NEC-4.1: Limitations of Importance to Hams

Antenna modeling seems deceptively easy. Come tour the pitfalls of the latest software.

By L. B. Cebik, W4RNL

Although most hams will not use NEC-4 *because of its cost, I asked L. B. to write this article because* QEX *readers are more likely to consider purchasing* NEC-4 *software than any other Amateur Radio publication audience. After reading what L. B. has to say, you may very well decide not to get* NEC-4 *for your applications—even if price is not a limiting factor. This article shows how important it is to select a modeling program with regard to how its strengths and weaknesses relate to your application. After reading this article, I will use* NEC-4 *only when it is clearly the better program for the problem at hand. Of particular interest to me is the modeling of sailboat antennas over salt water. That problem requires the modeling of multiple wires of radically different diameters, connected at common points with very small angles. For that application, the new* MININEC Pro *(with its new algorithms) is much superior to other software packages. In addition to the* NEC-4 *discussion, there are a number of comments relating to other commonly used antenna-modeling programs that are well worth reading. Overall, this is a very important cautionary tale. If you are into antenna modeling, I think you will find this article very interesting, maybe even a bit disturbing.*—Rudy Severns, N6LF, *QEX* Editor

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Although *NEC-4* (current version 4.1) has appeared to be a large jump from *NEC-2*, it is simply another step in the evolution of method-of-moments antenna modeling programs.[1] Three factors make *NEC-4* seem like so large a leap forward. First, it resolves the problem *NEC-2* has with stepped-diameter elements, so common in HF Yagi construction. Second, it adds the capability of handling buried radial systems (just when they are going out of style in favor of elevated radial systems). Third, it's not in the public domain, it's proprietary and requires a license, in addition to the purchase or development of interface software.[2]

Numerous ham users of *NEC-4* appear to have overlooked that, like all of its predecessors, *NEC-4* has some limitations that users must heed if they are to successfully model and analyze antennas with this program. Some of these limitations involve common rules of modeling that are covered

[1]Notes appear on page 16.

extensively in software manuals and elsewhere. These I shall bypass. Some of the limitations are published or unpublished recommendations that many ham modelers seem to overlook. These I shall review briefly. Finally, some of the limitations are relatively unpublished, and these I shall look at in more detail.

First, a couple of conventions: *NEC* handles angles of radiation as zenith angles, increasing from 0° at the zenith, directly overhead to 90° at the horizon. Hams are more accustomed to elevation angles, which count from 0° at the horizon to 90° overhead. I shall keep to the amateur convention wherever matters of up-down angles arise. Amateur and commercial interests are also more at home speaking of antenna element *diameter*; whereas wire *radius* is native to *NEC* calculations. Again, I shall adopt the convention more familiar to hams. Readers of the basic *NEC-4* manual must, of course, translate wherever appropriate.[3]

Some Commonly Abused, Known Limitations of *NEC-4*

Method of moments modeling requires the use of straight wires to form a close approximation of the antenna geometry. For longer linear wire lengths, wires may be segmented within a given wire specification. The recommended maximum segment length is 0.1 λ, with a more conservative limit of 0.05 λ recommended for critical regions of the antenna. Although the absolute limits permit as few as five segments for a 0.5 λ dipole, most modelers use 9 or 11 (adhering to the need for an odd number of segments for a single-source center-feed of the antenna). With 11 segments, each segment for a 3.5 MHz center-fed wire would be about 12.5 feet long. Quite good results emerge from this segmentation for simple antennas.

However, unconscious error occurs when modelers simply shift the frequency of the antenna to other amateur bands without changing the segmentation of the wire. At 28 MHz, the shortest segment should be no more than 3.5 feet, or more conservatively about 1.7 feet. If one is exploring the use of a 3.5 MHz dipole as an "all-band" doublet, the antenna should be resegmented for each frequency band or segmented sufficiently for all frequencies to be explored. *NEC-4* has no specific limit for segment shortness of thin-wire antennas.

NEC limitations on the minimum segment length occur in relationship to the wire radius or diameter. In general, the maximum wire diameter is limited so that π times the diameter, divided by the wavelength should be much smaller than one. HF antennas are highly unlikely to approach anywhere near this limit. However, highly segmented antenna wires with large diameters may approach the length-to-diameter limitations of the

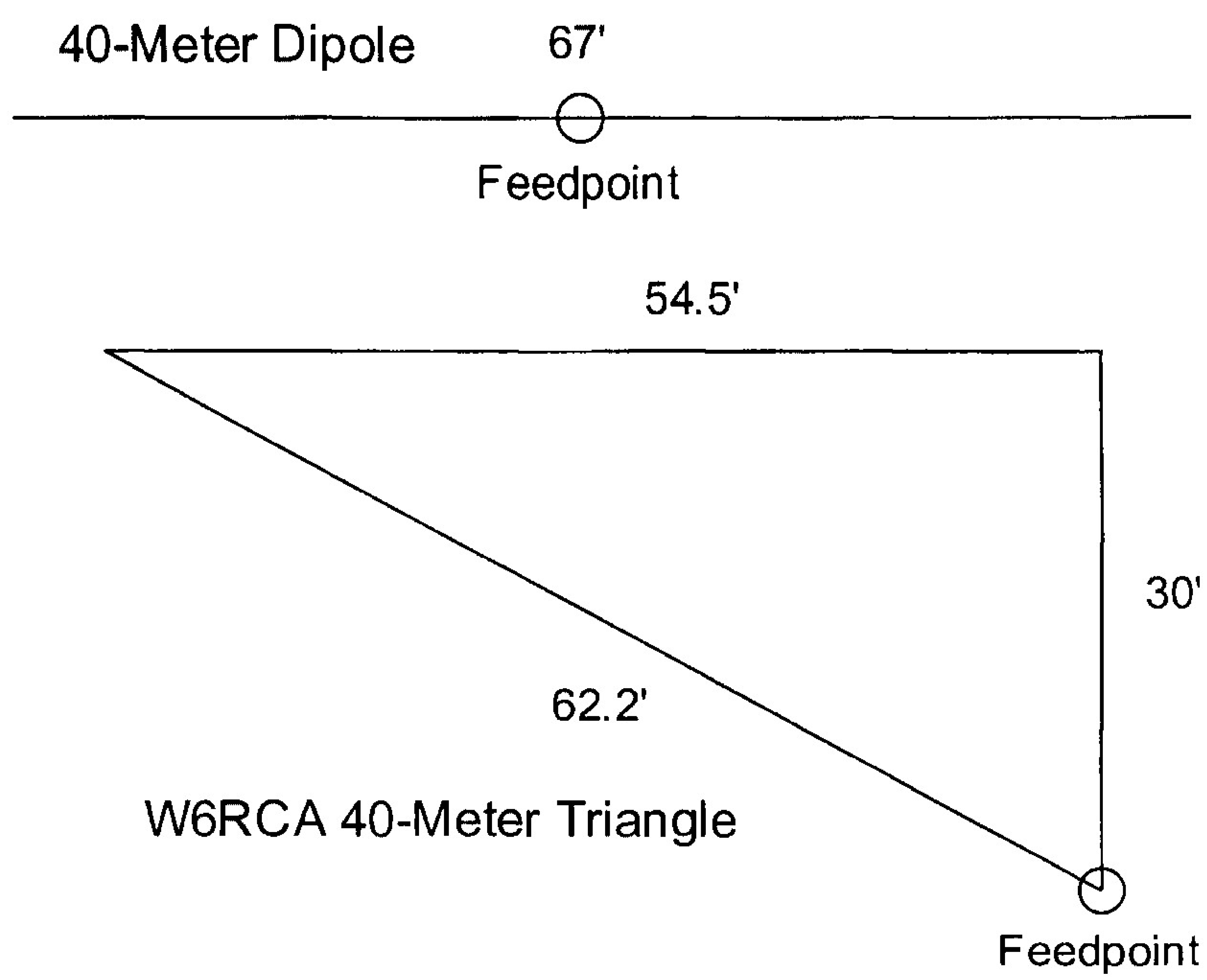

Figure 1—Two antennas for comparative convergence tests.

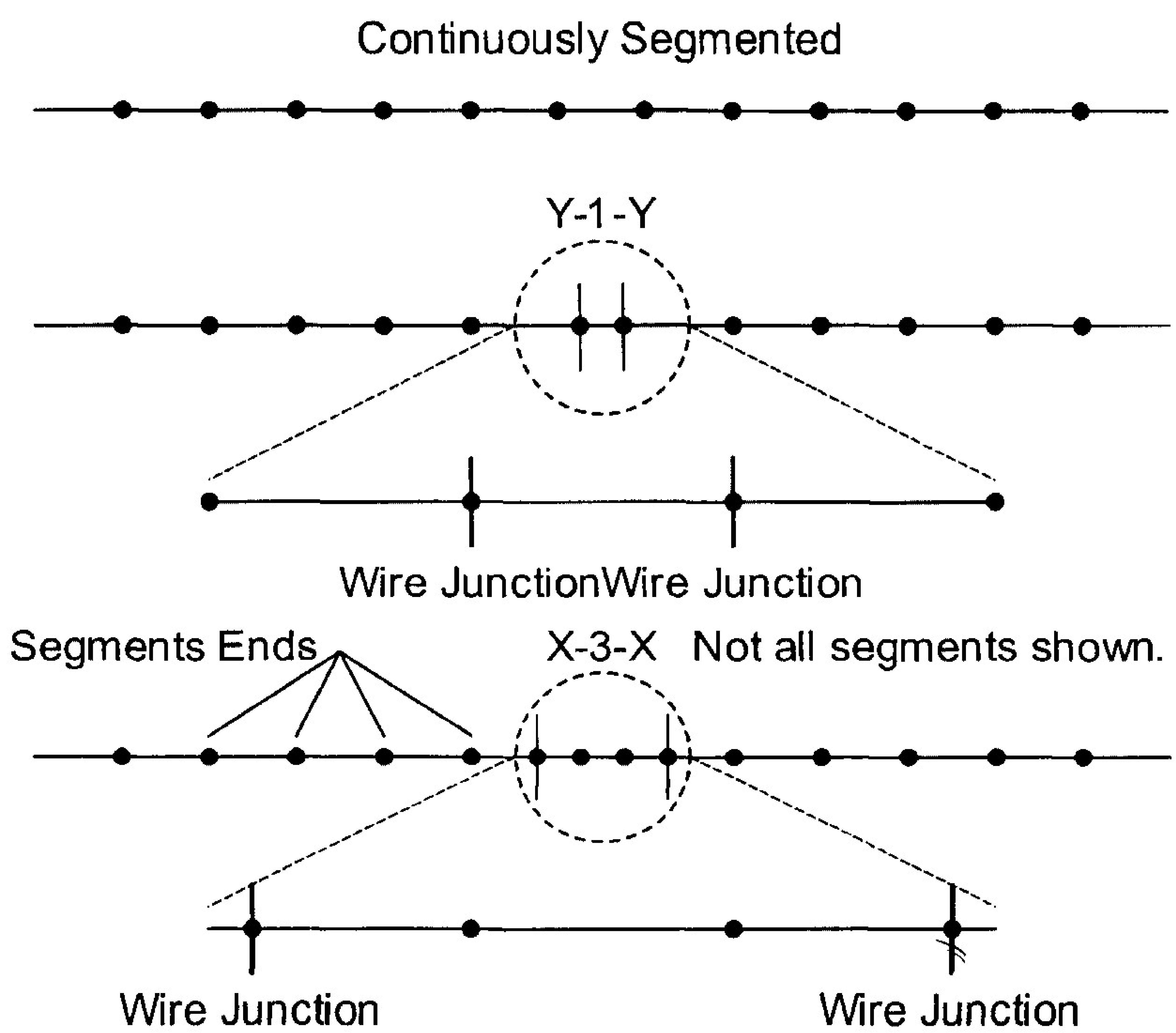

Figure 2—Three methods of segmenting a dipole.

program. The known error point occurs when the segment length is less than 25% of the wire diameter, but programmers strongly urge ratios of length to diameter many times larger, at least 1:1. Although this limitation is seemingly easy to avoid, it is often crossed when modelers begin increasing wire diameters in order to explore various affects on antenna length, resonant frequency, current phasing, etc.[4]

The exact number of segments needed in a half wavelength can be determined by *convergence* testing. Although this common test is rarely mentioned in modeling literature anymore, it remains a fundamental test of result reliability for antenna models in any of the *NEC* and *MININEC* programs. Convergence testing consists of increasing the number of segments per unit of length equally throughout the antenna structure and observing changes in the output data for parameters significant to the modeling exercise. Often, gain and feed-point impedance are used as leading indicators. If these figures change seriously, convergence has not been achieved. If they do not change seriously, we can consider the model to be converged. Exactly what counts as a serious change is subject to the nature of the test and the complexity of the antenna being modeled. Moreover, every change in segmentation will produce mathematically detectable changes.

Linear, simple wire antennas rarely require more than the minimum recommended number of segments per half wavelength to achieve convergence in free space. However, even seemingly simple antennas over ground may require denser segmentation. For example, an asymmetrical triangle that is vertically oriented may require considerably more segments to achieve convergence. Figure 1 and Table 1 illustrate the difference by showing some *NEC-4* output numbers for a standard dipole and a 1 λ triangular loop. Note that the simple dipole shows almost no change, except for minor changes in the feed-point impedance, after 11 segments per half wavelength. However, not until the triangle uses about 73 segments or about 36 per half wavelength, does the elevation angle of maximum radiation (or take-off angle, TO) stabilize, along with the feed-point impedance. The gain continues to vary even at 104 total segments.

One problem related to segmentation concerns the length of adjoining segments. Traditional cautions suggest keeping the ratio at 2:1 or less. However, the ratio required may be even less, especially in the region of the antenna feed-point. Consider a thin-wire center-fed dipole of 0.01 inch-diameter aluminum wire. One standard way to segment the dipole is to use a single wire with equal segments along its length. (We may call this continuous segmentation.) A second way to segment the antenna is to use three wires. The center, or feed-point, wire might consist of a single segment, which we shall arbitrarily set to 0.2 feet for a 20 meter operating frequency (a rate of about 170 segments per half wavelength). The outer wires may be segmented at the same rate or a different rate. We may designate this the Y-1-Y arrangement, as shown in Figure 2.

Table 1—Convergence Testing for Two Different Antennas

Total Segments	*Gain (dBi)*	*TO Angle (°)*	*Feed-point Impedance (R ± jX Ω)*
40-meter λ / 2 Dipole (See Fig. 1)			
5	5.82	49	102.90 – *j*38.83
11	5.86	49	92.38 + *j*6.47
15	5.87	49	91.08 + *j*8.59
19	5.87	49	90.51 + *j*9.18
23	5.87	49	90.21 + *j*9.42
40-meter 1 λ Triangular Loop (See Fig. 1)			
21	3.75	38	67.62 – *j*7.07
32	2.57	27	53.91 – *j*4.72
42	2.28	24	49.54 – *j*1.34
52	2.18	22	47.54 + *j*1.19
63	2.13	22	46.40 + *j*2.94
73	2.11	21	45.78 + *j*4.86
83	2.10	21	45.48 + *j*5.71
94	2.09	21	45.26 + *j*6.28
104	2.08	21	45.14 + *j*6.79

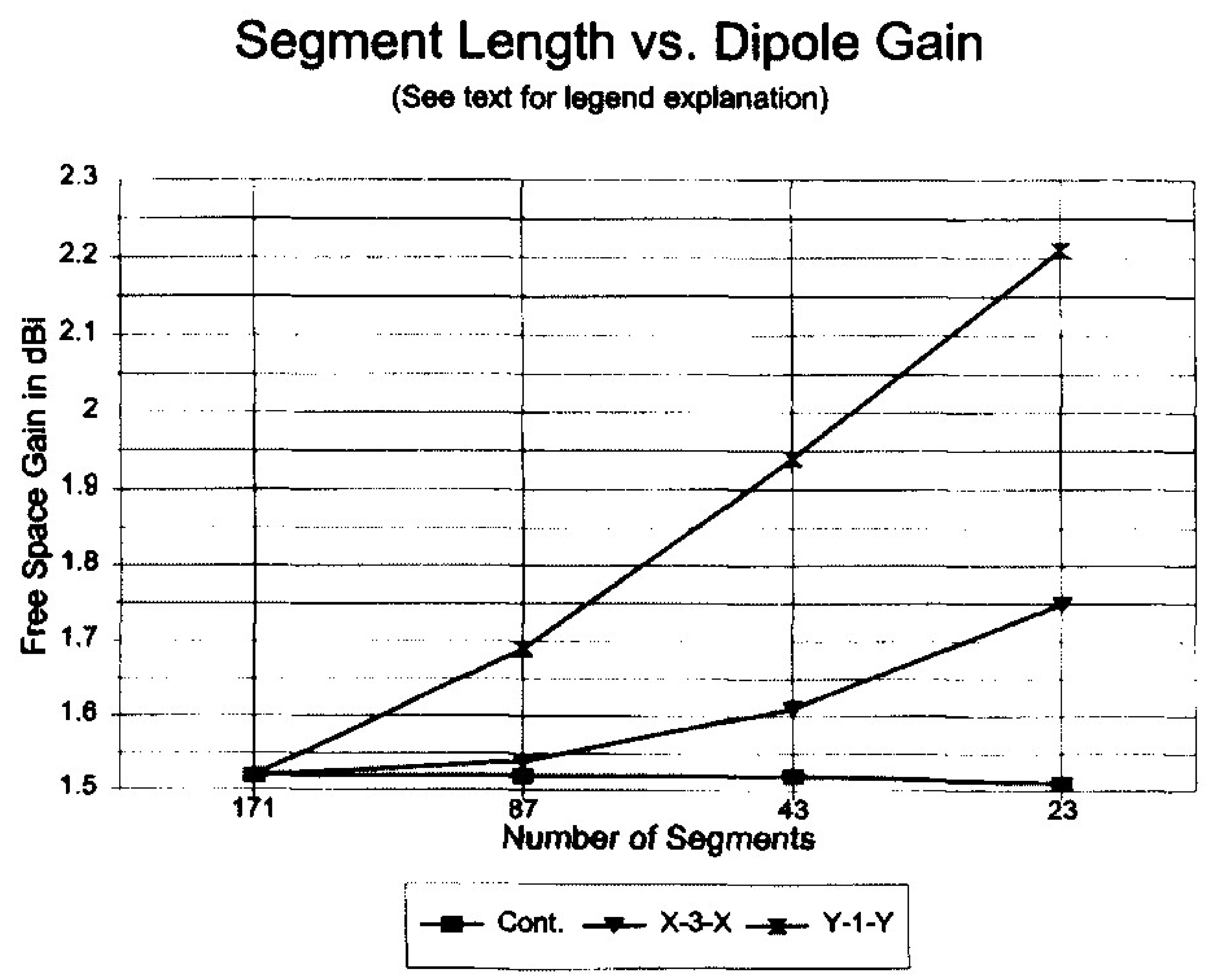

Figure 3—Segment length versus dipole gain for different methods of segmentation.

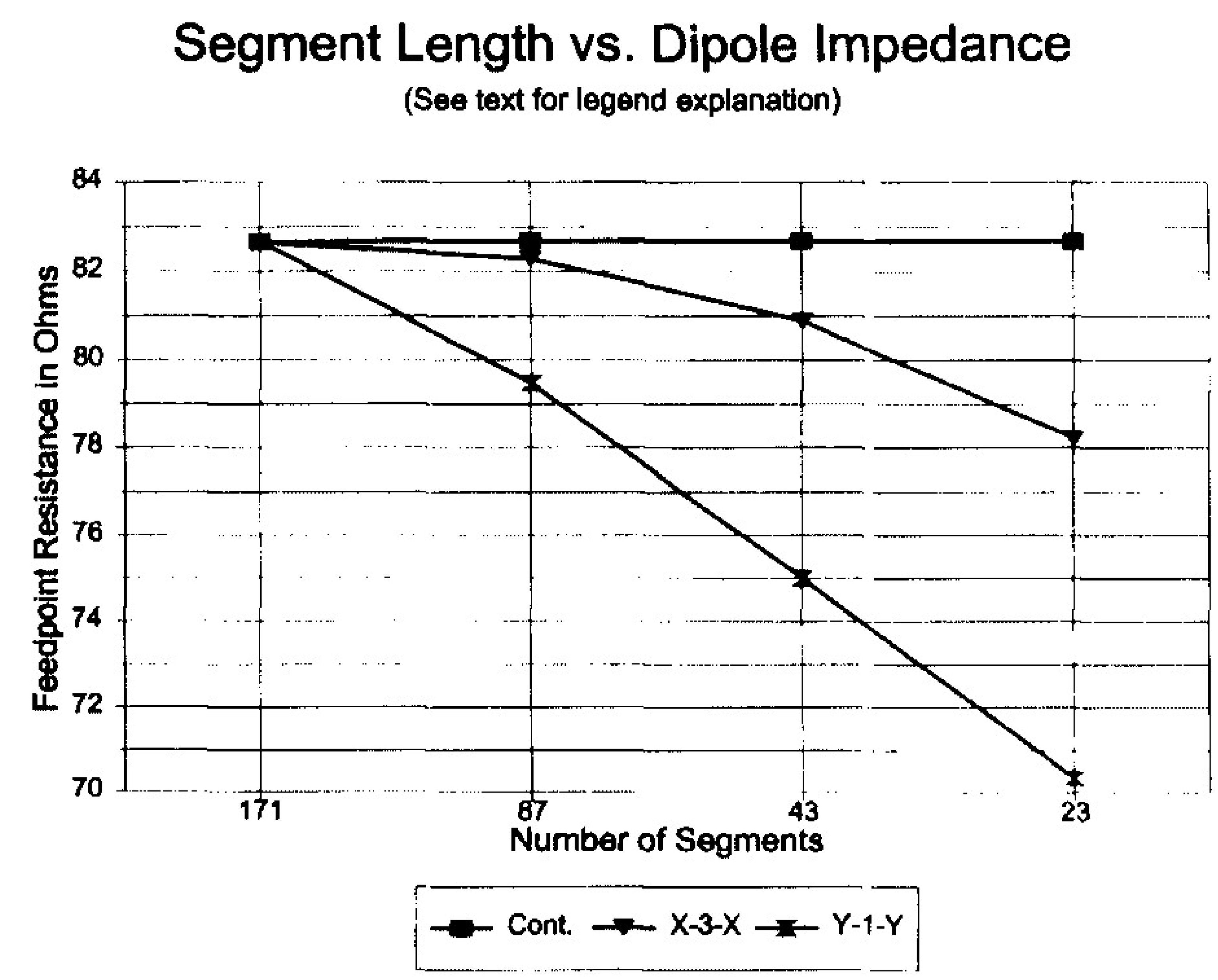

Figure 4—Segment length versus dipole impedance for different methods of segmentation.

Figures 3 and 4 graph the outputs of *NEC-4* with respect to gain and to feed-point impedance for both the continuous and the Y-1-Y configurations. So long as the total segmentation is such that adjoining segments are of equal length, results converge. However, even at an adjacent segment ratio of 2:1 (87 segments), reported gain for the Y-1-Y configuration is erroneously higher and feed-point impedance of the resonated antenna is erroneously lower.

An often-heard recommendation requires that the segments immediately adjacent to the feed, or source, segment are equal in length to that segment. The middle line of the graphs, designated X-3-X, traces this configuration in Figure 2. The source and adjacent segments are all 0.2 feet long at 14 MHz, while the end wires are variously segmented so as to increase the ratio of segment lengths in the outer wires to segment lengths of the center wire. Even in this configuration, a 2:1 ratio (number of segments = 87) yields a clearly detectable set of deviations from the continuously segmented model. Segment-length equalization is perhaps considerably more significant than many modelers suppose. An alternative is to taper segment lengths along each outer wire so that the segments adjacent to the center wire are nearly equal in length to the segments in the center wire. Existing software either supports the segment-length tapering (GC) input card or provides for segment tapering externally to *NEC-4* calculations. A further alternative, recommended where multiple diverging dipoles meet, is to use a three-segment wire of no less than 0.02 λ, with due caution paid to the length of adjoining segments.[5]

Segment-length equalization should not be divorced from the idea of selecting segment length as a function of the operating wavelength. When so segmented, wires in a more complex geometry adhere to the recommendation that the segments and their dividing points parallel each other to the degree permitted by the material structure of the antenna. Although this recommendation is made specifically for closely spaced wires, adherence to a general segmentation scheme ensures adherence to it as well.[6]

There are numerous other modeling cautions enumerated either in *NEC-4* documentation or in user's manuals for commercial implementations of the program. Among the areas in which modelers need to use caution are wire junctions and "near junctions," minimum angles of angular wire junctions and minimum loop-antenna element sizes. However, the items discussed above represent perhaps the most numerous problematic practices that I have encountered in looking at several hundred ham-generated models in all versions of *NEC*.

A Lesser-Known Limitation: Stepped-Diameter Difficulties

NEC-4 implemented changes in the method of handling currents and boundary conditions to overcome known inaccuracies that occurred in *NEC-3* and *NEC-2* with respect to antenna elements having stepped diameters. For many cases, these measures are completely effective, and the results of direct *NEC-4* modeling of standard Yagi designs with "taper schedules" have been very accurate.[7]

However, anomalies begin to appear when modeling, in *NEC-4,* Yagi designs developed by K6STI for the program *YA*.[8] When modeling in *MININEC*, no problems of convergence were noted with reasonable numbers of segments per half-wavelength. However, when modeled with *NEC-4*, convergence only occurred with very large numbers of segments per half-wavelength.

A feature of the K6STI designs is the use of a large-diameter, short-length center section for each element to simulate boom-mounting plates. This technique has proven sound, relative to real-world antenna construction. However, only after reducing the diameters of these element centers is *NEC-4* able to achieve convergence with a reasonable number of segments per half-wavelength.[9] The initial conclusions reached from these investigations are:

1. *NEC-4* has limits in dealing with stepped-diameter elements, especially where the step in diameters between adjacent element segments is large and the large step occurs in the region of maximum element current.

Achieving convergence under these circumstances may require quite large models relative to the number of antenna elements involved. These models grow larger for every diameter step involved in the structure of the element.

2. Inadequate segmentation in

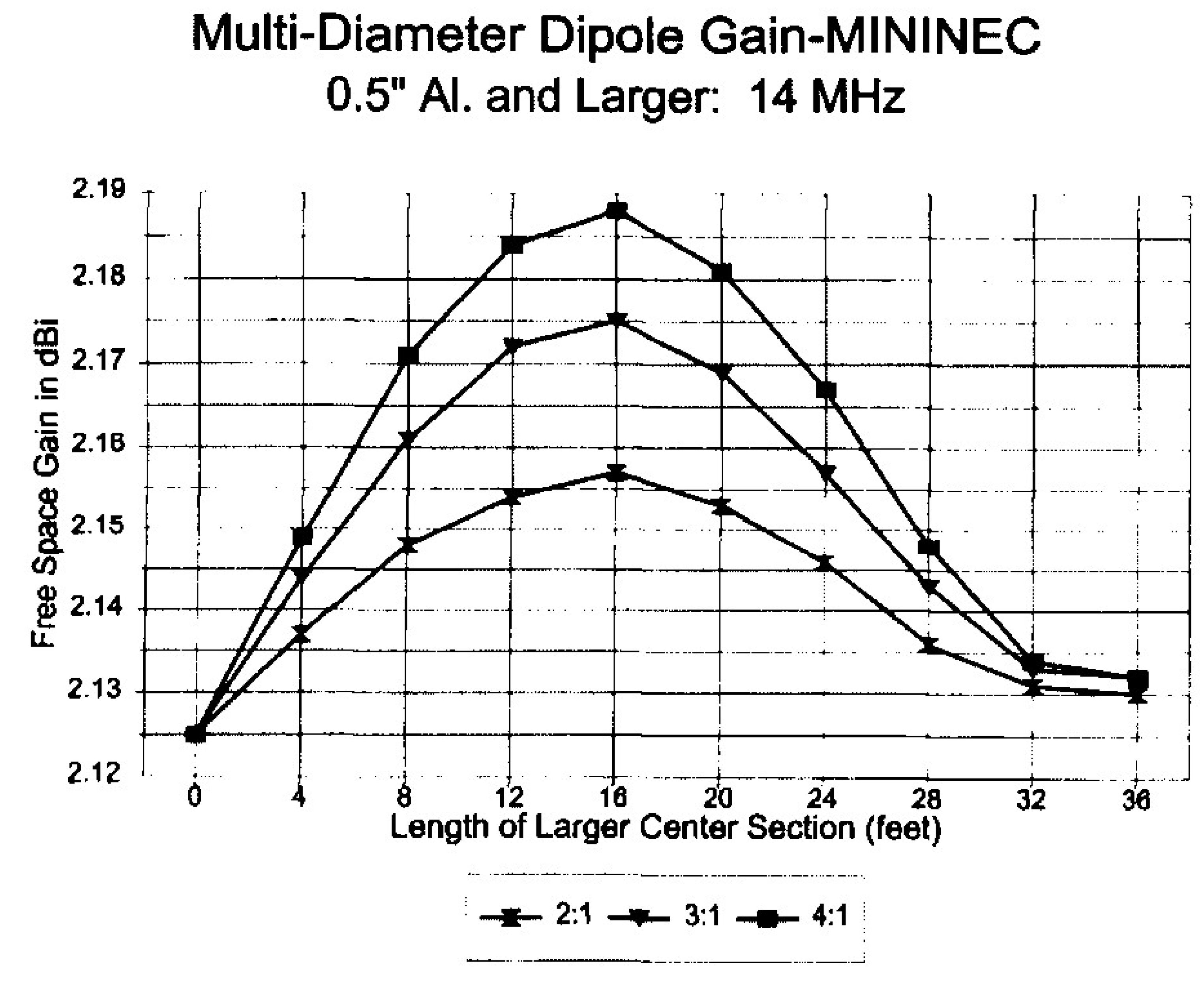

Figure 5—Multi-diameter dipole gain—*MININEC*.

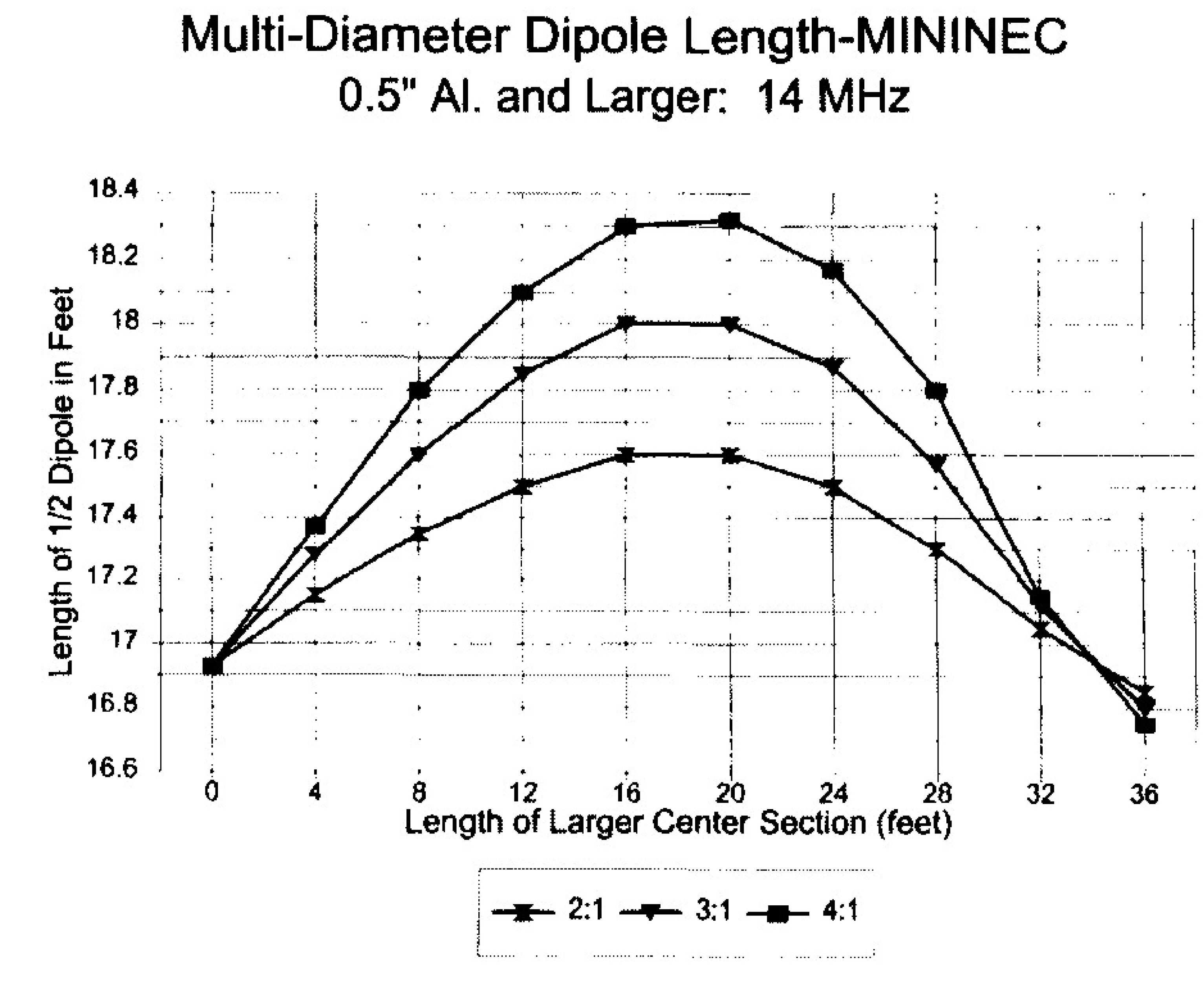

Figure 6—Multi-diameter dipole length—*MININEC*.

stepped-diameter elements in *NEC-4* may result in unrealistically high values of forward gain and low values of feedpoint impedance. Adequacy of segmentation includes the number of lements, equalization of segment lengths within the limits of the element structure and alignment of segments among the elements.

To explore these anomalies more systematically, I set up a small test systematically modeling dipoles with larger center sections. The test frequency was 14 MHz. The initial material was 0.5 inch-diameter aluminum. In increments of two feet each side of center, I increased the length of a larger diameter center section in progressive steps for total lengths of 4, 8, 12 feet, etc, up to and including the total antenna length.

Each antenna was then resonated to less than 1 Ω reactance. Thus, the length of each model differs. In the graphs that follow, the far right entry labeled "36" is a placeholder for the actual total length of the antenna at the increased diameter. That column, alone, violates the linear progression of the other enlarged center sections.

Each model was tested using ratios of 2:1, 3:1 and 4:1 relative to the original dipole diameter of 0.5 inch, for center-section diameters of 1, 1.5 and 2 inches. All antennas were modeled in free space.

The models were first run in *MININEC* 3.13 via *ELNEC 3*. Segmentation was set at 34 segments overall, using one segment per foot of enlarged center section, with the remaining segments split between the smaller-diameter end sections. This yielded segment lengths that are well within all *MININEC* boundaries for accurate results, as well as very reasonably close in length between the antenna wires.

Figure 5 shows the progression of gain figures for the *MININEC* runs. Interestingly, the gain of the models peak when the enlarged center section is just under half the total length of the antenna. As the larger center section is further lengthened, *MININEC* shows a decrease in gain. The curves for the three ratios are nicely congruent.

The length of the resonant antenna also changes with the length of the larger-diameter center section, as shown in Figure 6. Overall antenna length actually peaks with center-section lengths slightly longer than those for maximum gain. *MININEC* models do not reach a final shortened length associated with fatter elements until the entire antenna is at the larger diameter.

The same antennas were run with *NEC-4*, initially with EZNEC *Pro* and later with a beta version of *GNEC*. Segmentation was virtually the same as with the *MININEC* models with a single additional segment in the center section to permit the required midsegment feed-point. As with the *MININEC* models, each antenna was resonated to less than ±1 Ω of reactance for models using 2:1, 3:1 and 4:1 ratios of the center segment to the end sections.

The pattern of gain produced by the *NEC-4* models, shown in Figure 7, is quite unlike that yielded by *MININEC*. Maximum gain occurs with the shortest possible larger-diameter center section and progressively decreases as the center section is lengthened. The curves for *NEC-4* are less smooth than for *MININEC* because the former, in the commercial versions noted, yields gain figures to two decimal places, while the latter yields figures to three decimal places. Hence, *NEC-4* rounding yields somewhat stair-step curves. Within those limits, the curves for the three different diameter ratios are congruent.

Equally congruent are the overall antenna-length curves, as demonstrated by Figure 8. Notice that in all graphics in this series, antenna length is shown in terms of lengths each side of the feed-point.

Interestingly, despite the vastly different gain curves, the overall antenna length curves for *MININEC* and *NEC* are exceedingly comparable. *MININEC* yields slightly longer resonant lengths for each modeled case, a phenomenon long noted (and corrected for in some commercial versions of *MININEC*). Nonetheless, *MININEC* and *NEC-4* show the longest resonant length at just about the same length of larger-diameter center section, as shown in Figure 9. This graph uses the 4:1 ratio curves because they produce the sharpest length peaks and would be most sensitive to significant differences in the peaks for each modeling system, with these models.

The question that remains is "Which of the two gain curves is the more reliable?" The *MININEC* gain curves with a 2:1 diameter ratio of center

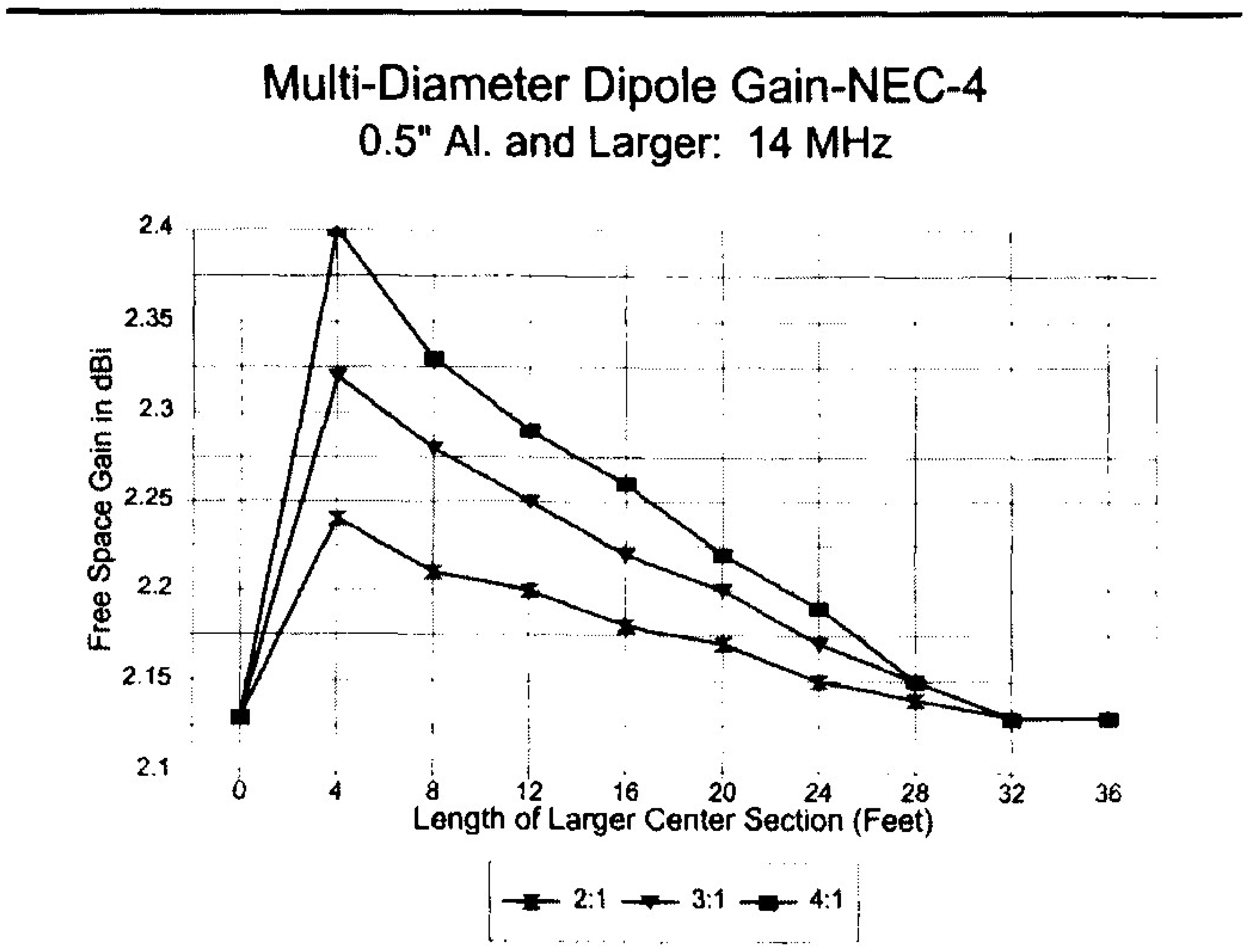

Figure 7—Multi-diameter dipole gain—*NEC-4*.

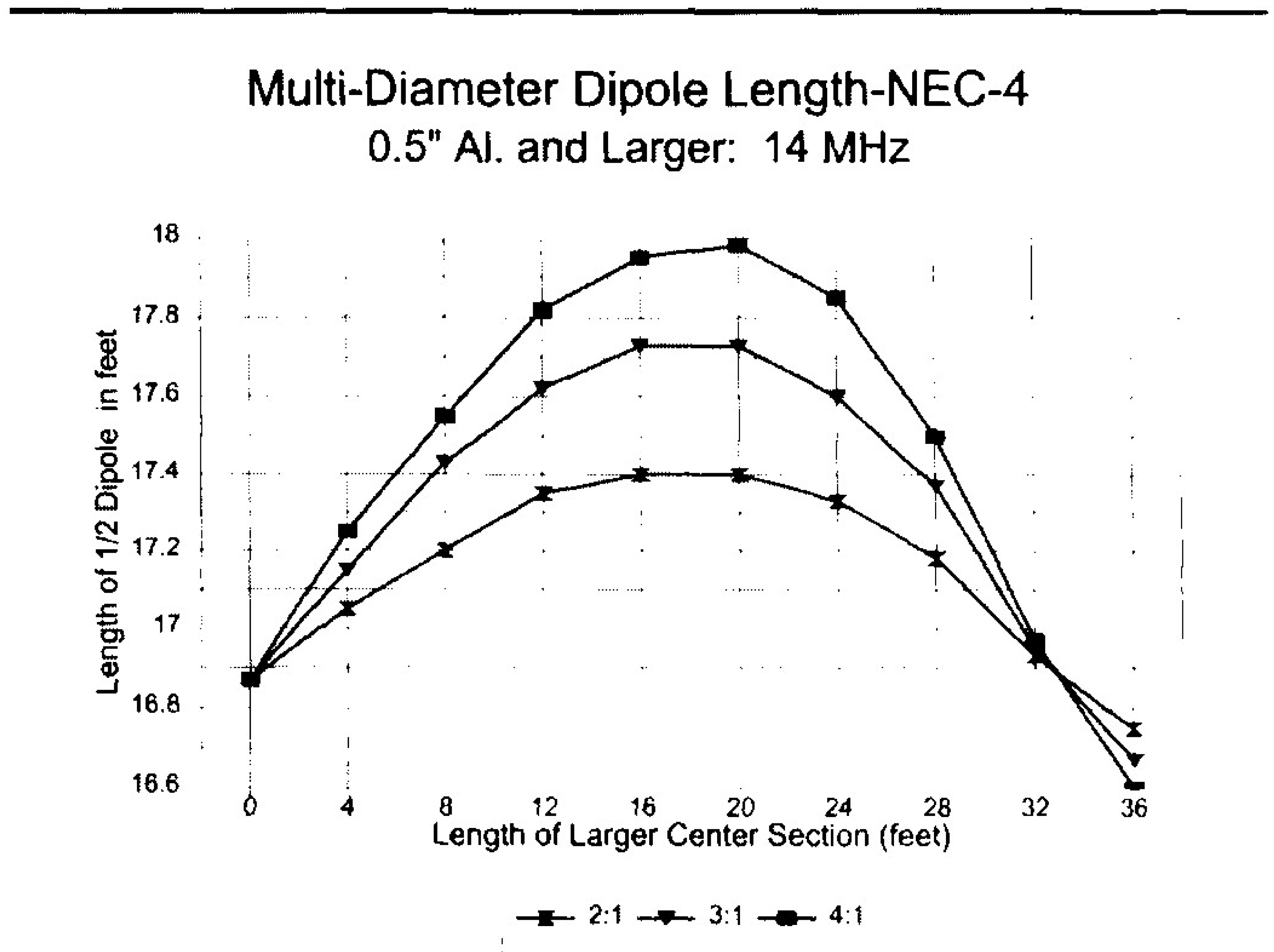

Figure 8—Multi-diameter dipole length—*NEC-4*.

section to end sections were rerun with twice as many segments. Gain figures are convergent, within a maximum divergence of 0.003 dB. In the comparable *NEC-4* models, segment numbers were doubled (and one segment removed from the wire containing the feed-point to retain an odd number of segments). The results show an order of magnitude less convergence with short center sections of 4 and 8 feet. Convergence within two decimal places occurred only when the center section reached 24 feet long. This result is consistent with the difficulty of convergence testing Yagi models employing short, large-diameter center sections for each element.

Moreover, the *NEC-4* curve totally envelopes the *MININEC* curve (as shown in Figure 10), for diameter ratios of 2:1. Within the limits of *NEC-4* rounding, nowhere does the *MININEC* curve exceed the *NEC-4* curve in gain value. In contrast, for shorter center sections, the reported gain of the *NEC-4* model is significantly higher.

The anomalous results yielded by *NEC-4* with shorter, large-diameter center sections of multidiameter dipoles gains importance as these figures accumulate in multielement antenna arrays. Since these gains are usually cumulative in most antennas designed for maximum or close to maximum gain, the reported gain may be significantly higher than reality.

The convergence test and the fact that the *NEC-4* curve envelopes the *MININEC* curve are strong indicators that *NEC-4* may be simply inaccurate when antenna elements consist of multidiameter sections, such that the center section is short and significantly larger in diameter than succeeding sections of the element. The degree to which such an inaccuracy becomes operationally significant to an antenna design depends on many variables of both design and engineering goals and cannot be independently estimated. Unless *NEC-4*'s results can be independently confirmed as accurate (with *MININEC*'s curves consequently invalidated), the phenomenon will be, at least, disconcerting to antenna modelers.

Attributing an anomaly to *NEC-4* in this case does not, itself, certify the accuracy of the *MININEC* result. Even if correct, the increase of gain may be of more mathematical interest than operational significance in many cases. At a diameter ratio of 4:1, the maximum gain is only about 0.06 dB relative to a dipole of the thinner size. However, where such gain increases accumulate on multielement antennas, the resulting gain figures may yield unrealizable expectations of real antenna performance. Those who model antennas should note the disparity between the two modeling programs wherever it emerges.

A Second Lesser-Known Limitation: Closely Spaced Wires

With respect to closely spaced parallel wires, *NEC-4* documentation notes that minimum separation is limited by the thin-wire approximation and that the actual error versus separation had not been well determined at the time of the manual release. The manual sets a "reasonable" limit on separation between wire axes of two to three times the largest diameter.[10]

Numerous Amateur Radio antennas contain quite closely spaced structural elements. Among these structures are open-sleeve coupled elements, Tee and gamma-match rods and folded dipoles. Therefore, it seemed reasonable to explore more methodically the possibility of a further systematic error. Apparently anomalous results occurred when antenna wires in *NEC-4* were placed in close proximity, despite following recommended guidelines for aligning the segments of the wires to the degree possible.

Therefore, I performed a simple modeling test. I modeled a 1 inch diameter aluminum dipole for 14 MHz. Then I created three different models of resonant 21 MHz dipoles, all aluminum, but having diameters of 0.5, 1.0 and 1.5 inches.

In separate tests, I placed each of these 21 MHz dipoles in proximity to the 14 MHz dipole at distances of 2 through 12 inches, in 2 inch increments. The 2 inch spacing was deemed the least permissible that would prevent the wire surfaces from touching. This spacing falls below the recommended *NEC-4* guidelines of wire

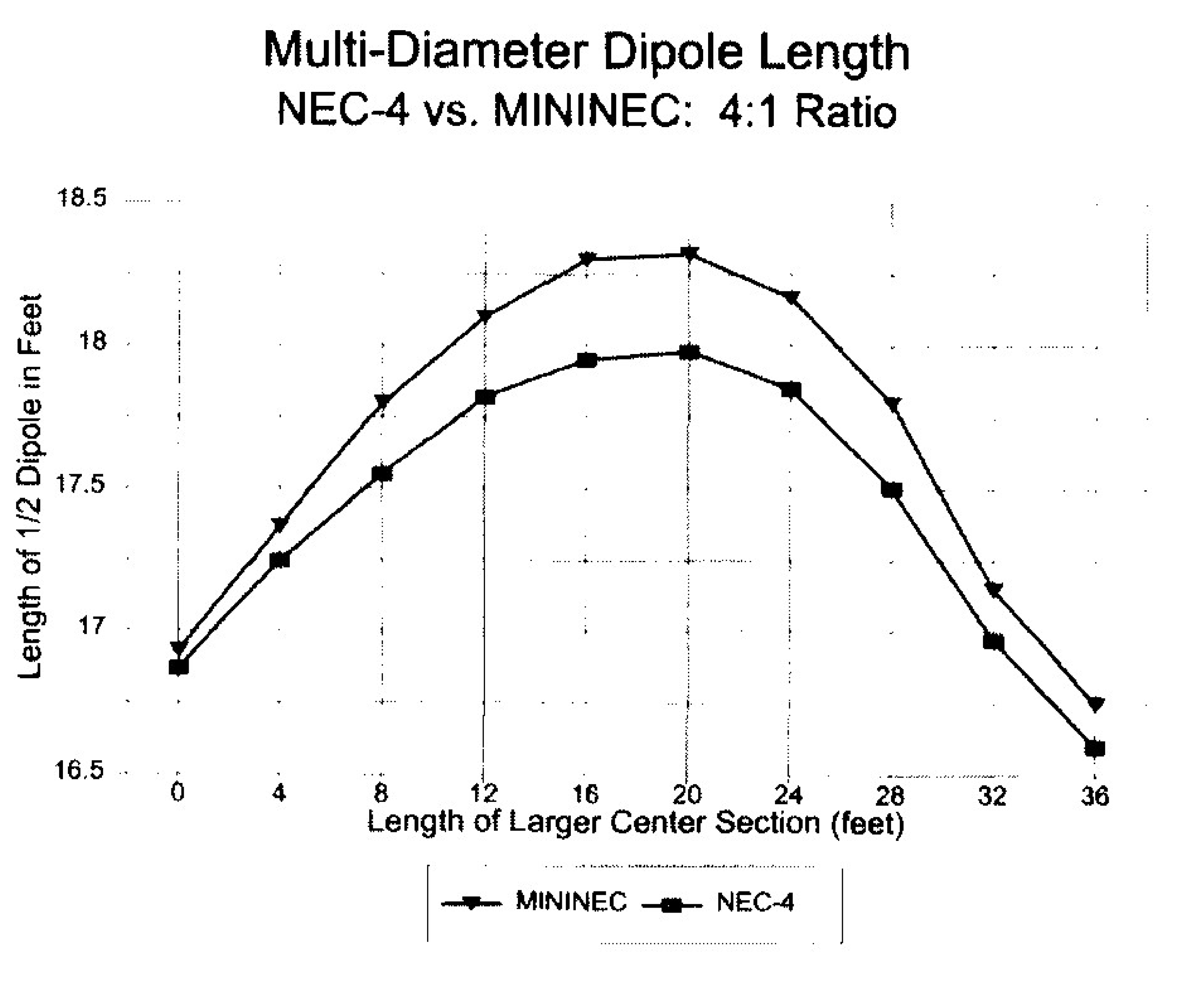

Figure 9—Multi-diameter dipole length—*NEC-4* versus *MININEC*.

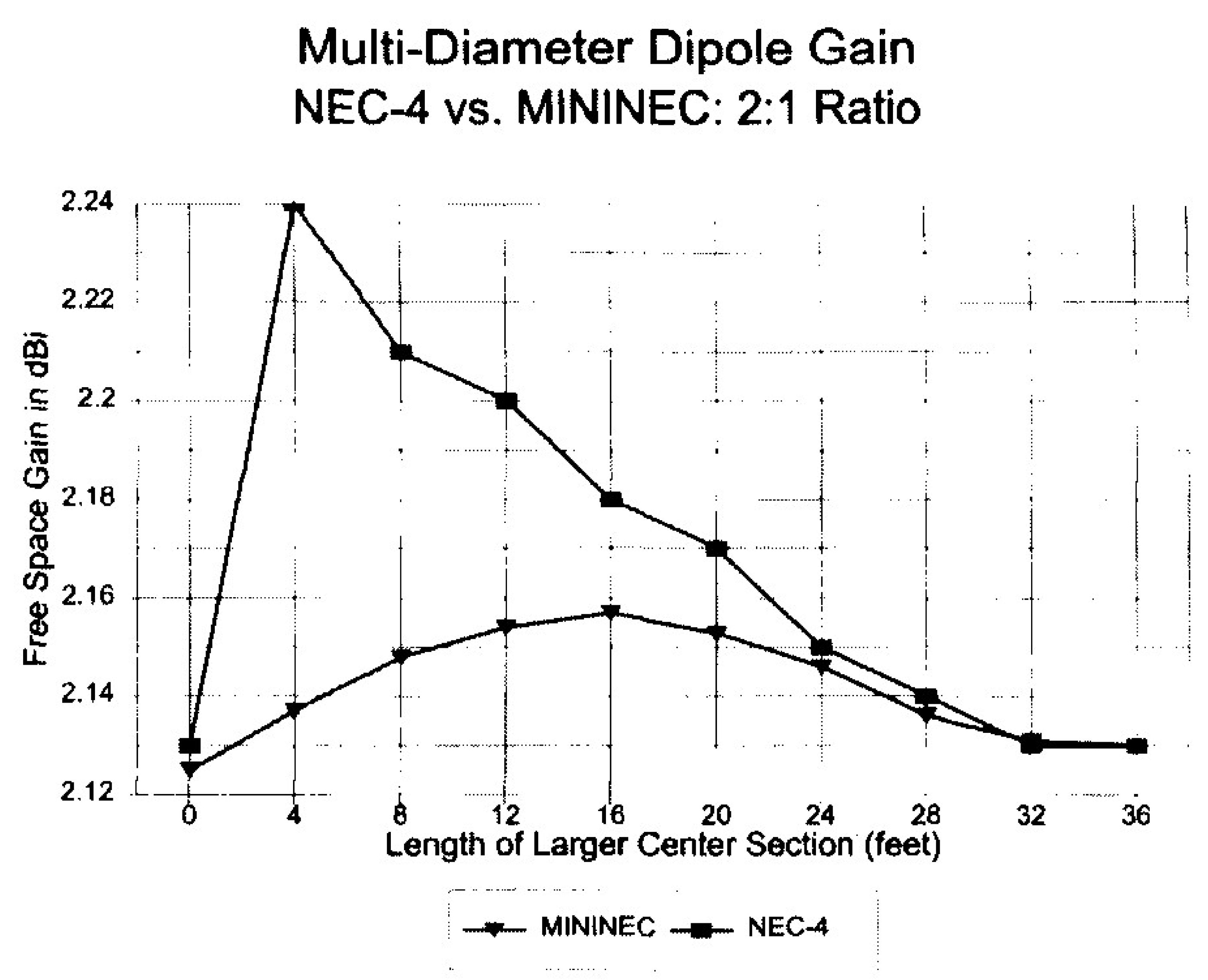

Figure 10—Multi-diameter dipole gain—*NEC-4* versus *MININEC*.

separation. For each test, the 14 MHz fed dipole was adjusted to resonance and the gain figure was recorded. As in past tests, resonance is defined as a feedpoint reactance of less than 1 Ω. Since the test was designed to reveal the effect of the shorter wire on the longer, the original lengths of the 21 MHz antennas were preserved for each size throughout the test runs.

The tests were performed on both *MININEC* 3.13 within *ELNEC* 3.0 and on *NEC-4* within *EZNEC Pro*. The lengths of the 14 MHz and the 21 MHz elements differed between programs from 0.5 inch for the smallest diameter element to about 1 inch for the largest.

The 14 MHz antenna used 34 segments in *MININEC* and 35 segments in *NEC-4*. The 21 MHz element was assigned 22 segments in *MININEC* and 23 in *NEC-4*. This segmentation aligned the segments quite reasonably. Since this segmentation already exceeds common practice in linear antenna design, convergence testing was not systematically undertaken, although the same performance curves appear with both fewer and more segments per half-wavelength.

All gain figures were recorded as free space gain in dBi. With respect to closely spaced elements, there are two gain figures of note: the in-plane gain and the out-of-plane gain. The former is the maximum gain of the dipole and extra wire in the plane that contains them both. The latter is the gain in a plane that is perpendicular to the wire axes and passing through the wire midpoints. Out-of-plane gain will ordinarily be less than in-plane gain, although in-plane gain will show a front-to-back ratio that is approximately double the difference of the two gain figures.

The tests were first run with *MININEC*. Figure 11 shows the in-plane gain for each diameter of extra wire as the distance between elements is decreased from 12 to 2 inches. Most noticeable in the graph is the flattening of the curves as the spacing reaches 2 inches, despite a reasonably linear progression to that point.

Some of the reason for the flattening appears in Figure 12, which records the out-of-plane gains for the wire pairs over the same range of spacings. As the distance reaches 2 inches,

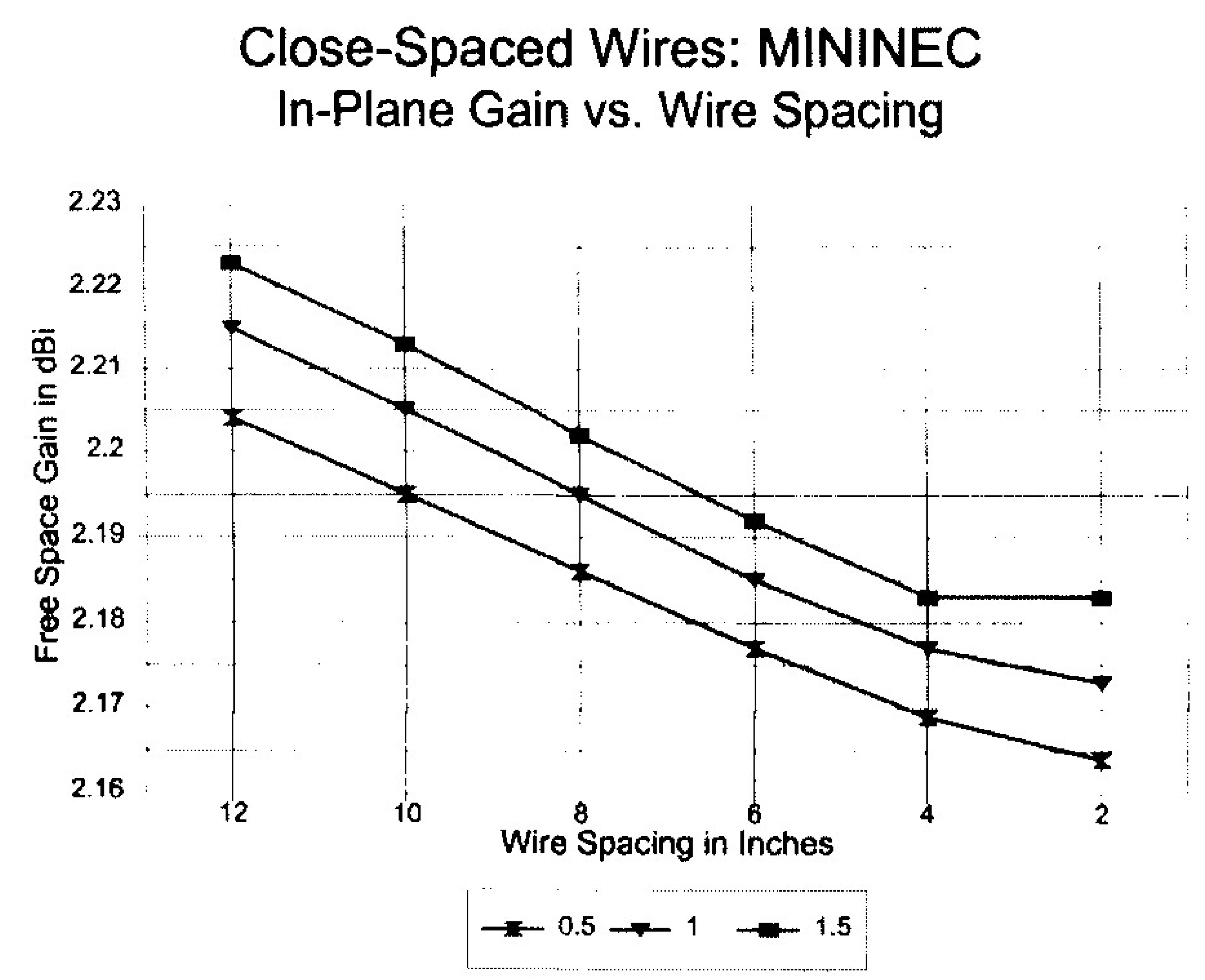

Figure 11—In-plane gain of close-spaced wires—*MININEC*.

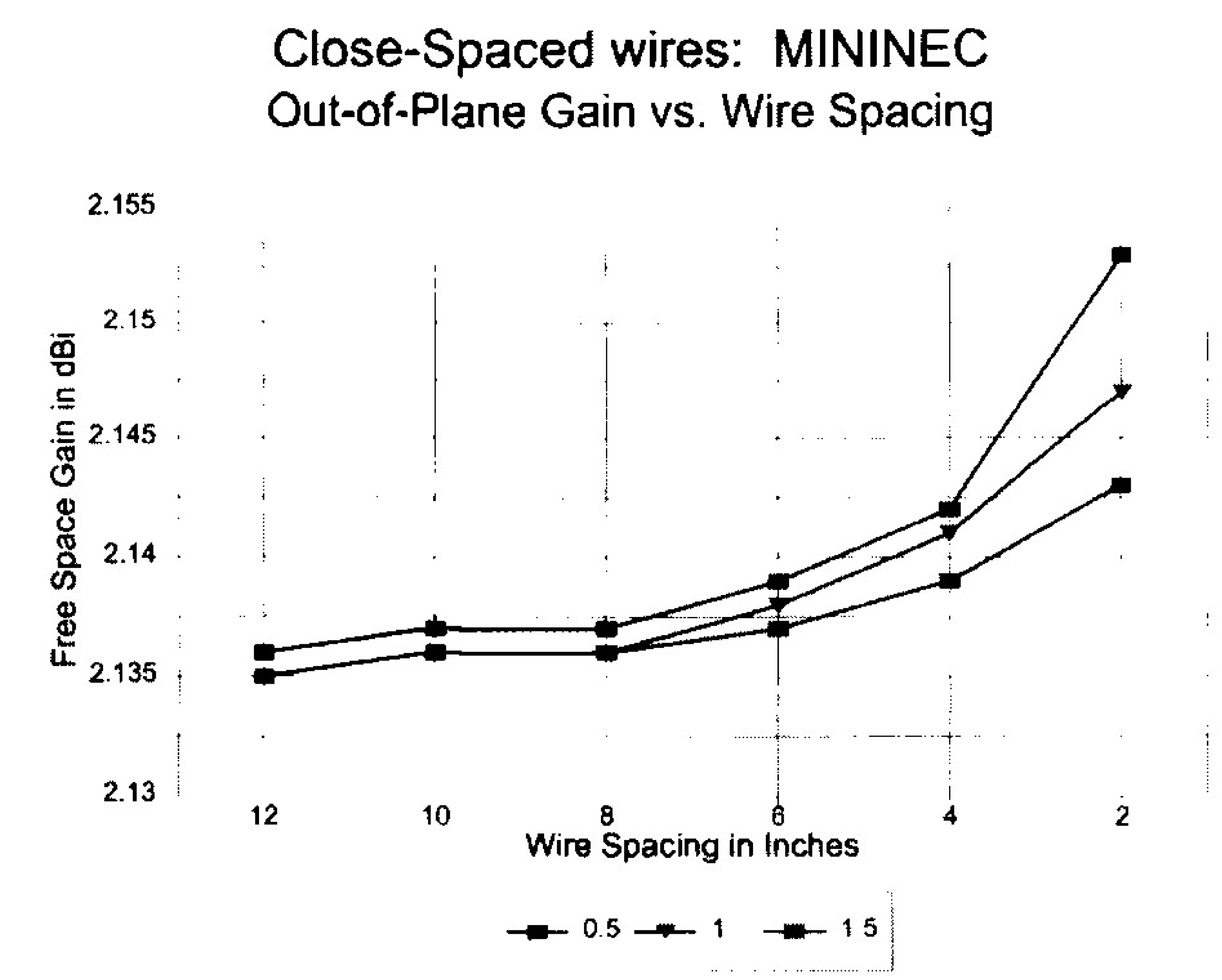

Figure 12—Out-of-plane gain of close-spaced wires—*MININEC*.

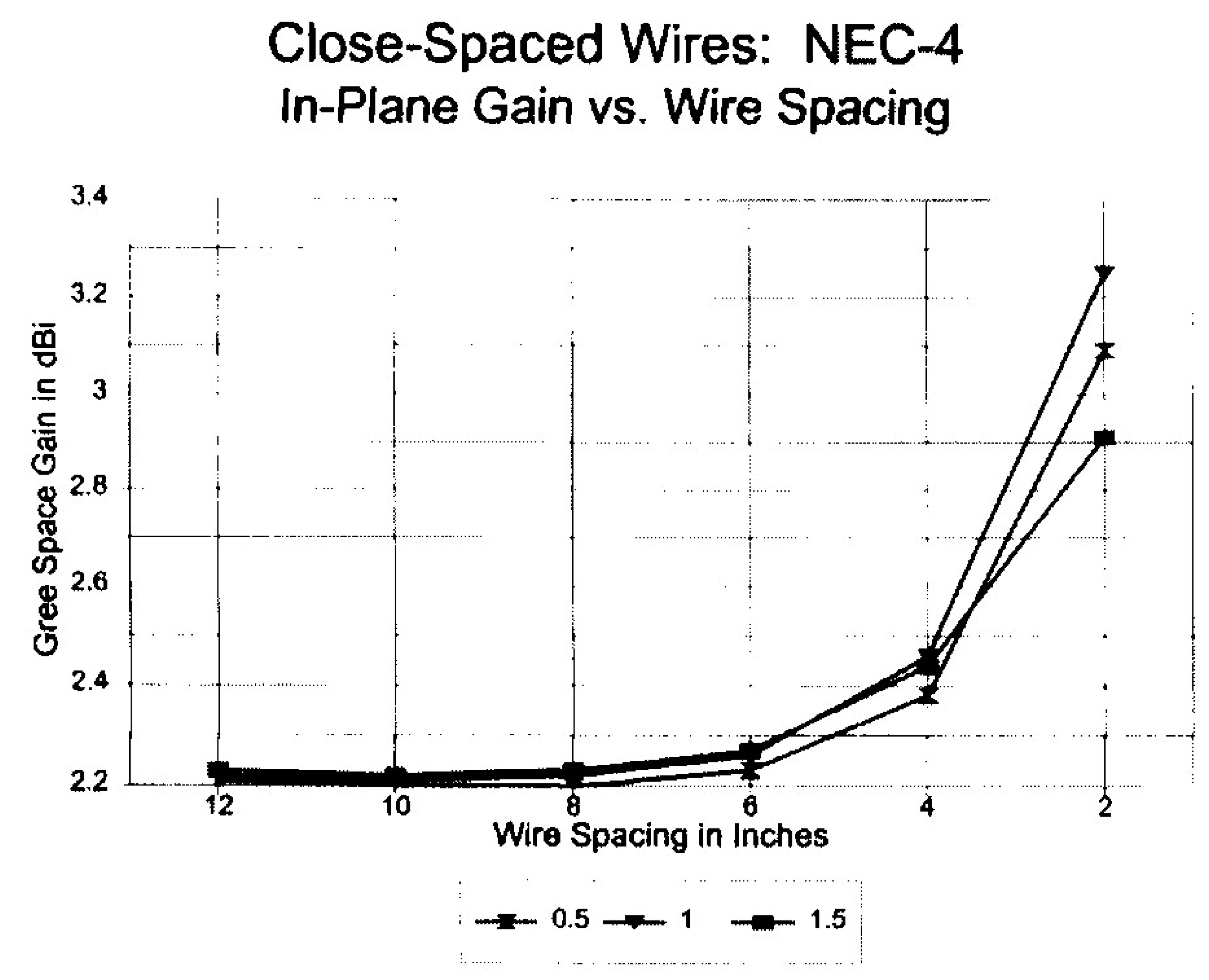

Figure 13—In-plane gain of close-spaced wires—*NEC-4*.

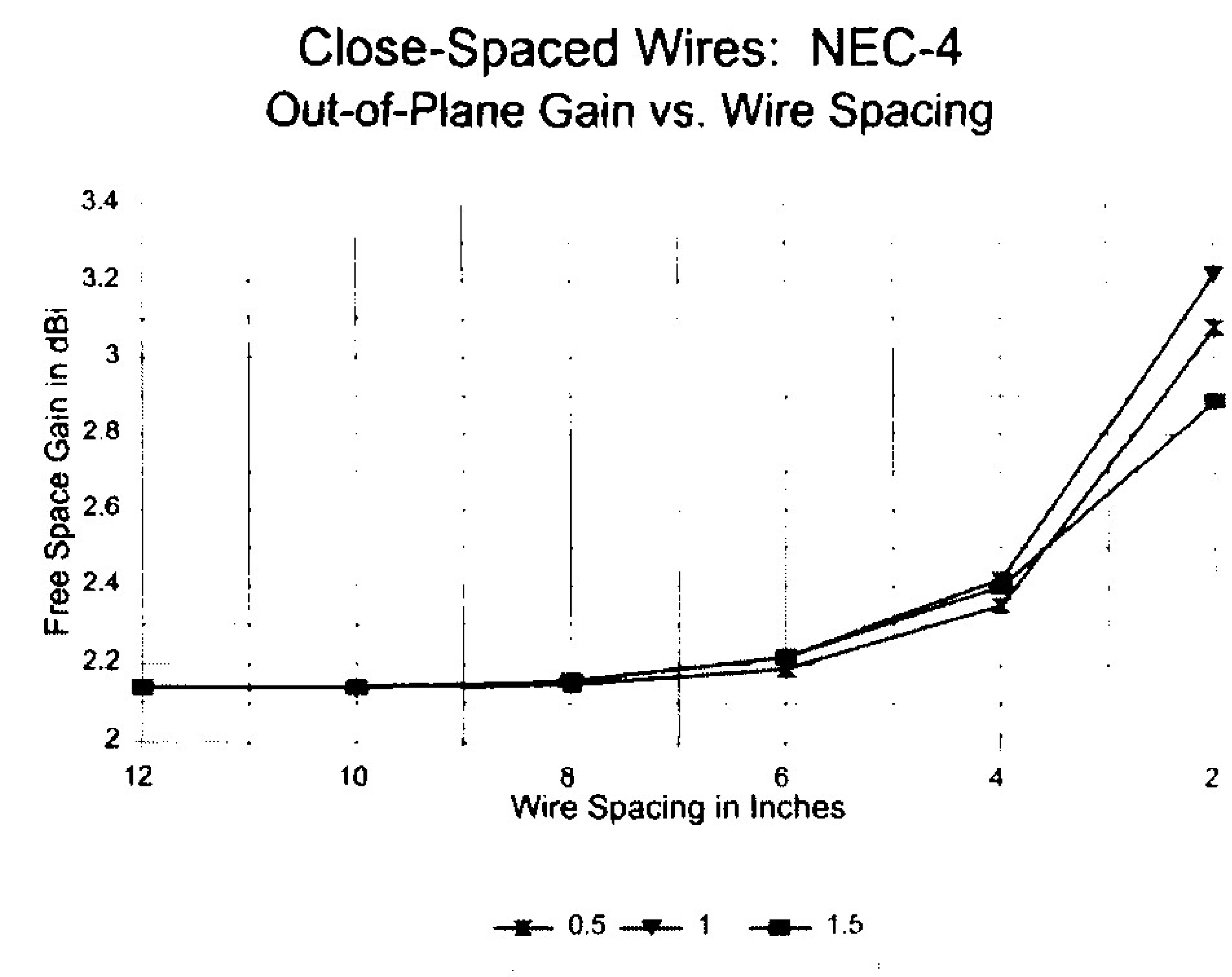

Figure 14—Out-of-plane gain of close-spaced wires—*NEC-4*.

the gain begins a steep increase. To all appearances, the two wires begin at this close proximity to act as a single fat wire. Whatever the true accuracy of the *MININEC* results, they do at least accord with normal expectations for closely spaced wires.

The *MININEC* results acquire a greater degree of confidence when one examines the range of variation. The total in-plane gain variation is less than 0.06 dB, while the out-of-plane gain variation is less than 0.02 dB.

The gain figures encountered with *NEC-4* show a quite different pattern. For example, the in-plane figures, which appear in Figure 13, show an overall increase through the same range of distances separating the two wires. The range of variation between 12 and 6 inch spacing is about 0.04 dB, but over the entire span of separations, the range increases to more than 1 dB.

Equally notable is the fact that *NEC-4* shows the highest gain when the two wires have the same diameter. How exact this equality is cannot be determined by this test, since the secondary wire diameters are widely separated.

A similar curve accompanies the figures for out-of-plane gain in Figure 14. There is a larger spread of gains in the 12 to 6 inch range (0.06 dB), but the overall gain increase with closing separation is greater than 1 dB.

At least for the case at hand, which uses a secondary wire about 66% as long as the fed wire, there appears to be a critical distance at which anomalous results begin to emerge. Figures 15 and 16 compare the in-plane and out-of-plane gains for *MININEC* and *NEC-4* when the elements have the same diameter.

Careful examination of the graphs shows that the curves overlap for spacings of 12 and 10 inches. However, between the 10 and 8 inch marks, the curves begin to diverge ever more radically.

It is also interesting to contrast *MININEC* and *NEC* with respect to the required length of the 14 MHz element for resonance with the 21 MHz wire in close proximity. As

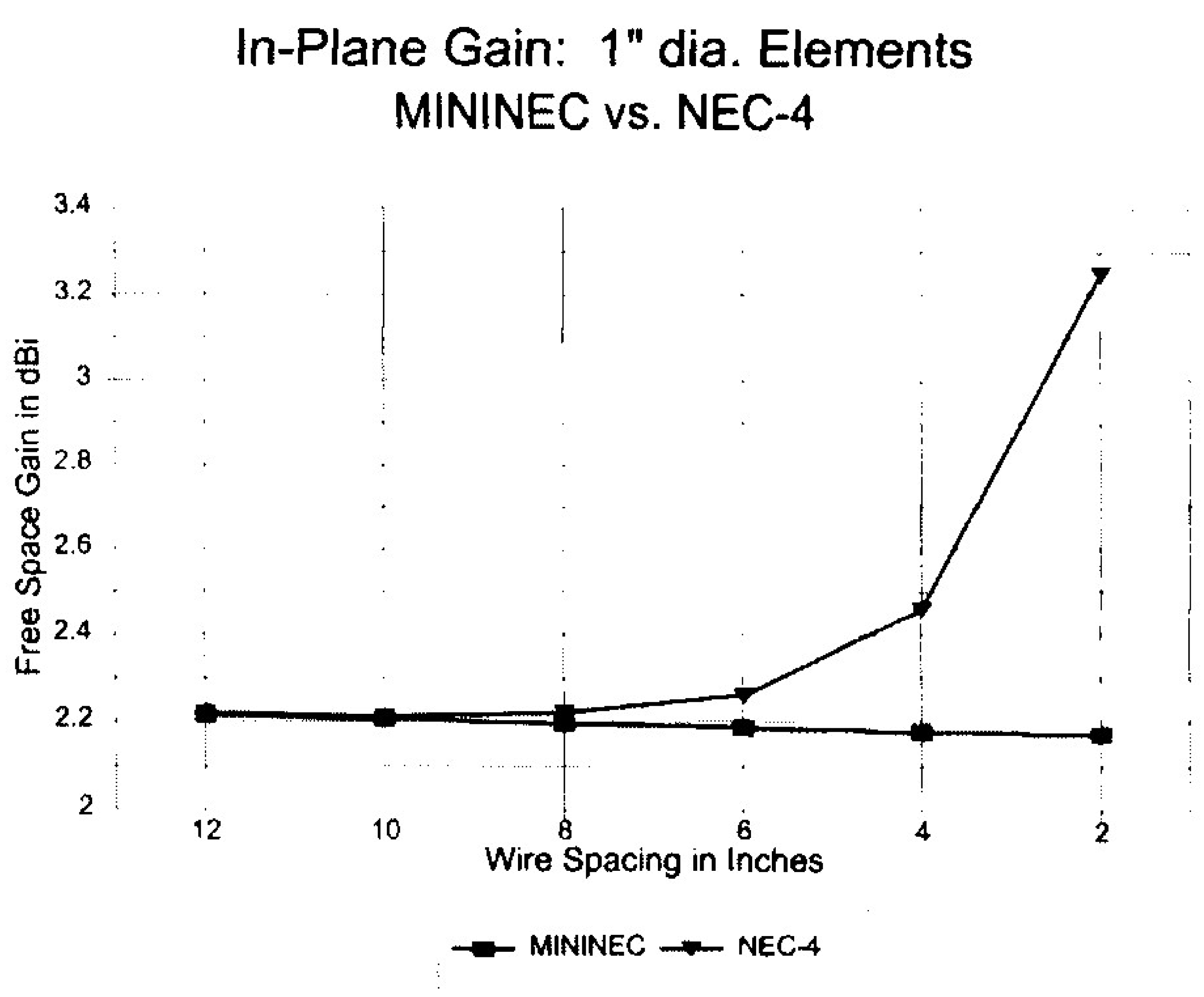

Figure 15—In-plane gain of close-spaced wires—*MININEC* versus *NEC-4*.

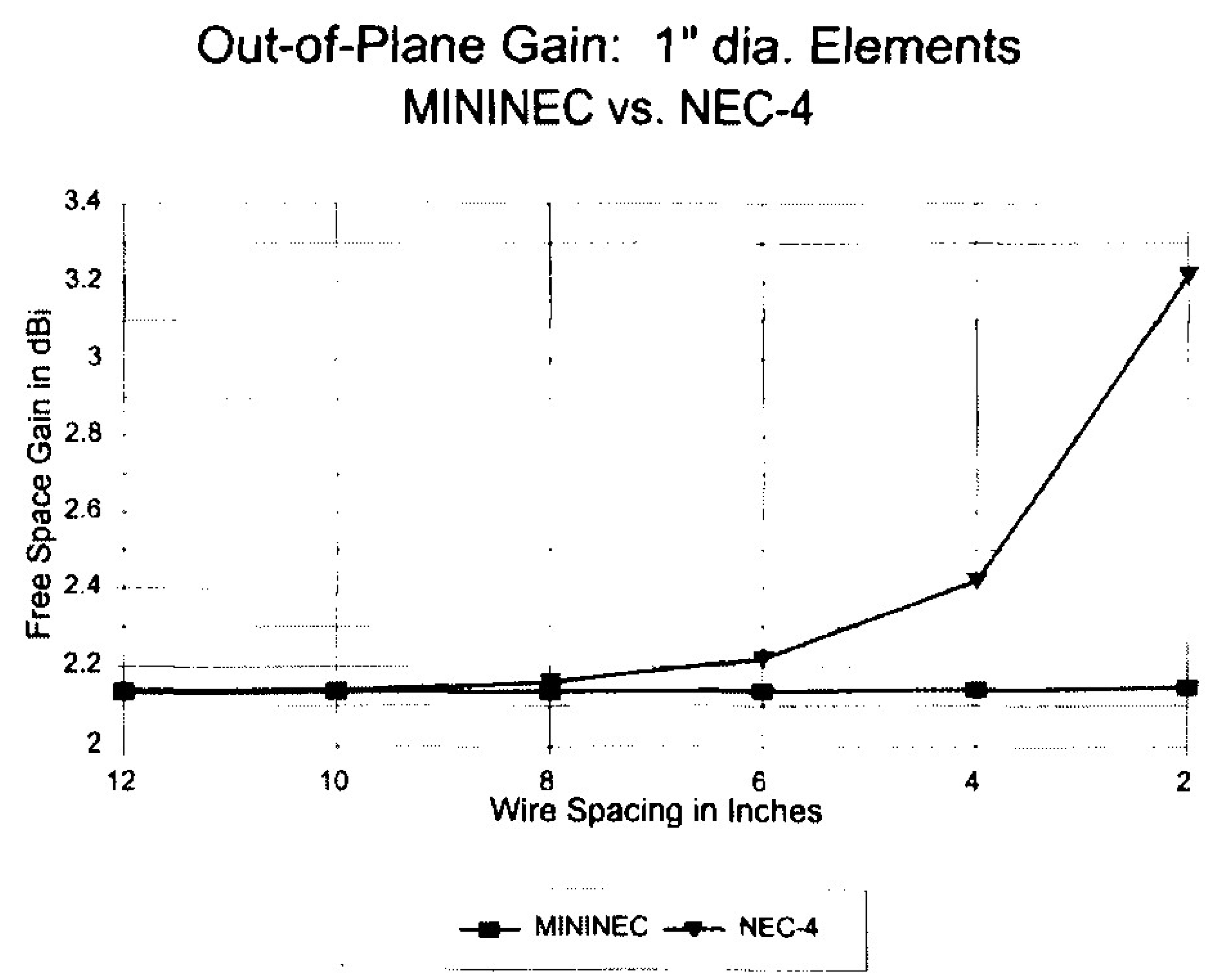

Figure 16—Out-of-plane gain of close-spaced wires—*MININEC* versus *NEC-4*.

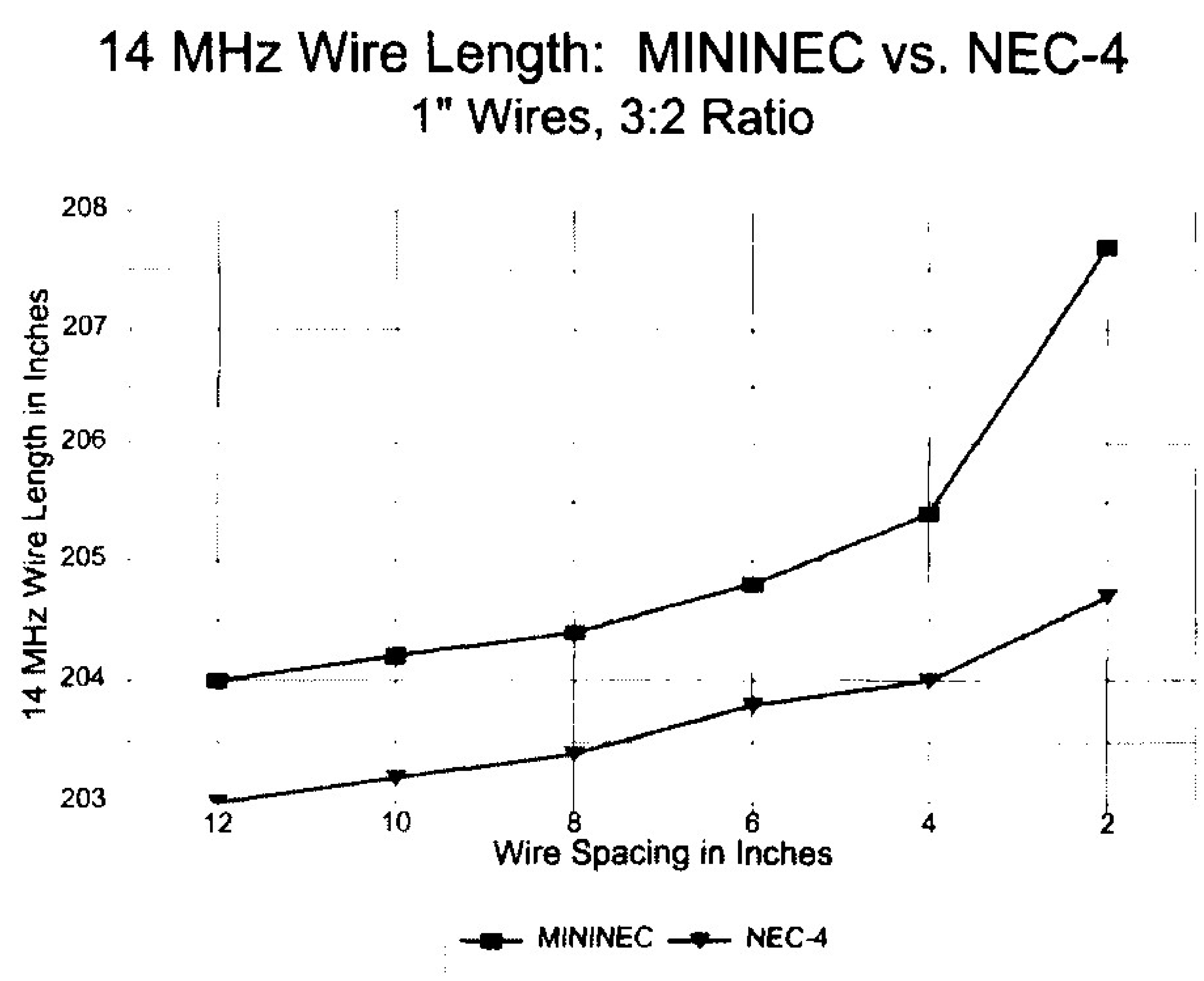

Figure 17—14 MHz wire length—*MININEC* versus *NEC-4*.

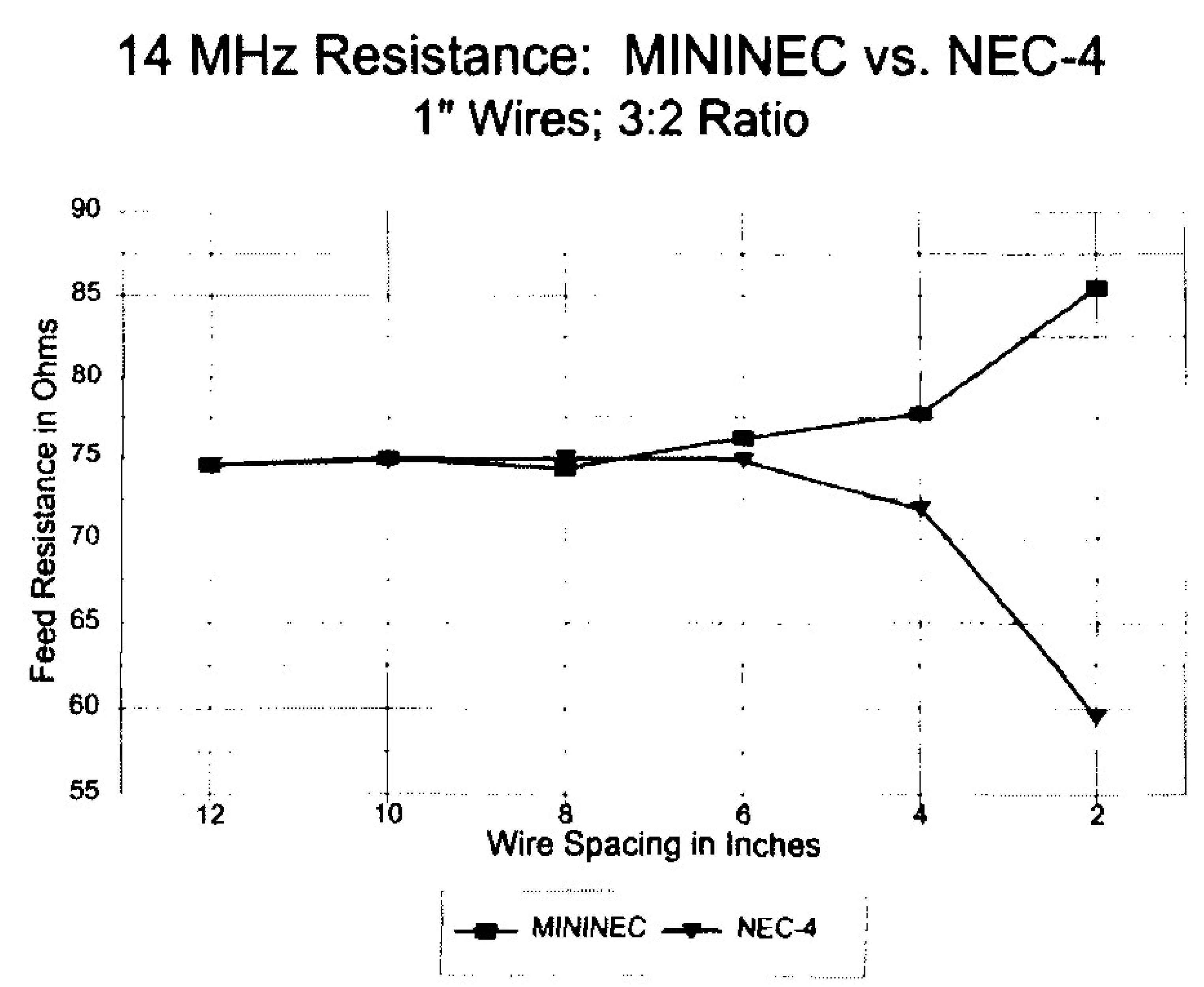

Figure 18—14 MHz resistance—*MININEC* versus *NEC-4*.

Figure 17 shows, once we allow for the slight length variation of the two systems, the *MININEC* curve is much steeper than the *NEC-4* curve at the closest spacings. However, the curve is in fact smoother than the *NEC-4* curve, as the break in the *NEC-4* curve at 6 inches is real and not a function of rounding.

Moreover, there are also interesting differences in the feed-point-resistance curves. As noted, the 14 MHz elements were resonated to less than 1 Ω reactance. In Figure 18, the *MININEC* feed-resistance curve shows a small dip at the 8 inch spacing and then a smooth progression upward. In contrast, the *NEC-4* curve shows a rapid progression downward past the 6 inch point. These same phenomena occurred with scaled VHF antenna models.

These tests are only the beginning of a systematic exploration of the differential in gain and other figures from the *MININEC* and *NEC-4* modeling systems. Here are a few further developments of these tests.

Scaling: Scaling all the dimensions of the situation by a factor of 10 upward (including frequency, lengths and wire diameters) produces curves that tightly fit those produced so far. This applies to both the *MININEC* and *NEC-4* curves. The resonant 140 MHz (0.1 inch diameter aluminum wire spaced from 1.2 to 0.2 inches) offsets from the resonant 14 MHz curves (1.0 inch diameter aluminum wire spaced from 12 to 2 inches) are so slight that they are negligible.

Wire Length Ratios: The 20-meter antenna with a 15-meter wire forms a length ratio of 3:2. A series of *NEC-4* runs compared this scenario to wires with a 2:1 ratio and with a 4:3 ratio, focusing on wires of the same diameter (1 inch aluminum). The results appear in Figure 19.

Interestingly, the departure of the gain from a typical *MININEC* curve is greatest when the fed wire is about 50% longer than the closely spaced unfed wire, at least when the wires have the same diameter. Once more, the widely separated selection of test ratios does not lend precision to this conclusion. Since wires having a 1:1 diameter ratio appear to have a greater departure from typical *MININEC* curves than other wire diameter ratios, it appears that (by chance) my initial tests have fallen into at least the ball park of greatest deviation.

Wire Diameters and Spacing: Just as wire-length ratios may be isolated for specific investigation, so too may be the relationship between wire diameters and spacing. A series of models were undertaken in both *MININEC* and *NEC-4* using a constant 3:2 wire-length ratio between the driven wire and its closely spaced undriven companion. Both wires were assigned the same diameter and checked at the standard 2 inch spacing increments. Wire size was varied through aluminum wire diameters of 1.0, 0.5, 0.1, 0.05 and 0.01 inch. A limitation of this test is that, for any spacing, the surface-to-surface distances vary as the wire size is changed.

Figure 20 correlates, for *MININEC* runs, the wire size and gain for 14 MHz dipoles with companion wires about 2/3 as long. Only with the largest wire diameter (1.0 inch) does the figure reveal a graphically detectable departure from otherwise flat results. (Note: The very low gain of the 0.01 inch diameter wire is due largely to the losses associated with using aluminum wire.)

Figure 21 shows the same runs (with wires adjusted in length for resonance) with *NEC-4*. Even with the thinnest wire size used, a graphically evident departure from a relatively constant gain is shown between 8 and 6 inch separations. For fatter wires, the increase in reported gain appears as early as between 10 and 8 inch wire separations. Although the erroneous gain increase report may not be operationally significant in many instances, the trends are at odds with the minimum separation recommendations in *NEC-4* documentation.

Frequency and Spacing: The effects of frequency on gain and feed resistance reported by *NEC-4*, when the wire size is held constant and spacing is varied, are also interesting. Models were constructed using 1 inch aluminum wire, with a 3:2 ratio of driven wire to companion wire lengths for 3.5, 7.0, 14.0, 21.0 and 28.0 MHz. Wire spacing was varied in 2 inch increments from 12 to 2 inches as with preceding models.

Figure 22 shows the reported antenna gain for the models in *NEC-4*. The 80-meter rise is steepest because the spacing represents a smaller fraction of a wavelength. Figure 23 presents the reported feed-point resistance

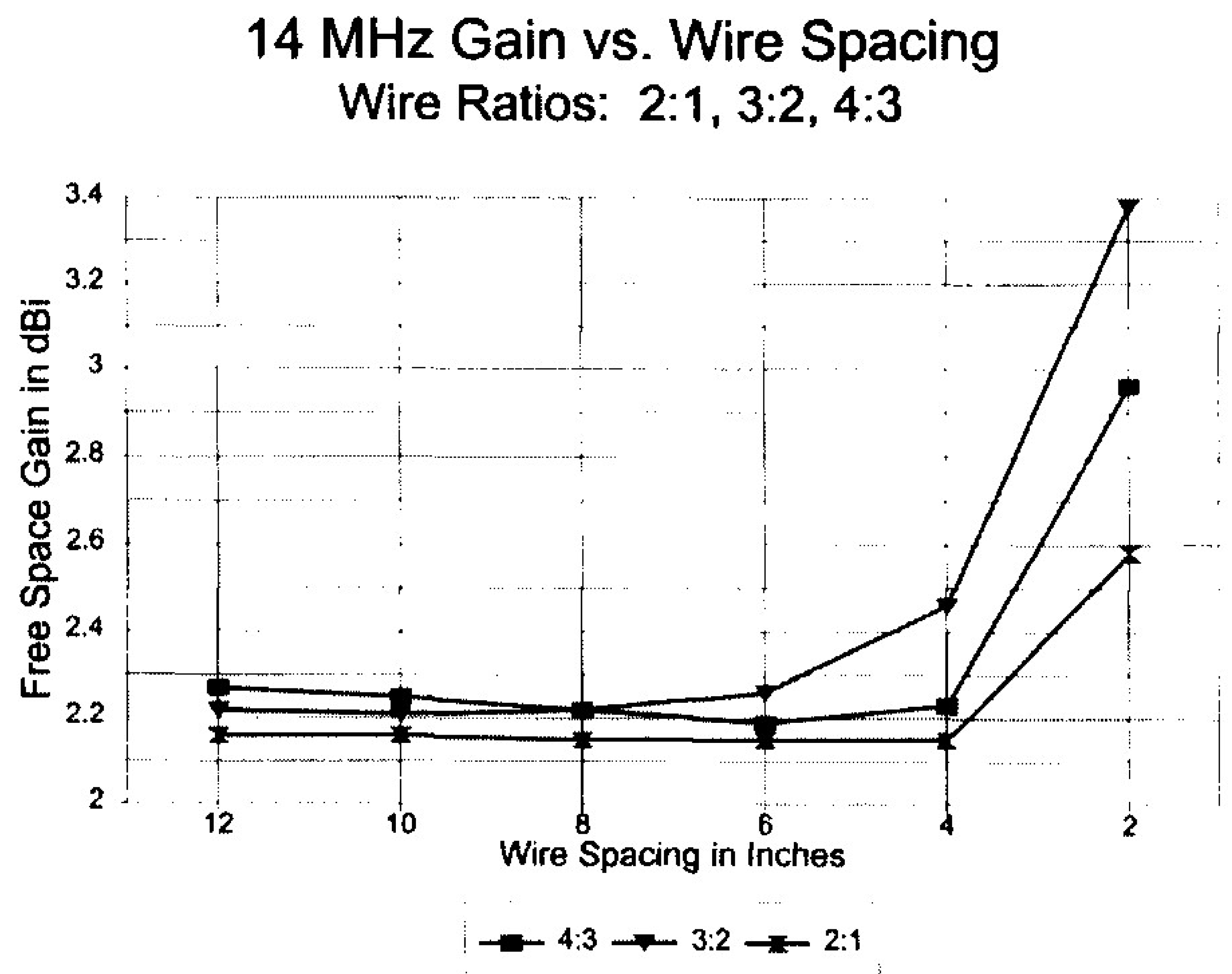

Figure 19—14 MHz gain versus wire spacing for different length ratios.

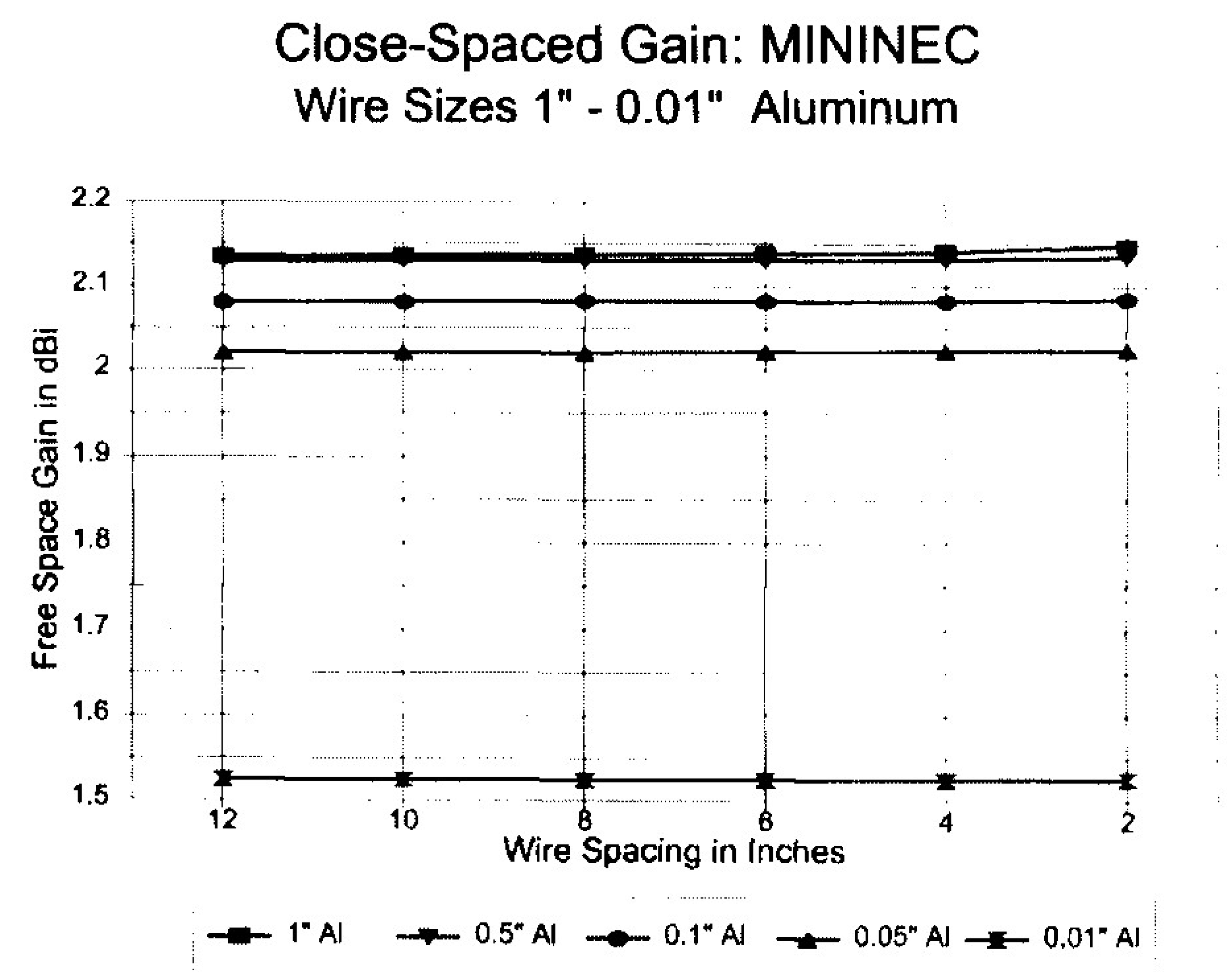

Figure 20—Close-spaced gain for wire sizes from 0.01 to 1.0 inch diameters—*MININEC*.

for each of the resonated models for each frequency and spacing. For all but 28 MHz, the downward curve of reported feed-point resistance is roughly proportional to the rise in reported antenna gain.

The seeming exception is 28 MHz, where the impedance appears to rise continuously. In actuality, there is a knee to each curve. For 3.5 and 7.0 MHz, the knee lies off the graph to the left. For 14 MHz, the knee that shows a higher feed-point resistance than adjoining values is at the 8 inch spacing marker, while for 21 MHz, the knee is visible in the graph at 4 inch spacing of the wires. The knee peak for 28 MHz is approximately at the 2 inch spacing marker, giving the illusion of further rise. However, with closer spacings, the feedpoint resistance may begin to decline. Since a 2 inch spacing is already beyond even the limits recognized by *NEC-4* documentation, the graph was not carried further than the values shown. However, it appears clear that close-spacing phenomena bear a relationship to the fraction of a wavelength that a given spacing represents.

Close Spacing and Multielement Arrays: The effects of a close-spaced wire on a dipole model are only indicators, not predictors of the effect of a close-spaced wire on a parasitic beam model. Indeed, the disparity of gain and other performance figures between *MININEC* and *NEC-4* might well be either profound or quite trivial.

I created a three-element Yagi model to check the potential for divergent readouts. An extra wire was placed ahead of the driven element at the spacing indicated in the tables. The results appear in Table 2.

The table holds some surprises. First, the *NEC-4* gain values diverge more radically than the *MININEC* numbers, especially for the 2:1 ratio of driven element to extra wire. Second, for the 3:2 and 4:3 ratios, *MININEC* and *NEC-4* gain numbers diverge in opposite directions. Nonetheless, the *NEC-4* figures are still farther from the "no-wire" baseline than those of *MININEC*. Third, unlike the simple dipole examples, the gain of some models may decrease in the presence of the extra wire.

Before we draw any conclusions, let me reveal that the above table is erroneous. It is based on a defective model that is nevertheless all too common in amateur modeling practice. All four elements, the three 20-meter elements plus the added wire, whatever its length, were assigned 10 segments in *MININEC* and 11 segments in *NEC-4*. The segments do not align, which is especially important in *NEC*, but significant in *MININEC* with some models. Moreover, neither model converges well with models having twice as many elements. These problems cast doubt on the reliability of the results.

Table 2—Closely Spaced Wires in *MININEC* and *NEC-4* Models of a 3-Element Yagi*

	MININEC			*NEC-4*		
Space (inches)	*Gain (dBi)*	*FB (dB)*	*Z (Ω)*	*Gain (dBi)*	*FB (dB)*	*Z (Ω)*
No wire	8.03	24.97	26.9 + *j*2.1	8.08	27.94	26.6 + *j*4.8
2:1 Ratio						
4	8.02	24.86	26.9 + *j*1.1	8.68	27.81	23.4 + *j*3.4
7	8.03	24.87	27.0 + *j*1.3	8.26	27.84	25.7 + *j*3.9
10	8.03	24.88	27.0 + *j*1.4	8.14	27.85	26.4 + *j*4.1
13	8.03	24.88	27.0 + *j*1.5	8.10	27.86	26.6 + *j*4.2
16	8.03	24.89	27.0 + *j*1.5	8.09	27.88	26.7 + *j*4.2
3:2 Ratio						
4	7.88	24.77	28.0 + *j*0.0	9.35	27.68	20.3 + *j*1.8
7	7.96	24.79	27.6 + *j*0.4	8.61	27.76	24.1 + *j*2.6
10	8.00	24.82	27.5 + *j*0.6	8.33	27.81	25.6 + *j*3.0
13	8.01	24.84	27.4 + *j*0.7	8.21	27.86	26.4 + *j*3.2
16	8.02	24.87	27.3 + *j*0.7	8.15	27.91	26.7 + *j*3.3
4:3 Ratio						
4	8.20	24.74	26.2 – *j*1.0	6.81	27.93	37.7 + *j*3.3
7	8.12	24.78	27.0 – *j*0.5	7.34	27.91	33.1 + *j*3.6
10	8.08	24.82	27.4 – *j*0.3	7.67	27.93	30.6 + *j*3.4
13	8.06	24.87	27.5 – *j*0.2	7.85	27.98	29.2 + *j*3.1
16	8.05	24.91	27.6 – *j*0.1	7.94	28.04	28.5 + *j*3.0

*This table is based on erroneously constructed models. See text for an explanation and see Table 3 for corrected figures.

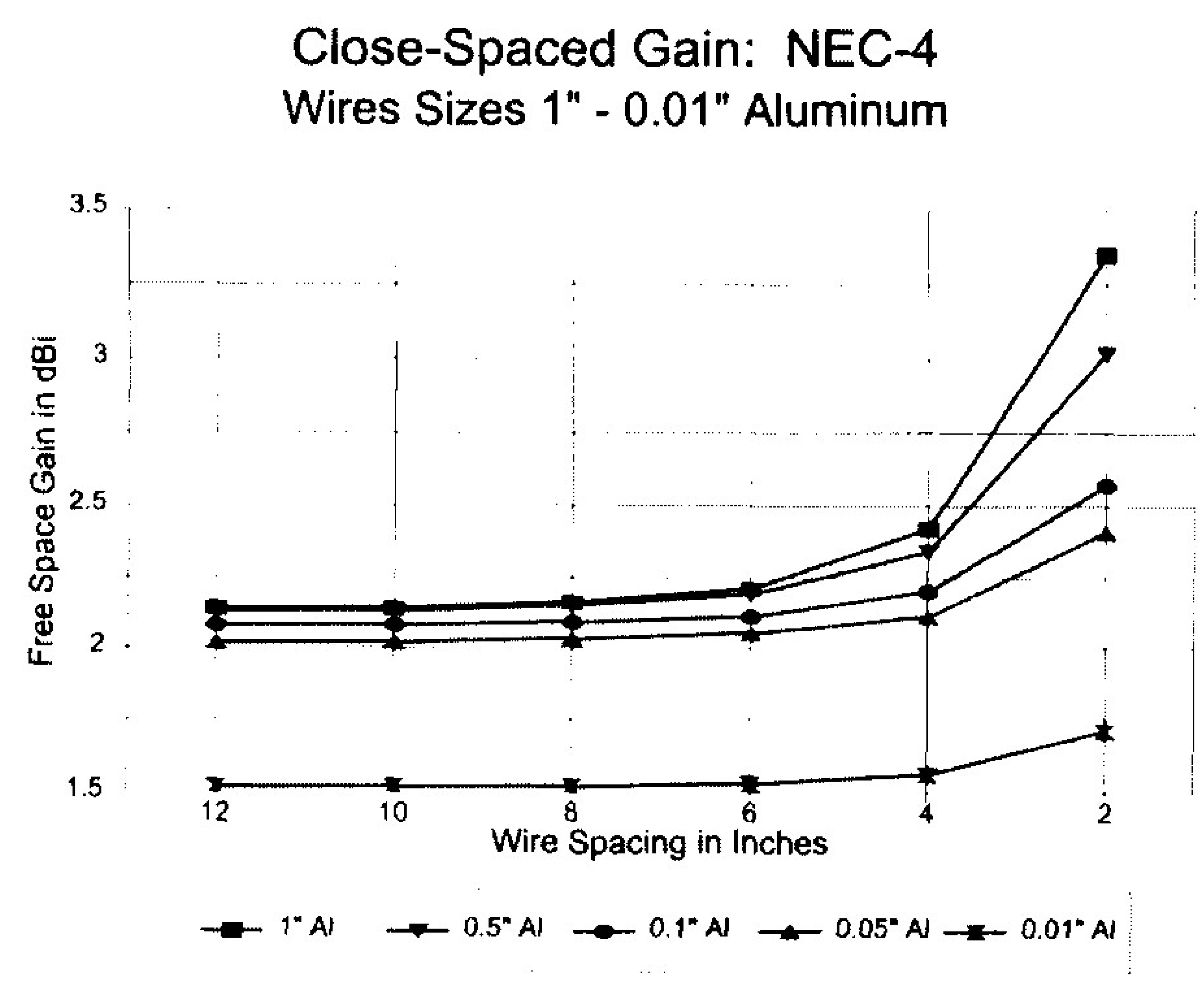

Figure 21—Close-spaced gain for wire sizes from 0.01 to 1.0 inch diameters—*NEC-4*.

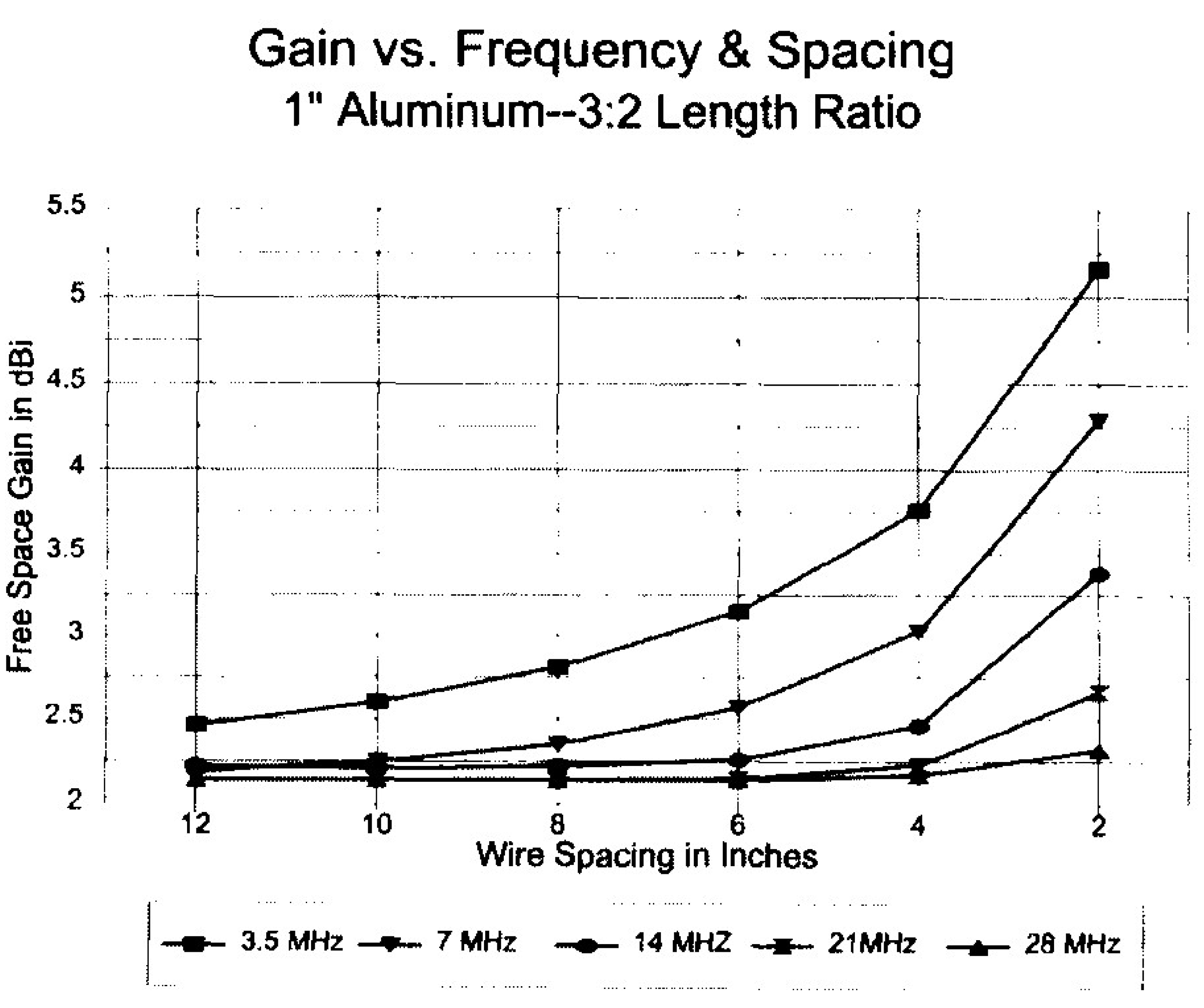

Figure 22—Gain versus frequency and spacing.

So I reset the models, using 34 segments per 20-meter element (35 in *NEC*) and a proportionate number for the shorter extra elements. Convergence with models having twice as many segments was excellent, with a gain difference of about 0.01 dB. Running these models resulted in a change of extra-element spacing, to begin at closest with 3 rather than 4 inches. Despite the closer spacing, interesting results developed, as shown in Table 3.

A comparison of the tables shows two very significant facts. First, when models are developed carefully, rather than casually, any tendencies for a program to deliver potentially erroneous results is lessened. All figures for each length of extra element are far more tightly grouped.

Second, despite the tighter grouping, the same types of curves develop as with the casual model. To two decimal places, *MININEC* results are totally stable, although the third decimal place shows the mathematical progressions that appeared in the earlier model. Likewise, *NEC-4* progressions show increasing gain with closer spacing for the two shorter lengths of extra elements and reduced gain with closer spacing for the longest extra element. In general, the instability with the figures occurs when spacings are closer than 6 to 9 inches at 14 MHz. Maximum deviations from the norm run from 0.2 dB to 0.5 dB for the example used. While less than with the casual model, the amounts of deviation from the normal can be significant, especially when compared to the extremely stable *MININEC* figures.

Conclusion: Each of these directions of research will require many more runs of wire combinations at many different frequencies before precise conclusions and systematic formulations of the *MININEC/NEC-4* differentials can be drawn. Nonetheless, the simple tests performed here are sufficient to suggest strongly that users of *NEC-4* model closely spaced wires with great caution. If *NEC-4* proves to be the anomalous case, then it may not be possible to routinely model closely spaced antenna structures with any presumption of accuracy with respect to resulting gain figures.

As with all such tests, the appearance of results is not a sufficient validation of a modeling system. Nonetheless, it appears safe to note that closely spaced wires modeled in *NEC-4* should always be approached with more caution than confidence.

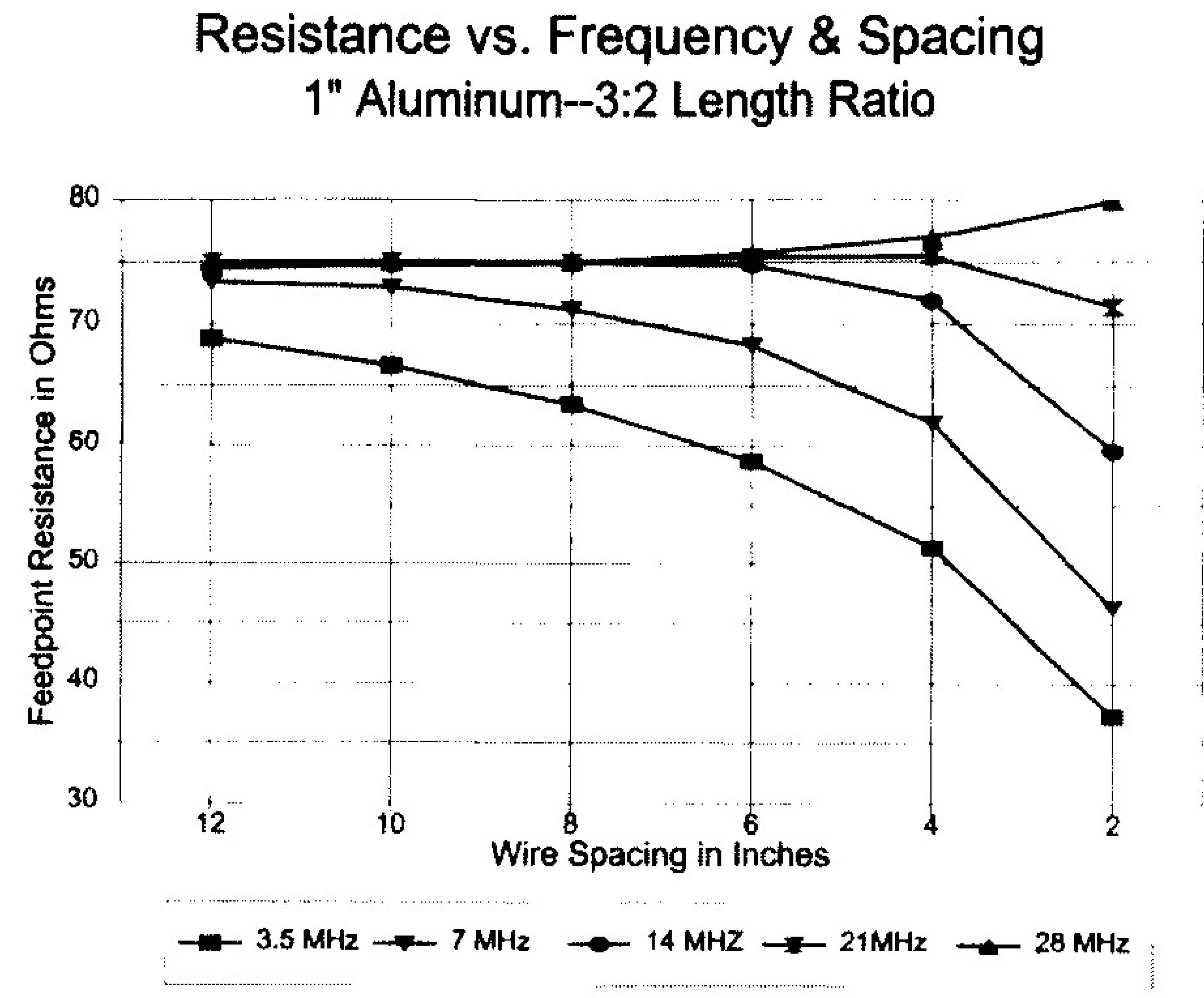

Figure 23—Feed-point resistance versus frequency and spacing.

Table 3 —Closely Spaced Wires in *MININEC* and *NEC – 4* Models of a 3-Element Yagi (Corrected Models)

	MININEC			***NEC – 4***		
Space (inches)	*Gain (dBi)*	*FB (dB)*	*Z (Ω)*	*Gain (dBi)*	*FB (dB)*	*Z (Ω)*
No wire	8.01	26.66	28.4 + *j*5.4	8.12	26.86	26.3 + *j*6.6
2:1 Ratio						
3	8.01	26.64	28.9 + *j*4.1	8.40	26.72	25.0 + *j*5.2
6	8.01	26.65	28.7 + *j*4.5	8.15	26.74	26.4 + *j*5.8
9	8.01	26.66	28.7 + *j*4.7	8.12	26.75	26.5 + *j*6.0
12	8.01	26.67	28.6 + *j*4.8	8.12	26.77	26.5 + *j*6.0
15	8.01	24.68	28.6 + *j*4.8	8.12	26.78	26.5 + *j*5.2
3:2 Ratio						
3	8.00	26.52	29.3 + *j*3.7	8.33	26.62	26.0 + *j*4.1
6	8.00	26.57	29.2 + *j*3.7	8.14	26.66	27.0 + *j*4.9
9	8.00	26.61	29.1 + *j*3.6	8.12	26.69	27.0 + *j*5.2
12	8.00	26.65	29.1 + *j*3.3	8.12	26.73	26.9 + *j*5.3
15	8.00	26.70	29.1 + *j*2.6	8.12	26.76	26.9 + *j*5.3
4:3 Ratio						
3	8.01	26.73	30.0 + *j*1.6	7.40	26.69	33.3 + *j*3.9
6	8.01	26.80	29.8 + *j*2.6	8.03	26.66	28.3 + *j*4.4
9	8.01	26.87	29.7 + *j*2.9	8.10	26.70	27.7 + *j*4.5
12	8.01	26.95	29.6 + *j*3.1	8.11	26.76	27.5 + *j*4.6
15	8.01	27.02	29.6 + *j*3.1	8.12	26.82	27.4 + *j*4.7

Table 4—Single Quad Loops of a Single-Wire Diameter

Antenna	*Output*	*MININEC*	*NEC-2*	*NEC-4*
0.0808" wire	Gain		3.26	3.26
9.146'; 31 segs	Feed Z		126.9 + *j*0.02	126.9 – *j*0.13
0.0808" wire	Gain	3.25	3.26	3.26
9.146'; 61 segs	Feed Z	126.3 – *j*7.93	127.0 – *j*0.27	127.0 – *j*0.69
0.0808" wire	Gain	3.26		
9.146'; tapered	Feed Z	126.0 – *j*3.38		
0.5" wire	Gain		3.37	3.37
9.364'; 31 segs	Feed Z		129.7 + *j*0.21	129.7 – *j*0.10
0.5" wire	Gain	3.36	3.36	3.26
9.364'; 61 segs	Feed Z	129.5 – *j*4.07	130.0 + *j*0.49	129.8 – *j*0.41
0.5" wire	Gain	3.36		
9.364'; tapered	Feed Z	129.1 – *j*0.42		

Two Practical Limitations of *NEC-4* and a Validation Test

The importance of respecting the limitations of *NEC-4* appears in many potential applications to amateur HF (and VHF) antennas, even of relatively standard design. I shall illustrate with just two examples, the latter of which will also comprise a validation of *MININEC* as the more accurate program in these regards.

Wires of Different Diameters Joined at Sharp Angles: A problem in the *NEC-2* calculation engine is the unreliability of results when wires of unequal diameter join at right or acute angles. Although *NEC-4* improves upon this situation, its results are not wholly reliable.

Single Quad Loops of a Single Wire Diameter: The foundation for testing the reliability of *NEC-4* outputs when wires of different diameter join at right angles is the single quad loop. The test employed loop materials of 0.5 inch and 0.0808 inch diameters. When only a single diameter wire is used, all programs perform credibly, as long as models adhere to the antenna geometry criteria of the specific program. All loops were modeled at 28.5 MHz, with copper wire in free space. All loops are square. Dimensions and segmentation are given for one side of the loop. The tapered-segment *MININEC* model employs the internal values of the *ELNEC* program.

Table 4 provides the results of the modeling. The initial models were created in *NEC-4* and tested on *NEC-2* and *MININEC*. A tapered-segment-length model was created in *MININEC* for comparison with the equal-segment models. Convergence of the two *MININEC* models is good for practical purposes, although a slight numerical difference shows.

For the *NEC* models, there is no significant numerical, let alone practical, difference between *NEC-2* and *NEC-4* models. Moreover, and especially significant for this test, there is no significant difference between the values achieved at 31 segments per side and 61 segments per side. Practical convergence of results is achieved at much lower levels of segmentation.

Single Quad Loops with Different Wire Diameters: To test the ability of the programs to handle wires of different diameter joining at right angles, I modeled a single square quad loop. The top and bottom wires were 0.5 inches in diameter, while the vertical wires were 0.0808 inches in diameter. This might be a model of a portable quad loop using tubing for the horizontal members and wire for the vertical pieces, thus allowing the assembly to collapse for transportation.

The initial model was constructed in *MININEC* and then tested in *NEC-2* and *NEC-4*, using 61 segments per side. The *MININEC* model required 10.15 foot side lengths to approach modeled resonance. Table 5 shows the modeling results.

The *MININEC* model converges well with its tapered alternative model. However, the *NEC* models diverge in values. Although the gain values are plausible, the feed-point impedance values indicate a condition far from resonance. The divergence from *MININEC* is worse for *NEC-2* than for *NEC-4*, suggesting that the *NEC-2* figures are least reliable. Since there is no simple theoretical calculation with which to compare the overall results, one cannot claim that *MININEC* qualifies as a standard against which to measure the other programs. However, given *MININEC*'s ability to handle wires of different diameters in other contexts and the general trend of *NEC-4* results under such conditions to be closer than *NEC-2* results to the *MININEC* figures, it seems likely that *MININEC* may yield outputs that are closest to reality among the three.

The *NEC-4* model with 61 segments per side can be brought closer to resonance by shortening each side to 9.94 feet. This figure might seem equally reliable with the *MININEC* lengths of 10.15 feet per side, except for one significant factor: The *MININEC* figures achieve convergence, while the *NEC* figures do not, especially with respect to feedpoint impedance. I ran the revised *NEC-4* model through various segmentations ranging from 21 to 121 segments per side. In Table 6, "ΔR" and "ΔX" indicate changes in the feed-point impedance values from the preceding level of segmentation.

The values for gain are well converged, but those for feed-point impedance are not. Compare, for example, the differences among figures for 31 and 61 segments per side for the equal-diameter wire loops, using either the 0.0808 or 0.5 inch models. *NEC-4* varies by only 0.1 Ω resistance and under 0.5 Ω reactance across that spread. With the present unequal wire-diameter loop, the same difference in segmentation yields a difference of 2.8 Ω resistance and 10.991 Ω reactance, a +200% difference for each output figure.

Moreover, the progression of values shows no signs of closure within the limits of practical modeling. Although there is a trend downward in the delta numbers, where closure will occur remains unclear. Without convergence, the figures cannot be regarded as reliable.

Table 5—Single Quad Loops of Different Wire Diameters

Antenna	*Output*	*MININEC*	*NEC-2*	*NEC-4*
10.15' sides	Gain	3.61	3.57	3.60
61 segs/side	Feed Z	137.2 – *j*5.71	175.4 + *j*140	150.3 + *j*44.3
10.15' sides	Gain	3.61		
tapered segs	Feed Z	136.7 – *j*2.30		

Table 6—Revised NEC-4 Model of a Quad Loop Using Different Wire Diameters

Segments Per Side	*Gain (dBi)*	*Feed-Point Impedance (Ω)*	*ΔR**	*ΔX**
21	3.54	133.4 – *j*13.280		
31	3.54	134.5 – *j*9.375	1.1	3.905
41	3.53	135.5 – *j*5.589	1.0	3.786
51	3.53	136.4 – *j*1.943	0.9	3.646
61	3.53	137.3 + *j*1.616	0.9	3.559
71	3.53	138.3 + *j*5.119	1.0	3.503
81	3.53	139.2 + *j*8.663	0.9	3.544
91	3.53	140.0 + *j*11.880	0.8	3.217
101	3.52	140.9 + *j*15.36	0.9	3.48
111	3.52	141.7 + *j*18.57	0.8	3.21
121	3.52	142.4 + *j*21.60	0.7	3.03

*See text for an explanation of ΔR and ΔX.

Conclusions and Implications: Because there is no independent standard at hand against which to measure the modeled results, the *MININEC* figures for the single quad loop cannot be certified as in fact closer to reality than those yielded by *NEC-4* for antennas constructed of different-diameter wires joining at right angles. However, *MININEC*'s achievement of reasonable convergence of results and *NEC-4*'s inability to achieve converged results suggests that the *NEC-4* results are less trustworthy than those of *MININEC*. *NEC-2* figures are most divergent and least reliable of the three modeling calculation engines.

It is clear that *NEC-4* will yield lower gain numbers and higher feed-point values than *MININEC* for a loop of a given size. Otherwise expressed, *NEC-4* will call for a loop of smaller dimensions to approach resonance.

These trends also apply to other antennas using wires of different diameters joining at right and acute angles. Models of folded X-beams show lesser gain and greater feed-point values on *NEC-4* than on *MININEC*.

Given the limitation of *NEC-4* with respect to parallel wires of different diameters, it is probable that the present limitation of *NEC-4* is an extension of the same root mechanism. Therefore, it is likely that *MININEC* remains the modeling engine of choice for antennas employing angular junctions of different-diameter wires.

Folded Dipoles: As a final test of *NEC-4* limitations, let us turn to even more compact closed antenna geometry—the folded dipole. Because the characteristics of the folded dipole are so well known, it is possible to calculate in advance the feedpoint impedance of a folded dipole using antenna wires of any ratio. This will provide a test of whether the presumed greater accuracy of *MININEC* in cases of the order discussed here is, in fact, justified.

Equal Diameter Folded Dipoles: The actual test consists of modeling a folded dipole. A folded dipole, where the long parallel wires have the same diameter, effects an impedance transformation of 4:1 for any spacing within reason. Thus, the anticipated feed-point impedance should be in the region of 288 Ω (72 × 4). Since folded dipoles also act like fat wires and are thus shorter at resonance than single-wire dipoles, the anticipated modeled feedpoint impedance was slightly lower than the theoretical calculation. The modeled folded dipoles used 0.5 inch diameter elements spaced 0.25 foot (3 inches).

MININEC tends to chop corners and give erroneous results unless one of two procedures is followed:

One may use as many segments as the program allows to minimize the size of the corner chopped.

One may taper the segment lengths approaching the corner so that corner segments are small while the overall segment count is held to a practical minimum.

The basic *MININEC* folded dipole used 66 segments longitudinally and 2 segments at the ends. *NEC* models added one segment to each longitudinal wire to maintain parallel segmentation. Tapered *MININEC* models used the internal segmentation values of the *ELNEC* program. Since these produced eight-segment midlength wires, the *NEC* models added one segment to this section to satisfy the need for an odd number of segments for center feeding. Finally, a more highly segmented model, using 120 segments per longitudinal wire was created to equalize the segment lengths with those of the 2-segment end wires. This last model was not adjusted for resonance.

Table 7 shows the modeling results. In practical terms, all programs do a satisfactory job of modeling a simple folded dipole when both wires have the same diameter. When sufficient segments are used in *MININEC*, tapering proves less accurate, assuming that the balance of results represents a consensus close to reality.

Systematically, *NEC-4* shows slightly lower feed-point impedances for these closed models than does *NEC-2*. Nonetheless, when all wires have the same diameter and other modeling geometry guidelines are met, all modeling programs give equally usable results.

Unequal Diameter Folded Dipoles: When the wires of a folded dipole differ in diameter, they effect (relative to a single-wire dipole) a different feed-point impedance-transformation ratio than do folded dipoles with equal diameter wires. The theoretical impedance transformation ratio is given by

$$R = \left(1 + \frac{\log \frac{2s}{d_1}}{\log \frac{2s}{d_2}}\right)^2 \qquad \text{(Eq 1)}$$

Where R is the impedance transformation ratio, s is the wire spacing (center-to-center), d_1 is the diameter of the fed wire and d_2 is the diameter of the second wire, and where s, d_1 and d_2 are given in the same units.

If we use a wire 0.0808 inch in diameter (#12 AWG) for the fed wire and a wire 0.5 inch in diameter for the second wire, maintaining the 3 inch spacing, then the impedance transformation ratio will be approximately 7.47. A folded dipole of this construction would have a calculated feed-point impedance of about 533 Ω. In practice, due to "fat wire" effect, we might expect a feed-point impedance slightly lower than this.

It should be noted that the impedance-transformation equation does not account for the end wires. In this

Table 7—Equal Diameter Folded Dipoles

Antenna	*Output*	*MININEC*	*NEC-2*	*NEC-4*
FD: equal seg	Gain	2.22	2.22	2.22
16.1'; 66/2×2	Feed Z	285.7 + *j*0.90	285.9 + *j*4.10	285.8 + *j*3.99
FD: tapered	Gain	2.21	2.21	2.21
16.06'	Feed Z	281.0 – *j*0.68	284.2 + *j*9.87	284.0 + *j*8.66
FD: equal seg	Gain	2.22	2.22	2.22
16.1'; 120/2×2	Feed Z	285.8 – *j*1.80	286.0 + *j*2.27	285.8 + *j*0.51

Table 8—Unequal Diameter Folded Dipoles

Antenna	*Output*	*MININEC*	*NEC-2*	*NEC-4*
FD: equal seg	Gain	2.21	0.69	1.59
16.2'; 66/2×2	Feed Z	530.5 + *j*1.47	375.2 + *j*25.8	462.6 + *j*17.4
FD: tapered	Gain	2.21	0.37	1.22
16.2'	Feed Z	526.5 + *j*10.8	347.2 + *j*38.5	423.4 + *j*37.5
FD: equal seg	Gain	2.21	0.56	1.53
16.2'; 122/2×2	Feed Z	527.6 – *j*2.99	364.1 + *j*25.1	456.0 + *j*15.43

test, the end wires were also 0.0808 inch in diameter.

If either version of *NEC* can handle parallel wires of differential diameters, then the results should coincide reasonably with those of *MININEC*, which takes such cases in stride. The test used models of similar construction to those for equal-diameter folded dipoles. A basic model used 66 segments per longitudinal wire and two segments per end wire; and a tapered-segment version of the antenna was created using internal tapering values. The results appear in Table 8.

The *MININEC* models clearly come very close to expectations. Since the tapered model was not adjusted to resonance, its values are lower, but the large equal-segmented model is likely more accurate.

NEC-2 models of parallel wires of different diameters (as has been well established) produce highly erroneous values. Tapering throws the values even farther off the mark. Although somewhat better, *NEC-4* values are also highly unreliable. Moreover, reducing segmentation of the *NEC-4* models produced nothing reliable. An autosegmented model at conservative minimums of 11 segments for the longitudinal wires and one segment each for the ends yielded a gain of 1.82 dBi and a feed-point impedance of $443.8 + j39.6\ \Omega$. Further reducing segmentation to the absolute minimums of five segments per long wire and one segment per short calculated a gain of 2.64 dBi and a feed-point impedance of $371.3 + j26.07\ \Omega$.

Conclusions and Implications: Because the behavior of a folded dipole is well-established and easily predicted, the antenna forms a very good test of the present modeling question—the adequacy of *NEC-4* to deal with parallel wires of unequal diameters. The conclusion is that *NEC-4* remains deficient in this regard, and antenna modelers are duly cautioned.

The inadequacy of *NEC-4* to model this situation casts doubts on a number of possible modeling challenges. For example, modeling gamma and Tee matching sections as physical elements contributing to the radiation pattern as well as effecting an impedance transformation is now dubious. Direct physical modeling of phasing lines and other close-spaced structures with closed geometries or variations in wire sizes at junctions will generally not yield reliable results for HF antennas unless validated by comparison with comparable *MININEC* models. There are alternative means of modeling some structures using the network input card or transmission lines. Moreover, careful construction of substitute models may yield results that can be tested against *MININEC* models. However, direct physical modeling of such structures often pushes *NEC-4* beyond its limits of reliability.

For situations with parallel wires of unequal diameter, close-spaced wires, or unequal diameter elements with large changes in diameter between wires, *MININEC* remains the modeling program of choice, despite its other limitations.[11] These other limitations are as important to respect as those we have uncovered in *NEC-4*.

Notes

[1]For a short history of antenna modeling software, see R. P. Haviland, W4MB, "Programs for Antenna Analysis by the Method of Moments," *The ARRL Antenna Compendium* (1995), pp 69-73.

[2]*NEC-4* is a proprietary code of the Lawrence Livermore National Laboratory, University of California, from whom a user-license must be obtained. Export restrictions apply. To obtain a user-license, contact Gerald J. Burke, L-156, Lawrence Livermore National Laboratory, PO Box 5504, Livermore, CA 94550. The price of the license is $850 ($150 for an approved educational site). There are only two commercial programs covering *NEC-4* available currently. One source is Roy Lewallen, W7EL. *EZNEC Pro* has an option for *NEC-4* (*EZNEC/4*), if the purchaser has a confirmed license for *NEC-4* ($600). The second source is Nittany-Scientific's *GNEC*, which is scheduled for appearance before you receive this article. The price is $795. Contact information for each of these sources was provided in my earlier article, "*NEC* and *MININEC* Antenna Modeling Programs: A Guide to Further Information," *QEX*, Mar/Apr 1998, pp 47-49.. All modeling for this article was initially done in *EZNEC Pro*, with confirmation models developed on a beta version of *GNEC*.

[3]The fundamental document for *NEC-4* users is Gerald J. Burke, *Numerical Electro-magnetics Code—NEC-4: Method of Moments*, UCRL-MA-109338 (LLNL), 1992. The manual appears in three parts: I. *NEC* User's Manual; II. *NEC* Program Description—Theory; and III. *NEC* Program Description—Code. References here will be confined to Part I, which we shall abbreviate *NEC-4-I* in further notes.

[4]The limitations noted so far appear in *NEC-4-I*, pp 3-4.

[5]Roy Lewallen, W7EL, *EZNEC Pro* (User's Manual, 1997), p 52.

[6]*NEC-4-I*, p 4.

[7]*NEC-4-I*, p 195.

[8]*YA*, a specialized version of *Yagi Optimizer*, by Brian Beezley, K6STI, is distributed with current editions of *The ARRL Antenna Book* (ARRL), 17h and 18th editions.

[9]Details of these initial studies appear in notes titled "*NEC-4* versus *NEC-2* with Stepped-Diameter Correction and Auto-segmentation," available at my Web site, along with numerous other entries from my antenna notebooks. **http://funnelweb.utcc.utk.edu/~cebik/radio.html.**

[10]*NEC-4-I*, p 4.

[11]Although *MININEC* 3.13 is public domain and the calculating engine behind numerous implementations, commercial versions may show variations in output data due to the inclusion of different correction algorithms. For example, *AO*, by K6STI, contains a frequency correction to align *MININEC* results with those of *NEC-2*. *ELNEC*, by W7EL, contains a parallel-wire correction factor. *NEC4WIN*, to the best of my knowledge, contains no correctives. *MININEC Pro* is a new proprietary version of *MININEC* by Rockway and Logan that is said to overcome many limitations of public domain *MININEC*, but I have not yet calibrated the program against others. Sources of these programs were provided in *QEX* (Mar/Apr 1998, pp 47-49). For the exercises involving *MININEC*, *ELNEC*, with the parallel wire corrector in operation, was used throughout for ease of input file transfer to *EZNEC Pro* and from there to *GNEC*.