

Getting Into Pockets & Purses

as published in GPS World, November 2005

Introduction

The market for consumer GPS products has exploded over the past several years due in part to the continuing improvements in receiver size, performance, and cost, and also due to increasing consumer awareness of the utility of GPS. Telematics systems, GPS-enabled PDAs, and more novel GPS products like pet finders have flooded the marketplace, with new products and applications seemingly announced daily. On the other hand, a basic lack of awareness of the limitations of GPS on the part of consumers has acted as a barrier to true mass adoption of the technology. Consumers expect a product to just work, irrespective of the conditions to which they



subject it. A GPS receiver should tell them where they are, whether they're inside a car or building, or whether the receiver is buried inside a pocket or purse. The consumer shouldn't be asked to shoulder the burden of ensuring the receiver has a clear line of sight on a cloudless, sunny day, while holding the receiver at arm's length.

In fact, it is a sure sign of a nervous GPS device demonstrator that the device is held between the thumb and the ring finger in the "genteel" manner in which one might hold a tea-cup! Such a delicate grip betrays an attempt to preserve the efficiency of the antenna, reducing the effect of body loading by minimizing the mass of human tissues in close proximity to the device. Body loading is a very important issue in the design of portable GPS products as it accounts for much of the loss of receiver sensitivity and can lead to unacceptable performance even when the device is used in the manner intended by the designer.

The mechanism by which receiver sensitivity is impaired is through the loss of electromagnetic resonance energy as it is dissipated into the lossy body. The function of the antenna is to resonate an electromagnetic cloud in the space surrounding the antenna. It is actually the resonance of that electromagnetic "near-field" which causes radiation of energy to the "far-field," the field thought of as the doing the antenna's work. Of course with GPS receivers we are dealing with the inverse of this process - energy from the far-field is causing a resonance in the near-field cloud surrounding the antenna. If the user presents their body into the space occupied by the near-field, energy that would ordinarily be available to the receiver is dissipated into the user and sensitivity is thus diminished. The problem is that with conventional antennas the near-field region is large (as much as three wavelengths in radius, which for GPS is almost 2 feet) and the loss of receiver sensitivity to loading can be as much as 10dB. Therefore, one of the key challenges the designer must face is the problem of antenna efficiency in a body-loaded environment.

While many advances have been made in receiver design, increasing receiver sensitivity to very low levels with or without network assistance, the drive to make antennas smaller runs counter to the need to make them more efficient – after all, with antennas bigger is better. Expressed simply, $(\text{Gain} \cdot \text{Bandwidth}) / \text{Volume} = \text{Constant}$. If the volume goes down, $(\text{gain} \cdot \text{bandwidth})$ must go down. Most device designers try to squeeze the maximum amount of gain from a small antenna by recognizing that a conventional antenna must resonate against a ground plane, that when coupled with the device effectively increases the volume of the antenna to the volume of the device itself. Unfortunately what follows is that user interaction with the device in applications where the device is to be held, worn, or will sit in the user’s pocket causes the antenna to de-tune and give up energy to the lossy materials surrounding it – a vicious circle.

What is required is an antenna that is large enough to provide sufficient signal to the receiver, small enough to attractively fit into small consumer products, and isolated from the device so it doesn’t interact with its environment – except of course to resonate with received GPS signals. Only then can we consider products that will work when sitting in the user’s pocket or purse. The dielectrically-loaded quadrifilar helix antenna provides such a structure.

The dielectric-loaded quadrifilar topology takes control of the resonant near-fields through the use of a high-dielectric core and employs a feed topology that isolates the antenna from the handset ground. A balanced feed system attenuates conducted in-band common-mode noise that would otherwise impair the sensitivity of the connected GPS receiver. This independence from its environment leads to electrical performance of the antenna that is predictable across all environments of normal use.

THE NEAR AND FAR FIELDS OF AN ANTENNA

The behaviour of antennas can be visualized in terms of the near/far field issues in the context of portable wireless devices using a mathematical analysis of the simple point-dipole antenna. It is easiest to put the argument in terms of radiating antennas but since antennas obey the law of reciprocity the same conclusions arise with receiving antennas. The analysis is couched in a polar co-ordinate system so that the angle ϕ denotes the angle concentric to the direction of the dipole and the angle θ represents the angle around planes that are bisected by the direction of the dipole. The size of the antenna is small enough to permit the assumption that the angle from a point to one pole is not significantly different from that point to the other pole; such that both paths have angle θ .

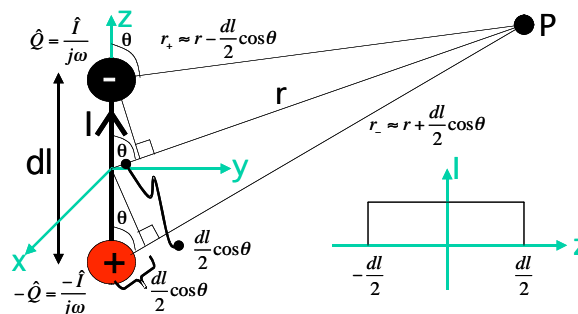


Figure 1: Fields around a point dipole.

The magnetic fields surrounding the point dipole can be calculated from the curl of the magnetic vector potential (\hat{A}) of the point dipole.

$$\begin{aligned}\hat{H} &= \frac{1}{\mu} \nabla \times \hat{A} \\ &= -i_\phi \frac{\hat{I} dl}{4\pi} k^2 \sin\theta \left(\frac{1}{jkr} + \frac{1}{(jkr)^2} \right) e^{-jkr} \dots 1.\end{aligned}$$

The electric fields surrounding the point dipole can be calculated from the curl of the magnetic field. From 1 and 2 the field structure of the point dipole can be represented

$$\begin{aligned}\hat{E} &= \frac{1}{j\omega\epsilon} \nabla \times \hat{H} \\ &= -\frac{\hat{I} dl k^2}{4\pi} \sqrt{\frac{\mu}{\epsilon}} \hat{r} \left[2 \cos\theta \left(\frac{1}{(jkr)^2} + \frac{1}{(jkr)^3} \right) \right] \\ &+ i_\theta \left[\sin\theta \left(\frac{1}{jkr} + \frac{1}{(jkr)^2} + \frac{1}{(jkr)^3} \right) \right] e^{-jkr} \dots 2.\end{aligned}$$

in terms of a polynomial in $1/jkr$ where k is the wavenumber ($k = \omega/c$). It is interesting to examine the physical basis of these terms. We see that, in line with the right-hand rule for a z-directed current the magnetic field circulates concentrically around the dipole and is therefore oriented purely in the ϕ direction. The term in $1/(jkr)^2$ is called the induction field or near-field because it is the dominant constituent of magnetic field close to the antenna. The magnetic field term that is responsible for the radiation function of the antenna is that in $1/jkr$ which dominates at distances far ($kr \gg 1$) from the antenna. This term can be shown to be responsible for the time-average power-flow from the source.

An examination of the electric field terms tells a similar story. The terms in $1/(jkr)^3$ are electric dipole field terms, often called the electrostatic solution because they are present at zero frequency. These together with the intermediate $1/(jkr)^2$ terms are dominant near the dipole and are near-field terms. For the function of the antenna the most important term is once again the $1/jkr$ field term in i_θ which is a radiation field term and is the dominant constituent of electric field at a distance that is far from the antenna.

The near-field terms do not contribute to power-flow from the antenna. They can be visualized as stored energy in the magnetic and electric fields and therefore are often referred to as the reactance fields. What this tells us about antennas is that they are surrounded by rather dense electromagnetic fields associated with the resonance of the

antenna close to the antenna. Further away from the antenna a radiation field predominates.

The format of equations 1 and 2 indicate that the near-field and far-field terms are, in the case of the simple point dipole, related in a polynomial function. If the space occupied by the antenna is uniformly a medium of dielectric permittivity (ϵ) then changing that permittivity will cause all near-field and far-field terms in equation 2 to change to the same degree. Intuition and empirical experiments do not support this interpretation for the case of multimedia antennas. Consider an electric field dipole built across a high dielectric core so that the electric field is mainly disposed between the charge poles in the dielectric medium but the actual position of the poles is on the surface boundary between the dielectric and free-space media. It is clear that the electric fields in such a structure would be concentrated into the dielectric medium, both by the balanced nature of the dipole offering field across the dielectric medium, and also because the energy density (ϖ) of an electric field is proportional to ϵ :

$$\varpi = \frac{1}{2} \epsilon E^2 \dots 3.$$

If apart from the introduction of the dielectric media between the poles of a dipole no other differences from the free-space dipole are introduced then the modified forms of equations 1 and 2 become very complex, reflecting the existence of a slow-wave/fast-wave media boundary acting in the region of the near-field terms and the absence of such influences in the far-field region. These relationships depend upon the geometry of the antenna system comprising the dimensions and shape of the dielectric medium and its position and orientation relative to the dipole. What we can say from empirical experience or analysis of simple antennas is that the dielectric loading reduces the volume in which reactive tuning of the antenna is caused by movement of RF reflective objects close to that antenna. We can also be fairly certain that to first order the gain of antennas dielectrically loaded with low-loss materials is dependent only on the enclosed volume of the antenna in the same continuum which encompasses conventional free-space antennas.

In practical application, the energy drained from the near-field region due to the presence of dielectric materials entering that region is energy lost from the GPS communications link. This can cause a significant impairment to the link performance of the communications system. Since tissues of the human body are known to have an $\epsilon_r \approx 40$, the user placing his hand in that region, i.e., by grasping the device on which the antenna is mounted, will reduce the antenna's efficiency. Therefore, containing the near-field very close to the antenna so that no opportunity exists for the user (or other dielectric materials) to interact with it is important in yielding a very stable and predictable performance from the antenna, and this is what is achieved by the dielectrically-loaded quadrifilar helix antenna.

THE DIELECTRIC LOADED QUADRIFILAR HELIX ANTENNA

One example of a such an antenna is realized as copper tracks surrounding a 10mm x 17.5mm high-dielectric core as shown in figure 2. An integral balun in the structure ensures a balanced feed signal is projected to the top of the antenna of the antenna. Just as importantly the balun provides isolation for the currents on the antenna element from the handset. The antenna has two quadrature phased bifilar helical loops, with the phase quadrature achieved by the two loops having slightly offset resonant frequencies.

One of the bifilar helices is adjusted longer than resonance to produce an input impedance with a phase angle of $+45^\circ$, and the other bifilar is adjusted shorter than resonance to produce an input impedance with a phase angle of -45° . This produces the 90° phase shift between the currents in the first bifilar with respect to the second bifilar required for quadrature.

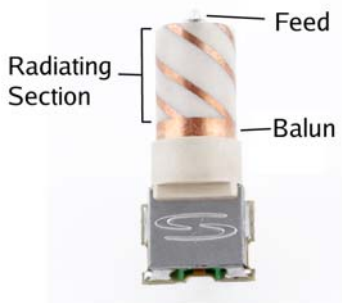


Figure 2: Structure of the dielectrically loaded quadrifilar helix.

When operating in the axial loop mode of resonance, the virtual electromagnetic dipoles formed by the two orthogonal bifilar helices are 90° out of phase and combine to give a virtual spinning dipole effect. The effective spinning dipole means the antenna is circularly polarized, yielding the characteristic cardioid right hand circular far field pattern.

At resonance the current propagation in the loop mode sees the current pass down one helix around the balun rim and back up the geometrically opposed helix to complete the 360° loop. This means at resonance the currents should be equal in magnitude and opposite in phase approximately half way up the radiating section. The crowned rim induces phase differentials in the helical loops required to complete the phase quadrature.

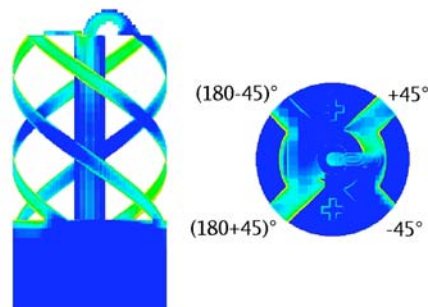


Figure 3: Current flow and phase quadrature in the axial loop mode

It can be seen in figure 3 that no currents are present at the base of the balun, demonstrating that the balun has prevented currents from flowing between the radio and the antenna radiating section, isolating the antenna from noise sources..

In measurement, the constrained near-field properties of this antenna are simply demonstrated by measuring the S_{11} parameter of the antenna. As can be seen in figure 4, the antenna exhibits a negligible frequency shift as a hand is moved closer to the

antenna, still with acceptable return losses ($VSWR < 1.5:1$) even when the hand is 5mm from the radiating surface of the antenna.

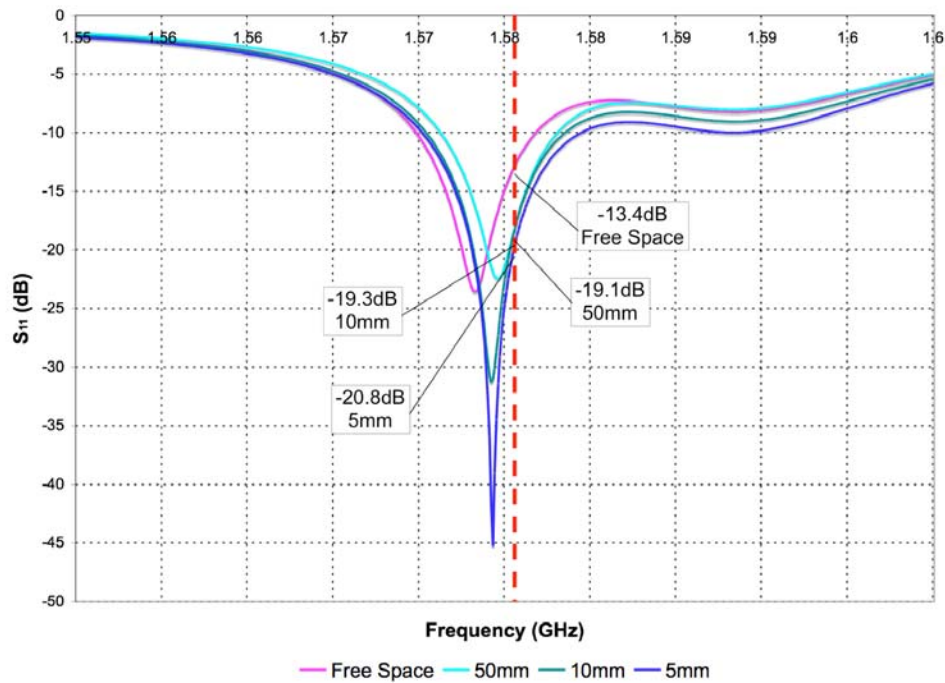


Figure 4: S_{11} plot of passive GeoHelix antenna in free space (blue), hand 10mm away from radiating section (red), and 5mm away (green)

Likewise, the radiation pattern of the antenna demonstrates its imperviousness to near-field loading factors. Figure 5 compares the radiation patterns of the antenna in free space versus hand-loaded. It is significant to note that the demonstrated radiation pattern approaches the Euclidean ideal for cardioid, even when loaded. This has important implications for GPS receiver performance, in that most of the antenna gain is concentrated in the upper hemisphere, indicating strong bias for circular polarization, and the antenna has very broad beamwidth giving much better reception of signals from satellites low on the horizon.

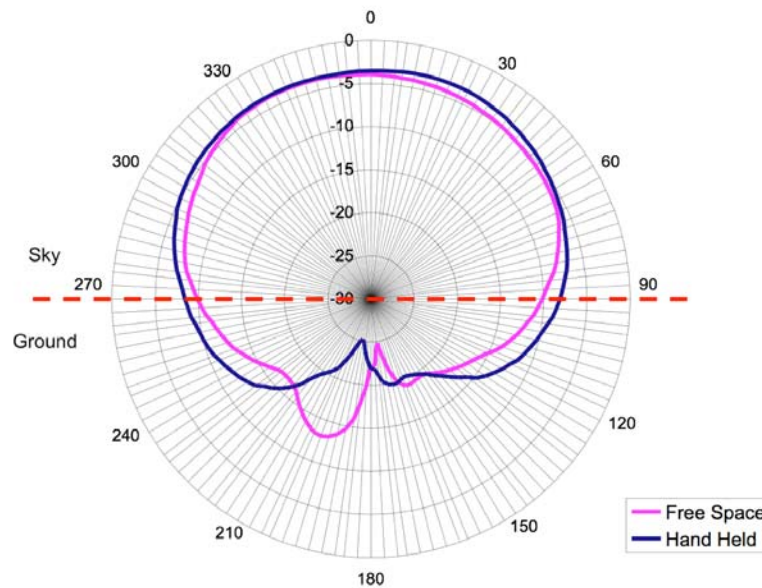


Figure 5: Radiation Pattern of GeoHelix Antenna in Free Space and Hand-Loaded

PRACTICAL DESIGN CONSIDERATIONS

An antenna with these properties has interesting implications for the receiver designer. First, the antenna's stability near dielectric materials will make the task of integration into the housing much simpler. With conventional antenna types, changes in the materials and shape of the radio lead to tuning effects on the antenna, in many cases enough to require alterations to the antenna's structure and resonating length. In the case of the dielectrically-loaded quadrifilar helix antenna, frequency stability around dielectric materials means that the antenna component can be standardized at the beginning of the design cycle rather than the end.

A second important consideration is how the antenna reacts to conducted in-band noise from other components in the radio. Under the conventional single end-fed antenna scenario, noise from electronics in the radio is conducted by the ground plane coupled with the antenna into the receiver. While filtering can remove out-of-band noise from the signal, the receiver is left with degraded carrier-to-noise levels from in-band sources. The choking effect of the antenna's integral sleeve balun ensures that no electrical coupling exists between the ground of the device and the antenna. In other words, there is no path for this conducted noise to enter the antenna to receiver chain.

Two interesting corollaries of this isolation property follow. First, the entire receiver device may now be made as small as the antenna. As can be deduced from figure 5, the total radiation efficiency of the antenna is approximately 23% whether the antenna is in free space or loaded. While this is approximately half what can be obtained from a 25mm microstrip patch antenna with a 40mm ground plane, roughly three times the radiating area of the quadrifilar antenna, the patch antenna remains quite susceptible to body loading effects, reducing its radiation efficiency by half when loaded (figure 6). Reducing the size of the device would further reduce the efficiency of the conventional antenna.

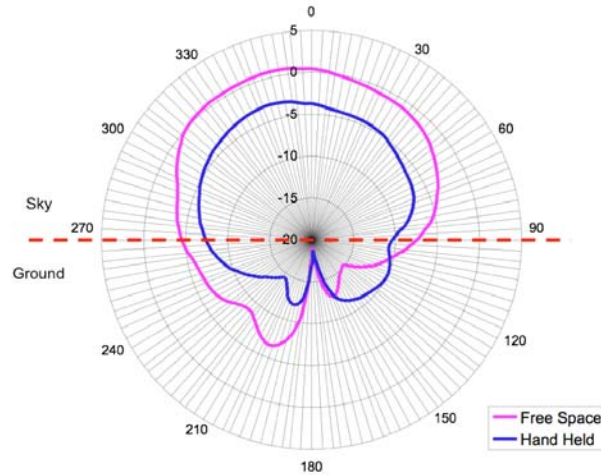


Figure 6: Radiation Pattern of 25mm Patch Antenna with 40mm Ground Plane in Free Space and Hand Loaded

In order to make up for these losses, the patch antenna must be made to look electrically larger, by increasing the size of the ground plane. This very quickly leads to unattractive products, and leads to the second corollary. Because the ground plane is not electrically coupled with the quadrifilar antenna, it can serve as a reflector, much like the dish portion of a parabolic antenna. Measured with the same 40mm ground plane as the patch antenna, the quadrifilar antenna’s radiation efficiency doubles, as shown in figure 7.

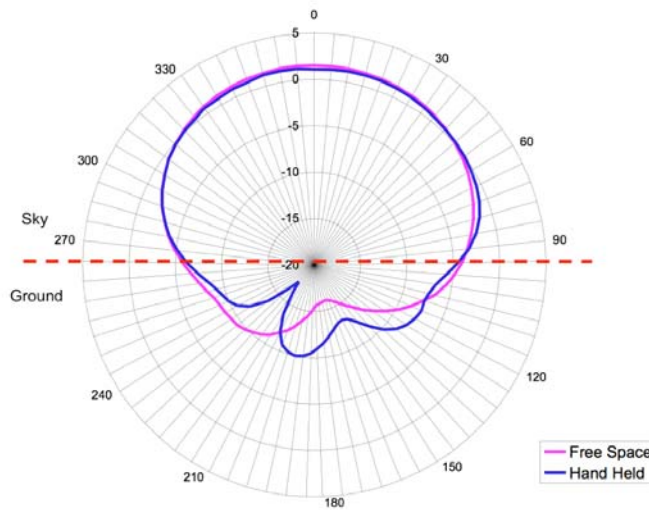


Figure 7: Radiation Pattern of GeoHelix Antenna with 40mm Ground Plane in Free Space and Hand Loaded

A final design consideration is that a “stub” style of antenna like the quadrifilar antenna with a broad, strongly circularly polarized radiation pattern, gives the user much more flexibility in how the device may be oriented. Unlike common mechanical packaging approaches for patch antennas, a stub style of antenna does not require hinged

mountings susceptible to mechanical failure, and presents a smaller profile to the device without sacrificing performance.

CONCLUSIONS

An electrically small antenna with predictable, stable performance seems a contradiction in terms, however that is what has been realized in the dielectrically loaded quadrifilar helix GPS antenna design. The combination of high dielectric materials, quadrifilar structure, and balun integral to the feed system of the antenna makes it much less susceptible to the proximity effects of dielectric materials in the near-field region. The balun ensures isolation from the application, leading to higher carrier-to-noise figures in the receiver. The quadrifilar structure of the antenna design yields a far field pattern much nearer the recommended GPS cardioid model than is possible in conventional GPS antennas, particularly when loaded. Future innovations in this design could include shrinking the volume of the antenna, improving the feed system, and taking advantage of other resonant modes in the structure for multi-banding.

As the mass market for GPS devices, and maybe more importantly for GPS functionality in multi-purpose devices, explodes, the GPS designer needs to take into account the whole receiver chain, including the environment into which the antenna is placed. Improvements in receiver sensitivity will be negated by antenna design that yields up dBs to real world application hazards, like body-loading or common mode noise. However, the combination of good receiver design with the dielectric-loaded quadrifilar helix will give the user a predictable, repeatable, practically unyielding response suited for demanding consumer applications, whether the device is sitting on a dashboard or resting in a pocket or purse.

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DEFINITION OF COMMON ANTENNA TERMS

Balun	A type of transformer that converts a balanced line (i.e., one using two conductors with equal but opposite currents) to unbalanced (one that uses a single conductor and ground). From "balanced/unbalanced."
Beamwidth	A measure of the angle in which a CP antenna is 3dB less than at the zenith angle; the Euclidean ideal cardioid pattern has a beamwidth of 180°.
Dielectric	A dielectric material is a poor conductor of electricity but an efficient supporter of electrostatic fields. Dielectric constants are stated relative to air, which has a relative constant of 1.
Dielectric Loading	Describes the effect of placing a dielectric material near an electrostatic field, thereby absorbing the field. E.g., the human hand has a relative dielectric constant ≈ 40 ; moving one's hand near a conventional, non-loaded antenna, would cause the near field of the antenna to be absorbed by the hand, as the near field is stored in a medium (air) with a much lower relative dielectric constant (1).
Dielectric Permittivity	A synonym for dielectric constant.
Efficiency	The measure of total radiated power integrated over a 360° sphere with respect to an isotropic reference of similar polarization.
Far-Field	The field represented by the radiated power of the antenna; the far field pattern describes the gain of the antenna over all angles.
Ground Plane	A planar surface that absorbs ground currents returned by the antenna. In theory, the surface area of the ground plane for a patch antenna should be infinite; in practice, the area of the ground plane should be twice the area of the antenna.
Near-Field	The energy stored by the antenna in the dielectric materials surrounding it. The near field resonates to create the far field. Perturbations in the near field can impair both the far field pattern and the resonant frequency of the antenna.
Polarization	Describes how the radio wave oscillates. GPS employs a right-hand circularly polarized (RHCP) wave that spins in a clockwise fashion.
Return Loss	Measures the amount of energy in dB that is not transmitted in the form of far field radiated energy, but instead reflected back to the transmitter. In general, the smaller the reflection (a larger negative dB value), the more efficient the antenna.
VSWR	The Voltage Standing Wave Ratio measures the impedance mismatch between the antenna and receiver, and can be calculated from the return loss. A VSWR of 1:1 is a perfectly matched system; VSWR < 2:1 is considered adequate for most systems.