Contrawound Toroidal Helical Antenna

Center for Industrial Research Applications (CIRA)
Mechanical and Aerospace Engineering Department
College of Engineering and Mineral Resources
West Virginia University
Morgantown, WV 26506-6106
(304) 293-3111 ext. 361
http://www.cira.wvu.edu
info@mail.cira.wvu.edu

Revised

November 1997

Summary

The Contrawound Toroidal Helical Antenna (CTHA) is a low profile, near isotropic, mixed polarization antenna that excels in many real world communication applications. Current research at West Virginia University's Center for Industrial Research Applications (CIRA) under the sponsorship of IAS Communications and Emergent Technologies Corp. seeks to characterize, optimize, and explore new embodiments of this antenna. This report contains a brief summary of this work.

Optimization efforts have significantly improved the gain of the CTHA. Two years ago, typical gains of wire-wrapped CTHAs were –20 to –30 dBd, and a year ago they were –10 to –20 dBd; currently, these gains range from –3 to –10 dBd. Higher gains with directivity are evident in the new circuit board antennas.

Some of these improvements were obtained through parametric optimization, but the greatest improvement was in moving to the third resonance. For applications where minimizing size is of utmost importance the first resonance should still be used; consider that all of the early successful tests by the U.S. Navy, which demonstrated a 300% advantage in range over a standard military monopole antenna, were conducted with an antenna at first resonance. Using the third resonance will often require a modest increase in overall size, but again the antenna is still small with respect to a conventional antenna, and with the added gain it should do even better than before.

The move from one resonance to another is not simply a result of improved gain but also as a result of a full radiation pattern study throughout the spectrum. The CTHA is even more isotropic at the third resonance than at the first, while the second resonance is the less isotropic of the three. The nature of the polarization changes throughout the spectrum as well, with mixed polarization at first and third resonances and only linear polarization at the second resonance. Current work is verifying the odd-even resonance characteristics higher in the spectrum, but from a size point-of–view the third resonance is an optimal design point for numerous applications. The discovery and subsequent testing of these unique characteristics will provide the designers with unique opportunities to incorporate this antenna into a myriad of field applications.

Another parameter that significantly affects CTHA performance is the major-to-minor radius ratio; generally, lower ratios lead to greater

maximum gains, but a best ratio for a fixed number of windings does exist. The best ratio is different for antennas with different numbers of windings and is a secondary result of more windings producing less gain. This represents a trade-off that can be varied for each antenna application. Increasing the number of windings to reduce size but increasing size to achieve third resonance is another design trade-off to consider for each application.

There are several additional CTHA characteristics that have been studied extensively this past year, which have been discussed in the past. Here are updated descriptions of some of these attributes reflecting new understandings of the CTHA.

Size: The CTHA is a physically short antenna, compared with a whip or dipole that it replaces, and therefore is a low profile device. Its overall size can be further varied to fit specific applications with tradeoffs in performance. Some of the increased gain due to higher resonance operation can be exchanged for more, tighter loops, thereby further reducing the antenna size.

Scalability: The CTHA has been demonstrated in a variety of frequencies, from 0.5 MHz to 2.5 GHz. At each new frequency the modelling has provided predictable design and fabrication parameters.

Resonance: Study has confirmed the belief that the third resonance is an optimal design point for the CTHA, providing the benefits of increased gain, and one of the better configurations for elliptical polarization.

Radiation Pattern: The CTHA radiates nearly equally in all directions when removed from ground effects and operated near an odd numbered resonance. At various parts of its field pattern, the radiation is present as theta-oriented field energy and at other times as phi-oriented field energy. The total gain pattern has only two small anomalies in its pattern, and they are near the regions of high elliptical polarization, perhaps suggesting a tradeoff in this region of the pattern. CTHAs seem to have an advantage when communicating with unknown polarity, i.e. when signals interacting with the environment have changed the polarity an unknown amount which is typical of real-world use.

Polarization: The sphere of far field radiation for a CTHA produces the gamut of polarization possibilities from left hand circularly polarization through various degrees of left hand elliptical polarization to linear polarization and again through various degrees of right hand elliptical polarization to right hand circularly polarization. The typical CTHA regions of circular polarization are 90º either side of the feed, just above and below the horizon.

Impedance Invariance: Internal interactions are the dominant effect on input impedance, completely overpowering any environmental effects. This means that tuning of the antenna in one environment will be minimally affected by a change in environment making it more adaptable to different usages and excellent for mobile applications.

Ground Plane Effects on Polarization: With respect to the effects of a ground plane on circular polarization, when the left-hand polarized energy region below the horizon in a free space CTHA's far-field pattern is reflected from a ground, it becomes right-hand polarized. Based on the geometry of the test field or the shape and size of the ground plane, it can have different effects, but typically it reinforces and even broadens the region of circular polarization. A well-placed ground plane could further capitalize on this effect and has been prominent in the second patent.

Ground Plane Effects on Gain: In general, much of the reflected energy from a ground plane goes into lifting the gain values near the poles of the CTHA with distorted reflection of the anomalies occurring nearer to the horizon, providing a unique pattern that further substantiates the horizon-to-horizon communication capabilities of the CTHA.

Also presented in this paper is a summary of the custom software developed to study the CTHA. Database and optimization improvements are constantly being added, so this is a snapshot of the development and not the final product.

Much of the data presented here are the results of numerical simulation using Numerical Electromagnetics Code (NEC) developed at Los Alamos Laboratories, but many field tests have been conducted to verify the authenticity of the models.

Description

A typical embodiment of the Contrawound Toroidal Helical Antenna (CTHA) consists of two windings wrapped with opposite pitch on a toroidal (donut-shaped) core fed as closed helical loops with opposite polarity. This same shape is closely followed, even in the new circuit board antennas. One of the most dramatic results of previous tests is the numerous geometric shapes this antenna can take and still deliver the dramatic capabilities that have been demonstrated for the pure donut shape. This is of particular importance since conformally mapping this antenna onto the contour of a vehicle (airplane, boat, car, military vehicle) will provide performance and design advantages not available with customary antennas.

Conception

The CTHA was invented at West Virginia University's Center for Industrial Research Applications (**CIRA**) while another toroidal antenna design was being tested for applicability in the Ground Wave Emergency Network (GWEN). The failure of that test antenna was the impetus for creating the CTHA. Two U.S. patents have been granted, #5,442,369 and #5,564,723, with others pending and several disclosures under development. It was inspired as a magnetic current antenna, a functional equivalent to a dipole, but in practice it has significantly different behavior than that of a dipole.

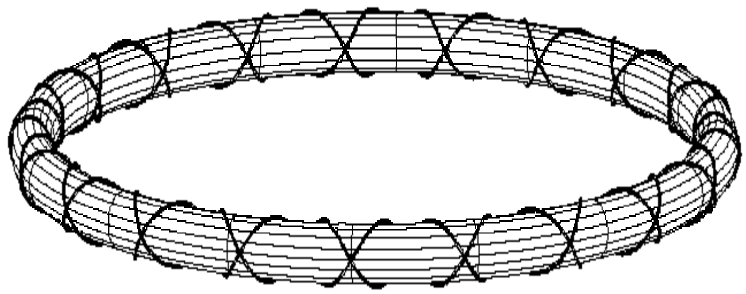


Figure 1 A Contrawound Toroidal Helical Antenna.

Size

The CTHA is significantly shorter than a dipole or monopole antenna as shown in Figure 2; for a given wavelength, λ, the dipole is typically $\lambda/2$ in length, and the monopole is typically $\lambda/4$ in length with a ground plane of $\lambda/4$ in diameter at its base. Optimally the CTHA is $\lambda/8$ in diameter and only about $\lambda/40$ in height. If the communications requirements can be met with less than the optimal antenna gain, then further size reduction is possible. Field testing to-date has shown that these even smaller CTHAs are often sufficient to meet task requirements where currently much larger monopole and dipole antennas are used.

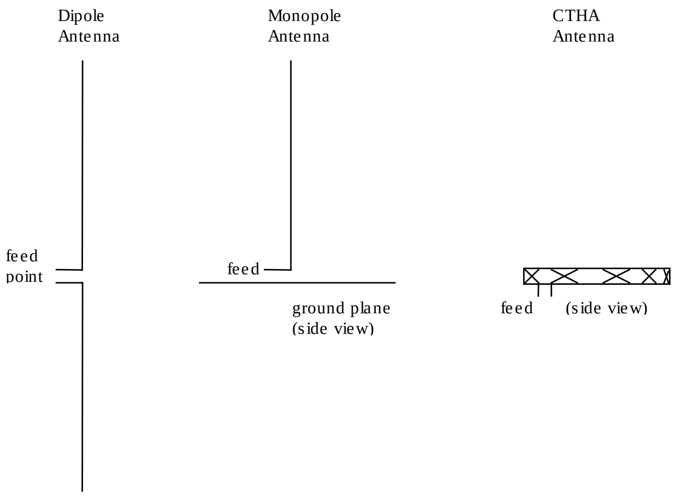


Figure 2 Height comparison illustration of the CTHA and conventional antennas.

Examples

GPS - An optimal toroidal GPS antenna for operation at 1.575 GHz is about 0.9 inches in diameter and 0.2 inches in height.

Cellular - An optimal cellular phone antenna is about 1.6 inches in diameter and 0.35 inches in height.

Applications specifically utilizing circular polarization have a significant volumetric advantage since CTHAs are smaller than commercially available crossed dipole arrays by 1/150th or smaller.

Scalability

The largest CTHA built to date is shown in Figure 3 and has a first resonant frequency near 500 kHz. This antenna demonstrates the portability of the CTHA; the core and conductor segments are snapped together and can be assembled and deployed by one person. At its first resonance it replaces a cut-to-frequency dipole of 300 m in length, and at its third resonance it replaces a dipole 100 m in length.

The other end of the explored spectrum can be seen in Figure 4, which is a printed circuit board version of the CTHA tested at 2.5 GHz for wireless computer LAN use. There is every reason to believe that the CTHA can be utilized just as effectively everywhere between these frequencies and outside of this tested range of the rf spectrum as well.

Figure 3 A 500 kHz CTHA deployed by one person which would replace a 300 m dipole.

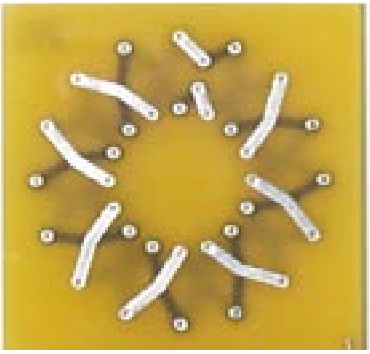


Figure 4 Multilayer printed circuit board version (<1 in^2) of the CTHA for wireless computer LAN.

Resonance Operation (Efficiency Study)

The question of where in the spectrum of the antenna the CTHA should be operated has reoccurred throughout the research project. It has been noted that the CTHA has repeating high and low impedance "resonances" as indicated by high and low resistance values (real component of impedance) where the reactance (imaginary component of impedance) goes to zero, as shown in Figure 5. Discussions have focused, perhaps misleadingly, on whether the antenna is operated "on" or "off-resonance," at the "first resonance,"

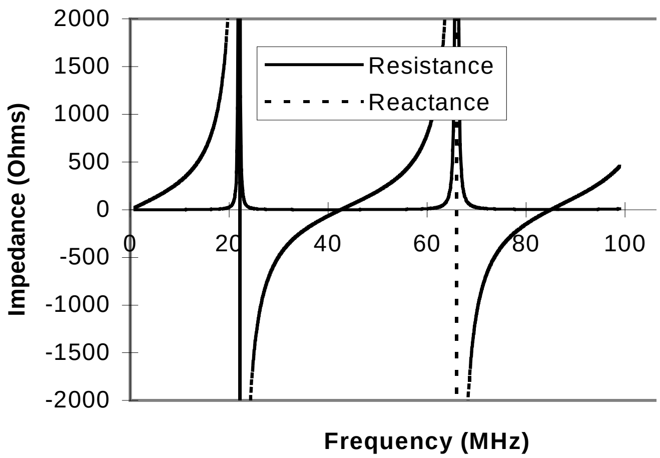


Figure 5 Typical CTHA impedance spectrum.

the "second resonance," etc. Previous attempts at predicting antenna efficiency as a function of frequency have met with limited success due to numerical instabilities in the NEC efficiency calculations near the resonance points. This recent study employed the more stable NEC measure of average gain which has given significant correlation with the field test results.

Standard Dipole Antenna

Before looking at the impedance spectrum of a CTHA, it is useful to first look at a more familiar antenna. Using NEC 4, the gain and impedance data for a standard copper dipole were computed; see Figure 6. Note that the dipole also has repeating low and high impedance "resonances," but the low impedance resonance comes first and the high impedance resonances are shorter and broader than those of the CTHA.

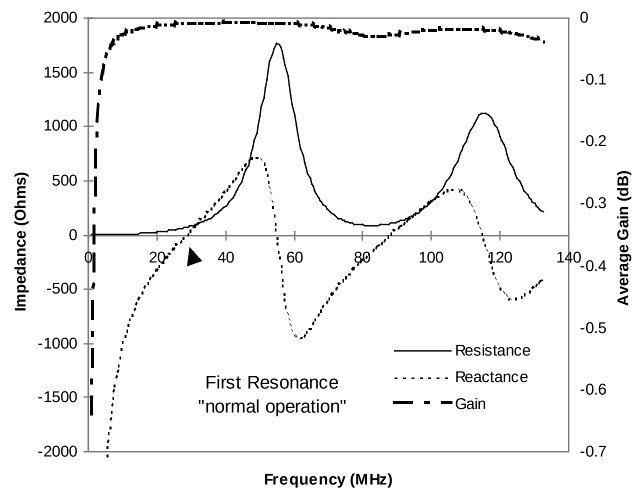


Figure 6 Gain and impedance spectrum of a standard dipole antenna.

The gain shown in Figure 6 is the average gain in dB over the entire far field sphere. If it were zero dB, then all of the energy put into the antenna would have been radiated, giving it 100% radiation efficiency. Note that the gain is near zero for most of the spectrum, indicating that there is very little change in radiation efficiency with respect to frequency for a dipole.

What does change throughout the spectrum is the input impedance and therefore the matching requirements to get energy into the antenna. Typically a dipole is operated near the "first resonance" because very little matching, if any, is required, thereby minimizing losses associated with matching circuits.

CTHA

In Figure 7, the gain and impedance spectrum for a CTHA are presented, where again, the gain is the average gain over the entire far field sphere. If all of the energy put into the antenna were effectively radiated, it would read 0 average gain. The CTHA in this example is not yet an optimal design and has the parameters listed in Table 1.

Table 1 Parameters of CTHA in Efficiency Study

Parameter	**Dimensions**
Number of Turns	5
Major Radius	28.1 in
Minor Radius	5.59 in
Wire Conductor Radius	0.025 in
Wire Outer Radius	0.035 in
Material	copper

There is no inherent reason to operate the CTHA at the first resonance as in the case of the dipole. In fact, at the first resonance, the CTHA is 15 dB down in this example. Figure 7 indicates that better performance can be obtained near the second resonance, where the antenna operates about 7 dB down, and even the third resonance where the CTHA is less than 3 dB down.

Since the CTHA radiates better near the second and third resonance points, the CTHA should be designed with 2 to 3 times longer wire length than earlier designs for a given target frequency. The determination of where in the impedance spectrum of the CTHA that it should be operated is governed by two additional factors:

- Efficiency of the CTHA / matching-circuit system throughout the impedance spectrum.
- Acceptable radiation pattern for a given application as a function of location in the impedance spectrum.

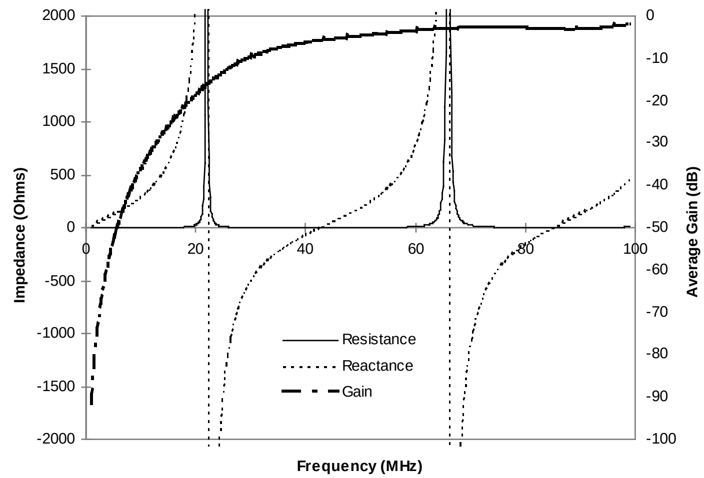


Figure 7 Gain and impedance spectrum for a CTHA.

To compare two antennas for real-world use, the entire system of the antenna and its matching network should be considered, both for difficulty and efficiency of use. It needs to be noted that while it is customary to compare new antennas against the industrial standard, the dipole, most real-world applications us monopoles which have much less gain than standard dipoles. Because of the CTHA's size advantage, as it approaches the performance of the dipole it clearly supersedes the performance of the monopole or the foreshortened dipole.

Radiation Pattern

If at least eight turns of wire are employed in a CTHA's design, then the shape of the far field radiation pattern is nearly spherical near the 1st and 3rd resonances. Resonance points are defined for this document as places in an antenna's impedance spectrum where the reactance is zero. The spherical

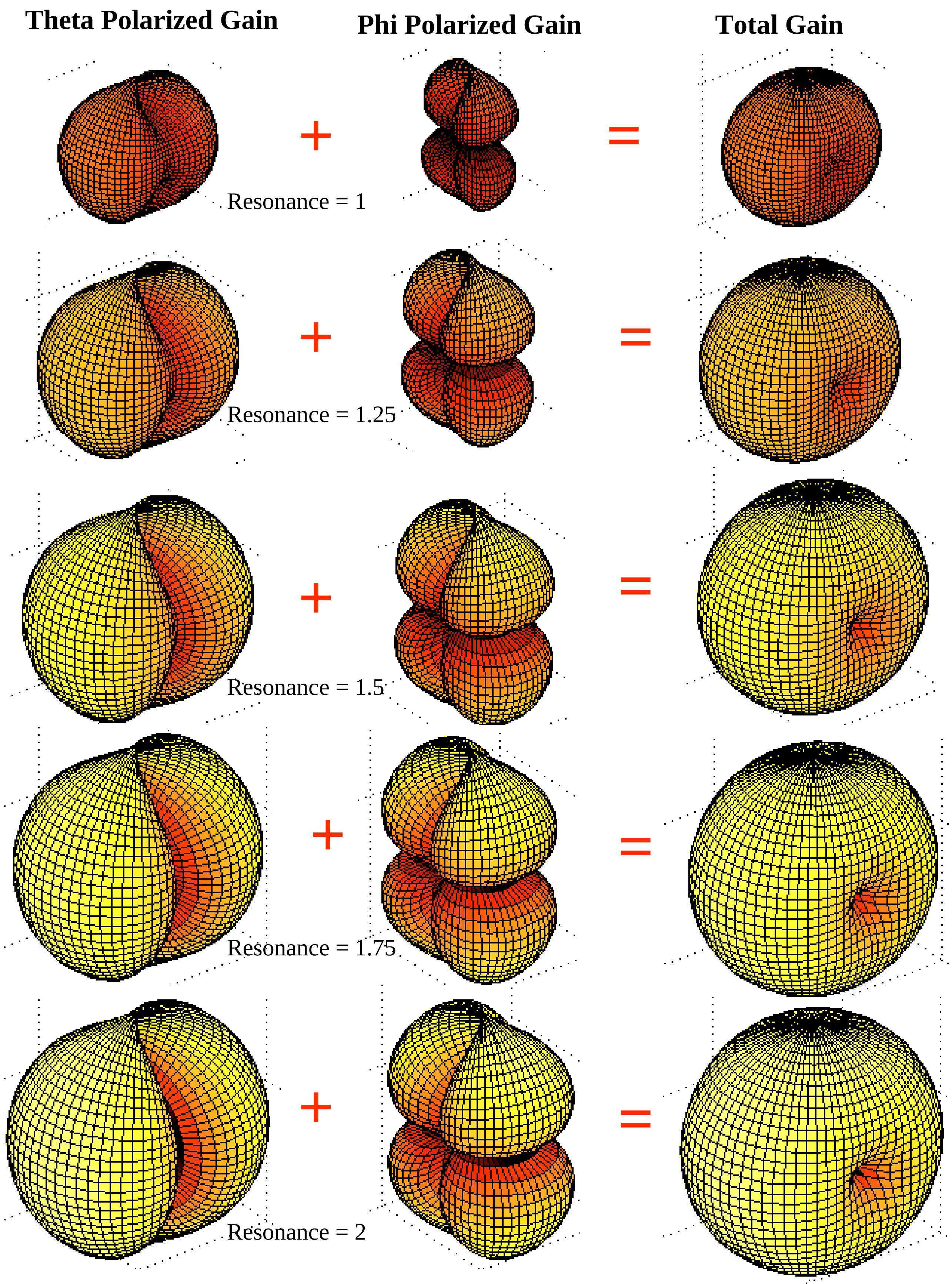


Figure 8 Far field radiation patterns for typical CTHA at various points of a normalized spectrum.

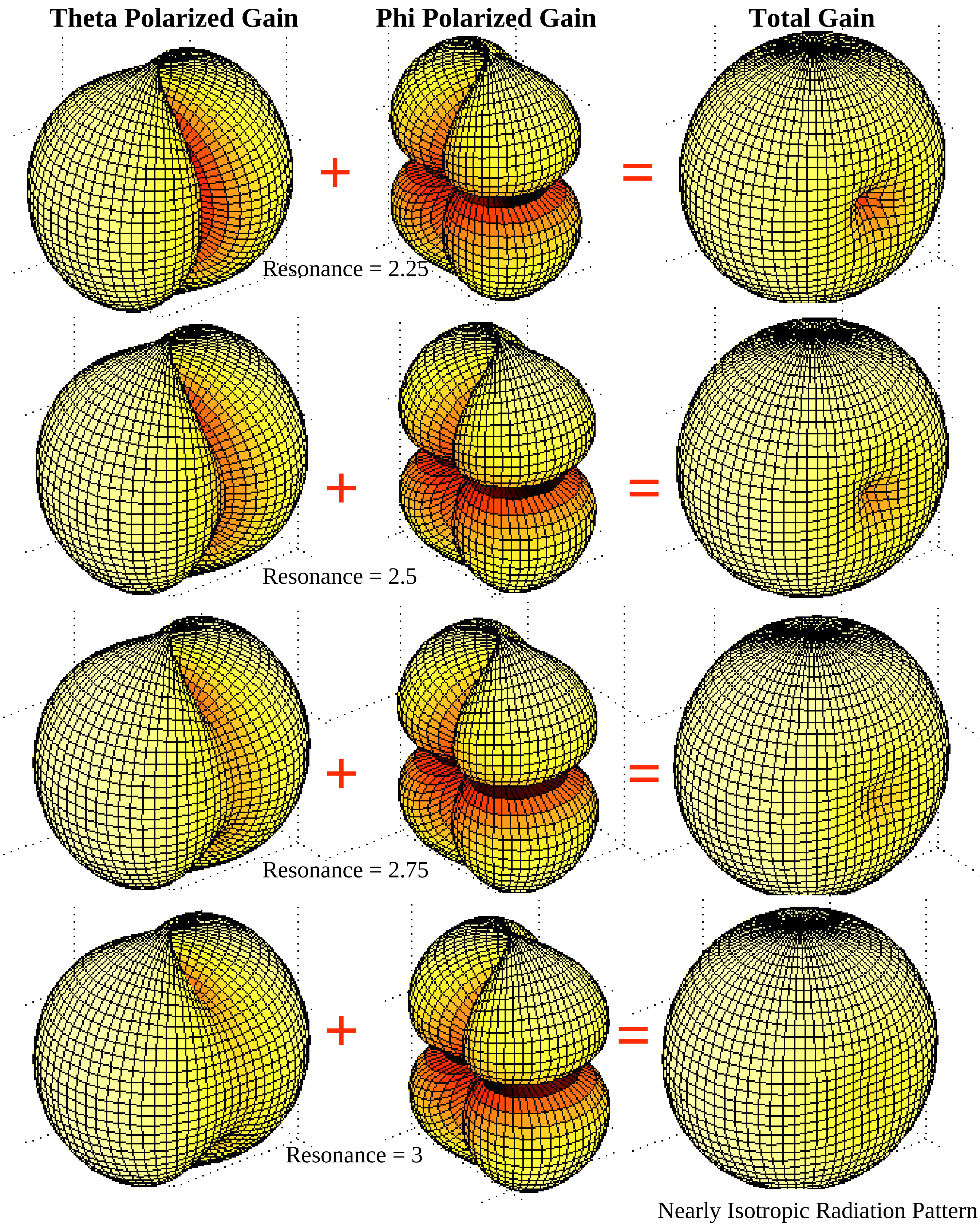


Figure 9 Far field radiation patterns for typical CTHA at various point of a normalized spectrum.

shape of the radiation pattern leads to orientation independence, a key factor for mobile communication. Factors governing the ability to shape the radiation pattern are currently being studied to facilitate the design for custom applications.

Figure 8 and Figure 9 show the far field radiation patterns of a single antenna at various resonances or points of operation throughout its normalized spectrum. The progressive size increase and color change in the figures reflect an increase in gain throughout the spectrum, while changes in shape illustrate the pattern of near isotropic radiation at the odd resonances and the largest nulls present at the second resonance.

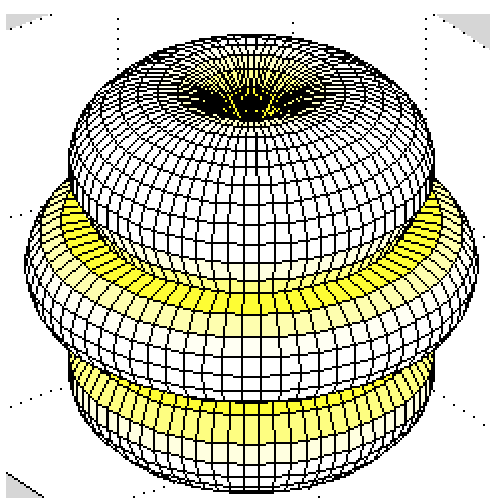


Figure 10 Third resonance far field pattern of theta-oriented gain for a dipole antenna.

In contrast, if a dipole antenna is operated at its third resonance the nice apple-shaped radiation pattern of a first resonance dipole has mutated into the lobed pattern shown in Figure 10. The third resonance dipole, in addition to being prohibitively larger, has only theta-oriented polarization and therefore loses communication with similarly aligned dipoles if the environment between the two antennas is conducive to polarization "roll-over."

Polarization

Polarization may be the best key as to why the CTHA performs very well against standard monopole antennas in many real world tests but is found to have less gain when tested on a line-of-sight test range. A vertical dipole cannot communicate well with a horizontal dipole because their polarizations are different, as shown in Figure 11. Similarly, signals that have changed polarization angle due to interactions with the environment won't stimulate a receiving antenna not realigned to the new angle of polarization.

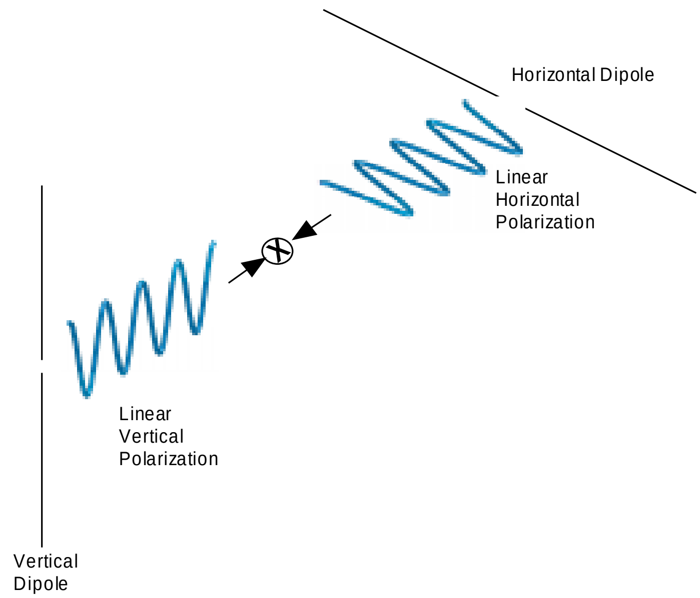


Figure 11 Orthogonal dipoles do not communicate.

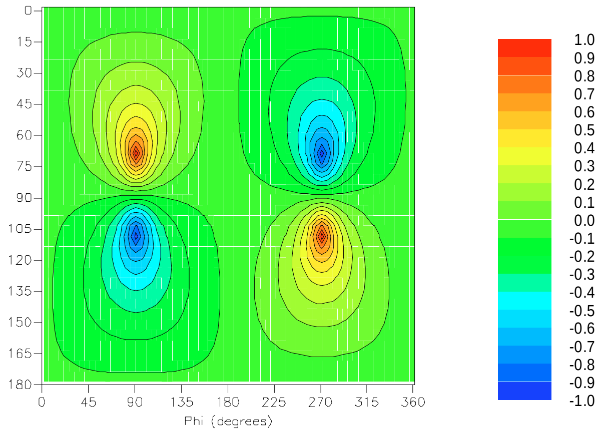
The CTHA has mixed polarization, which has been predicted and demonstrated to have both left and right hand regions of its far field pattern. The CTHA can be utilized in a variety of differently polarized systems, including those with unwanted polarization "roll-over." It can communicate with antennas of various polarizations including:

- Horizontal
- Vertical
- Linear at arbitrary orientation
- Right hand circular (elliptical)
- Left hand circular (elliptical)

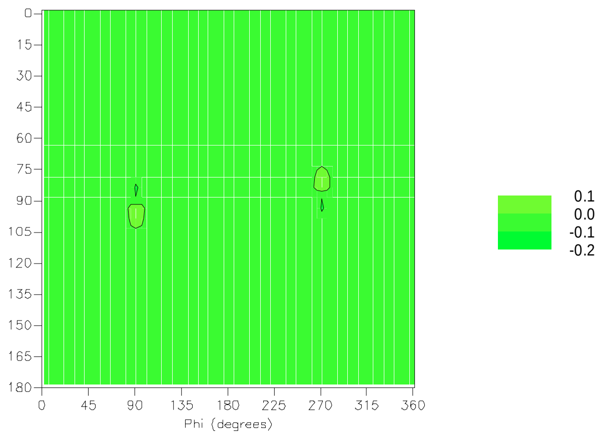
The axial ratio plots in Figure 12 characterize circular polarization in the CTHAs far-field pattern. A positive 1 denotes perfectly circular in the right-hand direction while a negative 1 denotes perfectly circular in the left-hand direction. A zero is linearly polarized, the angle of which cannot be determined from this figure, but by the vectorial sum of the theta and phi gains. Resonances between 0 and ±1 are various degrees of elliptical polarization.

Odd resonances have a regular pattern (for CTHAs with equatorial wire cross-over points) of four elliptically polarized regions. They are located at 90° from the feed about the equator and about 30° up or down from the equator. The even resonances have negligible elliptical polarization (i.e. no phase lag between theta and phi signals). An interesting note is that the positive and negative polarization regions switched from the first to the third resonance; this phenomenon is expected to be repeated for each odd multiple of the first resonance.

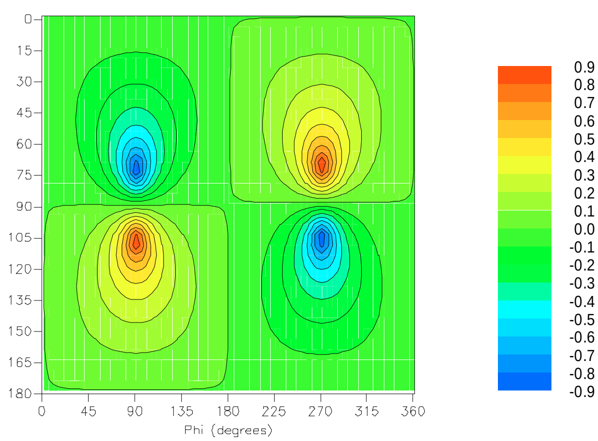
Current research is ongoing to understand the parametric combinations that govern the direction of circular polarization as well as the shape of the far field pattern. One such study varied the spacing between the two wires at their crossover points, which affects the magnitude of the axial ratio but does not change the pattern, as shown in Figure 13.



1st Resonance



2nd Resonance



3rd Resonance

Figure 12 Axial ratio plots of a CTHA for the first, second and third resonances.

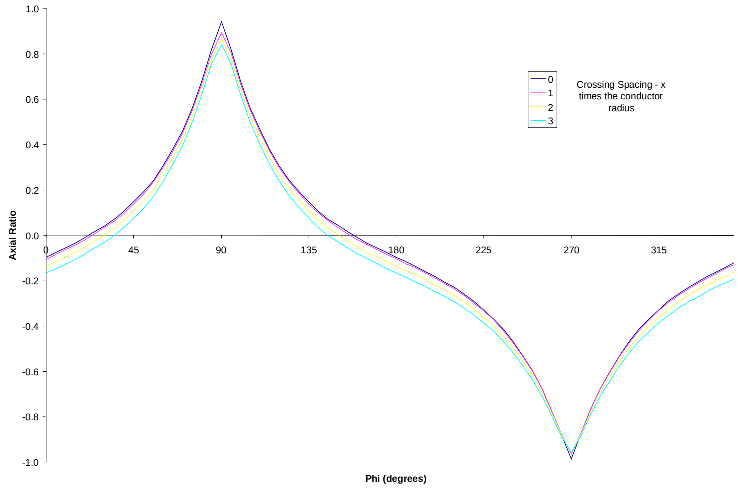


Figure 13 Axial ratio at theta of 45 degrees for several CTHAs with different cross-over spacings.

Gain

Study of the CTHA has demonstrated that lower ratios of the major radius (R_a) to the minor radius (R_b) result in better average gain and hence better radiation efficiency for the CTHA. It had been noted that within each fixed minor radius group, the gain increased with an increased number of windings. Since increasing the number of windings on a fixed minor radius also minimizes the R_a/ R_b ratio, it was unclear whether the increase in gain should be attributed to the number of windings or the change in R_a/R_b ratio. The relationship between gain and increased number of windings for a fixed minor radius was evaluated to clarify this uncertainty.

Figure 14 shows the gains for sets of antennas where the number of turns and the length of wire were held constant for each set and the major and minor radii were changed to obtain a range of R_a/R_b ratios. While it can be seen that in general lower R_a/R_b ratios yield better gain, there seems to be a maximum benefit obtainable for a specific number of turns. It is also clear that more turns for a given R_a/R_b ratio lessen the gain.

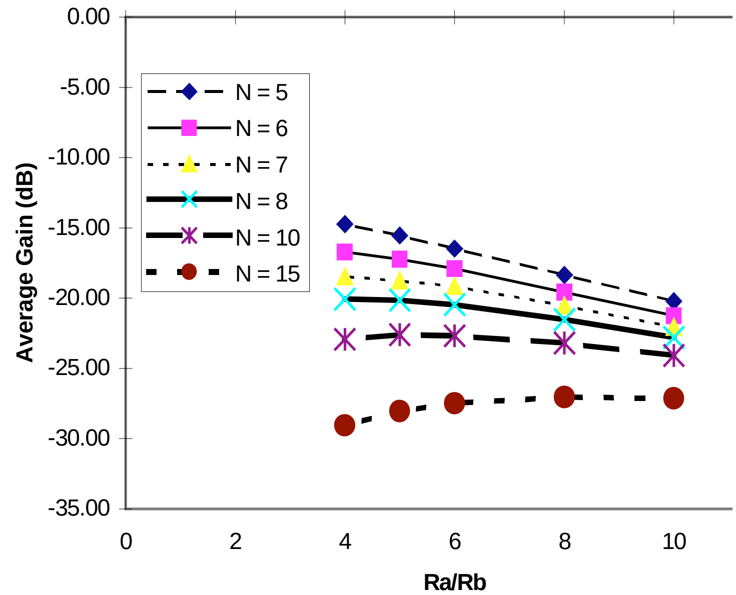


Figure 14 The effect of number of turns and R_a/R_b on relative average gains.

Many design parameters influence the gain of a CTHA, and often geometric trade-offs can facilitate a particular application's design goals. For a spherical radiation pattern (isotropic), the maximum gain achievable is by definition 0 dBi; prototype CTHAs exhibiting nearly spherical radiation patterns have been demonstrated to be less than -1 dBi, and prototypes with fewer windings exhibiting radiation patterns with slight lobes have been demonstrated to have peak gains in excess of +1 dBi. Various known parametric effects on gain can be summarized as follows:

- *Ratio of major to minor radius:* This ratio is one of the strongest gain relationships, where in general, smaller ratios yield higher gain. When the number of windings is held constant there is a ratio corresponding to a maximum gain for that family of antennas. Changing the number of windings produces a new family of antennas with a different maximum gain. For example, antennas with eight windings have their maximum gain at a major radius to minor radius ratio of about five, while antennas with 15 turns have a maximum gain at a ratio of about ten.

- *Relation to impedance spectrum:* Operating at higher frequencies relative to the first resonance tends to produce better gain. For example, the gain near the second resonance is significantly better than the gain near the first resonance, though deviations in the shape of the far field pattern from that of a sphere may make this area of the impedance spectrum inadvisable for some applications. Operation near the third resonance gives another significant increase in gain and again yields nearly spherical shaped far field radiation patterns.

- *Number of windings:* For a given fixed ratio of major radius to minor radius, decreasing the number of windings increases the average gain; however, fewer than eight windings can seriously affect the spherical shape of the radiation pattern. In general, using only enough windings to meet the requirements for radiation pattern shape and antenna physical size is advisable and easily accomplished for the majority of current design applications.

- *Wire thickness:* In general, larger wire diameters tend toward higher gain, but due to the complex geometry created at the crossing points and the mutual capacitance of the wires at these points, there are limits on increasing gain in this manner. Optimal relationships are under study.

- *Arrays:* Additional increases in gain may be obtained by combining several small CTHAs into an array. These studies are showing great promise for directed signal applications like satellite communications or ground-to-ground tight beam links.

Computer Program for Parametric Study

To facilitate an organized, scientific study into the parametric effects of the CTHA, a computer program, named AntModel, was developed with the following elements:

- Solver,
- Database,
- Geometry Generator,
- Results Parser, and
- Display.

Although the program is a single integrated entity rather than separate modules for each element, this discussion is in terms of the different logical units. The CTHA modeling program has undergone several iterations, but the discussion here is confined to the most recent version, which is the result of a massive rewrite to make the database more flexible, separate antenna parameters from test parameters, and incorporate a good ground model to better predict behavior observed at a test range.

Solver

The initial solver of choice is a method of moments code developed by Los Alamos Laboratories known as the Numerical Electromagnetics Code (NEC4), use of which is limited by U.S. government decree to U.S. citizens who have registered for it. The choice ensures that a nationally recognized and respected code will be employed, but it does not limit future selection of another solver should one be found that is more appropriate for CTHA modeling

The in-house developed method of moments solver could also be customized to this use. Currently two other codes are under consideration as NEC4 replacements, XFDTD, which uses the finite difference time domain method, and another method of moments code optimized for small loops.

In order to integrate NEC4 into the new parametric environment, it was modified to be a dynamic link library (dll) in the Windows NT environment. The transformation entailed changing the main routine to a function, and restricting all input/output (I/O) to use files instead of prompts from a console. Future improvements might entail direct passing of all data and multithreading the code to utilize multiple processors.

Database

The database is the foundation upon which the antenna modeling program is based. It permits different kinds of antennas to be created in a variety of ways, stores the parameters of the antennas for analysis and comparison, establishes various antenna testing scenarios, and stores the antenna simulation results for comparison and illustration.

Geometry Generator

AntModel was developed with the concept of using many geometry generators from one program with a common interface to permit study and comparison of the various geometries. Several geometry generators are currently incorporated in the program, but some are still being protected and will not be discussed here

Results Parser

The results parser is linked closely with the solver of choice. It is currently written to open NEC output files, extract the simulation results, compute relevant statistics, and store all of the results in the database.

Display

Many parts of the display cannot be shown due to the proprietary nature of the data that would be revealed. Figure 15 shows the tabbed output screen, which lets the researcher view the far field information in a variety of formats.

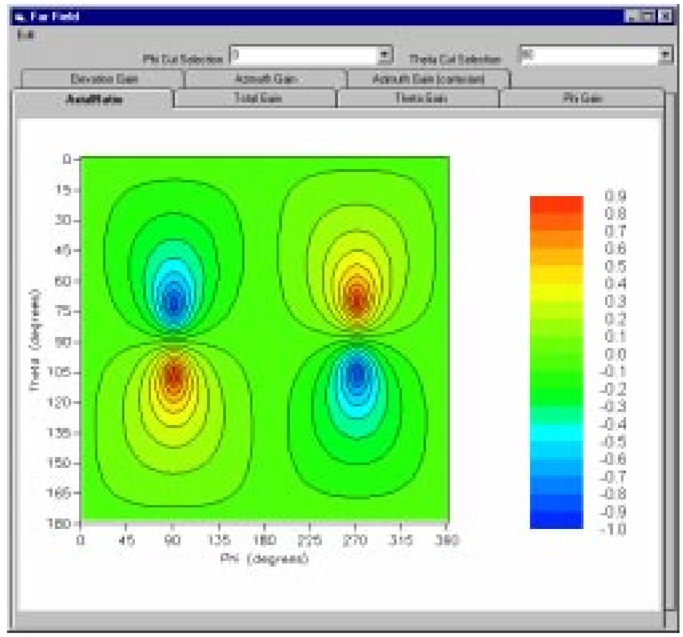


Figure 15 Graphical output display screen

Mobile Applications

The CTHA is especially suited to mobile applications due to its orientation independence, which results from its nearly spherical radiation pattern. Mixed polarization makes the CTHA well suited to satellite communication as well. The combination of small size, orientation independence, impedance invariance, and mixed polarization makes the CTHA a strong contender for mobile, satellite-based communications. Specific applications include:

- Cellular Communication (both data and voice)
- Global Positioning Satellites (GPS)

- Low Earth Orbiting Satellites (LEOS)
- Personal Communication Systems (PCS), both ground and satellite based
- Local Area Networks (LANs)
- Wide Area Networks (WANSs)
- Personal Digital Assistants (PDAs)

Conclusion

In general, the CTHA continues to prove itself a viable candidate for numerous current rf applications. For applications that are expected in the near future, like LEOS (low Earth-orbiting satellites), this antenna may prove the most effective, inexpensive solution to mobile and fixed communications available to date.