Effects of Boom and Element Diameters on Yagi Element Lengths at 144, 432 and 1296 MHz

Want to build some VHF/UHF/Microwave Yagis? Some up-front measurements can cut the time required for tuning. Use this method to determine boom-correction factors for Yagi elements mounted through the middle of —and in good electrical contact with—a metal boom.

By Guy Fletcher, VK2KU

Editor's note: Since this article originally appeared in Amateur Radio *magazine of the WIA in March 1999, corrections and clarifications have been provided by the author.*

My experiments were performed at frequencies of 144.2, 432.2 and 1296.2 MHz and provide data for boom diameters of up to 0.08 λ. They also explore the effect of element diameter. The results show clearly that the correction depends not only on boom diameter but also on element diameter and element length.

The effect of the boom on each element may be represented by a *negative* reactance at the center of the element. A simple empirical formula for this reactance agrees well with all the experimental data and allows correction for any combination of boom diameter and element diameter. These results are given in the form of a universal graph.

The observed dependence on element length is intrinsic to the model of boom reactance and leads to a correction that tapers as the element length decreases. This may be adequately represented in practice by a simple power-law modification of the value for a standard element length of 0.42 λ taken from the graph.

The use of tapered corrections for the different element lengths (rather than a single fixed correction) has been applied to examples of practical Yagis. The difference is negligible at 144 MHz and small at 432 MHz. At 1296 MHz, however, where boom diameters may be relatively large (in terms of wavelength—*Ed.*), the use of a fixed correction appears to change the performance parameters of the antenna quite significantly.

12 Sassafras Gully Rd
Springwood, NSW 2777
Australia
guy@ics.mq.edu.au

Background

Boom correction factors are discussed by Günter Hoch, DL6WU, in the *VHF / UHF DX Book* (edited by Ian White, G3SEK) and other similar references.[1] Günter's corrections may

[1] I. White, G3SEK, Ed., *VHF/UHF DX Book.* This book is available from your local ARRL dealer or directly from the ARRL as #5668. Mail orders to Pub Sales Dept, ARRL, 225 Main St, Newington, CT 06111-1494. You can call us toll-free at tel 888-277-5289; fax your order to 860-594-0303; or send e-mail to **pubsales@arrl.org**. Check out the full ARRL publications line at **http://www.arrl.org/catalog**.

be embodied in a formula developed by Ian:

$$\frac{C}{B} = 25.195\left(\frac{B}{\lambda}\right) - 229\left(\frac{B}{\lambda}\right)^2 \qquad \text{(Eq 1)}$$

where C is the correction and B is the boom diameter, both in millimeters. This formula is not valid for boom diameters greater than 0.055 λ, although diameters of up to 16 mm (0.07 λ) are common at 1296 MHz. Ian's formula is plotted in Fig 1. It includes no dependence on element diameter or length. Also, the curve is assumed to pass through the origin, although there is no real reason to expect this. C is obviously zero when B is zero, but the ratio C/B need not be zero to make C zero.

There seem to be no data available for larger boom diameters, which is perhaps why some amateurs have remarked on the difficulty of matching antennas correctly at 1296 MHz. The experiments to measure boom corrections are in fact quite straightforward, so I decided to make some simple measurements. The scope of the project expanded rapidly as the unexpected nature of the results appeared.

Theory and Model

The complex voltage reflection coefficient (ρ) represents the magnitude and relative phase of the ratio of the reflected voltage wave to the forward voltage wave at a load. In these experiments, the reflected power (P_R) and the forward power (P_F) were measured rather than the voltages:

$$|\rho| = \left(\frac{P_R}{P_F}\right)^{\frac{1}{2}} \qquad \text{(Eq 2)}$$

The voltage standing wave ratio (SWR), σ, is:

$$\sigma = \frac{(1+|\rho|)}{(1-|\rho|)} \qquad \text{(Eq 3)}$$

Any element of a Yagi antenna has energy stored in the fields surrounding it. Near the element center, the current is large and the voltage small; near the ends, the current is small and the voltage large. If the element passes through a larger conductive boom at its center, the skin effect forces the current to flow around the outside of the boom instead of directly along the element's surface. This reduces the volume of the magnetic field around the element and therefore reduces the energy stored there. Since the stored energy is directly proportional to the self-inductance (L) of the element, the effect of the boom is to contribute a negative reactance to the element's impedance, Z. This negative reactance contribution increases in magnitude as the boom diameter increases.

For thicker elements, the volume of the magnetic field is reduced anyway, because the field is limited to the region outside the element. Thus, there is less field volume for the boom to remove, so the effect of thicker elements will be to reduce the magnitude of the boom's effect, hence also reducing the correction required. [See the sidebar "Plumber's Delight Meets EM Theory" for another way of looking at this.—*Ed.*]

The element-plus-boom can be restored (approximately) to its original electrical state by lengthening the element so as to contribute a positive reactance to offset the boom effect. This is the boom correction. Brian Beezley, K6STI, writes in the handbook to his Yagi design and analysis program *YO6* that elements of different diameter are electrically equivalent when the *phase angles* of the complex self-impedances are the same. This differs from simply equating the imaginary components (the reactive parts) of Z.

The Experiments

Thirteen experimental measurements were made with the boom (B) and element (d) diameters shown in Table 1, as limited by available materials. The signal source was a Yaesu

Fig 1—Plot of G3SEK's formula for boom correction.

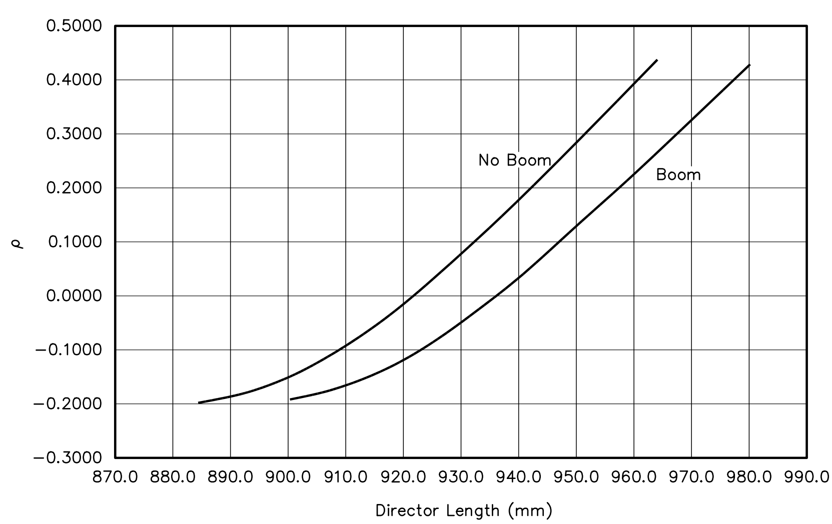


Fig 2—Data for frequency 144.2 MHz, *B* = 32.0 mm, *d* = 6.35 mm.

FT-736R transceiver, delivering 25 W on 144 MHz and 432 MHz and 10 W on 1296 MHz.

Forward and reflected powers were measured with a Bird 43 wattmeter using different plug-in elements for forward and reflected power. The relative precision for the reflected power was about 0.02 W on 144 MHz, 0.04 W on 432 MHz and 0.01 W on 1296 MHz. The absolute measurement accuracy was not nearly as good as this, but the experiments consisted essentially of comparing different antennas to obtain the same reflected power, so calibration errors are not as important as reading precision.

For each frequency and boom diameter, a simple three-element Yagi was designed using *YO6* and constructed on a dry wooden boom (usually rectangular). The feed impedance was around 25 Ω and T-matching was used with a conventional 4:1 balun. In each case, the elements were cut to the expected length; then the T-bars and the length of the driven element (DE) were adjusted for zero reflected power with no metal boom sleeve in place. The metal boom for the director (D1) was an exact sliding fit over the wooden boom and extended about half of the distance back toward the DE and a similar distance forward. Elements were pinned in place with self-tapping screws—which made no observable difference to any reading—to ensure good electrical contact between elements and boom. This arrangement guaranteed that the director could be repeatedly removed and replaced in exactly the same position.

To avoid ground effects, each antenna was mounted to radiate vertically upward. With the boom sleeve in place and the director cut deliberately long, the forward and reflected powers were recorded for each director length (*L1*), as the length was systematically reduced by small amounts until the reflected power was near zero. (Sometimes the measurements were continued well beyond this point.) The boom sleeve was then removed and the process repeated over a similar range of reflected powers. The reflection coefficient (ρ, equal to the square root of the power reflection coefficient) was plotted against *L1*. The expectation was that two parallel curves would result, their separation being the desired boom correction. In fact, the curves were not quite parallel!

Element lengths were measured with a steel ruler on 144 and 432 MHz to a precision of about 0.2 mm and with dial calipers on 1296 MHz to a precision of 0.01 mm. These two methods are not equivalent, in that the ruler measures a length averaged by eye over the end faces, whereas the calipers measure between the high points on each end face. However since all measurements in any one experiment were made consistently, the accuracy of the experimental boom correction factors found from a length difference should approach twice the appropriate precision above. The smoothness of the raw data curves supports this belief.

The Results of the Experiments

Figs 2, 3 and 4 are typical of the 13 graphs obtained for reflection coefficient ρ as a function of director length (*L1*) with and without a metal boom

Table 1—Thirteen experimental situations

144.2 MHz:	B = 32.0 mm, d = 4.76 mm, 6.35 mm
432.2 MHz:	B = 16.2 mm, d = 2.40 mm, 3.18 mm, 4.76 mm
	B = 20.2 mm, d = 2.40 mm, 3.18 mm, 4.76 mm, 6.35 mm
1296.2 MHz:	B = 16.2 mm, d = 1.60 mm, 2.40 mm, 3.18 mm, 4.76 mm.

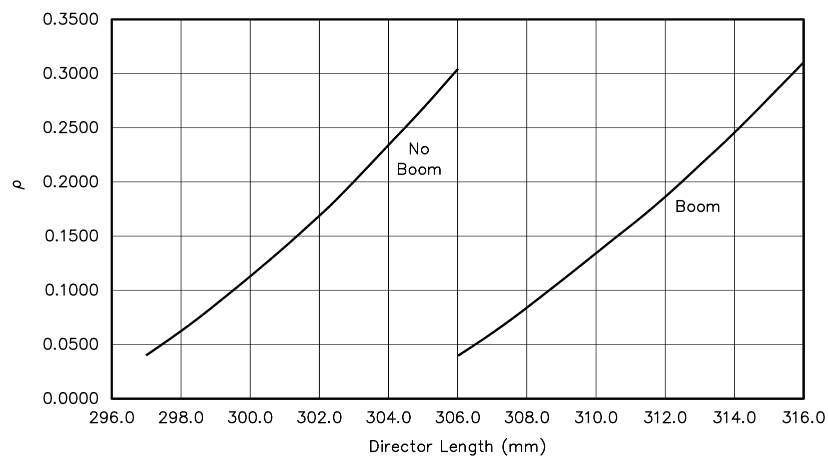


Fig 3—Data for frequency 432.2 MHz, *B* = 20.2 mm, *d* = 4.76 mm.

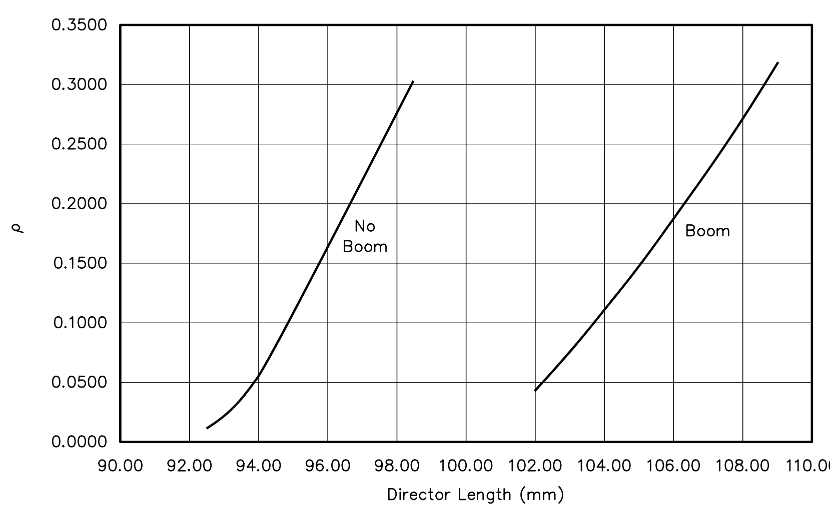


Fig 4—Data for frequency 1296.2 MHz, *B* = 16.2 mm, *d* = 4.76 mm.

sleeve. Careful study of these and other graphs shows that the boom correction, measured by the separation of the two curves, decreases slightly as the director length is reduced. This finding is not very surprising, but is significant because such a dependence has not previously been suggested.

From each graph, the director lengths with and without the boom sleeve were tabulated at several values of reflection coefficient ρ (eg, 0.1, 0.15, 0.2, 0.25 and 0.3) and a set of boom corrections was found. For each of the more than 50 pairs of director lengths, *YO6* was used to find the complex element impedance, Z. The program actually requires a reflector to be present, so this was placed 100 meters behind the driven element, where it would have no discernible effect. (The use of a particular program such as *YO6* to find element impedance is open to some criticism. This important point will be discussed below.)

The impedances from each pair of director lengths were used to find the negative reactance (X) contributed by the boom. This is best illustrated by an example. The results from Fig 3 for ρ = 0.1 are reproduced in Table 2.

The boom correction is here 9.15 mm. The X in the column for impedance with the boom sleeve present represents the unknown contribution of the boom to Z. The value of X was found by equating the phase angle (ϕ) of Z with and without the boom sleeve, so that the two situations are electrically equivalent. This gives $X = -j18.50\ \Omega$. Originally, the comparison was made by simply equating the imaginary components of Z, but this procedure led to model curves that did not converge in the way actually observed, so the phase-angle method was adopted. The values of X found in this way were reasonably consistent over the whole range of ρ and were averaged.

Finally, the value of X was used to predict boom corrections over a wider range of element lengths typical of a long Yagi by reversing the procedure. For the example in Table 2, the calculated boom corrections range from 7 mm (for the shortest director) to 12 mm for the reflector. This shows clearly the variation of boom corrections to be expected over the length of such a Yagi and the errors introduced by using a fixed boom correction for all elements. A table of such calculated boom corrections (which include the experimental values as a subset) was generated for all 13 experiments.

Each of these 13 tables of calculated corrections was plotted against director length $L1$, and they were all found to fit closely to a simple power-law relationship. The optimum value of the power varied slightly across the experiments, but a satisfactory fit for all the data was given by:

$$C = k(L1)^{1.8} \quad \text{(Eq 4)}$$

or

$$\left(\frac{C}{C0}\right) = \left(\frac{L1}{L0}\right)^{1.8} \quad \text{(Eq 5)}$$

where $C0$ and $L0$ correspond to some standard director length. For various reasons, this standard element length was chosen to be 0.42 λ, and the final graph presented in Fig 7 corresponds to this standard length.

Table 2 —Results taken from Fig 3 for ρ = 0.1

	No Boom Sleeve	*With Boom Sleeve*
Director Length (mm)	299.45	308.60
Impedance Z (Ω)	51.5 – *j*35.7	55.5 – *j*20.0+X

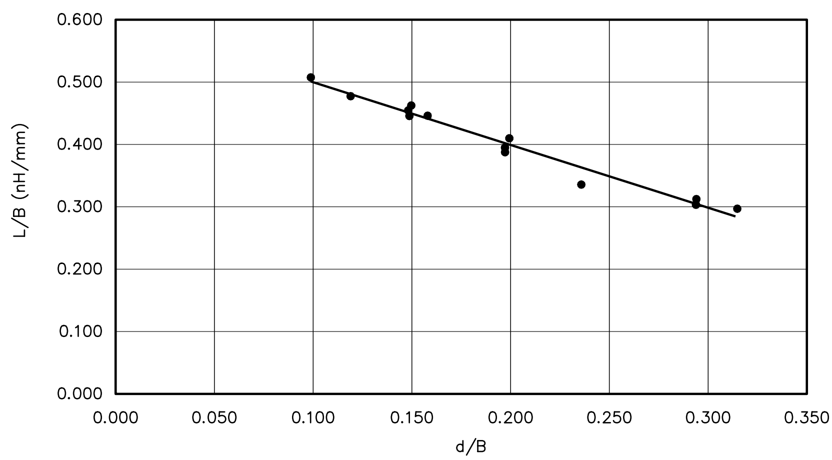


Fig 5—Dependence of inductance *L* on *B* and *d*.

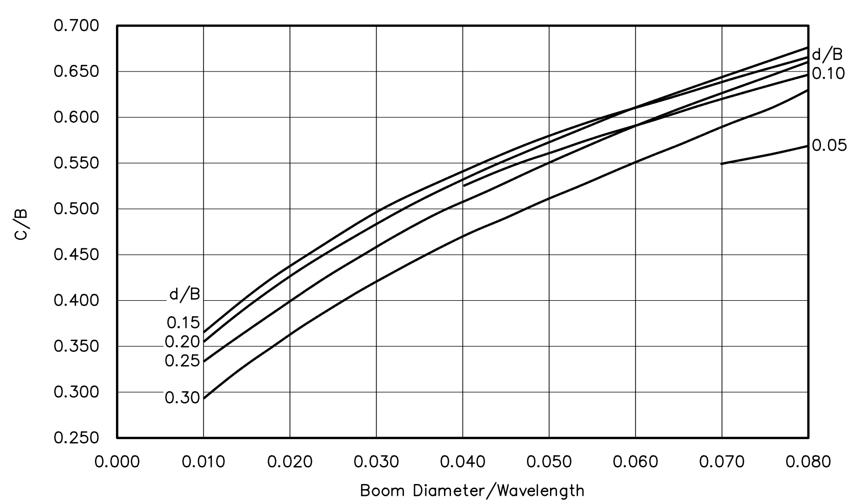


Fig 6—Boom corrections *C*/*B* for elements of length 0.42 λ and for various *d*/*B* values.

Effect of Boom and Element Diameters

In spite of trying many different plots, it has not proved possible to represent the dependence of the length correction (C) on element diameter (d) in any simple way. This is not entirely surprising because of the complexity of the effect on element impedance of varying the tip length to compensate for the effect of the boom. It has proved very helpful to break the problem into two separate parts:

1. *The effect of the boom on the element impedance:* As explained above, this can be represented as a pure negative reactance, the value of which depends also to a lesser extent on the element diameter.

2. *The increase in length required to compensate for this reactance:* so as to restore the original phase to the element impedance.

The boom reactances from the 13 different experiments have been converted to inductance (L) and plotted in Fig 5 as L/B versus d/B. The inductance is plotted as a positive quantity for convenience, but remember that it contributes negatively to Z.

The graph of L/B versus d/B shows a remarkable linear relationship:

$$\frac{L}{B} = 0.5994 - 0.999\left(\frac{d}{B}\right) \qquad \text{(Eq 6)}$$

Only one point (at 432.2 MHz) departs appreciably from the line of best fit. Having due regard to the accuracy of the data, this relationship is most simply expressed as:

$$L = 0.6B - 1.0d \qquad \text{(Eq 7)}$$

In this simple and elegant expression (Guy's Rule!), L is the value of the negative reactance contributed by the boom/element combination to the element impedance Z. For the values of the constants as presented, L is in nanohenries, while B and d are in millimeters. With this rule, the reactance of *any boom and element combination* can be predicted with reasonable confidence.

Calculation of Boom Corrections

It is straightforward—but not particularly convenient—to use the inductance value given by my rule to calculate a value for the boom

> **Seven Simple Steps**
>
> 1. Calculate the wavelength (in millimeters) from:
>
> $$\lambda = \frac{299792.5}{f} \qquad \text{(Eq 8)}$$
>
> where f is in megahertz: Eg, f = 1296.2 MHz, λ = 231.3 mm.
> 2. Choose a boom diameter B and element diameter d, both in millimeters. Eg, B = 16.2 mm, d = 3.18 mm.
> 3. Calculate the ratios B/λ and d/B. Eg, B/λ = 0.070, d/B = 0.196.
> 4. Refer to Fig 7. Draw a vertical line corresponding to the value of d/B and read off the value of C/B from the appropriate curve. Interpolate between the curves as necessary. Eg, C/B = 0.645.
> 5. Calculate C (in mm) from C/B by multiplying by B. This is the boom correction for an element of length equal to the standard length, $L0$. Eg, $C0$ = 10.4 mm.
> 6. Calculate the standard length $L0$ from $L0$ = 0.42 λ. Eg, $L0$ = 97.1 mm.
> 7. Calculate the correction C for any element of length L from Eq 5. Eg, for L = 90.0 mm, C = 9.1 mm.

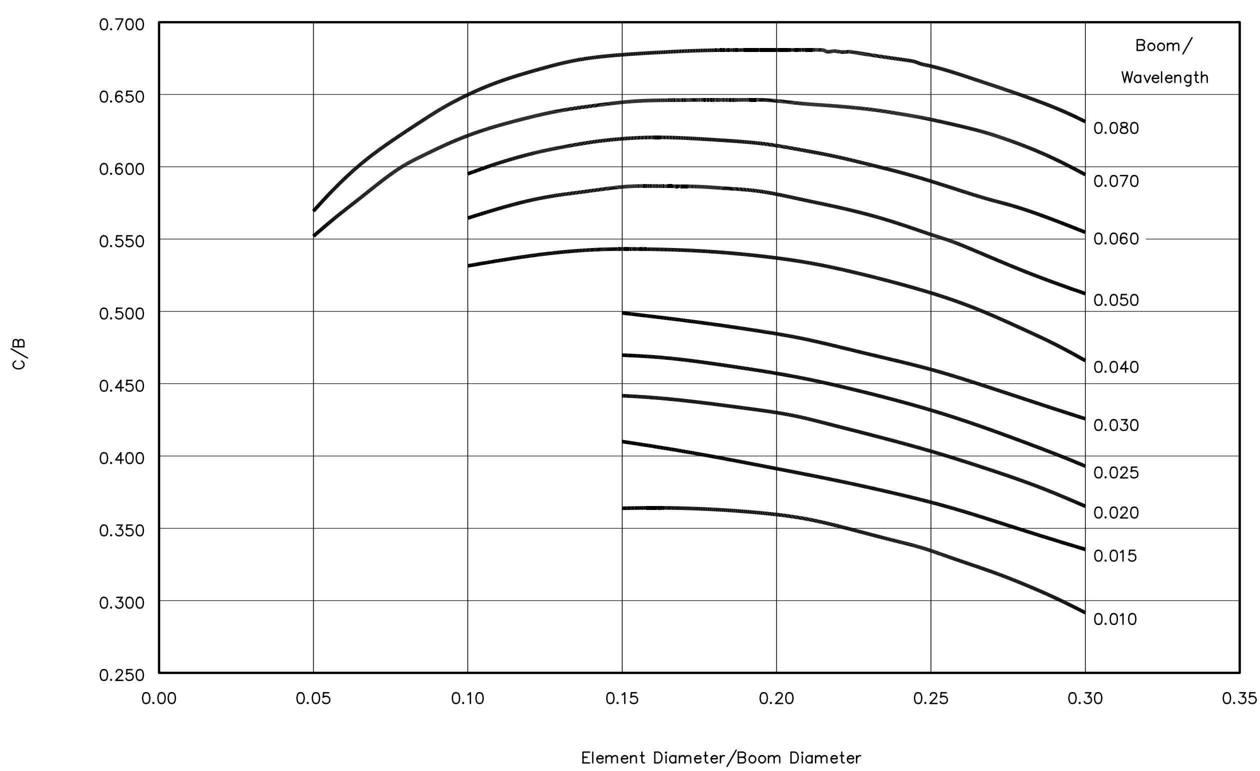


Fig 7—Boom corrections *C/B* for elements of length 0.42 λ. *B/λ* marked for each curve.

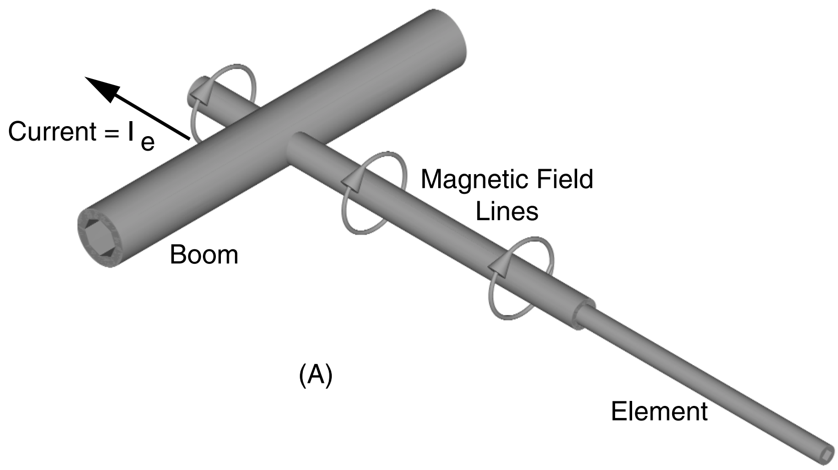
Plumber's Delight Meets EM Theory

Guy's theory about why Yagi elements appear electrically shorter when attached to a conductive boom proved difficult for me to understand at first. The following represents my perception of the effect as clarified by him. I hope it helps you, too.

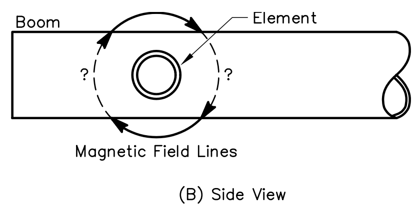
Current flowing in a conductor such as a Yagi element produces a magnetic field aligned everywhere at right angles to the direction of current flow. The shape of magnetic field lines satisfying this condition is a circle concentric to the element, as shown in Fig A.

The presence of a conductive boom interferes with the development of the magnetic field near the boom, thereby affecting the current flow there. See Fig B. Experiments verify the electrical shortening of the element. Using knowledge of how EM fields interact with matter, it seems to me this theory could be developed to predict the exact magnitude of the effect. What properties of the boom material are included in the solution? What geometries minimize the effect?

I do not find much mention or analysis of this idea in the literature. It appears to merit further consideration in modeling of antennas, especially at UHF and microwave frequencies. What do *you* think?—*Doug Smith, KF6DX.*



(A)



(B) Side View

correction C for any combination of boom diameter, element diameter and element length. This involves using *YO6*, first to find the complex impedance Z of the uncorrected element length and hence its phase ϕ. Then by a process of trial and error to find a new element length which, when combined with the negative reactance contributed by the boom, has the same phase.

Instead, for the standard element length of 0.42 λ, boom corrections have been calculated over a wide range of boom diameters (B) and element diameters (d) covering all the sizes likely to be met in practice. The results may be plotted in the form C/B versus B/λ, as in Fig 6, with separate curves for different element diameters. Alternatively, C/B may be plotted versus d/B, as in Fig 7, with separate curves for different boom diameters. Other possibilities include using d/λ in place of d/B.

Fig 6 may be compared directly with Fig 1, based on the G3SEK formula. The curve shapes in Fig 6 are generally similar to that in Fig 1, but it is apparent that the intercepts on the vertical axis of Fig 6 are well above zero for all values of d/B. The curves in Fig 6 also intersect, making it hard to use in practice. The reason for these intersecting curves is clearer in Fig 7. In general, as the element diameter increases, the boom correction factor C/B decreases as expected from the discussion earlier. In the case of thick booms however, the boom correction factor also falls for very thin elements, for which the reactive component is large. This is, in fact, a consequence of the use of a standard element of fixed length rather than fixed phase. The use of a standard length is much easier to use in practice, but leads to curves that intersect when boom diameter is used as the horizontal coordinate.

For the practical prediction of boom corrections, Fig 7 is significantly easier to use than Fig 6 because the various curves are well separated and generally less inclined.

Practical Significance of Length-Dependent Boom Corrections

The detailed results described in this article are novel in that they lead to boom correction factors that depend not only on the boom diameter, but also on element diameter and length. It is reasonable to wonder whether this has any real practical significance when compared with the simpler system of a fixed correction factor presently in widespread use. If the corrections should indeed taper from larger values for longer directors and the reflector to smaller values for the shorter directors, then the effect of using a single, fixed correction is to apply a correction that is too small for the longer elements and too big for the shorter ones.

This can be easily simulated in an antenna analysis program such as *YO6* by adding the fixed correction to every element and then subtracting the tapered corrections. Such simulations lead to the conclusion that—at 144 MHz—the difference between the two approaches is negligible. This is not at all surprising since the corrections are a small fraction of the element lengths. At 432 MHz, small differences are apparent, but do not appear very significant. At 1296 MHz, however, the fixed and tapered corrections differ by considerably more than acceptable construction tolerances. The predicted antenna properties also differ significantly, with some loss of gain when a fixed correction is used and major differences in the feed impedance. This is consistent with the matching difficulties previously experienced at 1296 MHz by some amateurs.

Several local amateurs have now constructed long Yagis for 1296 MHz using the VK2KU tapered corrections, and in each case, they have reported that matching the Yagi proved quite straightforward.

Conclusions

The raw data graphs—such as Figs 2, 3, and 4—appear to show unequivocally that boom corrections depend not only on the boom diameter (as a fraction of wavelength), but also on element diameter and element length. The dependence on element diameter may not be very startling, but the dependence on element length appears to be a novel idea that was initially unexpected.

The formula for calculating the negative reactance contributed by the boom/element combination is also new, but it fits the experimental data very well. This rule is the key to calculating boom corrections for any combination of boom and element diameter. It may well be that the use of a different computer program for finding element impedance would lead to somewhat different values for the negative reactance, and so to slightly different constants in the formula. When the procedure is reversed, however, and the same program is used to find the corrections in other situations, such differences between programs should largely be eliminated. In effect, the computer modeling is used to interpolate between boom correction factors that were found directly by experiment. Thus, I believe that the graphical results as presented in Fig 7 are substantially independent of the computer modeling and represent a close approximation to the truth.

The length dependence of the corrections appears to be best described by a power law of order 1.8, though this value does not seem to be very critical. The fixed boom corrections commonly used elsewhere extend up to a boom diameter of 0.055 λ. The experiments described in this article extend this range up to 0.070 λ and calculations have been carried out up to 0.080 λ, thus covering the important range of booms thicker than 12 mm at 1296 MHz.

Acknowledgements

I particularly thank Gordon McDonald, VK2ZAB, and Ian White, G3SEK, for their encouragement and advice in a project that threatened to get out of hand, growing rapidly from a planned single measurement at 1296 MHz into a comprehensive survey over three frequency bands, three boom diameters and five element diameters.

Guy Fletcher was a senior lecturer (associate professor) in Physics (electromagnetism and optics) at Macquarie University in Sydney until his retirement in 1997. He holds a masters degree from Cambridge, UK, and a doctorate from Macquarie.

Guy's previous call signs are G3LNX (UK 1957-1967) and VK2BBF (1967-1998). His amateur interests include VHF/UHF DX on 144, 432 and 1296 MHz, mainly SSB, some CW. He also studies propagation modes on those frequencies, including tropo', sporadic E, ducting and aircraft scatter. He is also active in antenna design and construction.