GPS & GNSS Antenna Configurations

White Paper

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Introduction

Though originally intended as only a radionavigation system, the global position system (GPS), and variant systems, have also become ubiquitous tools for the distribution of time and frequency signals. GPS is used in virtually all modern smartphones, tablets, automobile telematic systems, and aircraft. GPS relies on very precise timing signals and sophisticated electronics in orbiting satellites as well as terrestrial GPS receiver systems. GPS Disciplined Oscillators (GPSDO) are also used as a reference for frequency and time measurements around the globe. So, not only will you find GPS receivers/antennas on vehicles and within smartphones, but also in computing racks and edge-node electronics.

Six Orbital Planes

This whitepaper aims to provide some insights into how the GPS system works, and to provide a deeper perspective into the nuances of [GPS antenna] features/capabilities and how GPS antenna selection impacts GPS system performance.

GPS Primer

The GPS system, originally named Navstar GPS, consists of a constellation of satellites that are now operated by the United States Space Force, and is comprised of 24 satellites that orbit the earth. The GPS satellite system was originally operated by the United States Department of Defense (DoD) and is one of several global navigation satellite systems (GNSS) currently in operation that provide geolocation and time/frequency information around the globe. The GPS satellites are approximately 12552 miles (20,200 kilometers) from the surface of the Earth, in six fixed planes that are inclined 55 degrees from the equatorial line. Each satellite orbits the Earth in an 11 hour and 58-minute period, so that each GPS satellite is orbiting the earth twice in a single day.

Image Suggestion: https://wordpress.org/openverse/photos/b690e562-3e76-41aa-ae24-a2c18e728801
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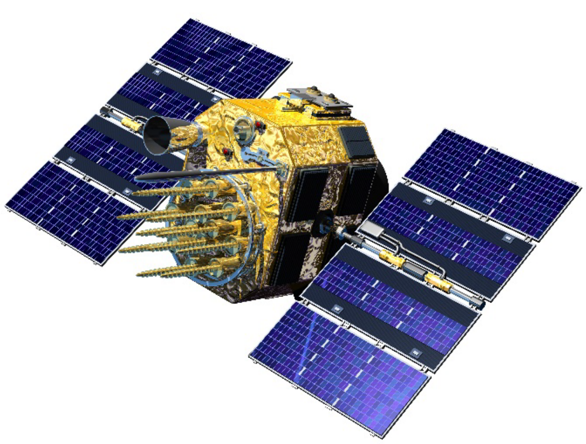
The broadcast from each GPS satellite is transmitted on two or three carrier frequencies, L1 (1575.42 MHz), L2 (1227.6 MHz), and newer satellites also with L5 (1176 MHz). Each GPS satellite broadcast is accessible across overlapping areas of the globe, with several satellites in view from any given position at any given time. However, the GPS satellite broadcast is line-of-sight, so a GPS receiver antenna must be directed toward the area of the sky where the GPS satellite is broadcasting, without obstructions, in order to capture the weak GPS signal. It is important to note that other than GPS ground stations, GPS user equipment does not transmit any information to the GPS system and merely is able to receive the GPS broadcasts.

The GPS satellite broadcast is a spread spectrum waveform using a unique pseudo-random noise (PRN) code on L1 and L2. In this way, each GPS satellite can be identified by its PRN code. L1 and L2 each broadcast different PRN codes with different acquisition accuracy. L1 broadcasts a course acquisition (C/A) code with a chip rate of 1023 chips per millisecond. L2 broadcasts the precision (P) code with a chip rate of 10230 chips per millisecond and enables much more accurate distance calculations than C/A code. The time of arrival (TOA) of a defined point in the code sequence at a GPS receiver is known as an epoch. Also within the GPS broadcast is a message that includes the time of transmission (TOT) of the code epoch in GPS time scale, and the satellite position information at the time of the signal transmission.



First Generation GPS Satellite

As of 2021 around 16 GPS satellites also broadcast L5. With L1 and L2, exhibit accuracy around 16 feet (5 meters), but GPS receivers with access to L5 can often reach position accuracy to within 12 inches (30 centimeters). Some applications with more sophisticated GPS Receivers and error correction systems can reportedly reach accuracies to a fraction of an inch (millimeters or below). Accuracy may increase when there are 24 GPS satellites capable of broadcasting the L5 frequency, which is slated for completion in the year 2027.

In order to reduce the error with the GPS system, each satellite must have high accurate absolute time keeping, which is done with an onboard rubidium and/or cesium atomic clock that provides the reference for both the carrier and broadcasts. There is also communication to the GPS satellites from GPS ground stations that correct the timing reference of each GPS satellite to Coordinated Universal Time (UTC), which is maintained by the United States Naval Observatory (USNO).

GNSS Systems

- United States Global Positioning System (GPS)
- Russian Global Navigation Satellite System (GLONASS)
- China's BeiDou Navigation Satellite System (BeiDou)
- European Union Galileo Navigation Satellite System (Galileo)
- India's NavIC
- Japan's Quasi-Zenith Satellite System (QZSS)

What is a GPS Receiver?

A GPS receiver's goal is to accurately calculate its four-dimensional position in spacetime relative to the data from multiple GPS satellite broadcasts. With each GPS satellite providing extremely accurate data of its position and timing, a GPS Receiver can compare the position and timing information from multiple GPS satellite broadcasts to calculate both the receiver's position using the timing data to provide enhanced accuracy and timing reference if needed. GPS receivers also contain their own oscillators that are slaved to the GPS timing, but depending on cost/sophistication, may be far less accurate than the atomic clocks on the GPS satellites/ground stations and require calibration from the GPS system to maintain accuracy.

A GPS Receiver calculates its position by first calculating the distance from the receiver to the GPS satellites using the known speed of the radio broadcast signal and the timing data embedded within the signal. With the timing data and the radio broadcast velocity, a GPS receiver can accurately determine the distance to several GPS satellites, with a minimum of four GPS satellites, to compute the systems x, y, z, and timing difference of its clock from UTC.

In more detail, the GPS Receiver determines the TOA of four or more satellite broadcast signals and calculates the time of flight (TOF) values using the TOA/TOT data. Using the speed of light, c, and the time difference between the receiver and GPS satellite timing (the pseudo-ranges), it is possible to calculate each of the four-dimensional variables in a set of equations, with UTC and the center of the Earth as the origin of the four-dimensional spacetime. The equations used to determine the TOFs are simply known as the navigation equations. Most GPS devices then convert the three-dimensional Cartesian coordinates to latitude, longitude, and height from Earth's sea-level using the ellipsoidal Earth model.

The conceptual time difference of arrival (TDOAs) is formed of a hyperboloid of revolution to define the measurement geometry. A line connecting the two satellites involved forms the axis of the hyperboloid, with the receiver located at a point where three hyperboloids intersect. This generally requires four satellites, except in the case where the GPS Receiver clock is accurately synchronized to the GPS satellite clocks. When this is the case, the GPS receiver can measure the true ranges to the satellites, rather than the range differences. However, the cost and complexity of a GPS user system with a synchronized clock is much more than a device that can simply use four GPS satellites for its calculations.

A GNSS surveying system.

GPS Disciplined Oscillator (GPSDO)

A GPS Disciplined Oscillator (GPSDO) is a self-calibrating standard that is commonly used as a reference for frequency and time measurements with a wide range of electronics. For example, networking systems with critical time requirements may use a network reference with a GPSDO. Also, GPSDOs are sometimes used in traffic signal timing, synchronizing cell phone base stations, amateur radio clock synchronization, astronomy/astrology, and a wealth of other potential applications.

A GPSDO is a GPS receiver that uses the GPS satellite broadcast to control the frequency of a local oscillator, often quartz or rubidium. A GPSDO generally consists of a GPS Receiver with a phase detector and a feedback network that forces a phase match between the GPS satellite broadcast and a voltage-controlled oscillator using control signals from a control system. The control system is often a microcontroller unit (MCU) or other control hardware that additionally helps to compensate for oscillator aging, temperature, and other environmental factors.

Role of a GPS Antenna

A GPS antenna is the hardware that captures the electromagnetic (EM) radiation from the GPS satellite broadcast signals and converts these signals to electric signals that travel through transmission lines to the GPS Receiver hardware. The signal strength and quality of the GPS signals seen at the GPS Receiver are extremely impacted by the performance and characteristics of the GPS antenna. Given that GPS signals are traveling thousands of miles through attenuation atmospheric gasses, and possibly other obstructions, it is critical that GPS antennas can capture GPS broadcast signals, even providing gain to the signals, while minimally adding noise and distortion. Therefore, some GPS antennas are active antennas and provide enhanced gain to the GPS signal.

The following are brief descriptions of the features and capabilities to consider when selecting a GPS antenna for a given application.

GPS Antenna Gain & Frequency

Antenna gain is a measure of an antenna's electrical efficiency and directivity compared to a lossless isotropic antenna that is intrinsically sensitive to electromagnetic radiation from all directions equally. In the case of GPS antennas, these antennas are generally non-isotropic, but may be omnidirectional, in order to capture GPS signals from multiple sources. Hence, the gain figure attributed to a GPS antenna is generally a description of the peak gain of the antenna in the main lobe of the antenna's radiation pattern.

The radiation pattern of a GPS antenna is a plot of the gain of an antenna as a function of direction. An antenna with higher gain generally has higher directivity, as there are tangible limits to antenna efficiency using available materials, such as copper/aluminum conductors. The efficiency of an antenna is the ratio of the antenna input power to the total radiated power. Due to conductor resistance, dielectric loss, and other high frequency phenomena, antenna efficiency cannot practically reach 100%.

Depending on the application, it may be desirable to select a GPS antenna with lower gain but a more desirable radiation pattern, or otherwise use a higher gain/directional antenna as the position of the antenna main lobe in respect to target GPS satellites is known and controllable. In mobile applications, this may be a challenge as placement of a GPS antenna may be limited due to interference and other design/operation considerations.

Antenna gain is also a function of frequency and gain parameters must be given for the intended frequency range of the antenna. Depending on the GNSS used, an antenna with frequency ranges that match the satellite broadcast signal frequencies needs to be chosen. This is known as the bandwidth of the antenna. As GPS satellites broadcast extremely specific frequencies with relatively narrow bandwidths, choosing a GPS antenna that has a bandwidth that encompasses the desired frequencies is critical. There are some GPS antennas that provide dual-/multi-band GNSS operation and can efficiently capture GNSS signals from two or more constellations.

Active Versus Passive GPS Antenna

A Passive GPS antenna is simply made of conductive antenna structures, dielectric, housing, and a connector interface. This type of antenna assembly is completely passive in that it doesn't require an external power source to function. For a passive GPS antenna to function it merely needs to be connected via a transmission line to a GPS Receiver. Though an antenna's gain is related to the size of the antenna, there are antenna topologies and design techniques to enhance an antenna's gain without significantly increasing the antenna size. This allows for relatively compact passive GPS antennas that can be easily mounted on the exterior of an electronics enclosure, the cab of a mobile vehicle, or outside an electromagnetically shielded room.

However, GPS signals, even with high gain GPS antennas, are typically very weak, and signal energy losses and noise injection are often a result of the interconnect and cables used to carry the signals from a GPS antenna to the GPS Receiver.

For these reasons, it is common to use active GPS antennas. An active GPS antenna benefits from an embedded RF amplifier within the antenna assembly. This means that an active antenna requires an external power source, and the power source as well as the amplifier may also inject noise into the system. Hence, for applications that necessitate the use of an active antenna, it may be important to consider the added noise figure (NF) of the antenna, any possible noise from the power supply, noise coupled in from the transmission line, and the limits of the noise floor of the GPS Receiver. In this same respect an active GPS antenna may be necessary if the GPS antenna can't be located near the GPS Receiver and a long transmission line cable is needed and additional signal gain is required to offset the additional loss from a longer cable run.

Another important factor to consider is the nonlinearity of an active GPS antenna. Any RF amplifier is intrinsically nonlinear, even though they are generally designed to operate within thresholds that ensure optimum linearity. Two key figures of merit of a RF amplifier that describe its linear performance are the 1dB compression point (P1dB) and the output third order intercept point (OIP3).

In order for an RF amplifier to operate as designed, the power supply input requirements need to be met as described in the data sheet. This is why, along with minimizing noise, an active GPS antenna should employ a high-quality power supply or otherwise filter a lower quality power supply to enhance the power quality. Key power supply factors to consider include voltage, current, and power quality. An active GPS antenna will require a certain amount of power within a described voltage range and the power supply will need to be able to provide the necessary current to meet those requirements without injecting added noise or otherwise fluctuating or conducting other electromagnetic interference (EMI) into the system.

Some Active GPS antennas may also include embedded RF filtering that can provide out-of-band rejection. These GPS antennas tend to include a bandpass filter with a bandwidth specifically designed to allow for GNSS frequencies to pass while rejecting others. Some GPS antennas with filtering may also include band-reject filters, to further enhance the out-of-band rejection, that are specifically designed to reject certain frequency ranges and pass all other frequencies within the filter's total bandwidth. With added filtering, however, comes additional insertion loss, slightly degraded voltage standing wave ratio (VSWR), and possibly higher noise figure even though RF filters tend to be passive.

For Active GPS antennas, it is also important to ensure that the antenna system stays with the specified operating temperature range. If the sensitive RF hardware within an active GPS antenna is subjected to environmental factors that exceed its specifications, it may sustain damage that results in degraded performance or destruction of the active elements within the antenna assembly. Other environmental factors to consider when deploying a GPS antenna are humidity and shock/vibration. Passive GPS antennas may be more resilient to harsh environmental factors, as passive antennas don't contain any additional hardware and it is relatively easy to seal off and protect the connector interface. However, active GPS antennas have additional power inputs, bias, RF amplification, and possibly filter circuitry that are all susceptible to degradation from harsh environmental factors.

GPS Antenna Connector Type

GPS antennas come with a variety of different RF connector types. These connectors are almost always coaxial connectors that are designed to work with common coaxial connector and cable types. The most common GPS antenna connectors are likely N-type and SMA, though mobile vehicle applications may benefit from the use of NMO style connectors and mounting fixtures. Given the extremely weak signal level of GPS satellite broadcast, it is important to select a GPS antenna connector and cabling that minimizes the losses through the connectors and cables. There are low loss connector and cable options that can be chosen to meet an application's requirements.

A Tri-band, NMO style GPS antenna mount kit with N-type coaxial connectors and cabling.
Source: https://www.pasternack.com/tri-antenna-0-gain-nmo-mount-pe51ak1002-p.aspx

Embedded GPS antenna

Unlike other types of GPS antenna, which are typically mounted external to a vehicle, assembly, or enclosure, an embedded GPS antenna is generally installed within the housing of a device. Devices that include embedded GPS antennas are generally portable devices, or small form factor devices with constraints that make having a GPS module within the housing desirable. Embedded GPS antennas are typically active antennas, are often multiband and can support GPS Receivers from a few different constellations. Since GPS is often found in devices that are used in remote or mobile applications, some embedded GPS antennas also support multiple cellular frequencies and separate connections to cellular modules.

Given the generally small size of embedded GPS antennas, the gain for these modules is likely lower than larger external GPS antennas, often due to lower antenna efficiency. These embedded GPS antenna modules are often designed for very low power consumption and to mate with common PCB surface mount coaxial connectors, such as UMCX.

An embedded GPS Antenna and cellular module.
Source: https://www.pasternack.com/multi-antenna-824-mhz-2.17-ghz-5-dbic-gain-umcx-pe51212-p.aspx

Conclusion

GNSS geolocation and timing technology is critical to virtually every industry and most people's lives around the globe. The ability to accurately locate objects in real-time and synchronize electronics over vast distances is essential for almost all transportation and military/defense use cases. A GPS antenna is a key part of a GPS system and correct selection of a GPS antenna for an application's specific requirements can be the difference between mission success and failure. With future GNSS/GPS systems coming online that promise even more refined position and timing accuracy, GPS antennas with L5 frequency capability may increase in demand in the future.

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