YAGI ANTENNAS

Principle of Operation and Optimum Design Criteria

by G. Hoch, DL 6 WU

Yagi antennas are well known in the VHF and UHF field since they allow a directional antenna with reasonable gain to be obtained in a simple manner. However, one is often disappointed with home-made Yagis, and even sometimes with those available on the market. This article is to show how design errors can be avoided, and what performance is to be expected.

1. UNIFORM YAGI ANTENNAS

This type of antenna was originally described by H. Yagi in 1928 (1), and possessed nearly all the features of modern long Yagi antennas. The theory of operation was not understood until much later. One of the best works regarding this antenna was published in 1939 by Ehrenspeck and Pöhler (2); they published measured values of extraordinary precision. Ehrenspeck and Pöhler showed experimentally that a radio wave is propagated along a Yagi structure with reduced phase speed, and exits the antenna in a similar manner as if it were exiting a tube. The director chain has the behaviour of an artificial dielectric, and there is a direct similarity to dielectric antennas (3).

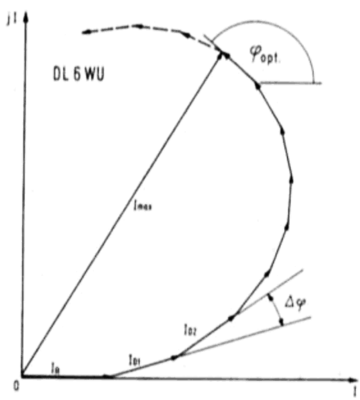

Fig. 1:
Vector diagram of the field strength in axial direction of a Yagi antenna
(I_r: current in the radiator, I_D: currents in the directors)

The vector diagram for the field strength at a distant point on the antenna axis is also very informative. It is proportional to the resulting vector of the currents in the individual elements. Since the current and phase angles in a parasitically energized antenna cannot be selected at will, the diagram given in **Figure 1** does not allow any quantitative information. However, the illustration shows clearly that the resulting vector will not be increased after a certain point by adding further elements when the phase angles are given, but will even decrease.

The delay component of an element and the current energized into it are both altered together with its length, which means that two demands are opposite in the case of long antennas: in order to limit the phase shift, it is necessary for the elements to be shortened until finally no noticeable current is able to flow. This means that the length and gain of a Yagi antenna is limited.

Ehrenspeck and Pöhler, as well as most of the other antenna specialists, examined uniform Yagi structures, that is antennas having constant director spacings and lengths. The following can be summarized for this type of antenna:

1. There is an optimum value of the phase speed and thus the total delay of the wave front for each antenna length. The most favorable delay increases with the antenna length, however, only up to a value of approximately 105° or 0.3 λ. This is obtained at an antenna length between 3 λ and 4 λ and remains constant for longer antennas.
2. The phase speed V along a director chain is dependent on the length, thickness and spacing of the elements. There are an infinite number of combinations that lead to the most favorable value of V. When using element spacings of 0.4 λ and less, the same maximum value of the gain will be achieved.
3. The maximum gain possible is only dependent on the antenna length if the most favorable value of V has been obtained.
4. No noticeable gain increase will be observed at greater antenna lengths than 6 λ; the maximum gain value of a conventional Yagi structure is in the order of 14 dB. **Figure 2** shows this relationship, as well as measured values of several antennas available on the market, and also some home-made antennas. The number given in the designation gives the number of elements.

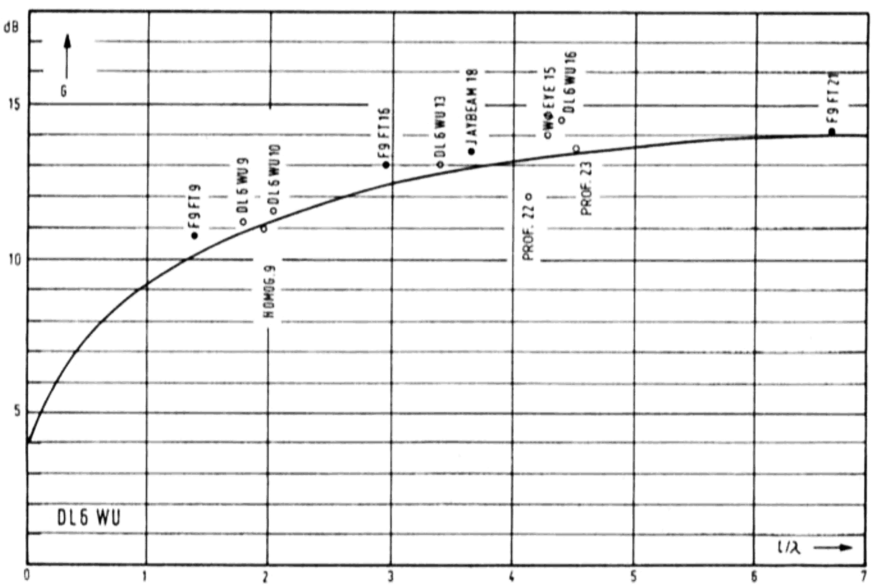

Fig. 2: Gain of Yagi antennas as a function of their length measurements: ● DL 1 BU; O DL 6 WU

2. NON-UNIFORM YAGI ANTENNAS

Since the above information is valid for uniform Yagi structures, this led to experimentation with non-uniform antennas to obtain further improvements. Due to the large number of parameters, further experimentation is very difficult. However, it has been found that it is more favorable for the delay to be concentrated in the vicinity of the radiator and this to be reduced towards the end of the antenna (3, 4). The current component of the elements should also be reduced together with the distance from the radiator (4). Both effects can be obtained together when using a continuous reduction of the element lengths and increase of the spacings.

These measures have the effect of reducing the minor lobes and widening the main lobe with respect to these of a uniform Yagi antenna. Maximum gain is obtained as a compromise between directivity and suppression of the minor lobes.

It is also necessary for the discontinuities at the open end of the antenna and at the radiator to be compensated since they can lead to interference effects on the travelling waves that are prevalent with well-designed antennas.

It is true that the above considerations have been partially assisted by computer simulation, however, it has been found that further experimentation is always necessary. For this reason, the proved knowledge about uniform antennas, which are a good approximation also for the mean values of non-uniform antennas, are extremely useful for use as basic values.

Even though, it seems that the maximum increase in gain to be expected is approximately 1 dB, over that given by Ehrenspeck and Pöhler, even after all improvements have been made. This means that the maximum gain that can be achieved with a single, conventional Yagi antenna, should not be much higher than 15 dB.

This shows that extreme caution is required when higher maximum gain figures are given in some publications, e.g. (5, 6). Usually these are then gain figures that have been calculated from the beamwidth, or values that have been falsified by ground reflection. Errors in the order of 3 dB are quite common. Gain measurements are to be discussed later in this article.

After completing the manuscript for this article, the information given in (9) became available to the author. In this article, controlled end reflection was used to obtain a further, small increase of gain, however, the design seemed to be very critical.

3. HOME CONSTRUCTION OF YAGI ANTENNAS

Home construction of antennas is still very rewarding, especially when large antenna arrays are to be constructed. Model antenna systems on the 70 cm or higher bands simplify the design, and the final results can be recalculated for the required frequency. However, anyone who wishes to construct well-known designs, to modify them, or to recalculate these for other frequencies should know the effect of all construction parameters on the operation of the antenna. Seemingly slight deviations can cause a complete failure !

The important dimensions are: antenna length, element spacings, element lengths, element diameter, and also the thickness of the boom.

3.1. Element Length and Diameter

Figure 3 shows the dependence of the element length as a function of the element diameter for reflector, radiator and directors (mean value for all directors), when the other dimensions of the antenna are already known. It may be surprising to see that it is not the antenna length and element spacing that it used as parameter but only the number of elements.

The reason for this is in the reciprocal relationship between the phase delay and element spacing (7). Since the most favorable delay remains practically constant with long antennas (as was already mentioned in section 1), the curves for the same number of elements coincide. This is no longer valid for short antennas (≦ 1.52) but the approximation is useful in all cases.

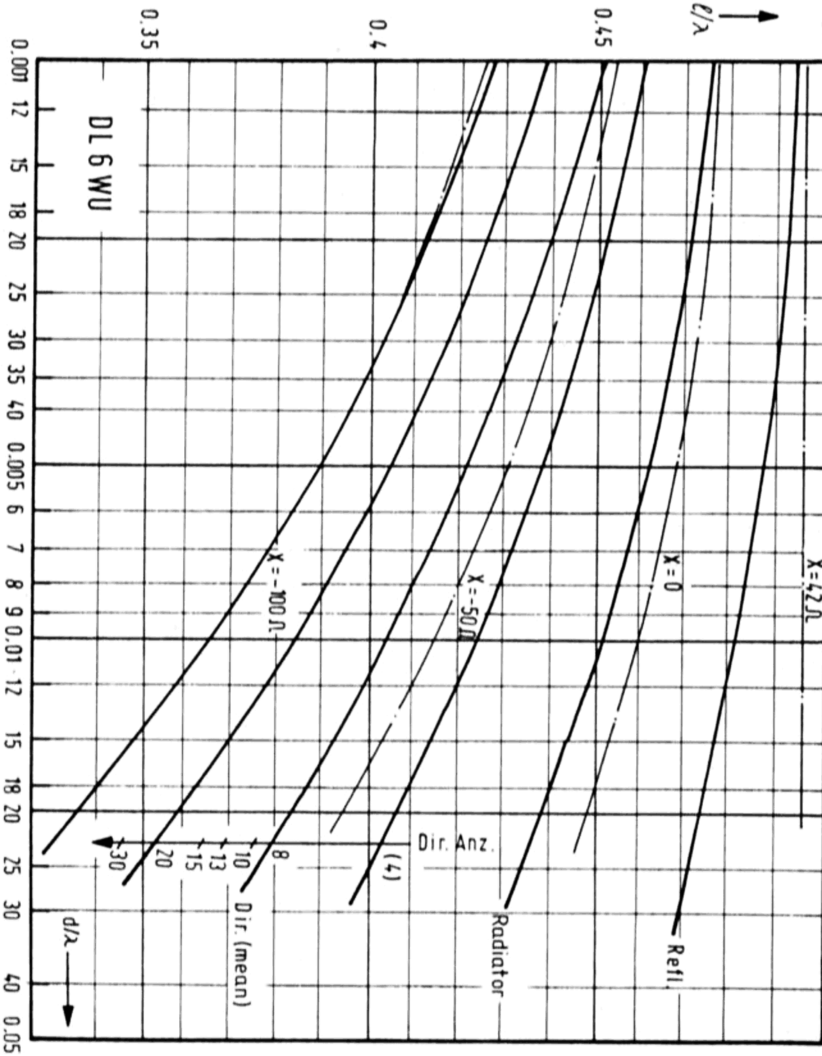

**Fig. 3: Optimum length of Yagi elements as a function of their diameter
Dashed lines: curves of constant reactance**

It will be seen that the element diameter dependence of the director length increases with the number of elements, and is far greater than that of the radiator and reflector. This is because the radiator and reflector are resonant circuits operated virtually in resonance, whereas the directors are strongly detuned capacitively. On increasing the diameter, the Q will decrease, which means that the detuning must be further increased in order to obtain the same phase position. When using the semi-logarithmic scale used here, it is easy to see that a shortening of approximately 7 % in the case of the radiator and reflector and approximately 14 % in the case of the directors is required when increasing the element diameter by ten times.

The curves of constant reactance of an individual dipole element, as taken from an engineering table, are given in **Figure 3** as dashed lines. The solid lines are experimentally derived curves of constant element performance. It will be seen from the great similarity in the curve that it is mainly its reactance that is important for the operation of an element. This means that when it is replaced by an element having a different diameter, the original reactance must be restored. The real component of the impedance, e.g. loss and radiation resistance, have a very small dependence on the length and diameter in the vicinity of $\lambda/2$.

The length/diameter diagram is therefore very advantageous when making calculations for elements of differing diameters: the values of length and diameter (l_1, d_1) should be found for the known element, through this point another curve is interpolated parallel to the nearest curves given in the diagram and the new values for the diameter d_2 and length l_2 read off at the required point.

If the element lengths differ noticeably, this calculation must be made for each element. It is usually sufficient to calculate the difference between the old and new average length and to correct the individual element lengths correspondingly. By the way, the length tolerance of an individual element is relatively large as long as the mean value is maintained within about 0.5 %.

No significant effect of the element diameter on the gain could be observed with antennas up to 4 λ. Diameters from 0.003 λ to 0.015 λ were examined. However, a loss of gain was observed with very thin brass elements, which was probably caused by skin effect losses.

3.2. Effect of the Boom Diameter

Virtually no information can be found on the effect of the element mounting. Sometimes it is mentioned that approximately 2/3 of the boom diameter should be added for elements that pass through a metallic boom.

Experiments were firstly made by comparing calculated and measured resonance positions of various antennas in order to obtain the required information, however, this was really inaccurate and only showed a general tendency.

For this reason, the author decided to carry out his own measurements. The detuning of a matched three-element antenna on altering the diameter of the (long) boom in the vicinity of the director was compensated for by retuning the director. This resulted in the curve given in **Figure 4**, which should be sufficiently accurate for practical application. No effect of the shape of the boom (circular, rectangular, or U-shaped) could be found. The element diameter seems to have little influence as long as it remains below boom diameter.

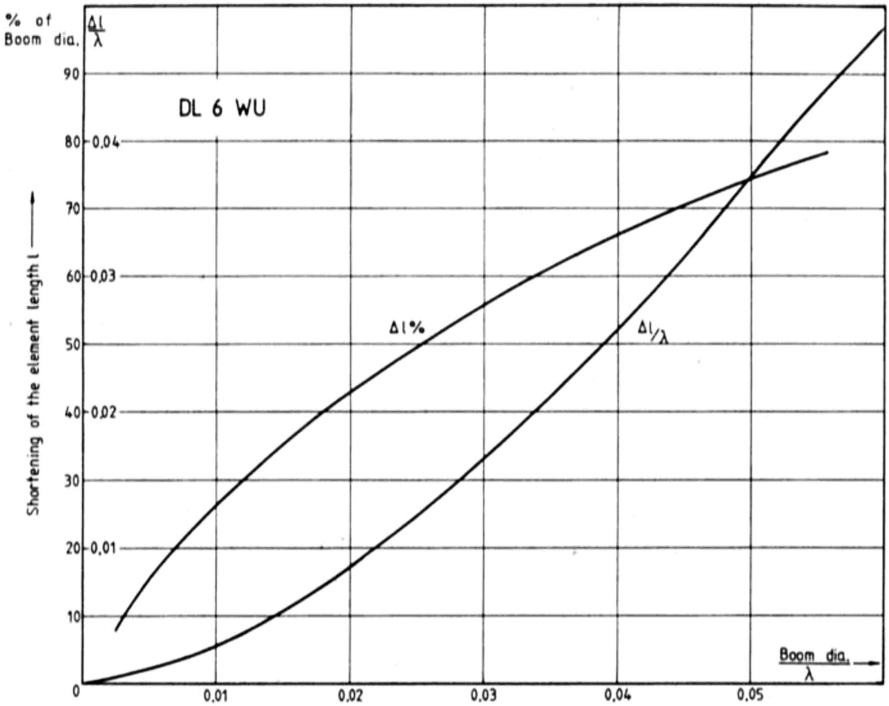

Fig. 4: Influence of metallic boom on resonant length of elements piercing it (median of measurements on .0029 λ, .0075 λ and .0145 λ dia. elements)

3.3. Matching

The matching of the radiator to the feeder cable is a critical point in the construction of parasitic antennas.

Many parameters have an effect on the radiation resistance of the dipole element: its length, length and spacing of the adjacent elements and also their position to another. Only those directors that are spaced further away from the element (director 4 and onward) have relatively little effect. The relationship is extremely complex. Generally speaking, the feed point impedance of the radiator will be reduced on decreasing the spacing of the neighbouring elements, and the intrinsic resonance of these elements approaches the designed frequency. However, under certain circumstances, this tendency can be reversed with very small element spacings. A first director in the direct vicinity of the radiator will have a similar effect as an element of a folded dipole. It is possible with correct selection of the parameters for a folded dipole to be matched to either 240 Ω or direct to 75 Ω. It is only necessary for a systematic experimentation to be carried out.

Two simple methods have been proved in practice: the antenna to be optimized is used as transmit antenna connected to a very long feeder (3 dB loss or more), or as receive antenna connected to a good terminating resistor. In both cases, the antenna is trimmed for maximum received voltage. The fine alignment is then made with the aid of a reflectometer, if required. In this way, it is not possible for the antenna to be matched correctly, but be completely detuned.

3.4. Gain Measurements

Exact measurements on antennas are very difficult, especially gain measurements. The demands made on such measurements are given in IEC 138 and DIN 45003. Especially the measures given in this standard to avoid interfering ground reflections are usually completely ignored in the case of amateur measurements. Usually, it is only possible for us to be able to measure the matching, and the horizontal polar diagram, e.g. the E-diagram in the case of horizontal polarisation. Since Yagi antennas possess a relatively close relationship between the E and the H-diagram as can be seen in **Figure 5**, this allows a certain criterion for estimating the gain. If the measured values are, however, placed in the gain nomogram (6), one will obtain a theoretical upper limit of the gain, but these values are most certainly too optimistic for practical applications, since the diagram assumes no-loss antennas without minor lobes. It is especially with very long antennas that the minor lobes increase with length and thus the losses.

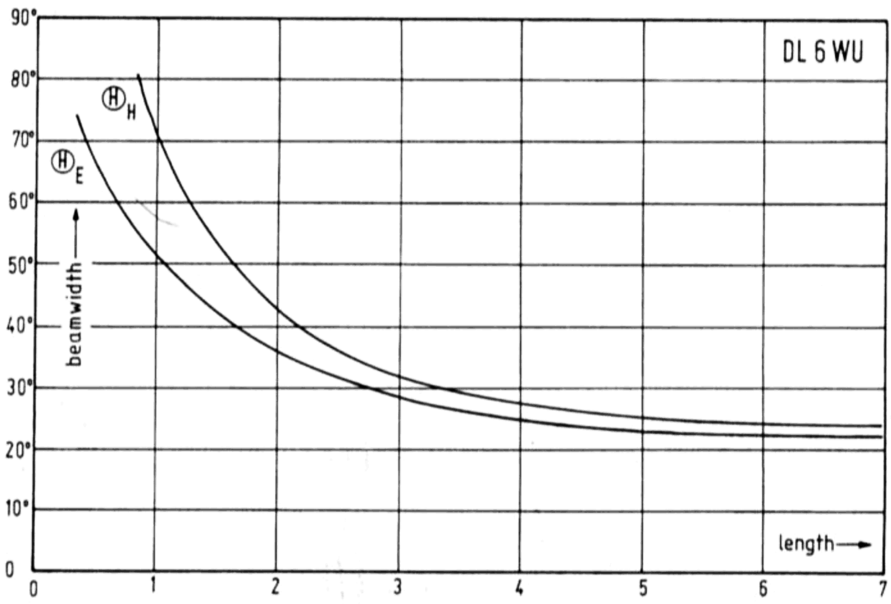

Fig. 5: Beamwidth of Yagi antennas as a function of the antenna length (mean values from numerous references and measured values)

3.4.1. Effect of the Minor Lobes on the Gain

The basis of all gain estimates taken from the polar diagram is the beamwidth Ø of the main beam (angle between the 3 dB points). The antenna is then assumed to be in the center of a sphere and the ratio of the surface illuminated by the main beam to the surface of the complete sphere (isotropic radiator) is established. In the case of the same input power, and negligible minor lobes, the gain coincides to the reciprocal of the surface ratio.

Since the energy flow density is not constant within the main lobe, corrections will be required for the effective surface area according to the assumed shape of the beam. The latest gain estimation formula given in (8) is as follows:

$$G_i = 32 \ln 2/(\varnothing^2_E + \varnothing^2_H)$$

In order to obtain some idea of the magnitude of the losses caused by minor lobes, a similar consideration was attempted for a typical Yagi diagram (see **Figure 6**).

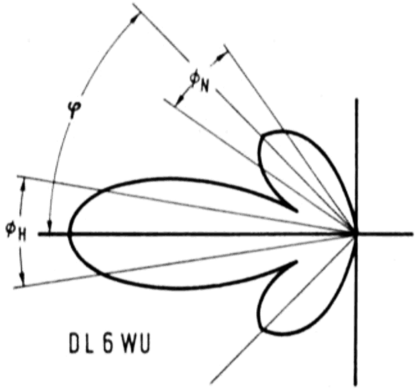

Fig. 6: Typical diagram of a Yagi antenna with one minor lobe

Assumed is a main beam of $\varnothing_H = 24°$ (3 dB points at ± 12°) and minor lobes with a maximum at $\varphi = \pm 36°$ and $\varnothing_N = 12°$. The diagram is assumed to be rotationally symmetrical with respect to the axis $\varphi = 0°$, which is virtually true for long Yagi antennas. The area S on the surface of the sphere for the beamwidth can be calculated as follows: $S = 2\pi (1\text{-}\cos\varphi)$

Main beam:	$\varphi = 12°$: $S_H = 0.138$
Minor lobe:	$S_N = S_{42°} - S_{30°} = 0.77$

This means that the minor lobes cover 5.6 times the surface area of the main beam ! Since one can assume the minor lobe to be in the form of a funnel around the narrower main beam, this is not surprising.

In order to keep the calculation as simple as possible, the 3 dB surface has been assumed to be the effective surface, however, since only the ratio of the surfaces to another is of interest, it is assumed that the error is not important.

The total energy flow P of the antenna is distributed onto the main lobe (P_H) and the minor lobe (P_N) in relationship to their surfaces multiplied with the value of the minor lobe suppression (N_N), thus $P_H/P_N = N_N \times S_H/S_N$.

Since $P = P_H + P_N$ is constant, only a correspondingly reduced component of the total energy is available for the main beam, and the gain will be reduced to the some ratio.

The decrease in gain amounts to:

$$R = \frac{G}{G_{red.}} = 1 + \frac{S_N}{N_N \times S_H}$$

With our example with $S_N/S_H = 5.6$, the following is valid:

N_N	R
5.6 (7.5 dB)	2.0 (3.0 dB)
10 (10.0 dB)	1.6 (2.0 dB)
20 (13.0 dB)	1.3 (1.1 dB)
50 (17.0 dB)	1.1 (0.5 dB)

It will be seen that when the minor lobe suppression is only 7.5 dB as in this case, half the energy will be »lost« in the minor lobes and the maximum gain will be reduced by half.

If one assumes the following data for the prototype antenna: $\varnothing_E = \varnothing_H = 24°$, and $N_N =$ 13 dB, the following gain calculation will result:

$$G_i = 55.7 = 17.5 \text{ dB (ref. isotropic radiator)}$$

$$G_D = G_i - 2.14 \text{ dB} = 15.36 \text{ dB (ref. dipole)}$$

$$G_{D\ red.} = G_D/R = 14.26 \text{ dB (ref. dipole)}$$

This value coincides well with the measured gain values of long Yagi antennas. For clarification, it should be noted that the above example is very typical, however, the position and width of the minor lobes vary. The tendency is, however, very clear: the effect of the minor lobes increases together with the directivity. It is also not possible for the back beam and higher-order minor lobes to be always neglected.

Practical experience gained since firstly writing this article tend to indicate that the gain calculation according to the Tai/Pereira expression (8) are somewhat low. The gain formula according to Kraus given in the same paper [$G \approx 4\pi (\varnothing_1 \times \varnothing_2)$] seemingly coincides with the measurements more accurately. In the above example, $G_{D\ red.}$ would be 15.34 dB.

3.5. Additional Details

When plotting the polar diagrams and making comparative antenna measurements, it is very important that a good matching is made. Most receiver inputs cause a considerable mismatch to the feeder which can cause a detuning effect on the antenna when using short feeder lengths. This can be avoided when using a 10 dB attenuator.

The author used an experimental arrangement for the preliminary experiments using an aluminium boom of U-shaped profile. The elements were soldered into brass blocks and could be shifted along the boom. The dimensions are very handy when these experiments are made in the 70 cm band. The determined lengths and spacings were then filed in a card index.

The large reflection-free antenna measuring range of the German Post Office was sometimes available for exact measurements. A typical example is that a 2 λ long uniform Yagi constructed according to data given by Ehrenspeck indicated a gain of 11.0 dB and thus showed only a deviation of 0.15 dB from the nominal value given in **Figure 2**. A 10-element Yagi of the same length derived from this showed a gain of 11.5 dB with a beamwidth increase from 34°, with minor lobe suppression increased by nearly 10 dB. In comparison, a series produced antenna available on the market of twice the length only provided 0.5 dB more gain.

4. REFERENCES

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