Chapter 5

Antennae

The antenna is the element that collects radio energy from its surroundings and converts it into an oscillating electrical signal in the tube or wire from which it is constructed. It is one of the most critical pieces of technology for any radio receiver. Get the antenna wrong, and no matter how good the receiver is, it will not perform at its best.

Antennae appear to be simple constructions of wire or tube, but proper understanding of their function and design is amazingly complex at times. There are many texts available on the subject, which could on its own fill this entire book. Presented here are several common designs that can be adapted easily to the frequency of choice.

All antennae have the following properties:

- Characteristic impedance
- Directional properties
- Forward gain
- Polarization
- Beam pattern

Characteristic impedance is described in ohms. The concept of impedance is discussed in more detail in the electronics chapter. Impedance of the antennae should be closely matched to that of the feeder cable, which in turn should be closely matched to the impedance of the input side of the receiver. Mismatched impedances at any point create internal reflections of the signal, reducing the amount of energy passed on to the next stage and thereby reducing the efficiency of the system.

The actual impedance of a practical antenna is complex and can vary with its proximity to the ground or other nearby structures. To aid in setting up you can purchase antenna analyzers from amateur radio supply stores that will allow the constructor to adjust and match systems for best efficiency. However these analyzers are set up mostly for amateur radio bands. Later we will describe the construction of an impedance bridge you can build yourself.

Although all antennae have some directional properties, it is desirable in radio astronomy to concentrate on systems that have significant forward gain. The directional properties and forward gain are closely related. So called omnidirectional antennae, often used by amateur radio enthusiasts for scanning the airwaves or for general communication, strictly speaking, do not radiate equally in all directions. Such antennae are often vertical and do not radiate well straight up, but then no

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one is transmitting above you, are they? Except maybe from outer space! For this reason we will not be discussing vertical or omnidirectional antennae here. Forward gain is a numerical measure of how much more efficient an antennae is in a beamed direction than an ideal omnidirectional (or isotropic) unit would be. The value is expressed as either a pure number (a ratio) or more often in the decibel notation dBi, where the "i" refers to the ideal isotropic radiator.

It is important to remember that all real antennae are polarized. To understand the meaning of this, consider the nature of the electromagnetic (EM) waves. An EM wave travels in a straight line in free space (for our purpose Earth's atmosphere can be considered free space, too); perpendicular to the path is an electric wave, and perpendicular to both is a magnetic wave. For the most part the antennae we use on conventional radios couple to the electric wave component of the radio signal. Radio signals are linearly polarized if all the electric wave components are parallel. For proper reception a linearly polarized antenna, such as a wire dipole, should be aligned with the electric vector of the impinging waves. In practice, for radio astronomy signals are often randomly polarized. This means that a single antenna will only collect half of the potential radiation.

The beam pattern of an antenna is another complex story. Beam pattern for, say, a simple dipole can be altered by changing its length! This pattern can become narrower and more complex by adding several antennae in an array close to each other. The beamwidth of a practical antenna is expressed in degrees. It is the similar to field of view of an optical telescope. Beamwidth is an angular measure between the half power points (3 dB points). The half power points are those "off axis" points at which the received power drops to half of the value of the center of the pattern. Note here that not all directional antennae have circular beam patterns.

When designing or evaluating an antenna system for a radio telescope – which is, of course, a radio receiver – it is often more useful to think of the antenna as if it was transmitting instead. For example, the majority of antennae have some directional properties called the beam pattern. It is easier to picture the beam pattern as if it were radiating away. The same beam pattern works in reverse for the receiver.

The Dipole

Although the simplest antenna is a long, straight wire, which will certainly pick up radio to some extent, it will not be considered here. A more practical antenna is the dipole, consisting of two lengths of wire or tube (later we will see a folded version) whose center connections are linked to the radio transmitter or receiver.

The most common dipole antennae are half a wavelength wide for the wavelength of interest. For example, let's take a Jovian decametric receiver working at 20.5 MHz. The length of a dipole can be easily calculated by this formula

$$L = \frac{143}{f}$$

where f is the frequency in megahertz and L is the total length of the dipole in meters.

This gives a dipole length of 6.98 m. Note that the formula takes into account some foreshortening effects of real antennae, so the resulting length is slightly shorter than half a wavelength.

The radiation pattern of a dipole is, when looked at in two dimensions, that of a figure of eight, with "lobes" extending perpendicular to the antenna. In three dimensions the radiation pattern is more like a doughnut. The key fact here is that a dipole does not work well in a direction parallel to itself. Equally, any noise within the receiving bandwidth which is in line with the dipole will be significantly suppressed. Because the antenna receives signals in a preferred direction and suppresses signals in other directions, and the length of it is tuned to the wavelength of interest and is less efficient at other wavelengths, we say it has gain. In our example, the dipole, the gain will be 1.64. Gain is a pure number, a ratio of the radiated power (remember it is easy to think in terms of a transmitting antenna) divided by the radiated power of an ideal isotropic antenna (one that radiates equally in all directions). Hence our dipole will provide a signal strength of 1.64 times better, in its beam direction, than a unit that is omnidirectional. The more directional the antenna is, the greater is its gain. This gain is free – it does not rely on electrical power!

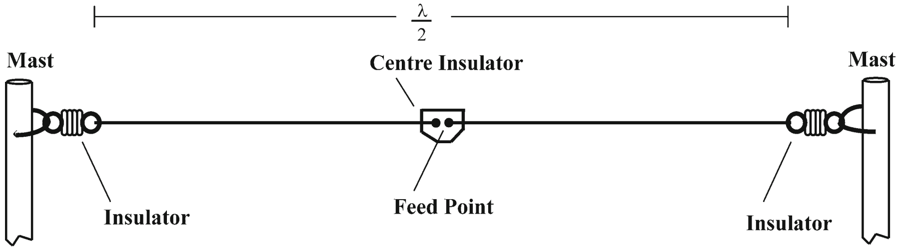
You might be thinking, why half a wavelength? Why not a full wavelength? Clearly for the dipole to be tuned to the wavelength of interest, it must have a length that is a clean fraction of receiving wavelength, such and a quarter, a half, a three-quarter, etc. Well, the effect of dipole length is not what you may be expecting. A quarter wavelength dipole has a wider beam pattern than a half wavelength version, and so it has less gain, but they both have that simple doughnut radiating pattern. A full wavelength dipole actually has a double doughnut radiating pattern and is most sensitive at a 45° angle! The three-quarter wavelength version is a hybrid, with weaker perpendicular lobes and stronger 45° lobes (see Fig. 5.1). Hence the half wave version gives us a nice simple radiating pattern.

A note of caution, then, for our example dipole working at 20.5 MHz. The 6.98-m dipole presents a full wavelength dipole at 41 MHz and will therefore be sensitive at 45° intervals at this higher frequency. The Jovian receiver should be suitably filtered at its input with at least a low-pass filter with a cutoff point below 41 MHz, and better still with a bandpass filter having a low cutoff above 10.25 MHz and a high cutoff below 41 MHz.

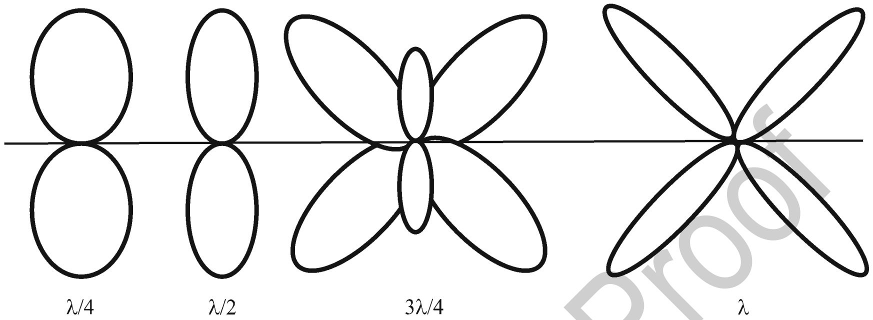
It is important to understand how to connect the dipole antenna to the receiver. All modern receivers have what is known as an unbalanced input. In plain words, this means that one of the input conductors is grounded to Earth (the outer conductor of a coaxial connector). The dipole, on the other hand, is balanced – neither half is grounded. If we were to just connect our coaxial feed cable to the center contacts of the dipole, the feeder would become part of the antenna and in the transmitting case would radiate energy. It would also affect the beam pattern for a receiving antenna and alter its tuned length. To combat this problem we need to provide a balun transformer.

The word balun comes from "balanced to unbalanced." In the case of the dipole antenna considered the center point impedance is about 75 Ω (although this will vary with height above the ground). This matches quite well to 75 Ω coaxial cable. The balun required is therefore a 1:1 balun, meaning it does not change the characteristic impedance. As we will see later a folded dipole will show an impedance of 300 Ω, so a 4:1 balun is used to transform the impedance down to 75 Ω. The properties of a balun provide equal but opposite phase currents to flow in the feed cable; therefore, the effects cancel each other out, and the feeder does not radiate power or affect the tuned length of the dipole.

Baluns can easily be purchased from amateur radio supply stores, but are equally easy to make. A simple ½ wave loop of coaxial cable, the same used to feed the receiver, can be used. The diagram below shows how this is done (Fig. 5.2).



Basic Diople Antenna



Beam pattern for simple dipoles

Fig. 5.1. Basic wire dipole with it radiation patterns. Usually the dipole is cut to a half wavelength, which provides the simplest beam pattern with reasonable gain.

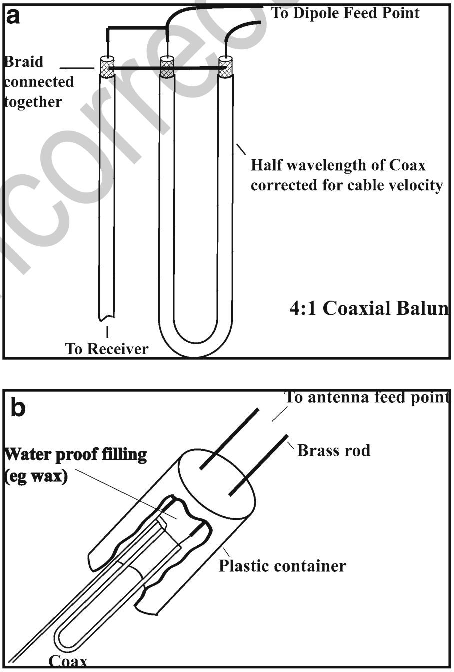


Fig. 5.2. (**a**) Balun coaxial cable. (**b**) Mounting and waterproofing the balun. If using silicone as a sealant build it up in layers to ensure it dries properly.

A Simple Dipole

The simple dipole is a resonant antenna with a very small bandwidth. It is tuned to one wavelength. This is fine for a fixed channel receiver dedicated to one job, but certain applications may require the receiver to be tunable over a range, to cover, say, a band of wavelengths allocated to radio astronomy, or so the spectrum either side of a center frequency can be studied. Going back to our Jovian decametric receiver scenario, let's look at how we can improve the dipole. In order to avoid local interference at 20.5 MHz we may want to tune the receiver between 18 and 24 MHz to find a suitably quiet spot away from ground-based channels. We can make three dipoles in one go with a common feed point. So let's make one for 18 MHz, one for 21 MHz, and the third for 24 MHz. The resulting lengths are then 7.94, 6.81, and 5.96 m. This technique works so long as any one dipole is not an odd integer multiple length of any of the others. A clever way to build this antenna is to use three core cable cut to the longest dipole, then shorten the other two cables to suit. At the center the three cores are connected together on each side.

A Folded Dipole

An alternative to multiple dipoles would be a single folded dipole. This is illustrated in the Fig. 5.3. Folding has two advantages; firstly, it is a much wider bandwidth, and secondly, it is narrower than the single equivalent.

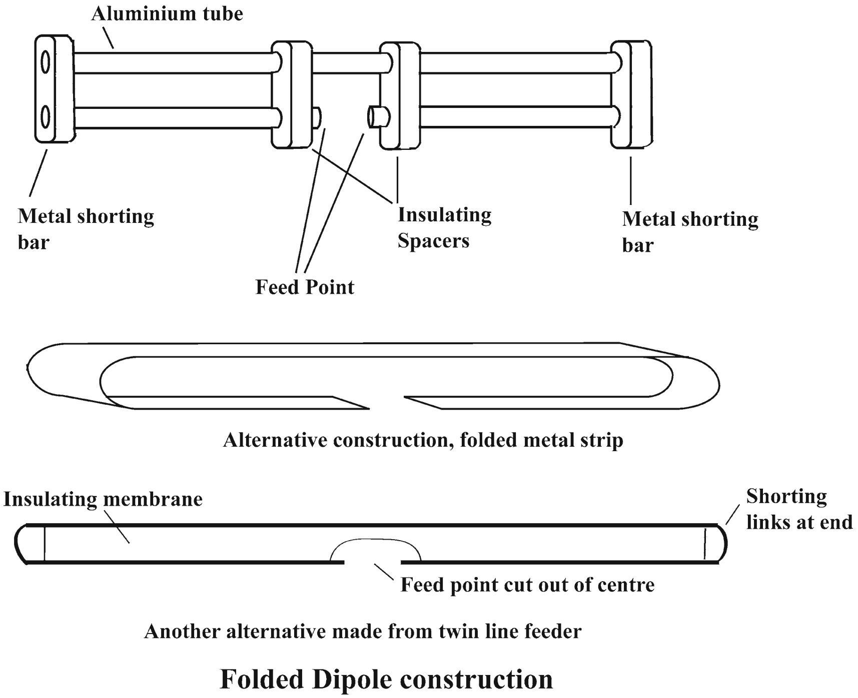


Fig. 5.3. Folded dipole ideas. The aluminum tube version is suitable for short wavelength because of its high rigidity. The twin line version suits long wavelengths, because it is lightweight. The twin line is automatically mounted parallel by virtue of its construction around the plastic sheet insulator. (For increased bandwidth extra shorting bars or wires can be added; see text for details).

The characteristic feed point impedance is now 300 Ω, so the balun must now convert the impedance as well. A 4:1 balun divides the impedance of the antenna by four and therefore matches well with 75 Ω coaxial feeders such as RG59. It can be constructed using a 300 Ω twin feeder, which used to be used for television applications. A length is cut to the total dipole dimension, the ends are shorted at both sides, and one of the conductors is broken at the center point, which becomes the feed point. Most 300 Ω cable is quite weak in construction and when subjected to the weather and wind loading forces may break if suspended on its own. It is advisable to provide support at least at the center and the tips. The diagram illustrates some techniques of construction and mounting. The total length of the loop should be as before, but the linear length is about half that of the unfolded version. A trick to increase the folded dipole bandwidth even more is to add an extra pair of shorts closer to the feed point. The distance from the feed point to these inboard shorts can be calculated from

$$L = \frac{61}{f}$$

where L is the length in meters, and f is the frequency in megahertz.

Folded dipoles are most often seen in the construction of Yagi antennae, particularly for UHF television reception. The improvement in bandwidth is suited to cover the range of UHF television channels employed in a given region. Yagis will be discussed in more detail later.

It is possible to improve the performance of a dipole and increase its forward gain and narrowing its directionality by adding a corner reflector. In theory a reflector would be a parabolic cylinder with the dipole at its focus. However, at the long wavelengths we are dealing with it turns out that a simple 90° corner reflector is a good enough approximation and works very well. The reflector should be slightly wider than the dipole, and the depth of the sides should not be less than 0.7 wavelengths. The dipole is placed at the focus of the corner, which is calculated as 0.35 wavelengths from the apex of the corner. The frame of the reflector can be constructed from wood. It needs to be lined with wire mesh or parallel wire lines. Wire line could be low-cost galvanized steel fencing wire and should be parallel to the dipole. The separation of the wires or the size of the mesh should be less than or equal to 1/10 of a wavelength (Fig. 5.4).

Inverted V Dipole

Normally wire dipoles are mounted horizontally, but they can be mounted in the form of an inverted V shape. A single mast is used to support the feed point, and the dipole "arms" are drooped at an angle of between 90 and 120° towards the ground. As with all such antennae, tip insulators (sometimes called dog bones) should be used. The best quality insulators are porcelain, although plastic ones can be found. Ropes attached to the insulators are then staked into the ground securely. The radiating pattern of the inverted V is essentially the same, but owing to the bend it is spread over a wider area. If the Jovian decametric receiving antenna were mounted this way on an east-west base line, it would increase the duration in

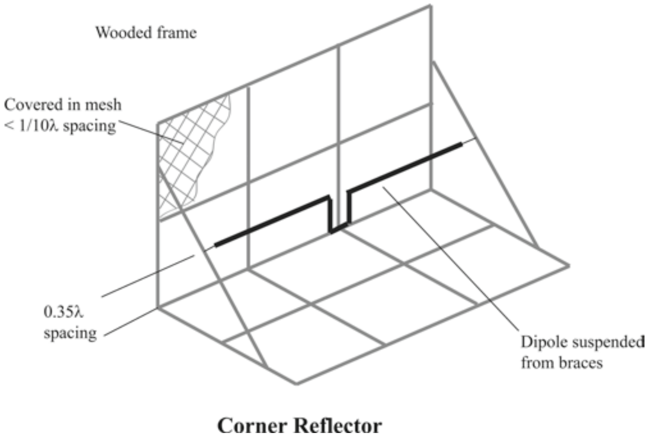


Fig. 5.4. Dipole corner reflector. Wire mesh needs to be finer pitch than 1/10 wavelength. The dipole is suspended 0.35 wavelengths above the center between both sides. Use a diagonal cross brace on each side to support it.

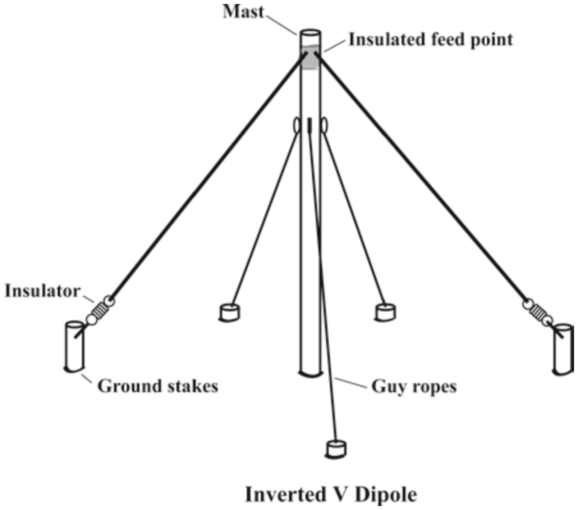


Fig. 5.5. Inverted V dipole.

which Jupiter would pass through the stronger part of the beam over an equivalent horizontal version. In this case the dipole length should be the full half wavelength long calculated from L = 150/f (Fig. 5.5).

There are many other variations on the dipole antenna out there. A common one is known as a G5RV. However, most of these more complex units are used by amateur radio enthusiasts to provide access to multiple frequency bands from a single antenna. Commercially made units will be tuned to amateur frequency bands and therefore would be less suitable for use in radio astronomy; they also require variable antenna tuners. In radio astronomy observing it is preferable to build an antenna tuned for one task, and dedicate it to that one job. The simple dipoles presented here are relatively narrowband and therefore have the advantage of rejecting a lot of unwanted noise. However, always keep in mind that these simple dipoles are resonant on odd harmonics of the design frequency, too. If one of these harmonics falls in a particularly noisy RF band it could cause undue interference. Therefore the receiver should be supplied via an appropriate low pass filter. Filter design is dealt with in a later chapter.

The amount of signal collected by an antenna is often expressed as its collecting area in square meters. It is not at first obvious how this relates to a dipole antenna. The definition of collecting area is the ratio of received power divided by the intensity of the collected wave. For a dipole this translates to about $0.13\lambda^2$, so for a working frequency of 100 MHz and a wavelength of 3 m the collecting area would be about 1.2 m^2. For a working wavelength of 1 m this would reduce to 0.13 m^2. Not very much considering the weak celestial sources we deal with.

One way to improve the situation is to increase the number of dipoles used and create an array of them. This quickly begins to demand a lot of space, though, because they need to be adequately separated from each other to avoid undue interaction playing all sorts of tricks. For one thing, if the aerials are too close together, the feed point impedance is badly affected, making impedance matching difficult. If they are spaced at least one wavelength apart in a horizontal line, then their combined effect is to multiply the collecting area by the number of dipoles used. Note, however, that the result is strongly sensitive along the line of the array. Not a great idea, as it is a potential source of interference from terrestrial sources. If the inter-dipole separation is now reduced to 0.8 wavelengths, the horizontal sensitivity is much reduced, but the central lobe expands from about 14° to a little over 17°. The beam pattern also becomes asymmetrical, as it is narrower in the horizontal plane and wider in the vertical plane. Array antennae are complex devices and a difficult area for the novice constructor. It takes a lot of care to ensure the interconnections are phase-matched correctly. More detail can be found in the ARRL antenna handbook and similar texts.

Large Loop Antennae

Loop antennae are often built in a square form, which lends itself to its common name of the Quad, or Quad Loop. A small multi-turn loop is discussed in the VLF receiver chapter. The larger cousin can be used at HF or VHF frequencies quite efficiently. Here the length of the loop from feed terminal to feed terminal is one full wavelength. The gain of the Quad is about 2 dB more than the half wave dipole. The radiating pattern is a twin-lobe form projecting from the faces of the loop. The total length of the loop can be calculated from the following formula:

$$L_A = \frac{306.4}{f}$$

where L_A is the length in meters and f is the frequency in megahertz.

Note here that these large loops use the electric field of the radio waves to function. In the case of the small VLF loop the coupling is magnetic and is therefore directional in the plane of the loop (Fig. 5.6).

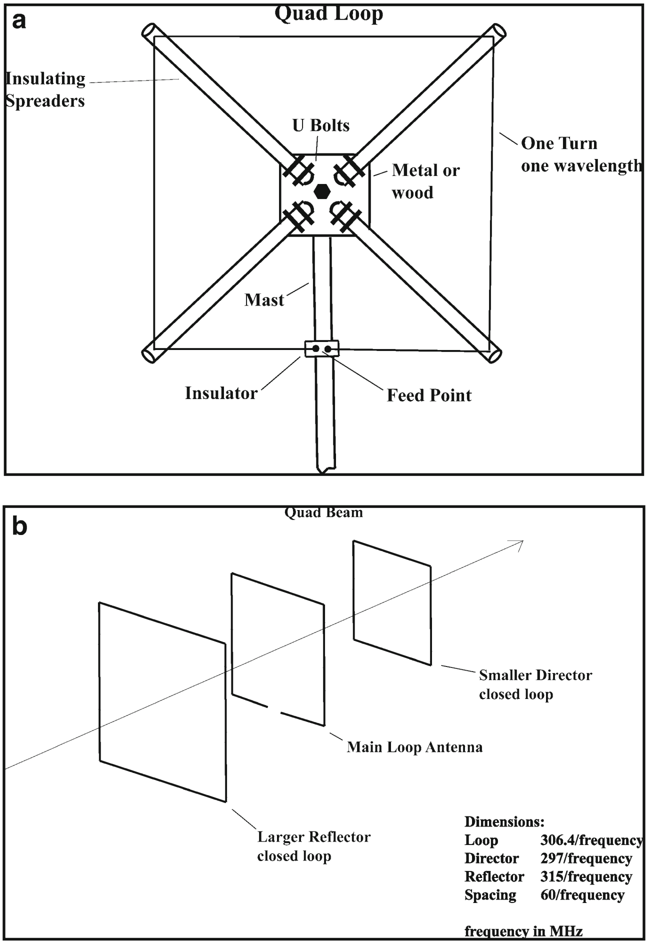


Fig. 5.6. (**a**, **b**) Large Quad loop antenna. By adding a reflector and a director the forward gain can be increased.

The loop could be constructed using a cross made from insulating material such as wooden dowels or marine plywood (weatherproof) strengthened at the center by a pair of square gusset plates. The Fig. 5.6 illustrates the details. The central gusset plates make it possible to mount it onto a mast.

The Quad is bidirectional. It is therefore advantageous for us to consider ways of making it unidirectional and more efficient in that direction at the same time. For the most part in radio astronomy, the objects we wish to observe are located in well defined directions, which move in unison with Earth's rotation. The more directional our antennae are, the better we are able to pull in the weak signals we seek.

For the Quad loop a reflector loop can be placed behind the main loop. The reflector is slightly larger than the main (or driven) loop. Its length can be calculated from the following formula:

$$L_R = \frac{315}{f}$$

In addition and less intuitively, the addition of a director loop in front of the main one further improves the forward gain. The length of this loop is given by:

$$L_D = \frac{297}{f}$$

Once again the units of L are in meters and f in megahertz.

The spacing between the three elements in meters is given by:

$$S = \frac{60}{f}$$

The resulting Quad beam antenna will have a forward gain of about 9 dBi. Some say the Quad beam works better than the Yagi antenna when it is close to the ground (less than half wavelength). The feed point impedance will be around 60 Ω, so this will be a fair match to either 75 or 50 Ω feeders, although a 1:1 balun will still be required.

Note here the Quad will be horizontally polarized if the feed point is at the center of the bottom section or the center of the top section; it will be vertically polarized if fed from either side.

Yagi Beam Antenna

The classic example of a Yagi antenna, or to give it its full name of the Yagi-Uda Array, is the UHF television aerial. Indeed, if you were planning to work in this range of frequencies it would make sense to buy a high-gain antenna off the shelf. This section discusses the design of Yagis in general so that you can experiment at other frequencies.

The Yagi is characterized by the number of elements, the elements being the dipole, reflector, and any directors used. The minimum is two elements, consisting of the driven dipole and a passive reflector behind it, or a dipole with a single director. Consider for now a two-element system with a straight unfolded dipole. Placing a reflector 5% longer behind with a spacing of 0.2 wavelengths from the dipole would yield a peak gain of a little less than 5 dBd (5 dB better than the dipole alone). The gain variation is fairly insensitive to spacing. Placing only a director (5% smaller) in front by 0.1 wavelengths would provide a gain of a little over 5 dBd. The gain this time would be quite sensitive to spacing. However the front to back ratio of a two-element design is quite poor. The feed point impedance is also a complex function of element spacing. Yagi design is far from simple; even after running calculations real world antennae can often be improved by spacing adjustments carried out by practical experiment.

Yagi's are most often used at VHF or higher frequencies, where their size is relatively compact. Here are the formulae for calculating the element dimensions and spacing for a two-element system.

$$Director_{2e} = \frac{138.6}{f}$$

$$Dipole_{2e} = \frac{146}{f}$$

$$Spacing_{2e} = \frac{44.98}{f}$$

where f is the frequency in megahertz and the dimensions provided are in meters.

Combining a reflector and director into a three-element beam should improve the front to back ratio and provide about an 8 dBd gain. The dimensions now are given by the following formulae:

$$Director_{3e} = \frac{140.7}{f}$$

$$Dipole_{3e} = \frac{145.7}{f}$$

$$Reflector_{3e} = \frac{150}{f}$$

$$Spacing_{3e} = \frac{43.29}{f}$$

where again dimensions are in meters and f is in megahertz.

The impedance at the feed point will be between 18 and 26 Ω, so some form of matching will be required to a coaxial feeder.

An extra 1 dBd of gain may be achieved by adding a second director, but the front to back ratio will be poorer unless the element spacing is increased; adding three directors oddly does not improve the situation much over a four-element, but a six-element has good gain and a good front to back ratio at the expense of extra length, making this impractical in the HF band.

The calculations for a six-element Yagi are:

$$Director_{6e} = \frac{134.39}{f}$$

$$Dipole_{6e} = \frac{145.05}{f}$$

$$Reflector_{6e} = \frac{145.56}{f}$$

$$Spacing_{6e} = \frac{44.8}{f}$$

where the dimensions are again in meters and the frequency f in megahertz.

The collecting area or efficiency of the Yagi is much improved over the open dipole and approximates to $0.65\lambda^2$ (Fig. 5.7).

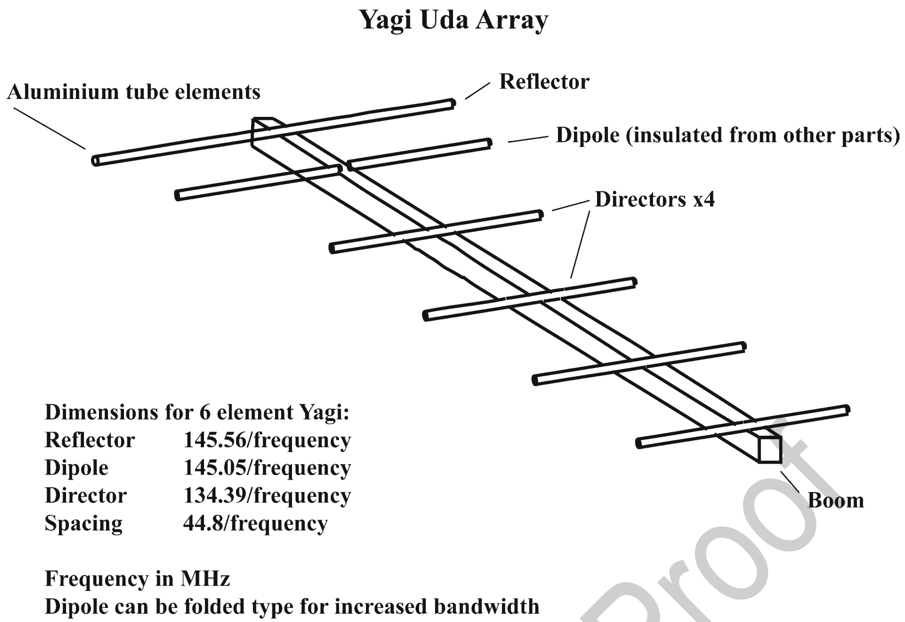


Fig. 5.7. Basic six-element Yagi beam. For the basic Yagi the dipole is split inside the boom where the feed point is, so it may need additional external support; however, if a gamma match is used the driven element is continuous (see impedance matching section). The dipole must be insulated from the boom if it is metal, but the directors and reflectors need not be.

The Yagi designs here are just a starting point for home experimentation. The possibilities for tuning them are endless, but space here is limited. There are some good books available on antenna construction, produced the Radio Society of Great Britain (RSGB) and the American Radio Relay League (ARRL) that are worth reading.

The Log Periodic Array

The log periodic array is similar in construction to the Yagi. This time all of the elements are electrically connected in a zigzag pattern. The result provides an antenna with reasonably flat response over a wide range of frequencies yet is still directional. Commercially available models can be purchased with coverage from 100 to 1,300 MHz within a quite manageable size, or 50 to 1,300 MHz, which is a bit bulkier. The gain of a log periodic is often lower than a given Yagi, but the big advantage of their wide bandwidth is particularly useful in frequency agile spectrometer applications. They are usually used only at VHF or higher frequencies, and construction for the HF bands would generate an enormously unwieldy design that would be difficult to mount and steer.

The design of the log periodic is shown in Fig. 5.8. There are three parameters used to describe the dimensions, α, τ, and σ. The semi angle of the antenna is α. The other two are defined in the formulae below:

$$\tau = \frac{R_{n+1}}{R_n} = \frac{D_{n+1}}{D_n} = \frac{L_{n+1}}{L_n}$$

where all lengths R, D, and L needed to be in the same units.

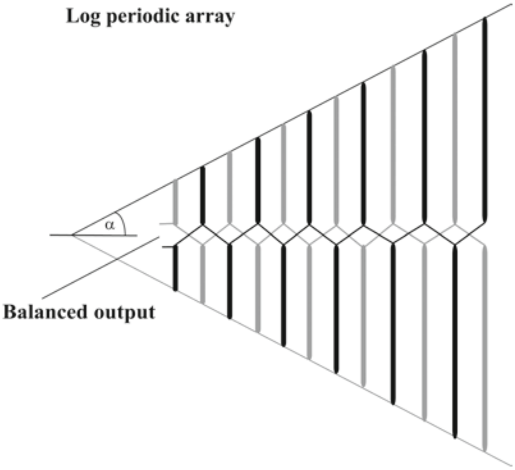


Fig. 5.8. Log periodic array.

$$\sigma = \frac{1-\tau}{4tan(\alpha)} = \frac{D_n}{2L_n}$$

where α is in degrees, and the length units of D and L should be the same.

The value of τ is always less than one and should be kept close to one typically in the range of 0.88–0.95; this leads to the optimal σ value in the range 0.03–0.06. Increasing τ increases the gain and the number of elements required, whereas increasing σ also increases the gain with increasing boom length. Choice of values may be a compromise to yield a manageable size of antenna. The starting point for construction is to decide what the lowest frequency of operation is to be, and for calculation purposes reduce this a further 7%. This will define the longest element width; as with the Yagi, this is calculated from the Yagi equation we saw previously:

$$L_{longest} = \frac{143}{f}$$

where L is in meters and frequency f in megahertz.

The maximum working frequency is usually chosen to be 1.3 times the desired upper frequency.

Let's look at an example. Say we need a log periodic array to cover the band IV/V UHF TV from 470 to 860 MHz. First calculate the longest element by subtracting 7% (33 MHz) from 470 MHz = 437 MHz:

$$L_n = \frac{143}{437} = 0.327 meters$$

Assuming a value of τ of 0.95 then:

$$L_{n+1} = \tau L_n = 0.95x0.327 = 0.311$$

So that:

$$L_{n+2} = 0.311x0.95 = 0.295 meters$$

Since the maximum desired frequency is 860 MHz, the upper working frequency is 1.3 × 860 = 1,118 MHz, and the length of the element is therefore 143/1,118 = 0.128 m, Once the chain of calculations above yield an element length of around 0.128 m, then stop.

Now for the element separations:

Choosing a σ value of 0.06 then the spacing between the longest element and the next is:

$$D_n = 2L_n\sigma = 2x0.327x0.06 = 0.039 m \text{ or } 39 mm$$

The next:

$$D_{n+1} = 2L_{n+1}\sigma = 2x0.311x0.06 = 0.037 m \text{ or } 37 mm$$

And continue to the end of the elements.

The length of the elements and their spacing therefore automatically define the angle of the array. It's a bit of a plod through the numbers, but it's worth it if you want to experiment with constructing your own device.

Construction involves a split boom with an insulator between the two layers. The insulator could be air with plastic spacers, or it could be a plastic or wood layer between flat metal strips or metal box sections. Each half of the elements are mounted one on top and one below, and the next pair alternate the opposite way. Larger arrays need to be built rigid, so a box section and round tube or rod is needed. Small arrays for high UHF or microwave use could be built by soldering wires onto a double-sided copper board strip. These arrays can be used at the focus of a dish reflector at microwave frequencies where the elements are very small by virtue of their short wavelength. In this case the elements could be etched onto a double-sided copper board like a circuit.

Circular Polarized Antennae

So far the designs we have looked at have been linearly polarized. Circular polarized antennae are typically used for satellite communication, because the orientation of a satellite is always changing and is often rotating. Satellite manufacturers therefore chose to install circular polarized antennae.

Polarization is seen in natural radio emissions, as was mentioned in the astrophysics sections, although more often there is a random mix of polarizations present. The classical circular polarized antenna is the helical, which looks like a large air-spaced inductor coil. These types of antennae are tricky to make well at home because they involve bending a self supporting conductor accurately, so we won't discuss the details here. The reader is referred to other sources, such as the *ARRL Antenna Handbook*. However there is an easier alternative – the crossed Yagi, the design of which follow the same rules discussed earlier.

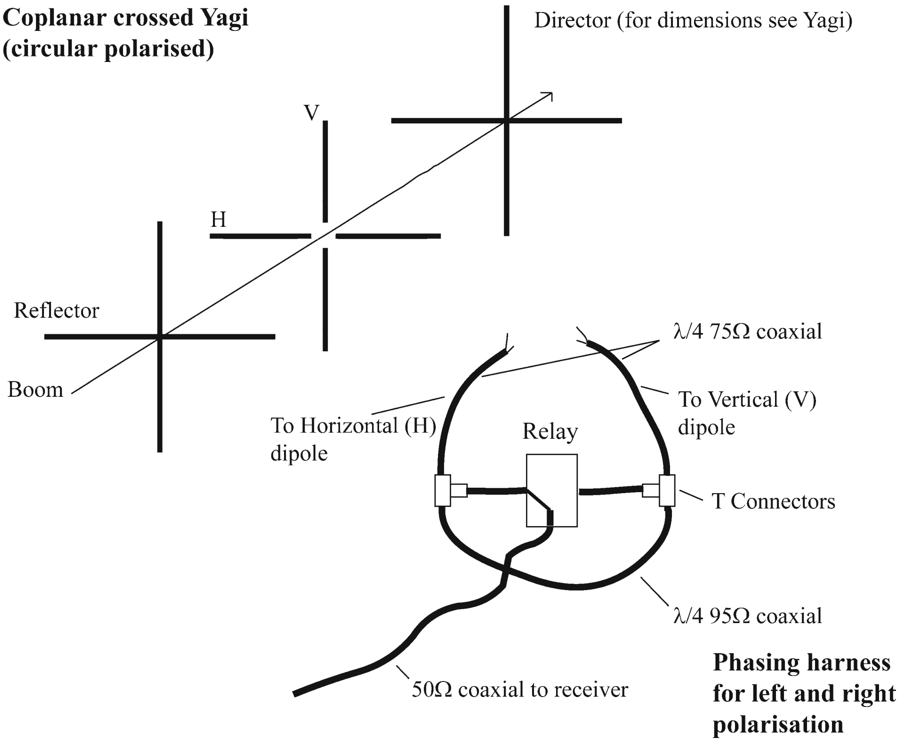


Fig. 5.9. Coplanar crossed Yagi for reversible phasing harness. This style is sensitive to circular polarization and is reversible with the changeover relay.

By mounting a pair of Yagi antennae side by side and 90° to each other they will effectively operate in a circularly polarized manor so long as they are phased correctly together. There are two ways to phase them:

- Coplanar construction, with phasing harness
- Relative offset mounting

The coplanar method means that all Yagi elements for both the horizontal and vertical parts are mounted onto the boom at the same positions, forming a series of crosses. The dipoles are fed by a phasing harness where one antenna has an extra ¼ wavelength of feeder, placing it 90° out of phase with its partner. The diagram shows a method of constructing the phasing harness and of providing a means of reversing the polarization sense from right handed to left handed.

The feed point impedance is affected and requires careful matching due to coupling between the two dipoles. The phasing harness in Fig. 5.9 illustrates how to match the impedance by using coaxial cables of different characteristics.

The Parabolic Reflector ("The Dish")

Now, when you say radio telescope to most people, they immediately think of a large dish antenna. The prevalence of direct satellite reception of television has provided a cheap source of components for the amateur radio astronomer. In practice the dish will be limited to microwave use for the home constructor. Dishes at UHF or VHF frequencies would require large diameters (at least ten wavelengths wide), which are simply not available as off-the-shelf components and would simply not fit in the garden!

Dishes are tricky but not impossible to make at home, but for practical sizes up to about 2 or 3 m they are easily available and are best purchased readymade. The most cost effective way of obtaining a dish for radio astronomy experiments is by searching for used surplus units, for example via online auction sites. It is important, however, to know what the original dish was used for, in order to know what frequency it was designed for. Although a dish will reflect any frequency of radio energy, its physical construction may restrict the upper frequency due to flexure and distortion under its own weight or in wind conditions, and if it is a mesh construction, by the hole size. Many of the large surplus television dishes of mesh construction in the order of 2–3 m in diameter may have been constructed for C band television channels around 4 GHz. Their stiffness may not be good enough to provide a surface accuracy of better than 1/8 wave at Ku band around 11 GHz, although structure could be added to improve this. Mesh hole size needs to be <1/10 wavelength in order that all the impinging radiation is reflected.

The construction of microwave receivers requires considerable skill and is not a task recommended for the beginner, so start out by using off-the-shelf components (see the project chapter devoted to this). With time and experimentation and when you learn more about radio it is certainly an interesting area to explore and offers lots of potential.

The forward gain of a dish is typically in the 20–34 dBi range, and their beamwidth to the half power points can be estimated from:

$$Beamwidth = \frac{57\lambda}{d}$$

where λ is the wavelength in meters and d the dish diameter in meters.

The actual beamwidth will be a factor of how well the antenna is illuminated. Illumination, again referring to a transmitter situation, is how well the antenna and feed horn can utilize the whole aperture of the dish, with minimum overspill.

Now the dish is not an antenna, of course; it is merely a reflector that gathers and focuses radio energy onto the antenna mounted at the focus of the dish. Television systems utilize a device known as an lnb (low noise block). The lnb is more complex than you may realize and consists of at least four elements:

- A feed horn and waveguide
- The antenna, which is a simple straight "probe" (actually two mounted orthogonally)
- An RF amplifier
- A frequency down converter

The feed horn is a collector, which gathers the reflected radiation from the surface. Its diameter is matched to the focal ratio of the dish. In general a short focus dish will have a small diameter feed horn, and the horn diameter will grow with increasing focal length.

Modern satellite TV systems work at frequencies in the range of 10.7–12.75 GHz. If only an antenna was mounted at the focus of the dish, it would need an exotic expensive cable to feed the signal to the receiver, and signal attenuation would be a serious problem. Therefore the signal is first boosted by as much as 40 dB and then reduced to a frequency in the range of 950–2,150 MHz, which is much more manageable and can be transmitted down a fairly inexpensive but low loss 75 Ω coaxial feeder to the receiver. Feeders should always be kept as short as possible. A practical length of up to 10 m will have an attenuation of less than 1 dB. Ku band lnb's can be used for radio astronomy quite effectively, although the average satellite receiver will be useless for this task. The lnb normally gets its power from the receiver, so it is necessary to build a simple device to inject power into the feeder but not the receiver! The project chapters in this book cover this topic.

For the experimenter who wants to try adapting the system to other wavelengths, such as the 21 cm hydrogen emission line, the following guidelines will help as a starting point for the construction of a simple "tin can" feed horn. Referring to the diagram, the critical dimensions are:

- Focal ratio of the dish
- Diameter of the feed horn
- Distance of the probe from the back wall of the "can"
- Length of the probe

The length of the can is not critical, but the probe should not be close to the open end. As a rule of thumb, the can length should be twice or three times as long as the distance from the probe to the back wall. The can is effectively a tube that is closed off at the far end. It acts as a waveguide. At most microwave frequencies, conventional copper cable is terribly inefficient, and "raw" RF signals are directed along metal tubes of very specific internal dimensions. Waveguide technology is affectionately known as plumbing in amateur radio circles (Fig. 5.10).

The antenna is a simple stub, known as the probe. It is essentially a straight wire approximately a ¼ wavelength long. The probe is soldered directly onto the center pin of an N type coaxial socket, which itself is mounted on the side of the horn.

Here we encounter the first problem. Many small dishes are offset types. These are tricky to convert to hydrogen line use, because the feed horn shape is much more complex. It is therefore strongly recommended that a concentric dish be used. Most dishes available in 1.8 m or greater sizes are fortunately concentric. The horn shape can be square, or even oblong, but for this exercise it is recommended that you use a round tubular can. It may be possible to find a metal food can of suitable dimensions. Items such as coffee tins or large cans obtained from commercial catering supply companies have often been used by amateur radio enthusiasts.

Inside the horn waveguide, you can imagine the propagation of radio waves along the tube as a series of zigzag reflections from the side walls, with a reverse reflection from the closed end. The reflected wave comes back up the guide, interfering with the incoming waves. The antenna or "probe," as it sometimes known, is placed at a location where the incoming and reflected waves reinforce each other. A full explanation of microwave waveguides is beyond the scope of this text, but the graphs and formula can be used to gauge the size of the horn and the placement of the probe.

Fig. 5.10. Can-type feed horn for 21 cm hydrogen line.

There is a complication – though isn't there always!? Something strange happens to the wave as it enters a waveguide; the effect is to increase its wavelength, known as the guide wavelength λ_g. All waveguides have a sharp cutoff wavelength below which radio energy will simply not enter the guide. A graph derived from the λ_g equation shows the probe location from the closed end and is of exponential form. The probe position rapidly increases on the left hand side of the graph as the critical cutoff wavelength is approached.

The formula for calculating λ_g is:

$$\lambda_g = \frac{\lambda_0}{\sqrt{1-\left(\frac{\lambda_0}{\lambda_c}\right)^2}}$$

and

$$\lambda_c = 3.42r$$

The minimum horn diameter for a cutoff wavelength of 21 cm is 12.3 cm. Our horn feed must be larger than that. A size of around 15–16 cm should work with most dishes. Probe length will be around 4.6–5 cm long. The probe is usually made adjustable in length. If the probe is a brass rod with a diameter large enough to drill the center and tap a fine thread, then the brass threaded rod is soldered to the center pin of the coaxial socket, and the probe screwed onto it providing adjustment. The exact length can be determined by testing the final system and adjusting for maximum signal. The focus of the dish should lie slightly inside the mouth of the "can style" feed horn. Once again this can be done by testing the final system. The mounting of the feed horn should be constructed in such a way as to provide a small amount of focusing capability (Fig. 5.11).

Simple can-style feed horns obtain most of their signal power from the central part of the dish reflector, where the outer regions are much less efficient. However, they are simple to construct by soldering or welding an end plate onto a metal tube of suitable diameter. There is nothing wrong in starting experiments with such simple devices.

An improved feed horn has a choke ring mounted on the open end. The choke ring should be made to slide up and down the cylindrical horn for fine tuning. This improves the "illumination" of the dish and improves its efficiency around the periphery.

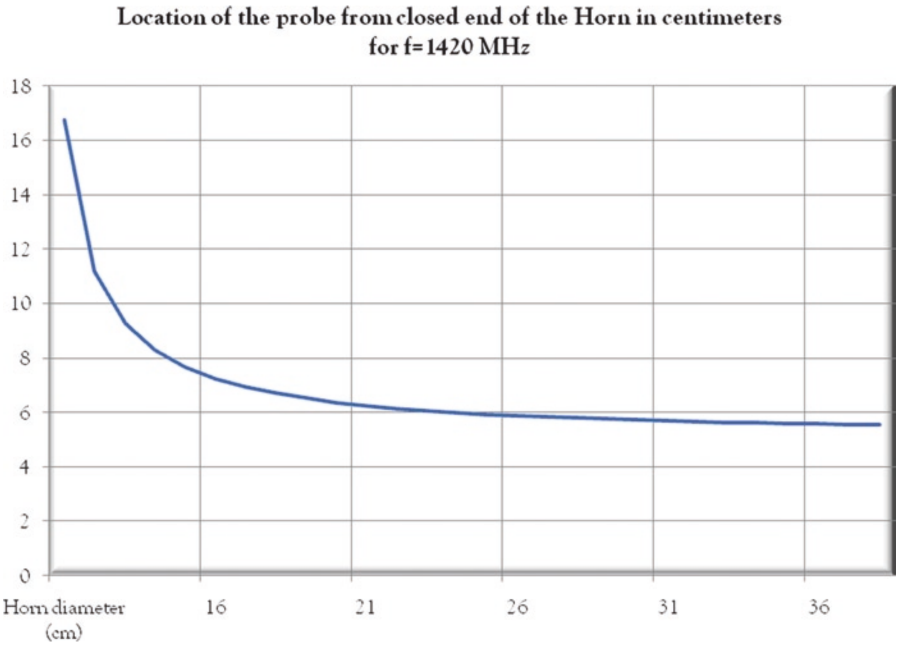


Fig. 5.11. Feed horn at a dish focus. The vertical axis of the graph represents the position of the probe from the closed end of the horn for a wavelength of 21.1 cm (the cold hydrogen emission line), and the horizontal axis is the diameter of the horn. The cutoff wavelength is around 13 cm at the left hand side of the graph. Clearly for a diameter of less than 16 cm the position moves quickly as the cutoff is approached.

Table 5.1. Dimensions of a typical 21cm horn feed

Frequency	1.42 GHz
Wavelength	21.1 cm
Horn (waveguide) diameter	15.2 cm
Lower cut off frequency	1.14 GHz
Upper cut off frequency	1.49 GHz
Waveguide (Guide) wavelength	35.2 cm
Probe placement from closed end	8.8 cm
Feed horn length	26.4 cm
Choke ring depth	10.6 cm
Choke ring diameter	36.4 cm
Dish focal ratio	0.4
Dish focal point depth inside horn	3.7 cm
Distance from front of horn to back wall of choke ring for minimum noise	10.4 cm
Distance from front of horn to back wall of choke ring for maximum gain	11.7 cm

To summarize the dimensions and design of a 1,420 MHz feed horn assembly for HI emission line work refer to the Table 5.1 and diagram. The dimension should be good for a dish with a focal ratio of between 0.25 and 0.5 (Table 5.1).

Antenna Impedance Matching

Correct impedance matching is essential to efficient operation, especially considering the weakness of the signals encountered in radio astronomy. Mismatched impedances at any point in the antenna/receiver chain will create internal reflections, reducing the amount of power passed on to the next stage.

Before we look at methods of impedance matching we need to take time out and look at feeder cables, connectors, and their properties.

Transmission Lines (Feeder Cables)

It would be wrong to call a feeder cable a "wire"; it is not just a wire. You must think of it as a component in the circuit, or even as a circuit in its own right. It will have inductance, capacitance, and resistance properties. If the feeder was only carrying DC signals, then only the resistance would matter, and that is very low for short runs. Dealing with RF signals is quite different. Capacitors and inductors can act to impede the flow of radio frequency signals in the same way resistance impedes the flow of DC signals (as well as AC signals).

For the purposes of RF antenna connections there are three main types of feeder constructions available:

- Twin lead, consisting of a pair of insulated parallel wires separated by a plastic sheet spanning the gap. The sheet may have regular holes in some types.
- Parallel open lead, similar to the twin lead, but uses plastic spacers to keep the wires apart, with much more free space between them.
- Coaxial lead, consisting of a central insulated wire, surrounded by a copper braided sheath which itself is insulated on the outside. Some types have an additional copper foil layer under the braiding to improve high frequency performance.

Twin lead is most often encountered with a characteristic impedance of 300 Ω used for television applications, fitted to the feed point of a folded dipole. It can also be found with an impedance of 450 Ω, where there are usually a regular series of holes cut in the insulation between the cores. The main consideration when using twin feeders is the routing of the feed must not pass close to metal structures, especially earthed metal structures, or anything likely to conduct electricity to earth.

Parallel Open Lead

This type is similar to twin lead. I consists of a parallel pair of wires, with regular insulating bridges between them to maintain a constant spacing. The impedance values available span the range from 300 to 1,000 Ω. The impedance being defined by the diameters of the conducting cables, and the spacing between them, greater spacing provides higher impedance values.

Coaxial Cables

Coaxial refers the concentric design, where one conductor is surrounded by another. They are available with impedance values in the range of 36–120 Ω, but 50 and 75 Ω values are most common. It is conventional, but not mandatory that 50 Ω (such as RG 58/U) is used in radio circuits, and 75 Ω (such as RG 59/U) in video and television circuits.

The many types differ in diameter, and in the type of insulators used. Insulators between the conductors are often polyethylene, polyfoam or Teflon and in some types there are air spaced channels running the length of the cable. It is important that connectors and connector joints that are exposed to the weather are carefully sealed against water ingress. Water in the cable center will change the dielectric properties seriously. A special tape known as self amalgamating tape is good for this. The tape is first stretched and then wrapped around the joints. As the stretched polymer relaxes it binds to the layers of tape above and below making an effective seal without the aid of glue which tends to dry out and come loose eventually.

One important property of transmission lines is their velocity factor. Velocity factor is denoted by V or VF, and is the ratio of the velocity of a signal in the cable, over the velocity in free space. Radio signals travel at the speed of light in open space, but the same signal captured by an antenna and converted to an electrical signal which travels more slowly in the feeder. Therefore the velocity factor is always less than one. The table gives the typical values for some cable types.

Cable type	Velocity factor
Parallel open line	0.95–0.99
300 Ω twin lead	0.82
300 Ω twin lead with holes	0.87
450 Ω twin lead	0.87
Coaxial cables	0.66–0.80
Coaxial with polyethylene insulator	0.66
Coaxial with polyfoam insulator	0.80
Coaxial with Teflon insulator	0.72

Fig. 5.12. Common RF connectors. From *top left*: BNC plug, BNC socket, PL259 plug and matching SO239 socket, UHF "TV" plug, N plug, N socket. From *bottom left*: F plug, F socket, SMB plug, SMB socket, SMA plug and SMA socket. Note that most types come in variations such as straight or angled and are available for different sizes of cable. There are also 50 and 75°Ω impedances in some types. SMA plugs come in normal and inverted pin types.

The velocity factor is important when you come to calculate precise lengths of cable in units of wavelength for making matching sections, cable baluns, or phasing harnesses. For example, the length of a half wavelength phasing section often referred to as the electrical length, made from polyethylene coaxial cable, is 0.66 times shorter than it would appear based on the actual wavelength. For a 2-m radio signal wavelength, a half wavelength is 1 m, but if this signal is carried in the above coaxial cable, the electrical length representing a half wavelength is 0.66 m or 66 cm!

Modern practice prefers the use of coaxial cables as feeders. These need to be connected to the receiving equipment using a convenient plug and socket arrangement. The most common connectors encountered are BNC, RCA (phono), N-type PL-259 (which mates to a So-239 socket), SMA, and SMB. BNC's are best avoided for RF use but are fine at low and very low frequencies. Although the RCA was originally introduced as a UHF connector, it is most often used as an audio connector now. The N-type is preferred for UHF applications but will work well at low frequencies, too. The SMA and SMB are very small and are used for UHF to microwave frequencies. If you like to salvage components from junk equipment, be aware that connectors also have characteristic impedances, again typically 50 or 75 Ω. Some, like the N-types, are not always compatible if you mix socket and plug impedances (Fig. 5.12).

Impedance Matching

Amateur radio enthusiasts often employ an ATU (Antenna Tuning Unit) to match the impedance of antennae to the receiver or transmitter. These come in a variety of shapes and sizes, and some are dedicated to a particular transceiver. All ATU's will only work efficiently at specified wavebands. Commercially built units will almost certainly be optimized for specific communications wavebands. They may not be suited to the frequencies required for radio astronomy. It is always preferable to construct the antenna to be a good match to the receiver without the need for intermediate variable tuners. However, even for a fixed frequency radiometer, some provision for matching is built into the system.

The Yagi antenna, sometimes known as a " beam," can be constructed slightly differently using a technique known as a gamma match. This provides adjustment for the feed point impedance. We saw that the feed point impedance of a dipole mounted in a beam is less than a dipole on its own and will be in a range typically from 20 to 36 Ω. If the impedance was as high as 36 Ω that would be considered a reasonable match to a 50 Ω coaxial cable, but could be improved using a gamma match system. Here the dipole is no longer split into two parts, or folded. The drive element is now a single rod of a length equivalent to that of the unfolded dipole. Note that this should be a self-supporting solid rod or strong tube. Alongside this is mounted a shorter rod of the same diameter, with one end mounted at the center point of the driven element a small distance away. An adjustable shorting link connects the short gamma matching rod to the driven element, and therefore "taps off" the driven element off center. The tap-off point is adjustable. The shorting link is made to slide along both the driven element and the gamma matching rod. Figure 5.13 shows the connection details and layouts. The formulae for calculating the dimensions are:

$$G = \frac{D}{10}$$

$$S = \frac{D}{70}$$

where D, G, and S are measured in the same units.

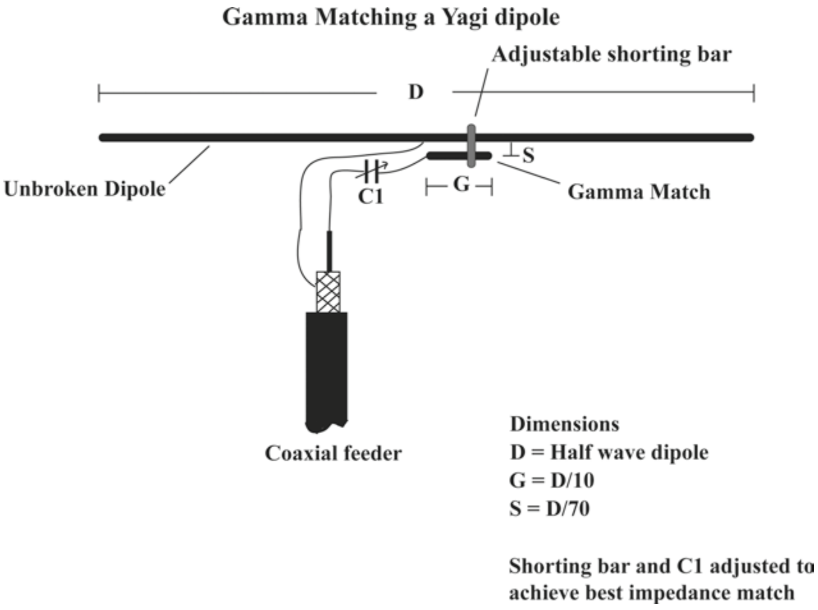


Fig. 5.13. Gamma match. Note that the driven element is no longer split in the center. It makes this an ideal addition for Yagi driven element matching.

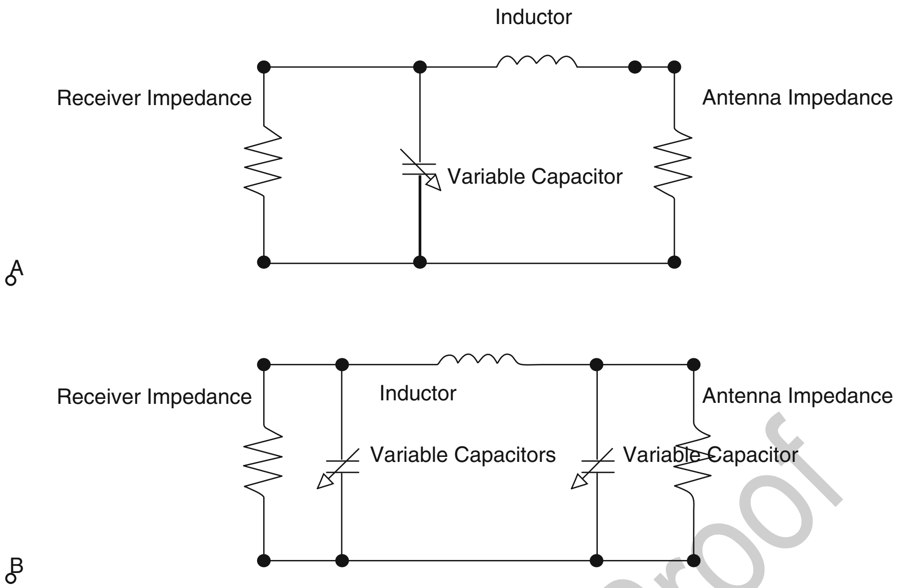


Fig. 5.14. Antenna matching networks.

The easiest way to set up an antenna like this is to use an antenna analyzer, such as the MFJ-269 manufactured by MFJ, although this is only valid for the frequency ranges 1.8–170 MHz, and 415–470 MHz. Alternatively use an impedance bridge, as we shall see in Chap. 8.

To adjust the impedance of an antenna, a capacitor and inductor may be used. The capacitor is usually made to be variable. The old-style air-spaced tuning capacitors are useful for this task but are becoming increasingly difficult to buy new now, although many can still be found at radio rallies salvaged from old equipment. An alternative would be to use a bank of fixed value capacitors and a series of dip switches to add or remove value from the stack. The inductor components in tuners are usually air-spaced again and can be constructed with "tap off" wires on some of the coils; so by using a rotary wafer switch longer or shorter sections of coil can be selected, thereby varying the inductance value.

Figure 5.14 illustrates two ways of connecting these components to an antenna. They are used where the receiver impedance is greater than the antenna, such as the case of the Yagi, where the feed point impedance is often less than 37 Ω.

Typical values of the capacitor are 140–250 pF and the inductor 18–28 μH.

Using Coaxial Cable as a Matching Unit

By design our receiver will have a standard input impedance of say 50 Ω, so we would feed it with 50 Ω coaxial cable. However, the antenna feed point, as we know, may well be different. It is often possible to use a quarter wavelength of coaxial cable of a different impedance to match the two, so long as the required value is available from the stock lists.

In order to calculate the details we not only need to work out what impedance value is needed but how long the section needs to be. Don't forget the electrical length of one quarter wave depends on the velocity factor of the cable used.

The following formula is used to calculate the impedance of the matching section:

$$Z_M = \sqrt{Z_L Z_F}$$

where Z_M is the impedance of the matching section, Z_L is the impedance of the antenna feed point, and Z_F is the impedance of the main feed line.

For example, if the antenna feed point impedance was 120 Ω and the main feeder is 50 Ω, then Z_M is close to 77 Ω. Therefore one quarter wavelength of 75 Ω feeder would be an excellent match. If this was operated at a wavelength of 4 m the velocity factor of RG59/U would be about 0.82, so one quarter wavelength is $4 \times 0.25 \times 0.82$ m, which is 82 cm.

If the feed point impedance was 28 Ω, then the matching section would need to be close to 37 Ω. Belden 8700 has an impedance of 32 Ω, which would be a fairly good match, but it is just over 1 mm diameter, not very practical, so another method of matching would be better.

Matching Stubs

The quarter wavelength stub is a useful way of matching a dipole antenna. Here a quarter wavelength of parallel transmission line is attached to the center feed point of the dipole. The conductors should not be insulated so that a tapping point can be found along the length of the stub that matches the impedance to the coaxial feeder. The parallel conductors could be made a structural part of the antenna and conductive clamps attached to the stub. The coaxial is connected to these via a 4:1 balun. Impedance matching is performed by moving the clamps up and down the stub. The end of the stub has a shorting bar across it that is also adjustable. Refer to the diagram for an illustration. The usual way of calculating the dimension L1 and L2 involves measuring the VSWR (Voltage Standing Wave Ratio), but this assumes the antenna is connected to a transmitter. For the purposes of radio astronomy the adjustment of the feed point and shorting could be done by trial and error to maximize a received signal close to the operating frequency, but this is likely to prove impossible. Once again refer to Chap. 8 for the discussion on impedance bridges. These really help to take the mystery out of the art of matching (Fig. 5.15).

Matching Transmission Lines to Multiple Antennae

One device used in radio astronomy is the interferometer. By using two or more antennae separated by at least a few wavelengths, higher resolutions can be achieved. Or simply by adding a pair of antennae their collecting area is effectively doubled.

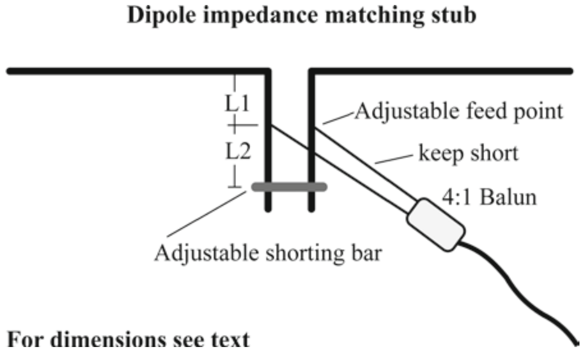


Fig. 5.15. Dipole with matching stub and variable feed point.

Since only one receiver is used, the two antennae need to be correctly matched for impedance. If a pair of 300 Ω twin line feeders was simply joined to one 75 Ω line, there would be a big mismatch, and a lot of signal power would be reflected back to the antennae at the joint. The pair of lines from the aerials is effectively in parallel, so their combined impedance will be 150 Ω. We need to transform the 150–75 Ω. This could be done with a quarter wavelength section of transmission line having an intermediate impedance of the geometric mean of the two parts. (The geometric mean of two numbers is $\sqrt{Z_1 Z_2}$). So if we could find a feeder with 106 Ω characteristic impedance then we are in business – hmmm, maybe not.

Well, it turns out that if we use a parallel conductor air-spaced feeder, we can manufacture a quarter wavelength section with any impedance value in the range of 210–700 Ω. That does not appear to help.

Let's now rethink the feeder scheme for a minute. If we have chosen to use a pair of antennae with a feed point impedance of 300 Ω, then the 300 Ω twin line feeder is easily obtained to interconnect the antenna pair. At the central point on the interconnection we can tap off a feed to the receiver, so that both antennae see exactly the same length of line to the back end. The new feed point impedance is 150 Ω. If we now match that to another length of 300 Ω twin line, then we need a matching section of 212 Ω feeder. The table shows how the values of impedance vary with separation for parallel air-spaced conductors.

This means that if we mounted a pair of 6 mm tubes rigidly with a separation of 1.9 cm (interpolating from the table), we can make a quarter wave transmission line. The air-spaced parallel line has a velocity factor of about 0.95, so that the length of the tubes will be 0.95λ. Plastic insulating mounts should be fabricated to hold the tubes.

The one thing to remember is that parallel lines must be kept away from structures, particularly metal ones. The advantage is a parallel feeder has lower loss than most coaxial lines. The feeders should therefore be suspended above ground. Once they reach the building housing the receiver then a 4:1 balun can be installed (see next section), which reduces the impedance to 75 Ω, and a short piece of 75 Ω coaxial line can be used to enter the building and connect to the receiver.

Table of impedance for open-air dielectric parallel transmission line

	Center spacing (cm)				
	1.25	2.5	5.0	10	15
Wire gauge					
20	420 Ω	500 Ω	580 Ω	660 Ω	710 Ω
16	370 Ω	440 Ω	515 Ω	610 Ω	650 Ω
12	300 Ω	380 Ω	460 Ω	530 Ω	590 Ω
8	240 Ω	320 Ω	410 Ω	480 Ω	530 Ω
Tube diameter (mm)					
6	157 Ω	230 Ω	330 Ω	410 Ω	460 Ω
12		157 Ω	250 Ω	330 Ω	380 Ω

Baluns

A balun converts a balanced unearthed antenna such as the dipole to an unbalanced system such as an earthed coaxial receiver input. A simple 4:1 balun required in the stub matching system described above can be made from a half wavelength of coaxial feeder of the same type used to connect the antenna to the receiver. The effect of this also reduces the impedance to a quarter of its original value. If our receiver is made to have a 75 Ω input impedance, then the combination of a dipole with a quarter wavelength stub and a coaxial 4:1 balun will provide a good match to a 75 Ω coaxial feeder (see Fig. 5.2).

The coaxial balun is only good at one frequency, so it would be suited to a fixed frequency radiometer. If a wider bandwidth is required for a tunable receiver or spectrometer, then a different scheme is required. Wideband baluns can be made using ferrite or powdered iron toroids.

The two most common styles of balun are shown schematically in the diagram. Style A is a 1:1 balun and offers no impedance change, while style B is a 4:1, which reduces the feed point impedance to a quarter of its original value. The coils are all wound together onto a ferrite or powdered iron ring. The two or three coils are made up from two or three strands of enameled copper wire laid side by side and wound as if they were one wire onto the toroid. This is known as bifilar or trifilar winding (Fig. 5.16).

The toroidal powdered iron and ferrite cores can be used to build baluns. At the same time they can be used to transform any practical impedance to match the receiver. There is a section in the introduction to RF electronics that gives a method of calculating the number of turns on each winding to match the impedance. Note that in the standard 1:1 and 4:1 versions illustrated here the number of turns on each winding is equal. When dealing with other impedance ratios the number of turns on each winding should be different. A toroidal balun transformer is a wideband transformer but is still somewhat frequency dependent. The balun should be wound for a particular center frequency of interest.

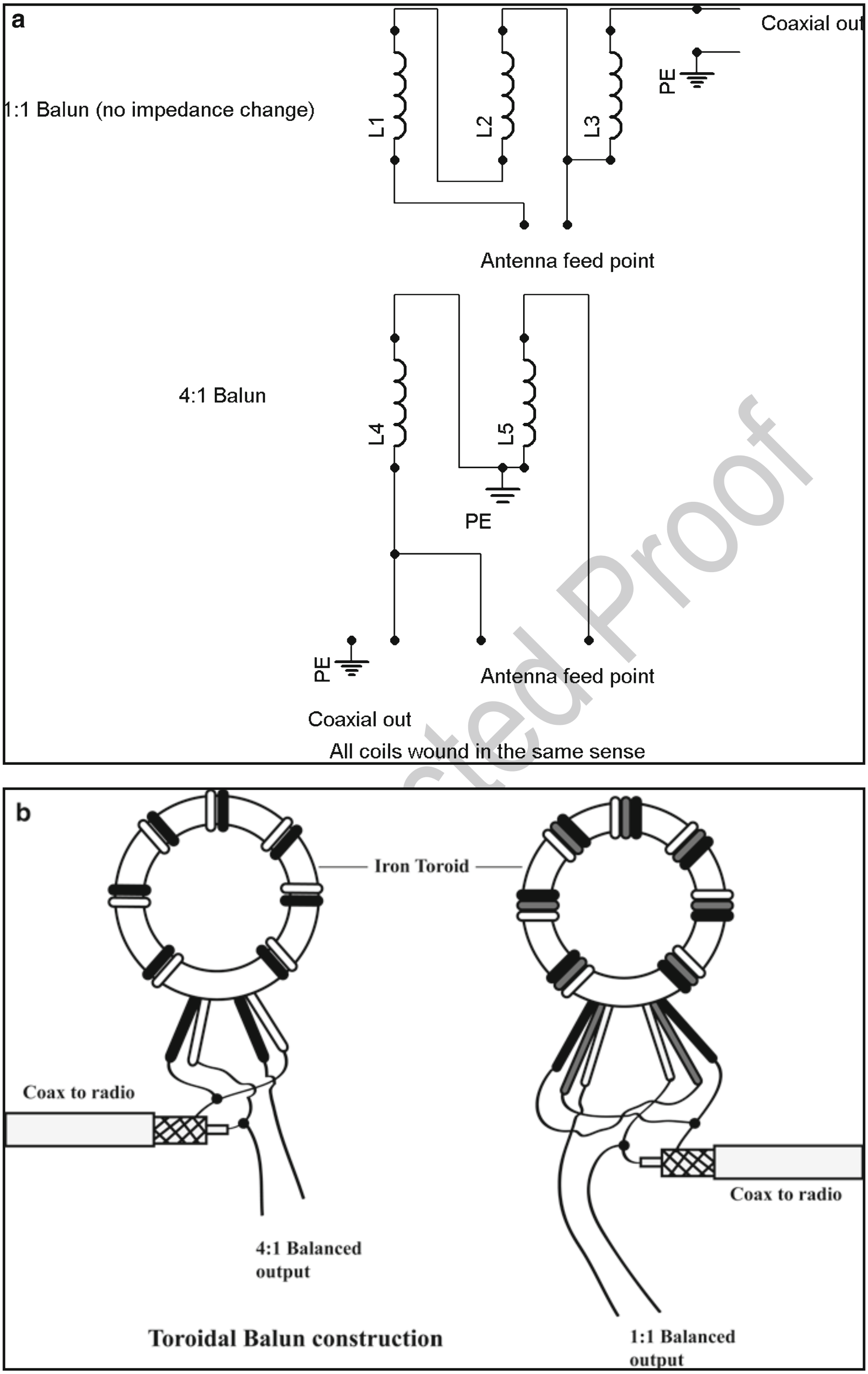


Fig. 5.16. (**a**, **b**) Toroid baluns 1:1 and 4:1, and toroidal winding style.