11: ANTENNA PERFORMANCE FOR NEAR VERTICAL INCIDENCE SKYWAVE COMMUNICATIONS

The special requirements for antennas for NVIS systems have been described in the previous articles in this series [1,2] and in the work of other authors [4,5,6]. Now, let's take a detailed look at the theoretical and practical aspects of various antenna designs in NVIS service. This look relies on computer analysis using the NEC-2 antenna modeling methodology as well as practical experience. NEC-2 provides analytical data that is very difficult to generate any other way. Practical experience helps address the non-theoretical aspects of erecting and using antennas in the field.

Antenna Performance Estimators

Antenna performance is measured by gain in a particular direction. Gain is expressed in decibels (dB) relative to some standard. The most common standard is the isotropic radiator in free space. Isotropic means that it radiates equally in all directions (sort of like a bare light bulb) so its pattern plot from any direction appears to be a circle. Free space means just that — space in which nothing interacts with the antenna. Gain relative to an isotropic radiator is denoted as dBi.

When an antenna has gain with respect to an isotropic radiator it means that it concentrates its radiation in some particular direction (at the expense of other directions). The antenna does not make power, it merely concentrates (focuses) the power delivered to it by the transmitter through the feedline. For NVIS purposes, the antennas pattern should concentrate most of the radiation field vertically, at angles above 45 degrees, and should be round (omnidirectional) in azimuth. How well it concentrates its pattern is measured by beam width and beam extent [2].

While antennas don't "make" power they certainly can lose some of that provided to them. They do this by dissipating it in their internal resistance and by interactions with nearby objects, such as the earth. Sometimes these interactions are beneficial — for example in many cases reflections from earth improve radiation in certain directions. They can also be harmful — for example, RF currents can be dissipated in the earth's resistance. Most NVIS antennas have a radiation resistance much larger than their loss resistance [2] so efficiency is not much of a problem. Since NVIS antennas are generally mounted low to the ground, detrimental ground interactions can be a problem.

Practical considerations

Tactical communications usually involve base stations, field stations, and mobiles. Base stations are those at which there are the time and resources to erect optimal antennas. Field stations are those in which field expedient (but highly effective) antennas can be erected in a half hour or so. Mobiles, of course, are vehicles that must maintain the ability to be in motion, or to quickly initiate movement.

Base stations are the great opportunity in NVIS communication. LTC Fiedler has noted [4] the importance of exploiting opportunities for optimizing base station performance as a way of augmenting the more limited capabilities of field and mobile stations. This means operating at higher power and erecting more complex antenna arrays. It can also mean exploiting opportunities to reduce ambient RF noise reaching the base station's receiver. This is a big subject and will not be covered here.

Mobile stations are limited in antenna type to those which can be carried on the vehicle while it is in motion, or can be quickly deployed while it briefly pauses. LTC Fiedler has presented considerable research and practical information on this [4,7,8]. While this is an interesting subject it will not be directly covered here.

Field stations provide an opportunity to explore the factors that effect NVIS antenna performance in any situation while simultaneously exploring some of the performance vs.

convenience trade-offs involved. There is an incentive to use antennas that can be deployed quickly, can be depended upon to perform properly, can operate (or be adjusted to operate) over an adequate range of frequencies, and are sufficiently rugged to withstand prevailing conditions.

Most high frequency military field antennas will be built using some number of GRA-4 mast kits with GRA-50 antenna kits (or similar equipment). This allows a maximum height of about forty feet and includes sufficient wire to build an antenna resonant below 1.6 MHz. This equipment is adequate to construct a wide variety of antennas and consequently it will enable a unit to meet all NVIS mission requirements.

Rapid deployment

Deploying a wire antenna requires erecting the required number of masts, measuring and assembling the antenna, connecting the feedline, raising the antenna, and tuning the radio to the antenna. Some antennas also require that a grounding system (e.g., a counterpoise or radial system) be deployed. Most of the time and effort involves erecting the masts, particularly when guying is necessary. Consequently, when time is a factor there is an incentive to use as few masts as possible.

The California State Military Reserve considers a field team to consist of four persons. Such a team is expected to get a station on the air within thirty minutes of arrival on site. Most of that time is spent deploying an antenna. (Initially, the radio is powered by battery. Another half hour is often required to get a generator properly grounded, interconnected, and on-line.) We expect that under normal conditions three soldiers can erect a guyed GRA-4 mast in about ten minutes. A well-trained and motivated team can erect three masts, rig an antenna, and put a radio on the air within the allotted thirty minutes. Obviously, the deadline is a lot easier to meet when only one mast is involved. Antennas that require more masts need to do something worth the trouble. On the other hand, an antenna that is quick to deploy but does not perform well isn't of any value.

Antenna performance benchmarks and compromises

What works best? It is hard to improve on the performance of a resonant half-wave dipole mounted about 0.2 wavelengths above ground. No antenna performs significantly better. Its only liability is that it requires at least two masts, and for frequencies below 4 MHz Army doctrine requires three. If height is to be kept in the optimal 0.1 to 0.3 wavelength range the following table provides a guideline on how long the masts should be:

Table 1: Optimal Antenna Height

Mast Height, ft.	Frequency (MHz) should be Above	and Below
20 ft.	4.7	14.0
30 ft.	3.1	9.4
40 ft.	2.3	7.0

Is there a way to get most of the dipole's performance without erecting two (or three) masts? An obvious compromise is a similar antenna that can be erected with a single mast: the Inverted V. As will be seen, its performance at the same mounting height is similar to the dipole and can be made nearly equal by increasing mast height while keeping the antenna as flat as possible. Installation convenience is gained by giving up a small amount of performance.

There are plenty of other alternatives and some of the better ones (see Figures 1a-1j) will be considered using the dipole as a benchmark.

Frequency agility

Practical around the clock NVIS operations require that we operate on more than one frequency. There is a substantial difference between day and night propagation so as a minimum two frequencies are essential. If automatic link establishment (ALE) is used to optimize propagation, a suite of several frequencies may be required.

The resonant dipole is a narrow-band device. Feedline losses, particularly when coaxial cable is used, can approach 3 dB as the frequency changes more than 15 percent. Yet the difference between day and night frequencies can be over 200 percent! At least two frequency changes are required during a 24-hour period. With wire antennas frequency changes are accomplished by lengthening or shortening the antenna wires. As long as the masts are set to accommodate the longest required antenna this is simply done. One shortcut is to string elements of two different lengths from the same feed point — one set forming a resonant dipole at the lower frequency with the other resonant at the higher. As long as frequency selection works as planned this simple technique provides near optimized operation on two frequencies without changing anything.

Antennas can be made broadband by loading which means adding a resistor somewhere in the design. Two examples are considered below — the T2FD (Figure 1f) and the End-Fed Terminated Wire (EFTW) (Figure 1j). Note that the inconvenience of physically modifying the antenna to change frequency is eliminated at the expense of a significant amount of gain (Figure 6).

Each antenna must be matched to the radio (by means of an internal or external antenna tuner). Losses in the feedline and matching system are not considered here. This is a significant simplification but it allows us to focus on the comparative performance of a large number of antenna designs.

Frequency agility can be addressed with designs in which careful selection of the antennas dimensions, type of feedline, and the means of matching it to the radio serve compromises that preserve both performance and convenience. This is a very interesting area but it is not the present subject.

Ruggedness

There are many tricks that can help get a station on the air quickly. For example, setup of an Inverted V using the GRA-4 with its tripod adapter can be managed by one soldier in a few minutes. This works well until the wind comes up. Another trick, which is regularly used when time is tight, is to use three guys per mast instead of four. Once again, this works well as long as the guys are well-positioned and in good soil. When the wind comes up on a dark and stormy night in which the ground has been softened by rain, the antenna can come down. This is embarrassing and inconvenient. It is usually easier to explain an extra few minutes spent getting on the air than it is to explain an extended forced outage at a critical moment. Always take every opportunity to enhance antenna ruggedness — even after a station is on the air.

Balanced and unbalanced antennas

Antennas can be broadly classified as electrically "balanced" and "unbalanced." All antennas have two sides — the current that promotes radiation must flow from somewhere to somewhere. Quarter-wave verticals, for example, find their second half in the earth. Inverted Vs find their second half in a counterpoise wire or in the earth. Antennas such as dipoles and Zepps have two obvious sides but not all antennas with two visible sides are balanced.

Consider a half-wave dipole. If one side is in the clear and the other is in trees, each side will interact differently with its environment.

An inclined dipole [11] has two obvious sides but one of them is much farther above ground than the other.

A sloper [12] uses the mast for one side and an inclined wire for the other. The feed point is at the top of the mast, hence there is a marked difference in geometry between the two sides.

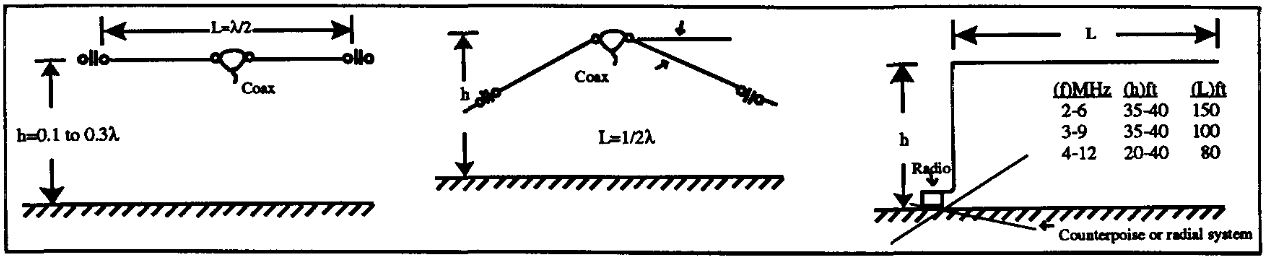
Each of these situations results in different currents in each side and consequently unbalanced currents on the feedline. This situation promotes feedline radiation, and hence, pattern distortion. Pattern distortion in this case means that some radiation we need for NVIS effect is going in some less useful direction, e.g., horizontally.

For present purposes, the following antennas will be considered balanced: Resonant half-wave dipole, AS-2259 Inverted V, T2FDV, and Zepp.

The following antennas have two obvious sides but lack symmetry. They don't require a counterpoise or ground radial system but may suffer pattern distortion from feedline radiation: Inclined dipole; Sloper.

The following antennas are inherently unbalanced and require some form of counterpoise or ground radial system if pattern distortion is to be minimized and efficiency maintained: Inverted L, Sloping wire, End-Fed Terminated Wire.

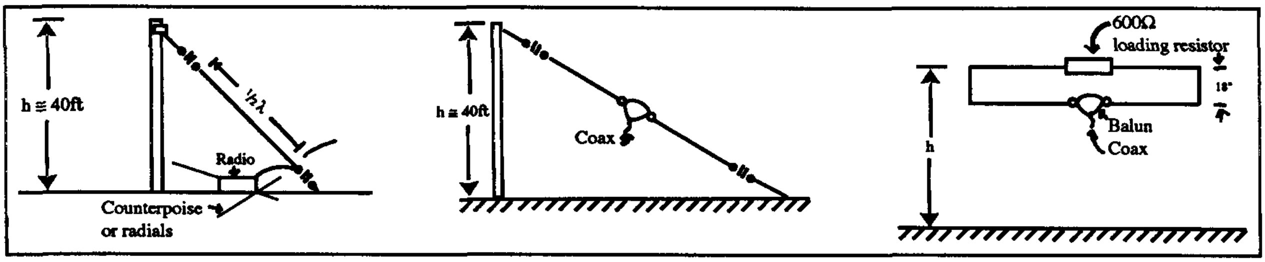
Figure 1. Diagrams of some NVIS antennas



a. Half-wave Dipole

b. Inverted V

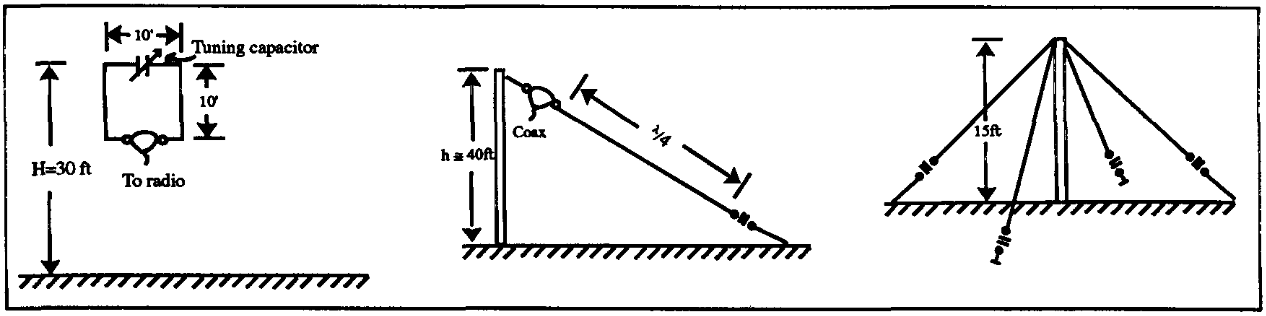
c. Inverted L



d. Sloping Wire

e. Inclined Dipole

f. T2FD

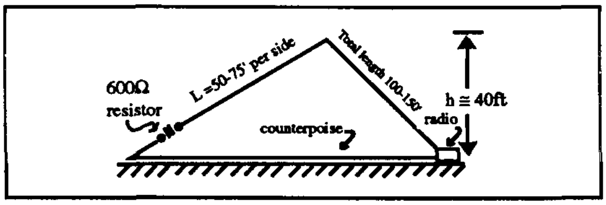


g. Small Loop

h. Sloper

i. AS-2259

(See [9] for general details). Scale distorted for clarity.



j. End-fed Terminated Wire

Starting with the half-wave dipole...

There is widespread agreement that a half-wave dipole (Figure 1a) mounted 0.1 to 0.3 wavelengths above ground is excellent for NVIS communication. Consequently, that antenna provides an excellent reference against which others can be compared. The key performance parameters are vertical gain, beam width, and beam extent. The key installation-related parameters are ground conductivity and mounting height.

A full-fledged dipole is fairly time consuming to erect. It requires at least two masts and below 4 MHz, possibly a third in the middle. While it seems as though the middle mast could be eliminated the long antennas frequently required for nighttime NVIS work suffer this poorly. The droop in the center forms a V antenna which effectively lowers the height. Also, without the center mast the strain on the two end masts is substantially greater thus making the antenna more susceptible to wind, poor guying conditions, and casual neglect.

Ground conductivity and its effect on vertical gain

Ground conductivity depends on the earth under the antenna. In order to avoid a lengthy discussion of ground conductivity and permittivity we will characterize ground as follows [9]: Figure 2 shows the vertical pattern plot of a half-wave dipole mounted at 0.2 wavelengths above each type of ground shown in Table 1. Note that ground properties produce a change of about 3 dB from the best to the worst. Three dB is equivalent to changing power by a factor of two. A 100-watt radio operating over very poor earth would produce about the same signal as a 50-watt radio operating over sea water.

Height above ground

There are two components to antenna height — the part you see and the part you don't see. The part you see is that represented by the length of the mast holding the wire above the earth. The part you don't see is the portion below the apparent surface through which radio waves travel before reflecting. For a very conductive ground, such as sea water, radio waves reflect from the surface. For a poor ground, such as fresh water, radio waves penetrate many feet. An antenna lying on the surface of rocky soil, for example, might have an effective "height" of 40 feet or more. This depth of penetration depends on the frequency as well as the ground itself. Ground is lossy and so it isn't as though "a mirror moves up and down." All computer-generated pattern plots presented herein consider this effect.

Figure 3 shows the vertical gain pattern of a half-wave dipole at various heights (in wavelengths) above average ground. Figure 3 also shows the vertical gain as a function of mounting height. Note that the vertical gain peaks at about 0.2 wavelengths — above that height the antenna begins to develop its characteristic "bat wings" which concentrate a higher percentage of the radiation at lower angles. At lower heights, ground interaction begins to consume the signal. Performance between 0.1 and 0.3 wavelengths is fairly constant — it varies about 1.5 dB. As the antenna is lowered further the gain drops off rapidly. When the antenna is lying just above the ground gain is reduced by about 15 dB from that at 0.2 wavelengths. Put another way, if we compare our 100-watt radio with an antenna lying on the ground against the same radio connected to an antenna at 0.2 wavelengths, we would discover that our signal was about the same as if the transmitter power were reduced to about 3 watts. It is important to note, however, that the pattern shape remains the same.

Effect of Ground on Vertical Gain of a Dipole Antenna Mounted at 0.2 Wavelengths

Ground Type	for Example	Legend	Conductivity Siemens/mtr	Permittivity
Very poor	Cities, industrial areas	VP	0.001	5
Poor	Rocky soil, steep hills, mtns	P	0.002	13
Average	Pastoral heavy clay, med Forestation	A	0.005	13
Fresh water	Fresh water	FW	0.001	80
Very good	Pastoral, low hills rich soil	VG	0.0303	20
Salt water	Salt water	SW	5	81

Table 2: Characteristics of Earth

For mounting heights of 0.2 wavelengths and below, the beamwidth and beam extent are nearly constant at about 135 degrees and 160 degrees, respectively. This beamwidth is more than ample to provide signal strengths within 3 dB over an area with a radius of 400 km or so. The beam extent is so broad that this antenna does not provide much attenuation for signals arriving from far away (at low angles).

Study these figures. They will help you develop a "feel" for the performance you can expect in each situation you will encounter.

The Inverted V

An Inverted V (Figure 1b) can be erected using a single mast in its center. This is much simpler and quicker than erecting a dipole.

It will perform almost exactly like a dipole mounted at a slightly lower height. Figure 4 shows the elevation pattern with the center at 40 feet and with various amounts of droop. Clearly, the flatter the better.

If you think about it, this is logical. It is RF current in horizontal wire sections that produces NVIS effect. The sharper the V, the less current there will be in the horizontal plane. Further, the fact that placing a V in the an-

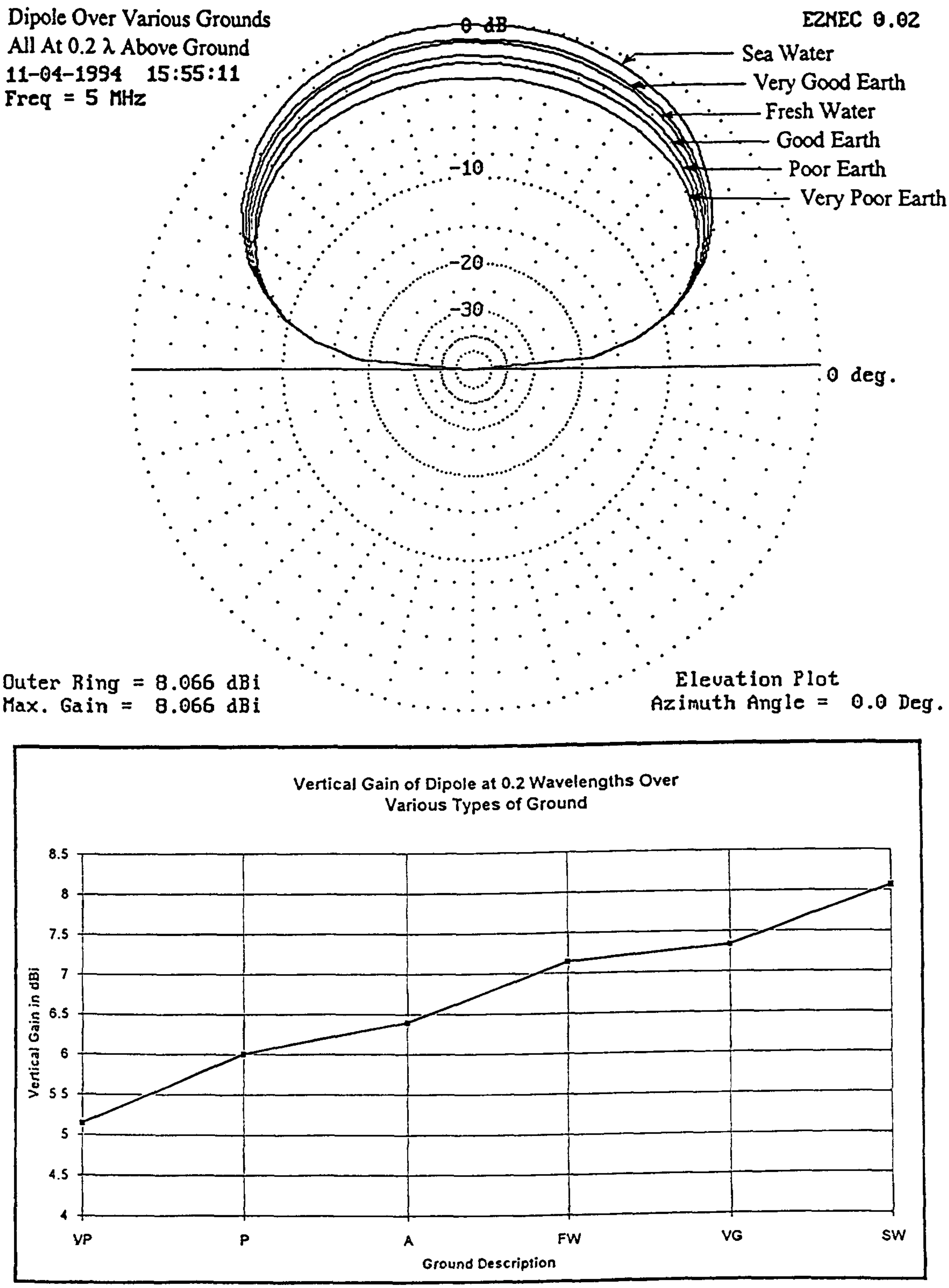


Figure 2. Half-wave dipole at 0.2 wavelengths over various grounds. While not much can be done to change the characteristics of the ground that is encountered, it is comforting to see that from the best to the worst the impact on radiated signal is only about 3 dB.

tenna effectively lowers it is also logical. The current that produces radiation is highest at the center of the antenna and it decreases sinusoidally along the wire arms, finally becoming zero at the end. When the antenna is not flat it is obvious that some of this radiation-producing current is flowing at lower height so we would expect the effect to be that of lowering the antenna. If you work through the math you will discover that a point on an element that is one third of the distance from the center to the end is useful for estimating the effective height of the entire antenna. A similar analysis can be made for the V antenna in which the center is lower than the ends.

The Center-fed Extended Double Zepp

If RF current in wire produces radiation then more wire should be better. This is true up to a point. As the wire becomes longer the pattern tends to become directional in azimuth as well as elevation.

An extended double Zepp antenna is a dipole in which each side is 5/8 (0.625) wavelength long. Obviously this antenna is over two and a half times the size of a standard half-wave dipole. Figure 5 shows the vertical gain (over average ground) compared with a half-wave dipole. Note that the Zepp produces over three dB of gain, thus converting our 100-watt transmitter to an effective power of 200 watts! The bad news is also shown in Figure 5 in which it is apparent that we only get all this gain along the axis, or perpendicular to the axis of the antenna. Note there are deep nulls at 45 degrees to the axis. Stations located in the direction of these nulls would find our signal down by over 10 dB when compared with a half-wave dipole. This serves as an important reminder that long antennas are usually directional in azimuth.

T2FD

While opinions vary, T2FD (Figure 1f) seems to stand for Tactical Terminated Folded Dipole or Terminated Two-wire Folded Dipole. (See [6], pp. 50, 51, 173,181) This antenna has also been called the squashed rhombic. A commercial version is manufactured by B&W. Its primary virtue is that it has a very high SWR bandwidth. This is achieved by loading the antenna in the center of the top wire with a 600-ohm non-inductive resistor. As with all loaded antennas, gain suffers significantly. Figure 6 shows the relative performance of the T2FD.

AS-2259/GR

This antenna (Figure 1l) was designed for use with the AN/PRC-47 and other manpack radios. [11]. It produces NVIS effect and can be tuned over a broad frequency range. It consists of a 15-foot mast which doubles as the coaxial feedline and four radiating elements of two different lengths which double as guys. Its performance depends on frequency but at 5 MHz you can gauge the performance relative to some other NVIS antennas in Figure 6. Its performance relative to a resonant dipole degrades as frequency is decreased. This antenna is tricky to tune and is notorious for problems in the mast/feedline assembly. In most cases a standard dipole is as easy to install and performs significantly better.

Throw it on the ground

Eyring of Provo, Utah is marketing an antenna they call the ELPA for "Extremely Low Profile Antenna." Some of these antennas have been purchased by U.S. and Canadian military units. Their design is very broadband and very large. See Figure 7. It is interesting to compare the NVIS performance this antenna (using NEC-2) with a dipole mounted at a similar height (three inches in this example). In this case the Eyring is set up in the 75 x 75 configuration they recommend for NVIS applications in this frequency range. Both antennas have omnidirectional azimuth patterns. Figure 7 compares their vertical gains at 5 MHz. Although larger and more difficult to install the Eyring exhibits a significant 4.5 dB advantage over the dipole.

Unbalanced Antennas

The usual unbalanced NVIS antenna is made by attaching one end of a wire to the radio and running the other end up and off in the horizontal direction for some convenient distance.

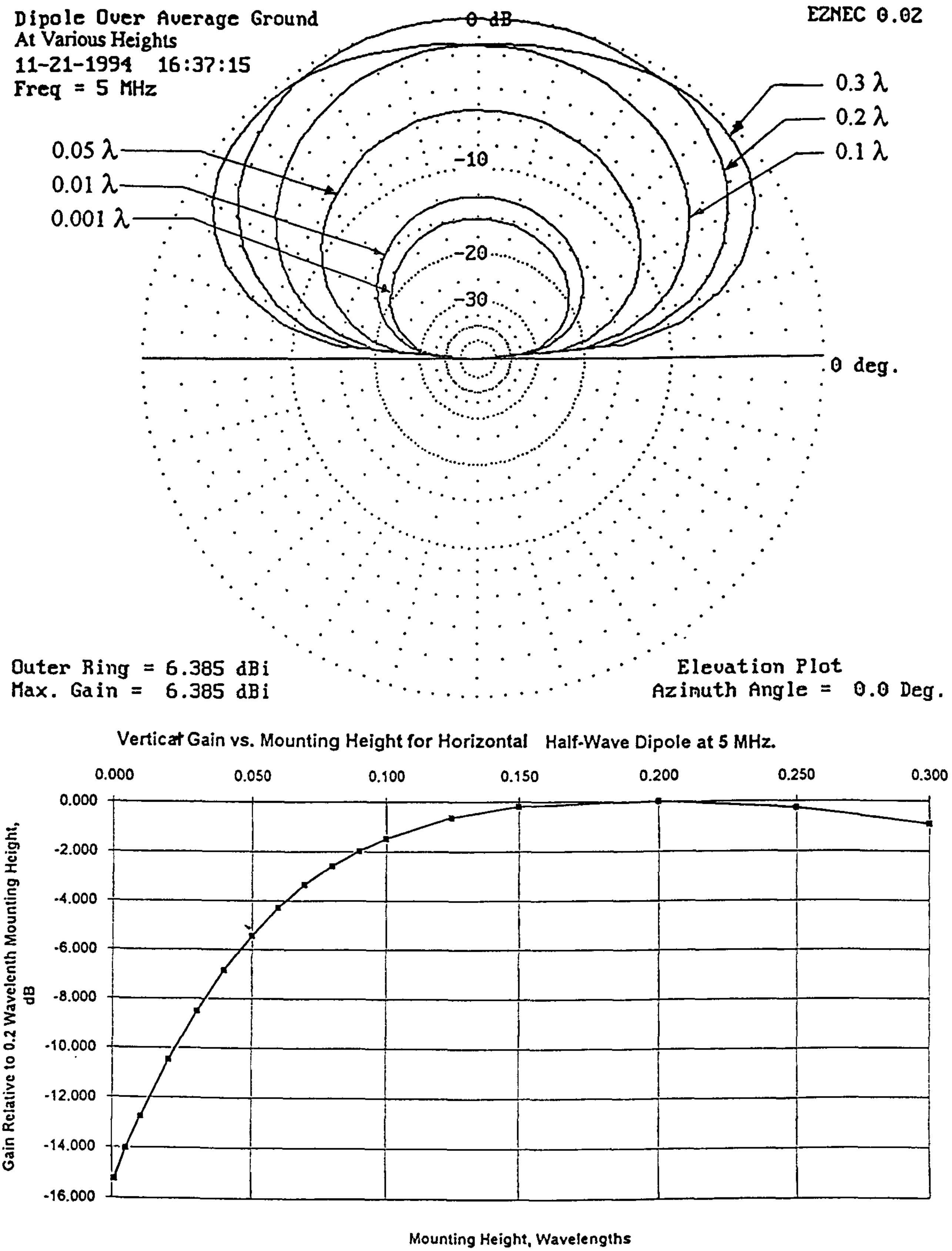


Figure 3. Pattern of a half-wave dipole at various heights (in wavelengths) above ground. Optimal performance for NVIS purposes is obtained at 0.2 wavelengths. Proper antenna height is essential for good NVIS performance. For an excellent treatment of the (non-NVIS) performance of a higher-mounted dipole, see [9], pg. 3-8, 9.

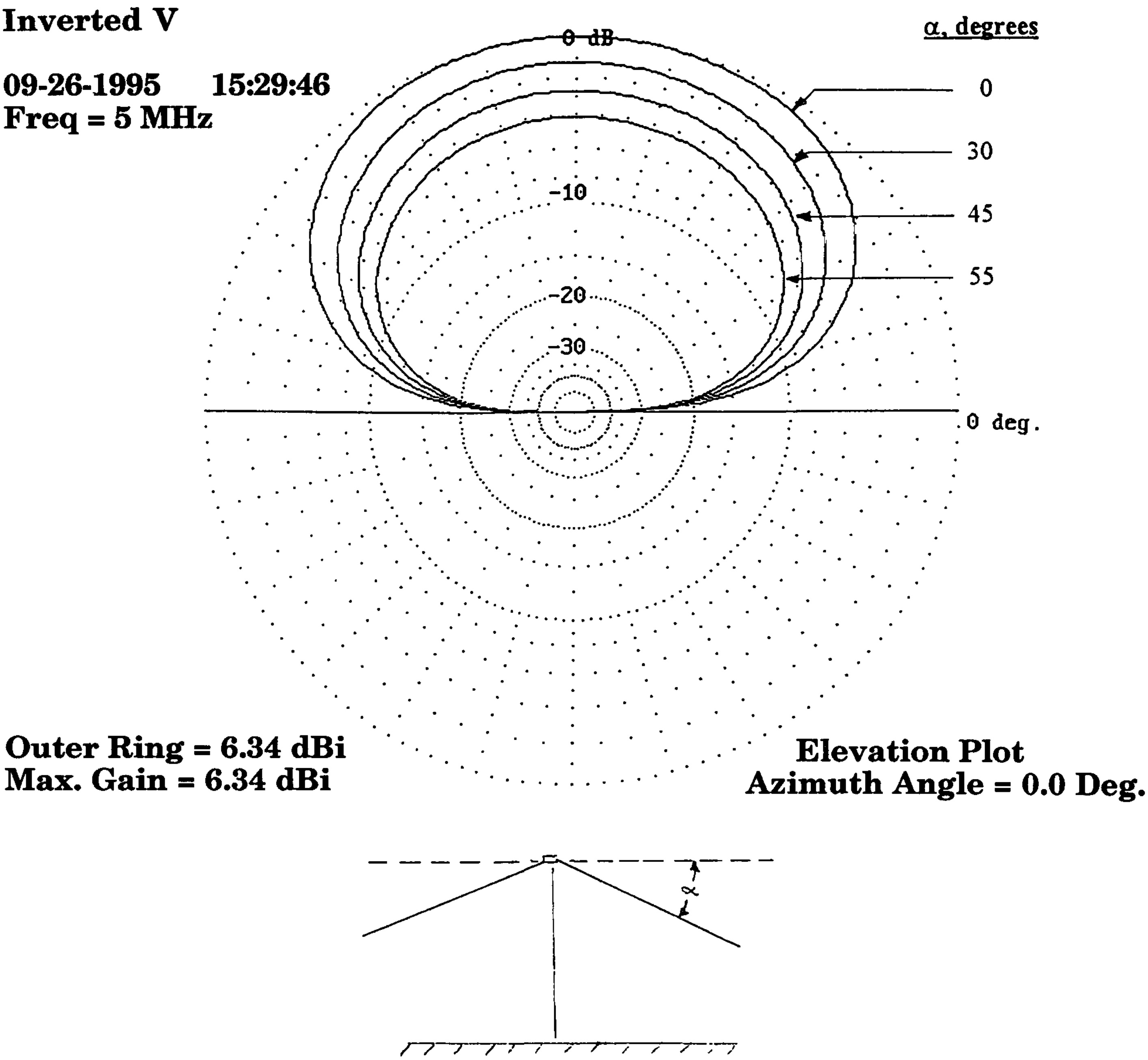


Figure 4. A 5 MHz Inverted V with the center at 40 feet but with various amounts of droop. Clearly, keeping the "V" shallow enhances performance. A 45-degree droop costs 3 dB.

If the antenna slopes uniformly up from the radio to its highest point we call it an inclined wire or random wire.

If it rises straight up to some height and then runs horizontally we call it an Inverted L. (Actually, the "classical" inverted L has a total length of about 0.5 wavelength. Such an antenna does not perform well for NVIS work — too much of the current is in the vertical section.)

As always, the performance is determined by where the RF current occurs. Remember, for NVIS work we want most of the current in a horizontal section that is between 0.1 and 0.3 wavelengths above ground.

In Figure 6, it is simple to compare an

Inverted L with several NVIS antennas. In this case the Inverted L rises up 40 feet and then runs 100 feet horizontally. While the vertical gain is about 4 dB less than the dipole, the on-axis beam width is a narrow 52 degrees and the beam extent is less than 90 degrees. While the vertical gain is lower, this Inverted L provides significant attenuation for distant signals that would be heard as interference if the dipole were used. Inverted Ls are directional and they require a counterpoise or radial system. For this analysis a four-radial system, with each radial 40 feet long, was used. Unfortunately the azimuth pattern (see Figure 8) shows significantly less gain on-axis than across-axis. Orientation is very important.

Field experience indicates this antenna, when properly erected, performs similarly to an Inverted V (which Figure 6 also bears out). The installation is actually somewhat more difficult than required for the Inverted V because of the counterpoise or radial system.

End-Fed Terminated Wire (EFTW)

The end-fed terminated wire (Figure 1j, see [6], pp. 117, 163) is another loaded antenna. As with all loaded antennas, some of the transmitter's power produces nothing but heat in the loading resistor. As Figure 6 shows, it is not an outstanding performer for NVIS work. It is actually somewhat better for long distance work as it produces significant radiation at low angles.

The Sloper and Inclined Dipole

The sloper (Figure 1h) consists of a wire sloping from the ground to the top of a mast. It is fed at the top of the mast in such a way that the mast is connected to the shield of the coax and the sloping wire is connected to the center conductor. The pattern from a sloper made using a 40-foot mast and a half-wavelength sloping wire is shown in Figure 6. A similar approach involves replacing the sloping wire with a center-fed dipole and eliminating the connection to the mast. This antenna is called an inclined dipole (Figure 1e). Its performance is also shown in Figure 6. (For details, see [6], pp. 148, 149 and [9], pp. 4-15 to 4-18.)

Small Loops

A compact antenna (Figure 1g) can be made by arranging conductor in a loop. (see [9],

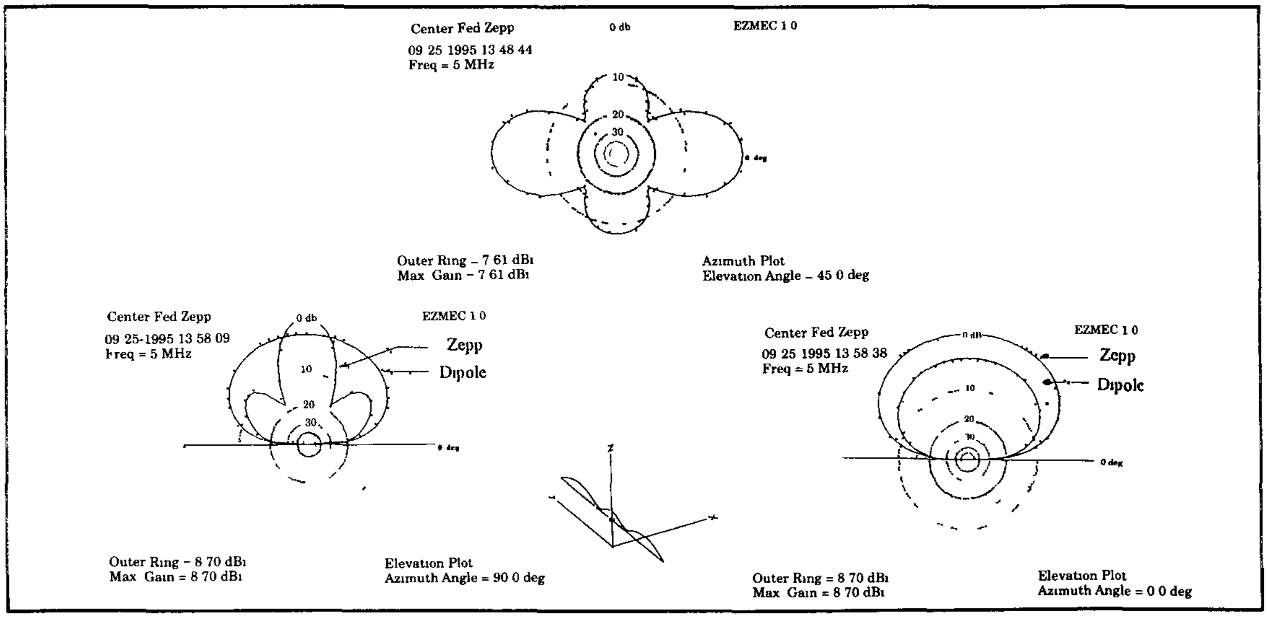


Figure 5. The dipole can be out-performed by the center-fed Zepp, but only in certain directions. In NVIS work, where omnidirectional coverage is usually the goal, it is important to keep in mind that as length increases, the antenna becomes directional. This phenomenon effects all antennas that are long — in terms of wavelengths.

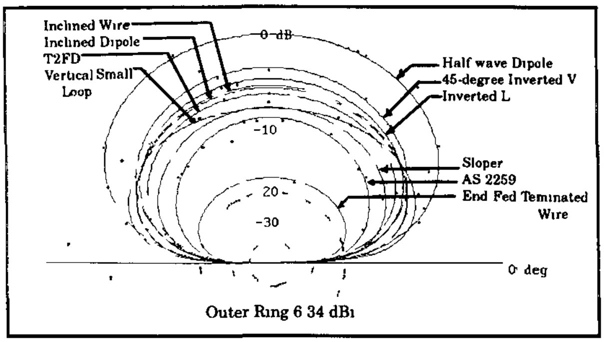


Figure 6. Performance of ten NVIS antennas at 5 MHz is shown. Note that a half-wave dipole has nearly a 3 dB advantage on any of them.

clined dipole (Figure 1e). Its performance is also shown in Figure 6. (For details, see [6], pp. 148, 149 and [9], pp. 4-15 to 4-18.)

Small Loops

A compact antenna (Figure 1g) can be made by arranging conductor in a loop. (see [9], pp. 5-2 and 5-11 to 5-17) The loop is fed in the middle of one side and tuned by means of a capacitor installed in the middle of the opposite side. The radiation resistance of this arrangement is very small, less than one ohm. Efficiency requires that all ohmic losses, in the connections and in the tuning capacitor, be minimized. Resistance of the loop itself must also be kept very small, which usually requires that the loop be made from large diameter copper pipe. For present purposes a square loop ten feet on a side was modeled. Optimum NVIS effect was produced with the loop arranged in the vertical plane and mounted with the top at thirty feet. Its performance can be evaluated by reference to Figure 6.

Small loops exhibit very high Q hence tuning is very critical — they must be carefully adjusted for each operating frequency. Broadband operation without retuning is out of the question. Tuning involves precisely manipulating the loop's variable capacitor, which is difficult to do quickly. Since current in the loop is very high and the voltage that appears across the capacitor can be very large, automatic tuners are not a good choice. Large metal objects, such as armored vehicles, moving near a loop will cause it to require retuning.

Conclusion

There are many antennas suitable for field NVIS applications. It is hard to improve on the resonant half-wave dipole and Inverted V. Practical considerations, in addition to performance, drive antenna selection in military applications. Rapid deployment and the ability to withstand the conditions of the day are important. Within broad limits most environmental effects, such as ground conductivity, have less effect than se-

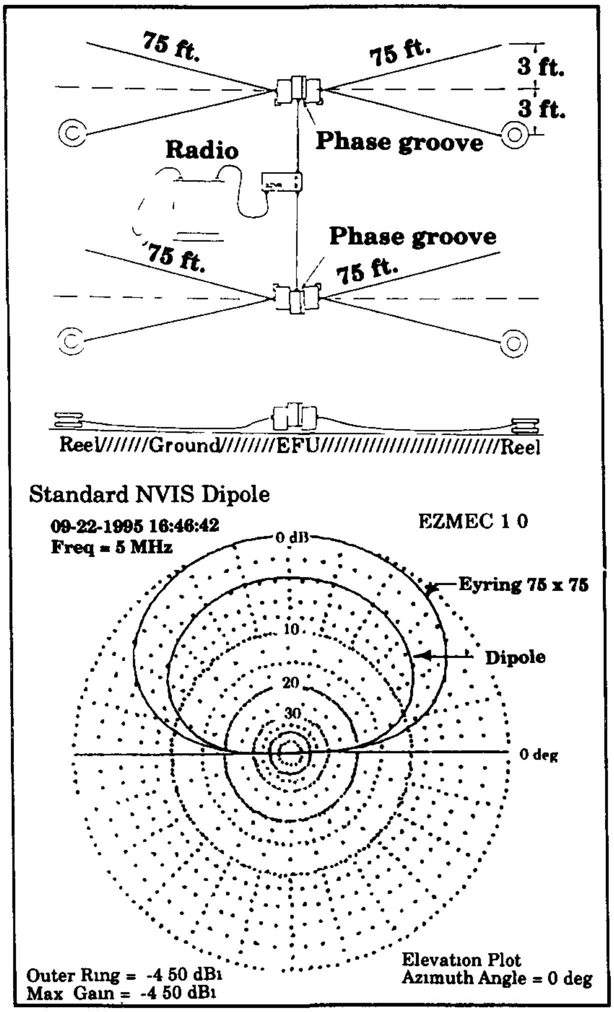


Figure 7. When properly configured in the Eyring - recommended "75 x 75" layout, their ELPA has nearly a 4.5 dB advantage over the simpler-to-erect half-wave dipole. Both antennas are omnidirectional azimuth.

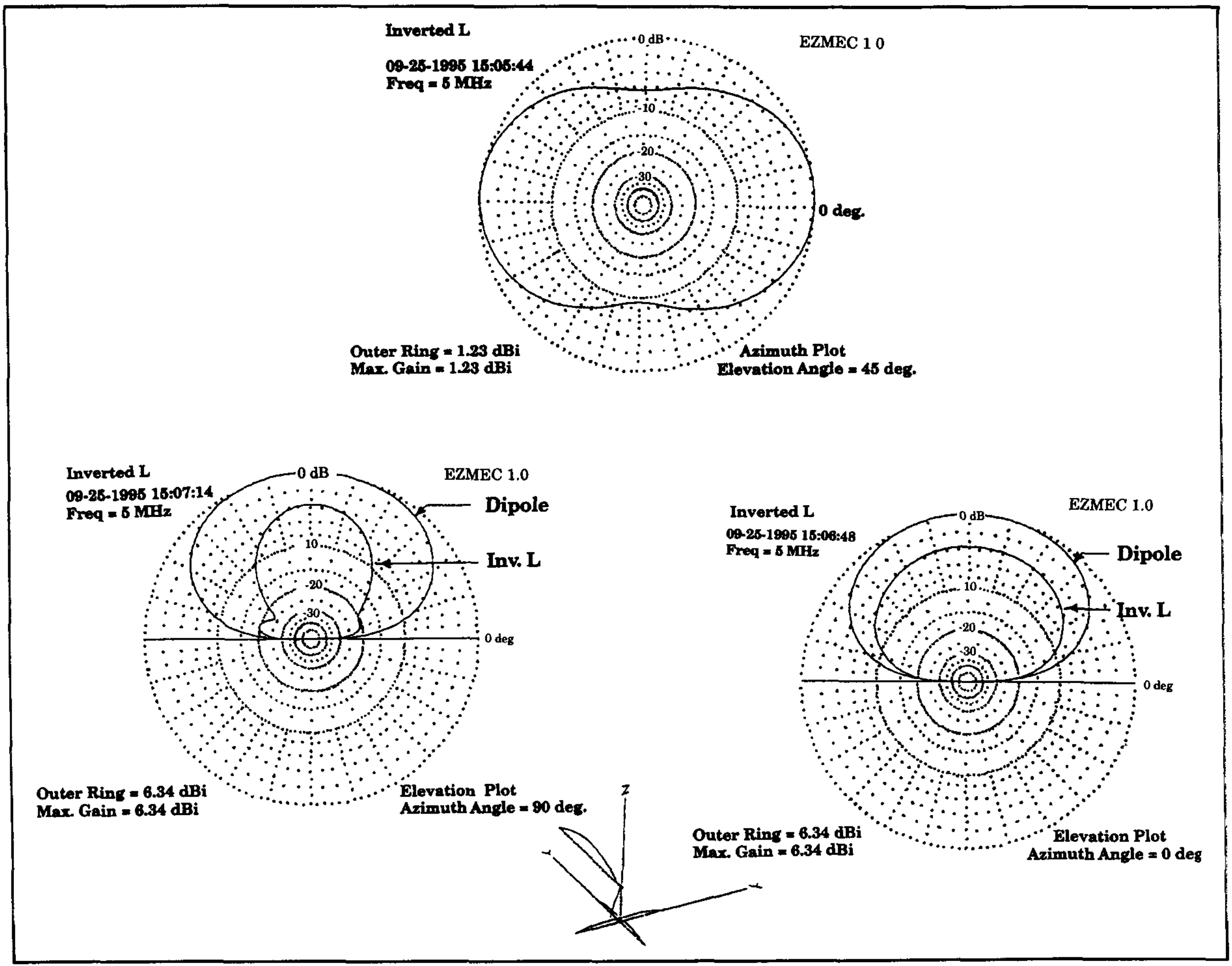


Figure 8. The Inverted L has directional aspects to its pattern. Note that in certain directions that beamwidth and beam extent are significantly narrower than a dipole, although vertical gain is lower.

lection of the proper antenna type.

In most situations, a unit that pays proper attention to basics and does a professional job of installation will find they are the CE heroes of the operation.

Footnotes:

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