

# GNSS Antennas

## An Introduction to Bandwidth, Gain Pattern, Polarization, and All That

Gerald J. K. Moernaut and Daniel Orban

**THE ANTENNA IS A CRITICAL COMPONENT** of a GNSS receiver setup. An antenna's job is to capture some of the power in the electromagnetic waves it receives and to convert it into an electrical current that can be processed by the receiver. With very strong signals at lower frequencies, almost any kind of antenna will do. Those of us of a certain age will remember using a coat hanger as an emergency replacement for a broken AM-car-radio antenna. Or using a random length of wire to receive shortwave radio broadcasts over a wide range of frequencies.

Yes, the higher and longer the wire was the better, but the length and even the orientation weren't usually critical for getting a decent signal.

Not so at higher frequencies, and not so for weak signals. In general, an antenna must be designed for the particular signals to be intercepted, with the center frequency, bandwidth, and polarization of the signals being important parameters in the design. This is no truer than in the design of an antenna for a GNSS receiver.

The signals received from GNSS satellites are notoriously weak. And they can arrive from virtually any direction with signals from different satellites arriving simultaneously. So we don't have the luxury of using a high-gain dish antenna to collect the weak signals as we do with direct-to-home satellite TV.

Of course, we get away with weak GNSS signals (most of the time) by replacing antenna gain with receiver-processing gain, thanks to our knowledge of the pseudorandom noise spreading codes used to transmit the signals. Nevertheless, a well-designed antenna is still important for reliable GNSS signal reception (as is a low-noise receiver front end). And as the required receiver position fix accuracy approaches centimeter and even sub-centimeter levels, the demands on the antenna increase, with multipath suppression and phase-center stability becoming important characteristics.

So, how do you find the best antenna for a particular GNSS application, taking into account size, cost, and capability? In this month's column, we look at the basics of GNSS antennas, introducing the various properties and trade-offs that affect functionality and performance. Armed with this information, you should be better able to interpret antenna specifications and to select the right antenna for your next job.

"Innovation" is a regular column that features discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who welcomes your comments and topic ideas. To contact him, see the "Contributing Editors" section on page 4.

**T**he antenna is often given secondary consideration when installing or operating a Global Navigation Satellite Systems (GNSS) receiver. Yet the antenna is crucial to the proper operation of the receiver. This article gives the reader a basic understanding of how a GNSS antenna works and what performance to look for when selecting or specifying a GNSS antenna.

We explain the properties of GNSS antennas in general, and while this discussion is valid for almost any antenna, we focus on the specific requirements for GNSS antennas. And we briefly compare three general types of antennas used in GNSS applications.

When we talk about GNSS antennas, we are typically talking about GPS antennas as GPS has been the navigation system for years, but other systems have been and are being developed. Some of the frequencies used by these other systems are unique, such as Galileo's E6 band and the GLONASS L1 band, and may not be covered by all antennas. But other than frequency coverage, all GNSS antennas share the same properties.

### GNSS Antenna Properties

A number of important properties of GNSS antennas affect functionality and performance, including:

- Frequency coverage
- Gain pattern
- Circular polarization
- Multipath suppression
- Phase center
- Impact on receiver sensitivity
- Interference handling

We will briefly discuss each of these properties in turn.

**Frequency Coverage.** GNSS receivers brought to market today may include frequency bands such as GPS L5, Galileo E5/E6, and the GLONASS bands in



**INNOVATION INSIGHTS**  
with Richard Langley

**A well-designed antenna is important for reliable GNSS signal reception.**

addition to the legacy GPS bands, and the antenna feeding a receiver may need to cover some or all of these bands.

**TABLE 1** presents an overview of the frequencies used by the various GNSS constellations. Keep in mind that you may see slightly different numbers published elsewhere depending on how the signal bandwidths are defined.

As the bandwidth requirement of an antenna increases, the antenna becomes harder to design, and developing an antenna that covers all of these bands and making it compliant with all of the other requirements is a challenge.

If small size is also a requirement, some level of compromise will be needed.

**Gain Pattern.** For a transmitting antenna, gain is the ratio of the radiation intensity in a given direction to the radiation that would be obtained if the power accepted by the antenna was radiated isotropically. For a receiving antenna, it is the ratio of the power delivered by the antenna in response to a signal arriving from a given direction compared to that delivered by a hypothetical isotropic reference antenna. The spatial variation of an antenna's gain is referred to as the radiation pattern or the receiving pattern. Actually, under the antenna reciprocity theorem, these patterns are identical for a given antenna and, ignoring losses, can simply be referred to as the gain pattern.

The receiver operates best with only a small difference in power between the signals from the various satellites being tracked and ideally the antenna covers the entire hemisphere above it with no variation in gain. This has to do with potential cross-correlation problems in the receiver and the simple fact that excessive gain roll-off may cause signals from satellites at low elevation angles to drop below the noise floor of the receiver.

On the other hand, optimization for multipath rejection and antenna noise temperature (see below) require some gain roll-off.

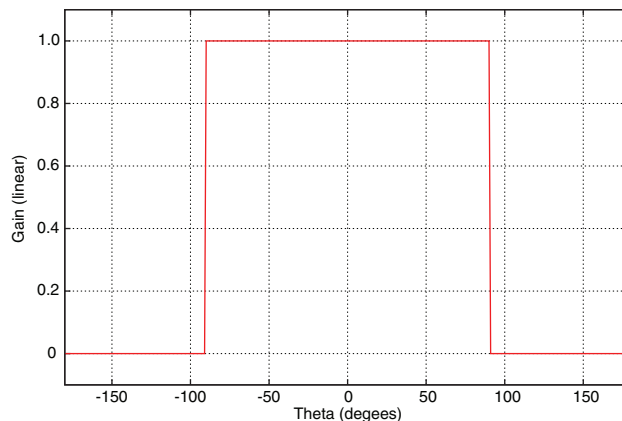
**FIGURE 1** shows what a perfect hemispherical gain pattern looks like, with a cut through an arbitrary azimuth.

However, such an antenna cannot be built and “real-world” GNSS antennas see a gain roll-off of 10 to 20 dB from boresight (looking straight up from the antenna) to the horizon. **FIGURE 2** shows what a typical gain pattern looks like as a cross-section through an arbitrary azimuth.

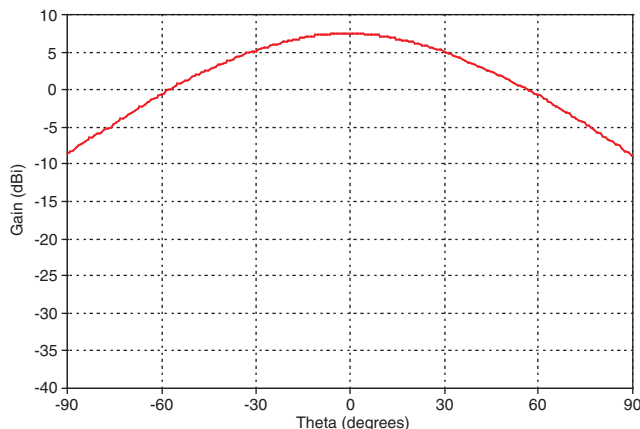
**Circular Polarization.** Spaceborne systems at L-Band typically use circular polarization (CP) signals for transmitting and receiving. The changing relative orientation of the transmitting and receiving CP antennas as the satellites orbit the Earth does not cause polarization fading as it does with linearly polarized signals and antennas. Furthermore, circular polarization does not suffer from the effects of Faraday rotation caused by the ionosphere. Faraday rotation results in an electromagnetic wave from space arriving at the Earth's surface with a different polarization angle than it would have if the ionosphere was absent. This leads to signal fading and potentially poor reception of linearly polarized signals.

System	Frequencies (MHz)				
	L1	L2	L3	L5/E5	E6
GPS	1563–1588	1215–1240	N/A	1164–1189	N/A
GLONASS	1592–1615	1237–1257	1194–1209	N/A	N/A
Galileo	1554–1596	N/A	N/A	1145–1238	1258–1300

▲ **TABLE 1** GNSS Frequency Allocations



▲ **FIGURE 1** Theoretical antenna with hemispherical gain pattern. Boresight corresponds to  $\theta = 0^\circ$ .

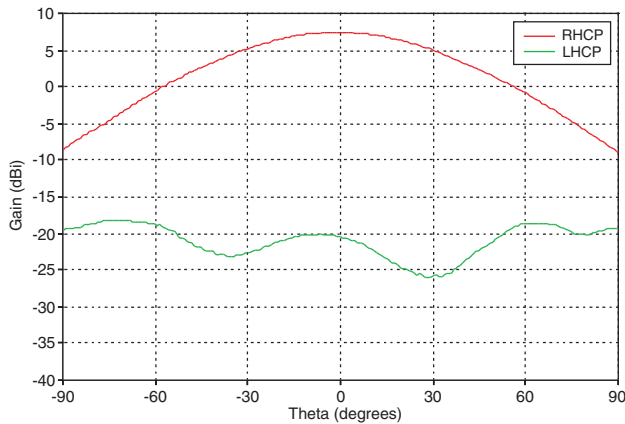


▲ **FIGURE 2** “Real-world” antenna gain pattern

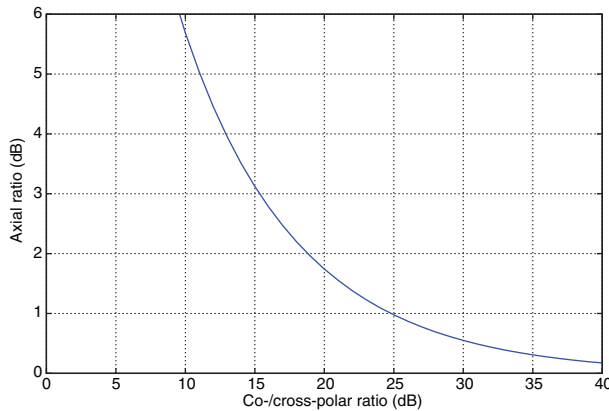
Circularly polarized signals may either be right-handed or left-handed. GNSS satellites use right-hand circular polarization (RHCP) and therefore a GNSS antenna receiving the direct signals must also be designed for RHCP.

Antennas are not perfect and an RHCP antenna will pick up some left-hand circular polarization (LHCP) energy. Because GPS and other GNSS use RHCP, we refer to the LHCP part as the cross-polar component (see **FIGURE 3**).

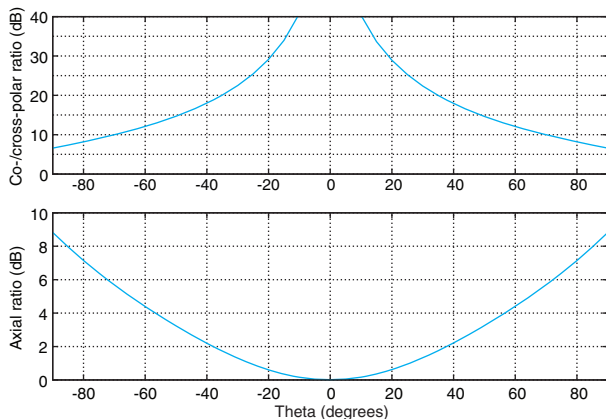
We can describe the quality of the circular polarization by either specifying the ratio of this cross-polar component with respect to the co-polar component (RHCP to LHCP), or by specifying the axial ratio (AR). AR is the measure of the polarization ellipticity of an antenna designed to receive circularly polarized signals. An AR close to 1 (or 0 dB) is best (indicating a good circular polarization) and the relationship between the co-/cross-polar ratio and axial ratio is shown



▲ **FIGURE 3** Co- and cross-polar gain pattern versus boresight angle of a rover antenna



▲ **FIGURE 4** Converting axial ratio to co-/cross-polar ratio



▲ **FIGURE 5** Co-/cross-polar and axial ratios versus boresight angle of a rover-style antenna

in **FIGURE 4**.

**FIGURE 5** shows the ratio of the co- and cross-polar components and the axial ratio versus boresight (or depression) angle for a typical GPS antenna. The boresight angle is the complement of the elevation angle.

For high-end GNSS antennas such as choke-ring and other geodetic-quality antennas, the typical AR along the boresight should be not greater than about 1 dB. AR increases towards

lower elevation angles and you should look for an AR of less than 3 to 6 dB at a 10° elevation angle for a high-performance antenna. Expect to see small (<1 dB) variations of AR versus azimuth at the low elevation angles.

Maintaining a good AR over the entire hemisphere and at all frequencies requires a lot of surface area in the antenna and can only be accomplished in high-end antennas like base station and rover antennas.

**Multipath Suppression.** Signals coming from the satellites arrive at the GNSS receiver’s antenna directly from space, but they may also be reflected off the ground, buildings, or other obstacles and arrive at the antenna multiple times and delayed in time. This is termed multipath. It degrades positioning accuracy and should be avoided. High-end receivers are able to suppress multipath to a certain extent, but it is good engineering practice to suppress multipath in the antenna as much as possible.

A multipath signal can come from three basic directions:

- The ground and arrive at the back of the antenna.
- The ground or an object and arrive at the antenna at a low elevation angle.
- An object and arrive at the antenna at a high elevation angle.

Reflected signals typically contain a large LHCP component. The technique to mitigate each of these is different and, as an example, we will describe suppression of multipath signals due to ground and vertical object reflections.

Multipath susceptibility of an antenna can be quantified with respect to the antenna’s gain pattern characteristics by the multipath ratio (MPR). **FIGURE 6** sketches the multipath problem due to ground reflections.

We can derive this MPR formula for ground reflections:

$$MPR = \frac{E_{RHCP}(\theta)}{E_{RHCP}(180^\circ - \theta) + E_{LHCP}(180^\circ - \theta)}$$

The MPR for signals that are reflected from the ground equals the RHCP antenna gain at a boresight angle ( $\theta$ ) divided by the sum of the RHCP and LHCP antenna gains at the supplement of that angle.

Signals that are reflected from the ground require the antenna to have a good front-to-back ratio if we want to suppress them because an RHCP antenna has by nature an LHCP response in the anti-boresight or backside hemisphere. The front-to-back ratio is nominally the difference in the boresight gain and the gain in the anti-boresight direction. A good front-to-back ratio also minimizes ground-noise pick-up.

Similarly, an MPR formula can be written for signals that reflect against vertical objects. **FIGURE 7** sketches this.

And the formula looks like this:

$$MPR = \frac{E_{RHCP}(\theta)}{E_{RHCP}(\theta) + E_{LHCP}(\theta)}$$

The MPR for signals that are reflected from vertical objects

equals the RHCP antenna gain at a boresight angle ( $\theta$ ) divided by the sum of the RHCP and LHCP antenna gains at that angle.

Multipath signals from reflections against vertical objects such as buildings can be suppressed by having a good AR at those elevation angles from which most vertical object multipath signals arrive. This AR requirement is readily visible in the MPR formula considering these reflections are predominantly LHCP, and in this case MPR simply equals the co- to cross-polar ratio.

LHCP reflections that arrive at the antenna at high elevation angles are not a problem because the AR tends to be quite good at these elevation angles and the reflection will be suppressed. LHCP signals arriving at lower elevation angles may pose a problem because the AR of an antenna at low elevation angles is degraded in “real-world” antennas. It makes sense to have some level of gain roll-off towards the lower elevation angles to help suppress multipath signals. However, a good AR is always a must because gain roll-off alone will not do it.

**Phase Center.** A position fix in GNSS navigation is relative to the electrical phase center of the antenna. The phase center is the point in space where all the rays appear to emanate from (or converge on) the antenna. Put another way, it is the point where the electromagnetic fields from all incident rays appear to add up in phase. Determining the phase center is important in GNSS applications, particularly when millimeter-positioning resolution is desired.

Ideally, this phase center is a single point in space for all directions at all frequencies. However, a “real-world” antenna will often possess multiple phase center points (for each lobe in the gain pattern, for example) or a phase center that appears “smeared out” as frequency and viewing angle are varied.

The phase-center offset can be represented in three dimensions where the offset is specified for every direction at each frequency band. Alternatively, we can simplify things and average the phase center over all azimuth angles for a given elevation angle and define it over the 10° to 90° elevation-angle range. For most applications even this simplified representation is over-kill, and typically only a vertical and a horizontal phase-center offset are specified for all bands in relation to L1.

For well-designed high-end GNSS antennas, phase center variations in azimuth are small and on the order of a couple of millimeters. The vertical phase offsets are typically 10 millimeters or less. Many high-end antennas have been calibrated, and tables of phase-center offsets for these antennas are available.

**Impact on Receiver Sensitivity.** The strength of the signals from space is on the order of -130 dBm. We need a really sensitive receiver if we want to be able to pick these up. For the antenna, this translates into the need for a high-performance low noise amplifier (LNA) between the antenna element itself and the receiver.

We can characterize the performance of a particular receiver element by its noise figure (NF), which is the ratio of actual

output noise of the element to that which would remain if the element itself did not introduce noise. The total (cascaded) noise figure of a receiver system (a chain of elements or stages) can be calculated using the Friss formula as follows:

$$NF = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \dots$$

The total system NF equals the sum of the NF of the first stage ( $NF_1$ ) plus that of the second stage ( $NF_2$ ) minus 1 divided by the total gain of the previous stage ( $G_1$ ) and so on. So the total NF of the whole system pretty much equals that of the first stage plus any losses ahead of it such as those due to filters.

Expect to see total LNA noise figures in the 3-dB range for high performance GNSS antennas.

The other requirement for the LNA is for it to have sufficient gain to minimize the impact of long and lossy coaxial antenna cables — typically 30 dB should be enough. Keep in mind that it is important to have the right amount of gain for a particular installation. Too much gain may overload the receiver and drive it into non-linear behavior (compression), degrading its performance. Too little, and low-elevation-angle observations will be missed. Receiver manufacturers typically specify the required LNA gain for a given cable run.

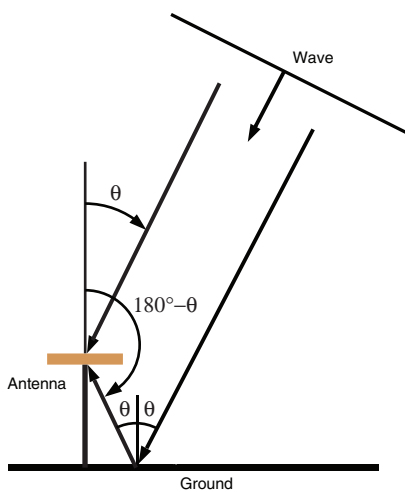
**Interference Handling.** Even though GNSS receivers are good at mitigating some kinds of interference, it is essential to keep unwanted signals out of the receiver as much as possible. Careful design of the antenna can help here, especially by introducing some frequency selectivity against out-of-band interferers. The mechanisms by which in-band and out-of-band interference can create trouble in the LNA and the receiver and the approach to dealing with them are somewhat different.

An out-of-band interferer is generally an RF source outside the GNSS frequency bands: cellular base stations, cell phones, broadcast transmitters, radar, etc. When these signals enter the LNA, they can drive the amplifier into its non-linear range and the LNA starts to operate as a multiplier or comb generator. This is shown in **FIGURE 8** where a -30-dBm-strong interferer at 525 MHz generates a -78 dBm spurious signal or spur in the GPS L1 band.

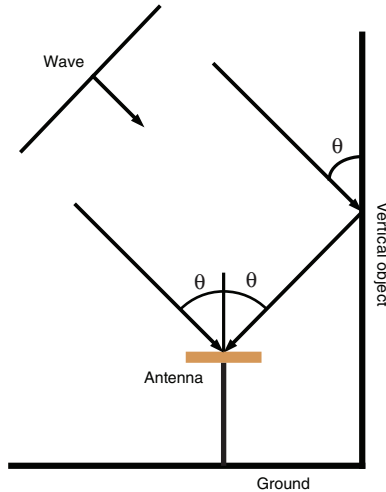
Through a similar mechanism, third-order mixing products can be generated whereby a signal is multiplied by two and mixes with another signal. As an example, take an airport where radars are operating at 1275 and 1305 MHz. Both signals double to 2550 and 2610 MHz. These will in turn mix with the fundamentals and generate 1245 and 1335 MHz signals.

Another mechanism is de-sensing: as the interference is amplified further down in the LNA's stages, its amplitude increases, and at some point the GNSS signals get attenuated because the LNA goes into compression. The same thing may happen down the receiver chain. This effectively reduces the receiver's sensitivity and, in some cases, reception will be lost completely.

RF filters can reduce out-of-band signals by 10s of decibels



▲ FIGURE 6 Quantifying multipath caused by ground reflections



▲ FIGURE 7 Quantifying multipath caused by vertical object reflections

interferer in the L1 band that generates -50 dBm at the input of the LNA. A 50 dB, high IP LNA will generate a 0 dBm carrier in the L1 band but the receiver will saturate.

LNAs with a higher IP tend to consume more power and in a portable application with a rover antenna — that may be an issue. In a base-station antenna, on the other hand, low current consumption should not be a requirement since a higher IP is probably more valuable than low power consumption.

### GNSS Antenna Types

Here is a short comparison of three types of GNSS antennas: geodetic, rover, and handheld. For detailed specifications of examples of each of these types, see the references in Further Reading.

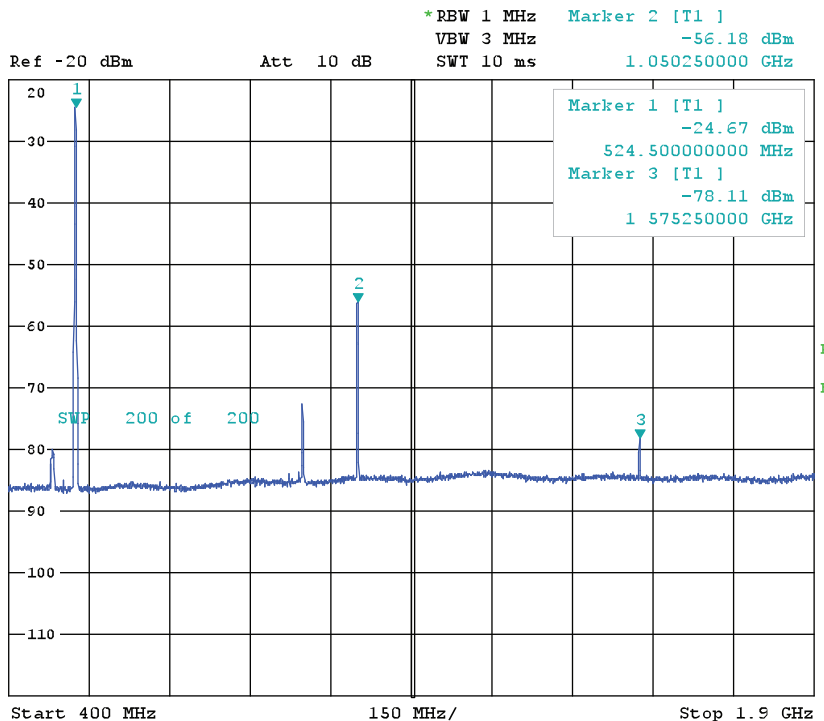
**Geodetic Antennas.** High precision, fixed-site GNSS applications require geodetic-class receivers and antennas. These provide the user with the highest possible position accuracy.

As a minimum, typical geodetic antennas cover the GPS L1 and L2 bands. Some also cover the GLONASS frequencies. Coverage of L5 is found in some newer designs as well as coverage of the Galileo frequencies and the L-band frequencies of differential GNSS services.

The use of choke-ring ground planes is typical in geodetic antennas. These allow good gain pattern control, excellent multipath suppression, high front-to-back ratio, and good AR at low elevation angles. Choke rings contribute to a stable phase center. The phase center is documented (as mentioned earlier), and high-end receivers allow the antenna behavior to be taken into account. Combined with a state-of-the-art LNA, these antennas provide the highest possible performance.

**Rover Antennas.** Rover antennas are typically used in land survey, forestry, construction, and other portable or mobile applications. They provide the user with good accuracy while being optimized for portability.

Horizontal phase-center variation



▲ FIGURE 8 Strong out-of-band interferer and third harmonic in the GPS L1 band

and this is sufficient in most cases. Of course, filters add insertion loss and amplitude and phase ripple, all of which we don't want because these degrade receiver performance.

In-band interferers can be the third-order mixing products we mentioned above or simply an RF source that transmits inside the GNSS bands. If these interferers are relatively weak, the receiver will handle them, but from

a certain power level on, there is just not a lot we can do in a conventional commercial receiver.

The LNA should be designed for a high intercept point (IP)—at which nonlinear behavior begins—so compression does not occur with strong signals present at its input. On the other hand, there is no requirement for the LNA to be a power amplifier. As an example, let's say we have a single strong continuous wave

versus azimuth should be low because the orientation of the antenna with respect to magnetic north, say, is usually unknown and cannot be corrected for in the receiver.

A rover antenna is typically mounted on a handheld pole. Good front-to-back ratio is required to avoid operator-reflection multipath and ground-noise pickup.

Yet these rover-type applications are high accuracy and require a good phase-center stability. However, since a choke ring cannot be used because of its size and weight, a higher phase-center variation compared to that of a geodetic antenna is typically inherent to the rover antenna design.

A good AR and a decent gain roll-off at low elevation angles ensures good multipath suppression as heavy choke rings are not an option for this configuration.

**Handheld Receiver Antennas.** These antennas are single-band L1 structures optimized for size and cost. They are available in a range of implementations, such as surface mount ceramic chip, helical, and patch antenna types.

Their radiation patterns are quasi-hemispherical. AR and phase-center performance are a compromise because of their small size.

Because of their reduced size, these antennas tend to have a negative gain of about -3 dBi (3 dB less than an ideal isotropic antenna) at boresight. This negative gain is mostly masked by an embedded LNA. The associated elevated noise figure is typically not an issue in handheld applications.

**Summary of Antenna Types.** TABLE 2 presents a comparison of the most important properties of geodetic, rover, and handheld types of GNSS antennas.

	Geodetic	Rover	Handheld
Frequency bands	Single to multiband Broadband	Single to multiband Narrow to broadband	Single band Narrow band
Gain pattern	Controlled	Controlled	Not controlled
Multipath suppression	High	Medium	None
Sensitivity	High	Medium to high	Low
Interference handling	High rejection	Good rejection	Minimal rejection
Phase center	Very important	Important	Not important
Dimensions	Large	Portable	Very small
Weight	Heavy	Portable	Lightweight
Cost	High	Medium	Low

▲ TABLE 2 Characteristics of different GNSS antenna classes

## Conclusion

In this article, we have presented an overview of the most important characteristics of GNSS antennas. Several GNSS receiver-antenna classes were discussed based on their typical characteristics, and the resulting specification compromises were outlined. Hopefully, this information will help you select the right antenna for your next GNSS application.

## Acknowledgment

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## FURTHER READING

### ■ Previous GPS World Articles on GNSS Antennas

“Getting into Pockets and Purses: Antenna Counters Sensitivity Loss in Consumer Devices” by B. Hurte and O. Leisten in *GPS World*, Vol. 16, No. 11, November 2005, pp. 34-38.

“Characterizing the Behavior of Geodetic GPS Antennas” by B.R. Schupler and T.A. Clark in *GPS World*, Vol. 12, No. 2, February 2001, pp. 48-55.

“A Primer on GPS Antennas” by R.B. Langley in *GPS World*, Vol. 9, No. 7, July 1998, pp. 50-54.

“How Different Antennas Affect the GPS Observable” by B.R. Schupler and T.A. Clark in *GPS World*, Vol. 2, No. 10, November 1991, pp. 32-36.

### ■ Introduction to Antennas and Receiver Noise

“GNSS Antennas and Front Ends” in *A Software-Defined GPS and Galileo Receiver: A Single-Frequency Approach* by K. Borre, D.M.Akos, N. Bertelsen, P. Rinder, and S.H. Jensen, Birkhäuser Boston, Cambridge, Massachusetts, 2007.

*The Technician’s Radio Receiver Handbook: Wireless and Telecommunication Technology* by J.J. Carr, Newnes Press, Woburn, Massachusetts, 2000.

“GPS Receiver System Noise” by R.B. Langley in *GPS World*, Vol. 8, No. 6, June 1997, pp. 40-45.

### ■ More on GNSS Antenna Types

“The Basics of Patch Antennas” by D. Orban and G.J.K. Moernaut. Available on the Orban Microwave Products web site: [http://www.orbanmicrowave.com/The\\_Basics\\_Of\\_Patch\\_Antennas.pdf](http://www.orbanmicrowave.com/The_Basics_Of_Patch_Antennas.pdf).

“Project Examples” <http://www.orbanmicrowave.com/project.htm>.

### ■ Interference in GNSS Receivers

“Interference Heads-Up: Receiver Techniques for Detecting and Characterizing RFI” by P.W. Ward in *GPS World*, Vol. 19, No. 6, June 2008, pp. 64-73.

“Jamming GPS: Susceptibility of Some Civil GPS Receivers” by B. Forssell and T.B. Olsen in *GPS World*, Vol. 14, No. 1, January 2003, pp. 54-58.