A NVIS-ALE Log-Spiral Antenna for 2.5-12+ MHz

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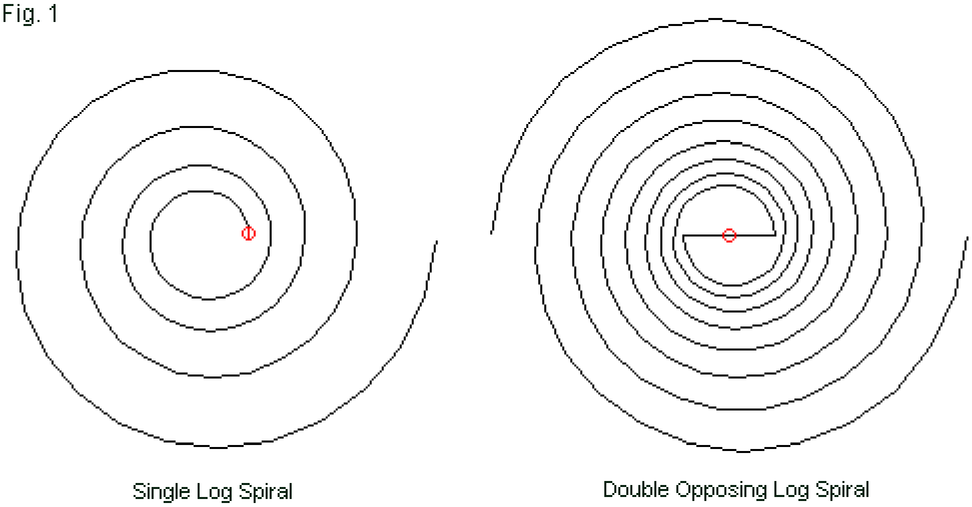
Not all log-based frequency-independent antennas are log-periodic antennas. Although not normally relevant to amateur activities, the log-spiral antenna has as long and interesting a history as its periodic cousin. Since that history goes back at least to the 1950s, most sample antennas employed UHF frequencies with both strip and wire element structures. Many have found successful use in practical antennas, especially as signal sources for wide-band UHF applications calling for directional signals and reflectors based upon principles derived ultimately from optics.

Recently developed needs for wide-band antennas with very extended frequency ranges in the HF spectrum have stirred some interest in adapting the log spiral design to lower frequencies. We shall briefly examine some of the limitations of such adaptations and then explore a semi-practical design to cover the frequency range from 2.5 to 12 MHz using common wire diameters. Initially, we shall look at the performance of a near vertical-incidence skywave (NVIS) antenna over real ground. Then, we shall modify the antenna to expand and extend its frequency coverage by adding end terminations to see to what degree terminations modify the performance of the unterminated version. Unfortunately, in either version, the antenna will be considerably larger and structurally more complex than most amateurs would consider feasible. However, the discussion may provide some insight into the available commercial antennas of similar design.

The Log Spiral

The log-spiral form of antenna element has undergone considerable development in the last half century, thanks to work by Rumsey and others. Relative to log periodics, it shares certain common characteristics. **Fig. 1** on the left shows a single log-spiral element composed of 4 turns with a minimum or inner radius and a maximum or outer radius. However, to form a viable bi-directional antenna requires that we place two opposing log-spiral element 180° apart, as shown on the right.

Fig. 1



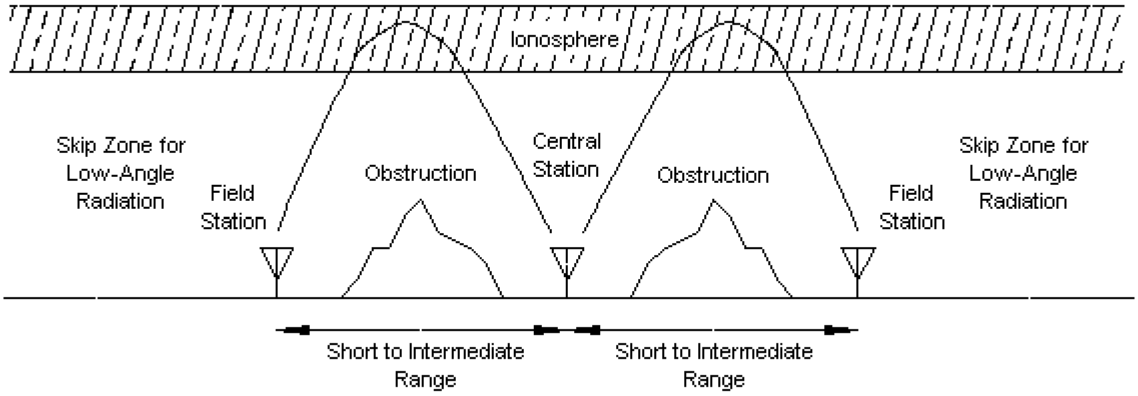
Single Log Spiral

Double Opposing Log Spiral

The Basic Flat Log-Spiral Helix and the Double Version
Necessary to Create an Effective Antenna

Basic theory suggests that anything we might accomplish with a log-spiral element pair also emerges from Archimedes spiral as well. The chief practical difference is that the Archimedes spiral will require considerably more wire for a given frequency span than a log-spiral version of the same antenna. In contrast to the additive constant used to define the growth of an Archimedes spiral, a log spiral grows by a factor of a^{Θ}. Hence, for any radial drawn from the spiral center outward, the distance between successive inner and outer lines increases continuously. The continuous growth requires that one use care in constructing a log-spiral antenna, although every point along the curve can be calculated and prepared in advance.

The relevance of the log-spiral antenna derives from two factors of recent vintage that have impacted communications in the lower HF range. One of those factors is NVIS communications, which answers a need suggested by the sketch in **Fig. 2**. NVIS operation in the lower HF region has intrigued many amateur radio operators. However, the evolving needs of military and civilian communications have made this mode or strategy of operation a virtual necessity. Wherever terrain may place obstacles between communicating stations, as suggested the figure, NVIS can often provide a propagation path. At the civilian level, the use of NVIS as a means of effecting emergency communications--especially in wilderness or other sparsely populated areas--has intrigued emergency and service organizations, such as the Civil Air Patrol and the Federal Aviation Agency.



The NVIS Situation

Fig. 2

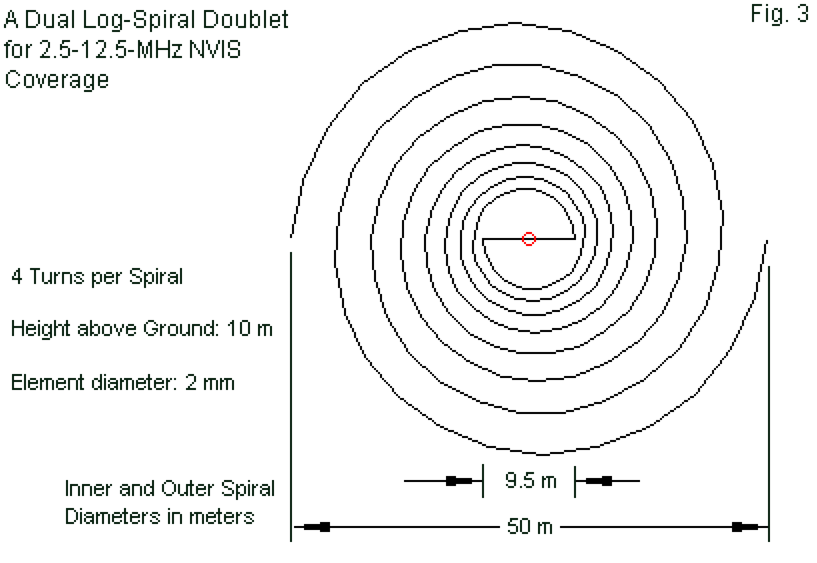
The widespread use of automatic link establishment (ALE) equipment (or adjunct software) has added a new layer of requirements on the stations. Virtually all early NVIS experiments occurred on discrete frequencies. In contrast, ALE rapidly scans a wide sweep of frequencies in search of a usable propagation path between linked stations. In the main, the equipment challenges associated with rapid changes of frequency have been solved. However, the weak link the overall operation is the antenna.

Strategies to provide wide-frequency coverage in the lower HF region where NVIS operation is feasible have taken two directions. One direction involves the use of standard wire antennas placed at optimal heights above ground to enhance NVIS radiation patterns. While such antennas offer full gain, they suffer a rapidly changing feedpoint impedance, which requires switching either antennas or matching components as the sweep frequency increments. The second strategic direction involves the use of resistively terminated antennas that first emerged just prior to World War II. These antennas offer relatively stable feedpoint impedance values over a very wide frequency range. However, they inherently reduce antenna gain relative to an unterminated antenna of the same size. If the antenna length is at least 1/2-λ, the loss is 3 to 6 dB, depending upon design. When the length is less than 1/2-λ, the losses increase exponentially.

The ideal NIVIS-ALE antenna is one that covers a defined frequency range with a relatively constant feedpoint impedance but without the losses associated with terminating resistors. All such antennas will still be subject to ground losses that are functions of both the ground quality and the height of the antenna above ground. Since the dominant radiation is in the antenna's E-plane to arrive at high field strength vertically, ground losses are the smaller concern. The ideal height for virtually any horizontal array is between 0.1-λ and 0.2-λ at the operating frequency, with a height of about 0.17-λ yielding maximum gain straight upward. For this reason, some commercial antennas that use spiral construction create a reverse cone (point downward) to equalize the height over frequency ranges wider than 2:1. However, a flat spiral is feasible for a 5:1 frequency range (2.5 to 12.5 MHz). By a frequency of 12 MHz, NVIS operation is generally not usable under either daytime or nighttime conditions. Hence, further use of the antenna beyond the defined upper frequency limit would be for normal skip communications.

An Unterminated Model of a Potentially Practical Flat Log-Spiral Antenna for 2.5-12.5 MHz

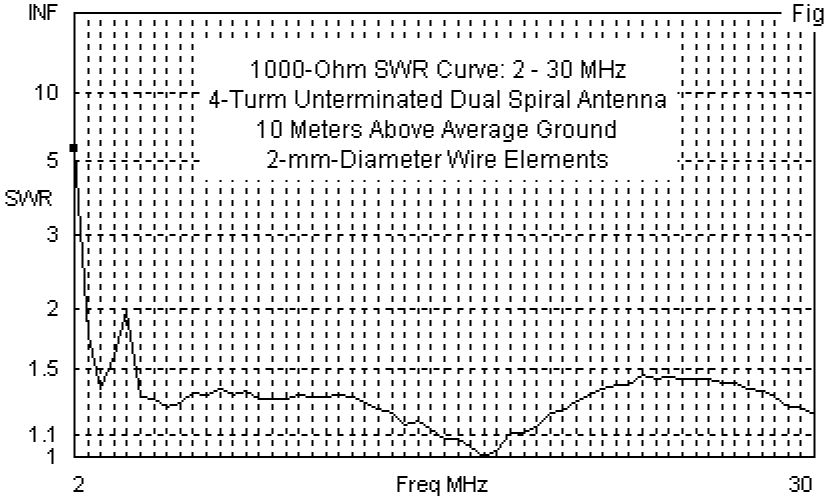
The design that we shall discuss has the general form shown in **Fig. 3**. It consists of two 4-turn log spiral elements opposed to each other about the center straight source wire. The inner spiral radius is 4.75-m, for an upper frequency limit that is very much higher than the 12.5-MHz limit set for operation. The outer radius is 25-m, a somewhat arbitrary limit set by practical considerations of construction. The total span of the antenna from one free end to the other is 50-m or about 164'. At right angles to the axis, the dimension is 46 m (150.9'). For each spiral, the design value of τ is 0.66.



Several factors impact the performance of an HF spiral. One is the use of wire having a constant diameter throughout the structure. For the antenna suggested here as an initial design, I used 2.0-mm wire, which is about halfway between AWG #12 and AWG #14. A second factor is the height above ground, which has an affect on the pattern shape at frequencies within the passband. For the test version of the antenna, I selected 10 m (32.8') as a satisfactory height. The array is level throughout. In fact, attempting to lower the inner rings has an adverse affect on the SWR curve.

A third influential factor is the number of turns in the spiral. For a fixed inner radius and a fixed outer radius, the number of turns affects the total wire length in the spiral antenna. Each antenna forms a doublet, with a center straight wire that is 9.5 m long. The inner radius of the spiral is 4.75 m. The outer radius varies with the number of turns in each of the two spiral doublet extensions and the value of τ. A 3.5-turn array requires a total of 545.9 m of wire, but has a minimum usable frequency of about 3.0 MHz. A 4-turn spiral with the same inner and outer radii requires 622.3 m of wire, but the minimum usable frequency drops to 2.5 MHz.

I set the criteria for the minimum usable frequency in terms of both maximum gain and SWR. Maximum gain had to exceed 5.5 dBi with an acceptably circular pattern. No pattern is perfectly circular, but at most frequencies within the anticipated passband from 2.5 to 12 MHz, the beamwidth in all directions is at least 70 degrees. The reference impedance for determining the SWR limits is 1000 Ω. The antenna will require a broadband low-loss transformer--or set of transformers--with a ratio of 20:1 to scale the impedance to the standard 50 Ω of common coaxial cables. I set the SWR limits at 2:1. The SWR remains low at least to 30 MHz, although the patterns are not acceptable for NVIS use outside the specified passband. The key SWR limitation occurs at the lower end of the swept spectrum. **Fig. 4** clearly shows the SWR 2:1 cut-off frequency just below 2.5 MHz.



The design employed NEC-4 as a pre-prototype test vehicle. The model employed the GH or helix command to produce the initial 4-turn log spiral, followed by the GM command to replicate the spiral rotated by 180°. The source wire required a separate GW command. The final structural detail uses the GM command to elevate the entire structure 10 meters above ground.

The required control commands included specifying a Sommerfeld-Norton ground of average quality (conductivity 0.005 S/m, relative permittivity 13). Since the beamwidth may vary according to the antenna orientation, the RP or far-field commands include a pattern at a phi angle of 0°, which runs across the antenna from one free end to the other or tip-to-tip, and another pattern at right angles (90°) to the first, which we may call broadside to the antenna. **Table 1** lists the entries of the required NEC-4 model.

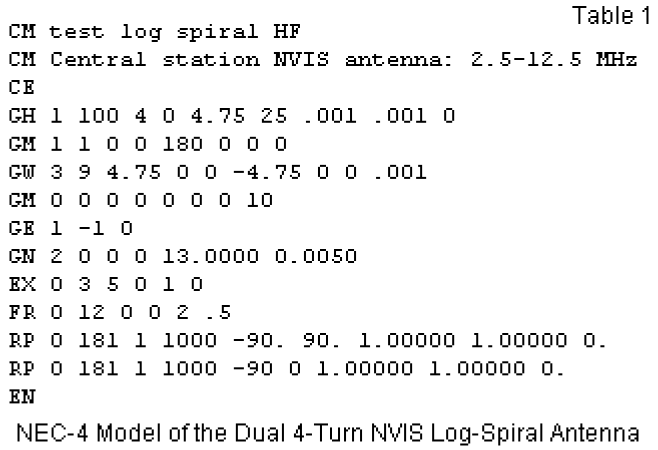
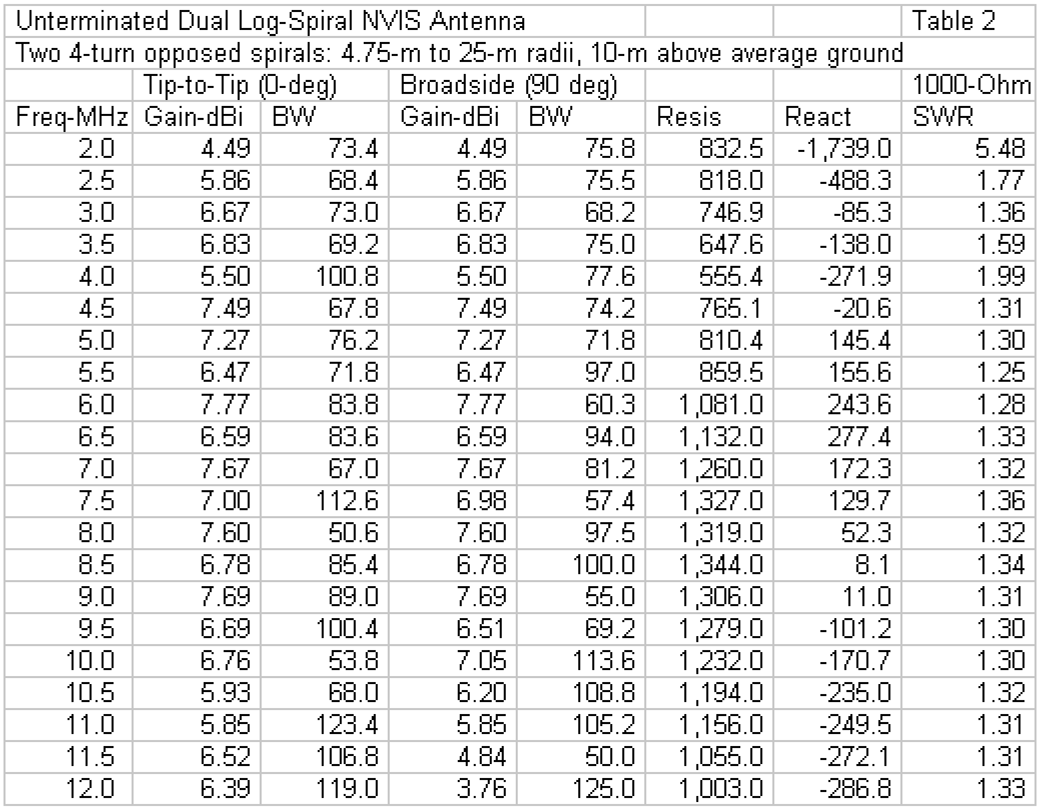


Table 1

```
CM test log spiral HF
CM Central station NVIS antenna: 2.5-12.5 MHz
CE
GH 1 100 4 0 4.75 25 .001 .001 0
GM 1 1 0 0 180 0 0 0
GW 3 9 4.75 0 0 -4.75 0 0 .001
GM 0 0 0 0 0 0 0 10
GE 1 -1 0
GN 2 0 0 0 13.0000 0.0050
EX 0 3 5 0 1 0
FR 0 12 0 0 2 .5
RP 0 181 1 1000 -90. 90. 1.00000 1.00000 0.
RP 0 181 1 1000 -90 0 1.00000 1.00000 0.
EN
```

NEC-4 Model of the Dual 4-Turn NVIS Log-Spiral Antenna

The collected data run from 2 to 12 MHz in 0.5-MHz increments. Data above 12 MHz is not significant for NVIS operation, as we shall see from both tables and pattern graphics. **Table 2** provides a listing of the basic performance information.



Unterminated Dual Log-Spiral NVIS Antenna							Table 2
Two 4-turn opposed spirals: 4.75-m to 25-m radii, 10-m above average ground							
	Tip-to-Tip (0-deg)		Broadside (90 deg)				1000-Ohm
Freq-MHz	Gain-dBi	BW	Gain-dBi	BW	Resis	React	SWR
2.0	4.49	73.4	4.49	75.8	832.5	-1,739.0	5.48
2.5	5.86	68.4	5.86	75.5	818.0	-488.3	1.77
3.0	6.67	73.0	6.67	68.2	746.9	-85.3	1.36
3.5	6.83	69.2	6.83	75.0	647.6	-138.0	1.59
4.0	5.50	100.8	5.50	77.6	555.4	-271.9	1.99
4.5	7.49	67.8	7.49	74.2	765.1	-20.6	1.31
5.0	7.27	76.2	7.27	71.8	810.4	145.4	1.30
5.5	6.47	71.8	6.47	97.0	859.5	155.6	1.25
6.0	7.77	83.8	7.77	60.3	1,081.0	243.6	1.28
6.5	6.59	83.6	6.59	94.0	1,132.0	277.4	1.33
7.0	7.67	67.0	7.67	81.2	1,260.0	172.3	1.32
7.5	7.00	112.6	6.98	57.4	1,327.0	129.7	1.36
8.0	7.60	50.6	7.60	97.5	1,319.0	52.3	1.32
8.5	6.78	85.4	6.78	100.0	1,344.0	8.1	1.34
9.0	7.69	89.0	7.69	55.0	1,306.0	11.0	1.31
9.5	6.69	100.4	6.51	69.2	1,279.0	-101.2	1.30
10.0	6.76	53.8	7.05	113.6	1,232.0	-170.7	1.30
10.5	5.93	68.0	6.20	108.8	1,194.0	-235.0	1.32
11.0	5.85	123.4	5.85	105.2	1,156.0	-249.5	1.31
11.5	6.52	106.8	4.84	50.0	1,055.0	-272.1	1.31
12.0	6.39	119.0	3.76	125.0	1,003.0	-286.8	1.33

We may break down the information into two groups. The first group includes the maximum gain—normally straight upward or close to the zenith angle—and the 3-dB beamwidth angle, shown as an included angle in the table. **Fig. 5** graphs the information across the sweep passband. Note that at certain frequencies, either the tip-to-tip or the broadside beamwidth may be wider, indicating the variability of the peak current magnitude along the spiral structure. At virtually all frequencies, the beamwidth in both planes is sufficient to provide not only pure NVIS service, but some degree of intermediate-range communications as well.

The peak gain in both planes is equal only if the direction of maximum radiation is the zenith angle (elevation 90°). Where the two values differ (above 7 MHz), the maximum gain values will differ because one of the two values represents an angle that departs from the zenith angle. The stronger gain value of such a pair ordinarily indicates an angle other than 90° elevation. Potentially significant—but not necessarily operationally important—differentials only occur above 11 MHz.

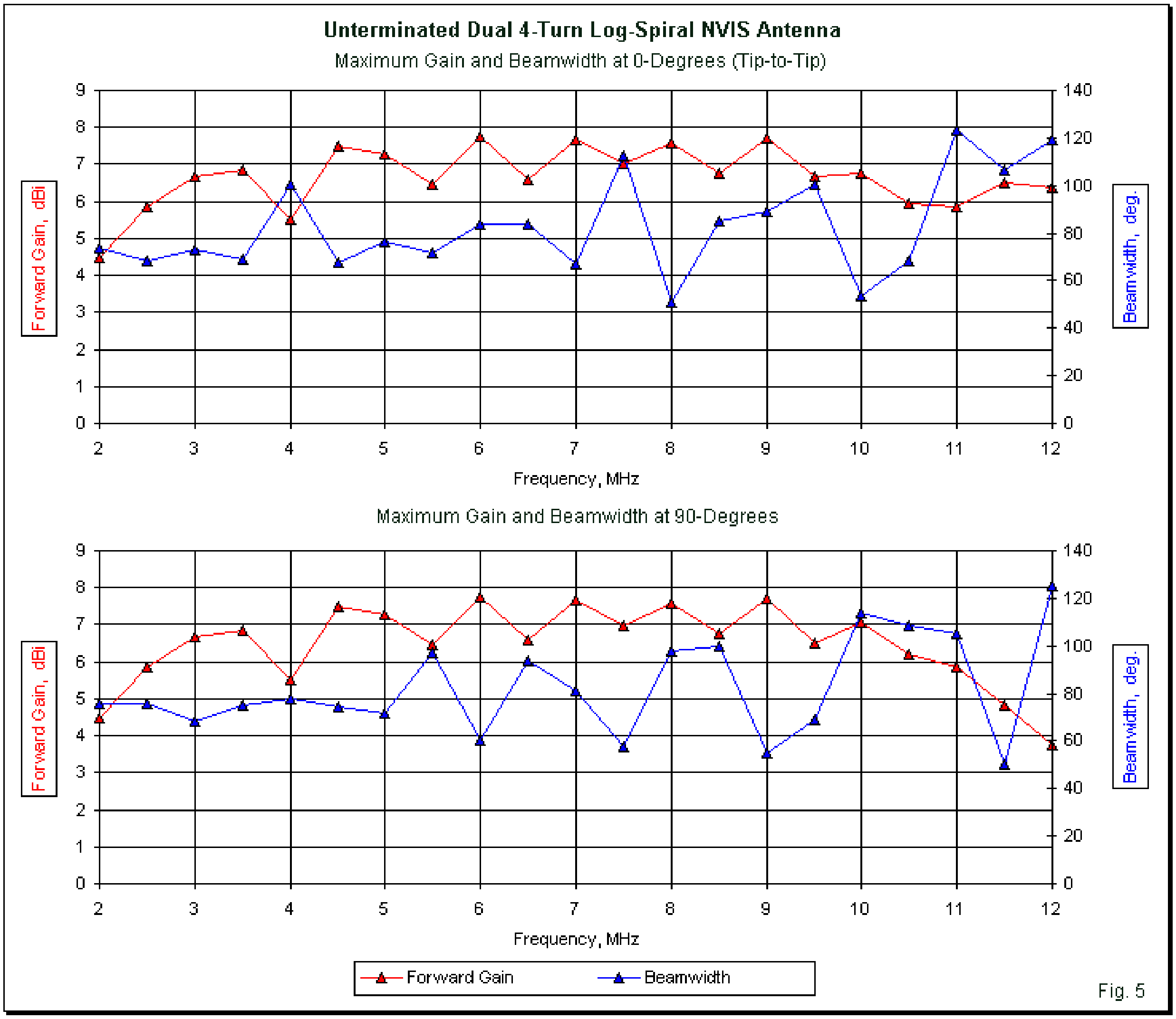


Fig. 5

Fig. 6 provides the second group of data, the feedpoint resistance, reactance, and 1000-Ω SWR values across the operating passband. The maximum right-hand Y-axis values would not have exceeded 2.0 if the graph had not included the information for 2 MHz. Extending the graph just below the limit of the design passband allows a view of the relatively rapid decay of impedance performance beyond the antenna's capabilities. To reach 2 MHz with an acceptable set of impedance values would require an upward scaling of the entire structure by a factor of 1.25. The end result would be a dual log-spiral area with an inner radius of 5.94 meters and an outer radius of 31.25 meters. Since the present structure requires approximately 622 meters of antenna wire, the expanded structure for lower frequency coverage would need about 778 meters of the same wire. The support requirements would also increase at least proportionately.

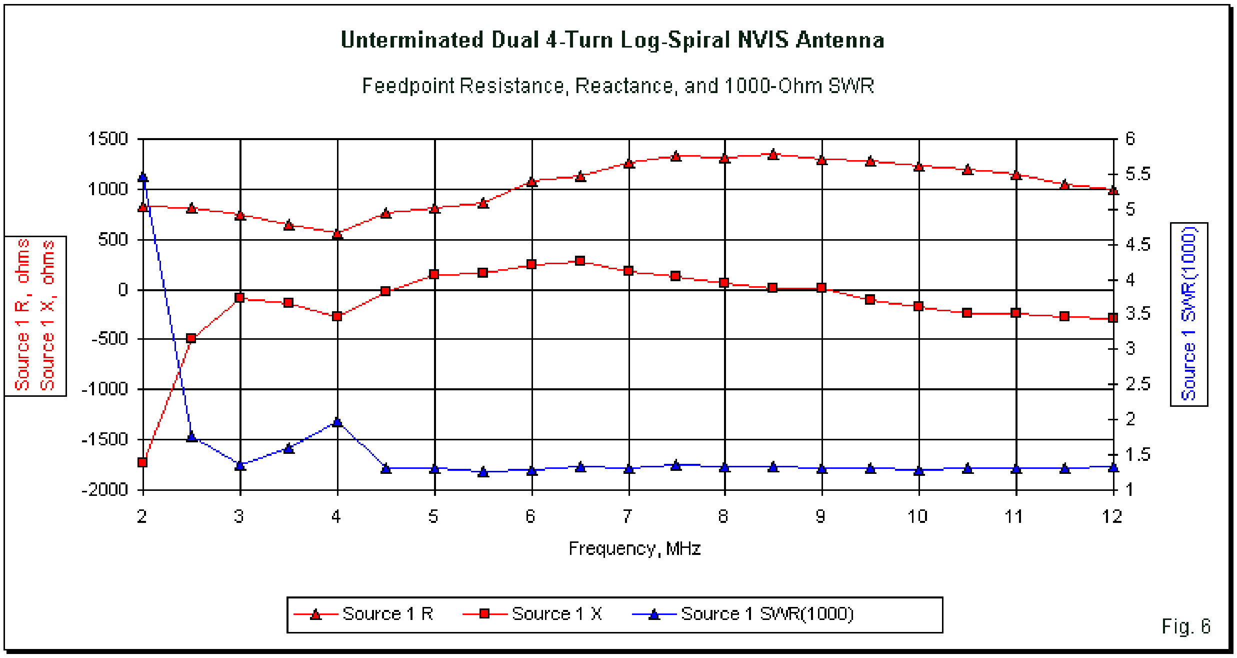
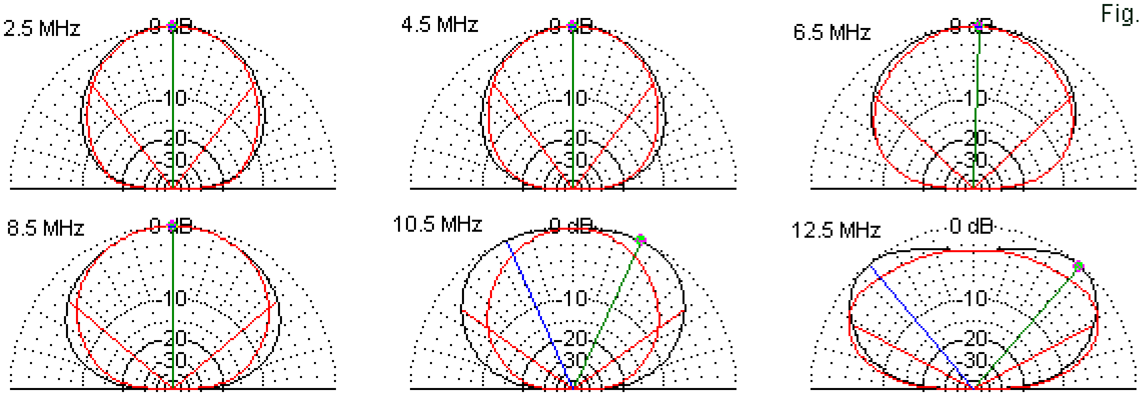


Fig. 6

We may obtain an alternative view of the antenna's performance potential by sampling combined elevation patterns at selected frequencies across the passband. **Fig. 7** provides patterns in 2-MHz intervals from 2.5 to 12.5 MHz. The selection is intentional to show the limitations of the antenna at the upper end of the operating spread. The 12.5-MHz patterns show considerable beamwidths in both planes, although the vertical gain is sufficient for virtually all NVIS applications that might us this frequency. At 10.5 MHz, the differential between the beamwidths in the two planes is visually noticeable, but is likely to be operationally undetectable. Below 10.5 MHz, the differences in beamwidth are too small to require mention.

Fig. 7



Red = 0-degrees (tip-to-tip) Black = 90-degrees (broadside)

Sample Elevation Patterns of the Unterminated Dual 4-Turn Log-Spiral Antenna

The design shown and tested in NEC-4 model form offers continuous coverage from 2.5-MHz upward with acceptable SWR levels and the highest gain levels obtainable from a single wire assembly. The system is suitable for use with ALE equipment using the highest speeds for frequency changes. The use of an unterminated antenna does set lower frequency limits to the use of the antenna, but above the minimum usable frequency, the performance suffers none of the losses associated with standard forms of terminated antennas. Gain and beamwidth values are competitive with narrow-band unterminated wire antennas at the same height above ground, such as dipoles and 1-λ closed loops. A ground screen that encompasses the entire structure plus about 0.5-λ in every direction beyond the limit of the spiral's outer radius would improve performance slightly—about the same amount as placing the antenna over very good ground (conductivity 0.0303, relative permittivity 20).

The log-spiral wide-band NVIS-ALE has both considerable size and a requirement of careful construction to preserve the log-spiral configuration. Therefore, it is suitable only for long-term installations and requires significant support. **Fig. 8** shows the probable nature of an adequate support structure, consisting of a system of perimeter support posts and non-conductive ropes or cables. A central non-conductive post would provide support for the wires and cables and also an anchor for the impedance transformation system that would allow the main transmission line to consist of a coaxial cable. The system stresses are mainly lateral, since the antenna height is only 10 meters (about 33'). The relatively low height of the antenna is a benefit for regions where harsh weather conditions may be common.

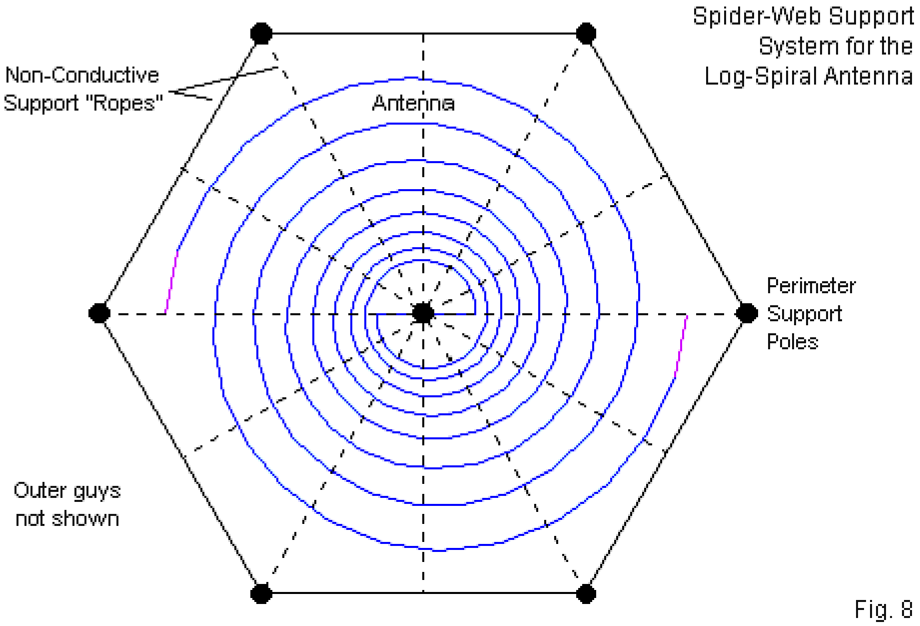
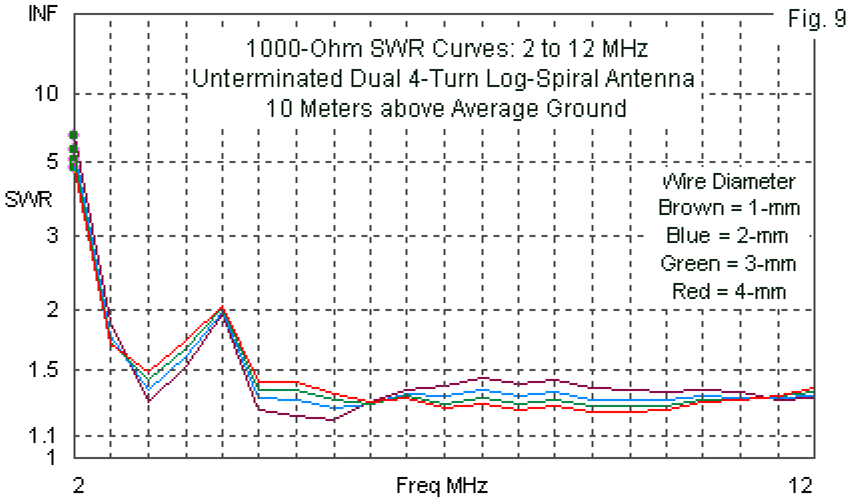


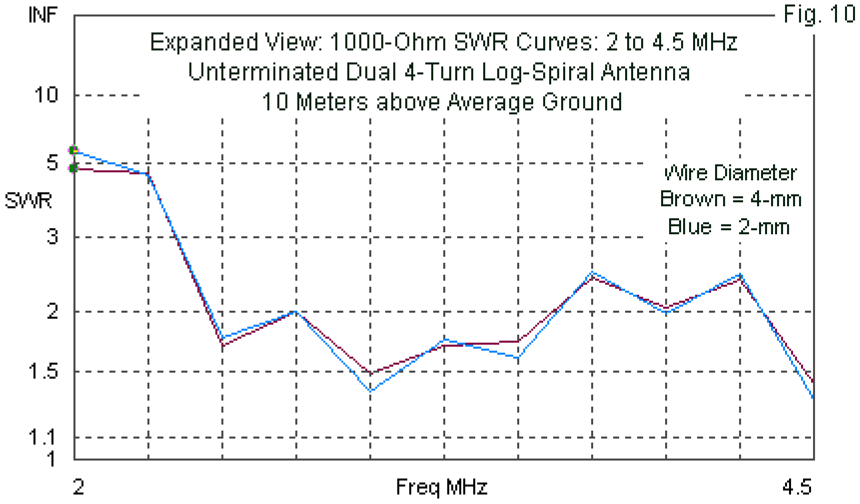
Fig. 8

The log-spiral shown in these notes shows very good performance for an antenna of its type. The formulation adheres to the dictum that the ratio of the higher frequency to the lowers frequency limit of operation should approximately equal the ratio of the outer limit radius to the inner limit radius of the log spiral. As a consequence, the structure has performance limitations. For example, alteration of either radius independently of the other radius is likely to change the operating characteristics, especially the SWR curves across the desired passband.

The system as shown uses 2-mm-diameter wire. The structure is mildly sensitive to changes in the wire diameter. I checked the SWR performance using wire diameters from 1 to 4 mm (0.04 through 0.156 inches or AWG #18 through AWG #6). **Fig. 9** shows the comparative SWR plots. At critical points in the sweep (for example, at 4 MHz and below 2.5 MHz), the 4 samples wires sizes track each other closely. The widest variations occur in regions where the SWR value is low enough not to be critical.



However, the broad frequency sweep does hide some significant detail in the SWR behavior, especially below 5 MHz. Therefore, I re-ran the sweeps from 2 to 5 MHz in 0.25-MHz increments. **Fig. 10** provides the revelations that only a detailed sweep can show. For all wire sizes (with 2-mm and 4-mm wire diameters sampled), the curves show peaks at about 3.7 and 4.3 MHz. The peak SWR values relative to the 1000-Ω reference are about 2.5:1. The source of these peaks is a high inductive reactance at each frequency. In the present context, it is not possible to say whether feedline and impedance matching losses would bring these values down to 2:1 at the operating position. The acceptability of the SWR peaks depends upon the equipment capability and the total antenna installation.



Nevertheless, the unterminated log-spiral antenna provides the widest frequency coverage without imposing gain losses of any antenna design with which I am familiar. The only losses associated with operation will be those inherent in the wire resistivity at each operating frequency and those associated with the ground quality relative to the height of the antenna at each operating frequency. Nevertheless, the log-spiral antenna for NVIS-ALE service is a large structure and suitable only for long term installations.

Design Variations and Log-Spiral Performance

Earlier, we noted the sensitivity of the design to the overall design parameters, especially the value of τ (0.66). The operating frequency range is related to the outer and inner radii of the array so that the 4-turn configuration provides optimal performance. With an inner radius of 4.75 meters and an outer radius of 25 meters, at the 10-meter height, the antenna provides NVIS coverage from 2.5 to about 12 MHz or so, with non-NVIS performance above that frequency. The design is subject to a number of practical variations, including mounting height, antenna dimensions, and soil quality. Therefore, I modeled the log-spiral array under a number of different conditions to provide some indication of the changes that may occur in performance.

1. *Height Variations*: The height above ground for a broadband NVIS antenna is a compromise that has two goals. At the lowest frequency, the height should allow adequate gain. At the highest frequency, the elevation patterns should not elongate enough to void effective NVIS operation. To sample the effects of changing height, I moved the antenna as presented earlier with 2-mm-diameter wire upward in 1-meter increments over average soil. The change in height from 10 to 12 meters affected both the SWR curves and the elevation patterns.

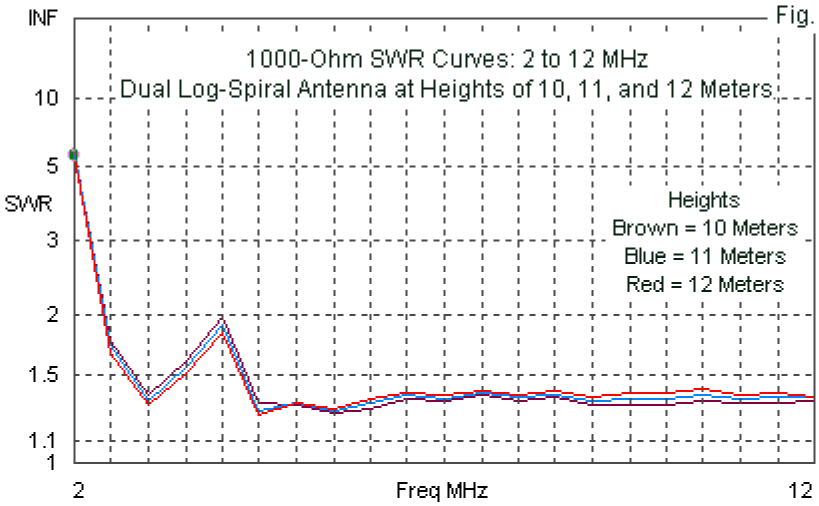
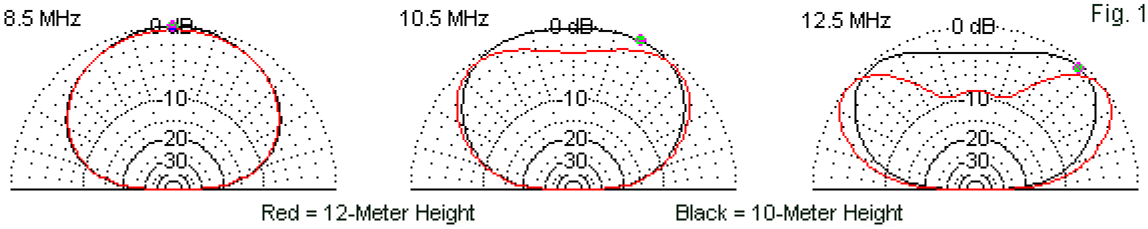


Fig. 11

The SWR curves in **Fig. 11** appear to show that height makes little difference on the SWR. Over much of the operating range, the appearance is correct. However, in the sensitive region around 4 MHz, the twin peaks diminish to a 1000-Ω SWR of about 2:1 at a height of 12 meters, down from the peak values of about 2.5:1 with a height of 10 meters. Whether the difference makes a difference is subject to the equipment limitations once appropriate matching devices and cables complete the total system.

Fig. 12

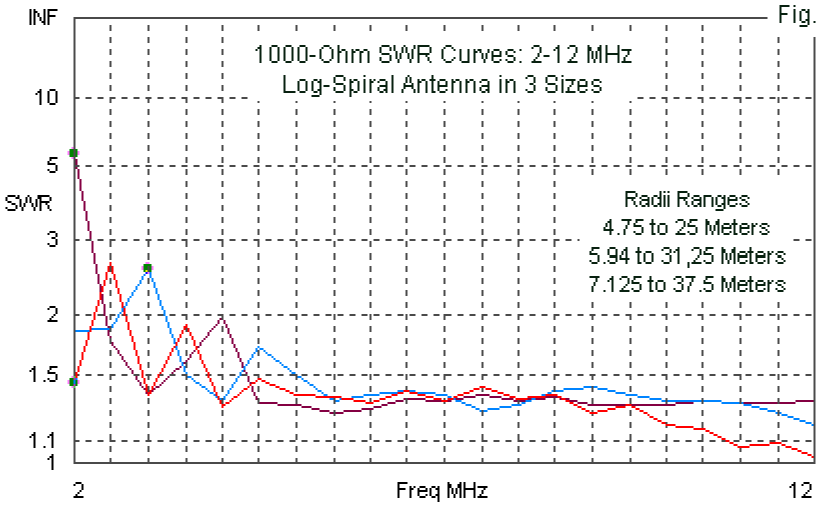


The Effect of Antenna Height on Broadside Elevation Patterns
in the Upper Frequency Range of the Dual 4-Turn Log Spiral

Fig. 12 provides a sample of the effects of changing antenna height on the elevation patterns at the upper end of the operating range. Through 8.5 MHz, we find essentially no change in the pattern shape. The broadside patterns do show growing changes in pattern shape at 10.5 and 12.5 MHz. Although the 10.5-MHz pattern remains usable for NVIS operation at reduced strength at the zenith angle, the 12.5-MHz pattern is suitable only for normal skip operations. Therefore, the appropriateness of increasing the antenna height above 10 meters (33') may depend upon the desired frequency range for NVIS operations.

2. *Antenna Size Variations*: To lower the minimum usable frequency with the array, I scaled it in two steps. The original antenna used an inner radius of 4.75 meters and an outer radius of 25 meters to obtain a minimum usable frequency of 2.5 MHz. To obtain a minimum usable frequency of 2 MHz, I scaled the antenna by a factor of 1.25 to an inner radius of 5.94 meters and an outer radius of 31.25 meters, with a scaled height of 12.5 meters. I also scaled the original antenna by a factor of 1.5 to obtain a minimum usable frequency of about 1.67 MHz. The resulting inner radius became 7.125 meters, with an outer radius of 37.5 meters, along with an adjusted height of 15 meters.

Fig. 13 provides 1000-Ω SWR curves for the 3 versions of the antenna over average ground. Essentially, the overall SWR curves simply move downward in frequency. The seemingly high peaks near the low end of the SWR sweep range represent one of the two peak values that are obscured in the pattern for the original size, since 4 MHz for that antenna falls between the peak values.



Increasing the antenna height with each increase in overall size is necessary to obtain adequate gain at the lower usable frequency. However, as suggested by **Fig. 12**, the increase in height will take a toll on elevation pattern shape at the upper end of the frequency range. Therefore, the advisability of using a larger antenna to obtain extended low-frequency coverage requires a balance with the intended range for NVIS operations.

3. *Ground Quality Variations*: The most significant effect of different ground qualities is in the anticipated 1000-Ω SWR curve for the antenna as the soil conditions vary. To show the range of possibilities, I swept the original array at a 10-meter height over three soil conditions: very good (conductivity 0.0303 S/m, relative permittivity 20), average (conductivity 0.005 S/m, relative permittivity 13), and very poor (conductivity 0.001 S/m, relative permittivity 5).

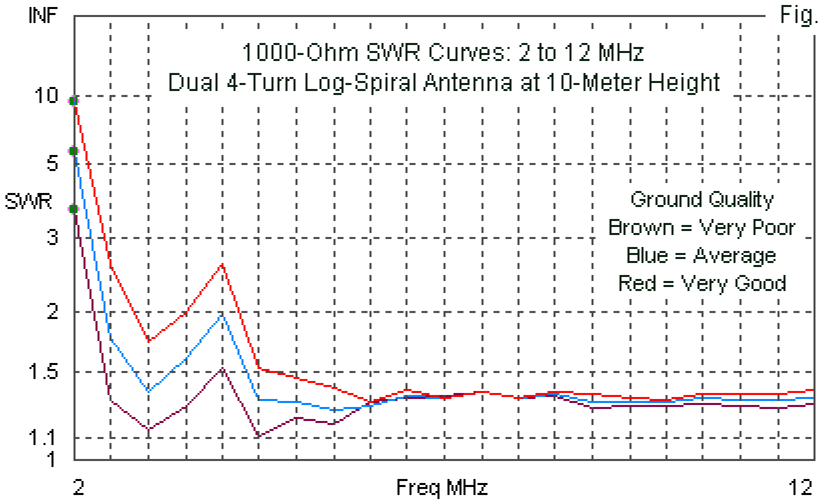


Fig. 14

As shown in **Fig. 14**, the SWR variation above 5 MHz is insignificant. Below 5 MHz, we find that the worse the soil quality, the better the SWR curve will be with respect to the ease of matching the system to standard cables and equipment. Improved soil conditions tend to increase the SWR peaks in the 4-MHz region closer to 3:1.

One solution to this problem is to raise the antenna height—perhaps to 12 meters—when the soil is better than average. **Fig. 15** shows what happens to the SWR curves under these conditions. The SWR peaks in the 4-MHz region are reduced to potentially harmless levels. However, the increase in height will result in the pattern variations at the upper end of the operating range, as suggested by **Fig. 12**.

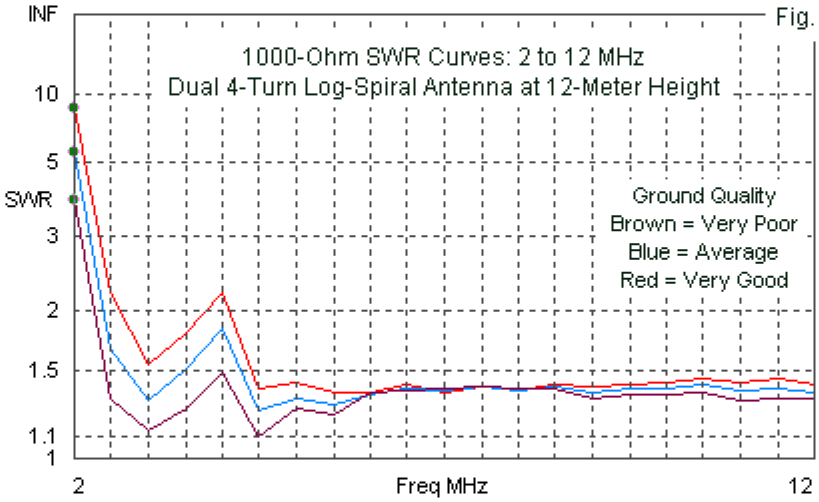


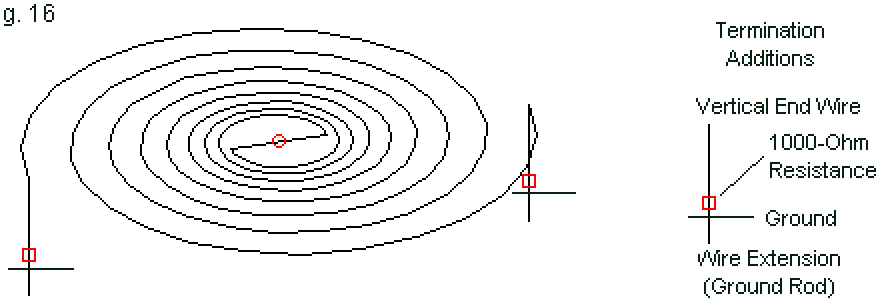
Fig. 15

The end result of these experiments in varying both the antenna and its conditions of installation is the conclusion that an unterminated dual 4-turn log-spiral antenna using a constant wire diameter has a wide but not an unlimited frequency range for effective NVIS-ALE operation. The chief limitations at the low end of the operating range is the SWR behavior, while pattern shapes suitable for NVIS operation are the main limitations at the upper end of the NVIS spectrum.

Extending Frequency Coverage via Termination

The log-spiral (or an Archimedes equivalent) is amenable to termination by installing resistance at each free end of the structure. **Fig. 16** shows the general outline of the log-spiral antenna fitted with end wires and 1000-Ω resistance loads at or close to ground level. Each end wire extends into the ground in the model, simulating typical ground rods that one might use in a practical installation. Since the spiral tips align with perimeter support posts, it is likely that the end wires may run down or parallel to the posts if they are non-conductive.

Fig. 16



Terminated Version of the Dual 4-Turn Log-Spiral
NVIS Antenna for 2 to 12.5 MHz Service

End termination does not reduce performance throughout the entire operating passband, as it would for a linear terminated antenna. Rather, as shown by the modeled performance values in **Table 3**, it has its most profound effects at the lower limits of the operating spectrum.

Terminated Dual Log-Spiral NVIS Antenna							Table 3
Terminated with 1000-Ohm resistors to ground at each spiral end							
Two 4-turn opposed spirals: 4.75-m to 25-m radii, 10-m above average ground							
	Tip-to-Tip (0-deg)		Broadside (90 deg)				1000-Ohm
Freq-MHz	Gain-dBi	BW	Gain-dBi	BW	Resis	React	SWR
2.0	-1.29	78.6	-1.29	76.6	919.8	-49.4	1.10
2.5	3.60	72.8	3.60	72.6	740.0	136.5	1.40
3.0	5.92	70.8	5.92	69.2	691.6	182.4	1.53
3.5	5.84	70.2	5.84	75.2	629.5	127.3	1.63
4.0	4.08	92.2	4.08	84.8	675.4	112.9	1.52
4.5	6.61	70.8	6.61	69.6	830.7	297.3	1.45
5.0	6.36	82.2	6.36	72.0	866.8	397.6	1.56
5.5	6.37	66.4	6.37	95.6	1,024.0	355.6	1.42
6.0	7.28	85.2	7.28	60.1	1,204.0	372.4	1.47
6.5	6.77	70.8	6.77	96.4	1,267.0	296.1	1.42
7.0	7.45	69.2	7.45	79.2	1,357.0	172.5	1.40
7.5	7.12	106.7	7.12	57.0	1,379.0	100.0	1.39
8.0	7.41	51.0	7.42	100.7	1,373.0	0.4	1.37
8.5	6.95	79.6	6.95	92.2	1,382.0	-79.0	1.39
9.0	7.33	96.2	7.33	53.5	1,324.0	-127.3	1.35
9.5	6.65	100.4	6.64	77.0	1,289.0	-211.2	1.37
10.0	6.55	52.8	6.89	110.6	1,234.0	-245.3	1.36
10.5	6.03	66.4	6.26	110.6	1,182.0	-299.2	1.38
11.0	5.85	121.8	5.66	95.2	1,132.0	-301.3	1.36
11.5	6.38	106.0	4.87	49.4	1,047.0	-323.2	1.37
12.0	6.34	120.8	3.69	128.6	1,007.0	-313.4	1.37

Fig. 17 provides a visualization of the gain and beamwidth data in the table. The beamwidth does not show significant adverse affects from the terminations. Most of the gain deficits appear below about 5 MHz.

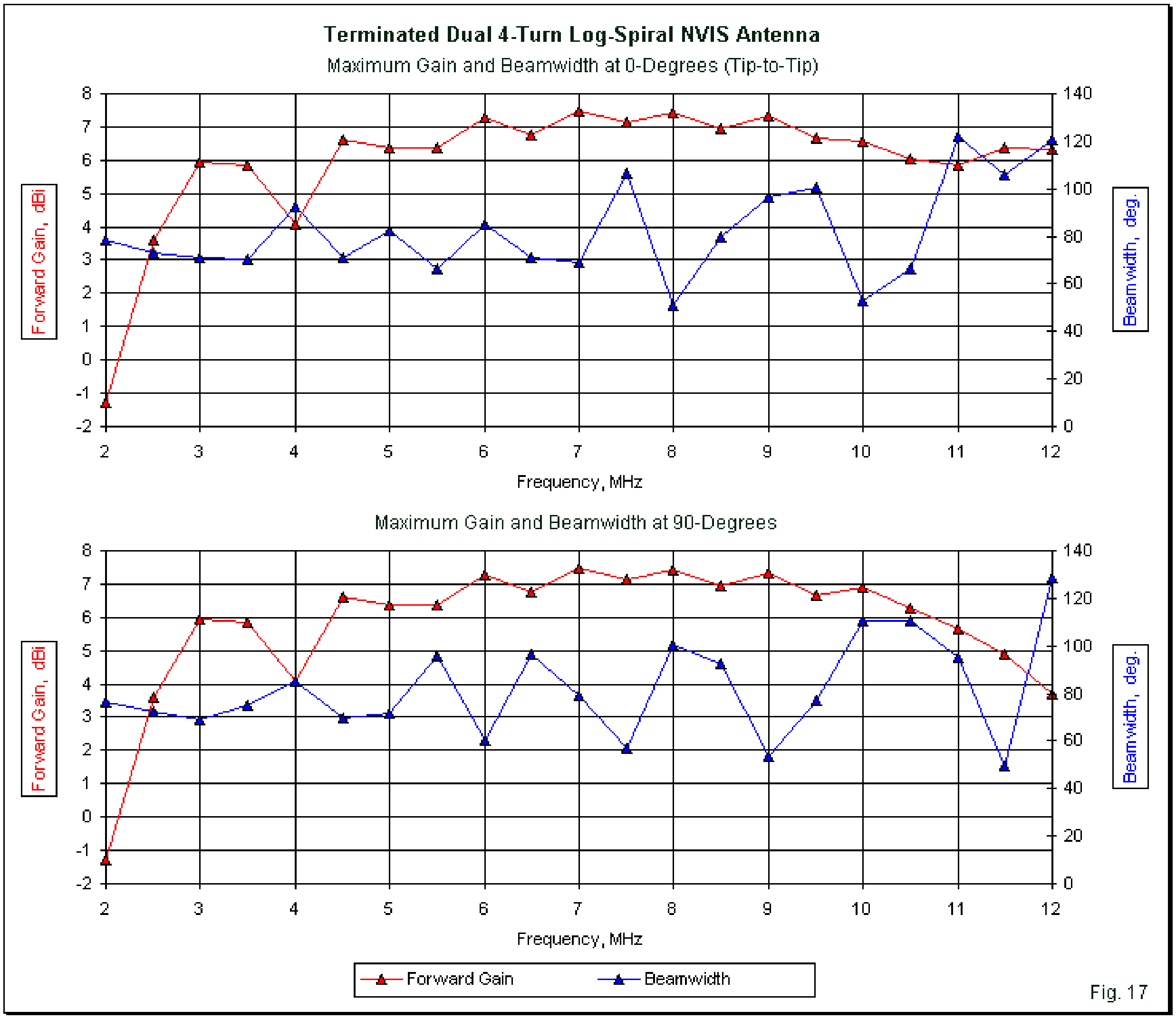


Fig. 17

In return for the low-frequency gain reduction, the terminated log-spiral shows a very smooth 1000-Ω SWR curve throughout the operating spectrum and below it. **Fig. 18** supplies the curves. Above the 5-MHz mark, the impedance values between the terminated and unterminated versions of the antenna are virtually the same with respect to both resistance and reactance. Below 5 MHz, the terminating resistors tend to reduce the reactance excursions. Below about 2.5 MHz, the terminations tend to control the resistive component of the feedpoint impedance.

Linear terminated antennas tend to have a knee frequency, which corresponds to the frequency at which the linear antenna is about ½-λ long. Above the knee frequency, the terminating resistors, however placed, tend to produce between 3-dB and 6-dB loss in antenna gain relative to an unterminated wire of the same length. The terminated log-spiral does not exhibit the same behavior, although there are critical frequencies that we should note.

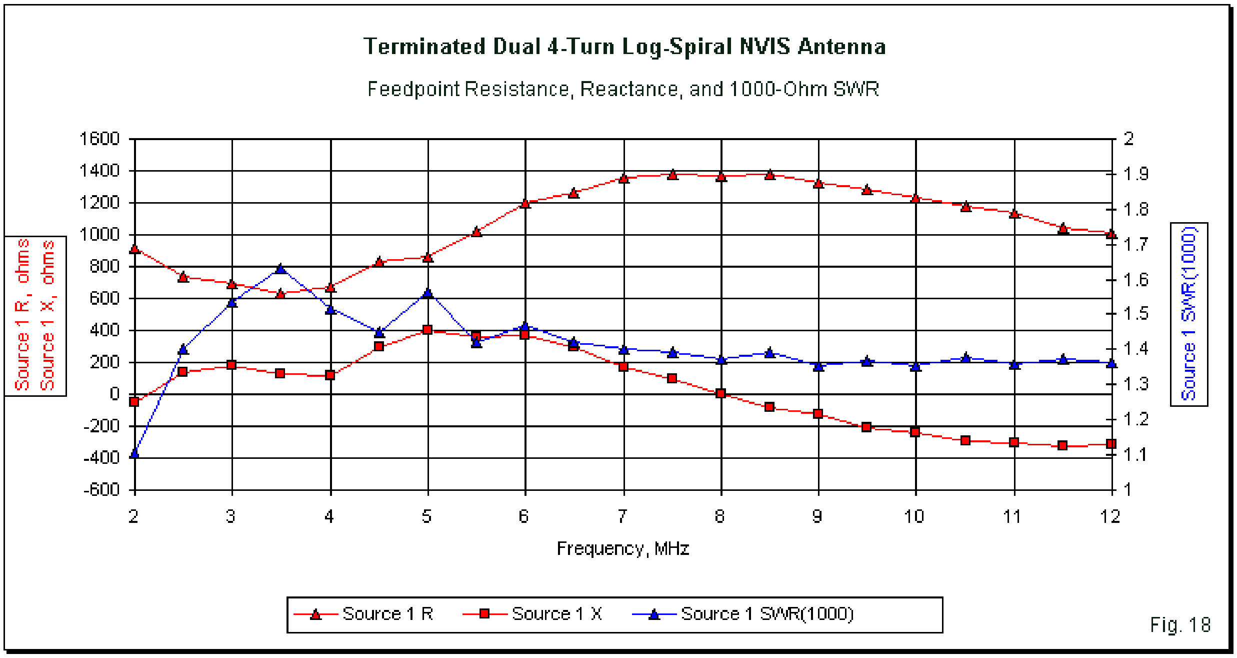


Fig. 18

Table 4 draws together gain information for the terminated and unterminated forms of the log-spiral antenna from 2 through 7 MHz. In all cases, the beamwidth values in each sampled plane show variations, but all of them are small and not operationally significant. The most fundamental variations relate to the maximum gain values. Since the maximum gain is at the zenith angle—as indicated by the coincidence of tip-to-tip and broadside gain values—we may easily calculate the gain differential between the two versions of the antenna.

Performance Differential 2 to 7 MHz: Unterminated and Terminated Log-Spiral Antennas									Table 4
	Unterminated Dual Log-Spiral				Terminated Dual Log-Spiral				
	Tip-to-Tip (0-deg)		Broadside (90 deg)		Tip-to-Tip (0-deg)		Broadside (90 deg)		*Delta*
Freq-MHz	Gain-dBi	BW	Gain-dBi	BW	Gain-dBi	BW	Gain-dBi	BW	*Gain*
2.0	4.49	73.4	4.49	75.8	-1.29	78.6	-1.29	76.6	*5.78*
2.5	5.86	68.4	5.86	75.5	3.60	72.8	3.60	72.6	*2.26*
3.0	6.67	73.0	6.67	68.2	5.92	70.8	5.92	69.2	*0.75*
3.5	6.83	69.2	6.83	75.0	5.84	70.2	5.84	75.2	*0.99*
4.0	5.50	100.8	5.50	77.6	4.08	92.2	4.08	84.8	*1.42*
4.5	7.49	67.8	7.49	74.2	6.61	70.8	6.61	69.6	*0.88*
5.0	7.27	76.2	7.27	71.8	6.36	82.2	6.36	72.0	*0.91*
5.5	6.47	71.8	6.47	97.0	6.37	66.4	6.37	95.6	*0.1*
6.0	7.77	83.8	7.77	60.3	7.28	85.2	7.28	60.1	*0.49*
6.5	6.59	83.6	6.59	94.0	6.77	70.8	6.77	96.4	*-0.18*
7.0	7.67	67.0	7.67	81.2	7.45	69.2	7.45	79.2	*0.22*

The table extends far enough to show that at some frequencies, the terminated version of the antenna may actually show a slightly higher gain than the unterminated version, for example, at 6.5 MHz. In practice, gain differences less than about 0.5-dB are operationally insignificant. Therefore, only at 5 MHz and below is the gain differential a measure of deficit that results from the use of terminating resistors. The table shows a periodic function in the gain deficit between 5 MHz and 2.5 MHz. Only in the lowest MHz of the defined operating range do we find the growing gain deficit that would correspond to the knee frequency in a linear terminated antenna. At 2 MHz, the gain deficit is nearly 6 dB.

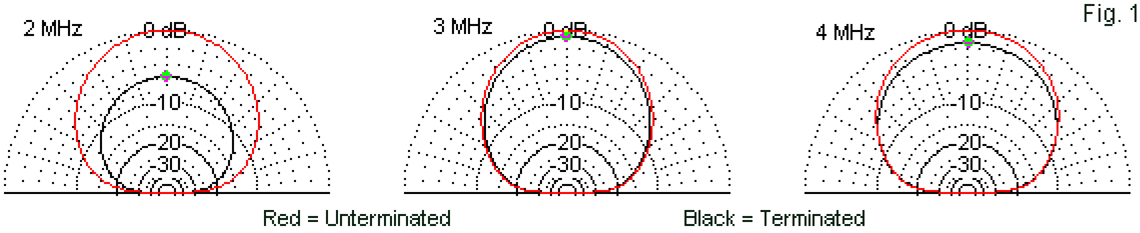


Fig. 19

Sample Elevation Patterns at 0-Degrees (Tip-to-Tip) of Terminated and Unterminated Versions of the Dyal 4-Turn Log-Spiral Antenna at 2, 3, and 4 MHz

Fig. 19 provides sample elevation plots of the terminated and unterminated versions of the antenna a 2, 3, and 4 MHz. The plots extend from tip-to-tip in both cases. The patterns illustrate the fluctuating gain deficit in the lower operating region. As well, they visually establish that the gain deficit may be less than serious except at the lowest operating frequencies, that is, well below 3 MHz. Above about 5 MHz, there is no significant difference between the performance of terminated and unterminated versions of the log-spiral antenna. This situations stands in high contrast to terminated linear antennas that show gain deficits relative to bare wires of the same length across the entire operating spectrum.

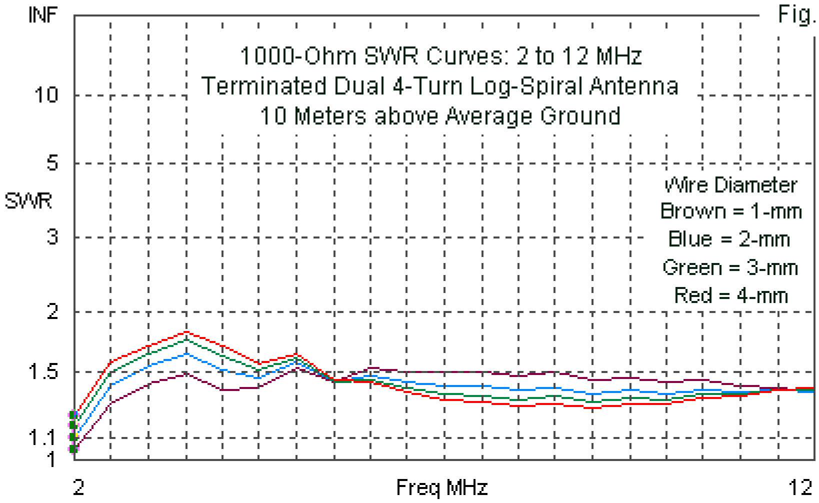


Fig. 20

In **Fig. 20** we can see the effects of changing the wire diameter from the 2-mm values used to obtain the sweep graphs shown earlier. For any practical wire size used to form the log spiral, the terminations control the reactance excursions that produced the mild twin peaks in the SWR value in the 4-MHz region. From 3.5-MHz downward in frequency, the terminations control the feedpoint impedance. This is the same region in which we find the most rapid decline in maximum gain relative to the unterminated version of the antenna.

Conclusion

The log-spiral antenna, as designed for this hypothetical exercise, is a large structure about 50-meters (164') in diameter. Due to its complex shape and the need for precision in construction, the antenna requires significant support systems. Despite these factors, the antenna provides the highest NVIS gain across the broadest frequency range of any antenna with which I am familiar. The values shown in the exercises are very likely close to reality, since all models of the antenna used an average ground environment (rather than creating a false optimism about performance by the use of a perfect ground).

The unterminated version of the antenna provides full gain performance down to about 2.5 MHz with a 1000-Ω SWR at or below 2:1 across the spectrum (except for the two frequencies noted in the text). The terminated version of the antenna can extend the SWR performance down to at least 2 MHz, although the gain deficit at the lowest frequency is close to 6 dB relative to the unterminated version. Unlike linear terminated antennas, the terminated log spiral does not carry the deficit throughout the operating range, but restricts it to the lowest frequencies.

For unterminated coverage of lower frequencies, the log-spiral can be scaled upward in direct proportion to the wavelength that defines the lowest frequency. The restriction that inheres to scaling is that the inner and the outer radii must both be scaled to the same degree to preserve the ratio between them. A scaling factor of 1.25 is necessary to provide unterminated service down to 2 MHz.

The log-spiral antenna is an example of a (limited) frequency-independent antenna based on antenna properties continuously scaled on a logarithmic basis, but it is not a log-periodic antenna. The application shown here is a practical implementation that shows the flexibility of the design principles in the face of being unable to scale the antenna conductor width with the changing frequency. Both the terminated and the unterminated versions of the antenna might fulfill the need for a NVIS-ALE base station, depending upon the circumstances and operational specifications.