NVIS Propagation and Antennas: Some Background Basics

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Near-Vertical Incidence Skywave or NVIS propagations has proven useful, if not vital, to radio communications since at least the World War II era in the 1940s. The mode has re-emerged in the 21st century as a focal point of research and practical field communications. The military, especially, has made it an essential part of its overall message-handling system. In the civilian arena, the mode has become a significant part of emergency plans.

Amateur use of NVIS propagation has grown almost exponentially over the last decade. Some amateurs use the mode for close in communications on 75 and 40 meters, with some work on the 60-meter channels and some activity on 160 meters. Hurricane Katrina proved the importance of NVIS communications when all terrestrial landline, cellular, and VHF modes fell to the fury of the storm.

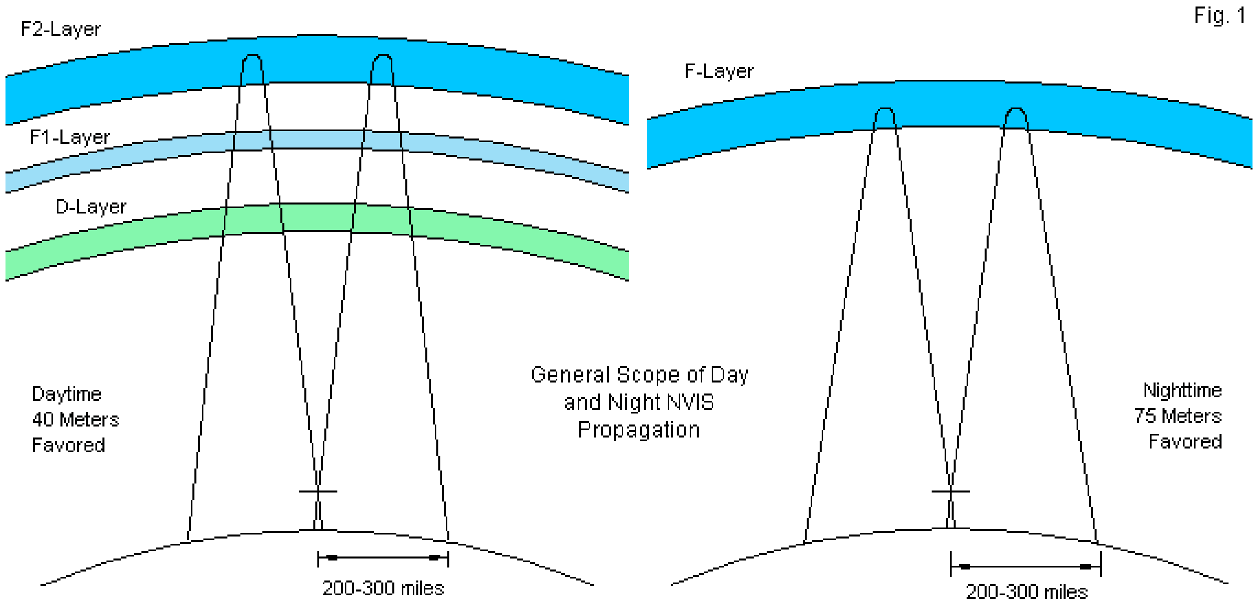
This overall collection of notes concerns the evaluation of amateur radio antennas for NVIS operation. The first section provides background on a number of matters that we must understand if we are to choose the correct antenna for NVIS work. In our initial discussions, we shall confine ourselves to antennas for the amateur bands that use NVIS and to fixed or base station permanent or long-term installations. Our goal for such antennas is not merely borderline success, but instead, optimal antenna installations that maximize the chances of successful communications.

Our first step will be to look at the ionospheric mechanisms that allow and define NVIS communications, and we shall integrate them with the typical NVIS operational situation. Together, these factors tell us what basic properties an "ideal" NVIS antenna should have in order to be effective. Although we shall not perform any evaluations of real antennas until the next episode, we can set up the conventions used to describe NVIS antenna performance, along with some good reasons to depart from the sorts of descriptions we might use with long-distance antennas. The final step in our preliminary notes will be to examine our primary tool for antenna analysis: antenna-modeling software. We shall see why only some of the available software is suitable for working with NVIS antennas.

NVIS Propagation and Situations

Apart from ground-wave signals, virtually all upper MF and HF communications occurs as a result of refracting radio waves through various layers of the ionosphere. The F-layers are the most important ones, although in a negative way, the D-layer also has significance. We identify layers mostly by reference to their height above ground. The D-layer is relatively low, while the F-layers are much higher—in the vicinity of 250 miles above the earth. We used to think that we needed very low angles of incidence between the F-layers and radio signals to effect communications of any strength. However, we later discovered that we obtained returns from signals transmitted directly upward. Initially used for radiosonde work, the realities of battlefield situations showed that we could transfer information by this mode of operation.

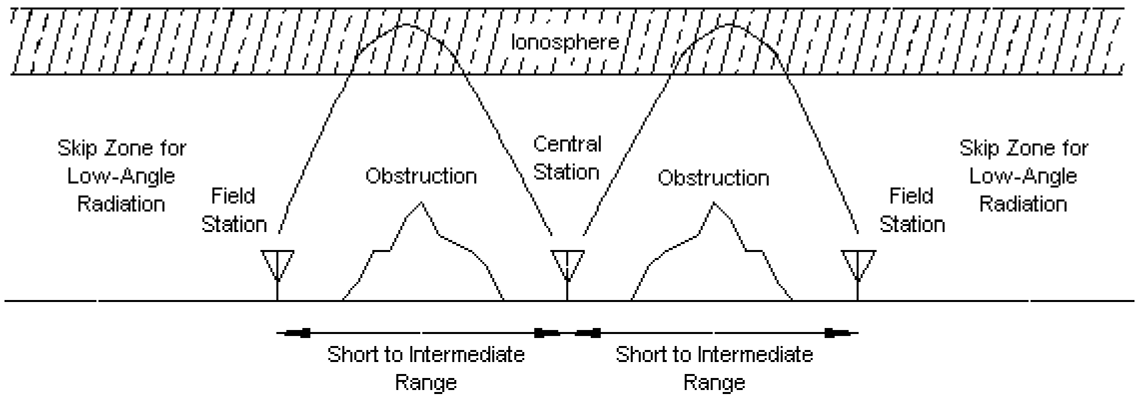
Ionized layers of the rarified upper atmosphere form under the influence of ultra-violet radiation from the sun. Some layers exist only when there is direct sunlight (the D-layer, for instance), while others persist after dark, although they may change some of their properties between daylight and nighttime hours. **Fig. 1** shows the day and night propagation situation as it directly applies to NVIS communications.



Each panel shows nearly vertical radiation from (and to) an arbitrary antenna. In daylight hours, the D-layer forms and absorbs radiation in the upper MF range and even in the lower HF range. Therefore, virtually all skip or ionospheric communications disappears from the 80-75-meter band in daylight. However, 40-meter communication is generally possible via refractions from the F2-layer (and occasionally from the F1-layer, although it is usually too weak to sustain good signal returns). After sundown, the D-layer dissipates and the two F-layers usually coalesce into a single layer that is weaker than in daylight hours. The single F-layer is capable of supporting effective communications, especially on 75 meters, with some work on 160 meters.

The sketches are not to scale, as suggested by the average range of NVIS communications compared to ionospheric layer height. In general, the NVIS range is about 200 miles from a reference station, with possible communications up to about 300 miles. The exact distance on any day depends on numerous factors. The quality of the station equipment (at both ends of the path) is critical. As well, the antenna installation design (our key interest in these notes) is a second contributor to success or failure. Although we can control these first two factors within the limits of the state of the art of radio, the third factor lies outside our control: the variables associated with the existence, strength, and height of the ionized atmospheric layers that make communications possible. These factors, as already noted, vary daily. They also vary seasonally, both in obvious ways (such as the relative length of daylight and nighttime) and in less obvious ways that stem from the changing angle of our station locations to the sun. Nevertheless, on most days and nights, we can achieve successful NVIS communications on one or another amateur band. Indeed, despite the severe power restrictions attached to the amateur channel allocations on 60 meters, the band is finding some good use during the twilight or transition hours between true daytime and true nighttime operations.

The importance of the NVIS mode of operation shows up clearly in **Fig. 2**, which portrays in very general terms the NVIS situation. For many practical—sometime vital—reasons, we need to communicate over a range that exceeds VHF and UHF line-of-sight abilities. However, the range is far shorter than we normally associate with HF skip transmissions. As well, the terrain may contain obstructions to ground-wave communications of any sort.



The NVIS Situation

Fig. 2

The NVIS communications mode allows us to leap tall mountains in a single bound, if we choose the correct frequency and if the ionosphere cooperates. Military applications are instantly clear. In fact, military research into NVIS operations is pressing the frequency limits of the mode, with investigations spreading from just above the AM BC band up to 12 to 14 MHz. Amateur applications generally focus on 75 and 40 meters, with SSB the primary method of encapsulating intelligence. However, as emergency service efforts expand, we shall find increasing use of digital message transfers and a host of other forward-looking methods.

The figure also hides an important facet of NVIS communications for our work. We shall focus initially on the antennas for the central station and presume that we have no major constraints for their installation. We shall treat the central station as having relatively unlimited power and resources with a location outside the troubles that may beset field locations. In contrast, field locations may lie within highly troubled areas—in military terms, a battlefield, and in civilian terms, a disaster area. In both cases, the field station may have limited transmitting power, limited receiving sensitivity, and somewhat primitive antennas. The field antennas may include bent-over whips, hastily erected dipoles using very low supports, and similar inefficient radiators (and receivers) of RF energy. As a consequence, a fixed position central station antenna should be—within the limits of the installation site—as efficient and effective as possible. Anything less places additional strains upon the field station, which is by definition operating under highly taxing situational stresses.

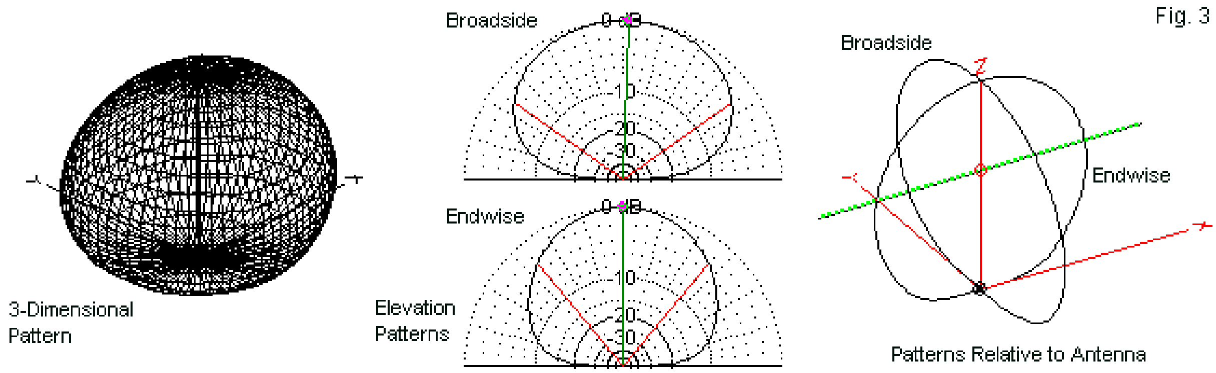
Having noted the importance of optimizing the central station antenna to the degree possible, we must also recognize that few amateur installation sites have unlimited space or other resources to erect a seemingly perfect NVIS antenna. The analysis of various antenna options for various relevant bands may help in the selection of the antenna design to implement on a given site, but the discussion will not create any automatic decisions. (The discussion will also help dispel some older misguided rules of thumb that some amateurs misapply to their NVIS antennas, thinking them to be optimal when they are not.) Equally critical to antenna decision-making is the overall mission of the NVIS station. Some stations devote their activity solely to NVIS communications. Others may have both short and medium range communications goals and require a compromise antenna system that allows both types of operation, even if neither is truly optimal.

In the field of antennas for NVIS service, there are many options. Fortunately, most of them involve rather basic antenna designs.

Antenna Analysis Conventions Used in These Notes

The analysis of NVIS antenna candidates requires that we alter some of the conventions that we use to portray information applicable to low-angle long-distance antennas. Most often, we show both the elevation and azimuth patterns of the subject antenna, especially for directional and bi-directional arrays. When our main radiation focus is straight upward, we need to change our perspective on the antenna. **Fig. 3** provides a guide to the conventions that we shall employ in these notes.

Fig. 3



Radiation Pattern Conventions Used in These Notes

On the left, we find a 3-dimensional radiation pattern for a simple NVIS antenna. The strongest radiation is upward at the zenith angle. Although the pattern is horizontally very round, it is not a perfect circle. On the right, we find a portrayal of the antenna with two nearly circular black outlines. One outline is broadside to the antenna wire—a simple dipole. The other circle aligns with the wire ends. (Virtually every NVIS antenna has a definable broadside and endwise pair of directions, even closed horizontal loops.) In the center of the sketch we find two elevation patterns, one broadside to the loop and the other endwise. We shall use these patterns—at right angles to each other—to characterize the far-field radiation patterns of all of the NVIS antennas that we consider.

In each elevation pattern we find a central line defining the direction of strongest radiation. Very often, the line may be a few (2-4) degrees off the zenith angle (90°) because in a given plane, the region of maximum gain is quite wide. We also find a pair of lines angularly equidistant from the maximum gain line. These lines define the half-power points along the pattern, the points at which gain is 3-dB lower than maximum gain. The angular distance between these lines is the conventional beamwidth of the antenna in each direction. We may define the circularity of the pattern by taking the ratio of the broadside beamwidth to the endwise beamwidth (in that order). Almost all patterns will show a larger beamwidth in the broadside orientation than in the endwise direction. Hence, most (but not absolutely all) antennas will have ratios greater than 1:1, the value for a perfectly circular pattern.

The beamwidth information will be as important to some installations as the maximum gain value associated with a given antenna. Since the beamwidth of the sample dipole is wider in the broadside direction than endwise, if a station has medium-range duties in addition to NVIS functions, orienting the wire broadside to the medium-range targets may increase communications reliability.

The analysis will bypass the azimuth patterns that we associate with long-range, low-angle radiation from the usual set of amateur antennas. **Fig. 4** shows part of the reason why we do not use azimuth patterns. The same sample dipole used to produce the elevation patterns in **Fig. 3** yields the set of azimuth patterns, which vary in shape according to the elevation angle at which we take the pattern. The patterns seem to change shape as we raise the elevation angle, starting at 30° as a sharp oval, but becoming a circle at the zenith angle. The patterns show very little relationship to the 3-dimensional pattern that we viewed in conjunction with the elevation patterns.

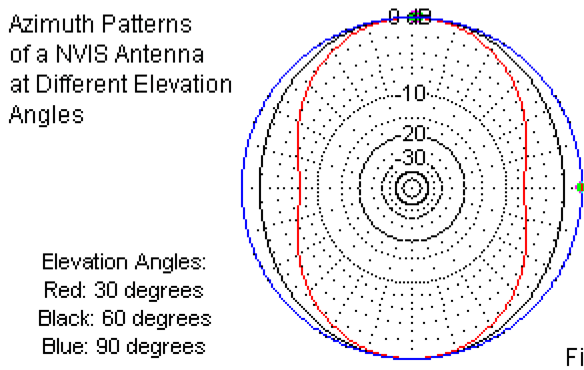
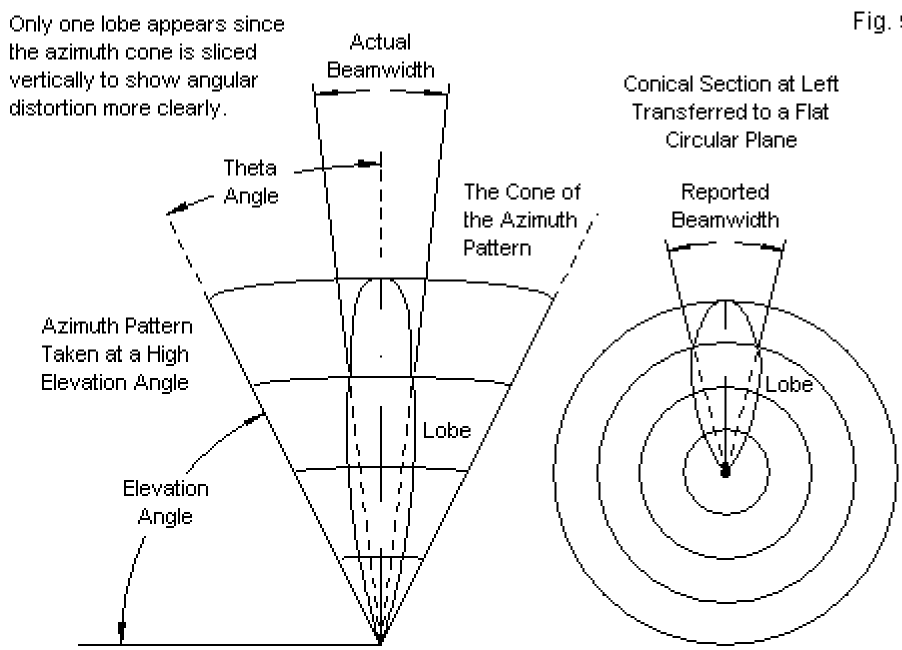


Fig. 4

Part of illusion fostered by the azimuth patterns arises from a systematic error that attaches to azimuth patterns as we raise the elevation angle at which we take the pattern. The higher the elevation angle for a given azimuth pattern, the greater the error that we find in the beamwidth of the azimuth pattern. The error is a function of the fact that the azimuth pattern actually forms a conical section that we then flatten into a planar azimuth pattern. At low elevation angles, the error is not sufficient to void the reported beamwidth (whether as a numerical value or as a visual impression).

Fig. 5



Azimuth Pattern Distortion at High Elevation Angles

As we raise the elevation angle, the error becomes very significant. **Fig. 5** shows a sample of the error. The views show only a single lobe, since the sketch slices the cone in half, eliminating one of the lobes. The flat azimuth pattern on the right shows and reports a wider beam angle than we find on the left. The differential increases as we increase the elevation angle at which we take the azimuth pattern. Let's let BWa be the actual horizontal beamwidth on the conical section, BWr be the NEC report of the beamwidth, while the indicated angles are the elevation or theta angle at which we take the phi/azimuth pattern. (Some NEC software employs the original notation of theta angles that count from the zenith angle downward, while most NEC implementations convert those angles to more familiar elevation angles from the horizon upward. Elevation + theta = 90°.) To correct the reported beamwidth we may perform a simple calculation.

$$BWa = BWr\ \cos(\text{elevation}) \text{ or } BWa = BWr\ \sin(\text{theta})$$

For example, at an elevation angle of 45°, we might have a reported horizontal beamwidth of 27.8 degrees. The cosine of 45° is 0.707. Multiplied times the reported horizontal beamwidth, we obtain 19.7° actual beamwidth. The 10° difference is significant. The cosine of an elevation angle of 60° (theta angle 30°) is 0.5, resulting in a more nearly correct beamwidth that is half the value reported on the azimuth pattern. (The correction is only approximate, since the cone itself is a curved surface.)

For low-angle azimuth patterns, the correction is not significant. For example, at an elevation angle of 20°, the cosine of the elevation angle is about 0.94, resulting in only a very slight change in the reported beamwidth. The importance of the required correction emerges at high elevation angles, typical of those we might use to try to portray a NVIS pattern in azimuth form. For general analysis of NVIS antennas, using a pair of elevation patterns is far more revealing of the antenna's far-field radiation pattern.

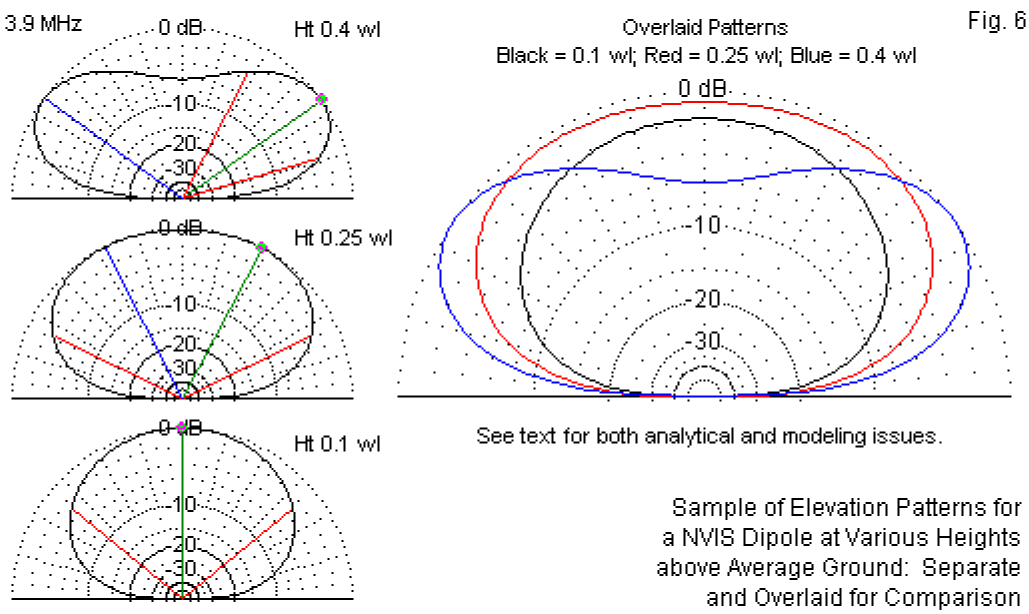
Modeling and Evaluating NVIS Antennas

The broadside pattern of a proposed NVIS antenna is often a key element in its evaluation. For virtually all NVIS antennas, free-space patterns that emerge from models or basic antenna theory have little or no bearing on the antenna's NVIS performance. Instead, the critical factors that create the far-field pattern are the antenna geometry, the height above ground, and the soil quality in the region of the antenna.

Antenna geometry is an obvious factor, since we do not expect a closed 1-λ loop to perform identically to a linear dipole or to an inverted-V dipole. Other antenna possibilities will each show performance differences from these three most basic forms in part due to their particular geometric features, that is, their shape overall and their shape relative to the position of the feedpoint in the assembly. Indeed, we may even press certain forms of beam antennas into NVIS service, not so much to create a clearly definable forward lobe as to tilt the upward NVIS pattern in a desired direction.

In the course of evaluating various candidates for NVIS service, we shall also discover that the proximity of the antenna to the ground magnifies the influence of the ground quality on various aspects of performance. The difference that ground quality makes will show up both in the maximum gain attainable from a given type of antenna and in the height above ground at which we attain the maximum gain. Moreover, when we supplement an active NVIS antenna element with additional structures in the form of reflectors—either as a single wire or as a ground screen—the degree of additional gain that we may obtain from the supplement will vary with the quality of the ground below the antenna and in the region surrounding the antenna. As is the case with all antennas, the far-field forms as a consequence not only of the ground immediately beneath the element, but as well at considerable distances from the antenna, where downward radiation intersects the ground and is reflected upward to combine with the upward incident radiation from the element.

The height above ground for a NVIS antenna is perhaps the key ingredient to the formation of the basic far-field or radiation pattern. Sometimes, individual elevation patterns (in this case, broadside patterns) can be misleading, as is the case with the patterns on the left in **Fig. 6**. The upper pattern, with the antenna 0.4-λ above average ground, is clearly less than optimal for NVIS work. The pattern shows a distinct null at the zenith angle.



Sample of Elevation Patterns for a NVIS Dipole at Various Heights above Average Ground: Separate and Overlaid for Comparison

Lowering the antenna to 0.25-λ above the same quality of ground produces a pattern without the distinct null, but the two maximum-gain lines indicating at least a small reduction in gain at the zenith angle. Further reduction of the height to 0.1-λ, still above average ground, produces a pattern that is similar to the one shown in **Fig. 3**. To resolve any question about which pattern of the three is best for NVIS operation in the absence of tabular data, we may simply overlay the elevation plots. The right side of the figure shows the result. The pattern for the highest antenna level shows the highest maximum gain, but at angles that clearly depart from the desired zenith angle. The nearly circular pattern at a height of 0.1-λ shows deficiencies in gain compared to the seemingly less perfect pattern for the antenna at 0.25-λ. The mid-level antenna placement not only yields more NVIS or zenith gain, but as well has (in the broadside direction) a wider beamwidth that might also serve for at least some medium-range communications needs.

Evaluation of NVIS antenna candidates requires close attention to the maximum gain, both overall and in the zenith direction, as well as to broadside and endwise beamwidth values. Because virtually all NVIS antennas will require heights that are less than ¼-λ above ground for some or all of their horizontal structures, we are limited in the computer-based antenna modeling tools that will produce reasonable accurate views of performance potential. The key limiting factor is not the basic core itself (NEC-2, NEC-4, or MIN问INEC).

The chief limiting factor is the ground calculation system. Only the Sommerfeld-Norton (SN) calculation system has sufficient accuracy to provide usable data on horizontal antennas closer than about 0.2-λ above ground. The SN system is a part of both the NEC-2 and NEC-4 calculating cores. One implementation of MININEC called Antenna Model has successfully grafted the SN system to its core. NEC contains an alternative ground calculation system that uses a Reflection Coefficient Approximation (RCA). The simplified calculations originally allowed faster core runs in the days of slow-speed personal and mainframe computers, but the results grow more inaccurate as any horizontal wire approaches ground level. Even less accurate is the ground calculation system that is part of the public domain version of MININEC (abbreviated here as a ground calculation system as MIN). In fact, the MIN system produces only feedpoint impedance values for perfect ground and not for the soil quality specified for the far-field pattern.

To illustrate the differences in the ground calculation systems, I used identical dipoles at identical heights above average ground to derive results for each of the ground calculation systems. **Table 1** lists the outcome of the exercise, which ran the dipole in 0.05-λ increments from a maximum height of 0.4-λ down to ground level (simulated by a height of 0.001-λ). The table lists the height in feet for each level as well as the height in wavelengths.

AWG #12 Copper Dipole Resonant at 3.9 MHz at 0.4-WL above Average Ground													Table 1
Ground Calculation System			Sommerfeld-Norton			Reflection Coefficient Approximation					MININEC		
Height wl	Height ft	Gain dBi	TO Ang	R	X	Gain dBi	TO Ang	R	X	Gain dBi	TO Ang	R	X
0.4	100.88	6.67	35	85.2	-0.3	6.65	35	85.5	-0.4	6.30	35	92.7	-2.0
0.35	88.27	6.27	40	91.8	6.8	6.25	41	92.2	6.9	5.91	41	100.0	10.0
0.3	75.66	6.08	48	93.7	17.4	6.07	49	94.1	17.9	5.84	47	99.7	25.8
0.25	63.05	6.16	62	89.3	28.6	6.16	63	89.3	29.7	6.17	60	89.8	41.0
0.2	50.44	6.44	87	78.6	36.7	6.50	90	77.5	38.2	6.93	89	71.0	50.0
0.15	37.83	6.28	87	64.2	38.3	6.53	90	60.8	39.6	7.67	88	47.0	48.0
0.1	25.22	5.05	89	51.6	32.5	5.81	90	43.3	30.9	8.42	89	23.8	33.0
0.05	12.61	1.09	90	51.3	26.7	3.09	90	32.0	8.8	9.48	90	7.3	6.5
0.001	0.25	-9.36	88	156.6	302.7	-4.61	90	52.6	-28.9	9.29	90	1.5	-16.7
Notes:	Gain dBi = maximum gain in dBi						R = feedpoint resistance in Ohms						
	TO Ang = elevation angle of maximum gain in degrees						X = feedpoint reactance in Ohms						

For each antenna height, the table reports the maximum gain and the TO (take-off) angle (the elevation angle of maximum gain) in degrees elevation. In some cases, the angle is close to but not exactly the zenith angle, because there is a range of elevation angles over which the gain does not change. The dipole is resonant in NEC-4 at 0.4-λ above ground and does not change its dimension as the height decreases. Therefore, the columns labeled R and X show the feedpoint resistance and reactance that results from using the unadjusted dipole.

For ease of seeing the differences, **Fig. 7** plots the maximum gain values of the dipole at each height using each of the three ground calculating systems. The SN and RCA systems show good coincidence down to a height of about 0.2-λ, below which we find a systematic departure. The RCA system somewhat overestimates the maximum gain as the antenna approaches ground level.

The MIN system begins to show a departure from the baseline SN system values at about 0.25-λ above average ground. One of the shortcomings of the MIN system, made publicly available in the 1990s in *QST* by Roy Lewallen, W7EL, the developer of ELNEC and EZNEC, is the radical overestimation of gain by the MIN ground calculation system for antenna at or below 0.2-λ above ground. The system provides wholly unreliable gain values for horizontal antennas close to ground. It is responsible for many misestimates of gain for 1990s 160-meter and 80-meter antennas. As well, the MIN system, when only it was available to PC users, created misimpressions about very low-height NVIS antennas.

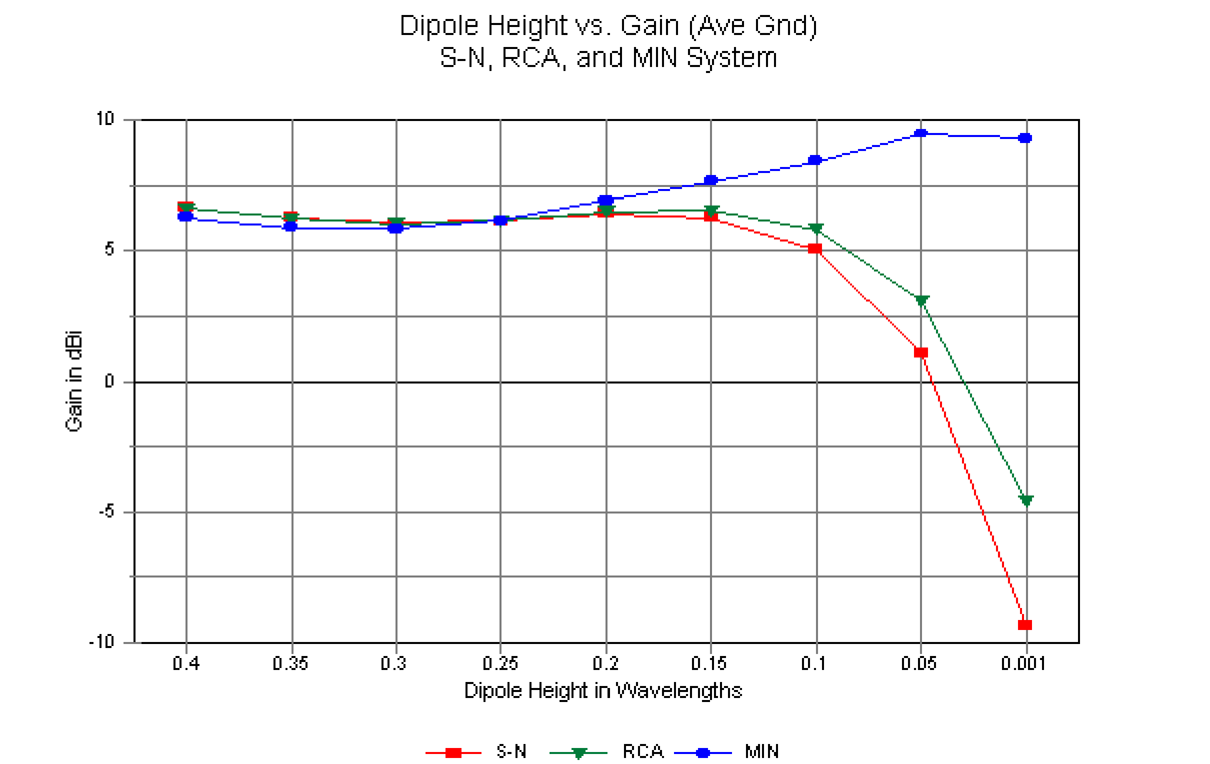

Dipole Height vs. Gain (Ave Gnd)
S-N, RCA, and MIN System
10
5
0
-5
-10
Gain in dBi
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0.001
Dipole Height in Wavelengths
S-N
RCA
MIN

Fig. 7

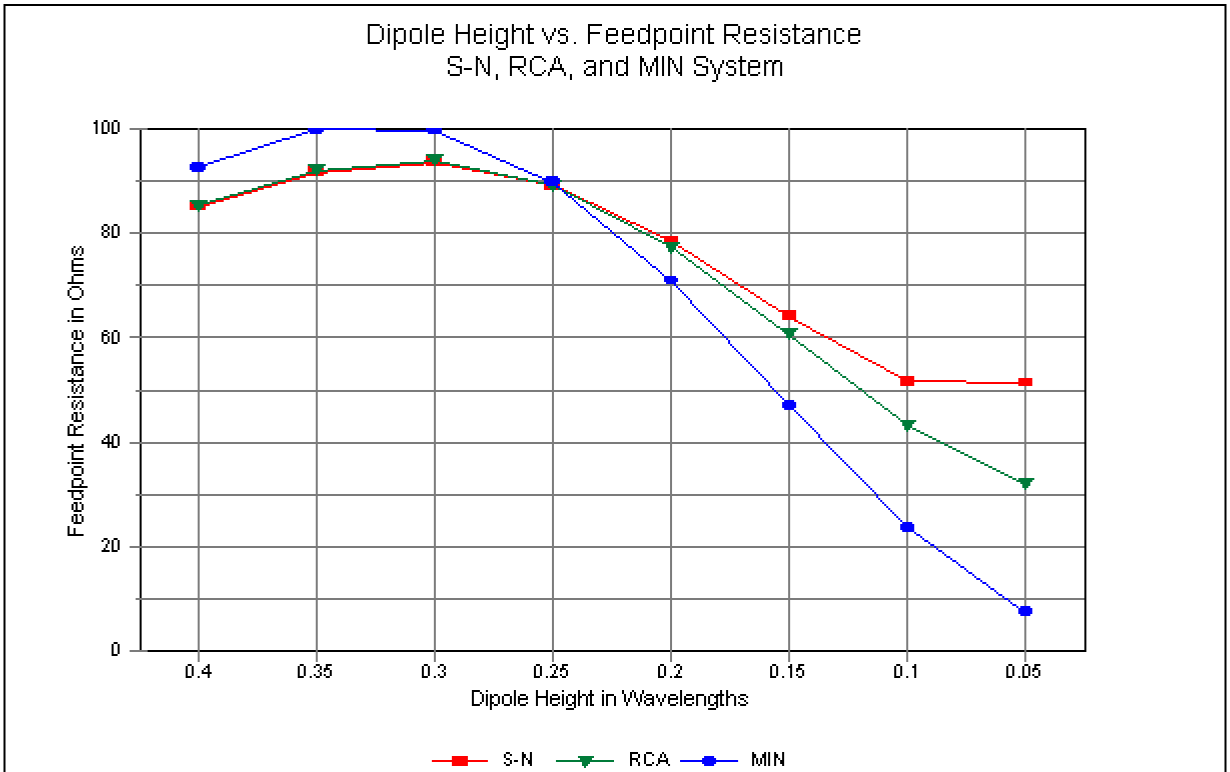

Dipole Height vs. Feedpoint Resistance
S-N, RCA, and MIN System
100
80
60
40
20
0
Feedpoint Resistance in Ohms
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
Dipole Height in Wavelengths
S-N
RCA
MIN

Fig. 8

Fig. 8 shows the feedpoint resistance values reported under all three ground systems. At lower heights, the RCA system reports values below those reported with the SN system. More radically different are the values reported by the MIN system. The excessively low feedpoint resistance values accompany the excessively high gain values that the system produces for heights below about 0.25-λ for antennas with any degree of horizontal component to the radiation pattern.

The end result is that we must set aside virtually all old reports on the performance of antennas installed at NVIS heights. In fact, we must begin again with an evaluation of basic antennas using only antenna modeling software with the SN ground. In fact, these notes will employs NEC-4 throughout, with the SN ground calculation system implemented. Equally important to our effort will be a systematic exploration of basic antennas using a variety of ground quality conditions.

The following soil descriptions are commonly used in antenna modeling. Always substitute more precise values wherever known. The table represents an adaptation of values found in *The ARRL Antenna Book* (p. 3-6), which are themselves an adaptation of the table presented by Terman in *Radio Engineer's Handbook* (p. 709), taken from "Standards of Good Engineering Practice Concerning Standard Broadcast Stations," *Federal Register* (July 8, 1939), p. 2862. Terman's value for the conductivity of the worst soil listed is an order of magnitude lower than the value shown here.

Soil Description	*Conductivity in S/m σ*	*Permittivity (Dielectric Constant) ε*	*Relative Quality*
Fresh water	0.001	80	
Salt water	5.0	81	
Pastoral, low hills, rich soil, typical from Dallas, TX, to Lincoln, NE	0.0303	20	*Very Good*
Pastoral, low hills, rich soil, typical of OH and IL	0.01	14	Good
Flat country, marshy, densely wooded, typical of LA near the Mississippi River	0.0075	12	
Pastoral, medium hills, and forestation, typical of MD, PA, NY (exclusive of mountains and coastline)	0.006	13	
Pastoral, medium hills, and forestation, heavy clay soils, typical of central VA	0.005	13	*Average*
Rocky soil, steep hills, typically mountainous	0.002	12 - 14	Poor
Sandy, dry, flat, coastal	0.002	10	
Cities, industrial areas	0.001	5	*Very Poor*
Cities, heavy industrial areas, high buildings	0.001	3	Extremely Poor

For our work, we shall use Very Good and Very Poor soil as extremes and Average soil as an intermediate value set between the two. Between any two of the three value sets, you can interpolate values close to reality.

NVIS antennas find applications under many circumstances for which the standard soil categories do not apply. For example, we find them in Antarctic regions placed over a mile or more of ice and snow. Therefore, as a further reference, the following table of values may have some useful data for special installations.

Soil Description	*Conductivity in S/m σ*	*Permittivity (Dielectric Constant) ε*
Poor	0.001	4.5
Moderate	0.003	4
Average	0.005	13
Good	0.01	4
Dry, sandy, coastal	0.001	10
Pastoral hills, rich soil	0.007	17
Pastoral medium hills and forestation	0.004	13
Fertile land	0.002	10
Rich agricultural land, low hills	0.01	15
Rocky, steep hills	0.002	15
Marshy land, densely wooded	0.0075	12
Marshy, forested, flat	0.008	12
Mountainous, hilly (up to about 1000 m)	0.002	5
Highly moist ground	0.005	30
City industrial of average attenuation	0.001	5
City industrial of maximal attenuation	0.0004	3
City industrial area	0.0001	3
Fresh water	0.001	80
Fresh water @ 10° C and 100 MHz	0.001	84
Fresh water @ 20° C and 100 MHz	0.005	80
Sea water	5.0	81
Sea water @ 10° C up to 1 GHz	4.0	80
Sea water @ 20° C up to 1 GHz	4.0	73
Sea ice	0.001	4
Polar ice	0.0003	3
Polar ice cap	0.0001	1
Arctic land	0.0005	3

We generally think of signals incurring greater losses as we reduce the ground's conductivity and permittivity. However, between the worst dry-land soil (city industrial areas) and icy regions, we discover an interesting phenomenon. With conductivity values below about 1e10-4 and permittivity values that drop close to the minimum value of 1 (the value of a vacuum), the region beneath the antenna begins to act more like a free-space environment than like what we think of as earth. The effect has interesting consequences for practical antenna operation.

The next step is to review some very fundamental antenna types: the linear dipole, the V dipole (with a droop or slope of 30° from the horizontal or a 120° included angle between legs, and the 1-λ closed loop. These three types of antennas are perhaps the backbone of fixed station NVIS work. We shall look at all three antennas in versions for 160 meters (1.85 MHz), 75 meters (3.9 MHz), and 40 meters (7.2 MHz). We shall try each antenna over each type of soil, seeking the best zenith-angle gain, but with an eye toward ensuring that we have an acceptable NVIS pattern throughout.

Although incidental to our work, you may wonder why I speak of “a NVIS antenna,” rather than “an NVIS antenna.” The acronym “NVIS” (at least where I come from) has acquired the pronunciation [nee’-vis], hence the article “a.” If you prefer to say [en vee eye ess], you may substitute the “an” at every suitable place.