MORE GAIN WITH YAGI ANTENNAS

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In an earlier article (1) the author discussed basic Yagi antenna principles. The present article mainly concentrates itself to the question: What gain can be obtained from a single Yagi antenna and stacked arrays, and how can it be achieved in practice ?

1. MAXIMUM OBTAINABLE GAIN

Much of the confusion about the gain obtainable from Yagi antennas has been caused by exaggerated claims of some antenna manufacturers. This has gone so far that the ARRL has banned advertisements containing antenna gain figures from its publications.

The difficulties encountered in the measurements of absolute gain figures have led to considerable discrepancies between the curves published in different amateur radio handbooks, and the values measured in practice.

In (1) the author based his findings on the only generally accepted gain data then available. They are results of measurements by Ehrenspeck and Poehler (2) carried out on uniform Yagi arrays (constant director length and spacing).

It has already been pointed out in (1) that an increase in gain can be obtained by individually optimizing both element spacings and lengths. Recently publications substantiate this increase in gain (3, 4). The results of this are shown in **Figure 1**. It should be noted that both gain and array length are in logarithmic scale which means a proportional increase in gain with length would result in a straight line sloped 45°, or 3 dB per doubling of antenna boom length (dashed line). Curve A shows results from uniform arrays according to Ehrenspeck and Poehler (2), and the US National Bureau of Standards (4). They clearly show a tendency towards a levelling off of the gain beyond about 4 λ length.

Curve B shows gains of arrays having constant spacings and individually optimized element lengths. These were also taken from (4), a belated publication of measurements made in the late 1950s. (A study of this report is highly recommended to anyone interested in the construction and optimization of Yagi antennas). The 4.2 λ long NBS array has been made popular by W 0 EYE.

A computer-aided approach at the Danish Institute of Technology at Lyngby (3) has shown that a further small improvement can be made by suitably tapering the spacing. The results have been verified by anechoic-chamber measurements. They are shown as curve C in Fig. 1. The extrapolation of this curve conforms well with the values found by other designers using two-way optimization. The »WCVHFC« values represent the mean of several measurements at the annual West Coast VHF Conference as cited by Overbeck (5). The »DL 6 WU« data has been obtained by anechoic-chamber measurements of arrays experimentally optimized by the author.

There is not one serious report regarding practical or even theoretical gain of a rod-type Yagi antenna that would surpass the gain of curve C. This means that it can quite safely be taken as the upper gain limit. Structures with multiple elements, loops, quads etc. may have higher gains if they have considerable extension perpendicular to the longitudinal axis.

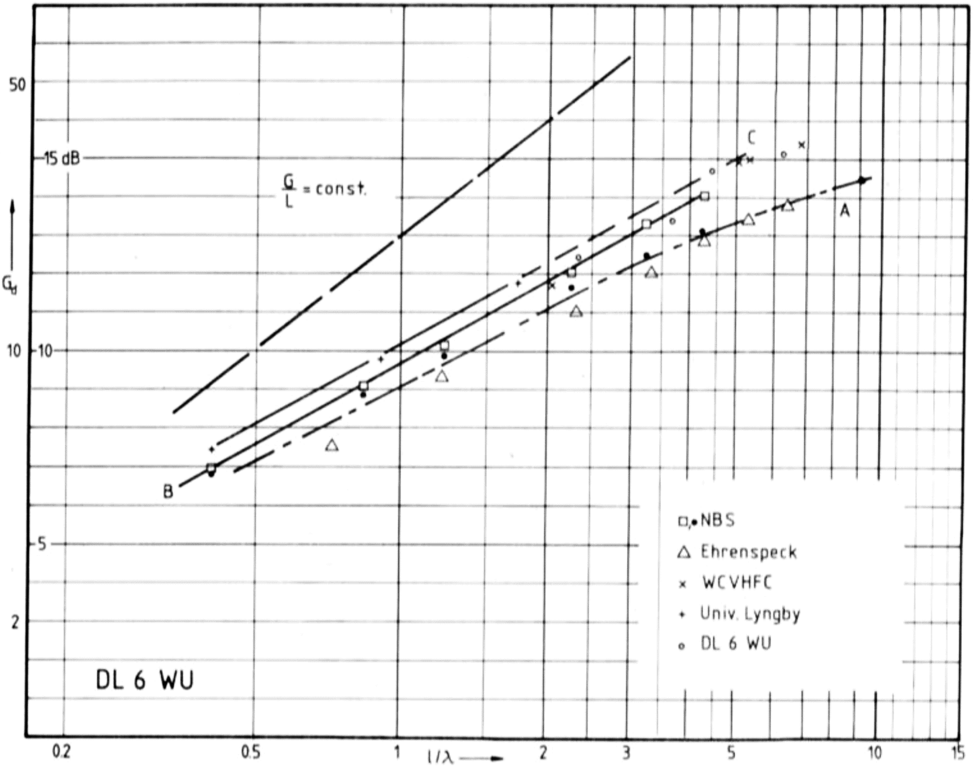

Fig. 1: Gain of Yagi arrays as a function of length
A uniform, B length-optimized, C length-and-spacing-optimized

All claims of higher gains given for Yagi antennas must be taken with extreme caution. One example is to be given to illustrate this: The gain of a very popular 2-m-Yagi of 3.05 λ length is catalog-rated at 16 dBd while curve C would limit its gain to 13.6 dBd. The E and H plane – 3dB – angles of 32° and 34° (the former being correctly stated in the catalog !) indicate a maximum of 13.6 dBd when entered into the Kraus formula (6). Comparison measurements yield 13 to 13.5 dBd which confirm the validity of the above considerations.

No reliable data is available on Yagi antennas longer than about 7 λ so the question of ultimate gain limitation cannot be answered yet. This limit, if existent at all, seems to be higher than experts have assumed to date. On the other hand the slope of all curves in Figure 1 is 2.2 dB per length doubling or less which is noticeably lower than the 3 dB commonly expected. This less-than-proportional gain increase quickly leads to very unhandy array lengths for higher gain values at lower frequencies.

Two further factors should not be overlooked which limit practical antenna length: Bandwidth and precision. Bandwidth tends to decrease with increasing array length with values around 1 % to be expected at 10 λ. The precision required for optimum results is stated in (4) to be 0.003 λ. At 1296 MHz this would call for an element length tolerance of less than 1 mm.

2. WHICH TYPE OF ANTENNA ?

With the previously mentioned limits in mind, a graph was drawn to compare the üerformance of different antenna types and to determine the bands most favorable for the use of Yagi antennas in high-gain arrays.

In order to make at least a rough comparison possible, **Figure 2** assumes a maximum antenna height or width of about 8 m which seems to be somewhat of a constructional barrier. Yagis are considered only up to 10 λ length for bandwidth reasons. Curtain arrays are considered in 16 element increments as this is a standard building block. It is quite evident that Yagi antennas can be used to greatest advantage on 70 cm. (The same is valid for the 220 MHz-band in the USA). On 2 m there is a challenge from phased arrays. These, however, have a disadvantage of the large number of feed connections which become the limiting factor at higher frequencies.

On 23 cm parabolic antennas can provide more gain (they are still rather clumsy on 70 cm) whereas the precision limit together with feed complications makes Yagi antennas somewhat questionable at least for high-gain arrays on this band.

The use of aperture antennas is a must on all higher GHz bands.

It is the author's opinion that work on Yagi antennas should be done especially with the 70 cm band in mind; they can then be easily recalculated to the 2 m and 23 cm bands due to the harmonic relationship.

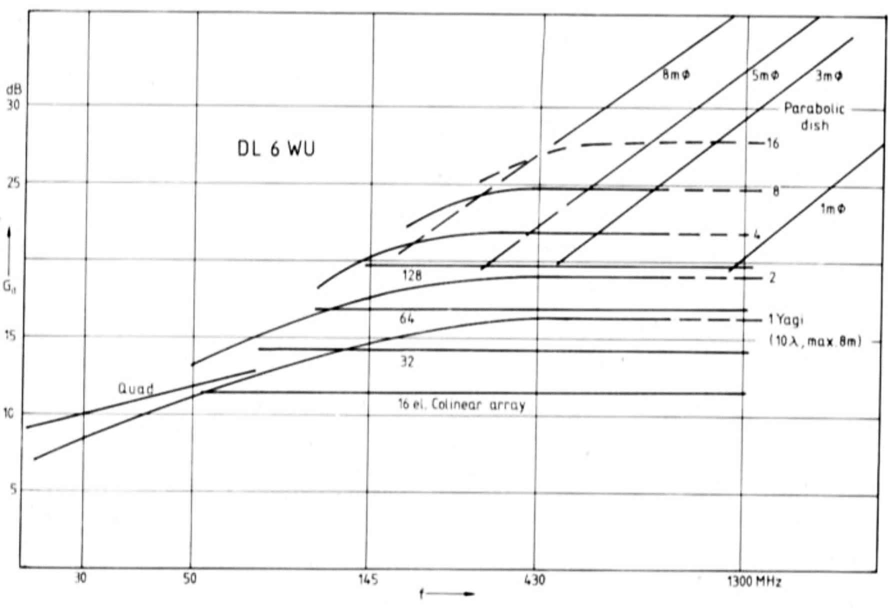

Fig. 2: Gain of different types of antenna arrays limited by maximum array dimensions of 8 x 8 x 8 m

3. PRACTICAL DESIGN

The question is now how the gains given in the curves can be obtained in practice ?

Excellent design criteria is given in (4), and the minute difference to the maximum gain theoretically possible is insignificant in practice. The »Quagi« antennas described in (5) also work very well although they are disliked by some because of the type of feed used. Still, it was found complicated that a completely different plan had to be followed for each desired array length. In order to find a more general approach, the author has collected data on two-way optimized long Yagis from numerous sources, together with data from his own experiments, and has standardized them with respect to frequency and element diameter. This was done with the aid of the equal-reactance graph given in (1). It turned out that the optimum element lengths agree so well that an average curve can be drawn with less than 0.01 λ departure from any individual value **(Figure 3)**.

This is not true to the same extent with the spacing values found to be optimum by different designers. However, the tendency is clearly that of an asymptotical approach up to about 0.4 λ with the initial value strongly influenced by the type of feed.

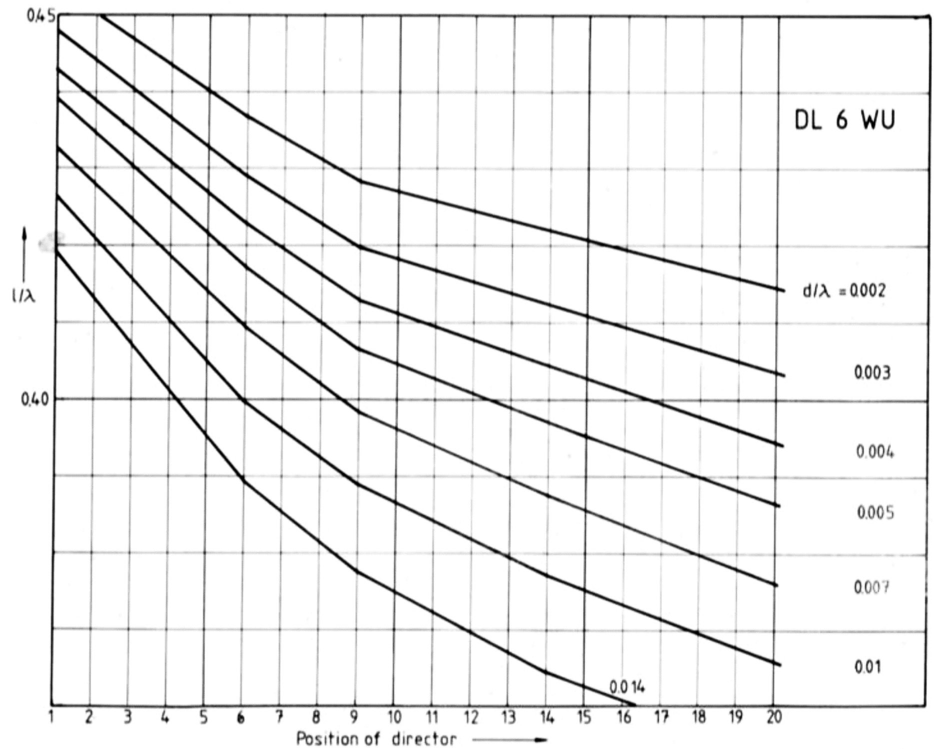

Fig. 3: Length of directors as a function of director position in long Yagi arrays (parameter: element diameter)

As many experiments have shown, a non-reactive feed using a self-resonant dipole element calls for a closely spaced first director – often called a launcher element. It takes about the position the radiator would take in designs with an adjustable impedance feed such as a delta or gamma match. For the sake of mechanical and electrical stability it was decided to concentrate on the equal-diameter folded dipole with halfwave (4:1) balun as driven element. Tests have shown that it can always be replaced with unaltered results by an open dipole with 1:1 balun transformer or, of course, any other desired matching device similar to those described in (7).

Measurements made with designs using both average element lengths and spacings showed such good results that it seems permissible to risk a »universal recipe« for long Yagi design. If the values given in Figure 3 and Table 1 are followed closely, a Yagi will result that has near-optimum gain for the length, and can be cut off anywhere beyond about 2 λ length with an SWR of less than 1 : 1.2. Data for short antennas follow a slightly different pattern and should be taken from (4).

Antennas constructed from the data presented here will perform markedly better than optimum uniform antennas of the same length. Radiation patterns will be slightly wider and a lot cleaner, the additional gain being taken from the sidelobes. It is not claimed, however, that there is no room for further improvement. Namely the backward wave reflected from the open end of the antenna causes a more or less pronounced distortion of the amplitude and phase profile depending on the point of cut-off. This means that the skilled experimenter with the necessary measuring equipment described in (8) may be able to squeeze out a few more tenths of a dB (this is about the maximum) by further slight modification of element lengths and positions. This can be a very time-consuming and frustrating process governed by the law of diminishing returns. Only a few hints can be given here. The director farest from the radiator has a great influence on the reflected wave. Optimizing its length and position seems the most rewarding adjustment with a slight variation of director positions near the center of the array being the next best bet. After any adjustment, the match must be checked and restored because even a slight mismatch might mask the minute gain increase that has been obtained. Never attempt to optimize without a reference antenna of known performance, and without equipment which meets the high reproducibility standards required.

The following procedure is given for the average ham who does not possess these means. All he needs is a stable power source for the design freqeuncy and an accurate (!) SWR meter.

a) Determine the desired antenna lengths in wavelengths and the corresponding number of elements. Take element positions from **Table 1**.

b) Determine element diameter in wavelengths and read off or interpolate director lengths from **Figure 3** respectively. Read off the lengths of radiator and reflector from **Table 1** or from Figure 3 in (1).

c) If the elements are to be mounted through a metallic boom, take the correction factor from Figure 4 in (1) into consideration or use **Table 2**.

d) Cut and mount elements leaving the driven element variable, if possible. Mount antenna facing towards the sky and check SWR. If it exceeds the expected value and all measures have been determined correctly (!), the fault will most certainly lie in the driven element. Adjust its position and length not forgetting the balun which might be too long or too short. Do not change other elements' length or position at this point !

Element	Spacing/λ	Spacing/mm 432 MHz	Length/mm 432 MHz, 4 mm dia.
Reflector	0.240	160	338
Dipole	–	–	322
Director 1	0.075	55	302
Director 2	0.180	125	299
Director 3	0.215	150	296
Director 4	0.250	175	293
Director 5	0.280	195	290
Director 6	0.300	210	287
Director 7	0.315	220	284
Director 8	0.330	230	282
Director 9	0.345	240	280
Director 10	0.360	250	278
Director 11	0.375	260	277
Director 12	0.385	265	276
Director 13	0.390	270	275
Director 14	0.395	275	274
Director 15	0.400	280	273
Director 16	0.400	280	272
Director 17	0.400	280	271
Director 18	0.400	280	270
Director 19	0.400	280	269
Director 20	0.400	280	268

Table 1: Dimensions of long Yagi arrays
(Dimensions of a model antenna for 432 MHz with insulated 4 mm diameter elements)

Boom dia./λ	Δ l / λ	Boom dia./mm 432 MHz	Δ l / mm 432 MHz
0.01	0.003	7	2
0.015	0.005	10	3.5
0.02	0.008	14	6
0.03	0.016	21	11.5
0.04	0.026	28	18
0.05	0.038	35	26

Table 2: Length correction Δ l to be added to length of elements passing through metallic boom. Influence of insulated elements falls quickly with rising distance, and can be neglected at about 1 boom radius from surface

4. STACKING

In general, directional antennas should be stacked at the distance where their effective apertures just touch (9). Unfortunately there is no definite border of the effective aperture so this distance is not well-defined. When two equal arrays are stacked, the stacking gain will rise with increasing distance reaching a first peak of about 2.5 dB and then fluctuate around this value (4, 10). These fluctuations can be explained either as varying mutual coupling or by addition and cancellation of minor lobes. A good rule of thumb is to use the distance at which the first null of the group pattern falls on the – 3 dB point of the individual pattern in this plane – approximately halving the beamwidth. By simple geometry this distance is found to be $D = \lambda/2 \sin(\varphi/2)$ where φ is the – 3 dB aperture angle of the arrays to be stacked. Note that distances differ in E and H planes if the patterns are not rotationally symmetrical. Greater spacings may result in slightly higher gain, 2.95 dB are stated in (10), but at the penalty of a sharper main beam and more and stronger sidelobes. Stacking distances below the above-mentioned value will quickly reduce the increase in gain obtained by stacking.

Use of the compromise formula will result in first sidelobes 10 - 12 dB below the main lobe, and an increase in gain of around 2.5 dB for a bayed array, as tests have shown in practice.

5. EXAMPLE

A 21 element Yagi antenna for 432 MHz was derived from the design data that has been given. Aluminium rod of 4 mm diameter (welding electrodes) was chosen because of its availability. The boom is 15 by 20 mm dry wood available in do-it-yourself shops (the central part must be reinforced by a support). A double reflector spaced 0.3 λ vertically was used instead of one, because on long arrays the gain increase of about 0.3 dB is higher than obtainable by a corresponding length increase of the boom.

Gain was measured to be about 15.5 dBd in substitution measurements. A separate measurement using the rear section terminating at director no. 8 showed 12.5 dBd. **Table 1** gives the dimensions of the antenna.

Correct stacking distance for the long Yagi antenna would be 1.6 m in both planes, whereas the 11 element array would need a stacking distance of 1.2 m in the E plane and 1.1 m in the H plane.

6. CONCLUDING REMARKS

There are a multitude of good VHF and UHF antennas available on the market. The author does not mean to preach an all-out do-it-yourself philosophy. There are, however, many occasions where a mass-produced antenna would not serve the purpose or would just be too expensive – e.g. for receiving weather satellite signals, testing a temporary location, monitoring a dx tv channel, to name just a few. A cheap and quickly-made Yagi array can fill the gap. Besides, in our time of highly complicated factory-made ham equipment a good self-made antenna can impart to the builder a feeling of achievement that is hard to reach otherwise.

Acknowledgement:
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