What Can We Expect from a 2-Element Beam?

Part 3
Shortened Dipoles and Capacity Hat Yagis

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There are two very general ways in which we may shorten a linear element and maintain resonance or some other desired property. One method is to add in one form or another inductive reactance to the capacitively reactive shortened element. The two most popular positions for placing inductive reactances are at the element center and somewhere outward from the center position. We normally use a single inductive reactance when we center-load an element. However, mid-element-loading requires 2 equal reactances placed equally distant from the element center.

The second form of achieving shorter but still resonant elements is to add hats at the element ends. Although we shall examine only symmetrical hats, it is also possible to use non-symmetrical structures, including lengths of wire compressed into a solenoid configuration. Since there are more forms of center- and mid-element-loading than of hats, let's begin with the hat.

Shortened Yagis with Capacity Hats

No 2-element driven-element-reflector Yagi with shortened elements can achieve the gain of a full-size Yagi of the same configuration over an extended bandwidth. However, a shortened Yagi often achieves a significantly higher front-to-back ratio than its full-size counterpart.

There is one seeming exception to these principles: the shortened Yagi "loaded" at the element outer ends with so-called capacity hats. The exception is an illusion, because the hatted dipole is not loaded in the conventional sense. Rather, the main linear element section is shortened and the remaining length is composed of a symmetrical array of wires that is at right angles to the linear section and whose net radiation is at or near zero. **Fig. 1** illustrates the hat-loaded dipole, and shows several configurations of hats.

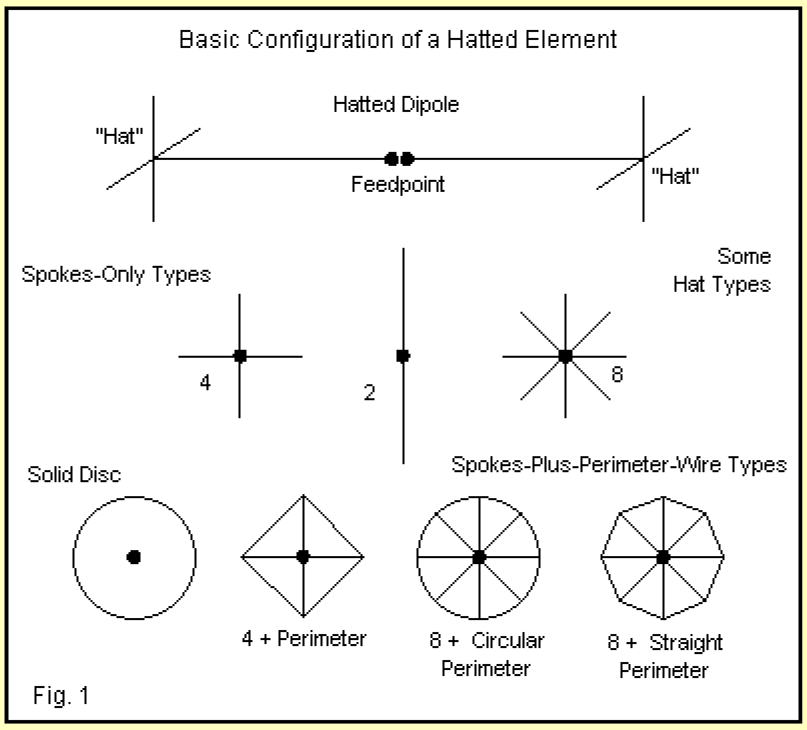


Fig. 1

Hats that use spokes alone require a larger radius than when the same number of spokes are terminated by a perimeter wire. Essentially, the perimeter wire continues each spoke in two directions, so that the zero-current point is midway between two spoke tips. With or without a perimeter wire, we require shorter spokes as we increase their number. Once we reach about 60 spokes, the length decrease ends, since the structure effectively simulates a solid disc.

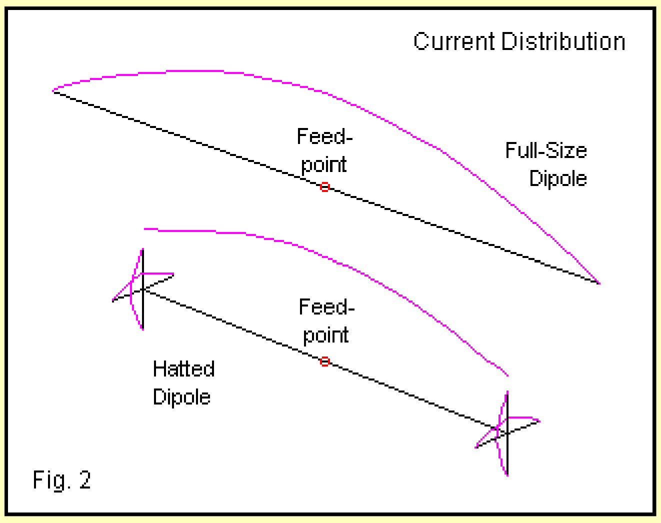


Fig. 2

Fig. 2 compares the current distribution along a standard full-size dipole and a hatted dipole that is about 70% full-size. Both antennas use 3/8" diameter aluminum elements throughout. Current along the linear section of the hatted dipole at the point where the hat begins is the same as it would be on a full-size linear element at the same distance from the feedpoint. The current divides among the wires of the hat array, and the hat array must be large enough to permit the element to reach resonance at the same frequency as the full-size element. The two assemblies in **Fig. 2** are 16.24' and 11.33' long, respectively for the full-size and the shortened antennas. The 4 spokes on the two ends of the hatted dipole are each 12" long.

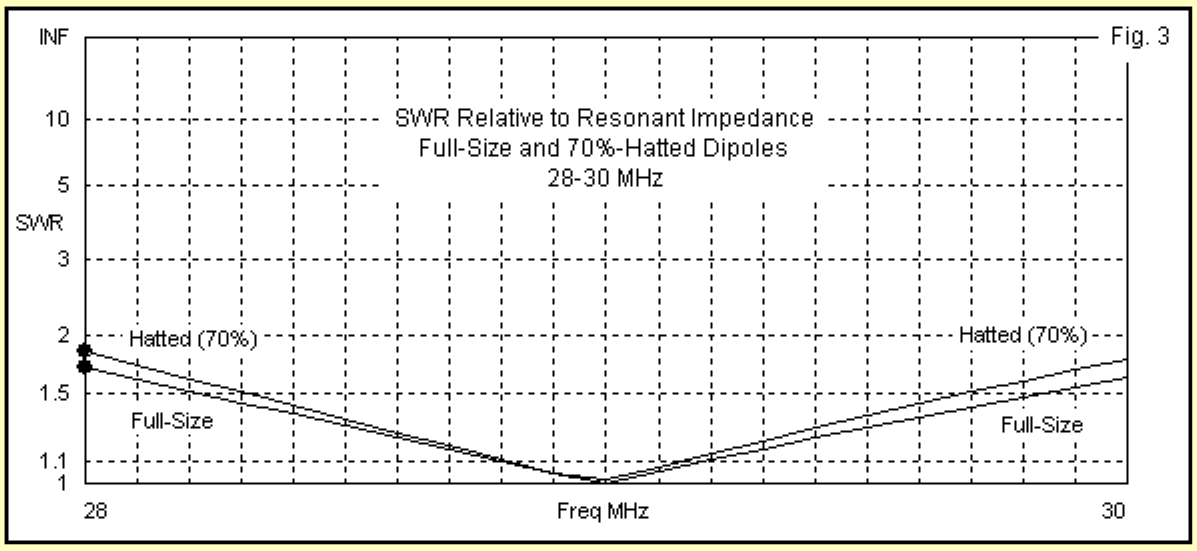
Under these conditions, the performance of a full-size dipole and a shortened, hatted version will be very similar, at least with shortening no greater than about 70% of full size. Since the distribution of current along the dipole element is roughly (but not perfectly) sinusoidal, most of the current contributing to the antenna radiation pattern occurs along the linear section of the elements and very little in the hat arrays.

Modeling an element-end hat is not so problematical in NEC as modeling closely spaced wires of complex geometries. Because the net radiation from a hat is zero, interactions with the main element that might make results unreliable when adjacent segments differ in diameter are minimized. NEC hat models correspond very closely with those created with MININEC. The potential slight differences are minimized in this exercise by making the hat wires of the same diameter as the main element: 0.375 inch.

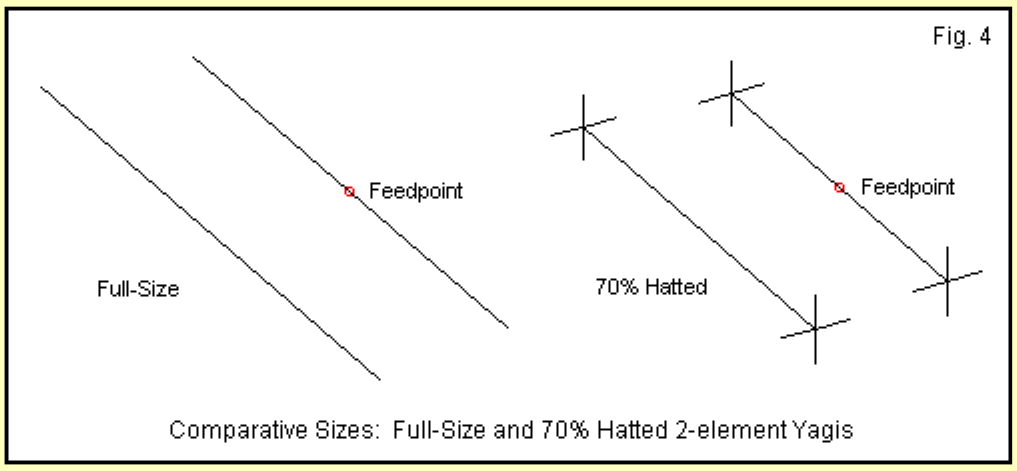
Table 1. A comparison between a full-size and a 70%-hatted dipole

Antenna	Frequency MHz	F-S Gain dBi	Feedpoint Z Ohms	SWR
Full	28	2.09	64.82 - j35.98	1.700
Hat		2.00	52.77 - j33.78	1.833
Full	28.5	2.11	68.34 - j17.87	1.296
Hat		2.01	55.61 - j16.39	1.338
Full	29	2.12	72.04 + j 0.18	1.003
Hat		2.02	58.60 + j 0.95	1.018
Full	29.5	2.14	75.94 + j18.20	1.286
Hat		2.03	61.75 + j18.27	1.356
Full	30	2.16	80.05 + j36.19	1.622
Hat		2.04	65.06 + j35.58	1.776

Although the hatted dipole at 70% of full size has a lower feedpoint impedance and a 0.1 dB lower gain, in practice, no difference in performance could be detected by any station using the two antennas side-by-side. If we plot the SWR performance of each type of dipole, as in **Fig. 3**, we discover that the hatted dipole has an SWR curve with nearly the same operating bandwidth as the curve for the full-size dipole. In fact, for any level of element shortening, hatting provides a wider operating bandwidth than any method of inductive loading. Nonetheless, all forms of element shortening result in lower feedpoint resistive impedance values. With a length of 70% of full size, the shortened dipole has an impedance about 14 Ohms less than the full-size antenna. For a fixed element length, all forms of inductive loading result in much lower impedance values.



A similar situation accrues to 2-element Yagis when we shorten each element to 70% full size and add hats. Let's compare the full-size Yagi from the last episode to a version that uses the 4-spoke hats of the dipole that we just created. **Fig. 4** shows the comparative sizes of each beam, using 0.12-wavelength (4.1') spacing.



Note an important aspect of Yagi design. Just because we may use various means to shorten the element lengths of a Yagi, we cannot significantly shorten the element spacing and hope for comparable performance. **Table 2** shows the dimensions of each array.

Table 2. Dimensions of full-size and 70% hatted Yagis. All elements 3/8" aluminum.

Spacing		Driver Length		Reflector Length		Hat-Spoke Length	
WL	Feet	WL	Feet	WL	Feet	WL	Feet
Full Size Yagi							
0.12	4.07	0.466	15.82	0.503	17.06	---	---
70% Hatted Yagi							
0.12	4078	0.322	10.92	0.348	11.80	.0293	0.99

There are numerous ways in which to apply hats to elements. The technique used here, which has proven itself in prototypes, is to set a fixed size for the hats, regardless of whether they go on the driven element or on the reflector. As a result, the linear portions of the two elements have different lengths. This technique appears to yield somewhat better performance that using the same length for both linear element sections, with differences in the length of the spokes of the hat.

Table 3 provides a comparison between the performance of full-size and hatted Yagis.

Table 3. A comparison of the modeled performance of full-size and 70% hatted Yagis

Antenna	Frequency	Gain	F-B	Feedpoint Z	SWR

	MHz	dBi	dB	Ohms	
Full	**28**	**6.98**	**5.43**	**15.49 - j48.55**	**7.34**
Hat		**6.53**	**2.47**	**10.39 - j48.51**	**11.29**
Full	**28.5**	**6.74**	**9.79**	**23.05 - j22.49**	**2.37**
Hat		**6.94**	**9.28**	**16.99 - j21.54**	**2.88**
Full	**29**	**6.25**	**11.20**	**32.14 - j 0.00**	**1.00**
Hat		**6.35**	**13.85**	**26.74 + j 0.77**	**1.03**
Full	**29.5**	**5.82**	**10.37**	**40.83 + j20.05**	**1.82**
Hat		**5.78**	**12.41**	**36.03 + j19.22**	**1.95**
Full	**30**	**5.48**	**9.17**	**48.75 + j38.76**	**2.78**
Hat		**5.34**	**10.15**	**43.81 + j35.77**	**2.99**

The designer may select almost any proportion to use in dividing the element lengths between the linear section and the hat spokes. The combination used here actually gives the hatted Yagi a slight performance improvement at the design frequency. As is clearly visible in **Fig. 5**, the chief advantage occurs with respect to the hatted Yagi's front-to-back ratio.

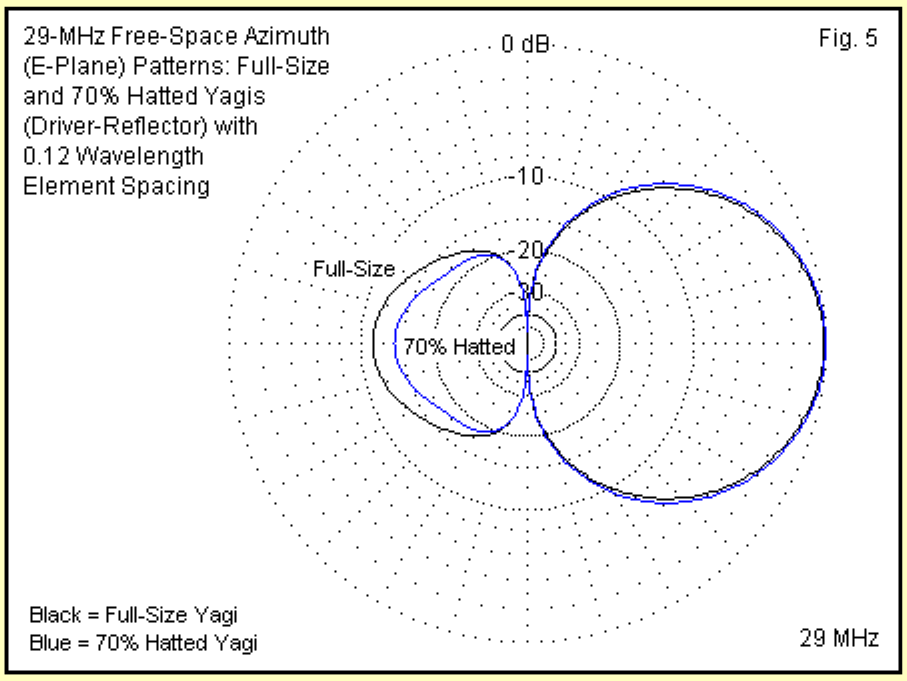


Fig. 5

If we only view the data and patterns for the design frequency, we might go away with a misimpression about the seeming superiority of the hatted Yagi. However, a careful check of the tabular data across the 28-30-MHz sweep suggests that the hatted Yagi has a somewhat narrower operating bandwidth in every category. For example, as shown in **Fig. 6**, the hatted Yagi's gain curve is somewhat steeper than the curve for the full-size version, especially at the low end of the sweep. The hatted Yagi is on its way toward the point of pattern reversal, just where the full-size Yagi is reaching maximum gain.

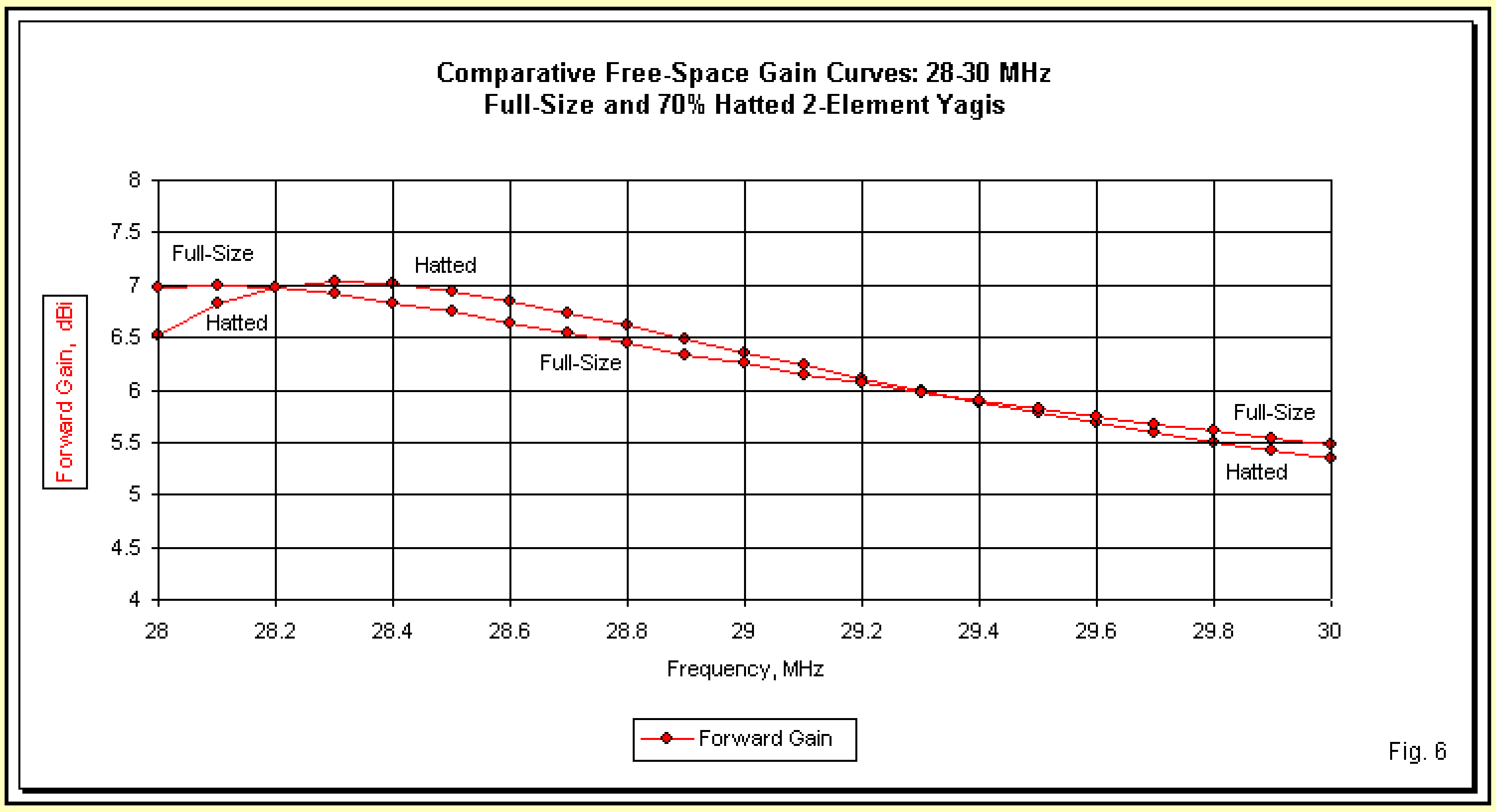


Fig. 6

The same general phenomenon appears in the curves for the front-to-back ratio, shown in **Fig. 7**. The hatted curve is steeper, and the increased rate of fall-off is especially apparent at the low end of the sweep. In both cases, one might juggle the reflector length slightly so that the curves have equal front-to-back ratios at both ends of the sweep span, although the change might move the frequency at which the ratio reaches its peak value.

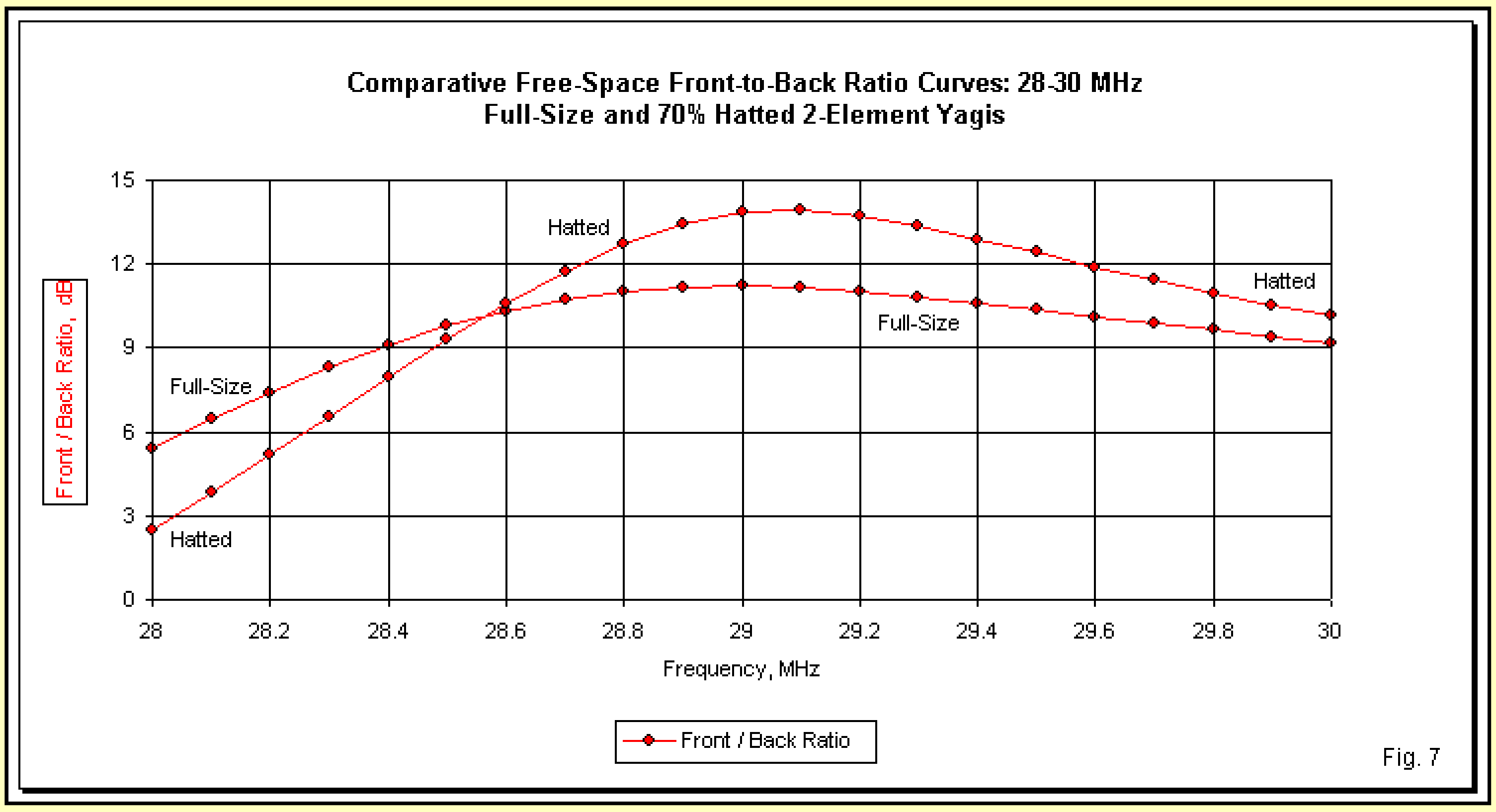


Fig. 7

Because we have shortened the elements in the hatted Yagi, the design-frequency resonant impedance will be lower than for the full-size Yagi. In addition, as shown in **Fig. 8**, the SWR curves relative to the resonant impedance is steeper, resulting in a reduced operating bandwidth using perhaps the 2:1 SWR value as the bandwidth marker. Nevertheless, as we examine other forms of loaded Yagis in the next episode, it will be useful to keep these curves and the data in **Table 3** at hand for comparisons. In general, hatting elements of a set length yields the widest operating bandwidth of any form of element shortening.

As will be evident later, hatted Yagis perform like what they are: almost full size beams. The slight performance differences are due to two variables: the shorter elements and the revised geometric relationships offered by those shorter elements.

Loaded Dipoles

A truly shortened element is one that terminates at its linear end. Such elements are not inherently resonant, but show significant capacitive reactance. To achieve resonance requires the insertion of a largely non-radiating inductive reactance. The form of the inductive reactance can be either a solenoid inductor or a shorted transmission line length: the latter are usually called linear loads. Linear loads are placed at the feedpoint (even when they may appear to have been placed elsewhere). Solenoid inductors are placed either at the feedpoint (center-loading) or somewhere farther out along the element as a pair of solenoids, one on each side of the feedpoint (mid-element loading).

Wherever an inductive load is placed, there is a current gradient representing the missing linear length for which the loading element substitutes. Compare the current distribution curves in **Fig. 9** for a full-size and a loaded dipole. Note the sharper step in current at the loading coil positions. Because such loads are only effective where antenna current is relatively high, the missing lengths of linear element represent radiation that for all purposes does not occur. Moreover, inductive loads, whatever their form, have losses associated with their resistance. Even high Q inductors introduce losses into the antenna element.

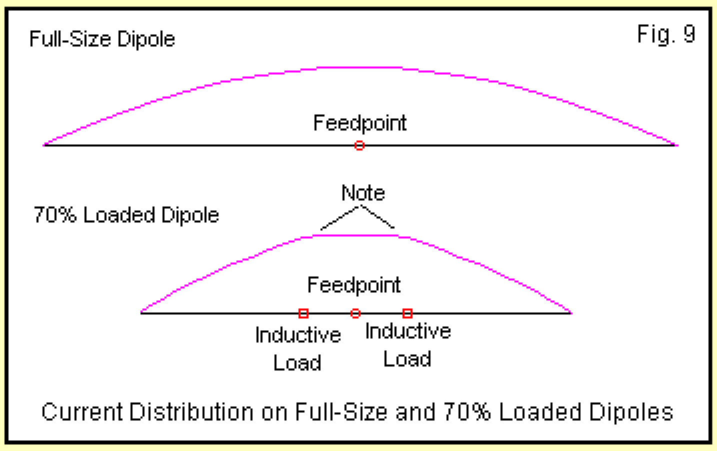


Fig. 9

Current Distribution on Full-Size and 70% Loaded Dipoles

Both of these phenomena may be demonstrated by reference to shortened dipoles relative to full-size counterparts. Some loads are more difficult to model than others, but simple solenoid inductors may be modeled well within the limits of variables affecting any model's transfer to fabricated reality. NEC models treat solenoid inductances as wholly non-radiating elements, which is largely but not absolutely true in reality. Physical coils do radiate a bit as a function of the fact that the current magnitude at each end of the coil is not equal, a necessary condition for a solenoid being a "pure" inductance. However, the model also assigns the coil an effective zero space by distributing its loss along the element segment to which it assigned. That segment functions like a linear element, which in a real antenna is missing and replaced by the coil. The results remain as accurate to real antennas as any other aspect of antenna modeling. The more significant keys to accurate modeling lie in the realm of using adequate load values, placing them precisely, and using the proper technique of load assignment for the modeling task at hand.

To see effects of shortening antenna lengths alone, however, requires no load, but only an examination of short dipoles. For any model, the capacitive reactance at the feedpoint can be canceled by a lossless center inductance without any change of antenna radiating characteristics. Notice in **Table 4** the reduction of gain of the following antennas gradually shortened from full size to 40% of full size. All antennas are at 29 MHz in free space, with the same 0.375" diameter aluminum element.

Table 4. The effects of simply shortening the length of a dipole.

% of Full	Gain	Feed R	Feed Xc
100	2.13	72.04	0.79
90	2.05	52.41	102.3
80	1.98	37.76	205.0
70	1.92	26.71	312.5
60	1.87	18.33	430.8

50	1.83	12.01	568.6
40	1.79	7.31	741.6

These gain reductions are equivalent to using lossless center inductors as loading elements, each sized exactly to compensate for the capacitive reactance remaining at the feedpoint. Although the loss of gain is modest per step, it adds up quickly as we shorten the antenna. Missing gain in the individual dipoles of a 2-element Yagi cannot be restored for any given design. Notice also the reduction of resonant feedpoint impedance down to values where basic efficiency may become a concern.

If we use real inductors having a finite Q, the losses grow even faster with element shortening. **Table 5** gives free space gain figures for coil Qs ranging from 300 to 50. Although higher values of Q are possible using coils with a high radius-to-length ratio, a Q of 300 may be about the best obtainable in a practical coil before weathering effects reduce that value. A Q of 50 represents a worst-case scenario where maintenance is lax and acid rain is heavy.

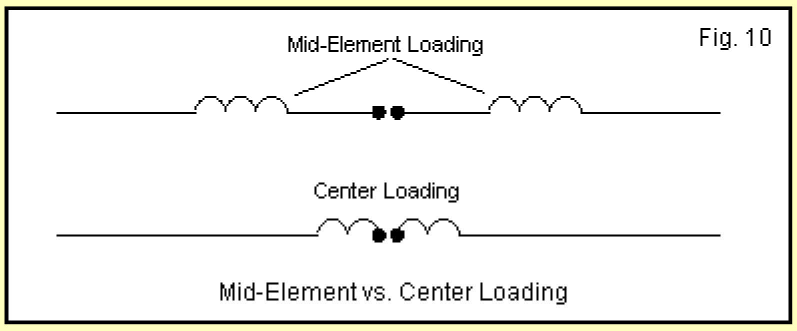
Table 5. Some dipole gain values for center-loaded dipoles of various lengthswith inductors having various values of Q.

% of full	Gain with Q = 300	200	100	50
90	2.02	2.00	1.96	1.88
80	1.90	1.86	1.75	1.53
70	1.75	1.67	1.44	1.01
60	1.54	1.39	0.95	0.20
50	1.19	0.90	0.14	-1.07
40	0.52	-0.01	-1.25	-3.03

A dipole 50% of full size with a loading coil Q of 300 has lost nearly a full dB of gain, while the loss at 70% of full length is less 0.4 dB. Obviously, the gain loss increases faster than the rate of shortening. The rate of loss for lower Qs increases proportionately.

A center-loaded dipole can present the user with an illusion of well-being. The feedpoint impedance at resonance will be roughly the sum of the feedpoint impedance with no losses plus the resistive component of the coil's Q. With time, weathering, and lowering Q, a short, loaded dipole may seem to show an improvement in SWR relative to a 50-ohm feedline. In actuality, it is more likely that coil losses are increasing, and the additional resistance is simply converting power to heat.

An alternative to center loading is mid-element loading, that is, the placement of loading inductors somewhere along each element away from the feedpoint. **Fig. 10** shows the physical difference between the two methods of applying inductive element loading. Claims for significantly increased efficiency unfortunately do not materialize from this arrangement, although the arrangement does show a slightly lower rate of gain decline.



As the loading coil is split and moved outward from the antenna center, the required value of inductive reactance necessary to achieve resonance increases. By the time the coils are midway between the element center and the element ends, each coil must have an inductive reactance of about 93% of what a single center-loading inductor would require. For equivalent coil Q, the nearly doubled series resistance of mid-element loading coils tends to wash out most of the gain increase occasioned by letting full current exist at and near the feedpoint.

As **Table 6** shows, gain improvements are marginal. The chief benefit of mid-element loading is that the feedpoint impedance remains higher than with center loading. As with the previous table, dipoles are 3/8" diameter aluminum in free space.

Table 6. Dipole Performance with mid-element loading coils of various values of Q.
Coils are located at the mid-point of each element half.

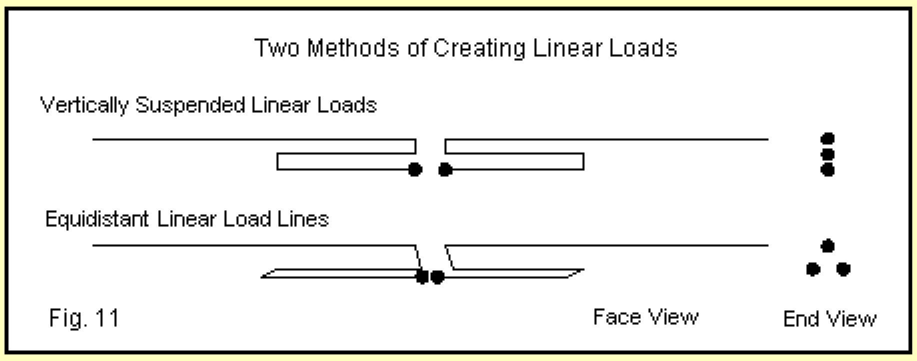
% full	Load coil reactance per coil	Feed R Ohms	Gain (dBi) for Q = inf.	300	200	100	50
90	93.0	63.16	2.06	2.03	2.02	1.98	1.90
80	188.0	53.66	2.00	1.93	1.89	1.78	1.57
70	288.0	43.86	1.94	1.80	1.71	1.50	1.09
60	399.0	34.20	1.89	1.59	1.45	1.05	0.35
50	528.0	25.02	1.84	1.27	1.01	0.32	-0.8
40	690.0	16.78	1.80	0.68	0.21	-0.9	-2.6

Mid-element feedpoint impedance figures average about 10 ohms higher than center-loaded dipole feedpoint impedances for equivalent shortening. However, even with this improvement, illusions of well being are possible. If one ends up with loading coils with a Q of 50 in a dipole only 40% of full size, the antenna will seem to match a coax cable very well--because the RF resistance in the coils will roughly add to the natural resonant impedance of the antenna. In that extreme case, the loss resistance would double the antenna resistance and occupy corresponding amounts of power.

In the end, there is little to choose between center and mid-element loading except feedpoint impedance and such mechanical considerations as may apply to the antenna structure. Center loads are more easily supported, but in some cases are a problem to feed. Mid-element loading coils often require one or two upward steps in element diameter to support the coil. Gains for the two systems, with coils of equivalent Q, would be indistinguishable in practice.

Linear-Loaded Dipoles

An alternative to either system of loading is the use of a linear load. Once veiled in mystery, linear loads turn out to be simplicity itself. In purest form, they are nothing more nor less than shorted series transmission line stubs used to provide the necessary inductive reactance for center loading. Each side of the feedline attaches to a section of line run parallel to the main element. The line continues back to the original center junction area and attaches to the main element. **Fig. 11** shows two popular ways to configure linear loads.



If both lines are equidistant from the main element, then straightforward shorted transmission line stub calculations are sufficient to calculate the required length of each stub. Each stub will provide 1/2 of the reactance required for center loading. If the stub lines are not equidistant from the main element, unequal currents will be induced by the field from the main element, resulting in longer linear load lines for the same degree of loading. (For more on this subject, see "Modeling and Understanding Small Beams: Part 4: Linear-Loaded Yagis." *Communications Quarterly*, Summer, 1996, pp. 85-106.)

In some commercial beams, the linear load is made to appear to be placed farther out along the element. The main (large-diameter) element is fed and, on each side, breaks at some distance from center. Smaller lines are run back toward the feedpoint, make a turn and return to the break, to be connected beyond the break point. Despite appearances, these antennas have center-loading linear loads composed of one fat wire and one thin wire. The main antenna element is actually the return thin wire back to the break point where it attaches to the tubing used to finish the element. Although the system has much in the way of mechanical soundness to recommend it, and although the difficulty of calculating the precise length of needed linear load makes empirical experimentation more efficient in antenna development, the system is electrically quite normal.

To gain a sense of the advantages of linear loading, let's look at a dipole 70% of full length (11.4') and try to model linear loads of varying proportions upon it. For consistency and comparability of results, all models were done in NEC-4. Due to constraints within NEC, this procedure restricted the construction of linear loads using the same diameter material as the main element: 3/8" diameter aluminum.

Two types of linear loads were modeled: those placing both load lines equidistant from the main element and those lining up the lines vertically beneath the element. For these rough samples, variations were limited to changing the spacing from the main element and from line to line. The spacing values were equalized; that is, if the space between lines was 3", then the space from the main element was also 3" for both types of loads. Where E = equidistant load lines and V = vertically suspended load lines, the sample models appear in **Table 7**:

Table 7. Sample linear load models used for comparisons

Antenna	**Specification**
E3	**Equidistant lines 3" apart and 3" from the main element**
E6	**Equidistant lines 6" apart and 6" from the main element**
V1	**Vertically suspended lines with 1.5" spacing**
V3	**Vertically suspended lines with 3" spacing**
V6	**Vertically suspended lines with 6" spacing**

In **Table 8**, the meaning of all values is obvious, except perhaps equivalent Q. Replacing the linear load with an inductor of sufficient size to resonate the antenna and then adding resistive losses until the element gain equals the gain of the linear-loaded element derives the value of equivalent Q. Although these values are useful markers with respect to gain, they will be less useful with respect to operating bandwidth. "Length" indicates the total length of the linear load from outer tip to outer tip.

Table 8. Modeled performance of the sample linear-loaded dipoles

Antenna	**Length**	**Gain dBi**	**Feed Z (R +/- jX Ohms)**	**Equiv. Q**
E3	**4.46'**	**1.88**	**24.1 + j0.12**	**1150**
E6	**3.14'**	**1.89**	**21.3 + j0.32**	**1400**
V1	**7.50'**	**1.71**	**25.7 - j0.37**	**230**
V3	**5.36'**	**1.83**	**22.9 + j0.16**	**500**
V6	**3.64'**	**1.90**	**20.2 + j0.31**	**2000**

For each type of linear load (equidistant and vertically spaced), wider spacing results in a shorter load length. The inductive ractance of a shorted transmission line is the characteristic impedance of the line times the tangent of the lines electrical length. Since we need the same reactance in each case, as the characteristic impedance of the lines goes up the length comes down. As we increase the spacing between the lines, the characteristic impedance goes up. Even though vertically spaced linear loads do not adhere strictly to the general equations due to varable coupling on the two lines of the load, they do follw the trands very well. From these few samples, some other trends (verified by a large number of file samples) are also evident:

1. The wider the spacing among elements, the higher the element gain and equivalent Q at the design frequency.

2. Vertically suspended linear loads vary more widely in length, gain, and equivalent Q than equidistant linear loads.

3. The wider the spacing (between lines and from the antenna to the lines), the lower the feedpoint impedance of the resonant element.

Most notable is the lack of significant variation in the gain of the two equidistant linear load models. The spacing is doubled between the two, but the gain varies by almost nothing. These models correspond most closely to a pair of series connected shorted transmission line stubs. Independent calculation of required stub lengths produces values for each side of center that are longer than the modeled stubs by about the length of the vertical connectors. The connecting lines are not the entire story here, since stub line calculations presume that the shorting connection at the stub end is insignificant. However, 3" and 6" connecting rods are likely of some significance at 29 MHz.

Vertically suspended linear loads vary more widely, in part due to the unequal induced currents from the nearby main element. For these loads, the designer is faced with a trade-off: load spacing and element gain on the one hand and feedpoint impedance on the other. Equidistant load lines may be placed close to the main element to increase the feedpoint impedance without significant loss of element gain.

For a final comparison, we may look at the operating bandwidths of all the loaded elements, including those with a center-loading inductor, mid-element-loading inductors, and linear loads. As before, the table will show calculated SWR values for 28 through 30 MHz at 0.5 MHz intervals. Linear loaded antennas will be designated as given in this section. Center-loaded and mid-element-loaded antennas will be called CL and ML, respectively, and followed by a number representing a value of Q used in earlier comparisons. The inductor-loaded antennas will be restricted to those 70% of full size to correspond to the linear loaded models. A full-size dipole and a 70% hatted dipole for 29 MHz are included for comparison. See **Table 9**.

Figures for inductor-loaded models were developed by introducing the model load(s) as inductors (values of inductance in uH) with the requisite reactance for resonance at the design center frequency. Since reactance varies with frequency, using a constant reactance in the load model would have produced too optimistic a set of SWR figures. All models retain the 3/8" diameter aluminum construction, and figures are for free space.

Table 9. SWR performance of all of the types of dipoles in this episode
Note: all shortened dipoles are 70% of full size.

Antenna	SWR at 28	28.5	29	29.5	30 MHz
Full size dipole	1.71	1.30	1.00	1.28	1.62
70% hatted dipole	1.83	1.34	1.02	1.36	1.78
CL-300	4.06	2.06	1.00	1.99	3.57
CL-200	3.96	2.03	1.00	1.96	3.50
CL-100	3.72	1.96	1.00	1.90	3.31
CL-50	3.32	1.84	1.00	1.79	3.00
ML-300	3.77	2.00	1.02	1.89	3.32
ML-200	3.70	1.98	1.02	1.86	3.28
ML-100	3.51	1.92	1.02	1.81	3.11
ML-50	3.20	1.83	1.02	1.71	2.82
E3	4.35	2.14	1.01	2.08	3.87
E6	4.34	2.12	1.02	2.10	3.88
V1	4.53	2.22	1.01	2.10	4.03
V3	4.30	2.12	1.01	2.08	3.85
V6	4.35	2.12	1.02	2.10	3.88

Carrying out SWR to 2 decimal figures is largely spurious in terms of practical operation. However, adding the final decimal place makes the trends clearer and also clarifies the lowest SWR on which the other figures are based.

All forms of element loading narrow the operating bandwidth and are roughly related to the Q of the loading element(s). For inductor loading, the 2:1 SWR bandwidth increases as Q decreases, but the differences are small. The differences between comparable Q-values for center and mid-element loading are smaller yet.

The operating bandwidth for a linear loaded element shows the inherently higher Q of the system, but the actual figures are not directly related to an assignable value of Q. Among the vertically suspended linear loads, V1 had the lowest assignable Q in terms of gain equivalence, but also displays the narrowest bandwidth of the entire group. Once a certain lower limit of element spacing is exceeded, operating bandwidth tends to be the same for all practical purposes.

In the end, the use of linear loading trades higher gain for a narrower operating bandwidth than inductor loading. Mid-element loading provides a higher feedpoint impedance than either form of center-loading. (However, the hat-method of shortening elements yields the broadest bandwidth of all of these 70%-length elements.)

The next question is how the characteristics of inductively loaded elements will show up in 2-element Yagis.

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