Günter Hoch, DL 6 WU

Extremely Long Yagi Antennas

In earlier publications (1, 2) the author has discussed Long Yagi-Uda antennas. The longest arrays then tested were less than 10 wavelengths long. The question of what happens at extreme lengths remained unanswered.

The following article is to give details and data on Yagi beam antennas up to a length of nearly 20 wavelengths !

1. FUNDAMENTALS OF LONG YAGI ANTENNAS

With the increasing popularity of the UHF bands the problem of cheap and inconspicuous (as compared to parabolic dishes) high-gain antennas has gained importance.

G 3 JVL's well-known Loop Yagi (3) has been a great step in this direction but it has had the side-effect of making many amateurs believe »normal« yagis would not work at GHz frequencies or at these lengths.

There has been evidence in scientific literature, partly dating back to the '50 s, that there should be no major difference in performance of disk, ring, or rod type elements and that arrays tens of wavelengths long were feasible (4, 5).

On the other hand the famous Ehrenspeck yagi-array measurements (6) hinted at a saturation of gain at greater lengths. Later experiments by Viezbicke of NBS (7) confirmed this tendency but showed the saturation to occur only with uniform (equi-spaced equal-element length) arrays.

Element tapering seemed to be the answer, but to what extent would this be valid ? Could element lengths dwindle down to nothing and still provide gain ?

1.1. TAPER PROFILES

Experiments were carried out with various length- and spacing-tapered and uniform arrays. Several conclusions resulted:

1.1.1. Uniform Profile

The apparent gain saturation of uniform arrays is probably caused by lack of excitation. If, by means of a tapered »funnel« section, a travelling wave has once been established on the director chain, the remaining portion need not be tapered to reach maximum possible gain. However, as length is added, the side-lobes increase in strength. When they exceed a level 13 dB below the main lobe the addition of further equal length directors causes the frequency of maximum gain to shift downward, necessitating a re-design. Bandwidth decreases quickly with increasing array-length.

1.1.2. Linear Taper

If a linear taper is used throughout, reducing the length of each succeeding element by a constant amount, sidelobes tend to decrease in strength as elements are added. When sidelobe attenuation exceeds 19 dB, excessive widening of the main lobe occurs and gain falls short of the possible maximum. The frequency of optimum performance shifts upward. Bandwidth is larger than with uniform or quasi-uniform (funnel-type) arrays and remains fairly high even at great array lengths (8).

These effects are more or less pronounced, depending on the taper rate chosen, but in any case the solution is valid for a limited range of array lengths.

1.1.3. Logarithmic Taper

In search of a »universal formula« which permits stopping at any desired array length without shifting the optimum frequency , a logarithmic taper was tried.

The transition section needed to get the travelling wave started, had been determined in earlier experiments. This section is tapered in both element lengths and spacings.

Spacing cannot be increased much beyond 0.4 wavelengths without gain sacrifice, so the logarithmic section is length-tapered only with the starting slope given by the transition section. On the equispaced part of the director chain, the length ratio between elements no. n and 2n is always kept constant. This profile doesn't dwindle to nothing (at least not on finite arrays). Optimum frequency remains constant and sidelobes stay around – 17 dB for any chosen array length.

1.2. BANDWIDTH

It has been written many times that very long Yagi arrays suffer from extremely low bandwidth, especially if wide spacing is used. Tapering, even at the very modest rates used here, increases bandwidth considerably. The longest array tested (18. wavelengths long) had a – 1 dB-bandwidth in excess of 4 %.

Bandwidth isn't only determined by gain response, however. The second, no less important constituent is matching. By using wideband exciters like folded-dipoles, loops, etc., and avoiding narrow-band (high ratio) impedance transformation, a sufficiently great matching bandwidth can be provided.

1.3. BOOM INFLUENCE

Several authors have warned not to use metal booms of appreciable thickness, especially with elements not insulated from them. This fear has prompted funny solutions like elements on poles, etc. Both insulated and mounted-through versions were tested by the author. When properly length-corrected **no** difference in performance could be detected. Of course non-insulated elements must be centered and be in good, lasting contact with the boom ! The shortening effect itself was found to be somewhat less than anticipated, not surpassing 2/3 of a reasonably thick boom's diameter.

1.4. SKIN EFFECT

With increasing frequency skin effect losses are known to rise. They are partly compensated for by decreasing resonant length of elements.

No significant difference could be measured between aluminium, copper, and silver-coated elements. At GHz frequencies high specific resistance materials like brass should be avoided or used for thick elements only. (Brass tubing is not recommended for outdoor application because it tends to crack up).

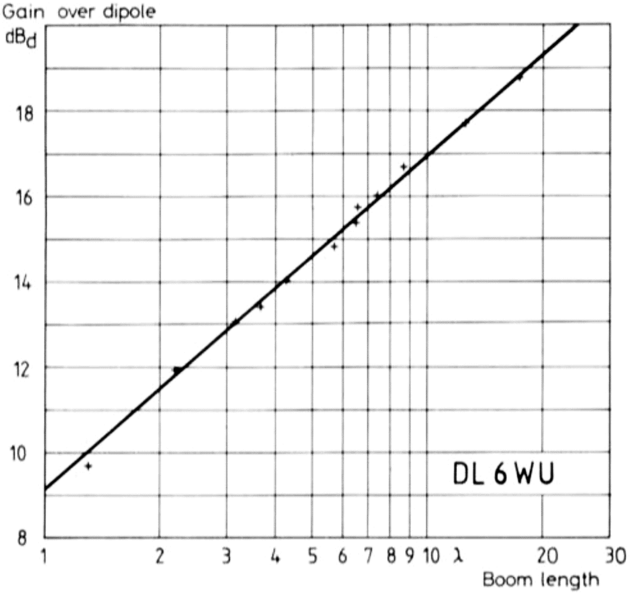

Fig. 1:
Gain of Yagi antennas measured by DL 6 WU at 432 MHz and 1296 MHz (October 1981)

1.5. GAIN

While it was clear now that gain keeps on rising at great arry length, the absolute values still seemed debatable.

Although space requirements for antenna ranges are greatly alleviated at UHF, other problems associated with stability, cable and connector losses, reflexions etc. become more prominent. At 23 cm window-panes can reflect like sheet-metal ! The author's experience with gain measurements at »lower« frequencies was helpful in preliminary back-yard work but serious measurements had to be postponed until recently when a professional antenna measuring range, owned by the German Federal Post Office, became available.

Using an EIA standard gain aerial (7.7 dBd) as a reference many pattern and gain measurements were made on 432 and 1296 MHz. The 70 cm results were consistent with earlier anechoic-chamber values and the 23 cm gain figures line up perfectly with them. Accuracy is believed to be within 0.5 dB.

Figure 1 shows the slightly sub-proportionate increase of gain with array length, the rate of 2.35 dB per octave is in good agreement with earlier measurements on shorter arrays. There is no sign of saturation so it can be expected that further extrapolation be permissible.

2. PRACTICAL DESIGN

Of course, antenna constructors prefer »hard data« in the form of tables containing all dimensions but it seems impossible to provide such data for all thinkable applications.

So only two typical examples will be described in some detail while experimenters are referred to the graphs given in **Figure 2**. After all, these super-long yagis aren't as critical as many people used to think !

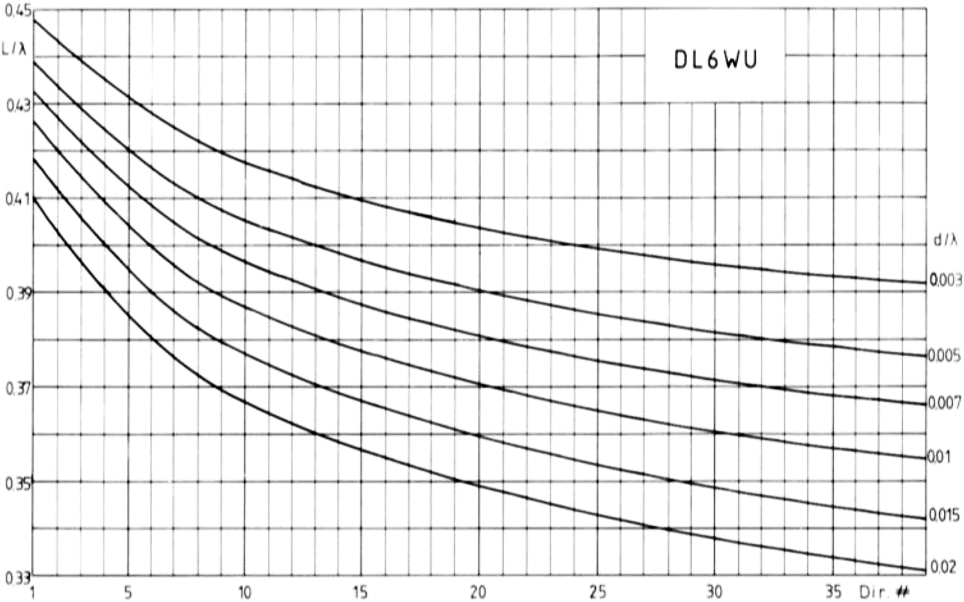

Fig. 2: Optimum director lengths (standardized). Parameter: standardized director diameter

A few checks to be given later should assure even the less-experienced builder without intricate test equipment that his array is working correctly.

2.1. A 23 ELEMENT YAGI FOR 432 MHz

A long-boom model was constructed using TV aerial material and parts **(Table 1)**.

All elements are 10 mm ∅ aluminium tubing mounted on a 20 x 20 mm square boom by means of plastic insulators. Separation is about 4 mm which nearly eliminates the boom influence. Folded dipoles are very uncritical with respect to element thickness, limb and end separation, so any dipole box at hand can be used. Feed point impedance is near 200 Ω so a 4:1 coax balun provides a good match to 50 Ω coaxial cable.

Element	Length	Distances
Reflector	330	130
Driven El.	325	–
Director 1	295	55
Director 2	290	125
Director 3	285	150
Director 4	280	195
Director 5	275	195
Director 6	275	210
Director 7	270	220
Director 8	270	230
Director 9	265	240
Director 10	265	250
Director 11	265	260
Director 12	260	260
Director 13	260	270
Director 14	260	280
Director 15	260	280
Director 16	258	280
Director 17	258	280
Director 18	258	280
Director 19	255	280
Director 20	255	280
Director 21	250	280

Table 1:
Dimensions of a 23 element Yagi antenna for 432 MHz using insulated 10 mm elements

2.1.1. Performance

Gain of the 23 element long-boomer was measured to be 16.0 dB over a dipole. Half-power beamwidth in both planes varies between 22° and 24° across the 70 cm band (430-440 MHz). **Fig. 3a and 3b** show the original diagrams measured at 433 and 439 MHz, resp.

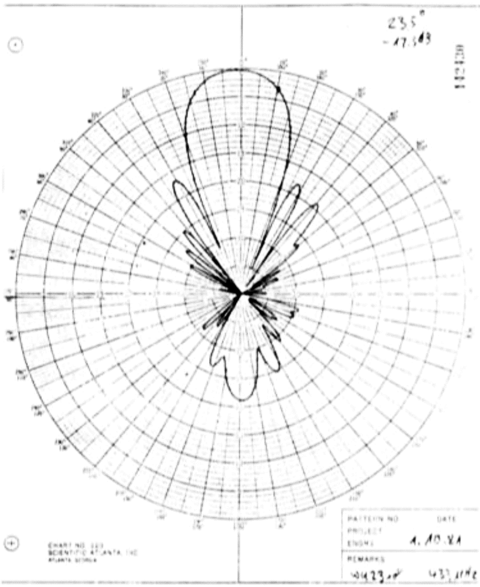

Fig. 3a:
E-plane diagram of the 70 cm antenna with 23 elements at 433 MHz

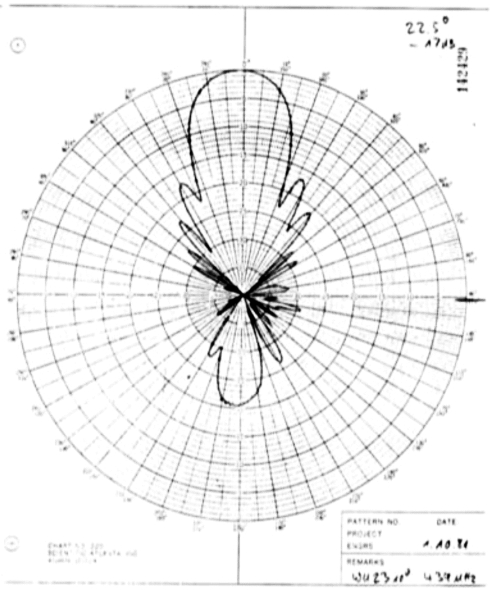

Fig. 3b:
As Fig. 3a but measured at 439 MHz

2.2. A 49 ELEMENT YAGI FOR 1296 MHz

Material chosen for the long-boom 23 cm array was 4 mm ∅ hard aluminium for the elements (AlMg5 welding electrodes) and 1/2" (12.7 mm) alu tubing for the boom. The latter is readily available at hardware stores.

A supporting structure is necessary to keep the boom from sagging and to keep the bulky mast clamp at least a wavelength away from the elements.

2.2.1. Feed Arrangements

Several feeds were tried with more or less satisfactory results. While a stepped-diameter folded dipole soldered directly to a hardline balun and a folded dipole with integral three-wire symmetry transformer proved best, the rather simple solution shown in **Figure 4** was nearly as effective (about 1/4 dB extra loss).

2.2.2. Element Mount

Elements must be centered to better than 1 mm and have good contact to the boom. 3 mm ∅ holes were drilled and then widened to 3.9 mm from both sides (to avoid a loose fit in the »upper« hole). Elements were then driven in with a hammer.

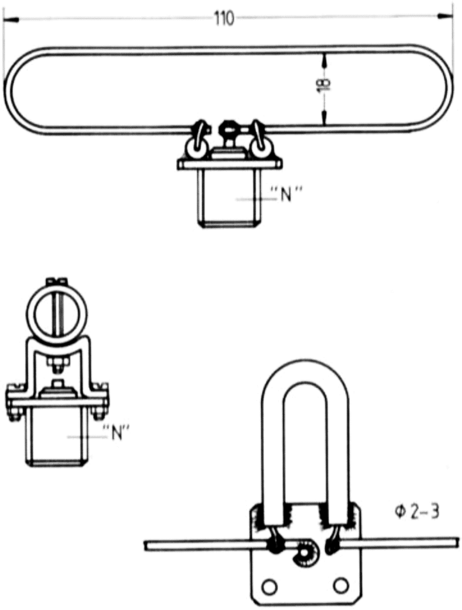

Fig. 4:
23 cm balun arrangement from semi-rigid cable. Balun length (outer conductor): 80 mm

Element	Length	Distances
Reflector	118	50
Driven El.	110	–
Director 1	104	18
Director 2	102.5	42
Director 3	101	50
Director 4	99,5	58
Director 5	98	65
Director 6	97	70
Director 7	96	73
Director 8	95	76
Director 9	94	80
Director 10	94	83
Director 11	93	86
Director 12	93	90
Director 13-15	92	92
Director 16-18	91	92
D+irector 19-21	90	92
Director 22-24	89	92
Director 25-28	88	92
Director 29-32	87	92
Director 33-37	86	92
Director 38-43	85	92
Director 44-47	84	92

Table 2:
Dimensions of a 49 element Yagi antenna for 1296 MHz using 4 mm elements through a 1/2" (12 mm) boom

2.2.3. Dimensions

Table 2 gives element lengths and spacings. Although spacings are not overly critical they should be checked »from both ends« especially if several identical arrays are to be built.

2.2.4. Performance

With the feed shown, a gain of 18.8 dB over a dipole was measured, so probably 19 dB_d are within reach. E- and H-plane beamwidths were measured to be 15°. **Fig. 5** shows the original diagram.

2.3. IMPROVED REFLECTORS

Very long Yagis inherently have a high front-to-back ratio. It should be remembered, however, that pickup from behind can be considerable, in absolute terms. 21 dB F/B in a 16 dBd gain array means that the rear lobe is just 5 dB below dipole level. If this is considered insufficient – for instance in EME work – several improvements over the single reflector version are possible.

2.3.1. Dual In-line Reflector

This arrangement, made popular by Dick Knadle, K 2 RIW, can be applied to nearly any Yagi aerial: A second, slightly longer, reflector is added about 0.5 wavelengths behind the first. This improves the F/B ratio some-what and adds up to 0.2 dB to forward gain. Match remains unaltered.

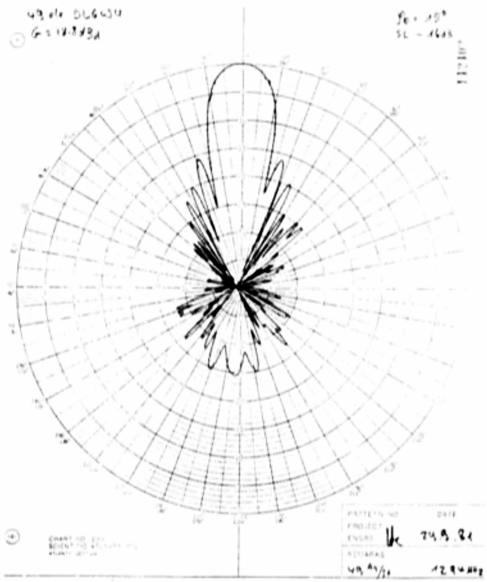

Fig. 5:
E-plane diagram of the 23 cm antenna with 49 elements and a gain of 18.8 dB_d

2.3.2. Multiple Reflectors

Instead of a single reflector element an array of reflectors in a plane perpendicular to the boom can be used. A double reflector should be spaced 0.3 λ vertically and approx. 0.15 to 0.2 λ behind the radiator. Length should be slightly greater than for the single reflector. 4 reflectors spaced about 0.2 λ and approx. 0.6 λ long will improve F/B ratio further.

The additional gain will normally not exceed 0.2 dB with any of the arrangements mentioned. No serious matching problems should arise, usually the multiple reflectors tend to raise the impedance somewhat and to broaden the response toward lower frequencies.

2.3.3. Reflector Planes

A metal sheet or grid 0.6 λ wide and high can replace a quadruple reflector with no change in performance.

3. CHECKING THE PERFORMANCE

The most significant feature of any antenna is its radiation pattern. So even a rough check can tell a lot about performance. Yagi patterns possess characteristic features which are helpful in performance tests.

At array lengths beyond about 7 wavelengths E and H patterns become almost identical, at least around the boresight axis, so it is sufficient to test one plane – usually E.

If the array works properly there are pronounced nulls between main lobe and first sidelobes. The angle between these first nulls is very close to twice the aperture angle or half-power beamwidth (slightly larger in the E plane). With the profiles given here the first sidelobes should be suppressed by about 16-17 dB.

At frequencies below optimum the main lobe widens with only minor changes in the pattern's appearance, except that the first nulls become deeper. Gain decreases slowly.

When the optimum frequency is exceeded, the first nulls quickly fill in and the first sidelobes begin to merge with the main lobe, increasing in amplitude. The main lobe becomes narrower at the tip despite quickly decreasing gain. Patterns 3a and b show first signs of the effects mentioned – optimum operating frequency is near 436 MHz.

If the radiation patterns look like the ones shown and there is no serious mismatch (1:1.3 at feedpoint or better), one can be sure tha performance is correct.

4. STOCKING

After it has been assured that single arrays are working correctly they can be grouped in the usual manner.

4.1. OPTIMUM SPACING

For beamwidths Φ below about 30° the optimum stacking distance D_{opt} is with sufficient accuracy:

$$D_{opt} \approx \frac{57.3\,\lambda}{\Phi}$$

For the 23 ele array with $\Phi \approx 24°$

D_{opt} is 2.39 λ or 1.66 m at a wavelength of 70 cm. With the 49 ele array ($\Phi \approx 15°$)

$D_{opt} \approx 3.82\,\lambda$ or 0.9 m at wavelength of 23 cm.

4.2. MAST CLEARANCE

No conducting structures should run between elements if they are thicker than about $\lambda/10$. Metal structures parallel to the elements should be kept at least half the stacking distance away.

5. OWN DESIGNS

Using the graphs in Figure 2, long Yagis can be designed for any frequency and for a wide range of length and element dimensions.

5.1. SCALING

Scaling is done by first calculating the element diameter/wavelength ratio at design center frequency and then reading off the director lengths from Fig. 2. If elements run through a metal boom uninsulated, 66 % of boom diameter must be added.

Folded dipole and reflector elements can be scaled from the dimensions given here as their lengths are almost independent of element diameter.

Spacings should also be scaled from the dimensions given here, inversely proportional to the frequencies.

5.2. PERFORMANCE

Gain to be expected can be estimated from Figure 1, which relates gain to array length. Radiation patterns given for the two model arrays indicate the beam pattern to be expected. The front-to-back ratio fluctuates with array length with minima about 2 dB below dipole level. It can always be improved by the measures mentioned in chapter 2.3. Bandwidth shows only a very slight tendency to decrease with growing length and should remain more than 3% even for the longest manageable arrays.

5.3. EXTENSION

If it is desired to continue beyond the dimensions given, extrapolation should follow the logarithmic law, keeping constant the length ratio between elements no. n and 2n. The checks named in chapter 3 should suffice to assure optimum performance.

ACKNOWLEDGEMENT

The author wishes to thank his superiors for the friendly permission to use the antenna range and his colleagues at the Research Institute of Deutsche Bundespost at Darmstadt for their assistance.

6. REFERENCES

(1) Hoch, G.: Yagi Antennas
VHF COMMUNICATIONS 9, 3/1977,
Pages 157-166

(2) Hoch, G.: More Gain with Yagi Antennas
VHF COMMUNICATIONS 9, 4/1977,
Pages 204-211

(3) Evans, D.S. and Jessop, G.R.:
Long Quad Yagi for 1296 MHz
RSGB VHF-UHF Manual, 3rd Edition,
Pages 8.48-8.49

(4) Simon, J.C., and Biggi, V.:
Un Nouveau Type d'Aérien ...
L'Onde Electrique 34, 1954,
Pages 883-896

(5) Appel-Hansen, J.: The Loop Antenna
with Director Arrays of Loops and Rods
IEEE Trans.Ant.Prop., Juli 1972,
Pages 516-517

(6) Ehrenspeck, H.W., and Poehler, H.:
A New Method for Obtaining Maximum
Gain from Yagi Antennas
IRE Trans.Ant.Prop., Oct. 1959,
Pages 379-386

(7) Viezbicke, P.P.: Yagi Antenna Design
NBS Technical note no.688, Dec.1976
(summarized in HAM Radio, Aug.1977,
Pages 22-31)

(8) Sengupta, D.L.: On Uniform and
Linearly Tapered Yagi Antennas
IRE Trans.Ant.Prop., Jan. 1960,
Pages 11-17