Antennas for Global Navigation Satellite System (GNSS)

Global Navigation Satellite System receive antenna technologies are reviewed in this paper, and the design challenges of this exciting area of antenna design are discussed.

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ABSTRACT | Global Navigation Satellite System (GNSS) will in effect be fully deployed and operational in a few years, even with the delays in Galileo as a consequence of European Union's financial difficulties. The vastly broadened GNSS spectra, spread densely across 1146–1616 MHz, versus the narrow Global Positioning System (GPS) L1 and L2 bands, together with a constellation of over 100 Medium Earth Orbit (MEO) and Geostationary Earth Orbit (GEO) satellites versus GPS' 24 MEO satellites, are revolutionizing the design of GNSS receive antennas. For example, a higher elevation cutoff angle will be preferred. As a result, fundamental changes in antenna design, new features and applications, as well as cost structures are ongoing. Existing GNSS receive antenna technologies are reviewed and design challenges are discussed.

KEYWORDS | Broadband antenna; Compass; Galileo; GLONASS; GPS antenna; satellite navigation system antenna

I. INTRODUCTION—FROM GPS TO GNSS

Since the deployment of the Global Positioning System (GPS) by the United States and a similar GLONASS system by the Soviet Union around 1990 [1]–[3], GPS applications have proliferated globally, not only in the military arena but also in commercial and consumer markets. While the importance of GPS antenna relative to GPS receiver is obvious and remains, the performance and cost issues have fundamentally changed. For example, due to drastic price reduction of GPS low noise amplifier (LNA), from \$800 in early 1990 to under \$1 per unit today for a medium-quality single-band LNA, GPS antennas today routinely include LNA. The price of a GPS antenna also varies widely, ranging from \$4 to \$8000, sometimes higher than that of the receiver.

Application of GLONASS has been minuscule after dissolution of the Soviet Union. Recent recovery of the Russian economy propelled by the oil boom has enabled the revitalization of GLONASS, which restarted full-constellation operation in April 2011.

In 2002, the European Union started to develop Galileo. Originally targeted to start operation in 2008, Galileo suffered from years of delays due to financial and technical troubles. In 2011, its delayed plan was to have full global coverage in 2019. China began to develop Compass (Beidou) in the late 1990s, but has been fast moving in recent years, and is positioned to have a full-fledged GNSS within a few years [4].

Additionally, GPS, GLONASS, and Compass are also being augmented by Geostationary Earth Orbit (GEO) satellites to complement their Medium Earth Orbit (MEO) satellites. Several other countries have also started their regional satellite navigation systems, such as Japan's Quasi-Zenith Satellite System (QZSS). All these satellite-based systems constitute the Global Navigation Satellite System (GNSS), with GPS, GLONASS, Galileo, and Compass being the four cornerstones with global coverage.

The upcoming availability of so many satellites, and over such a wide frequency range, in GNSS constellations, as well as the move toward more unified code-division multiple-access (CDMA) approach, in the near future will offer superior performance and lower life-cycle cost, as well as new features and capabilities. These game-changing events are also enabled by newly available low-cost software-defined radio (SDR) technologies and the unprecedented global economy. To meet the anticipated market needs, GNSS receivers covering two or more GNSS systems have been developed and deployed at fairly low costs.

While GNSS antennas will be pivotal in enabling superior performance, lower life-cycle cost, and new features

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and capabilities of new SDR receivers, books covering this topic are scanty, scattered, and mostly outdated (e.g., [5]–[7]). To the author's knowledge, a book [8] and a book chapter [9] on GNSS antennas were scheduled for publication in 2011 and 2012. This paper provides a bird's eye view on GNSS receive antennas, written in the context of the latest developments and their consequential fundamental changes in design principles, which are departing conventional GPS antennas.

II. RADIO-FREQUENCY (RF) PERFORMANCE PARAMETERS OF GNSS ANTENNAS

The impact of the fundamental changes from GPS to GNSS has been recognized and taken advantage of by receiver manufacturers. Several GNSS receivers have recently showed up in the marketplace; and they can easily adapt to large future changes in GNSS waveforms since they are based on SDR technology. These GNSS receivers readily benefit from the fairly mature and low-cost SDR technology, which has been under continuous multibillion dollar development programs funded by the U.S. Government since 1980 as the SPEAKEASY programs, which were transitioned around 2000 to the Joint Tactical Radio System (JTRS) programs. In the commercial world, SDR development and application have been growing rapidly since about 2000.

On the other hand, SDR antenna development has not had such success as the receiver. In this context, we will discuss RF performance parameters of GNSS receive antennas, highlighting changes from those for conventional GPS.

A. Operating Frequencies and Bandwidth

Table 1 displays signals and constellations of the four major GNSS systems: GPS, GLONASS, Galileo, and Compass, with the data on maximum bandwidths largely derived from [4] and [10] for interoperability issues. GNSS spectra are spread densely across 1146–1616 MHz, covering a frequency bandwidth of 470 MHz or an octaval bandwidth of 1.41 : 1, with a gap of 259 MHz (1300–1559 MHz). Obviously, future GNSS antennas will strive to cover more bands and constellations like SDR antennas driven by their receivers.

Note that the maximum bandwidths shown in Table 1 are the maximum instantaneous bandwidth of each of the four major constellations. Note also that they are considerably larger than those adopted in many conventional GPS antenna and receiver designs. For example, the maximum bandwidth of conventional GPS L1 was about 20 MHz (or $\pm$10 MHz) and is now 30.69 MHz in the GNSS scenario.

Since the receivers will be increasingly more able to cover the entire GNSS spectrum, and take advantage of it, it is desirable and sometimes necessary that their antennas' operating frequencies and bandwidths be consistent with those of the SDR receivers. Additionally, large bandwidths are needed to mitigate detuning due to changes in antenna's installation environment. In practical applications, there is also a growing trend for GNSS antennas toward multifunction that covers not only GNSS but also some satellite communications such as satellite radio, Iridium, etc.

B. Gain Pattern and Polarization

Fig. 1 depicts two ideal elevation gain patterns, one before and one after 2010, to highlight the fundamental changes. The polar patterns are in spherical and rectangular coordinates, with the z-axis pointing to the zenith.

The gain pattern optimizes gain and coverage for satellites over $0° < \theta < \theta_C$ and mitigates problems due to multipath from satellite platform, ionosphere, troposphere, and platform environment, as well as interferences

Table 1 Signals and Constellations of Major GNSS Systems: GPS, GLONASS, Galileo, and Compass

System	Country	Constellation	Coding	Carrier/Center Frequency (MHz)	Maximum Bandwidth (MHz)
GPS	USA	24 MEO (32 satellites in orbit in 2011 and under modernization)	CDMA	L1/ L1C: 1575.420 L2/ L2C: 1227.600 L5: 1176.45	30.69
GLONASS	Russia	24 MEO (24 satellites in orbit in 2011 and 6 active spares to be added)	FDMA CDMA FDMA CDMA CDMA CDMA	L1: 1602.000+k×0.5625* L1: 1575.420 L2: 1246.000+k×0.4375* L2: 1242.000 L3: 1202.025 L5: 1176.450	40.96
Galileo	European Union	27 MEO plus 3 spares (2 in operation in 2011)	CDMA	E1: 1575.420 E6: 1278.750 E5b: 1207.140 E5: 1191.795 E5a: 1176.450	40.96
Compass	China	27 MEO plus 5 GEO and 3 IGSO (4 MEO, 5 GEO, 5 IGSO in 2011)	CDMA	B1: 1559.052~1591.788 B2: 1162.220~1217.370 B3: 1250.618~1286.423	30.69

*k=0 to 24; each satellite having an FDMA channel.

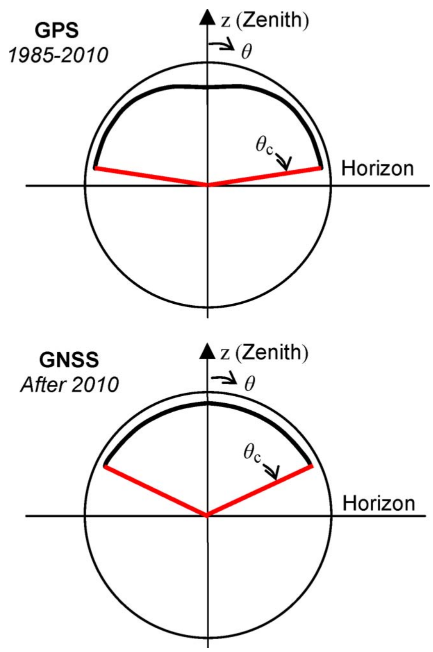

Fig. 1. *Ideal antenna gain patterns for GPS antennas (1985–2010) and GNSS antennas (after 2010).*

and noises over $\theta_C < \theta < 180°$. The sharp turn at elevation "cutoff angle" θ_C is a major design difficulty; a real-world GNSS antenna generally has a smooth cardioid pattern with hemispherical coverage. θ_C is a crucial parameter varying between applications, but is moving higher toward the zenith with the advent of GNSS.

Right-hand circular polarization (RHCP) is universally required for GNSS. The quality of the pattern's polarization is expressed in either axial ratio (AR) or the relative magnitude of its cross polarization. Generally, AR < 3 dB or cross polarization (LHCP) of <-10 dB is desired over $\theta < \theta_C$ for a medium-quality GNSS antenna.

A minimum antenna gain $G_{\min}$ in RHCP is desired over angles $\theta < \theta_C$. Generally, $G_{\min} > -10$ dBic in RHCP is needed to provide sufficient signal-to-noise ratio (SNR) for detection. But this low gain requirement can be further relaxed by up to 10 dB or so by using various software and hardware techniques for applications with lower precision requirement. At elevation angles below θ_C, i.e., $180° > \theta > \theta_C$, a vanishingly small gain is desired to mitigate terrestrial multipath and interference signals generally strong near the horizon.

The ideal gain pattern and spatial coverage vary from application to application. Before 2010, conventional GPS generally called for $80° > \theta_C > 70°$ for terrestrial applications and $100° > \theta_C > 80°$ for airborne applications. After 2010, GNSS applications are expected to move toward a higher cutoff elevation angle, probably about $70° > \theta_C > 50°$ for terrestrial applications and $80° > \theta_C > 60°$ for airborne applications.

The trend toward a higher cutoff elevation angle θ_C is due to: 1) increasingly higher interference noises near horizon, 2) availability of more satellites near zenith, and 3) superior performance using near-zenith coverage. Issue 1) is epitomized by the controversial terrestrial transmission by LightSquared near GPS L1 with 1500-W transmitters at 1525–1559 MHz, which at a half mile from the ground station is roughly 1 billion times higher than GPS signals [11].

Issue 2) is due to the upcoming completion of the four major GNSS constellations, with more than 100 satellites. Issue 3) has just been successfully demonstrated by Japan's QZSS, which will have three geosynchronous satellites in orbits to augment GPS in an Asia/Pacific region. QZSS uses only satellites at elevation angles near zenith to improve signal reception in urban canyons and mountainous terrain. With only one satellite launched in 2010, tests have shown continuous 3-cm positioning accuracy for a car driving at 20 km/h using a conventional GPS receiver equipped to receive correction from the QZSS satellite. The same GPS equipment relying only on GPS signals has accuracy of about 10 m.

C. Multipath Mitigation and Interference Suppression

The antenna is primarily a spatial filter to elevate the SNR of line-of-sight signals from selected satellites, by suppressing multipath and interference signals. A GNSS antenna with higher cutoff angle θ_C above horizon and good axial ratio (or low cross polarization) would have higher antenna gain over noise temperature to detect low line-of-sight CDMA signal desired, as demonstrated in the QZSS tests.

To suppress multipath and interference signals below the cutoff angle θ_C, choke ring, resistive loading, conducting ground plane, or metamaterials are placed at the rim of high-performance GPS antennas. The anticipated change in θ_C would affect their design methodology and usage in GNSS antennas, as they are generally bulky, heavy, and expensive.

D. Phase Center Stability

Stability of a GNSS antenna's phase center over frequency and spatial angles is a serious problem for high-performance GNSS antennas, especially as they strive to cover more GNSS bands and wider bandwidth. This is an ultimate performance parameter as well as a limitation posed by the GNSS antenna [12], [13], which will be addressed later.

III. DESIGN CHALLENGES—SIZE CONSTRAINTS, FEED NETWORK, AND COST

Challenges facing the design of GNSS receive antennas stem from two major premises: the greatly enlarged bandwidth requirement and the constraints by the platform on which the antenna operates. Feed network and cost are other major challenges. These are discussed as follows.

A. Platform-Imposed Size Constraint

Antenna size constraint and simultaneous broadbanding are conflicting requirements facing fundamental physical limitations, established in a rigorous analysis six decades ago [14], which relates the fundamental limitation of the gain bandwidth of an antenna to its electrical size.

Also, for a GNSS antenna, its platform (in a broad sense including the platform's immediate environment) dictates how, and how well, the antenna can mitigate problems due to multipath signals from satellite platform, ionosphere, troposphere, and terrestrial environment, as well as natural and man-made interferences and noises.

B. Feed Network

The feed network bridges between a coaxial cable and the radiating aperture, providing excitation to generate RHCP. Since the GNSS antenna needs to detect extremely low GNSS signals, about 25 dB below noise level on Earth, the use of LNA close to antenna is highly desirable. LNA elevates the signal strength so that it would not be attenuated away before reaching the receiver, usually via a cable 1–3 m long, which adds more noise as well. Additionally, the LNA augments frequency filtering and further enhances SNR. Because of the high-performance benefit and low cost, use of LNA as part of GNSS antenna is ubiquitous today. For high performance, a user may select antenna and LNA separately.

With the transition from the narrowband, and mostly single band, GPS to the multiband broadband GNSS, feed network design will be fundamentally changed not only by performance considerations but also by production cost issues. This challenge will be even more serious in the more complex feed network of anti-interference GNSS arrays with fixed or adaptive gain pattern.

C. Cost

The cost of a GNSS antenna is a fundamental design consideration driven by the market. A testimony is the patch antenna, whose widespread use is not only due to its low-profile, platform-compatible structure, and medium-to-small size, but also for its low cost enabled by its simple feed. However, the patch antenna's performance and cost advantages will be challenged by other antennas in the new multiband/broadband GNSS scenario.

IV. CLASSIFICATION OF GNSS ANTENNAS AND THEIR CHARACTERISTICS FROM USER'S PERSPECTIVE—BASED ON INSTALLATION PLATFORM

Section III demonstrated that a GNSS antenna's platform (in a broad sense including its environment) drives and constrains its design. The broader the bandwidth, the greater the difficulty is; and the smaller the platform, the greater the difficulty becomes. Thus, most of the design criteria and challenges are rooted in the platform. Accordingly, it is reasonable to classify GNSS antennas first by their intended platforms.

A review of the numerous products in *GPS World* in the annual survey of GNSS antenna manufacturers [15] confirms the need for a more readable classification. Table 2 proposes a simple top-level classification, dividing GNSS antennas into four types based on their intended platform: large, medium, small, and handheld platforms. Conventional application-based classifications are used as second-tier subclassifications (similar to how auto tires are classified).

V. BASIC GNSS ANTENNA APPROACHES

It is also desirable to know what basic antenna approaches are taken for GNSS antennas. The answers can be found in several books [5]–[9] covering GNSS antennas, as well as in general antenna books, outside the GNSS context,

Table 2 GNSS Antennas Classified Based on Intended Platform, With Their General Characteristics and Anticipated Changes

Platform	Applications	Bands*	Instant. Bandwidth*	Gain Pattern	Multipath Rejection*	Interference Rejection*	Phase Center Stability**	Size	Weight	Cost
Large	Geodetic, ships, etc.	2 or more	> 40 MHz	Very strict*	High	High	Good	Diameter > 15 cm	Heavy*	High*
Medium	Car, truck, train, aircraft	1-2	> 10 MHz	Somewhat strict*	Medium	Medium	Fair	Diameter > 3 cm	Medium	Medium
Small	Body-wearable, laptop	1	> 2 MHz	Not strict	Low	Low	Poor	Small and conformal	Light	Low
Handheld	Cellphone, GNSS receiver	1	> 2 MHz	Ignored	None	None	Very poor	Very small	Very light	Very low

* Large changes in a few years are expected. ** Some will have serious degradation when bands and bandwidth are expanded.

Table 3 Basic Antenna Types Used in GNSS and Their General Characteristics

Basic Antenna Type	Applications	Inherent Band-width	Gain Pattern*	Multipath Rejection	Interference Rejection	Phase Center Stability	Size	Profile	Weight	Cost*
Patch antenna	Most	Narrow	Strict	Medium	Medium	Medium to poor	Small to medium	Low	Medium	Low if single band
Quadrifilar helix	Handheld and small platform	Narrow	Somewhat strict	Medium	Medium	Poor	Small to medium	High	Small	Medium
Cross slot/dipole	Medium/large platform	Narrow	Strict	Medium	Medium	Medium	Medium	Low	Medium	Medium
*Planar spiral***	All but handheld applications	Very wide	Strict	Medium to high	Medium	Very good	Medium	Low to medium	Medium	Medium
4-element ring array	All but handheld applications	Narrow to wide	Strict	Medium to high	Medium to high	Poor to food	Generally large	Low to high	Medium to heavy	Medium to high
*Traveling-wave (TW) antenna***	All applications	Very wide	strict	Medium to high	Medium	Good to very good	Medium to small	Low	Medium	Medium
Adaptive 2-element array	Handheld and small platforms	Narrow	Not strict	Medium	Medium	Poor	Small to medium	Low to high	Light	Low to medium
Adaptive multi-element circular array	Medium to large platforms, mostly military	Narrow to wide	Very strict	High	Very high	Medium	Medium to large	Low to medium	Heavy	Very high

* Large changes in a few years are expected. **Spiral antenna and TW antenna overlap each other considerably.

under the category of antennas of circular polarization with a broad symmetrical unidirectional beam and a peak directivity of 3–10 dBi. (A higher directivity leads to a narrower beam, and thus a higher cutoff angle θ_C above horizon.)

This author also contacted, by both e-mail and letter, eight of the 35 manufacturers of GNSS antennas listed in the annual survey of *GPS World* [15] that had products covering all, or almost all, GNSS bands, asking for information on design principles and technical details of these products for possible coverage in this paper. The responses were not enthusiastic and had little detailed information. This lack of adequate response was likely due to concerns on intellectual property rights, in particular patent rights.

Nevertheless, we can summarize the basic antenna types applicable to GNSS, and a broad overview of their characteristics, in Table 3. Of those listed, some are fairly clearly defined and well known, and some need further clarification. While most GNSS antennas fall into one of the eight types, some fall into more than one.

Patch antennas are the most common, and have a very wide range of variations, e.g., slot-loaded patch antennas, stacked patch antennas, E-patch antennas, etc. However, the patch antenna is a resonant antenna, thus inherently narrowband; many elaborate efforts have been made to add more bands and bandwidth.

The four-element ring arrays consist of four radiating elements fed with a four-way hybrid or beam-former of $0°$–$90°$–$180°$–$270°$ to effect RHCP. Each radiating element can be a slot, a conducting patch of some shape such as a triangle, a Vivaldi element, an H-slot antenna, or an F or inverted-F antenna, etc. As a multiband GNSS antenna, it is necessary that the element radiators have some inherent broadband or multiband potential.

The spiral antenna and the quadrifilar helix antenna are also common GNSS antennas. Planar spiral antennas have several variations, mostly for changing their bidirectional radiation to unidirectional. The traveling-wave (TW) antenna is one technique that overcomes this problem by employing the spiral or other broadband planar radiators and having a closely spaced conducting ground plane [16], [17]. Potential use of the broadband thin TW antenna as a GNSS antenna was recognized as early as 1991. The slow-wave (SW) antenna [18] is a subset of the TW antenna, which reduces its size by using high-permittivity dielectric substrates and superstrates. With recent drop in cost of low-loss ceramics by an order of magnitude, the SW antenna emerges as a promising approach for medium, small, and even handheld platforms [19].

Adaptive multielement circular arrays are called controlled radiation pattern antenna (CRPA) in GPS. Note here that even though this paper is focused on fixed-beam single antenna, called fixed radiation pattern antenna (FRPA) in GPS convention, there is often an implicit complementary CRPA for GNSS. The CRPA follows similar trends of FRPA for each of the four platforms in Table 2.

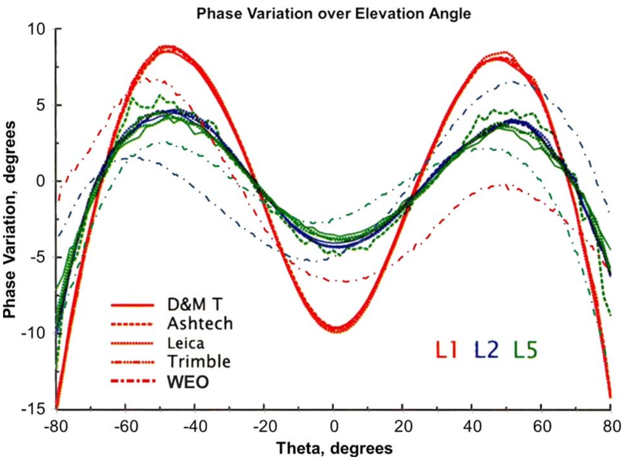

Fig. 2. ***Comparison of measured phase variation of five high-performance GNSS antennas.***

VI. HIGH-PERFORMANCE GNSS ANTENNAS

High-performance GNSS antennas will clearly be the first to respond to changes in the marketplace. Their growth path will reflect the state of the art and cost structure of relevant GNSS antenna technologies, monitored by government agencies, with data available on their websites. The use of choke rings and other software and hardware techniques in geodetic GNSS antennas tends to mask the inherent merits and shortcomings of the basic antennas. Here we attempt to present a simpler overview from a pure antenna perspective.

Two key performance issues in long-term evolution of GNSS antennas, as discussed, are their potential to adapt to the requirements of broadened bandwidth and elevated cutoff angle θ_C. We will focus on these two characteristics by comparing the measured data on four high-performance GNSS antennas [12] and those on one of the Wang Electro-Opto Corporation (WEO, Marietta, GA) latest four-arm spiral TW antenna measured in WEO's anechoic chamber.

Fig. 2 shows comparison of their phase, thus phase center, variation over elevation angle θ. The red, blue, and green colors designate carrier frequencies L1, L2, and L5, respectively. The data show that WEO's spiral TW antenna has smaller phase variations, consistent with the observation by Granger *et al.* [13] on spiral antennas. The WEO GNSS antenna's four-arm spiral, fed with an innovative feed network [20], is in the form of a circular pillbox, 15 cm in diameter and 3 cm thick, with an inherent conducting ground plane. It does not use choke ring, dissipative material, or metamaterial.

Fig. 3 shows measured relative polar gain patterns for these five GNSS antennas. Note their different rates of gain drop near the horizon, leading to 10-dB beam widths differing by 10°–20°. The differences translate to a difference of 5°–10° in their ability to accommodate a higher θ_C above the horizon desired in GNSS. Thus, the narrow-beamed WEO antenna is more able to achieve a desired higher cutoff angle θ_C above the horizon than the other four.

While the measurements at WEO and those in [13] were limited by their test chamber facilities, which apparently were not as accurate as the anechoic test chamber of the Goddard Space Flight Center utilized in [12], their results are similar and in favor of the spiral antenna approach.

The findings are also consistent with theory. From the viewpoint of geometry, phase center variation with frequency and spatial angle in azimuth vanishes with increasing uniformity of the radiating structure versus angular coordinate φ and improved feed network accuracy. Similarly, and by invoking the image theory, phase center variation in elevation vanishes with decreasing thickness of radiating structure and accuracy of feed network. The higher cutoff angle of the spiral TW antenna stems from its equivalence to an array of concentric annular slots with phased excitation.

VII. CONCLUSION AND FUTURE RESEARCH

Vastly broadened spectra and constellations of over 100 MEO and GEO satellites in GNSS are game-changing events that are reshaping antenna requirements toward much broader bandwidth and higher cutoff elevation angle. They pose new challenges not faced by conventional GPS and give rise to new features and applications as well

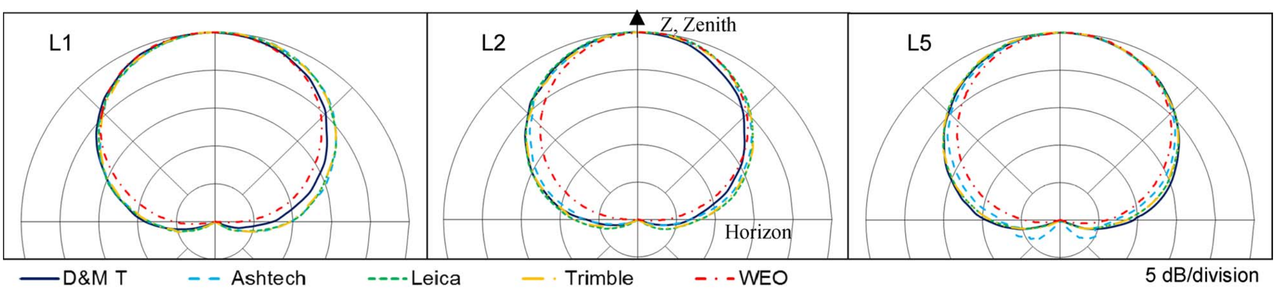

Fig. 3. ***Relative gain pattern for five high-performance GNSS antennas showing different amenability to higher cutoff angle θ_C.***

as cost structures. Several high-performance GNSS antennas are evaluated to highlight the state of the art, with the four-arm spiral TW antenna showing the highest potential.

Future research will be redirected by these changes. For size reduction, the slow-wave technology appears to be a practical solution for applications from handheld to medium platform, but needs considerable research. For pattern control, in particular higher cutoff angle above horizon, use of metamaterial will be pursued by some, especially for medium and large platforms. Smart antenna techniques will be developed to enhance performance in small and handheld platforms in the increasingly noisier terrestrial environment. ■

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