# Measuring Yagis

**Paolo Antoniazzi and Marco Arecco have devised a simple yet accurate method of measuring the gain of Yagi antennas for the 2m band.**

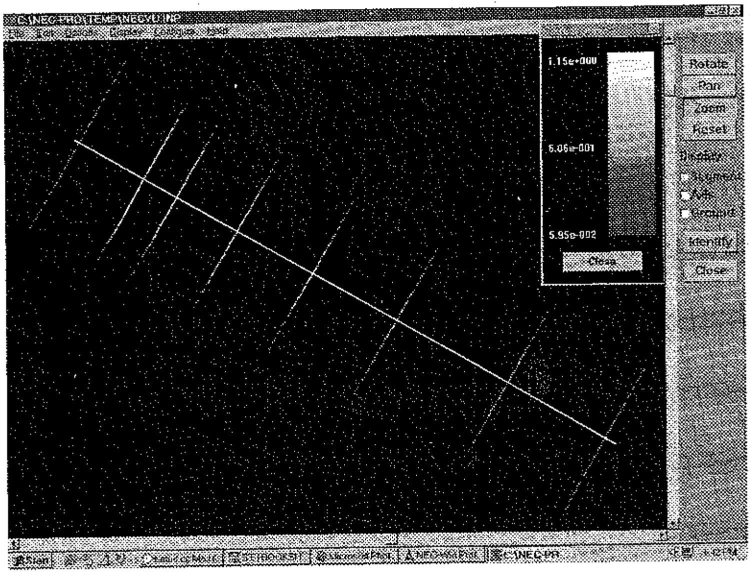
Measuring a Yagi is much more difficult than simulating one. Henry Jasik[1] once said, "The measurement of total gain of antennas is probably the most difficult measurement of antenna technology..."

For decades the Yagi antenna has been the first choice for television reception and amateur radio applications. But the most important properties – gain, efficiency and radiation pattern – could be evaluated only by difficult and time consuming measurements. The accuracy of these measurements was poor too.

During the seventies, large simulation programs for antennas were developed on mainframe computers for research purposes. These simulators were eventually modified for use on microcomputers.[2]

Today, good programs such as *NEC-Win Pro* for Windows NT/98, are available for all serious experimenters. The simulations they produce are often more accurate than the results obtained from making field measurements.[3] **Figure 1** shows a current-density optimised plot of an eight-element Yagi simulated using *NEC Win Pro*.

*Fig. 1. Current-density optimised eight-element vhf Yagi, simulated using NEC-WinPro.*



## Measuring antenna gain

Many people have attempted to measure Yagi antennas. For all of them, the biggest problem during tests on field strength has been that of interaction between direct and reflected wave.[4,5,6]

Due to this interaction phenomenon, the level of the signal received by the horizontal Yagi antenna at the receiving site changes when the height of the antenna is altered.

By linearly varying the height of the antenna under test by about 3m, which is slightly more than one wavelength at 144.5MHz, it is easy to see where the minimum received signal occurs, i.e. when the reflected signal at the antenna is in antiphase with the direct signal. If the reflection is almost total, the notch depth can exceed 20dB.

In the case of the maximum reflected signal being in phase with the direct signal, the sum could be as much as, but not exceed, +6dB. Of course, all intermediate values are possible. But when the ratio between the direct and reflected waves exceeds 24dB, the curves in figure 1 have converged to a maximum error of ±0.5dB.

**Figure 2** thus shows the maximum error that can occur when positioning the antenna at any given height. Note that it is not easy to reduce the reflected wave significantly. But by measuring and plotting the received signal at various heights, it is possible to determine exactly the direct/reflected signal ratio and, therefore, the value of the direct signal itself.

By comparison with the results for a reference antenna, more accurate results can be derived. These, together with information from the horizontal radiation pattern, permit a more accurate estimation of the true value of the gain of the antenna under test. Note that since the vertical radiation patterns of both the transmit antenna and the antenna under test affect the value of the received wave, it is important to compare both plots of the received signal versus height, and no just the two apparent gains.

One of the most important sources of information is that produced by Kraus.[7] His work shows that the reflected-wave problem can be reduced by making measurements using buildings of 5-10 storeys high, **Fig. 3**.

To obtain a 25-30° angle for the reflected wave over a useful distance of about 100m, two buildings between 30 and

50m high are needed. As you we will see later, the 100m distance necessary for long-Yagis.

We carried out such testing using a 16-element high-gain Yagi. We placed the transmitting antenna on the roof of a 14m high house and orientated it towards a park with no obstacle around, **Fig. 4**. This diagram allows you to calculate the effective radiation angles and the path of direct and reflected signal for the 6dBd reference yagi and for the eight-element antenna under test. The test antenna was 3.2m long and had a simulated gain of about 10.6dBd.

## Analysing the theory

The following considerations assume a horizontally polarised wave since horizontal polarisation is most widely used in both television broadcasting, ssb, cw and tropospheric links at 300-1000km.

As is well known, the electrical field received from the antenna is given by the vectorial sum of direct and reflected wave.

The electrical field equation is,[5]

$$E = E_d\sqrt{1 + k^2 + 2k\cos\left(\frac{2\pi\delta}{\lambda} + \pi\right)}$$

where,

$E$ is intensity of the resulting field in V/m,
$E_d$ is field intensity of the direct wave in V/m, $k$, which is less than unity, is the ratio between reflected and direct electrical field,
$\pi$ is 180° rotation of the reflected wave relative to the direct one (horizontal polarisation)
$\delta$ is the difference of path in metres between direct and reflected wave ($\sim 2h_t h_r/d$)
$\lambda$ is wavelength in metres.

There is an accurate expression for calculating the difference in distance between direct and reflected wave, δ. This expression was the starting point for a simplified formula that can be used when $(h_t+h_r)^2/d^2$ and $(h_t-h_r)^2/d^2$ are both much less than one,

$$\delta = \sqrt{(h_t + h_r)^2 + d} - \sqrt{(h_t - h_r)^2 + d}$$

Here, $h_t$ is the height of transmitting antenna, $h_r$ is the height of receiving antenna and $d$ is the distance between the foot of the two antennas. All three distances are in metres.

We used this expression for our analyses. Thanks to personal computers, it can be applied for very complicated designs. We estimated that the simplified formula results in an error of about 7%.

To reduce measurement errors, the distance between transmitting and receiving antennas has to be considered. To determine this distance, you need to be able to measure the signal level easily with a filtered rf voltmeter having a 30-40dB dynamic range. Also, the wave reaching the receiving antenna should be as planar as possible.

The first condition can be easy established starting with the received power and calculating the attenuation experienced by the wave in the open space,

$$\alpha = 32.4 + 20\log(f) + 20\log(d) - G_t - G_r$$

Here, α is attenuation in decibels, $f$ is frequency in megahertz, $d$ is distance in km, $G_t$ is the gain of transmitting antenna in dBi and $G_r$ is the gain of receiving antenna, also in dBi, obtained by simulation.

There is also a simple, easy to remember method of calculating the attenuation by considering the distance between the two antennas in terms of wavelengths.

When $d=\lambda$, α is always 22dB between isotropic antennas. This equates to 2.08m at 144MHz. The attenuation increases by 6dB for each doubling of the path distance. This means that the free space attenuation is 22dB at 2m, 28dB at 4m, 34dB at 8m, etc.

To make the wave reaching the receiving antenna as planar as possible, the capture area in square metres of the receiving antenna and the maximum acceptable phase error are needed,

$$A_c = G_r\frac{\lambda^2}{4\pi}$$

This expression is valid for an antenna with no thermal losses and was certainly useful for our experiments.

Assuming that the capture area is circular, the minimum distance in meters between the two antennas will be,

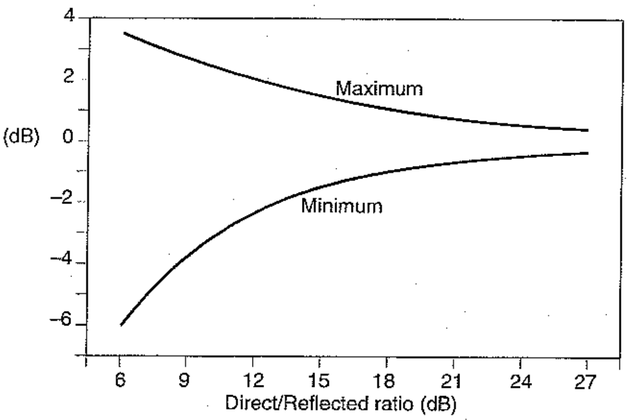


***Fig. 2. Absolute maximum test error versus direct/reflected signal ratio. This is the maximum possible gain measurement error when moving the antenna up and down the mast. As you can see, the error in decibels can be positive or negative, depending on the relative phase of the two signals.***

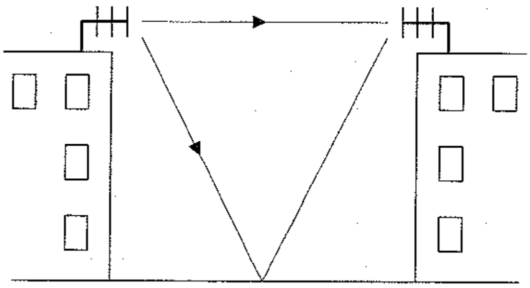


***Fig. 3. Kraus suggests that Yagi tests should be carried out using two reasonably high buildings to reduce reflection errors.***

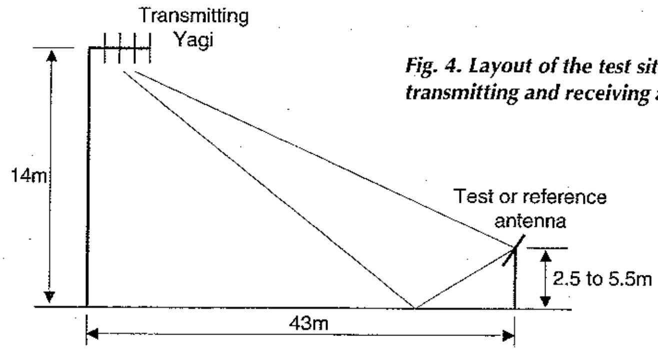


***Fig. 4. Layout of the test site with transmitting and receiving antennas.***

$$d > nG_r\frac{\lambda}{\pi^2}$$

For a maximum phase difference of 22.5°, which is usually enough, $n$=2. If a phase error of only 5° is required, $n$=9. In the case of Yagi antennas, where one dimension prevails over the other ones, the maximum length, instead of the capture diameter, is used. In this case, the minimum distance in metres becomes,[4,8,9]

$$d > n\frac{L}{\lambda^2}$$

where $L$ is the maximum Yagi length in metres.

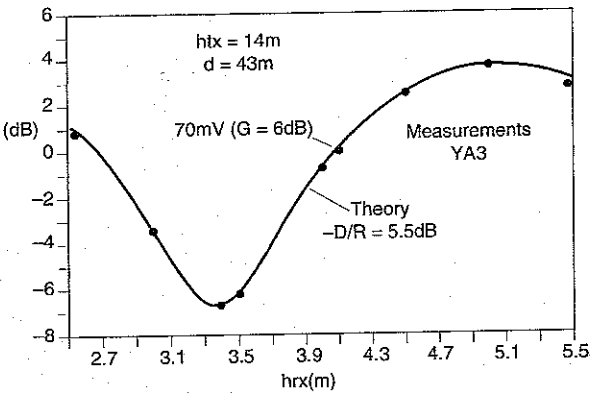


*Fig. 5. Calculated and measured values of signal level versus antenna height and direct-to-reflected signal ratio. These values are for the three-element reference Yagi at 144.5MHz.*

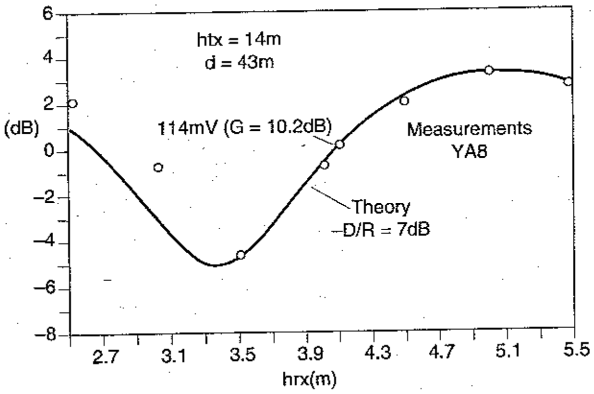


*Fig. 6. Performance of the eight-element Yagi at 144.5MHz. As with the previous graph, these are calculated and measured values of signal level versus antenna height and direct-to-reflected signal ratio.*

## Siting and antenna height

The minimum height from ground of the antenna under test is another parameter to be controlled during the measurements. This is because the proximity of ground can modify the radiation resistance.

In our case, the minimum height is $h_r$ is more than λ, but the relevant points of the curve have been measured at 2λ and above. Note that the simulation software that we used used (NEC-WinPro) does not take into account the ground plane. Also, the typical parameters of the antenna – gain, radiation angles, impedance – are calculated in the free space.

To define the correct receiving height, it must be considered that the electrical field, and hence the voltage measured by the millivoltmeter – have maximum and minimum values due to the different path of direct and reflected wave, sum or difference.

To be confident about the measurements, it is necessary to find at least a maximum and the nearest minimum using the first two formulas. This was done allow us to draw the curves of **Figs 5, 6**.

A suggestion from an article that appeared in *VHF Communication*[10] convinced us to incline the antenna to be measured with respect to ground. This allowed us to have the maximum signal for the direct wave and the maximum attenuation for the reflected one, exploiting the shape of Yagi radiation diagram. In particular, the approximate 40° angle of reflected wave relative to the receiving antenna attenuates it by around 2 to 4dB.

We decided not to incline the transmitting antenna to improve the ratio between reflected and direct wave. Instead, we exploited the directivity of the antenna. The advantage is about 5dB as the reflected wave is about 23° under the plane of maximum radiation and 13° under the direct wave path.

Another way to reduce the reflected wave, which we did not try, is to place a metal screen near the reflection point. This plate needs to have significant dimensions with respect to the wavelength: 2 by 4m for instance.

According to previous considerations and the availability of a suitable area for field testing, the conditions of the measurement site are defined as follows:

Transmitting Yagi, – 16 elements, $G$=13dBi, $h_t$=14m with the boom parallel to the earth plane.

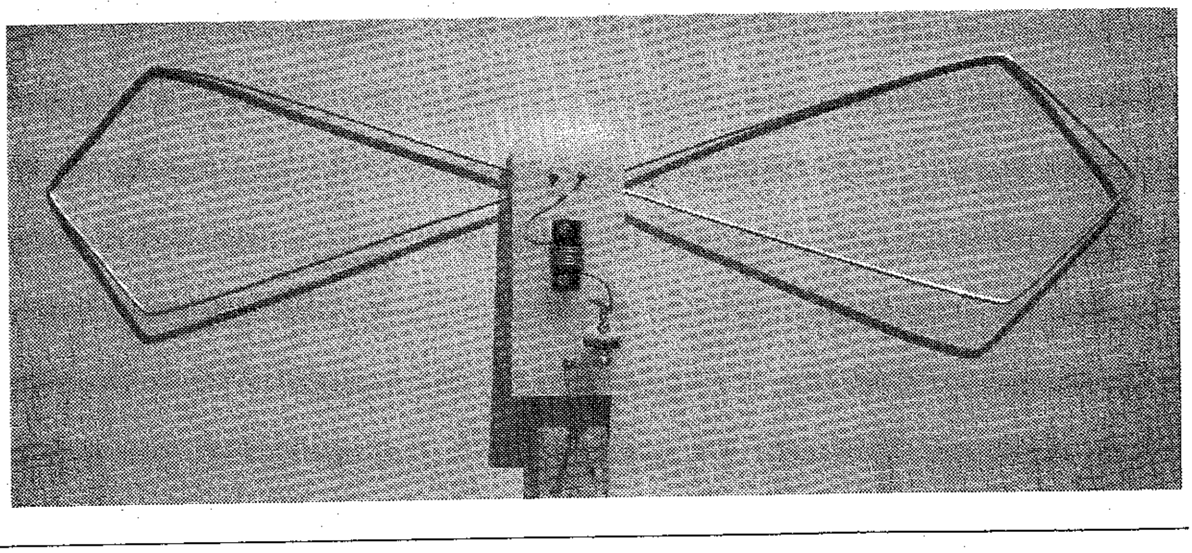


*Fig. 7. Rhombic reference dipole realised for comparison tests.*

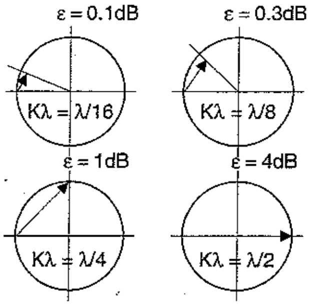


*Fig. 8. Planar wave concept and phase error.*

Reference antenna – home-made three-element Yagi, G=6dBd, calibrated by the reference dipole described next and shown in **Fig.** 7, $h_r$=2.5 to 5.5m. Minimum received signal was at 3.4m and maximum at 5.1m. The boom had a 13° angle with respect to the ground plane.

Antenna under test – this was a 3.2m long (1.8λ) eight-element home-made Yagi.

The site we selected is useful for measurements of antennas up to 6m long. This equates to about 3λ at 144.5MHz).

For accurate antenna gain measurements, the distance between the transmitting and receiving (test) antennas should be greater than that needed to satisfy the far-field conditions for $d$>5λ and greater than the approximate uniform plane wave.

So if you want to measure a 10m long Yagi, it is necessary to increase the distance using,

$$d > n\frac{L}{\lambda^2}$$

to maintain the error due to a non-uniform plane wave within a fraction of decibel, **Fig. 8**.

To detect the received signal at the receiving antenna we used a Boonton *92B* millivoltmeter. This meter is well suited for these applications but it is possible to make your own instruments with good sensitivity and accuracy. The signal under test ranged from 143 to 146MHz and was swept by means of a small remote control.

To conclude, Figs 5 and 6 show the obtained values superimposed with the curves calculated with the first two formulas, normalised to the direct wave and given in decibels.

The difference in signal between the 6dBd reference Yagi YA3 and YA8 at the null point – i.e. with no reflected wave – is 4.2dB. This allowed us to conclude, after a critical analysis, that the gain of the 1.8λ long eight-element Yagi is 10.2dB.

The analysis considered the optimum matching between measured and simulated radiation diagram was ±20° at –3dB. The maximum test error is probably around 0.5dB.

The measured value of front-to-back ratio at 180° is 21.5dB.

## Error sources

Most errors that occur during antenna measurements are related to the reflected wave. The total error can vary from a maximum of +6dB, when the direct wave is summed to the reflected one, to –20dB or less when the two components of received signal are subtracted each other according to the first mathematic relation we presented.

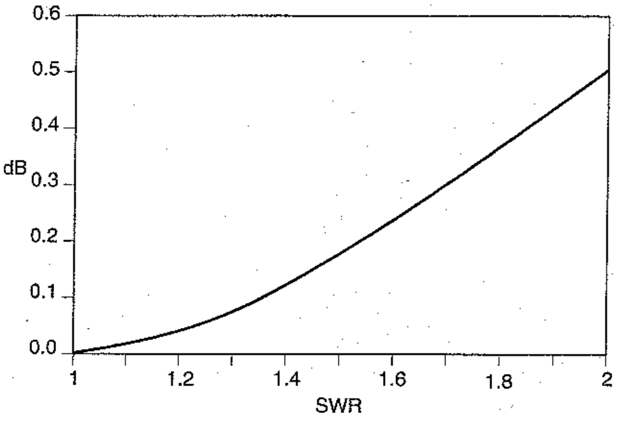


*Fig. 9. Maximum error versus standing-wave ratio of the antenna under test.*

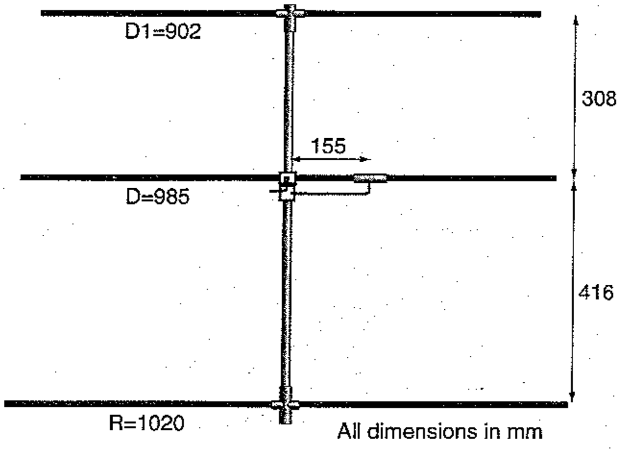


*Fig. 10. Three-element reference Yagi dimensions.*

Broadcast fm signals received by the antenna under test can affect the measured voltage significantly. To minimise this problem, we performed the measurements as near to the antenna as possible. How close the measurements can be made depends on the antenna dimensions and the planar wave effect must be catered for. We incorporated a good helical filter for 144.5MHz, ±5MHz to reduce interference and obtained a useful received signal of about 100mV.

Another source of error is related to the antenna impedance mismatch, relative to 50Ω. The mathematical relationship that describes the signal loss on the receiving antenna output or on the load is given by the following equation when the antenna impedance is greater than 50Ω,

$$\frac{V_a}{V_o}(\mathrm{dB}) = 20\log\left[2\frac{1}{1+SWR}\sqrt{\frac{Z_a}{Z_o}}\right]$$

Here,

$V_a$ is antenna voltage in volts when $Z_a \geq 50\Omega$
$V_o$ is antenna voltage when $Z_a = 50\Omega$
$SWR$ is standing wave ratio
$Z_a$ is antenna radiation impedance
$Z_o$ is load impedance (50Ω)

When $Z_a>Z_o$, $SWR=Z_a/Z_o$. For an antenna impedance of less than 50Ω, the equation becomes,

$$\frac{V_a}{V_o}(\mathrm{dB}) = 20\log\left[2\frac{SWR}{1+SWR}\sqrt{\frac{Z_a}{Z_o}}\right]$$

Here, $SWR=Z_o/Z_a$ when $Z_o>Z_a$. The behaviour of the maximum error versus receiving antenna standing-wave ratio is shown in **Fig. 9**.

A load impedance different from 50Ω can also introduce a measurement error which is minimised using a 10dB fixed attenuator connected directly to the antenna output. In our practical case, load standing-wave ratio was better than 1.05 with a tiny error of less than 0.03 dB.

A 10MHz-wide band-pass filter is normally included to screen out possible out-of-band strong signals mainly from fm broadcasting stations.

## Reference antenna

The reference antenna is a log-periodic wide-band type that is frequently used in this type of application. Its approximate bandwidth can be calculated by using the lengths of shorter and longer elements. Bandwidth is about half of the maximum and the minimum wavelength at which the antenna can be used.

When working at a single frequency, only part of the whole antenna is active: the elements have a physical dimension nearest to one half of the wavelength. It is important to remember that input impedance and radiation properties of this antenna are repeated periodically with the logarithm of the frequency.

Commercial log-periodic antennas often used in electromagnetic-compatibility measurements are manufactured by companies including Hewlett Packard and Emco and are available with calibration graphs. The *HP11966D* for example covers the range 300-1000MHz and costs around £1500 pounds.

Considering the narrow band involved in our measurements, and the consequent small variation of standing wave ratio versus frequency we decided to build-in a reference Yagi with similar behaviour and accuracy as the log-periodic.

We calibrated our Yagi with reference to a half-wave dipole, the performance of which is well documented.[9] Assuming no losses, the features of a half-wave dipole are,

| | |
|---|---|
| Horizontal half-power beamwidth | 78.1° |
| Directivity | 2.14dBi |
| Receiving area | 0.131λ |
| Effective length | 0.318λ. |

The main characteristic needed for our reference dipole is a standing-wave ratio lower than 1.2 with a negligible error of ±0.05dB. As a result, we made our dipole rhombic in shape. Its length is 798mm, its width is 180mm and it is made from 4mm diameter aluminium wire.

It is necessary to 'balance' the antenna using a choke comprising six turns of teflon-coated cable on a 20mm diameter insulated support. Due to the addition of this cable, 0.2dB must be subtracted from the gain of the dipole, making it –0.2dBd instead of the 0dBd theoretical value.

We do not advise the use a dipole for repeated tests since it is omnidirectional. It also has a significant gain in the fm broadcast range, which contains strong unwanted signals.

A dipoles[11] can be useful as a reference, but it does not have the flexibility and measurement reliability of a Yagi with more than 25dB of front-to-back ratio.

At the beginning we though of a two element Yagi, i.e. a dipole plus reflector, but its front-to-back ratio was not high enough for our needs. Also, to optimise standing-wave ratio, we would have had to work with many different values of gain.

After may hours of simulation with NEC-Win Pro 1.1[3] and some field measurements, our choice was a three-element Yagi built with 10mm diameter rod. It had a gamma matcher made from copper and teflon.[10] Its gain was 6dBd and it had a high front-to-back ratio.

The passive elements have insulated supports 30mm high, while the dipole has an aluminium support, connected electrically with the boom via a type-N connector.

The final reference antenna, **Fig. 10**, is easy to make and repeatable. When made precisely to the drawing and well trimmed for standing-wave ratio, it meets the design requirements of 6dBd gain at 144.5MHz.

## In summary

There are many potential sources of error when performing Yagi gain measurements and there has been a great deal of optimism when analysing them.

If you consider that a typical site for professional measurements described in reference 12 certifies the gains of the antennas under test within ±2dB between 30 and 1000MHz, you can better understand the difficulties that arise.

We have examined the subject of dipole calibration and presented a three-element reference yagi for easy comparison tests at very high frequencies.

We believe that by averaging repeated measurements, it is possible to obtain results with maximum error of around ±0.5 dB. ■

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### Further reading

Brown, F, W6HPH, 'Antenna Gain Measurements,' *QST*, Nov. and Dec. 1982.

* **Reference Data for Engineers** is now published by Newnes and available via *Electronics World*'s editorial offices. E-mail jackie.lowe@rbi.co.uk or fax 0181 652 8111 for details.