

## **Aerials, not Antennas**

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### Abstract :

How and why aerial systems behave and radiate. Materials and their losses are considered including an explanation of skin losses. Ways of impedance matching and its application. Both vertical and horizontal systems with either centre or end fed power are considered. Differences and behaviour of balanced and concentric feeders are detailed together with a practical all band system with tuned feed lines is given.

### Introduction :

I have added this comment here, after completion of the text, and I would urge the reader to try and read slowly enough to try and absorb and digest the text herein.

I have tried to explain a principle or phenomenon in the simplest words as my experience of over thirty years with physics undergraduates has taught me to pursue. Very few of us are gifted to follow with ease, any complex theory, me included !

Needless to say, that which I have written, I have re-read and scrutinised many times with very careful thought and to correct any errors. I hope it may, in some instances, create discussion or even controversy, which in itself is healthy debate. I am prepared to receive queries via Email of aerial designs, comments or queries.

At the age of sixteen, while still at secondary school, I passed the RAE (Radio Amateurs Exam) and the twelve words per minute Morse test, thus obtaining my amateur radio class licence as G3PKW. In due course I received my blue tinted licence document with its embossed crown emblem. That was way back in 1961, when only one type of licence was available and the exam was a three-hour written paper, there were no 'tick the box' answers in those days. That was over fifty years ago and I decided to write this, with the idea of passing on my experiences, plus any useful knowledge which I may have obtained in using radio aerials and, in particular, for the lower frequency bands. I have recently retired after thirty one years in the capacity as a technical officer in a university physics department. Early days enabled me to study part time and obtain my qualifications and my hands-on skills allowed consultation by staff and researchers in details of instrumentation and measurement. I also spent a number of years in test and development in manufacture of military HF radio equipment.

I always refer to them as 'aerials', as I always think of antennas (or is it antennae?) as being those appendages on a moth-like creature of the Lepidoptera group.

Experimentation with aerials is a fascinating and engaging pastime because time and effort improving an aerial system has a double reward, with respect to both the transmitted signal and the received signal strength. It also provides some beneficial physical activity to the otherwise sedentary activity of being a seated radio operator. Over my many years of involvement, both as an amateur radio experimenter and professionally in the radio communications world, I have tried many aerial systems. To relate to one such experiment, although on a VHF allocation, I made several plots, with the aid of a pen recorder, the polar diagram of a beam system consisting of four, 8 element Yagi's of a co-linear broadside array, amounting to 32 elements of active aerial system. Needless to say once it was phased correctly it gave a very impressive performance.

### Aerial Considerations :

When deciding on a suitable aerial system for HF use, a number of things need careful thought. The physical site conditions dictate the space available and that is one of the first considerations. Obviously, in the case of an aerial system which is fitted to a moving vehicle with no real estate on which to erect an aerial, it will be completely different from that of a station with an acre of land.

Many radio amateurs are reluctant to use the lower frequency bands (160m, 80m, & 40m) complaining that you need a lot of space for an efficient aerial, together with the cry that these bands are too noisy. I must admit that the general noise floor of the lower frequencies is slightly higher than say fifty years ago, due to the much wide spread use of high frequency switching systems. However, by applying the current knowledge available, good results can be obtained in all situations.

The use of ADSL for internet connections over a twin lead telephone line, which in many cases is carried on telegraph poles above ground, has not helped. A useful tip to reduce common mode radiation from overhead telephone cables, carrying data, is to wind many turns of the lead between the outside junction box and the data router / modem device over a ferrite ring or a discarded core from an old line transformer. This has reduced considerably the common mode radiation that I experienced from my own overhead phone line. It is to be hoped, that eventually, the growing demand for internet and data communications, that many systems requirements will transfer to fibre optic transmission and thus help to alleviate the electrical noise problem.

The first thing we need to do is to ensure that a few basic matters of theory are fully understood. I make no apology for starting this text like a physics lesson as I have often been surprised at the existing paucity of basic understanding concerning radio aerials and the associated theory. Throughout this text there will be comments on the reason for a particular effect and mention of the pioneers who discovered it. This information of the pioneers may aid further research by the reader. This is important because the laws of physics are absolute and cannot be changed, however much we might wish to.

### Basic understanding of electrical conductors :

Consider the situation of a length of aerial wire with a DC (Direct Current) source such as a 1.5 volt 'D' cell connected across it. If the wire has a total resistance of 1.5 ohms a steady current of one ampere will flow in the wire. Such a current does not in itself radiate a usable signal. All it does is create a steady fixed magnetic field and heat, the amount depending upon the power used, which in our example is 1.5 watts. However, this intrinsic resistance will influence the ability of the wire to act as an efficient radiator and we refer to it as the  $R_{\text{loss}}$  component. This simple effect was first visualised over 200 years ago by a French mathematician, André Ampère. The unit of current is named after him in his honour.

So far, this is simple schoolboy physics but deeper inspection shows that this current cannot suddenly appear, instantaneously in the wire. It takes a certain time to establish or induce itself. Every piece of wire has this attribute, which we refer to as its inductance and we must always keep in mind this fundamental physical property, which is time related.

Two pioneering giants in physics, Joseph Henry and Michael Faraday who both published their findings in 1830, first observed these effects.

We can increase the inductive property of a wire by winding it into a coil. This has the effect of strengthening the magnetic field which builds up around the wire. At the same time as it is being built, it is trying to oppose its own generation. This is at the very heart of the reason why it is taking time to build up, as was demonstrated after work carried out by an Estonian physicist, Heinrich Lenz. This effect of the current inducement reacting against itself in a conductor, is commonly known as Lenz's law. Coiling the wire will increase this inductive effect of the wire, however, it will reduce its linear exposure to the surrounding atmosphere. Nevertheless, we can use this technique to make an aerial which is physically smaller than that which would otherwise be possible, but that will reduce its ability to couple to the 'aether' which surrounds it. More about this coil effect later.

'Aether' is a word taken from Greek mythology which describes the surrounding atmosphere but takes into account that the atmosphere has properties that can support an Electro-Magnetic wave. How radiation propagates through the aether was deduced from work carried out by a brilliant English physicist, John Henry Poynting.

Another parameter which any aerial wire has, is its relationship to the ground where it is situated. Any voltage or electric charge which this wire has with respect to the ground is related to its capacity to hold an electrical charge above ground. Similar to the inductive effect the charge takes time to be built up. The relationship of electric charge throughout the universe was established from painstaking mathematical work by Carl Gauss. Gauss being a brilliant mathematician loved to solve such problems and was probably the first person long before Einstein to understand that space is non Euclidean. Euclidean space is that which is only three dimensional and finite. The work of Gauss was built upon the earlier work of Charles Augustin de Coulomb and his basic law of electric charge.

So, we can conclude that any conductor or piece of wire has both natural electrical capacitance due to a voltage and natural magnetic inductance due to a current and these two time-related properties are referred to as the reactive or X components of any aerial system.

This idea of reactive components was not completely understood until Sir Oliver Lodge and his research into lightening conductors illustrated their importance. From his research he also discovered the principle of 'syntony' which we now know as resonance or frequency tuning. Having regard to this discovery by Lodge, it is often quoted that he could have been considered to be the father of wireless.

#### Electrical Harmony of an Aerial system :

When handling reactance in a calculation, we say that it is positive for inductive reactance and negative for capacitive reactance.

The inductive reactance is due to the fact that a voltage or potential difference appears first and from this, a current begins to flow.

So the current lags behind the onset of the voltage.

In the case of the capacitive reactance, a current has to begin to flow to establish a potential difference of charge to be built up.

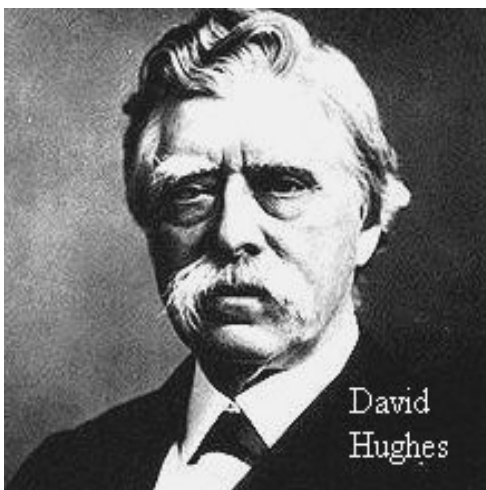
So the current is leading or ahead of the voltage.

This harmony or 'hand-shaking' between current and voltage is the key to understanding how a standing wave is established along a resonant length of a conductor and may help to visualise how an aerial can couple itself to the aether. To think of this in another way, the voltage establishes a current, and this current builds up a voltage, which then creates a current, and so on, and so on. The timing of this current-voltage-current exchange is dictated by the physical size of the wire. This process keeps re-occurring over and over again, provided that it is being fuelled by the driving source of the transmitter. The frequency of the drive occurring at the correct time (resonant). Also remember, that this can even occur in the deep vacuum of space. No air or physical medium is needed to support this phenomenon, apart from our piece of wire which is needed to establish the process in the first place.

At the present time, understanding in physics has the means and expertise of handling and calculating such EM (Electro-Magnetic) radiation from a conductor, it hasn't, as yet, in detail, the knowledge of what this wave effect at a distance actually is. It is often quoted that the Michealson-Morley experiment and their work with interferometry never found the existence of an aether, but that was before we had the knowledge of Einstein and his relativistic theory in unison with the Fizeau experiment. Sir Oliver Lodge also spent many of his experimental years in the old Mountford engineering building in William Brown Street, Liverpool, looking for the existence of an aether, but was never able to find it. It may have been a case of looking in the wrong direction. I am of the firm belief, based on Maxwell's equations, that EM waves are basically similar to gravitational waves, which by their nature, are a distortion of space and time. So the word 'Aether' may be just another name to describe 'Space-Time', but that's a whole fascinating discussion, in its own right.

As John Henry Poynting 'pointed out' (excuse the pun!), an EM wave has to contain both electric and magnetic components to exist, you can't have only one or the other. Thus, non-ionising radiation from an aerial has, intrinsically and mutually, both reactive parameters. As the wave launches from the aerial the electric and magnetic components act and remain at right angles to each other. A very important point which must be realised is that the reactive characteristics of the aerial play no direct part in the actual radiating of the signal. The reactive part is that intrinsic parameter which comes about by the mere existence of the wire and only determines the resonant frequency of its operation, 'per sae'.

#### Radio Pioneers :



E.M. Waves were known about by the select few who worked in their research, but the first ever recorded public demonstration of EM waves was when David Edward Hughes, born in London of Welsh descent, lectured to the Royal Society in February 1880 using a Hertzian spark type generator.

It was in 1894 at a lecture by Sir Oliver Lodge given in Liverpool that the first public demonstration of Morse code was being radiated. This was the first demonstration of communicating by the use of such waves. The code was sent by a famous Scotsman, by the name of Alexander Muirhead.

### Skin Effect :

In our example it was suggested that the wire had a loss resistance of 1.5 ohms. When used with high frequency currents the  $R_{\text{loss}}$  resistance would be rather more than this because of something called the 'skin effect'. When a wire carries a steady direct current the magnetic field is stationary, but with alternating current the magnetic field is changing continually. This changing magnetic field which is happening around the wire is itself inducing back into the wire, producing its own internal secondary circulating currents. These were later called 'Eddys'. These Eddy currents force the main current to flow only along the outer surface of the wire. This process of 'Eddys' was first noticed in the mid 1800's by none other than the French premier Francois Arago, but was not investigated until a much later time by the efforts of a less well known Mancunian experimenter, who was later knighted for his work, which was relating to eddy currents in water connected with shipping. He was Sir Horace Lamb who was also recognised in the scientific world by becoming an FRS (Fellow of the Royal Society).

At frequencies of only tens or hundreds of kilo-Hertz, the effect of these Eddy currents is considerable, compared with the DC case. Skin loss is even given fervent consideration by the electric supply industry who are using frequencies of only 50 Hz.

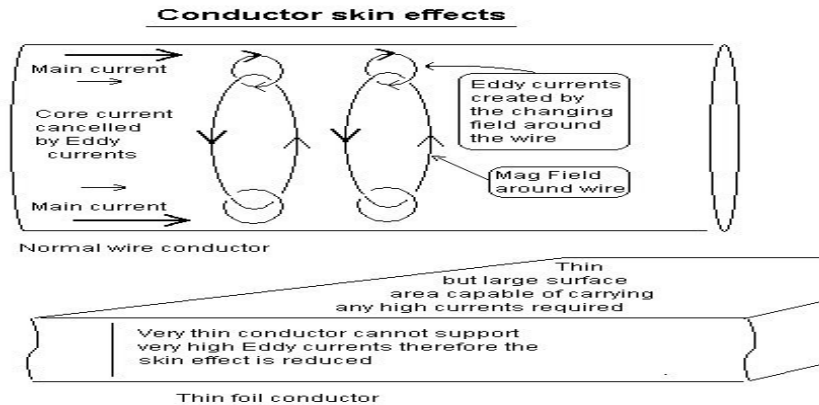
Having regard skin effect, an efficient type of aerial element would be to make it into the form of a cage, so that each individual conductor can be allowed to use its surface skin without significant influence by its neighbour. However, this is particularly useful when an aerial is to be used at much lower frequencies than the 160 metre band, giving it a higher quality factor or 'Q'. This may need more consideration in light of the new amateur radio allocation of 472 to 479 kHz which has now been made available.

A different approach has to be applied in practice to reduce skin effects at frequencies approaching several megahertz and above. Skin losses at these higher frequencies are usually better managed by using tubular elements. Where the surface area is greater and therefore the alternating current carrying capability is much improved.

It must be stated that the  $R_{\text{loss}}$  resistance which also directly includes the skin effect losses is not, in any way, connected to the amount of basic inductance or capacitance which the aerial wire exhibits. They are entirely separate parameters.

By using a conductor consisting of many strands of wire, to increase the surface carrying capability of the wire element, helps to reduce these skin losses. This type of wire adopts the German word 'litzendraht' or its shorter form 'litz' which actually means 'braided'. Litz wire is often used for winding IF (Intermediate Frequency) transformers in the region of 455 kHz in an effort to maintain a higher quality factor to improve the selectivity, of perhaps, an IF amplifier stage. The skin effect on linear aerial radiators is similar to that which occurs in wound inductors, where the close proximity of the windings, influences the effect.

Another possible way to reduce skin losses is to use a flat foil type of conductor. In this case, the surface area of the conductor, that part that carries the RF (Radio Frequency) current, is a maximum for a minimum of cross-sectional area. Such a cross sectional geometry can help to reduce the eddy current strength acting on the large surface area of the conductor with which to carry any high radiator current.



The thin nature of the material geometry helps to reduce the transverse field effect of the resultant Eddys from disturbing the main current which is using the larger surface area to enable its transport. This is a similar technique that has been used for many years with the core of a mains transformer where the core is laminated into thin sheets to reduce eddy current losses. It is a geometry which denies the eddy currents the means to have a lot of strength in the transverse plane and to disturb the main current. (see diagram)

### Materials :

The choice of materials used, also has interesting characteristics. Consider the case of Aluminium which has a DC resistivity which is nearly twice that of copper, but the resistivity to RF is virtually the same.

Physics has developed a theoretical model, that conducting materials rely on the way that the overall bonding of molecules behave, and the movement of the outermost orbiting electrons in the atomic shell structure. As a consequence the high frequency AC resistivity is somewhat different from the electron movement, as that observed in the DC case. Recent research in the study of super conducting materials, and quantum physics has enabled a better understanding, at a molecular level, of how charged carriers behave in a material. The skin effect for aluminium is different than in copper due to the fact that the Eddy currents set up in aluminium are not as intense, as a result of the electron mobility behaviour in the atomic shells, which reflects in the permeability of the material itself. This means that the surface skin depth of an aluminium sample results in much more of a skin depth than that which exists for copper having the same dimensional parameters. Suffice to say, that the difference of the RF resistivity between these two materials is quite small indeed.

In an effort to clarify the use of aluminium foil as an efficient conductor for RF current. I thought that the best way to experiment and verify this, would be to build an aerial system.

After a discussion between G4ROJ and myself, I encouraged him to have a go at building a magnetic loop type radiator using aluminium foil. Roger, being a hands on chap and his interest of using light weight aeralis as in his kite experiments, fabricated a very neat looking system. (see picture below) Using such an aerial system, demonstrated that a flat foil aluminium radiator can be very efficient. It is capable of carrying high RF currents. Such small systems typically have very high circulating currents (15 to 25 Amps) due to the very small radiation resistance (explained later). Therefore to verify the effectiveness of this system as a means to couple RF energy to the aether, it was a simple matter of comparing its effect versus a standard reference dipole radiator.



The loop as shown, was designed to be used on the 40 metre band. It was fabricated using a 10 cm (4 inch) wide foil with an 8 metre circumference. Operating this loop aerial at ground level gave comparable signal strengths when compared at the same time and place with a full size dipole at 25 feet. My thanks to Brian G3GKG and the GOM group on 7157 for providing many reliable quantitative signal reports from around the British Isles.

### Warning

A point of warning is worth mentioning here. When energising such a loop aerial make sure to keep at least several metres away from the loop while it is transmitting. The circulating currents in the loop using a hundred watts can be typically in the ten to twenty amperes region which means the close-in RF field is very intense. This must be taken seriously.

Such a level of invisible radiation, although non ionizing, represents a serious health hazard. Estimates of the near field intensity at a hundred watts of radiated power is capable of heating delicate cells in the body after comparatively short time periods. For example, red cells contain haemoglobin which is a compound containing ferrum metalica (iron), can have a relationship with respect to magnetic fields. The knowledge of the behaviour of such cells with RF fields is still being researched.

### Radiation Resistance

The radiation resistance is the third property of a radiating aerial system which we need to recognise and quantify. This is expressed as another resistance which has no direct relationship with any of those previously mentioned properties, but comes from the fact that the aerial wire, when used as a radiator, is dissipating energy off and away from itself. This constitutes an equivalent power loss, although it is not lost, in the true sense, but is power expended in our radiated useful signal. It occurs due to a standing wave on the aerial which is coupling our signal to the aether and is represented using a quantity referred to as the radiation resistance,  $R_{\text{rad}}$ . Think of this parameter as a kind of 'goodness' or 'convenience', a kind of coupling coefficient of an aerial or to put it another way it is a parameter which expresses how easy it is to couple energy to the aether. The higher its value the easier it is to couple the attendant power. This is the only parameter which is a function of getting our signal heard at the receiving end.

It may be obvious that the physical size of the aerial system with respect to the wavelength which it is to use, will dictate the radiation resistance. However, as long as the losses in a physically small system are kept to a minimum, and the aerial is able to support the high currents which will endeavour to flow. This will enable the overall efficiency of the system to be maintained at a high level.

### Applying power to a wire aerial :

So far, we know that our radio aerial has three basic components which are distinctively separate from each other : -

1. Its intrinsic lossy part,  $R_{\text{loss}}$
2. Its intrinsic reactive part,  $X$
3. Its intrinsic radiating part,  $R_{\text{rad}}$

In a number of practical cases we could assume that the  $R_{\text{loss}}$  of our wire is relatively small with respect to the  $R_{\text{rad}}$  and therefore we could ignore it for those cases. If the  $R_{\text{loss}}$  was significant, it would waste some of the power which should have been used by the radiating part  $R_{\text{rad}}$ . It has been stated that a physically small aerial has a small radiation resistance and in such circumstances the  $R_{\text{loss}}$  component even if fairly small would then become quite significant in hindering the high currents attempting to flow in the aerial. So we must in those circumstances do everything possible to keep the loss resistance to a very small amount.

As an example. If we had an aerial system with a one ohm radiation resistance and only a one ohm loss resistance then the system can only at best be fifty percent efficient. So this system would effectively be throwing away half of the power supplied by the transmitter. That is, of course, providing, we have matched out any reactance which may be present. If there is any reactance still present then the efficiency will be even lower.

When we use any type of conductor to act as a transmitting aerial we need to know how to get power into the radiating part but we also need to avoid the reactive part, which just gets in our way. The reactance just hinders the flow of current, so it has to be eliminated by taking it out. This is the job of the aerial matching network. In those cases where the aerial is cut to a specific and deliberate size then it should be without any reactance at its design frequency and the problem in effect, does not exist. This could mean that any aerial is intrinsically only good for a specific frequency, or a narrow band of coverage.



## Resonance

Any given length of wire, as an aerial or otherwise, will have a particular inductance and capacitance value which, from the work of Lord Kelvin and his equations, enables us to work out the natural resonant frequency. He was a Scottish mathematician and physicist who established that when the inductive and capacitive reactances are equal, and we know that they are opposite in their effect, so they disappear from the calculation so therefore this becomes the basic resonant frequency. (Remember the current and voltage harmony that we spoke about earlier.) At or near to this single frequency, the only parameter which we are left with is the radiation resistance part,  $R_{rad}$ .

However all is not lost, providing that we can recognise the things that get in the way we can do something about them.

In summary our transmitter has to match its generated power into the radiation resistance while avoiding, by use of a matching network, any reactive component which tries to get in the way.

Any aerial wire cannot be 'tuned' by connecting another circuit to it. It only exhibits pure resonance at its fundamental or harmonically related frequencies and we can only deal with those parameters which it presents to us. So the only way that an aerial can actually be tuned is by altering its own physical attributes. Therefore the only way an aerial radiator can be tuned intrinsically is with a pair of wire cutters to alter its length !

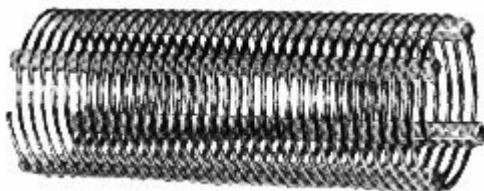
The term 'ATU' (Aerial Tuning Unit) is incorrect, it is a misnomer. More correctly, the required unit should be referred to as an 'AMU' (Aerial Matching Unit) or the even more appropriate term of 'Trans-match'. Meaning that we are transposing one impedance to another more useful value. This does not mean to say that a random length of aerial wire cannot be used on any desired frequency. From that which follows, we can use an aerial matching system or network which will take account of the reactive components that we are presented with, as well as adjusting the load resistance to suit the device or equipment that we are connecting. So try and get used to the idea that a matching network is there to cancel any reactive parameters that the aerial presents us with. This is the reality, and contrary to the mistaken belief that many radio amateurs hold. It is also providing an impedance transformation to enable the maximum power to be transferred. (explained later)

If we were to make the length of a radiator (such as a centre fed half wave dipole element) slightly longer than the resonant frequency of interest, the inductive reactance part will be greater than the negative capacitive reactance part and the wire becomes top heavy with inductance. We can explain this by the fact that any wire, at its end, has a current diminishing to zero so any excessive length of wire becomes relevant at the feed end, where current is associated with it. Remember, the inductance is effective from the part which is carrying the current, and in this example is at the centre, where the feeder is connected. However, we can correct for this by simply adding capacitive reactance to cancel this extra inductive reactance. So connecting a suitable value capacitor in series with its feed, at the point where the feeder is connected to the radiator, will enable the excess inductance to be cancelled out. An aerial system of this type has been developed, which is called a 'stretched dipole', where the use of a series capacitor allows an element to be constructed which is physically longer than a normal resonant length. The advantage of this longer length of element, is to increase its radiation resistance  $R_{rad}$ , thus improving its coupling to the aether and therefore its ability to radiate. The radiation resistance has increased due to the fact that there is a greater linear length of radiator actively able to couple energy into the aether.

I have been fortunate to hear the effectiveness of such an aerial system from a GM amateur station located in Dunoon, Scotland, who on 80 and 40 metres is a noticeably commanding signal compared to others.

Conversely, if our dipole aerial wire is shorter than a half wave, then the reverse is the case and the aerial has less than the inductance required for the frequency of interest, but we can add extra inductance in the form of a coil. As previously stated, this coil having no linear dimension, is not very good at coupling a signal to the aether and therefore doesn't contribute much in reducing the current along its length. It only provides the required inductive reactance to effect resonance. As the current through this coil does not reduce over its length, it contributes very little to the radiating property of the whole aerial system. Thus the total aerial system will have a much smaller radiation resistance component  $R_{rad}$  and therefore tries to pass a much higher radiator current in an effort to couple itself to the aether. So this aerial system would be influenced considerably by its  $R_{loss}$  effects. As if that wasn't enough to contend with, there is another problem with the internal self capacitance which the added coil exhibits. All coil windings which have the conductor running closely together have a capacitance effect between turns, and as a consequence, suffer from their own high circulating current between these turns. This increases the places for losses!

It is possible to reduce the self inter-winding capacity which exists between windings of an inductor by using particular ways of winding them. For instance the coil could be wound so that the adjacent turns are spaced apart. Many coils used for aerial matching units adopt this method. Have a look at many of the commercially manufactured aerial matching networks. Many use the commercially named coil type 'Air-Dux', which are air wound coils using small support strips with spaced out windings.



Another way and one of the most effective ways which was first carried out in the early twentieth century is called 'Basket Weave'. This is also known as 'wave winding', where the windings are wound over a former using an odd number of insulating spokes. Having an odd number of spokes means that the adjacent turns follow a line which is different than the previous one and therefore cross over each other at very nearly a right angle. Coils constructed in this way can have a typical quality factor ( $Q$ ) of several hundreds and thus exhibit a very much smaller amount of loss due to their low inter-winding capacity.



The basket wound coil illustrated here was sufficient to resonate an eight foot radiator on a motor vehicle for the 160 metre band, together with just a few extra feet of wire acting as a capacity hat above it. The physical construction can be seen in the picture, using nine wooden dowel spokes arranged around a tough plastic centre piece. Such a construction is not too difficult for the average radio amateur to make and will enable an efficient mobile aerial system. This coil assembly sat on top of an eight foot aluminium, one inch diameter tube, which was the main radiator piece. The end of the coil was terminated with about three feet of wire, to form a capacity hat, end effect. This capacity wire was dressed over an insulating chord which formed part of the physical restraint to guy the aerial itself. The resonance of the aerial was simply and easily adjusted by altering the length of the capacity hat wire.

#### The radiating space (Aether) :

The free space of the aether, has its own parameters associated with it.

As our radiated EM wave propagates through space it does so with an equivalent surge impedance of the free space. Think of space as being a virtual transmission line, which we know to have an equivalent radiating surge resistance of about 377 ohms ( $120 \text{ times } \pi$ ). More about surge impedance later. This free space impedance comes about from the fact that there is a relationship between the magnetic component (the permeability) and the electric component (the permittivity) of free space, itself. The magnetic permeability is that parameter which allows a magnetic field to exist in space, and the electrostatic permittivity is that which allows an air-spaced capacitor to hold a charge in space. The detailed study of them is a fascinating subject but rather complex, and serves no purpose, to detail them here. This has all been possible by the work of many different researchers from a number of nations. Names such as Coulomb, Faraday, Fitzgerald, Gauss, Hertz, Heavyside, Lodge, Maxwell, et al., to mention only a few. It may also be noticed that mention of the venerable Mr Marconi has not been mentioned. Guglielmo Marconi could be described as a technical salesman who managed to gather together the technical information and gain popularity by conducting experiments for the admiralty at the turn of the 20<sup>th</sup> century. Being publicised in the media he became a household name and attracted an association with the new-fangled wireless. Most of the physics of EM radiation had already been discovered before that time.

The parameters of the atmosphere's ability to support an EM wave are the magnetic and electric properties of space, and their understanding by the early physics community has enabled radio, television and all other wireless systems possible. Therefore such radio systems have been made possible by the work of many and not by just one individual. As has previously been said elsewhere, and quoted by Albert Einstein. "It is only because one individual can stand on the shoulders of giants, so to speak, that enables him to see further than any other."

A radiating aerial wire will itself have some specific values associated with it. Using a mathematical technique of surface integration we can calculate its radiating parameter. A particular wire length, such as a half-wave, when used at its natural resonant frequency will have its reactive parts cancel to zero, and will have one current maximum at its centre. This maximum point is known as an anti-node. A node is a point where something passes through zero.

A half wave radiator will have an  $R_{\text{rad}}$  value of approximately 75 ohms. Accurate calculation gives 73.13  $\Omega$  although not of our concern here, this is a mathematical exercise of integrating over a three dimensional volume in a 377 ohms space.

When fed at its centre, the feed impedance will exhibit only its true 75 ohm radiation resistance part, assuming the wire is well away from any disturbing fields or effects, such as the ground or mother earth.

So, in this simple case of resonance in free space, the feed impedance is the same as the  $R_{\text{rad}}$ . At other frequencies, away from resonance, the centre feed point will exhibit reactance as well as resistance. As previously stated, if the aerial element is too long the reactance will be positive, and if it is too short it will be negative.

The feed impedance, which is referred to with the symbol 'Z', is the vector sum of the feed R and X components. R and X cannot be added directly because, as we previously stated, they are not directly related in time. So we have to express the feed impedance of a wire using a particular form of mathematics.

The equivalent radiating resistance, R, exists from time zero, so we say that this resistance is real and we use this as a reference. Mathematically, we say that this is a 'real' vector quantity whereas the reactance, X, is termed the 'imaginary' vector quantity. Vectors are not just values with a given magnitude but also have direction in the form of a phase relationship to each other. You don't need to know the details of this unless you are interested in the mathematics. Suffice to say, that the real and imaginary vectors are always acting through a right angle to each other. Hence the time is fixed by a phase of ninety degrees, which is thus related in a particular way to the angular frequency in use.

Mathematically the feed impedance Z is written as being equal to R plus (+) or minus (-)  $j X$ . The 'j' is a mathematical operator device to indicate that the following quantity is acting at right angles to the Real quantities. To simplify matters all that we need to say, is that, any aerial system can be represented by a resistor in series with either a capacitor ( $- j X$ ) or an inductor ( $+ j X$ ). Furthermore, cutting the wire to a specific length, such as a resonant dipole will leave only the R, as the reactances will be equal and opposite and therefore cancel to zero.

For those who are interested in calculating the resultant value of Z when knowing the R and X values. This can be done using a simple mathematical system known as the theorem of Pythagoras. Find the square of the R and X terms (being the sides of a right angle triangle), add them together, and then find the square root. This gives the value for Z (the hypotenuse). perhaps you remember doing this from early days at school ?

### Feeding the Power In :

The radio amateur has a far more difficult task in selecting an aerial system than, say, the professional engineer, because he is trying to build a system which will provide coverage over many different frequency bands, whereas the commercial station may only need to cater for one channel or band. However, the radio amateur enthusiast does have, or should have, more technical expertise than a non technical radio operator, to take control of any aerial coupling or matching systems between the transmitter and his radiating aerial system.

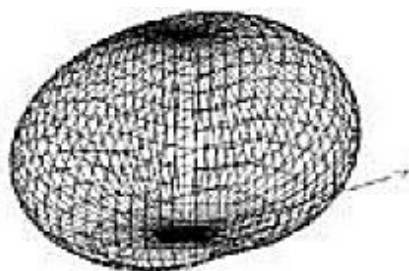
We can feed power into an aerial system at almost any point we wish, providing that we can match the impedance at that point. It can have either only resistive or resistive and reactive components.

There are two normal and basic methods of feed, end-fed or centre-fed. The centre-fed is a well-balanced system and as such will be able to help cancel any locally generated noise, on receive, from nearby objects such as TV's, computers or heating systems, and so on. It is possible to have a compromise of the two in an off-centre feed arrangement like that of the so called 'Windom' aerial. Local site conditions will dictate which system is suitable to use, but a fully balanced system is preferred. The more accurately that a system is balanced, then the more it is capable of reducing any common mode noise trying to enter the system.

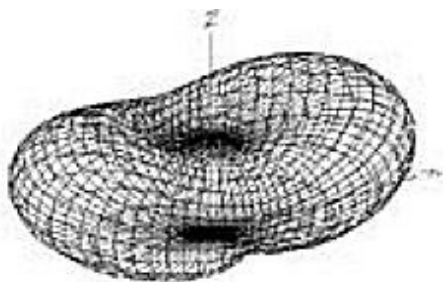
Many designs of multi-band radiator systems have been suggested. One which is quite commendable employs separate resonant dipole elements, co-sited and all terminated on a common feed line. If provided with a wide band balancing transformer, this can be a very effective multi-band aerial. This multi-band system uses the principle that the unused elements do not interfere by any significant amount with the wanted resonant dipole, by virtue of the higher impedances presented by all the others at the operating frequency. However this system only provides a radiation pattern which is that of a half wave dipole and it also uses up a wealth of copper wire. Fortunately, by the careful thought given to the original allocations, some of the amateur radio bands have certain harmonic relationships. A good example is that of the 7 and 21 MHz bands, where the 7 MHz aerial will naturally resonate on its third harmonic of 21 MHz; thus saving some copper wire.

### Effect of height :

Aerials on the lower bands are seldom high enough to avoid being significantly influenced by the ground. For example, a horizontal 40 metre dipole at 33 feet (10metres) will radiate its entire signal vertically upwards because the ground acts as an efficient reflector at a quarter wave behind this driven element. The high angle radiation is ideal for working stations within your own country, but it is no good for any low angle DX (distant) signals. At this low height, due to the ground influence, the radiating resistance and therefore the feed impedance will be lower than 75 ohms and the dipole will have increased circulating current. This comes about by the fact that the current at the voltage node, where the voltage passes through zero, is a maximum. It's here where the bulk of its radiation takes place.



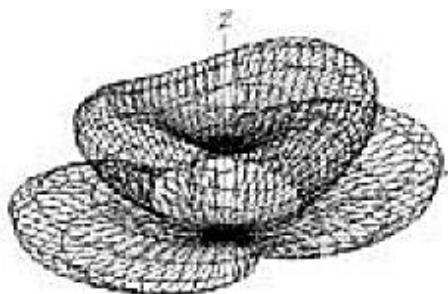
*1/4 wavelength*



*$\frac{1}{2}$  wavelength*

slight tendency to favour either East-West or North-South directivity. This is still at fairly high incident angles, and will depend upon which cardinal points the aerial is sited.

In the few cases of the wire being raised to over a half wavelength above ground its influence will have a small opposing effect which will raise the feed impedance to a moderately higher value than 75 ohms. This occurs because the ground reflected signal is now in a forward phase relationship with the radiator and as such assists the radiator's standing wave. At these elevated heights the more classic doughnut shape tries to appear but is still very much distorted and compressed due to the continued action from the ground. Achieving this latter distorted pattern, would mean raising a 40 metre dipole to well over 70 feet (20+metres), and for an 80 metre aerial, to over 140 feet (40+metres) etc.



*1 wavelength*

For those who have such mast facilities it would be more prudent to consider other aerial systems such as Bruce, Franklin, Sterba, Kraus or similar broadside or end-fire arrays which can give considerably more directive gain, and with switched directionality. Any aerial design will be influenced by what the operator wishes to achieve with his available space, in terms of band and distance that he wishes to cover etc. Here, we are considering aerial systems which apply to the average radio amateur, and his facilities in a modest sized city garden.

#### Feed impedance and Radiation Resistance

If we decided to feed power in at one end of a half wave radiator, the feed impedance will be very high, which could be anywhere from 2 to 5 thousand ohms. However the Radiation resistance of the wire is still 75 ohms because the ability of the radiating part to couple to the aether has not changed. The ability to couple energy to space is the same for all half-wave aerials, irrespective of where the power is fed in. Either end of a half-wave of wire would theoretically present an infinite impedance and an infinite impedance would not allow any current to flow. This is a theoretical case, but it is something which many amateurs and even professionals have difficulty to take on board. In practice, it would be impossible to transfer any power to such an absolute current node point. No current, no power! So in real terms the end fed will have a small current and high voltage associated with it.

When feeding an aerial against ground at a high impedance point it does offer some advantages. One of these advantages is that the loss resistance associated with the return to ground is relatively much lower. As the current is lower and the voltage is higher than that experienced at the centre of a half wave, this end feed reduces the earth loss component of the aerial as a complete system. If as an example an impedance of say two thousand ohms is fed against an earth connection, of let's say a resistance of one hundred ohms to the true virtual earth point, then the relative loss from the earth connection is small by comparison. There is no way that a vertical quarter wave aerial with an input impedance of only several tens of ohms could tolerate such a high earth resistance within the feed system (see later about vertical systems). In such a case, the vertical aerial system efficiency would be very low.

However, feeding at a point which has some current, together with some voltage means that this point is reactive. Remember that the current and voltage are not in the same phase relationship so a reactive component exists. Depending on where this point is along the length of the wire will determine whether the current is leading or lagging, which in turn will dictate if it is either a capacitive or inductive reactance. More about this later.

The previously suggested impedance value of an end fed half wave is practical in the real world, but it can vary by a considerable amount and can be dictated to, by local site conditions. Suffice to say that it is a fairly high impedance and this high voltage, low current, point could be safely fed using a 'Pi' or 'L' network (see later).

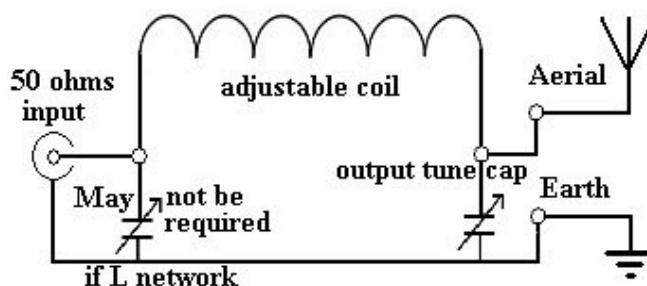
Where we feed power into this wire, will determine the size of the reactive component. To clear up any misunderstanding any half wave aerial whether centre fed or end fed is referred to as a dipole. The only difference is in the feed impedance encountered for the position chosen to feed in the power, derived from the voltage to current relationship at any chosen point along it. An easy way to think of this, is by using a mechanical analogy:

Think of a rope supported at each end by solid brick walls. You can stand at the centre and wave the rope up and down to supply it with energy. Provided that you are moving your hand in unison with the rope's natural resonance it will oscillate and you will encounter the minimum resistance to your effort. You could make the rope perform the same motion by standing nearer to one end, but in this case you would notice more difficulty applying the 'drive' due to the greater resistance, or stiffness, of the rope. But, being nearer to the wall, this higher resistance would now only require you to move the rope a smaller distance to repeat the same effect as in the first case. Thus simulating a smaller current into a higher resistance.

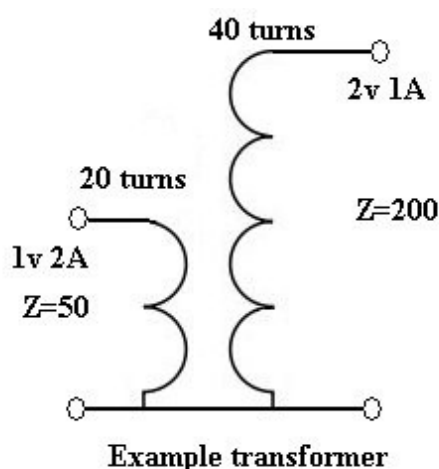
Remember that the very centre of a resonant half wave has no voltage, it is a voltage node and thus only a current exists there, which will be used to carry out the radiating properties of the system and therefore shows no reactance. As soon as we move away from this ideal point, both current and voltage exist and therefore from their phase difference, results in a reactive component existing. More about this later.

#### How a Pi network gives an impedance transformation : -

Mention has been made on a number of occasions about an L or Pi network. If we need to raise the impedance as needed for an end fed half wave this can be achieved using an L network or Pi network as the following picture shows

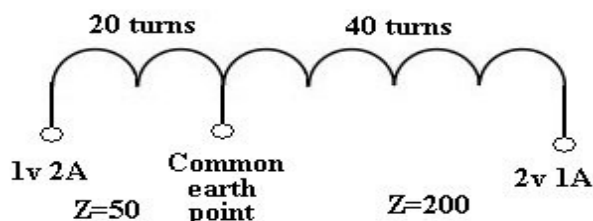


The following diagrams shows how to understand the way that a tuned 'pi' network can give an impedance transformation ratio like that which we understand with a transformer.



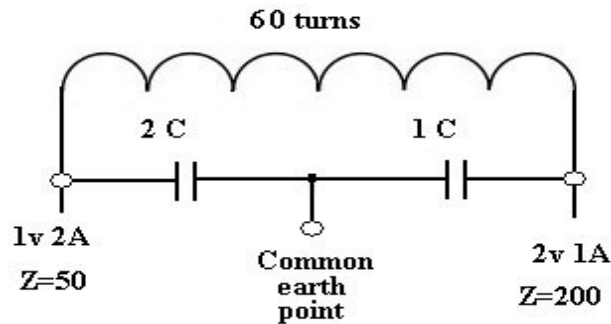
Consider a transformer for any particular frequency where the primary winding has 20 turns and the secondary has 40 turns. From this turns ratio it will transform one volt going in to the primary to become two volts coming out of the secondary. However the available current will be reduced to half, to maintain the power passing through the system to be the same, assuming a simple case with no losses. Thus, this two times voltage with half times the current means that impedance of the system has been transformed by four times. We can achieve this same transformation using a system which uses capacitors to effect an equivalent ratio over the coil.

Consider the following which shows how we can achieve this transformation effect.



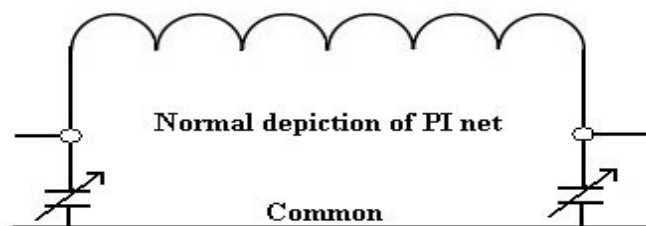
First the transformer with a common earth point can be re-drawn in another way to show that the coil could be continuous but still has an input and an output part.





Then we can replace the earth point by creating an equivalent tap using two capacitors. If the capacitors are of equal value then the input to output transformation would be one to one. If we make the input capacitor twice the value of the output capacitor then the output voltage will be twice that of the input.

So we have an impedance ratio of one to four, as mentioned in the previous case.



However, this simplification of the way that a network transforms an impedance has to satisfy another situation. The two capacitors are in series across the coil and their series capacity value has to be correct to maintain that the coil is tuned to the frequency of the operation of the transmitting system as a whole. Of course we normally make both these capacitors variable types and also the inductance of the coil can be made adjustable.

Therefore by setting the input and output conditions as we wish, we can create a very wide range of impedance transformations, only limited by the size of the components used.

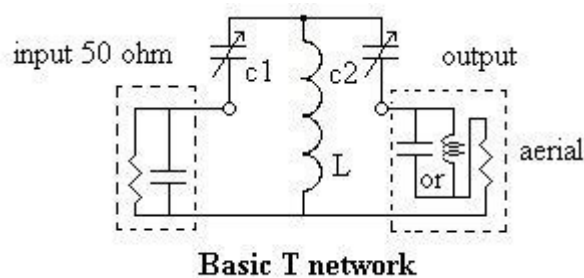
As the impedance will be a complex result of real radiation resistance and reactance the adjustment of the output side of the network will be modified to accommodate any reactive part which may be presented by the feeder or aerial.

As the low impedance side may be connected to a fixed source impedance from say a transceiver it may be quite possible that the input capacitor is not required. Therefore a simple L network is sufficient to enable the transformation to a higher impedance at the aerial connection. In this case the 50 ohms side will be tied to 50 ohms by the equipment and the co-axial line connecting it. The equivalent capacity may exist in the connected equipment. This would be the case for an old transmitter using a valve output stage and a Pi network which is internal to the transmitter. This type of pi network is transforming the high anode impedance of the output valve(s) to a 50 or 75 ohm output and thus already has an output capacitor connected there, which is usually referred to as the 'loading' capacitor.

Perhaps it is worth mentioning here that any adjustment or load which appears at the end of the network line will be reflected throughout the system as a whole. So if you have a pi network feeding through a reflectometer (SWR bridge) into an L network and onto the aerial, then changes at the aerial will be evident as changes at any point along the system. The reflectometer will indicate any changes. Also, don't forget that the reflectometer is designed to work at a nominal impedance, usually 50 or 75 ohm real. Therefore the SWR indicated can only be relied upon when this condition is near to that 50 or 75 ohm designed value.

#### The corresponding Tee network :

The other popular network is the so called 'T' network as shown in the diagram. The coil now has only one end at earth and the impedances in and out are tapped into the coil using a capacitance tap arrangement which acts in a similar way as in the L network.



Adjusting C1 for the input, and C2 for the output, effectively taps the coil L. As the capacity values of C1 or C2 are decreased, this makes tapping points which are effectively lower down the coil impedance. This keeps the top of the coil at the highest voltage and impedance. As mentioned in the L network the coil also needs to be adjustable to maintain resonance. Many commercial networks use a 'roller coaster' type of inductor. The source is normally a fixed 50 ohm source and the aerial will either have positive or negative reactance plus a real radiation part.

The difference between an L network and the T is that the L network being a low pass type of filter will help to assist the suppression of any harmonics. However the T network is considered easier to set up and can have a greater impedance adjustment range, hence it is more popular in commercially manufactured networks.

Also some commercial matching networks, such as Palstar and MFJ incorporate a balun into the feed line to enable the T network to float when used in a balanced feed arrangement. This is a convenient way to press a single ended network to operate in a balanced system, but it may suffer more losses than a properly balanced and purpose built design.

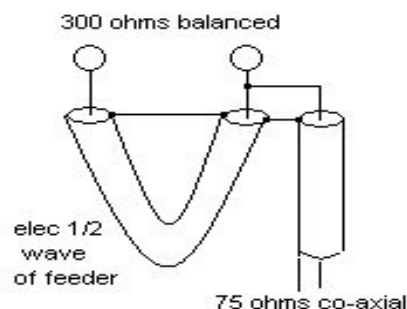
### Impedances transformed :

The voltage to current relationship can be demonstrated in other ways. For instance, if we make a dipole element consisting of two wires each a half wavelength long, which are closely spaced, parallel to each other and joined at the outer-most ends, we have what is referred to as a 'folded dipole'. When this system is driven, each piece of wire will now have only half the current that would be associated with a single wire fed with the same power. If we connect a twin feeder to the centre of one of the half wave elements it will exhibit a feed impedance of four times that of a single wire aerial because the impedance is a function of the inverse square of the current. This would equate to 293 or approximately 300 ohms.

However the radiator still has no reactive components at the centre, as it is still working as a resonant half wave. and the total current flowing in the system as a whole is the same as before, so its ability to communicate EM energy to the aether is still 75 ohms. Power fed into one of these elements is the same as previously so the  $R_{\text{rad}}$  hasn't changed, all that is taking place is an impedance transformation within the system. If one carries out a detailed network analysis of a folded element aerial it supports the reasoning that the above comes about from the fact that each side of the folded element acts as a quarter wave transformer. The feed point on this type of aerial is at the current anti-node, where the voltage is zero so no phase error between the voltage and current can exist and thus no reactance. Therefore this aerial could be fed with 300 ohm ribbon as a flat line and a four to one balun at the shack end would bring the feed down to a manageable 75 ohms real.

In fact, we could take this effect even further and use three half wave elements all connected together at the outer ends. Feeding only one of them at the centre would exhibit a feed impedance of about 660 ohms ( $9 \times 73$ ). However each time we add an element in this way it increases the peak voltages at the feed point, which will increase accordingly for a given power level, and could result in insulation breakdown. The ability of this multi folded element to radiate has not changed, thus the radiation resistance is still 75 ohms, in free space, even though the feed impedance is very much higher.

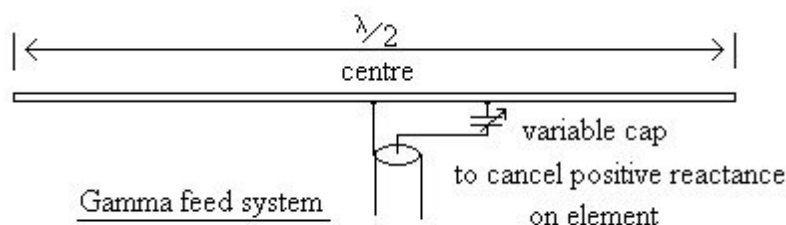
Another popular method to obtain a one to four balanced feed to satisfy a folded element is to use a half wave delay line. An electrical half wave of feeder creates a phase shift of 180 degrees, and thus creates a type of push pull situation. This is often used on VHF systems as the length of cables on HF systems would be excessive. The feeder, usually of the co-axial type, is connected as shown. This transforms the 75 ohms concentric feed to 300 ohms balanced, provided it is feeding a non reactive point.



### Gamma feed arrangements :

There are other methods which can be used to change the voltage versus current, feed parameters. One such method is called a 'gamma' feed. Again this doesn't make the radiator any better or worse in its ability to radiate, it just makes a suitable transformed feed impedance when and where it is required. This is popular when a radiator is part of, for example, a yagi aerial system and therefore surrounded by parasitic elements.

The presence of parasitic elements causes a lower radiation resistance of the driven element which results in higher circulating currents to flow. Therefore feeding the current anti-node of the driven element directly would require a much lower feed impedance of perhaps, say 12 ohms. As 12 ohms is an awkward feed impedance, and no standard feeder cable is produced for this situation, a remedy is to use a gamma match. Gamma feed arrangements transform the impedance up to 50 ohms, and provide a means of connecting an unbalanced co-axial feeder to a balanced radiator system. Thus killing two birds with one stone.



Gamma feed arrangements are not too difficult to achieve, physically. The only time needed is usually in its adjustment. It also simplifies connecting a co-axial feed to a balanced aerial system. A half wave conductor has at its actual centre a voltage node (zero) so this is the natural earth point for the co-ax braid to be connected to. No need to have any insulator or break here, the half wave is a continuous conductor. So all that is left is to connect the co-ax inner to some point along the radiator away from this point. This 'feed place' has to be at a point which will transform to the 50 ohm or whatever feed impedance is used. However there is one extra thing which needs to be finalised. A series capacitor is needed to cancel the inherent inductance which exists at this point along the radiator. So a small variable capacitor will be needed. This component needs to be protected from the weather, so it is usually fixed inside a water-proof container. Some designs make this capacitor in the form of a rod inside a tube which helps to make a more practical design. By adjusting the position of the tap connection and the capacitor adjustment, a unity match can always be found for the co-axial feeder in use.

### Relationship of one aerial to another :

If the aerial location has enough room it may be possible to erect two half wave aerial systems which are spaced side by side by at least a tenth of a wavelength apart, at the lowest frequency of interest. As an example, consider two centre fed 40 metre horizontal dipole aerals spaced 4 or 5 metres apart. By bringing the two feeders into the radio shack, it is then only a matter of feeding power to each feeder at an appropriate phase. This can be achieved using different lengths of feeder. Feeding in this way has the effect of making the radiated signal follow a defined path dictated by the action of one element working against the other. For example, if both feed lines are of equal length and each element is fed equal power in the same phase, it would re-enforce the upward radiation, which will favour the high angle signals.

Conversely, by feeding them in anti-phase, by swapping over one of the feed lines, will have the effect of cancelling the high angle radiation in favour of the horizontal component, forcing the radiated lobe to act at a lower angle. The radiated signal, in this case, cannot be parallel to the ground because the ground effect is always present and therefore is going to have a big influence on the system as a whole. But the radiated signal will be at a much lower angle.

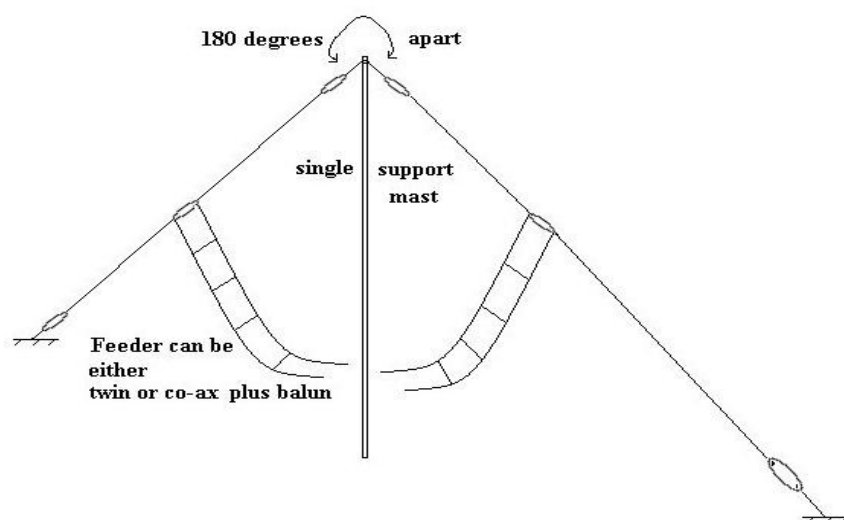
In all these situations it is necessary to ensure that the conductors used are of sufficient construction to reduce any losses due to any high circulating currents encountered. Particularly in the case when they are in anti-phase and at a low height above ground, where the radiation resistance will be forced to become quite a low value. This means that the element current is trying to be much higher to give an effective coupling to the surrounding aether.

If even more room is available, we could separate the radiating elements further apart by their physical spacing. This can help to make the feeding easier due to the fact that the interaction between the elements is going to be less and the behaviour of the current in each will become slightly more manageable.

Alternatively, feeding one element by 135 degrees delayed from the other will create a relationship that favours a radiation which is only in one cardinal direction from any another. This can be done by using suitable lengths of co-axial feeder to effect the required signal phase delay.

Aerials of this type are referred to as 'driven arrays' and can be very effective where the extra space is available. They can be made very effective for lower radiation angles and their radiating parameters can be set up from the comfort of the radio room, using suitably constructed coax delay line systems and or phasing networks. Although, as with all aerial systems the surrounding terrain will influence the radiating angles and properties, quite significantly.

A popular way to erect this type of aerial system is to use a single supporting pole with two sloping radiators physically spaced at 180 degrees, on either side of the support. (see diagram) This can be made into a very useful system and surprisingly has had little interest from the amateur radio fraternity. Although the time needed to prune and adjust such a system may be a factor in that choice. However once set up and adjusted it can give really good DX results.



### Noise : -

A big problem, with any vertically polarised aerial system, is noise. Noise, by its association with the mother earth, has an electrostatic component which acts up from the ground as a vertical component and therefore a vertical receive aerial is certainly not electrically quiet. The reciprocal likelihood of causing interference when transmitting is also an increased possibility. However, if another separate aerial system is used for receiving, vertical radiators have very good potential. Many amateur stations have used this type of system very successfully which also becomes possible in a very limited space garden.

### Vertical radiators:

As just previously mentioned the half wave dipole can be used in a vertical sense and fed in any of the ways discussed above. A vertical aerial is very efficient at radiating the low angles required to communicate ionospherically at long distances.

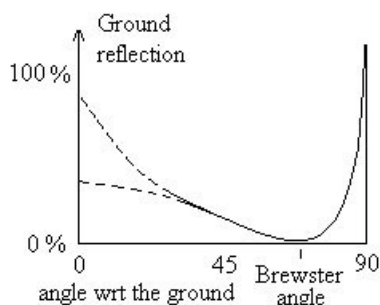
Providing that the vertical is furnished with a good surrounding earth or ground plane system, it is possible to feed only a single quarter wave vertical radiator satisfactorily while creating a 'mirror image' in place of the missing quarter wave, using a ground plane, either real or simulated, as a reflecting surface. The ground plane system is the only way that this mirror effect can exist, so it is very important to the aerial's operation. It is futile trying to create this type of aerial by relying on a simple or poor ground connection. An efficient earth plane must be established to make the quarter wave aerial capable of any efficient radiation. In fact, if a radial earth system is laid out in a particular direction, the radiating wave is encouraged toward that direction and a very efficient long distance radiator is established.

The vertical does lend itself to harmonic use on some bands. Many commercial verticals use traps to make them into truly multi-band aerial systems. When operated as a quarter wave in its fundamental mode with an earth mirror, the calculated feed impedance is 36.6 ohms, without reactance. The other half of the image impedance occurs in the earthed mirror effect of the ground plane system. As the loading  $R$  is half that of the dipole, this makes it more susceptible to  $R_{\text{loss}}$  effects so it is important to ensure that the  $R_{\text{loss}}$  component is at a minimum. Using suitable tube sections for both the vertical element and also the earth plane will help keep these losses down to a manageable level. Do not rely on the goodness of the ground to create a reflective surface. In fact the surrounding area over many wavelengths will have a considerable influence on the effectiveness of this type of radiator. Vertical quarter wave systems are therefore much better at low locations near to the sea and coastal areas where the ground conductivity is better. Unfortunately, there is nothing that the amateur can do to change this situation except move.

A half-wave vertical radiator will couple energy more effectively to the aether and could help to launch a signal even on what could be considered as poor ground. Power can be fed in at any point, just as in the horizontal case. As long as it is suitably matched, to the centre or the end, etc. The improvement offered by a half wave system is due to the fact that the launch angle from it is lower than that of a quarter wave with mirror and consequently makes use of the ground effects over a much farther field. Although not fully detailed here, this ground influence occurs on all aerials and in particular the vertical. This is due to the fact that the magnetic component which is at right angles to the electrostatic component and thus in this case horizontal, is subject to a phenomenon known as the Brewster effect.

### Brewster Effect : -

This was work carried out by a Scottish physicist Sir David Brewster. Although Brewster worked with light-waves and optics as his EM radiation, the same principles apply to longer EM radio waves.



An example of the Brewster effect.

This can vary considerably at different locations and is influenced by a number of factors of the ground / earth polarisation is also affected

Think of the earth plane being just like a mirror in optics and capable of reflecting EM waves. The ground over which the RF signal propagates has dielectric properties of its own, thus the polarisation

and behaviour of the signal, as it is re-radiated from the ground, is influenced by its incident angle. This is the angle at which the signal arrives at the true ground interface. The resultant signal that gets re-radiated by the ground reflection has its magnitude affected by the ground parameters, and therefore the magnitude can be quite variable at shallow angles which are subject to the ground conductivity. This behaviour of an EM wave and its polarisation relative to the angle of incidence over the surrounding terrain occurs over a considerable distance and can suffer a change in its polarisation. The transposition of the waves polarisation does not pose a problem, as the wave when returned as a sky wave has a mixed polarisation from the ionosphere.

To try and simplify an explanation of this effect, certain launch angles are more difficult to achieve due to the available di-electric properties of the surrounding ground. Think of a mirror which you view at an angle, other than perpendicular to its surface. Imagine that at a certain angle this mirror blanks out but at other angles the reflection effect is there. This is how the EM radio wave sees the ground. These properties can occur over many wavelengths around the radiator and will vary from one location to another. This may help to explain why two stations using the same aerial can get differing results that are at odds as to their expected performance. As stated before, the di-electric properties of the surrounding ground over many wavelengths is a matter of local conditions and cannot be changed by the station.

It is possible to energise a vertical radiator that is a different length than a half wave, providing that the necessary height can be accommodated by the mast system. Radiator lengths of three eighths, five eighths and three quarters of a wavelength are effective and popular but need a suitable matching system which, when base mounted, can be made to accept a 50 ohm co-axial line. Matching can be achieved easily, for any of these lengths, using the simple L or T network. The only difficulty being that the matching network has to be at the base of the aerial to feed power to the bottom of the radiator.

Many systems use motor driven tune methods and can be driven manually or automatically using complex control systems. Usually the RF power is fed to the matching network using the convenience of co-axial cable from the transmitter. The co-axial feeder can be used to also carry a DC control voltage to enable an automatic tuning motor to be energised. Such vertical aerals are extremely good for DX working..

### End-fed Wires :

The prevalent end-fed arrangement is where a single horizontal aerial wire needs connecting to the equipment. This would be a common way to 'get on the air quickly', and the behaviour of such a system is not often understood.

If the wire is two or more wavelengths long, it can reasonably be termed a 'long wire', and anything shorter is simply an 'end fed wire'.

The practical conditions will dictate whether the lead-in wire is horizontal or vertical and the length of the aerial itself will determine whether the feed end is carrying a heavy current or exhibiting a high voltage, which will be dependant upon the frequency in use. So the performance of such a system is very variable, but it will usually be more quiet on receive than a single vertical system. If the wire is of a random length, that is, not possessing a resonance on any desired amateur radio frequency band, it is a fairly simple matter to provide an effective match and couple power using a single L or T network as stated previously, or even just a single cancelling reactance. This can be either a simple variable capacitor or variable inductor, as required. A simple rule can be applied to determine which conjugate (opposing) reactance is needed to cancel the system reactance in an end fed system.

If the end fed wire length is : -

Less than an even number of quarter waves and more than an odd number of quarter waves in length then it can be driven via a capacitor. For example : - a wire over a quarter wave and less than a half wave (which is two quarter waves) can be easily fed by just using a variable capacitor in series with the feed.

If the end fed wire length is : -

Less than an odd number of quarter waves and more than an even number of quarter waves in length then it can be fed via a variable inductor. For example : - a wire over a half wave and less than a three quarter wave can be fed via a variable inductor. Another example could be a wire from zero up to a quarter wave long. If you think about it, this will also satisfy the condition ! Although in this extreme example the shorter the wire gets the harder it gets to radiate.

To achieve any of these feed situations in practice with any piece of end fed wire the output of the transmitter is coupled via an SWR bridge operating at the normal load impedance (say 50 ohm) to the matching device (capacitor or inductor). The matching is then adjusted to give a low SWR match at the 50 ohm transmitter output as indicated on the bridge. The outer braid is connected to the earth return system, of course.

In this very basic matching arrangement the resultant real load of the aerial may not be exactly equal to the fixed 50 ohm source of the transmitter, but never the less, will be a real load without reactance so will be close to unity SWR. So for a quick and simple system it may be quite acceptable. To achieve a perfect match would require the additional components as in a T or L network to give the necessary transformation of the real load part plus cancellation of any reactance present. This is normally known as 'conjugate' matching.

In the case of horizontal wire aerials which are several wavelengths long, and the reason why they are referred to as 'long wire' aerials, is that the EM wave launches itself in a particular way. As the standing waves on a long aerial create more than one point of radiation, they tend to hug the wire and radiate close-in to the wire. This has the effect of making a number of close strong lobes. These radiated signals are a few tens of degrees on either side of the plane of the wire. Rather like tight cones of radiation at either end of the wire. Although the part of the cone nearest to the ground would be non existent due to the influence of the ground forcing the signal upwards.



Systems such as the Beverage and Rhombic use this effect to gain their directivity. They also realise some gain albeit from their large use of real estate. They are also quite popular by professional radio systems due to their wide usable bandwidth.

A number of aerial designs using this Beverage technique, suggest resistive loading be applied at the far end. This is useful for a receive only system to influence its directivity, and make the lobes become re-enforced in a particular direction. It would not be a good idea to use this as a transmitting aerial, being of the firm opinion that a dummy load is a poor radiator.

However terminating with a 600 ohm load at the end of a full size rhombic is acceptable as most of the power will have dissipated through its efficient radiating properties, thus the 600 ohm termination will have very little power left to absorb. Rhombic arrays are not strictly aerials but are transmission line radiators and can realise huge gains at very low radiating angles to the horizon. They are in a completely different class, because of their size and the way that they radiate, but sadly are not realisable by amateurs who have only a town sized garden.

#### Centre Feeding:

Returning to balanced systems, we must now consider how to feed power to the centre of the radiator. We have a number of options but the two basic alternatives are to use either co-axial line or balanced line:

As was explained previously, all wires have reactive properties associated with them and a feeder is no exception. From their physical dimensions, feed lines exhibit a characteristic 'surge' impedance derived from the reactive components that they contain. Common surge impedances are 50 or 75 ohms for co-axial lines and 300 or 450 ohms for balanced line. Such feed lines derive their surge impedance from the inductance per unit metre of length in relation to their capacitance per unit metre of length, which comes about from their physical attributes of spacing, insulating material and wire size. In general, if the capacitance per metre is greater in one type of feeder than another then the surge impedance will be lower.

#### Co-axial line:

Co-axial transmission line was first patented by Oliver Heavyside towards the end of the nineteenth century and was much later brought into popular use by the military to provide a convenient means of transferring RF power in the arduous conditions of the battle-field. Nowadays, it appears to have become accepted as normal for an amateur radio aerial, but is it the best?

Co-Axial line, more commonly called 'co-ax' is normally more lossy than balanced line and if deviating by any amount from its characteristic impedance will cause it to have losses which increase substantially as the divergence increases. So it is not a good idea to operate co-ax very far from its designed surge impedance. This is a problem at any frequency but becomes more serious as the frequency is increased. A feed line when terminated with a pure load value equal to its characteristic surge value is operating in what is referred to as a 'flat line' and therefore operates with the same impedance along its entire length. This means that it maintains the same voltage and current relationship along its entire length.

Co-ax, is inherently unbalanced so some means has to be provided to enable it to work in its intended concentric form.

What we mean is that the inner line is balanced by the fact that it is covered by the outer braid, but the outer braid is open to the outside, so is capable of radiating in its own right. A centre fed half wave dipole aerial is a balanced system, but does have the correct impedance to satisfy the typical impedance of co-axial lines. Therefore we can either use some balancing arrangement at the end of the co-ax where it connects to the aerial radiator part, or we can choke off the radiation from the braid. This can be achieved by using either a matching transformer (sometimes referred to as a voltage balun) or a choke balun (properly referred to as a current balun). These are quite often constructed using a ferrite core to provide sufficient inductance in a common mode choke arrangement. Personally, I try to avoid such methods of using ferrite loading as they are normally associated with giving off some heat and as such are therefore dissipating useful power.

Ferrite, or more correctly dust iron cored loading, has its uses in such applications as semiconductor power stages where the operating impedances are very low, but the physics associated with this is complex, such as material type and size of particles etc., and they all need careful consideration. I spent some months with a well known manufacturer of military radio equipment to obtain acceptable 'mil-spec' results with semiconductor power stages and core materials, but that's another story. Simply winding a section of the co-ax cable into a coil should be capable of choking off any braid currents. Having said that, it is valuable to have knowledge of the problems that can be associated with various core materials, but try a balun if it is felt absolutely necessary, but check for heat and losses.

There are many other feed variations, with names such as a 'Bazooka balun'. The Bazooka balun is popular for vertical dipoles where the co-axial line is fed up inside the lower half of the radiator. The resultant quarter wave element over the coax acts as a choke balun.

All these systems are trying to make unbalanced co-ax line couple correctly to a balanced radiator system. It is possible to achieve an unbalanced to balanced feed using a quarter wave transformer of open wire or balanced line. Of course this does limit it to a particular band.

This is a popular technique as used by Louis Varney G5RV in his famous aerial which was originally designed as a 'double extended Zepp.' for 20 metres. The name of this aerial is related to the type as used on the Zeppelin airship and it forms a pair of elements in a co-linear plane (in line) which are each a bit longer than a half wave. In the case of the '5RV' the total element radiator is equivalent to three half waves on 20 metres, giving three quarter waves each side of the feed point and therefore realising a few deci-Bells of gain over a single half wave dipole. In view of the length of the radiating element and the feeder length and its velocity factor, the '5RV' aerial can be matched adequately on other bands. The feeder effects an impedance transformation on a number of other bands. The original design with a quarter wave of balanced feeder with respect to 40m., which is about 10 metres, then could be continued with a co-axial feeder to the equipment location. So it became a compromise of low feed impedances on a number of bands. However, the same aerial fed entirely with open tuned line all the way into the radio shack can be fed with power on any band with impunity. However, a suitable trans-match with balanced feed needs to be used in order to achieve that.

Another factor requiring some consideration, but often overlooked, is that 75 and 50 ohm cables need to be terminated with connectors of the correct type to maintain the correct impedance.

Co-ax connectors are different for 50 ohm and 75 ohm and would cause an unnecessary reflection the difference representing a standing wave ratio of about 1.4 to one.

### Balanced line:

In the normal case, when an aerial is fed with high impedance balanced line, such as 300 or 450 ribbon, the feeder is operating in what is referred to as a 'tuned line'. The only situation where 300 ohm line is used as a flat line is when it is terminated with a pure 300 ohm load, as would be the case for a folded dipole.

As mentioned previously, the main radiating element may not be naturally resonant on any of the amateur bands, in which case the feeder will not see its natural surge impedance value, at its end. This is referred to as, the feed line is operating as a 'tuned line', and not as a flat line. Since the connecting point on the radiating element will have some reactance associated with it, therefore the load is not pure, and the feeder cannot maintain a constant surge impedance. What this means is that the feeder will experience a changing R and X value along its length. The feed line is experiencing an impedance which is being transformed along its length, but it is not able to radiate because the currents in each leg are in anti-phase or para-phase. Taking both sides into account, this is known as the common mode current and will be zero. However the actual intrinsic current and voltage values in each leg of the feeder is a different amount at different points along its length.

This situation can put a high demand on the di-electric strength and the copper losses in the feeder but, being air spaced and suitably stranded, it should exhibit a very small loss. Surprisingly, with all this extra strain it may still have a lower loss than matched co-ax cable.

Truly balanced air spaced line is very much more acceptable in view of its efficiency, even when operated as a 'tuned line' at impedances many times greater than its nominal surge value. This is due to a number of factors. Balanced line normally exhibits a higher characteristic surge impedance than co-ax and, as a consequence, the mean value of current will be lower at any given power level. The copper losses are comparable in each case. It also exhibits a much lower di-electric loss between the lines as the spacing material is basically air. However some commercial feed lines do have a separating membrane which may be polythene, PTFE or a similar material. So commercially manufactured feed lines are not quite so efficient as that of a home constructed air spaced line. They also experience some extra losses when they become wet. When buying a balanced type of feeder always look at the velocity factor.

Generally, a line with a velocity factor nearer to one and it will have lower losses. This comes about from the fact that the separating material has a lower di-electric constant in a line that has a factor near to unity. Air spaced balanced line with sufficient conductor in each leg is by far the preferred form of feeder but needs to be fabricated on site.

A balanced feeder is therefore capable of coupling power to a radiator which exhibits various reactive components. It has low losses, so therefore is at a distinct advantage. The only drawbacks in using balanced line are practical ones imposed by its physical requirements to use gradual curves and to keep it away from any other conducting objects.

It is desirable to bring a balanced line away at right angles from any radiator, but having some common mode pick up by the feeder is not generally a problem. This is only a problem where the feeder length has some relationship to the radiated frequency. However these drawbacks can be accommodated as we will learn later. Such practicalities shouldn't be too much of a problem in a fixed, peacetime, aerial installation.

### A practical aerial consideration:

So lets look at the evidence and the requirements to erect an aerial in a modest sized garden. Apart from a vertical radiator system which would be ideal for those who wish to communicate with low angle DX, we will consider a horizontal wire aerial. We will consider an aerial which is electrically quiet and capable of multi-band use on 160, 80 & 40. To be electrically quiet suggests that it should be a balanced system.

Erect the radiating element, the top section, in such a position that the central point is high and conveniently situated to feed in the power. This is quite often a location on the house roof or possibly a mast on the chimney stack. This is a popular point to locate the central feed of a radiator, or it could be a suitably located tree. To accommodate the 160 metre band and have a realisable efficiency the radiator element will need to be at least 100 feet (30m) in length. Obviously, by making it longer is better, to achieve a higher radiation resistance, so will be more efficient.

To bring this into perspective, a 100 feet (30m) of horizontal wire operating at 2 MHz at a height of 30 feet (10m) has a typical radiation resistance of about 6 ohms. Therefore with consideration of what has been stated earlier, we can achieve a fairly good radiating element but great care will be needed to reduce any losses of any kind.

In an attempt to keep the skin effect losses to a minimum, use stranded, separately insulated, conductors in both the radiator and the feeder. I found an abundant and cheap source of wire could be got from TV tube scan coils. As the new forms of display hardware such as LCD etc. become available, there are many old CRT-type displays being discarded. Stripping these of components not only stops them from becoming 'land-fill' but also provides a wealth of free materials for all kinds of use. It includes some valuable ferrite materials in various useful shapes. In fact the scan ferrites themselves are very useful items. They can be dismantled, as they are usually held together with small clips. It is a simple matter to wind, say, a mains lead on them to choke off any RF from entering the mains supply.

So, it is possible to erect an efficient aerial system in a space of about 100 feet (30m) which can be used on all bands, all the way from 2 right up to 150 MHz. If operation on the 160-metre band is not considered then a smaller length may be possible. But, bear in mind that, the longer possible linear length of wire is the best radiator to couple our transmission to the aether. Once we have realised the most efficient use of our real estate by configuring a radiator element which is coupling the maximum amount of EM energy, all we then need to do is build a suitable network to transfer power to that system. This we can do in the comfort of the radio room.

### Trans-match Networks

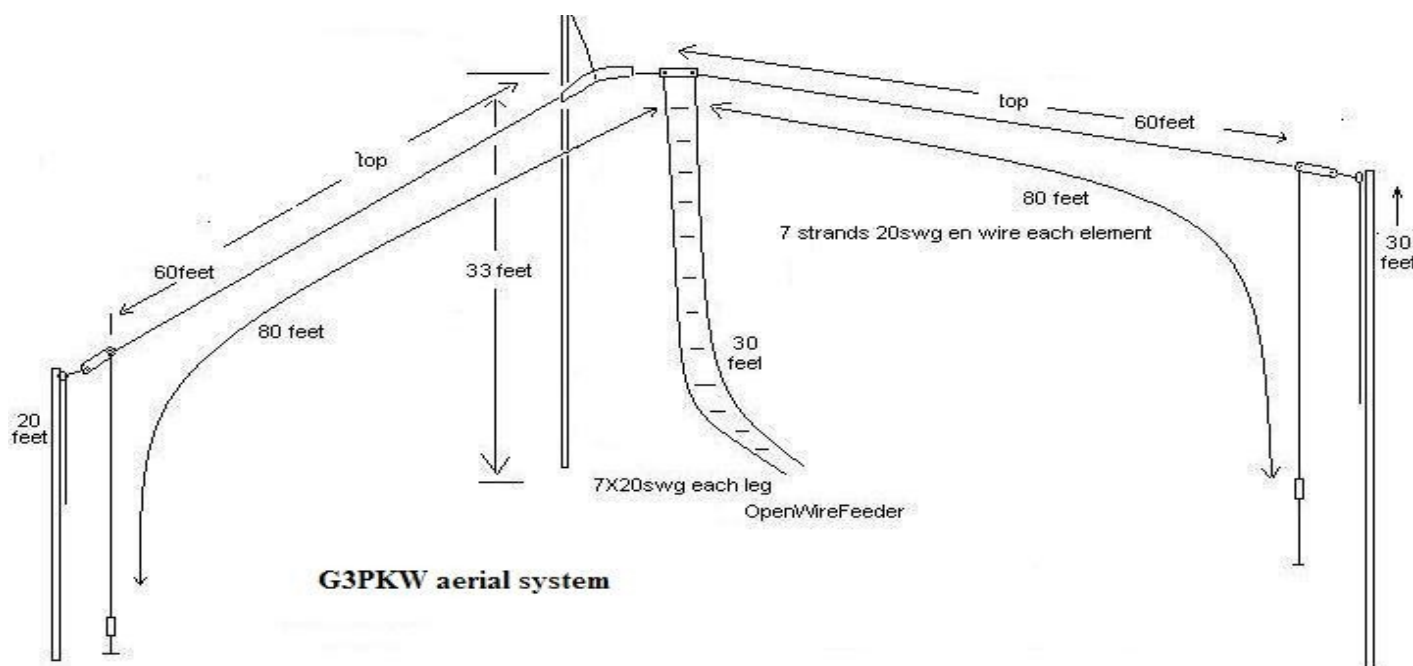
When considering construction of a trans-match to feed a balanced line it is worth considering the components which it uses. The capacitor should be air spaced. Capacitors using any other dielectric are too lossy to even consider. It is possible to obtain a capacitor which is in a vacuum but they are generally extremely expensive and only needed where extreme voltages are present. The air spaced capacitor is extremely efficient, and as a single component will exhibit the lowest losses. Air spaced capacitors of good quality and with sufficient voltage rating, are extremely expensive and therefore it is worth considering to make them yourself.

The wound inductors will have more losses associated with them than any air spaced capacitor losses and therefore need to be carefully designed to make them exhibit a minimum loss. Close wound coils have high inter-winding capacitance and as such, have high circulating currents, which circulate despite any other current. Many radio amateurs wind their own coils and those with at least an adjacent turns spacing equal to the wire diameter is much preferred. Or maybe a coil which is 'wave wound', rather like the basket weave as shown earlier, is a possibility. A balun can be useful in a balanced matching network but if after use it is found to increase in temperature then it is certainly losing a considerable amount of real power in watts. In fact if any component such as a balun is placed in a known amount of distilled water it is a simple matter to calculate the power lost by that component. Measuring the temperature rise over a given time, and using the specific heat capacity formula for water which is 4200 Joules / kilogram / deg. Kelvin (ie centigrade), and together with the fact that one Joule is one Watt Second. It is possible to evaluate the lost power in the balun in equivalent watts in a given time. This may also be a suitable way to evaluate a given power into, for example, a dummy load resistor.

The L network, derived from the Pi network as previously described, consists of, in one case, a series coil followed by a variable capacitor to ground. Remembering that the moving blades, attached to the frame, are the earthed connection and the fixed plates are the signal side. The coil is normally furnished with a number of tapped points to select the required inductance. This is the normal configuration for an L network where a fifty ohm co-axial feed line is transformed to a higher impedance plus any associated reactance. This is a common system as used with a random end fed piece of wire. In some cases, such as a mobile whip aerial where the radiation resistance is much lower than fifty ohms then the capacitor is on the feed side followed by the series coil, to enable the impedance to be transformed to a lower value than 50 ohms.

For balanced feed lines there are two approaches possible. Either a purpose built balanced network is used or an isolated L or T network fed with a balun. A lot of commercial networks use this second method as it is easier to fabricate. Commercially manufactured aerial networks such as that made by Palstar and MFJ use this system. The purpose built balanced network may be slightly better in that it maintains a perfectly balanced system without the use of any ferrite materials. Some of these balanced systems use plug in coils to simplify the switching and generally this type of network is very efficient, as each coil assembly will be idealised for each band. There are plenty of network designs available and the later reference includes some of the best system designs.

### An Efficient Aerial System



Shown here is my present aerial system which I use on all HF bands. Also, with a suitable matching network, I have used this aerial on 2 metres with surprising results.

As the operating frequency is raised and therefore the radiator has more wavelengths active, this aerial shows distinct directional properties. Obviously I cannot change their fixed direction but it is interesting to take 'pot luck' and be amazed at their capabilities. As the diagram shows the maximum amount of space has been used even to the extent of dropping the ends down. This is done to favour the lower frequencies such as top band. It increases the end effect capacity and therefore draws the current to be distributed over more of the radiating element which is up in the clear. Measurements of this system were taken using a double beam oscilloscope to establish at what frequency the current and voltage showed no phase shift. This showed it to be non reactive and resonant at just above 2 MHz. I can usually contact stations on 160m SSB around Europe with good signal reports. Similarly, on 80m and 40m much DX is possible plus the usual local contacts. Had I been more interested in working long haul contacts, I would have probably used a vertical radiator with radials in the preferred direction.

### Possible Problems

It is often reported that certain feeder lengths must be avoided if certain frequencies are contemplated. I personally have never had a problem with this. On reflection, I think it is a comparatively rare condition and anyway, it's a simple matter to add an extra foot or two to correct it. I recently received an Email from an amateur station with an open wire fed top band aerial that was experiencing high voltage flash-over. He couldn't change the feed length because of practical constraints. Even modest power produced flash-over on a commercial kW rated matching unit. After exchanging a few E-mails, a few feet added to hang

down at each far end cured the problem. With any radiating element which is able to radiate power the highest voltages to be experienced should not be excessive at modest power levels. This is because any reactive component which has been cancelled by the transmatch and the subsequent loading of a correctly matched radiator should damp any excess voltages. Obviously, this is subject to the power levels involved. To clarify this, the worst case would be to have a top section of a half wave centre fed with an open wire feeder which is electrically an odd multiple of quarter waves long. The far end of the feeder is loaded by a low value which over the odd quarter wave of feeder will be transformed to the highest impedance at the bottom where the transmitter is to be connected. This would result in a very high voltage point in the shack.

When terminating the outer ends of any aerial design, do not put the insulator at the very end of the wire. The very end of any aerial wire has the highest voltage of any point and by fitting the insulator say one or two feet in and letting the absolute end hang down ensures the breakdown losses are considerably reduced. This is particularly evident when the insulator becomes wet and after the surface of the insulator has become contaminated with carbon film from vehicle exhausts and alike. Many of these things are forgotten when erecting an aerial system.

I would suggest that when considering an aerial design, it is worth while to calculate and plan out the approximate expected feeder lengths required. Remember to also include the radiator length in the equation, together with the feeder length, and the knowledge that a quarter wave of feeder will transform a high impedance to a low impedance and vice versa. A half wave length of feeder transforms back to the starting point. Ideally, this needs to be evaluated for each band required. It then becomes possible to avoid any awkward high voltage situations at the feed point in the shack. In designing a suitable aerial system, there are many tables that exist which detail the many variations of radiator and feeder sizes to use. These can be found in most aerial data books. I would also refer the reader to a most excellent article which appeared in Rad. Comm. 2004, for January, page 53. A very informative work by Brian Horsfall, G3GKG. (a pdf of this article are available) This gives details of an aerial system similar to my own which is suitable for use on all bands. It also details the construction of an efficient balanced feed network.

It is possible to make a balanced feeder which is not influenced by nearby objects, in the following way. Strap two lengths of co-ax side by side and make the braids a common connection. If 50 ohm co-ax is used this will result in a balanced line with a surge impedance of 100 ohms. However, this is not the best form of balanced line but, providing the feed length is not excessive, its losses are much lower than that of using single co-ax with a balun. It is not recommended to use such a line in a tuned line situation as the di-electric losses would be much greater than that of the air spaced case. The two inners become the balanced line and the braid can be either left to float to a pseudo earth point or connected to mother earth. Such lines can be used near to any earthy influences or conductors without a problem.

Personally I have never had any ill effects from nearby objects when using a standard balanced line. Gone are the days when cast iron down pipes and alloy gutters were used. Materials used to build houses are for the most part pretty good insulators; i.e. brick, wood, glass, plastic etc. I used a tuned line in one aerial system which lay for most of its length along a tiled roof ('Red-land' two and half lap tiles) which in winter would be subject to being covered with snow. During which time no noticeable difference was evident on any measurements taken at the transmitter end.

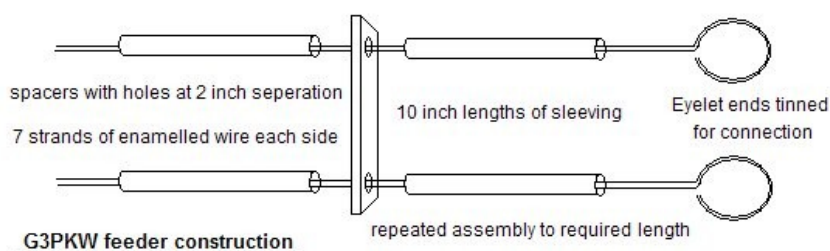
There are some commercially manufactured balanced feed lines available which come in various fixed surge impedance values. The most popular and cost effective types are 300 ohm ribbon and 450 ohm balanced line. Commercial 300 ohm

ribbon does suffer to a small degree when wet. Interestingly, in Europe VHF and UHF TV installations commonly used 300 ohm ribbon where-as here in Britain it is very rare to see ribbon. For the amateur transmitting aerial a purpose-built air spaced balanced line is preferred as it has such low losses that in many cases they are not even measurable, even over hundreds of feet. Some commercial and military LF aerial installations use a four wire feeder to reduce skin effect losses, this is done to allow the MOD and similar users to accommodate much lower frequency operation. The differences, from practical experience are not worth the huge effort required to make it for use on the amateur bands.

To emphasise a point concerning the efficiency of open lines, I would point out that some of the standard frequency transmission aerials as used at the old Rugby MSF (Mean Standard Frequency) station were situated several miles away, yes, miles from the transmitter hall. They used standard open wire line to deliver the power, without any noticeable loss! I hasten to say that these open lines were operated as flat lines at a constant 600 ohms. That might appear extreme but none of us wants to lose those precious watts that we have so painstakingly produced. Paying attention to all these small details is absolutely necessary to get the best results. From personal experience I have learned that such attention to detail will make a noticeable difference.

#### A suitable balanced feeder construction :

Described below is the open wire feed line that I assembled about thirty years ago and which is still currently in use here. This line has a particular freedom of movement, which I believe has enabled it to withstand high winds and weather stresses. May I remind constructors to take care to remove any burrs or sharp edges on holes drilled, which could cause the wire to fracture or break.



Prepare fourteen lengths of 22 gauge enamelled copper wire to the required

feeder length. Make up some plastic or acrylic strips and drill a three sixteenth hole at each end, with a spacing of about two inches, giving the spacers an overall length of about two and half inches. I normally separate them about ten inches apart, along the feeder and this is achieved using 3mm plastic sleeving cut to lengths of ten inches. Check that the enamelled wire that you are using is a neat fit with seven strands inside this sleeving. You may need to alter the sleeving diameter to effect a snug fit. Don't make it too tight because it needs to be able to slide over the full length of the wires. The number of spacers and separating sleeve pieces needed will depend upon the length of the feeder required. Thread the seven pieces of wire into the sleeve and fit onto one side of the separator. The reason for using seven strands is that it is a standard number used in flexible cables, such that six strands will neatly encompass the seventh central one. Continue this for the line length and for each side. This results in a very neat and efficient feeder capable of handling frequencies up to about 150 MHz. See accompanying picture of a constructed feed line. With the feeder assembled all that remains is to prepare the ends. This is done by cleaning the enamel off and forming the end into an eye shaped loop. This can then be tinned all over with solder and is now ready to attach to the radiator element.



A picture of the feeder as constructed : -



This method of feeder construction has been used for over thirty years and has survived during that time. The eyelet ends of the feeder and another eyelet formed on the end of the radiator element are compressed together in intimate contact using two suitable plastic spreader pieces furnished with two screws and nuts to tighten. This makes a very efficient low-loss connection. I would also recommend the fitting of some plastic spiral cable relief coils where the radiator emanates from the connecting point. This will reduce the risk of conductors breaking at their point of entry. This a well-known high failure point of any wire aerial system.

The radiator element is also constructed from multi-strands of enamelled copper wire. Normally seven strands is sufficient to enable good efficiency concerning losses, but if it is not too heavy, more could be accommodated or it could be separated out into a small caged element.

I wish to thank Brian G3GKG and members of the GOM group for their encouragement and suggestions while writing this text. With thanks to Roger G4ROJ for his assembly of a foil loop. Copies of Brian's text can be obtained via Email in PDF form from me :- ([Andy3PKW@Gmail.com](mailto:Andy3PKW@Gmail.com))

End of text