DL6WU YAGI DESIGNS

The outcome of my own investigations into Yagi design and performance has been a ‘family’ of Yagis which can be designed to meet your own size and performance requirements using just a few charts and tables. These are developed from material originally published in *VHF Communications* [9, 10], and more recently in a Dutch translation by PA0MS [11].

The design guidelines include optimized director spacings and lengths which give a combination of high gain and good suppression of minor lobes over a broad bandwidth. Using these dimensions, longer or shorter Yagis can be designed by simply adding or subtracting elements, down to ***a minimum of ten***. Another design objective was a feed-point impedance close to 50Ω, to avoid the need for a high-*Q* impedance transformer which would restrict the VSWR bandwidth.

ELEMENT SPACINGS AND LENGTHS

Element spacings are given in the table on this page, both individually and measured cumulatively from the reflector. As you will see, the minimum number of ten elements implies a minimum boom length of 2·85λ, *ie* almost 6·0m (20ft) on 144MHz and *pro rata* on the other bands. The spacing increases gradually towards the constant value of 0·40λ for the 13th director and beyond and further directors can be added at this spacing, without limit as far as anyone can see. Yagis of more than 50 elements have been built for 1·3GHz and perform exactly as expected.

To select a suitable boom length, you can start with some idea of the physical size you want, or use the estimated gain figures in the table of element spacings. You must then choose the Yagi which most closely fits your requirements, and accept that particular boom length. You can**not** squeeze or stretch the spacings to fit some stock length of tubing!

Although any DL6WU Yagi will perform well, some are better than others by virtue of having a ‘naturally’ good front/back ratio in excess of 20dB, which may also lead to

ELEMENT SPACINGS FOR DL6WU LONG-YAGIS

Element		Distance along boom (λ)		Approx gain dBd
		Relative	Total	
Reflector		0	0	
Driven		0·200	0·200	
Director	1	0·075	0·275	
	2	0·180	0·455	
	3	0·215	0·670	
	4	0·250	0·920	
	5	0·280	1·200	
	6	0·300	1·500	
	7	0·315	1·815	
	8	0·330	2·145	11·9
	9	0·345	2·490	12·4
	10	0·360	2·850	12·8
	11	0·375	3·225	13·2
	12	0·390	3·615	13·6
	13	0·400	4·015	14·0
	14	0·400	4·415	14·3
	15	0·400	4·815	14·6
		(constant)		
	20		6·815	15·8
	25		8·815	16·6
	30		10·815	17·3
		...and so on		

Fig. 7.7. Optimum director lengths for DL6WU Yagis

slightly improved forward gain. These especially favourable lengths occur in the Yagis with ten elements, 14 or 15 elements, 19 or 20 elements, and so on at intervals of approximately five directors or 2λ in boom length. On the other hand, if you are mostly interested in gain, just go for the longest boom you can manage.

As already stated, the performance of a parasitic director is closely related to the reactive component of its impedance. Elements with equal reactances are essentially interchangeable. Reactance depends on both electrical length and diameter, so a chart of optimum element lengths and diameters will look very much like a reactance chart. Fig. 7.7 shows the optimum length for the first, second, third... director as a function of element diameter in wavelengths. This chart is valid for Yagis with eight or more directors, *ie* ten or more elements in total.

As you might expect, the element lengths 'taper' along the boom. After the first few elements which launch the travelling wave, the director lengths reduce in a logarithmic manner, each being a constant fraction of the length of the one before. Also, thicker elements need to be shorter to give the same reactance as thinner ones.

To use Fig. 7.7, first select an appropriate element diameter. If it doesn't correspond to one of those plotted, sketch in your own curve using the plotted curves as guidelines. Then simply read off the length of each director, in wavelengths, and convert to the frequency of your choice.

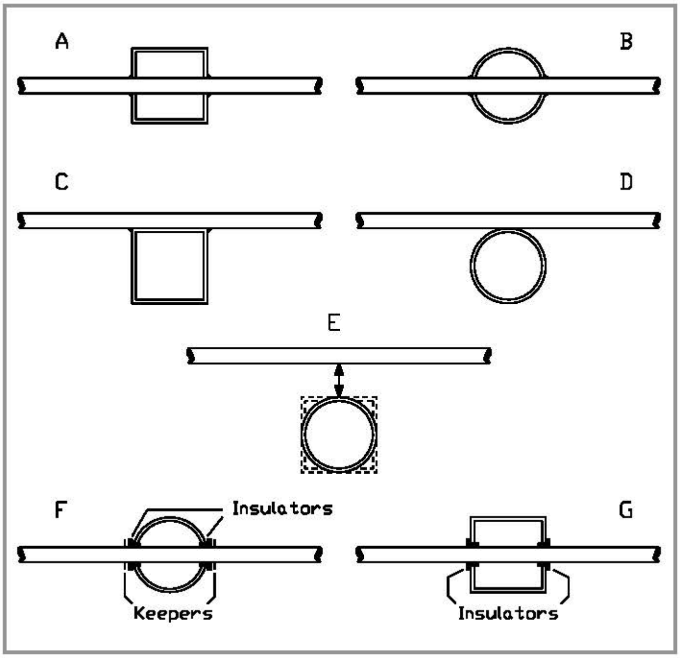
The driven element and reflector lengths should both be a little less than 0·5λ, though both may need to be adjusted. The driven element length should be adjusted for the best match to 50Ω, and the reflector length for best front/back ratio. Neither length is particularly critical as to element diameter except for very thick elements, and the following table gives suitable starting values (in wavelengths) for experiment:

Element diameter	Driven element length Simple dipole	 Folded dipole	Reflector length
0·0001	0·483	0·488	0·494
0·001	0·477	0·482	0·489
0·01	0·456	0·470	0·480
0·02	0·445	0·464	0·474

In fact it is seldom practical to match a simple dipole driven-element directly to 50Ω; you should plan to use a folded dipole and a half-wave balun, especially on the higher bands – see later. The length of the folded dipole is surprisingly independent of the spacing between the two parallel limbs.

Instead of working with charts and tables of dimensions, you can use a home-computer program to automate the design procedure. This has the advantage of allowing you to explore a range of possibilities quickly and easily, without a lot of tedious arithmetic. Jerry Haigwood (KY4Z) has developed a simple and accurate numerical representation of the chart shown in Fig. 7.7. An extended version of his DL6WU Yagi design program is publicly available as a BASIC listing or on disk; further details of availability of computer programs are given elsewhere in this book.

Fig. 7.8. A selection of element mounting methods



The DL6WU designs are really intended for ***long*** Yagis, and are mechanically feasible only at 144MHz and above. There are many suitable designs for shorter Yagis for the lower VHF bands, some of which are recommended in Chapter 9, and also of course there are plenty of other long-Yagi designs. I recommend that, in making your choice, you use only modern designs backed up by some form of accurate evaluation – either by measurements on a test range or at the very least by extensive tests on the EME path – a hard test which tells no lies.

I don't want to decry computer-designed Yagis, but I wouldn't recommend any design that has not also been proven by practical testing in the real world.

ELEMENT LENGTH CORRECTIONS

The element lengths in Fig. 7.7 refer to elements somehow suspended in free space. Lengths of practical elements generally need to be corrected for the effect of the boom and mounting clamps. Also you may want to adapt other Yagi designs besides my own, and this may involve changing the element diameter. If so, you'll need to correct all the element lengths, so I'll show you how to do that too.

BOOM EFFECTS

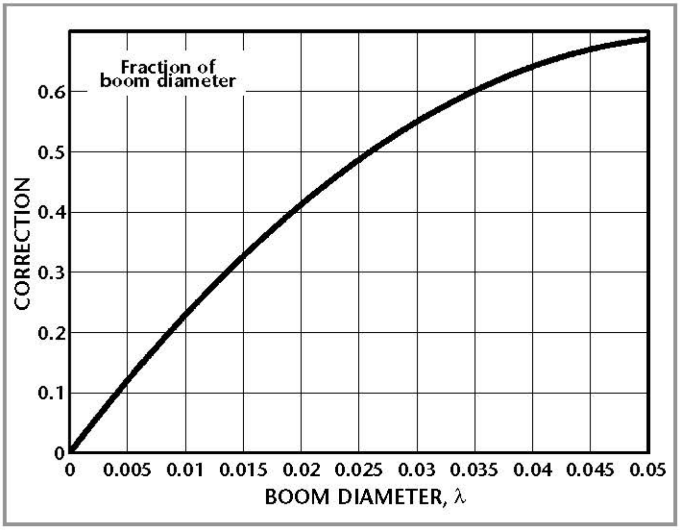
Unless you use only insulating materials to support the elements, the presence of a nearby metal boom and other metal fittings will partially 'short-circuit' the centre of the element and reduce its electrical length. So you will always have to ***lengthen*** the elements to compensate. Ignorance of these boom effects led to Yagis gaining a reputation for being difficult to reproduce, and later to some curious attempts to avoid the need for corrections. However, boom-effect corrections are now quite well understood and you can approach them with some confidence.

The required correction depends on the

element mounting method, and on the thickness of the boom. It also depends to a smaller extent on the length and diameter of the element itself. But your first option is whether to use a metal boom at all or something made of an insulator such as wood or fibreglass. The attraction of insulating booms is that they require no element length corrections. Wooden booms are often touted as being low in cost, but in fact the costs of buying good-quality, straight-grained, knot-free timber and of weatherproofing it so that it ***remains*** an insulator are not insignificant. Fibreglass is a better insulator than wood, but is less rigid and much more expensive.

If you are using a metal boom, your basic options are to connect the elements securely to the boom or to insulate them in a fixed mechanical relationship to the boom. Of the two, the all-metal method has been more thoroughly explored but is open to the effects of corrosion. Insulated mounting schemes to side-step corrosion problems are more recent and less well characterized, but fortunately the corrections are smaller. Fig. 7.8 shows some of the options for element mounting.

Fig. 7.9. Boom-effect correction to be *added* for elements passing through the centre of a metal boom, with a metal-to-metal connection at each side (as in Fig. 7.8A and 7.8B), or connected across the top of a square boom (as in Fig. 7.8C)



Corrections for elements mounted through the centre of a square or round metal boom ***and securely connected to it*** (Fig. 7.8A, B) are shown in Fig. 7.9 as a function of boom diameter in wavelengths. The correction to be added to all element lengths is approximately one-quarter of the boom diameter for a boom diameter of 0·01λ, and a somewhat larger fraction of the boom diameter for thicker booms. A diameter of 0·01λ corresponds to 20mm at 144MHz, so you'd need to add about 6mm or 0·25" to all element lengths if you chose this mounting method. For elements sitting on top of a square metal boom (Fig. 7.8C), the correction is about the same as that for mounting through the middle; but once again you'd need to ensure a solid long-term electrical connection. The correction for elements either touching or almost touching the top of a round boom (Fig. 7.8D) is approximately halved. Elements mounted on insulators further away from the top of the boom (Fig. 7.8E) require very little adjustment, the correction dwindling rapidly from 50% of the through-boom value to 5% or less for elements mounted one boom-radius away from the boom surface.

Another mounting method which has recently gained popularity is to mount the element through the centre of the boom on insulating shoulder washers. The correction required depends on the type of washer, and also whether metal 'keepers' or pure friction are used to hold the element in place (Fig. 7.8F, G). K1FO has published corrections for elements of $^3/_{16}$" diameter at 432MHz, for a specific mounting method using shoulder washers and metal keepers [6, 12]. A correction of 5mm has been determined at 432MHz for 4mm diameter elements mounted in 6·3mm diameter holes through a 20mm square boom, as in Fig. 7.8G. This is about 50% of the through-boom value in Fig. 7.9, and I would estimate a similar fraction of the through-boom value for 144MHz also.

It is difficult to predict the effects of the many element-clamping arrangements used in commercial antennas from which you might salvage the fittings. Fortunately it's quite easy to measure the corrections using a two- or three-element Yagi with an insulating boom: just replace the original director with a test element mounted in your chosen manner and change its length to restore the original VSWR conditions [13, 14].

ELEMENT DIAMETER

In presenting the design tables for DL6WU Yagis, I've already mentioned the effects of element diameter (thickness). The same effects apply if you want to build some other published Yagi design using elements of a different diameter. This often happens because continental Europe works in metric sizes, the USA works in inches, and the UK is caught between the two – which means that whatever size you need, it will always be out of stock!

The way to tackle this problem is to remember that elements having equal reactance are interchangeable. So you first calculate the reactance of the original element, and then calculate the length of the new element having a different diameter but the same reactance.

A formula for element reactance is:

$$X = \left\{430\cdot 3\log_{10}\left(\frac{2\lambda}{D}\right) - 320\right\}\left(\frac{2L}{\lambda} - 1\right) + 40\Omega$$

where D is the element diameter and L its length. This is a bit of a mouthful, but is easily handled by a programmable calculator or a home computer.

Let's assume that we start with a 144MHz director element of $^{3}/_{8}$" diameter, length 35", and we want to convert this to use 4mm-diameter aluminium welding-rod. Inserting the numbers into the formula (don't forget to use λ in inches, the same as the other dimensions) gives a reactance of –79·1Ω. Now work the formula backwards to calculate a new value for L, given X and the new D=4mm.

$$L = \left[\frac{(X-40)}{\left\{430\cdot 3\log_{10}\left(\frac{2\lambda}{D}\right) - 320\right\}} + 1\right]\frac{\lambda}{2}$$

The new value for L is 914·2mm, which is 25mm longer than the original 35", as you'd expect for a thinner element. The program disk mentioned earlier has a simple BASIC program called ELE to automate this entire process.

Whatever element diameters you select, the best material is generally aluminium alloy – preferably a corrosion-resistant grade, especially if you live in an industrial area or near the sea. Welding rod of 4mm diameter is an excellent choice for both 432MHz and even 144MHz, although it may not be available in the metre lengths required for the latter band. Hard-drawn enamelled copper wire of about 3mm diameter can be used for 432MHz elements. Brass is not a good material for antenna elements, because it is prone to fatigue cracking. Although stainless steel is springy and highly resistant to corrosion, it is also lossy; its use may cost up to 0·5dB of gain at 144MHz and even more at 432MHz.

Element diameters for 144MHz and below depend critically on whether your winter climate includes storms which build up thick and heavy layers of ice. If so, the elements must be strong enough to support the ice loading, which rules out thin aluminium rods and tubes. Ice storms are fortunately rare in most of the UK, so element diameters as thin as 9mm ($^{3}/_{8}$") can be used down to 50MHz. Elements for 50 and 70MHz made from thick-wall 9mm tubing can withstand practically any gale, if reinforced at the centre with a 12mm sleeve (no length correction is necessary if the sleeve is less than about 200mm long).

By the way, if you are modifying someone else's practical design, you'll need to remove his boom-effect correction before applying the above formulae and then apply a new correction for your own element mounting method. The hardest part of this is to estimate someone else's boom-effect correction, though fortunately more and more designers are mentioning this in their published articles.

MAKING THE ANTENNA WORK

Adjustment of a DL6WU or any other type of

Yagi should be straightforward, especially if you know what to expect.

First, check the VSWR. All the DL6WU Yagis give a fairly good match to 50Ω, although this can be improved in any particular case by minor adjustments to the lengths of the folded dipole and the first director, which functions mainly as a matching element. Note that I said ***minor*** changes in those two element lengths, to improve a match that's already reasonably good. If the antenna shows absolutely no sign of matching properly, there's a fault somewhere in its construction and you will need to find it and fix it. Other types of antennas which require matching adjustments are best dealt with by pointing the antenna towards the sky and adjusting the driven element while it's comfortably within reach (Fig. 9.43).

Any major faults in antenna construction will show up in the radiation pattern. As a preliminary check, look for a symmetrical E-plane pattern with deep nulls at ±90° and reasonably well-suppressed minor lobes. You can't tell too much from the rear lobe, although it should be well-suppressed, but the first sidelobes can be very revealing. The following remarks apply only to long multi-element Yagis; Yagis with six or fewer elements tend not to have first sidelobes at all, or else they are completely hidden by the ±90° nulls.

All the DL6WU long Yagis have first E-plane sidelobes about 17dB down, which should be separated from the main lobe by a distinct null. If the nulls are too deep and the first sidelobes are too well-suppressed (–19dB or more), the antenna is operating on too low a frequency, *ie* its elements are too short. This can easily happen if you've underestimated the electrical shortening effect of the boom. On the other hand, if the first sidelobes of a long Yagi are poorly suppressed (–15dB or less) or merge into the main lobe, the antenna is operating on too high a frequency, *ie* its elements are too long. Either case – all elements too long or all too short – will produce less than the maximum attainable forward gain.

The gain reduction is less rapid if the elements are all too short, so it's better to err on that side than to fall over the steep 'cliff' on the HF side of the gain-frequency curve. Rain will also move the antenna HF on its gain-frequency response, so all the DL6WU Yagis contain a 1-2% element length allowance to guard against this possibility. K1FO has found that stacking his own highly-optimized Yagis tends to detune them in the same HF direction; he believes that antennas that are already close to the gain cliff can be pushed over when stacked in arrays, with disappointing results [6, 12]. If part of the process of optimization has been to move the Yagi to the top of its gain curve, any change due to interactions or rain will obviously be even worse.

WHICH COMMERCIAL YAGI?

It can be very difficult to choose a commercial Yagi on the basis of the manufacturer's claimed performance, because many claims are notoriously inflated. To give you some standard for comparison, overleaf are two tables of Yagi performance predicted by Rainer Bertelsmeier DJ9BV using the NEC3 computer program [15, 16]. The apparent accuracy of NEC in these applications is about ±0·2dB on gain and ±0·5dB on sidelobe levels down to –20dB; this is at least as good as any commercial antenna range at VHF or UHF. Moreover, NEC provides a constant yardstick against which we can judge antennas, regardless of where and when they were manufactured.

The antennas featured in these tables are a mixture of commercial products and published amateur designs. Most of the designs are for long Yagis, although the 144MHz table includes some shorter Yagis which could be suitable for 50MHz or 70MHz. The tables show the boom length, number of elements, and the calculated and claimed forward gains. As an additional measure of performance, the gain calculated by NEC is compared with the gain to be expected from a Yagi of the same boom length using the equation I gave earlier; this column is labelled 'Gain/exp'. Data on beamwidths and front/back ratio are also given.

As you might expect, some antennas are good for their length, and one or two are very bad! This is shown most plainly by the deviations from the expected relationship of gain versus length. 50MHz and 70MHz enthusiasts will already have noticed that the five- and six-element NBS designs are good performers for their size. A few of the longer Yagis also seem to give a little more gain than expected, especially if they have a favourable boom length like the DL6WU 30-element, or have been highly optimized like the K1FO 22-element. Within reason, the number of elements is not relevant, especially when some designs use multiple reflectors and others do not.

Unlike simpler types of gain calculation, including those using the W2PV program and MININEC, the calculations by DJ9BV using NEC take account of skin-effect losses, which affect some designs worse than others. Typical efficiencies for antennas using aluminium elements are 98% or greater, equivalent to resistive losses of less than 0·1dB. However, these losses are proportional to the squares of the currents flowing in the elements, so the effect of undue concentrations of current into a few elements can be quite marked. Computer analysis of well-optimized Yagis shows that the magnitudes of the currents in all elements are quite similar and vary in a progressive manner. However, optimization using computer programs which take no account of resistive losses can easily go 'off the rails', leading to designs which do not perform well in reality.

Considerably greater loss of efficiency arises from the use of elements made from poorer conductors than aluminium. For example, although the HAG range of antennas are DL6WU designs and should in principle fall close to the standard gain projection, the use of thin stainless-steel elements leads to low efficiency and loss of gain.

YAGI PERFORMANCE

144MHz

Design/type	Boom (λ)	Ele	Gain (dBd) NEC	Claim	Gain/exp (dB)	φE (°)	φH (°)	1sl (dB)	F/B (dB)	Notes and references
CC DX-120	0·7	20	12·1	14·0	–	47·0	27·5	–	22·8	Colinear (Fig. 7·3D)
NBS 5-el	0·8	5	9·0	9·2	+0·5	48·0	58·0	25·0	14·1	[5]
JB Q6/2M	1·2	6	9·85	10·9	0·0	46·5	49·0	21·5	11·0	Quad
NBS 6-el	1·2	7	10·2	10·2	+0·3	41·5	47·5	19·2	17·4	[5]
Tonna 9-el	1·65	9	11·0	10·95	0·0	40·0	45·4	20·4	16·7	Newer version only
W1JR 8-el	1·75	8	11·0	>10·85	–0·2	37·2	41·0	17·0	16·7	[8]
Tonna 13-el	2·13	13	11·35	11·85	–0·5	36·3	40·0	17·0	17·5	
HAG FX-224	2·35	11	11·8	12·4	–0·4	35·2	38·5	16·8	17·1	DL6WU (steel eles)
JB PBM14	2·8	14	12·6	13·7	–0·15	30·7	33·5	13·1	13·6	Parabeam
Tonna 16-el	3·1	16	12·65	15·65	–0·4	34·0	37·0	18·8	21·0	
CueDee	3·1	15	12·9	14·0	–0·2	33·0	35·5	17·5	21·5	
Tonna 17-el	3·2	17	12·9	13·15	–0·3	33·0	35·7	19·0	30·0	
CC 3219	3·2	19	13·1	16·2	–0·1	29·4	31·2	13·5	30·5	
DL6WU	3·6	15	13·6	13·6	0·0	30·5	32·5	18·2	36·0	[17]
HG 215B	4·1	15	12·85	15·65	–1·2	25·0	26·0	10·4	15·6	
KLM LBX-16	4·1	16	14·05	14·5	0·0	28·0	29·5	15·6	22·6	Mod DL6WU
CC 4218	4·2	18	14·1	17·2	0·0	27·0	28·5	15·4	18·5	Mod NBS
KLM LBX-17	4·5	17	14·4		0·0	27·0	28·5	15·8	20·0	Mod DL6WU
M2-5WL	4·8		14·4	15·0	–0·2	26·3	27·5	16·5	20·0	
KLM-16	5·2	16	14·15	–	–0·7	25·0	26·0	11·5	19·8	
K2RIW 19-el	5·6	19	14·95	15·1	–0·2	27·0	28·3	17·0	20·4	[18]
K1FO-22	6·1	22	15·7	15·7	+0·3	24·7	25·7	17·2	21·2	[12]
Tonna 21-el	6·7	21	15·75	16·05	–0·2	24·0	25·0	15·7	40·0	With balun
HAG 723	7·3	23	15·4	15·8	–0·6	23·0	24·0	17·5	18·5	DL6WU (steel eles)
CC 424B	7·6	24	15·9	18·2	–0·2	20·3	20·9	12·7	29·2	
DL6WU 30-el	8·8	30	16·8	16·6	+0·2	22·1	22·9	16·1	40·0	
W1JR 31-el	10·4	31	17·55	17·25	+0·35	20·8	21·2	18·8	28·1	Mod DL6WU [19]
K1FO-32	10·5	32	17·55	17·5	+0·35	20·0	20·5	17·2	23·7	[6]
M2-13WL	13·3		17·95		–0·05	19·3	19·8	15·4	24·4	

Manufacturer abbreviations: CC = Cushcraft, JB = Jaybeam, HG = Hy-Gain, M2 = M^2 (K6MYC)

You'll also surely have noticed that there is scarcely a single instance of over-modest claimed gain! Some claims are grossly inflated, especially for the older designs and for certain manufacturers. It is ironic that many of the antennas with highly exaggerated claimed gains are actually quite good, so the advertising 'hype' was unnecessary. Some manufacturers, for instance Antennes Tonna, are now taking great trouble to make realistic and verifiable performance claims for their current production antennas. This is a highly creditable policy, especially since new antennas may have ***lower*** claimed gains than the products they replace. A manufacturer who has had the courage to take this step should ***not*** be rewarded by 'clever' people asking embarrassing questions about their old catalogues!

FEEDLINES, TRANSFORMERS AND BALUNS

A chapter on antennas would be incomplete without consideration of the feedlines connecting them to your station. After all, a 3dB cable loss means converting half your precious power into heat, and to make up for that loss you'd have to double the size of your antenna at least. Impedance transformers are important because they are used as power dividers in stacked arrays. I'll also have something to say about the much-misunderstood subject of baluns.

FEEDLINES

In 99% of all cases, 'feedline' today means coaxial cable. But it wasn't always so; VHF amateur radio began with home-made open-wire feedline, and open wire has recently made a comeback in the highly demanding area of moonbounce antennas. So let's begin by taking a critical look at both types of feeder.

Open-wire feeders – or parallel lines – are characterized by their spacing and wire diameter. These parameters determine the characteristic impedance (Z_0) by the simple relationship:

$$Z_0 = 276 \log_{10}\left(\frac{D}{r}\right)$$

where D is the centre-to-centre spacing and r is the wire radius.

In principle, open-wire feeders can have very low losses. Apart from the insulating spacers, the dielectric between the lines is air and only a vacuum has lower dielectric losses. Radiation losses are surprisingly low provided that the wire spacing is a small fraction of a wavelength, leaving only the ohmic resistance of the conductors themselves as a source of loss. As the power dissipated is proportional to the square of the current, higher values of Z_0 are more favourable. For example 2mm wires spaced 100mm apart have a characteristic impedance of 552Ω. Assuming a λ/D ratio of 25 to be acceptable, this line could be used on HF and up to 70MHz with excellent results. For 144MHz, the spacing must be reduced to avoid radiation losses, and rather than use thinner wire it's generally better to accept the slight increase in resistive losses due to the lower value of Z_0. Such an open-wire line would still outperform half-inch coax as far as loss is concerned.

The situation on 432MHz is a little worse, though open wire still can have lower losses than coaxial cable. A further reduction in spacing is dictated by the wavelength, but it also becomes reasonable to increase the wire diameter to make the feeder semi-rigid and almost self-supporting. With a spacing of 25mm and 2mm wire, Z_0 is reduced to 386Ω. Other problems then emerge, like keeping the spacing constant, preventing dirt from forming current bridges on the spacers, and the field distortion by the spacers which can upset your calculations of impedance and velocity factor. Even so, there is still a case for using open-wire feeders for interconnections within an array of several Yagis for 432MHz EME, where 0·1dB may make a noticeable difference. 432MHz marks the upper-frequency limit of parallel-wire feeders. I won't even discuss TV ribbon, which has no place in serious VHF/UHF work.

Turning to coaxial cable, the advantages are obvious: the dielectric and current-carrying surfaces are inside, free from mechanical, electrical and climatic influences. Ground potential on connectors and the cable sheath reduces hazards and the danger of short-circuits. Unwanted radiation, signal pickup or coupling to other circuits are almost non-existent. Cables are (mostly) flexible and easy to install, *etc etc*. The main drawbacks of coaxial cable are weight, cost and particularly loss, which can be a real headache for VHF and UHF amateurs.

The main sources of loss in coaxial cables are – in approximate order of importance – resistive (skin-effect) loss in the centre conductor, RF leakage through a braided outer conductor, dielectric losses in the insulating material, and resistive losses in the outer conductor. The reason that losses in the centre conductor are so important is that the current density on its surface is much greater than on the outer conductor, and this is made worse by the low impedance of coaxial cables. A 50Ω cable carries ten times the current of a 500Ω line at the same power level. Dissipation in the centre conductor alone is 50 times greater than in open-wire line with the same conductor diameter!

This example shows how unfortunate the choice of 50Ω as standard impedance was. It owes its widespread acceptance to its abundant use by US armed forces during World War II and afterwards – as also does the horrible PL259/SO239 'UHF' combination. The 60Ω standard used in European broadcast applications was chosen for maximum breakdown voltage in a given outer diameter, and 75Ω TV cable was designed for lowest loss per unit weight. In principle, either would be preferable to 50Ω in applications where loss is critical, but cost and compatibility usually make it more economical to use a heavier 50Ω cable instead.

For a fixed cable diameter, loss is not dictated by the characteristic impedance alone because the diameter of the inner conductor also depends on the dielectric. In coaxial lines the characteristic impedance is given by approximately:

$$Z_0 = \left(\frac{138}{\sqrt{\varepsilon}}\right)\log_{10}\left(\frac{D}{d}\right)$$

where ε is the dielectric constant of the insulator, D the ***inner*** diameter of the outer conductor and d the diameter of the inner conductor.

The higher the dielectric constant of the insulating material, the thinner the centre conductor needs to be, which may be useful if low cost is more important than low losses. Our priorities are different: we are always looking for lower losses in our coaxial cables and are generally prepared to spend a little more. Moving upmarket, foam insulation has a lower dielectric constant than a solid. This means that the diameter of the inner conductor must be increased to maintain a 50Ω impedance, so the cable has lower losses but costs more. Taking this one step further, air-dielectric cable is widely used in professional installations and sometimes appears on the surplus market. It is recommended only if it has always been pressurized to exclude moisture, and if you're prepared to continue to look after it in the same way (not too difficult: use a fish-tank pump). Semi-air-spaced cables like H100, Westflex 103 or Belden 9913 are just as vulnerable to moisture ingress, and can be a load of trouble unless you seal the joints with extreme care [20].

A small part of the attenuation in coaxial cables is caused by leakage and resistive losses in the outer conductor. A smooth, solid tube would be best, of course, but some flexibility is almost always necessary. The first steps up from ordinary single-braid coax (*eg* RG213 or URM67) are double-braid (RG214) or cables with braid over copper foil (H100, W103 and 9913), both of which have good flexibility. Better still is solid copper or aluminium, ribbed for flexibility. Despite the lower conductivity of aluminium compared with copper, it is acceptable as an outer conductor because of the lower current density and also allows considerable savings in cost and weight over solid copper.

Further cost savings are possible by taking advantage of the fact that the RF current on the inner conductor flows only on the surface, so the entire conductor doesn't need to be solid copper. A solid copper conductor is preferable in small cables because it has lower losses than a stranded conductor, but in larger cables the centre conductor is often either a copper coating on an aluminium core or a hollow copper tube.

The table of cable data is intended mainly to illustrate the differences between various cable types rather than as a complete reference. It also serves to show that RG213 (URM67), the old standby, should really be used only where it cannot be avoided. The other 50Ω cables are manufactured and sold under a variety of names (Flexwell, Cellflex, Heliax *etc*). Except for the low-cost H100/W103/9913 the best cables are of rugged construction with solid corrugated copper shields. For amateur installations the polyethylene and PTFE foam types are the easiest to use.

Special highly flexible versions of these cables (*eg* Kabelmetall HCF) are ideal where frequent bending is necessary, although the connectors are heavy and costly.

Summing up the practical implications of all these various kinds of coaxial cables, it is advisable to make the long cable run from stiff, low-loss cable and use a short piece of flexible line to bridge the rotator. If the bridge is made using good connectors (a pair of N-types has less than 0·05dB loss at 432MHz) that is a tolerable sacrifice.

Be prepared to spend good money on the main cable run, and look after it well, because it's one of the most important parts of your station.

IMPEDANCE TRANSFORMERS AND POWER DIVIDERS

Transmission lines find widespread usage as matching devices in VHF/UHF equipment. Although in principle they can accomplish any kind of complex impedance transformation, we amateurs rarely have instruments suitable for measuring complex impedances at VHF and UHF under outdoor conditions so we try to make our antenna impedances straightforward and non-reactive. We can therefore manage very well with simple quarter-wave transformers for matching to the feedline.

COAXIAL TRANSFORMERS

Transformation between 'real' (*ie* non-reactive) impedances is easily checked by VSWR measurement and substitution of loads by terminating resistors – see Chapter 12 for a full explanation. To transform between two real impedances Z_1 and Z_2, all one needs is a quarter-wave line with the characteristic impedance $Z_0 = \sqrt{Z_1 Z_2}$. Coaxial transformers for outdoor use are most easily made from square tubing, with cylindrical wire or tubing for the centre conductor (Fig. 7.10). The characteristic impedance of such a line is:

$$Z_0 = 138\log_{10}\left(1{\cdot}08\frac{D}{d}\right)$$

MATCHED ATTENUATION OF 50Ω COAXIAL CABLES

Type	Atten (dB/100m)				OD	CC	Dielectric	Notes
	50MHz	70MHz	144MHz	432MHz	(mm)	(mm)		
UR76	12	14	19	32	5·0	7/0·32	PE	Near equiv. RG58
UR67	4·6	5·6	8·4	15·5	10·3	7/0·77	PE	Near equiv. RG213
H100	3·2	3·8	5·5	9·8	9·7	2·5	PE/air	
Westflex 103	2·0	2·5	4·5	7·5	10·3	2·7	PE/air	
¼-inch	3·8	4·6	6·9	12·6	various		Foam PTFE	Corrugated hardline
½-inch	1·5	1·8	2·8	5·1	various		Foam PTFE	Corrugated hardline
$^7/_8$-inch	0·9	1·1	1·5	2·8	various		Foam PTFE	Corrugated hardline

Values for amateur bands are estimated from data for other frequencies. Values for hardline are typical of that size.

OD	outside diameter over plastic sheath	PE	polyethylene
CC	centre conductor diameter	PTFE	polytetrafluoroethylene

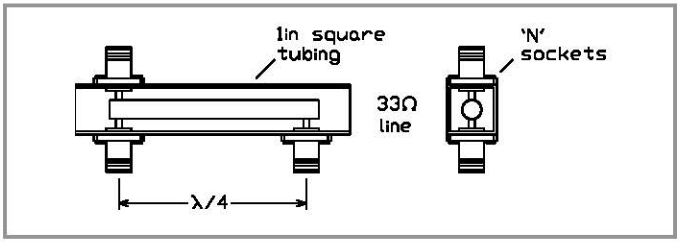


Fig. 7.10. A 50Ω two-way power divider made from square-section tube

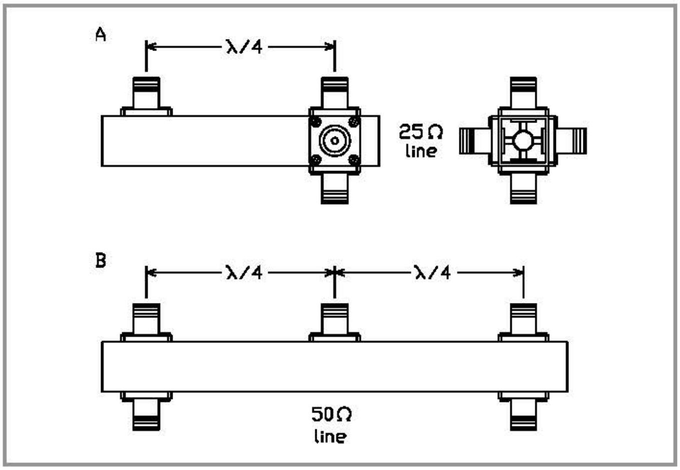
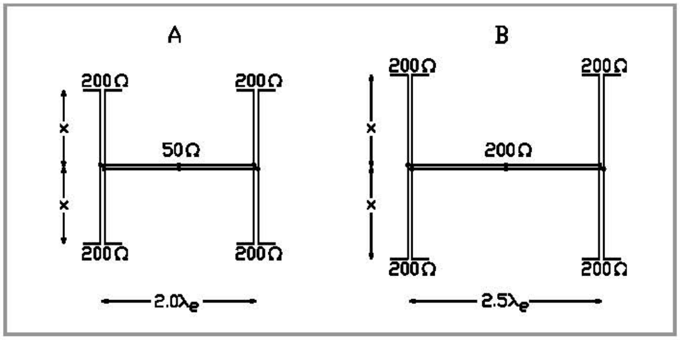


Fig. 7.11. Two types of four-way 50Ω power divider: quarter-wave (A) and half-wave (B)

Fig. 7.12. Two possible ways of feeding four 200Ω Yagis using 200Ω open-wire line. Dimension 'x' is the optimum vertical stacking distance for the Yagis in use. A and B show alternative methods, depending on the horizontal stacking distance required



where D is the ***inner*** width of the square tubing and d the ***outer*** diameter of the centre conductor. Air is used as the dielectric so there is no velocity-factor correction; the end-to-end length of the inner line must be ¼ of a free-space wavelength.

When line transformers are used as combiners (also known as power dividers) in stacked arrays, some thought should be given to low-loss design. As pointed out before, high currents should be avoided; this means keeping impedance as high and VSWR as low as possible. Take for instance the case of four 50Ω antennas to be connected to a common 50Ω line. This could be done by paralleling all four and then transforming the resulting 12·5Ω with a 25Ω quarter-wave section (Fig. 7.11A). Or it could be done in two steps (Fig. 7.11B): combine each pair of antennas to give 25Ω, and use a 50Ω quarter-wave transformer to give 100Ω; when the two 100Ω points are connected in parallel at the centre, the result is 50Ω. This latter method, called a half-wave combiner, is far superior to the simple quarter-wave combiner in both bandwidth and low-loss performance.

As a general rule when working with coaxial lines, and especially on the higher bands, treat interconnection and impedance transformation as two separate functions. Transforming should be done in low-loss air-dielectric line sections, and interconnecting by (short) runs of matched cable. In other words, don't use ordinary coaxial cable for impedance transformation if you are at all concerned about losses.

Construction of 'square-line' impedance transformers is very simple. Begin by finding some 25mm or 1" square aluminium tubing, which will conveniently accept N-type connectors on its flat faces (Fig. 7.10). Measure the inside dimension and work out what diameter of copper or brass tubing you need for the inner line. The only difficult bit may be to find this tubing! If in doubt, you can use the next smaller size and bring the characteristic impedance down to the exact value you require. You can do this either by mounting the tube slightly off-centre, or by lining the tube with a thin flat sheet of aluminium. If you use these tricks, make sure the effects apply equally to both sides of the power division; you can only do this for two-way or half-wave four-way dividers.

You can leave the ends of the inner tube open. The ends of the square tubes are also field-free if they extend a few centimetres beyond the connectors, so they only need to be sealed against water ingress. It would be nice to make one end-cap from something transparent, so you can see at a glance if any water has crept in.

The following table shows the impedances to be used for quarter-wave and half-wave 50Ω combiners, and the corresponding D/d ratios. Since we all seem to have access to differing sizes of tubing, you probably need to take a pocket calculator to the metal shop and work out what can be done with the materials available.

		Z_0	D/d
Two-way	λ/4	35·4	1·67
Three-way	λ/4	28·9	1·50
Four-way	λ/4	25·0	1·41
Four-way	λ/2	50·0	2·13
Six-way	λ/2	40·8	1·83

The largest number of Yagis to be joined in a single combiner is six. For an eight-Yagi system, make two groups of four and then connect the two groups to a two-way combiner at the central feedpoint. A sixteen-Yagi system will require a total of five four-way combiners – plus at least 25 N-type plugs and sockets... quite a strong argument for open-wire feedline!

OPEN-WIRE FEEDLINE

The inherent balance of parallel open-wire lines makes them well suited for both interconnections and impedance transformation. Yagi antennas with 200Ω folded-dipole driven elements are ideal for feeding with 200Ω open wire. Fig. 7.12 shows two schemes for combining four Yagis in this way, with very simple matching to 50Ω coaxial feeder. Since the Yagis and the open-wire feedline have the same characteristic impedance, any vertical stacking distance can be used without affecting the impedance matching. The length of the horizontal cross-piece of feeder depends on the horizontal stacking distance for the particular Yagis in use. Shorter Yagis which require horizontal spacings in the range 1·9-2·2λ can use a 2·0λ (electrical) cross-piece as shown in Fig. 7.12A. This transforms the feedpoint impedance of the array of four Yagis to 50Ω, which can be connected to the coaxial feeder via a λ/4 sleeve balun. For longer Yagis requiring horizontal stacking distances of 2·2-2·5λ, the cross-piece should be 2·5λ (electrical) which gives a feedpoint impedance of 200Ω, the same as an individual Yagi.

The velocity factor relating the physical to the electrical length can be very high for open-wire feeders – as high as 0·975 if the dielectric spacers are few in number and located away from voltage maxima. Measurement of the velocity factor is very simple. Connect a length of the open-wire line to a low-power RF source (*eg* by a 4:1 coaxial balun), terminate the far end and monitor the VSWR in the coax line from the RF source. If you lay an insulated screwdriver across the open wire and slide it along, you will see a disturbance in the VSWR which repeats itself every electrical half-wavelength.

Doing away with baluns, cables, transformers and connectors saves a lot of weight, loss and money. But there is a price for everything; open-wire feeders are quite critical in dimensions and installation and they can also be weather-sensitive and mechanically unstable unless you're very careful. And open-wire lines cannot be lengthened or shortened very easily, so you'd better be sure about your velocity factor and stacking distances before you commit yourself.

When working with open-wire feeders, small impedance errors tend to accumulate and the bandwidth of satisfactory performance is usually very narrow; fortunately, this doesn't matter for DX antennas. Be prepared to do a lot of experimenting, but also be prepared for some benefits: you can trace the voltage maxima and minima by just waving your hands around the feedline and watching the VSWR, and you can also fine-tune the impedance match by bending the wires in the right places! Naturally, these hands-on adjustments should be made using extremely low power (Chapter 12). Most open-wire feed systems require an adjustable impedance transformer somewhere in the system, probably at the central feedpoint. This can be combined with the symmetry transformer (balun) required for the transition to coax.

The rules for installing open-wire feeders have been set down by DL9KR and G3SEK in K2UYH's *432MHz Moonbounce Newsletter*.

1 Use heavy-gauge enamelled copper wire, *eg* 3mm, to make the feedline largely self-supporting. Avoid clear polyurethane enamel; it doesn't stand up to sunlight. The best grade of enamel is dark brown, and very difficult to scrape off for soldering.

2 Buy soft-drawn wire, and stretch it out straight immediately before use. For heavy wire, you'll need a stout post or tree and a towing hitch on the car!

3 Use only straight runs of feeder and make all joints at right-angles. This is ***vital***.

4 Pre-stretch the individual wires, and then construct each section of feeder to the correct length ***before*** installation. Keep the two sides of each section of feeder ***exactly*** the same length.

5 Use a minimum of spacers made from solid PTFE rod, and avoid placing them at voltage maxima.

6 To make a straight joint between two wires, use a small sleeve made from brass or copper tubing. To make a T-joint, drill a hole across the end of a piece of tubing. Slip one of the wires through the hole and the other wire into the open end of the tube. Crimp the wires in place and then use an enormous soldering iron. Waterproof all joints with polyurethane spray; although susceptible to sunlight, polyurethane varnish has the great advantage that it doesn't need to be scraped off before soldering if repairs should be necessary at a later date.

7 Keep the feeder well away from other conducting objects.

8 Avoid using mechanical supports for the feeder, other than the antennas and the junction to the main feedline.

9 Avoid high VSWR in any section of feeder, to minimize the effects of rain and frost at high-impedance points. The two arrangements in Fig. 7.12 involve a VSWR nowhere greater than 2.

The overall result may be well worth the effort. EME operators have reported up to 3dB improvement in noise performance over crude coax feed in large 432MHz arrays, although that is extreme. More often you could expect an open-wire feed system for a large 432MHz EME array to be at least as good as a coaxial system made from heavy hard-line – and probably cheaper, lighter and easier to construct. But don't expect miraculous results in horizon modes and on lower frequencies. If you want an all-purpose array for both ends of the band and in any kind of weather, open-wire feed is probably not for you.

BALUNS

Most antennas are symmetrical, *ie* balanced with respect to ground, so a transition to unsymmetrical coaxial cable must be provided somewhere in the system. A balance-to-unbalance transformer or *balun* is usually fitted at each individual antenna feedpoint, or at the central feedpoint if open-wire line is used within the array. There are many types of balun; some of them involve impedance transformation as well, although that is not essential to the balun function.

There are a lot of misconceptions about baluns and whether you really need them, so

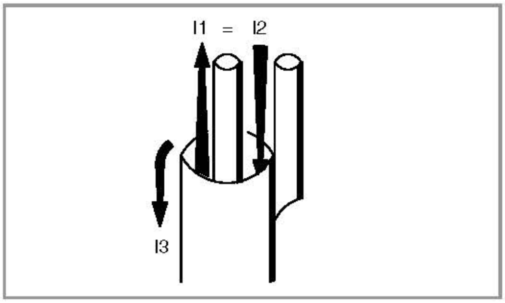


Fig. 7.13. Currents flowing on the inside and outside of a coaxial cable. Currents I1 and I2 on the inside of the cable are always equal. If the system is unbalanced, a current I3 will flow on the outside of the outer sheath

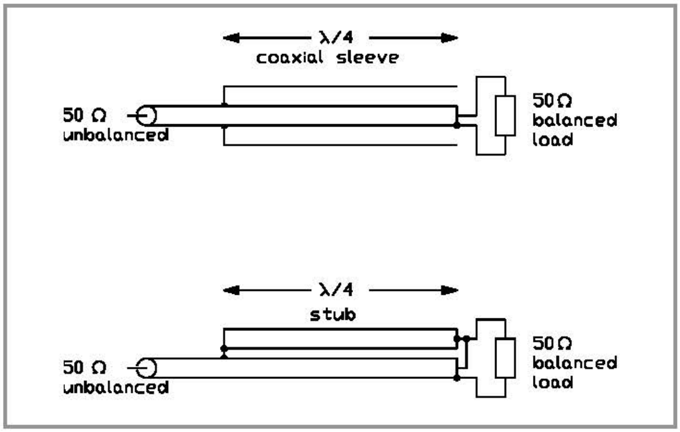


Fig. 7.14. Quarter-wave sleeve and stub baluns, which give no impedance transformation

let's establish what a balun needs to do. Beginning at the coaxial side of the junction, the currents I1 on the inner conductor and I2 on the ***inside*** of the outer conductor are always equal (Fig. 7.13), because the inner and outer conductors of the coax are very closely coupled. However, as a result of the 'skin effect' which confines RF currents to the surfaces of conductors, there is another possible path for a current I3 on the ***outside*** surface of the outer conductor. If the antenna feedpoint is truly balanced with respect to ground, a voltage minimum occurs at that precise point along the driven element. When you connect the coaxial feeder, there would be no EMF to drive the current I3 along the outside surface and all would be well.

In real life, however, the antenna feedpoint is never exactly balanced so an outer-surface current ***will*** flow unless something is done to stop it. Otherwise, stray RF currents can flow along the boom and the boom braces, down the mast, into the rotator cables, down the main coax feeder and into the shack. These in turn give rise to unwanted radiation, pattern distortion, RF feedback, TVI and all kinds of funny effects. So you ***do*** in fact need a balun, to force the system into balance and actively prevent currents from flowing down the outer of the coax.

To see whether you have problems with feedline radiation, check for energy on the outside of the feedline and for radiation off the sides of the beam where the ±90° nulls should be. Another fairly reliable test for RF currents on the outside of the coaxial cable is to see whether different lengths of cable affect the VSWR. In principle this shouldn't happen, because the VSWR is an indicator of conditions ***inside*** the cable and an extra length of the same type of cable should have no effect. But if there are currents on the outside of the cable, changing the length will affect the current distribution all the way up to the feedpoint, and will therefore affect the VSWR. If merely grasping the outside of the cable changes your VSWR, something is *very* wrong!

Low-impedance symmetrical feedpoints should ***never*** be connected to coaxial cables without some sort of symmetry transformation. The very least you can do is to ground the cable shield to the metal boom ¼ wavelength (in air) from the feedpoint. This creates a high impedance against outer-surface currents at the feedpoint and hopefully discourages current flow. That technique was recommended for many years by Antennes Tonna and is better than nothing, but it's still rather a weak method of forcing balance upon the system. If you want a 50Ω balun without an impedance transformation, it's much better to use a proper quarter-wavelength sleeve balun or a quarter-wave stub (Fig. 7.14). On 50MHz and 70MHz you can also use a trifilar-wound balun, either air-cored or wound on a ferrite rod [20], but take great care to keep the wires closely coupled and all leads short [4]. One-sided matching devices – gamma matches and the like – are not very satisfactory because they don't actually make a proper balance-to-unbalance conversion and you may have to take additional precautions to eliminate the last traces of current on the outer surface of the feedline and along the boom.

The most successful VHF/UHF balun is the half-wave coax loop transformer which converts 200Ω symmetrical to 50Ω unsymmetrical (Fig. 7.15). This method is state-of-the-art and to be preferred to most others, because the close coupling between

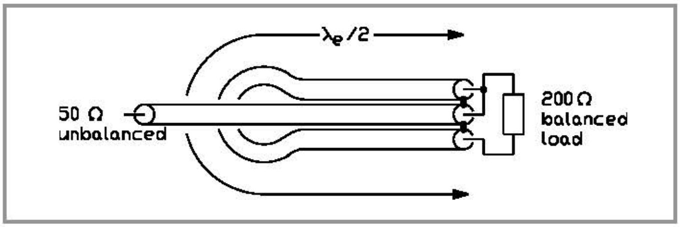


Fig. 7.15. Half-wave balun, which also transforms 50Ω unbalanced to 200Ω balanced. The loop is an electrical half-wavelength long

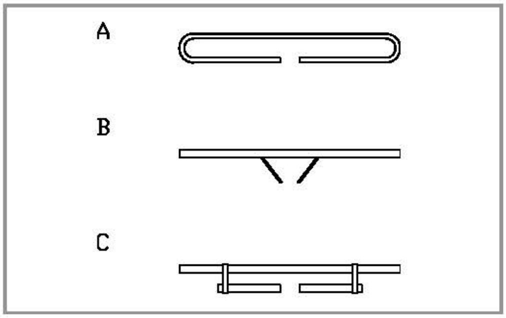


Fig. 7.16. Three methods of matching a driven-element to 200Ω balanced, for use with a half-wave balun (Fig. 7.15). If the driven element impedance would be 50Ω, a simple folded dipole (A) can be used. The Delta-match (B) and T-match (C) are adjustable

the inner and outer conductors of the coaxial cable forces the system towards balance. The DL6WU Yagis have a natural feedpoint impedance close to 50Ω and could therefore be used with a simple sleeve or stub balun. However, it is far better in practice to go up to 200Ω by means of a folded dipole (Fig. 7.16) and then to use a half-wave balun for the transition to 50Ω coaxial. Fig. 7.16 also shows the delta match (B) and the T-match (C), the latter being the symmetrical form of the gamma match. Both of these can be adjusted to accommodate 'odd' and reactive feedpoint impedances; the width between the tapping points mainly affects the transformation ratio, and the element length can be shortened for reactance compensation.

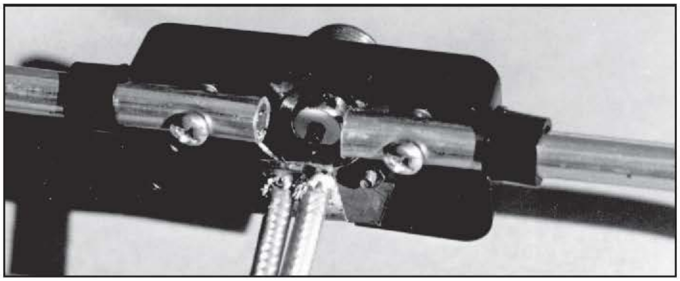


Fig. 7.17. Constructional details of a folded dipole and half-wave balun for 432MHz, using a commercial plastic moulding and an N connector. Fill with closed-cell aerosol foam for waterpoofing

Fig. 7.17 shows constructional details of a half-wave balun. The length of the loop should be an ***exact*** electrical half-wavelength, so don't forget to allow for the velocity factor. Do not use thin low-grade cable for the balun line; doing so would cause unnecessary extra loss and might result in breakdown at high power levels. The characteristic impedance of the cable is unimportant; if available, low-loss 60Ω or 75Ω cable can sometimes be used to advantage in 50Ω systems. If the cable ends cannot be enclosed as shown in Fig. 7.17, use semi-rigid line which doesn't suck up water as readily as braided cable, and use sealant [21].

The loss in a good coax balun is much less than 0·2dB on 432MHz, and less than 0·1dB on 144MHz and below. By the way, if you're not sure of the loss in some dubious device, put power through it. A loss of 0·2dB at 500W means about 25W dissipated. If the balun catches fire, it was too lossy anyway!

Having fitted a balun, don't imagine that you can then forget about symmetry. Unless the coaxial cable is taken symmetrically along the boom (preferably on the opposite side from the elements), and then runs away at right-angles to the plane of polarization, you'll be back in trouble again. This applies particularly to crossed Yagis: the ***only*** satisfactory way to mount these is on an insulating mast, and to take the cables symmetrically out of the ***rear*** of the Yagis. Final traces of current on the outer surface of coax feedlines can be eliminated by threading the cable through giant ferrite beads, or by winding it on a ferrite rod or toroid, but this should be tried only as a last resort after a thorough search for some underlying problem.

CONCLUSION

Yagi antenna technology has stabilized in recent years. The application of computers has shown that decades of experimentation have left but a very narrow margin for improvement. Therefore anybody who expected sensational revelations from this chapter must have been disappointed.

On the other hand, design of antennas and especially of large arrays is one of the last domains of amateur ingenuity. It is not difficult to design and build an antenna that works – but it's just as easy to commit a series of minor errors that will keep it from performing optimally. I hope I've alerted you to most of them.

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