains.

Table 1. Comparative summary of principal GNSS antenna types.

Type	Typical Gain (dBic)	Frequency Coverage	Key Strengths	Key Limitations	Primary Applications
Patch	3 to 7	Single or dual-band	Low profile, low cost, easy integration	Narrow bandwidth, limited multipath rejection	Consumer devices, vehicles, UAVs
Helical	5 to 12	Multi-band	Natural CP, good multipath rejection, wide beamwidth	Taller profile, not flush-mountable	Surveying, aviation, LEO-PNT payloads
Choke Ring	5 to 9	Multi-band	Excellent multipath suppression, stable phase centre	Large, heavy, expensive	Geodetic stations, CORS, scientific monitoring
Chip	< 0 (passive)	Single-band (typically)	Very compact, low cost, PCB-mountable	Low gain, poor CP, ground-plane dependent	IoT, wearables, asset tracking
Stacked Patch	4 to 8	Dual or triple-band	Multi-frequency in compact form, good	Fabrication complexity, layer	Precision receivers, geodesy,

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			CP	alignment critical	agriculture
Dipole-based	2 to 5	Single or dual-band	Simple, lightweight, omnidirectional	Polarisation mismatch (unless modified), poor multipath rejection	Low-cost navigation, maritime, IoT
Array (CRPA)	Configurable	Multi-band	Beam steering, interference rejection, anti-spoofing	High cost, complexity, power consumption	Defence, critical infrastructure, autonomous vehicles

Key Performance Parameters Of GNSS Antennas

The performance of a GNSS antenna cannot be meaningfully evaluated by any single metric. Several interrelated parameters collectively determine how effectively an antenna captures satellite signals, rejects interference, and supports accurate positioning. This section examines the parameters most relevant to GNSS antenna performance, with attention to their physical basis, mathematical description, and practical significance.

Radiation Pattern

The radiation pattern of a GNSS antenna describes its sensitivity to signals as a function of direction. An ideal GNSS antenna would have uniform, high gain across the upper hemisphere (to receive signals from all visible satellites) with a sharp cutoff at the horizon and zero gain below it (to reject ground-reflected multipath signals). No real antenna achieves this perfectly. Patch antennas approximate a cosine-shaped pattern with moderate horizon suppression, while choke ring antennas achieve a steeper roll-off near the horizon at the cost of size (Wang et al., 2021).

The practical consequence is that antenna pattern shape directly affects the satellite geometry available to the receiver. An antenna with poor low-elevation gain may lose satellites near the horizon, degrading the geometric dilution of precision (GDOP). Conversely, an antenna with too much low-elevation sensitivity will admit multipath-contaminated signals. The design objective is a controlled trade-off between coverage and multipath rejection, tailored to the application.

Antenna Gain

Antenna gain quantifies the ability of the antenna to concentrate received power relative to an isotropic radiat-

or. For a GNSS antenna, gain is a function of elevation and azimuth angles, and is given by:

$$G(\theta, \emptyset) = \eta \cdot \frac{4\pi A_e}{\lambda^2} \quad (1)$$

where η is the antenna radiation efficiency, A_e is the effective aperture (m²), λ is the signal wavelength (m), and (θ, φ) denote the elevation and azimuth angles, respectively (Tupek et al., 2023). Higher gain improves signal-to-noise ratio, which is particularly important for GNSS because satellite signals arrive at the Earth's surface at very low power levels (typically around −130 dBm for GPS L1 C/A). Gain values quoted for commercial GNSS antennas typically refer to the zenith direction and range from below 0 dBic for chip antennas to above 10 dBic for multi-turn helical designs.

Bandwidth

Bandwidth defines the frequency range over which the antenna maintains acceptable performance (typically defined by a return loss threshold of 10 dB or better). For GNSS, the required bandwidth depends on both the signal structure and the number of frequency bands to be received. The Nyquist bandwidth for a modulated signal is:

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$$B = 2f_m \qquad (2)$$

where f_m is the maximum frequency component of the modulating signal. For BPSK-modulated GNSS signals, the occupied bandwidth approximates $2 \times R_c$, where R_c is the pseudo-random noise (PRN) code chipping rate (Pizzo et al., 2022). GPS L1 C/A, with a chipping rate of 1.023 MHz, requires approximately 2 MHz of bandwidth, while GPS L5, with a 10.23 MHz chipping rate, requires approximately 20 MHz. An antenna designed for simultaneous L1 and L5 reception must either provide continuous bandwidth across the full 1176 to 1575 MHz range (which is impractical for most resonant structures) or provide separate resonant bands centred on each frequency, as achieved by stacked patch designs.

Axial Ratio and Polarization

GNSS satellites transmit right-hand circularly polarized (RHCP) signals. The receiving antenna must therefore also be RHCP to minimize polarization mismatch loss. The quality of circular polarization is measured by the axial ratio (AR), defined as the ratio of the major to minor axes of the polarization ellipse:

$$AR \ in \ dB = 20\log_{10}\left(\frac{|E_{major}|}{|E_{minor}|}\right) \qquad (3)$$

An axial ratio of 0 dB represents perfect circular polarization, while 3 dB is the conventional upper threshold for acceptable GNSS performance (Yuan et al., 2021). The practical significance of maintaining a low axial ratio extends beyond simple polarization matching. After a single ground reflection, an RHCP signal becomes predominantly left-hand circularly polarized (LHCP). An antenna with good RHCP purity and high cross-polarization discrimination will attenuate these reflected signals, providing a form of multipath rejection that operates independently of the antenna's spatial pattern (Liu et al., 2022).

Impedance Matching, Return Loss, and VSWR

Impedance matching ensures that the maximum amount of signal power captured by the antenna is transferred to the receiver front end, with minimal reflection. GNSS receivers conventionally use a 50 Ω reference impedance. The quality of the impedance match is characterized by the reflection coefficient (Γ), the return loss (RL), and the voltage standing wave ratio (VSWR) (Govind, 2020; Ibrahim et al., 2022):

$$\Gamma = \frac{Z_A - Z_R}{Z_A + Z_R} \qquad (4)$$

$$RL\ (dB) = -20\log_{10}|\Gamma| \qquad (5)$$

$$VSWR = \frac{1-|\Gamma|}{1+|\Gamma|} \qquad (6)$$

For GNSS applications, a return loss of at least 10 dB (corresponding to VSWR of less than 2:1) is generally required, while precision applications typically demand 15 dB or better (VSWR below 1.5:1). Poor impedance matching reduces the effective signal power available to the receiver, which is particularly problematic given the already weak power levels of GNSS signals at the Earth's surface.

Phase Centre Stability

The phase centre of a GNSS antenna is the effective point from which the antenna appears to receive signals. In an ideal antenna, this point would be fixed regardless of the signal's frequency or direction of arrival. In practice, the phase centre shifts as a function of elevation angle, azimuth angle, and frequency. These shifts, known as phase centre variations (PCVs), translate directly into positioning errors if they are not calibrated and corrected (Cao et al., 2020).

The PCV at a given direction (θ, φ) is expressed as:

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$$\Delta\Phi(\theta, \emptyset) = \Phi_{measured} - \Phi_{ideal} \quad (7)$$

For geodetic and real-time kinematic (RTK) applications targeting centimetre-level or better accuracy, PCVs must be characterized through absolute antenna calibration (using anechoic chambers or robotic field calibration) and applied as corrections during data processing. Choke ring antennas exhibit the smallest and most stable PCVs among common GNSS antenna types, which is the primary reason they are standard equipment at geodetic reference stations. For array antennas and CRPAs, phase centre compensation becomes more complex because the effective phase centre moves as the beam is steered, an issue that is receiving growing research attention (Cao et al., 2020).

Front-to-Back Ratio

The front-to-back (F/B) ratio measures the difference in gain between the antenna's main beam direction (zenith for GNSS) and the opposite direction (nadir):

$$F/B = G_{front} - G_{back} \quad (8)$$

A higher F/B ratio indicates better suppression of signals arriving from below the antenna, which reduces multipath contamination from ground reflections and improves positioning accuracy. Choke ring antennas achieve high F/B ratios (typically greater than 20 dB) through their corrugated ground plane structure, while simple patch antennas on small ground planes may have F/B ratios of only 10 to 15 dB (Li et al., 2024).

Group Delay

Group delay describes the time delay experienced by different frequency components of a signal as they pass through the antenna system. It is defined as the negative derivative of the antenna's phase response with respect to angular frequency:

$$\tau_g = -\frac{d\emptyset(\omega)}{d\omega} \quad (9)$$

A constant group delay across the operating bandwidth means all frequency components of the signal experience the same delay, preserving the signal's shape. Variations in group delay distort the correlation peak used for pseudo range measurement and introduce errors into carrier-phase observations, both of which degrade positioning accuracy (Beer et al., 2021). Group delay variation is particularly important for wideband signals such as GPS L5 and Galileo E5, where the signal bandwidth is large enough that frequency-dependent delay variations within the antenna become significant.

FREQUENCY BAND SUPPORT FOR GNSS CONSTELLATIONS

GNSS signals are transmitted in the L-band, spanning approximately 1.1 to 1.6 GHz. Each constellation uses specific frequency allocations, and antenna designers must account for these allocations when specifying bandwidth and resonant frequency coverage. Table 2 summarizes the primary frequency bands for the major GNSS constellations, including the regional augmentation systems QZSS and NavIC.

Table 2. Frequency bands for GNSS constellations (adapted from Ogaja, 2022; updated with current constellation data).

Constellation	Band	Frequency (MHz)	Primary Service
GPS (United States)	L1	1575.42	Civil, military
	L2	1227.6	Dual-frequency correction
	L5	1176.45	Safety-of-life, high precision
GLONASS (Russia)	G1	1598.06 –	Standard positioning

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		1605.38	
	G2	1242.94 – 1248.63	Dual-frequency correction
Galileo (European Union)	E1	1575.42	Open, PRS, HAS
	E5a	1176.45	Open, HAS
	E5b	1207.14	Open, safety-of-life
	E6	1278.75	HAS, PRS, commercial
BeiDou (China)	B1C	1575.42	Open, interoperable
	B1I	1561.1	Open (legacy)
	B2a	1176.45	Open, interoperable
	B2b	1207.14	PPP, precise point positioning
	B3I	1268.52	Authorised service
QZSS (Japan)	L1	1575.42	GPS augmentation
	L5	1176.45	Safety, high precision
NavIC (India)	L5	1176.45	Open service
	S-band	2492.03	Restricted service

Several observations are relevant for antenna design. The L1/E1/B1C band at 1575.42 MHz is shared across GPS, Galileo, BeiDou, and QZSS, making it the single most important frequency for a GNSS antenna to cover. Similarly, the L5/E5a/B2a band at 1176.45 MHz is shared across multiple constellations and is increasingly used for dual-frequency positioning. An antenna covering just these two bands can support multi-constellation, dual-frequency operation, which is why the L1+L5 combination has become the target for mass-market dual-frequency receivers. The E6/B3I band around 1268 to 1278 MHz supports specialized services (Galileo HAS, BeiDou PPP) and is relevant for high-accuracy applications. NavIC's S-band signal at 2492 MHz is unique among GNSS constellations and requires a separate antenna element or a wideband design, posing additional challenges for multi-constellation antenna designers.

APPLICATIONS OF GNSS ANTENNAS

Transportation, Navigation, and Autonomous Systems

GNSS antennas are integral to vehicle navigation, fleet management, aviation approach and landing systems,

maritime positioning, and the emerging field of autonomous driving. In autonomous vehicles, the antenna must support dual-frequency, multi-constellation reception for sub-metre lane-level positioning, and increasingly must be paired with anti-jamming and anti-spoofing capabilities. Aviation applications demand certified antenna performance with guaranteed phase centre stability and multipath suppression. Maritime systems, where GNSS spoofing has been documented in the Baltic Sea and other regions, are driving demand for resilient antenna solutions including CRPAs (Ahmed et al., 2025).

Geodesy, Surveying, and Structural Monitoring

High-precision GNSS applications require antennas with well-characterized phase centres, high multipath rejection, and stable multi-frequency performance. Choke ring and geodetic-grade stacked patch antennas are standard at continuously operating reference stations and in networks that define national and international geodetic reference frames. Structural monitoring of bridges, dams, and tall buildings uses permanently installed GNSS antennas to detect millimetre-level deformations over time (Ahmed et al., 2025).

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Precision Agriculture and Environmental Monitoring

Precision agriculture uses GNSS for automated steering of tractors, variable-rate application of inputs, and field boundary mapping. RTK-corrected GNSS with dual-frequency antennas provides the centimetre-level accuracy required for pass-to-pass guidance. GNSS antennas are also used in environmental monitoring applications, including measurement of tectonic plate motion, glacial movement, soil moisture retrieval (via GNSS reflectometry), and atmospheric water vapour sensing.

Timing, Telecommunications, and Critical Infrastructure

GNSS provides the primary timing reference for telecommunications networks, financial trading systems, and power grid synchronization. These applications depend on stable, continuous reception of GNSS timing signals, making antenna reliability and interference resistance important. The vulnerability of GNSS timing to jamming and spoofing has led to the adoption of holdover oscillators (such as SiTime's Endura Super-TCXO) alongside GNSS antennas, providing continued timing accuracy during periods of signal disruption. Multi-antenna, multi-constellation receivers are increasingly deployed at critical infrastructure sites to provide redundancy.

IoT, Wearables, and Consumer Electronics

The proliferation of location-aware IoT devices, wearable fitness trackers, and asset management tags has created demand for extremely compact, low-power GNSS antennas. Chip antennas dominate this segment, though dual-frequency chip antenna designs are now emerging to take advantage of the improved accuracy offered by L1+L5 mass-market chipsets from manufacturers such as u-blox, Qualcomm, and Broadcom.

EMERGING DIRECTIONS AND RESEARCH FRONTIERS

Anti-Jamming and Anti-Spoofing Antenna Technologies

The electromagnetic threat environment for GNSS has worsened in recent years. Consumer-grade jamming devices are widely available despite being illegal in most jurisdictions, and spoofing attacks have been documented against civilian shipping, aviation, and drone operations. This has moved anti-jamming and anti-spoofing from a purely military concern into the civilian domain. At the antenna level, CRPAs with adaptive null-steering provide the most capable interference mitigation, but their cost and complexity limit deployment. Research is focused on reducing CRPA element count (from seven or eight elements to three or four), developing lower-cost digital beamforming architectures, and integrating anti-spoofing signal authentication at the receiver firmware level alongside antenna-domain spatial filtering (NovAtel, 2025; Septentrio, 2025).

LEO-PNT and Multi-Layer Navigation Architectures

The concept of using Low Earth Orbit satellites to provide a complementary PNT layer below the traditional GNSS medium Earth orbit has gained substantial momentum. LEO satellites offer stronger signals (due to shorter range), faster geometric diversity, and a degree of natural resilience against MEO-targeted jamming. ESA's Celeste LEO-PNT programme launched its first demonstration satellites in March 2026, carrying deployable quadrifilar helix antennas designed for L-band PNT signal transmission from a 510 km orbit (Anywaves, 2025). The integration of LEO-PNT signals into existing GNSS receivers will require antennas capable of tracking both MEO GNSS satellites (slow-moving, predictable geometries) and LEO satellites (fast-moving, with high Doppler rates and frequent overhead passes). This places new demands on antenna beamwidth, gain uniformity, and the receiver's ability to acquire signals from rapidly changing directions (De Gaudenzi et al., 2025).

GNSS and 5G/6G Non-Terrestrial Network Convergence

The convergence of satellite navigation with 5G and planned 6G terrestrial and non-terrestrial networks represents a significant development for antenna design. The 3GPP NTN standards define how LEO satellite

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infrastructure can extend 5G coverage and support positioning reference signals. This creates the possibility of integrated antenna systems that serve both communication and positioning functions, potentially on shared hardware. However, the optimal antenna characteristics for communications (maximizing spectral efficiency, using small spot beams) conflict in some respects with those for positioning (maximizing multi-satellite visibility, broad beam coverage). Resolving this conflict is an open research problem with direct implications for antenna array design, beam management, and signal processing (De Gaudenzi et al., 2025).

Reconfigurable and Metasurface-Based Antennas

Reconfigurable antennas, capable of dynamically adjusting their frequency response, polarization, or radiation pattern, are an active research area with potential GNSS applications. Metasurface-based antennas, which use arrays of sub-wavelength elements to manipulate electromagnetic wavefronts, offer the possibility of electronically steered beams without the cost and complexity of traditional phased array architectures. Reconfigurable intelligent surfaces (RIS) have been explored for wireless communications, and their application to GNSS interference mitigation and signal enhancement is a natural extension (Zouhdi et al., 2022; Mu et al., 2025). However, most metasurface antenna research to date has focused on frequencies above the GNSS L-band, and practical GNSS implementations remain at an early stage.

Compact, Wearable, and Textile GNSS Antennas

The growth of wearable technology and body-worn GNSS tracking have stimulated interest in textile and flexible GNSS antennas that can be integrated into clothing, helmets, or equipment harnesses. These antennas face additional challenges beyond miniaturization: their performance changes with bending, folding, and proximity to the human body, which detunes the antenna and absorbs radiated power (Wang et al., 2025). Research in this area is focused on conductive textiles, flexible substrates, and antenna geometries that maintain acceptable GNSS performance under mechanical deformation and body-loading conditions.

CONCLUSION

This review has examined the principal GNSS antenna types, their performance characteristics, frequency band support, and application domains, set against the backdrop of a GNSS landscape that is simultaneously expanding in capability and facing growing threats to signal integrity. The core finding is that no single antenna design is universally optimal; the choice between patch, helical, choke ring, stacked, chip, dipole, and array configurations involve trade-offs across size, cost, gain, bandwidth, multipath rejection, and phase centre stability that must be resolved in the context of each specific application.

Several directions deserve particular research attention. First, the development of affordable, compact CRPA solutions for civilian anti-jamming applications is a pressing need, given the documented increase in GNSS interference events. Second, the emergence of LEO-PNT as a complementary navigation layer introduces antenna requirements that differ from those of traditional MEO GNSS reception, particularly in terms of tracking fast-moving satellites and handling higher Doppler rates. Third, the convergence of GNSS with 5G/6G non-terrestrial networks demands antenna architectures capable of serving both communication and positioning functions, a design problem with inherent conflicts that current solutions do not fully resolve. Fourth, the mass-market transition from single-frequency to dual-frequency (L1+L5) GNSS reception is creating demand for compact, low-cost multi-band antenna designs, including chip antennas and stacked patches, that maintain acceptable polarization and bandwidth performance within tight form factors.

Addressing these challenges will require advances in antenna materials, fabrication techniques, adaptive signal processing, and system-level integration. The trajectory is toward antenna systems that are smaller, more versatile, and more resilient than those currently deployed, capable of operating within the multi-source, multi-layer PNT architectures that are taking shape for the next decade of GNSS applications.

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