LECTURE NOTES FOR:

ENG4002M ANTENNAS: PRINCIPLES & PRACTICE
ENG3023M ANTENNAS & MOBILE PROPAGATION

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Introduction

- Copies of these notes are available in PDF format on Blackboard under the appropriate module code.

- There are 2 modules which share this 5 week lecture series: for the final year students as part of Antennas & mobile propagation and for the MSc students as part of Antennas: Principles & Practice.

- The structure and assessment for these two modules is as follows:

A&MP – 5 weeks of lectures on antennas followed by 6 weeks of lectures on mobile propagation. The assessment for the module will take the form of a 2 hour exam comprising of short and long questions and will be at the end of the semester.

A:P&P – 5 weeks of lectures on antennas followed by a computer lab series using antenna CAD software to design an number of antennas. The assessment for the module will take the form of a 1 hour multiple choice exam and 1000 word course work report based on the antennas CAD work. This will also be at the end of the semester.

- The main objective of the antennas lecture series is to provide you with an insight into the way antennas work from a conceptual point of view, rather than a deeply analytical one. You should also have an appreciation of why there are so many types of antennas of all shapes and sizes and to what purpose they are put.

You should, at the end of the lectures be able to see an antenna at the top of a mast or on a roof and be able to say 3 things about it:

1) The main characteristics of the antenna, hence the reason for it being of that particular design (configuration).

2) The approximate frequency at which it operates, if not that, then the frequency band in which it operates.

3) The most likely application of the antenna, eg: TV receiving antenna, mobile phone base station antenna, satellite uplink etc.

WHAT IS AN ANTENNA ?

In any wireless communication system, there is one component which fundamentally affects the performance of the system and if it is not working properly, then the system as a whole will not. This component is the antenna.

The primary function of an antenna is to couple RF power into free space at the transmit end and retrieve it again at the receive end, losing as little power and information as possible. Therefore, it can be said to be an **interface** device.

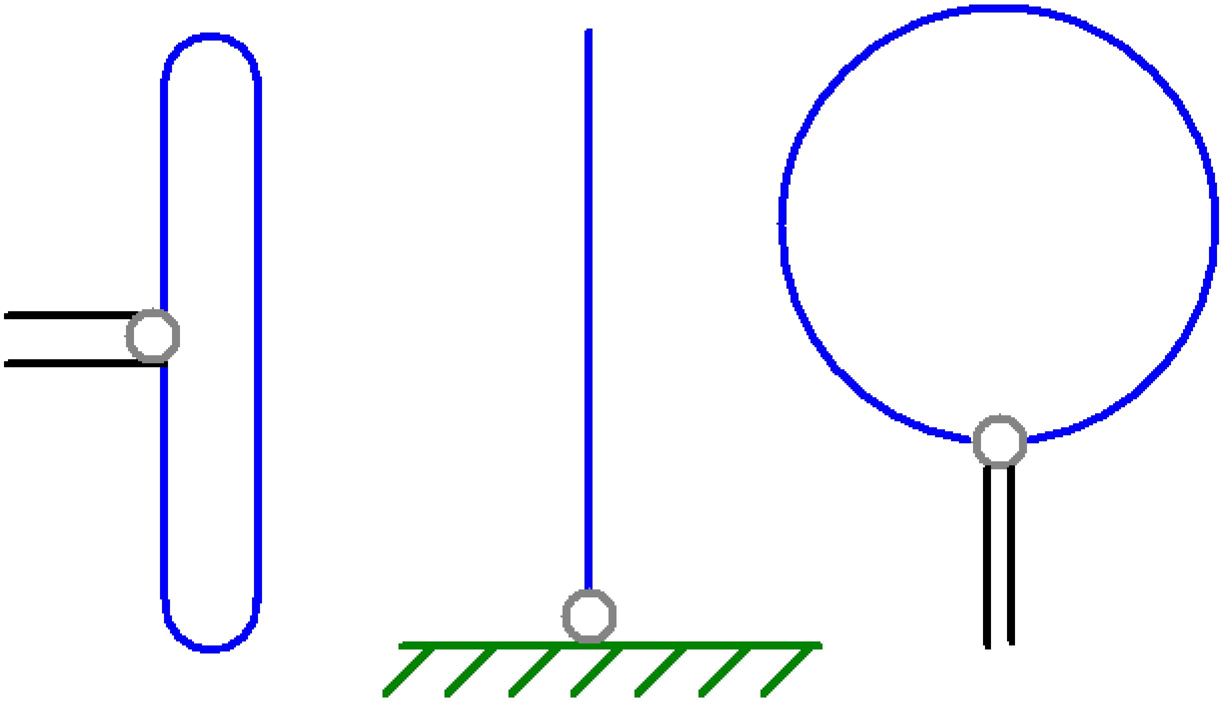
<u>Antennas</u> ***Lecture 1***

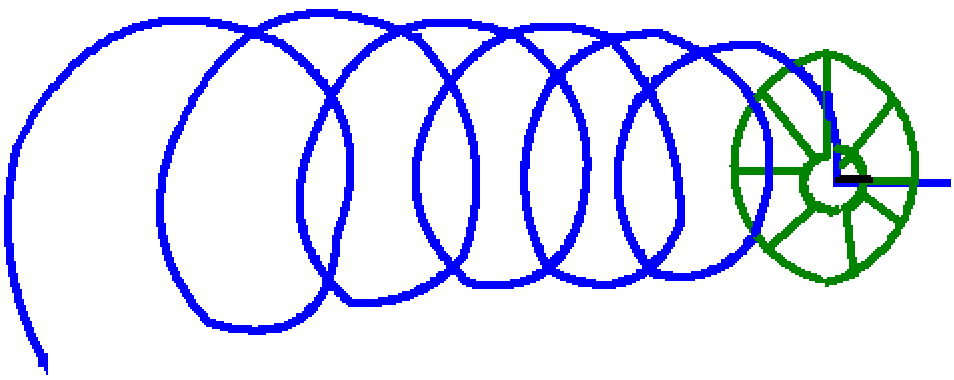
What do antennas look like and how many different types of antennas are there ?

There are 7 main types of antennas the grouping of which is based primarily on the way they operate, rather than the use to which they are put. The groups are as follows:-

1.Element antennas.

Element antennas consist of simple structures based on wires or rods (ie: the elements). A number of examples are shown below (L–R), dipole, monopole, loop and helix.





The defining characteristic of element antennas is that they are almost always resonant structures, and hence have dimensions which are commensurate with the signal wavelength.

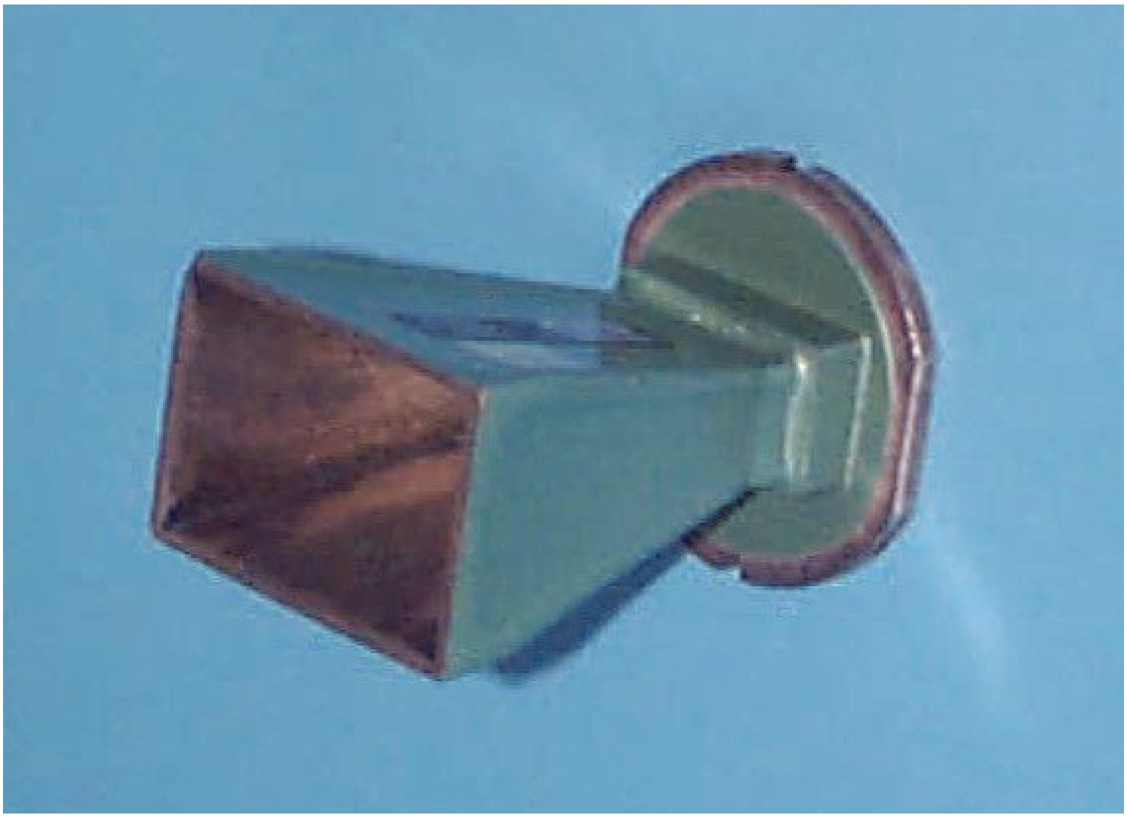
These antennas have a wide range of general characteristics with regard to gain, polarisation etc.

2.Aperture Antennas

This type of antenna is exclusively used with rectangular or circular waveguides, since they are formed in most cases, by flaring out the open end of a waveguide. This means that the frequency range is restricted to the UHF and microwave region.

The reason they are called aperture antennas is because the collecting area of the antenna (the aperture) is precisely defined by physical size of the "hole". However, **the aperture** of antenna is a term which is applied to all antennas and will be discussed later.

The figures below show some examples of aperture (or horn) antennas.

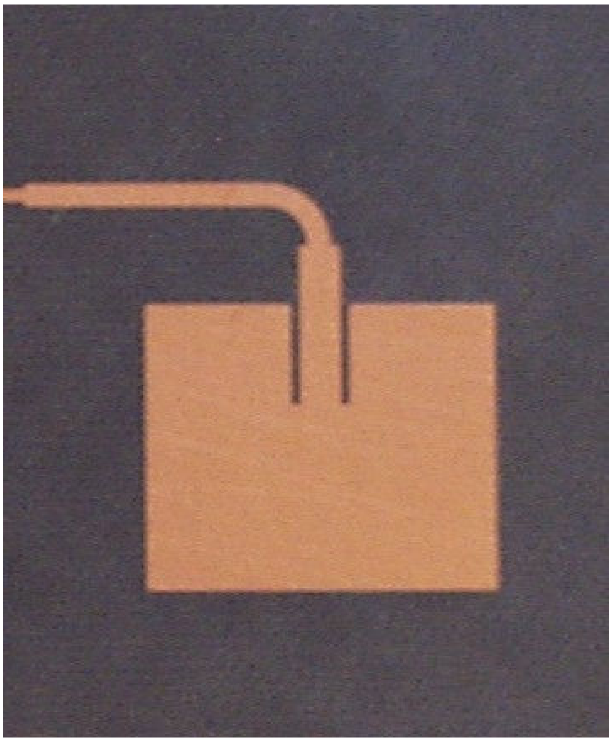


3.Printed Antennas

Printed patch radiators come in all shapes, sizes and configurations and are a subject in their own right. However the basic patch antenna consists of a metallic patch on a dielectric substrate whose shape is formed by the etching process. They also invariably use a ground plane on the underside of the substrate. Frequency ranges for this type of antenna are usually in the GHz region and they have a number of advantages over conventional fabrication methods such as:

- Cheap and easy to manufacture
- Light and robust
- Can be incorporated into existing structures ~ mobile phones aircraft etc.

An example of a of patch antenna is shown below:-



4.Reflector Antennas

Reflector antennas are utilise the fact that electromagnetic waves can be reflected to a focal point using a shaped metal plate. They usually take one of two forms i) the corner reflector ii) the parabolic reflector and are generally characterised by having very high gain. It should be pointed out that the reflector itself is not that antenna and therefore some form of conventional antenna is placed at the focal point of the reflector, eg a monopole.

The most widespread and obvious application of the parabolic (dish) antenna is of course the satellite receiving antenna. An example is shown below.

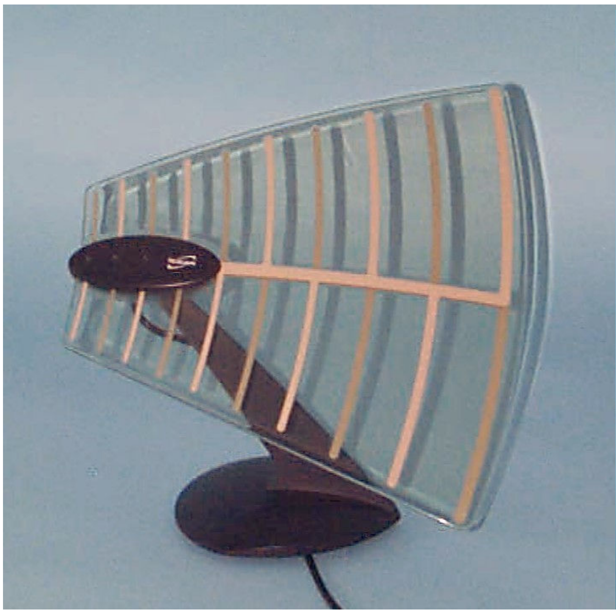
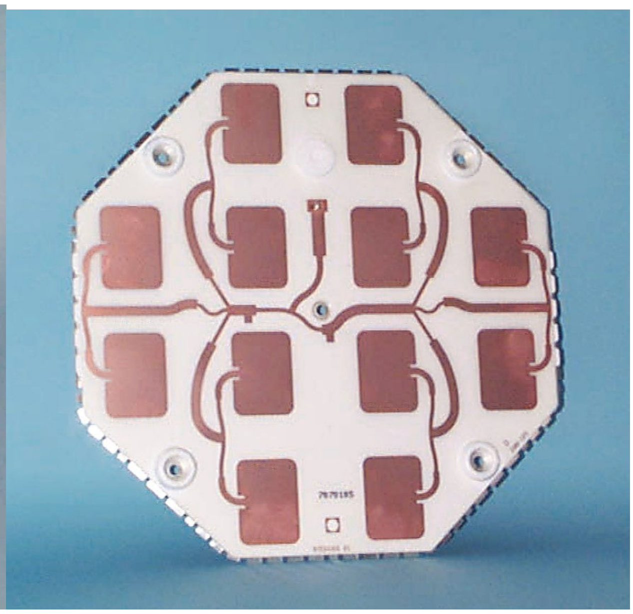
5.Array Antennas

An antenna array, as it’s name suggests is a collection of antennas arranged in such a way as to produce a radiation characteristic that would not be produced by a single antenna.

The array could consist of a number of simple antenna elements eg: dipoles arranged either in parallel or co-linearly, or both, to enhance the directivity and in some cases provide a means of main lobe steering.

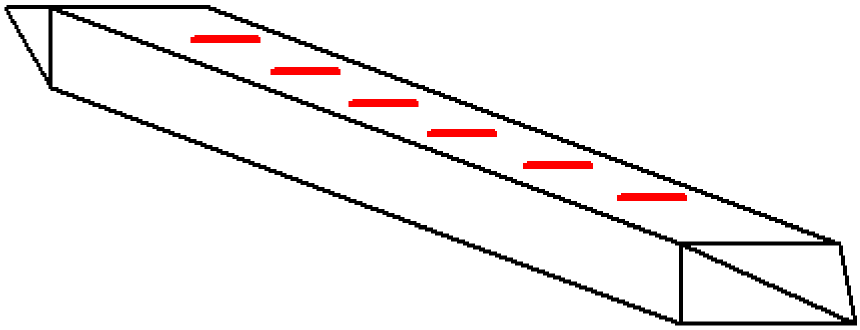
Virtually any type of element or patch antenna can be used in array and some even take the form of slots cut into a piece of waveguide.

Some examples of arrays are shown below. (L-R) log-periodic dipole array, and a microstrip patch array.

6.Leaky wave antennas

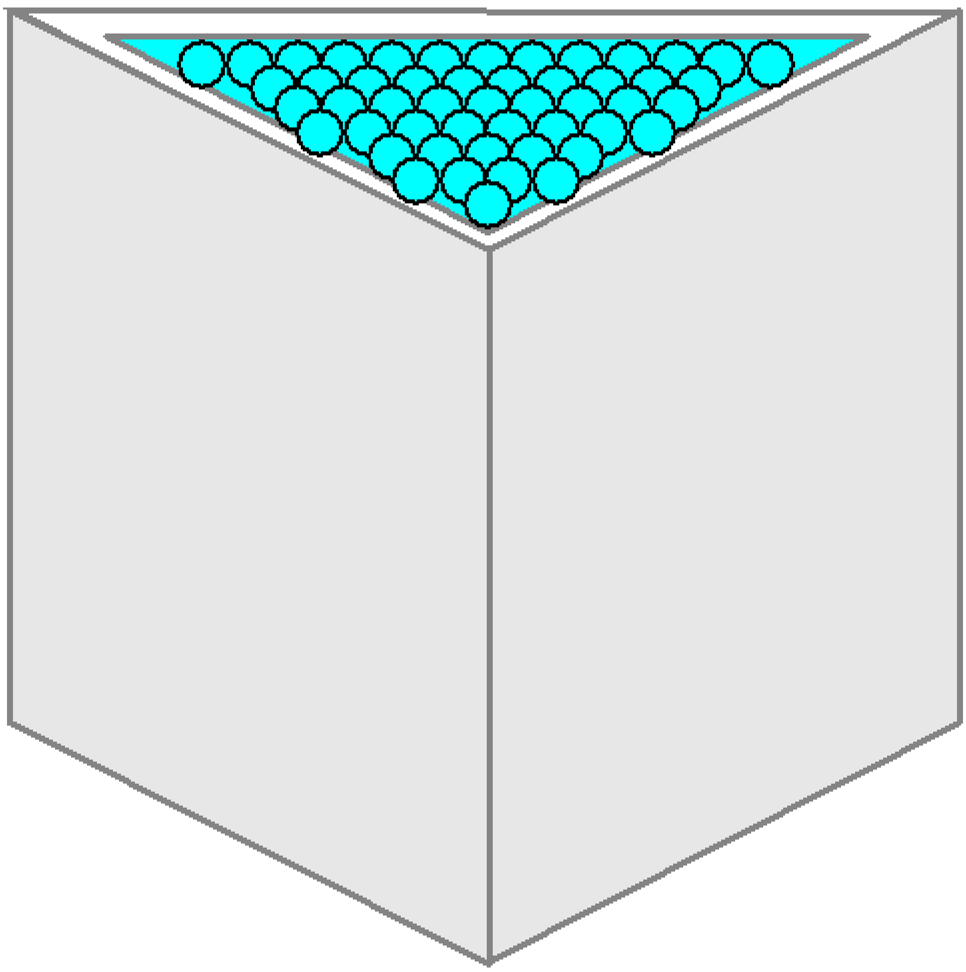
These are antennas formed from dielectric mm-wave guides and are predominantly used above 30GHz and up into the infrared region. They make use of the fact that radiation occurs from discontinuities in transmission lines which contain semiconductor devices. An example of such an antenna is shown below.



7.Lens antennas

Just as light can be refracted and collimated by a glass lens, so can microwaves, though it is usually only has practical applications above 10GHz, an example of this is poly-rod feeds which have been used on satellite dishes instead of horn feed, at 12GHz.

Glass is not used for the lenses because of the refractive index required at relatively long wavelengths, so plastic or wax is usually used. The figure below shows a microwave prism made using a foam mould containing styrene pellets.



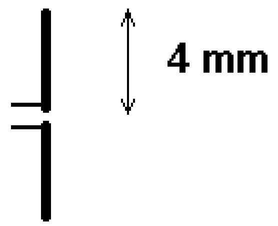
General properties

Frequency scaling

Any antenna will be designed to operate at particular frequency or range of frequencies and its physical size will in some way be related to that frequency. The most obvious examples of this are the element antennas whose defining characteristic is the element length which is generally a fraction of a wavelength. (eg: one arm of a dipole being $\lambda/4$ long)

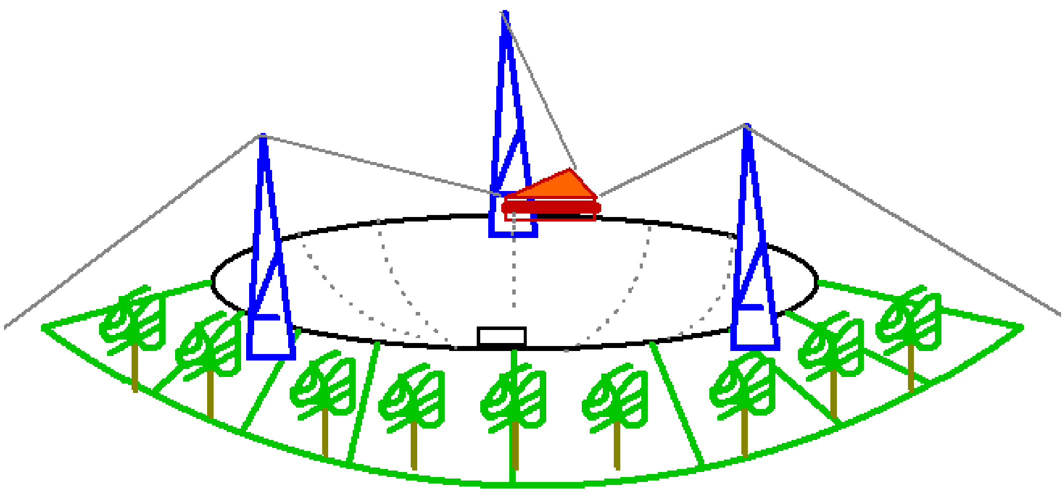
It stands to reason that all you would need to do in order to make an antenna work at different frequency (or wavelength) is to make the antenna either larger or smaller. Generally speaking this is precisely what you would do and it is termed **frequency scaling.**

An extreme example of this is again the case of the dipole antenna. Going from the smallest which is designed to work up to about 18GHz and whose length is just a few mm long (you can actually get them even smaller !), as shown below:



to the sort of antenna that you would need in order to communicate with a submarine at a depth of tens or hundreds of metres in sea. Since this would require extremely low frequencies in the range of 30 to 300 Hz and would require using a antenna which is hundreds of kilometres long (this has actually been tried !) as illustrated below.

This is scaling by a factor of about 100,000,000 and represents about the maximum you could expect to scale an antenna. Not suprisingly, most other antennas don't come anywhere near this in terms of scaleability, particularly complicated high gain antennas and this is mostly due to mechanical constraints rather than electrical ones. A good example of this is with parabolic dishes. With 76m being about the largest dish size you can have and it be still be fully steerable, any larger than that and it would need much more mechanical support as shown below with the 305m Arecibo dish, which is the largest dish in the world.



For anything more complicated, than simple wire antennas the maximum scaleability is somewhere between 100 and 1000.

The radio spectrum (note the most popular bands, λ !!)

Frequency	λ (fs)	Band	Applications
3-30 Hz	10^4 - 10^5 km	ELF	Detection of buried metals
30-300 Hz	10^3 - 10^4 km	SLF	Power transmission, submarine comms
0.3-3 kHz	100-1000 km	ULF	Telephone, audio (mid C @ 262Hz)
3-30 kHz	10-100 km	VLF	Navigation, positioning, naval comms
30-300 kHz	1-10 km	LF	AM broadcast (LW), navigation, beacons Time signals, Rugby etc: (66.6-75 KHz)
0.3-3 MHz	0.1-1 km	MF	AM broadcast (MW)
3-30 MHz	10-100 m	HF	Short wave, CB, model control, military
30-300 MHz *kHz* = 10^3 *Hz* *MHz* = 10^6 *Hz* *GHz* = 10^9 *Hz* *THz* = 10^{12}*Hz*	1-10 m *km* = 10^3 *m* *cm* = 10^{-2} *m* *mm* = 10^{-3} *m* *μm* = 10^{-6} *m* *nm* = 10^{-9} *m*	VHF	Short range devices (30-33 MHz) Radio mics, alarms, phones (47-50 MHz) Repeaters, beacons, amateur (50-60 MHz) Meteor burst, packet (70 MHz) Government (70-87 MHz) FM broadcast (88-108 MHz) VOR beacons (108-118 MHz) Aviation bands (118-137 MHz) Weather satellites NOAA (137-138 MHz) Government (138-144 MHz) Amateur (144-146 MHz) Taxis, marine comms (156-163 MHz) Short range devices (173-177 MHz) Digital audio broadcast (217-230 MHz) Space shuttle (259.7 MHz)
0.3-3 GHz	10-100 cm	UHF	Car alarm key fobs (418-420 MHz) Amateur (430-440 MHz) Government, emergency (450-470 MHz) Private mobile radio (446 MHz) Television broadcast (470-854 MHz) Cordless phones (863-865 MHz) GSM mobile phones (935-960 MHz) Aviation transponder (1.03-1.09 GHz) Global positioning, GPS (1.576 GHz) Satellite phones, Iridium (1.61-1.627 GHz) Weather satellite, Meteosat (1.69-1.71 GHz) PCN mobile phones (1.805-1.877 GHz) 3G mobile phones (1.9-2.025 GHz) Bluetooth digital SRD (2.402-2.48 GHz) ISM band, microwave oven, W-LANs (2.45GHz) S band surveillance radar (2.7-2.9 GHz)
3-30 GHz	1-10 cm	SHF	Radio internet access (3.425-3.49 GHz) Satellite TV, C-band (3.675-4.2 GHz) Hiper-LANs, telemetry, ISM (5.655-5.945 GHz) Police radar, alarms, X-band (10.7 GHz) Satellite TV, Ku-band (10.7-12.7 GHz) Amateur (24 GHz)
30-300 GHz	0.1-1 cm	EHF	Amateur, mm waves (40-240 GHz)
0.3-3 THz	0.1-1 mm	mm	Astronomy, meteorology
1-100 THz	3-300 μm	I.R.	Heating, night vision, optical comms
395-770 THz	390-760 nm	Visible	Vision, optical comms, surgery

Reciprocity

When we consider a particular antenna, we generally think about it in a particular application and usually this means that it is used either to transmit or receive a signal. However, in virtually every situation an antenna that is used for transmitting will be equally good at receiving the same signal and vice-versa, they will even have the same characteristics in either mode.

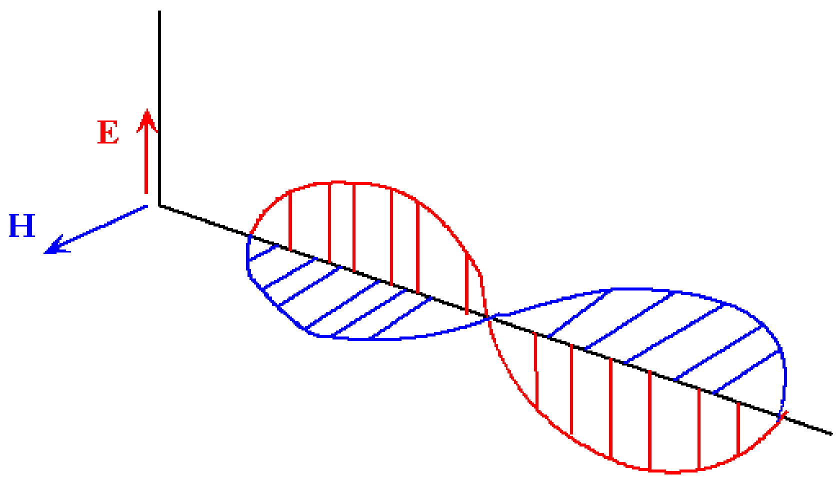
The only situations where reciprocity may not apply are:

- Where the transmit and receive power levels were massively different. For instance if you were broadcasting a signal at very high power levels (kW or MW) then you would certainly have to consider insulation breakdown problems and would not be able to use a standard receive antenna.
- The case of ferrite rod receiving antennas. These are also known as magnetic antennas and are used at long and medium waves. This type of antenna would be no good as a transmitting antennas (to any effect).

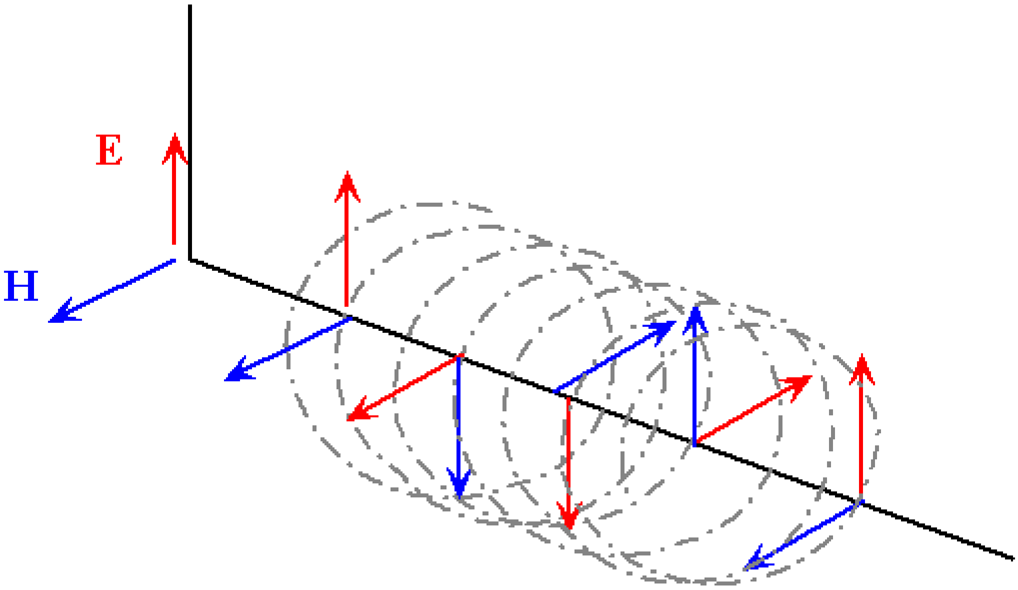
Polarisation

The polarisation of an electromagnetic wave is determined by the orientation of the electric field vector. In general terms there are two types of EM wave polarisation, linear and circular.

With linear polarisation there can horizontal (H) or vertical (V). The polarisation is determined by the propagating antenna eg: a dipole, in this case vertically oriented and hence vertical polarisation.



With circular polarisation there can be left-hand (LH) and right-hand (RH). This form of polarisation is generated by antennas that put a spin on the EM wave as it is launched e: a helical antenna.
The figure below shows a circularly polarised EM wave. And from the perspective of the antenna it is RH polarisation (clockwise).



It is possible to have elliptically polarised radiation, but this is usually accidental, unwanted and is usually the result of the electric field vectors being of different magnitudes in the horizontal and vertical planes, for whatever reason.

In terms of the performance of antennas with different polarisation, the table below shows the results of mixing polarisation and gives an indication as to what can and cannot be done. For example it is quite possible to receive a circularly polarised signal using a dipole, which is linearly polarised, and only lose about half of the signal power (-3dB).

Transmit Pol'n	Receive Pol'n	Loss (theory)	Loss (practice)
Vertical	Vertical	0	0
Vertical	45 deg	-3dB	-3dB
Vertical	Horizontal	∞	-20dB
Vertical	Circular (R or L)	-3dB	-3dB
Circular (RH)	Circular (RH)	0	0
Circular (RH)	Circular (LH)	∞	-10dB

What is the function of antennas, why and how do they radiate ?

An antenna is a structure, which when connected to a radio frequency system, enables electromagnetic waves to be radiated into, or received from, free space. In other words it is an interface device.

Fig.1 shows a standard representation of an electromagnetic wave propagating in free space. **Fig.2** shows a generalised view of an antenna it's transitional role.

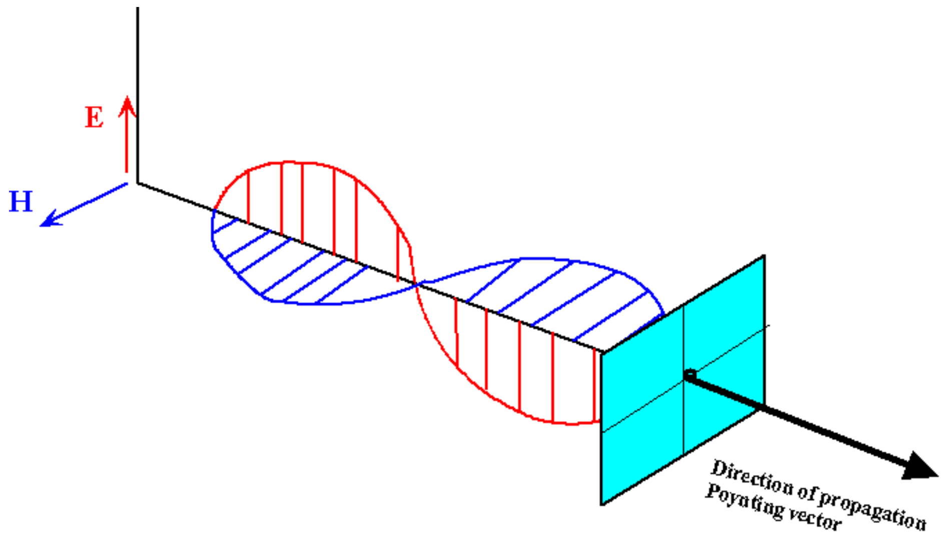


Fig.1 An electromagnetic wave

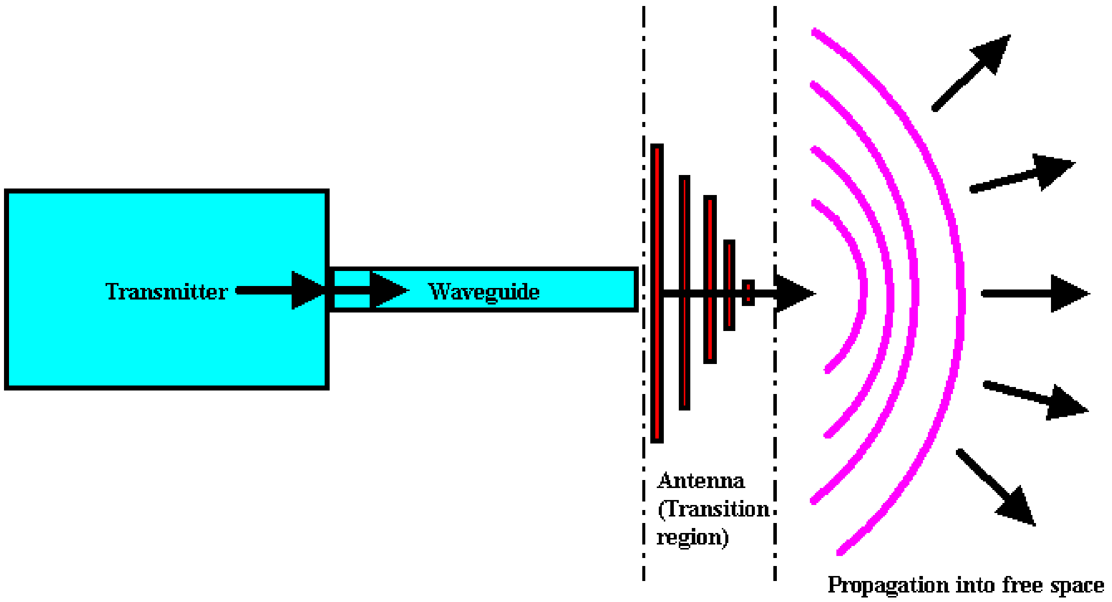


Fig.2 An antenna as a transition device

- In order for radiation to occur, a charge travelling along a wire / transmission line has to be subject to acceleration. It will not radiate whilst in uniform motion.

- Acceleration of a charge can be achieved in a number of ways.

  i) Leaving the wire un-terminated (ie: open ended)
  ii) Bending the wire
  iii) Using an alternating current (signal changing direction)

Fig.3 Shows the different ways a wire can radiate.

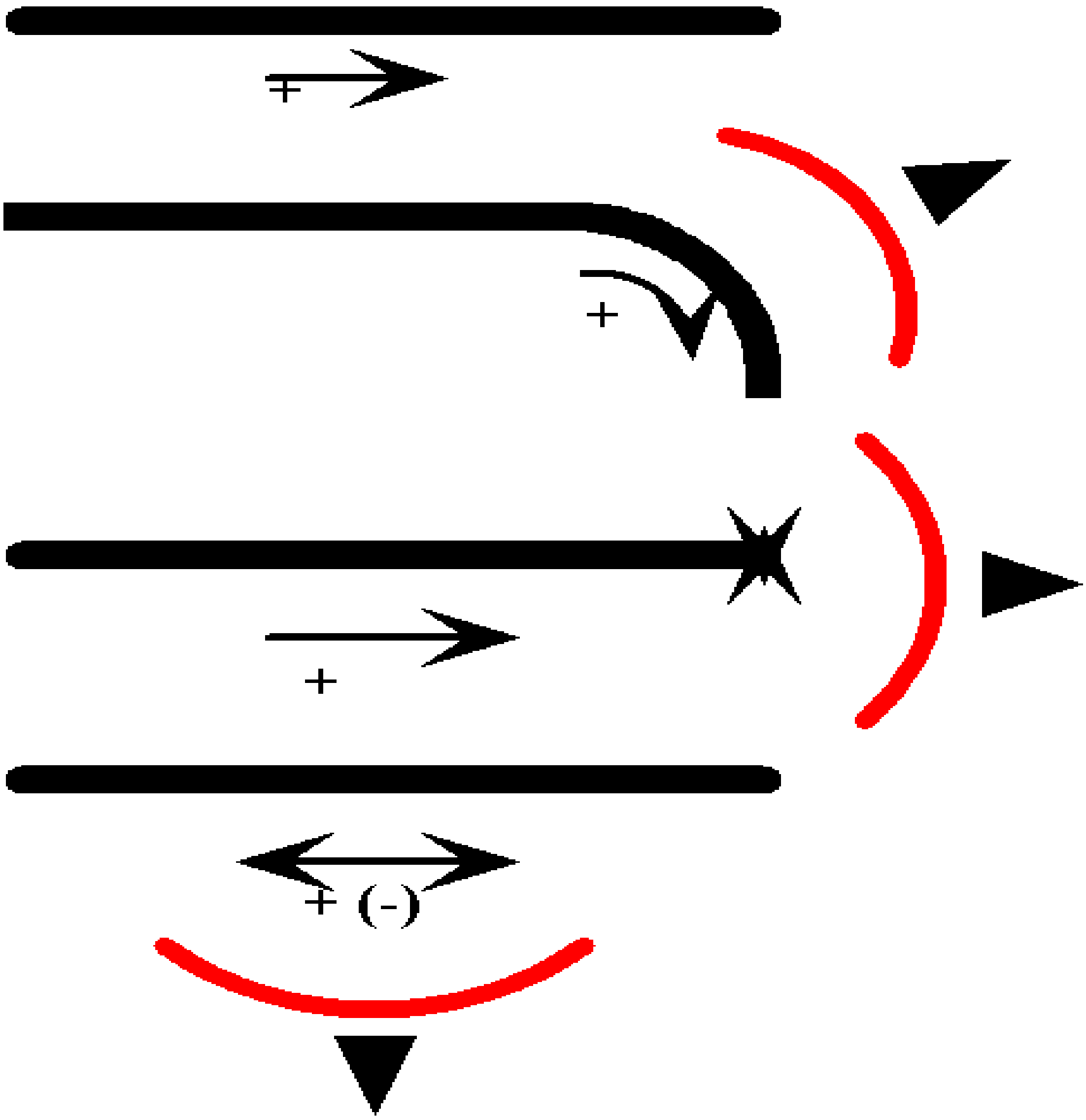


Fig.3 Wire radiating mechanisms

In the case of a twin wire transmission line as shown in **Fig.4** the parallel lines will not radiate because the currents are travelling in opposite directions and therefore will cancel. However when the lines are bent outwards the **E** fields tend to reinforce each other rather than cancel the net effect is to produce radiation.

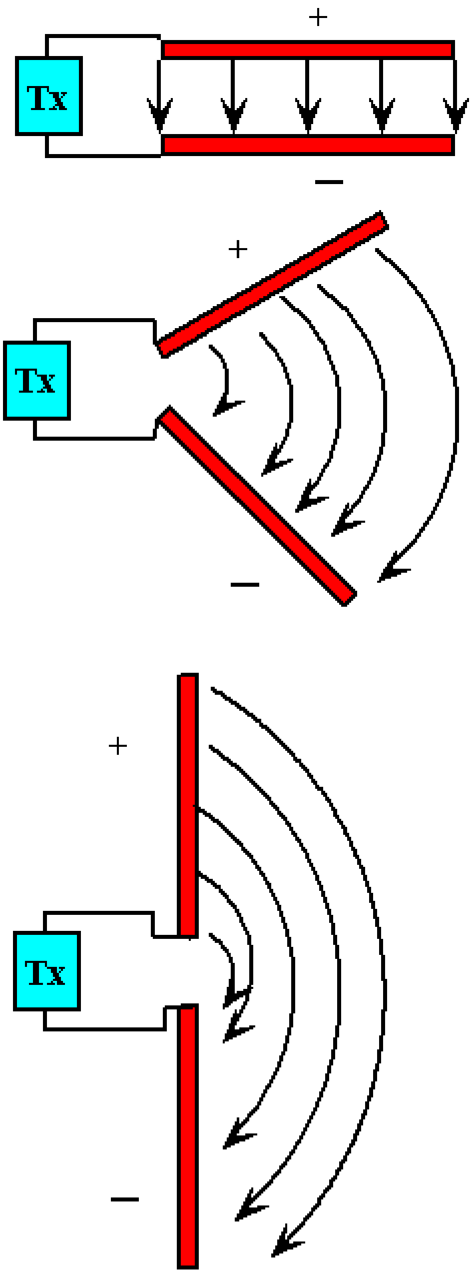


Fig.4

The charge and current distribution will produce both electric and magnetic fields as shown in **Fig.5.**

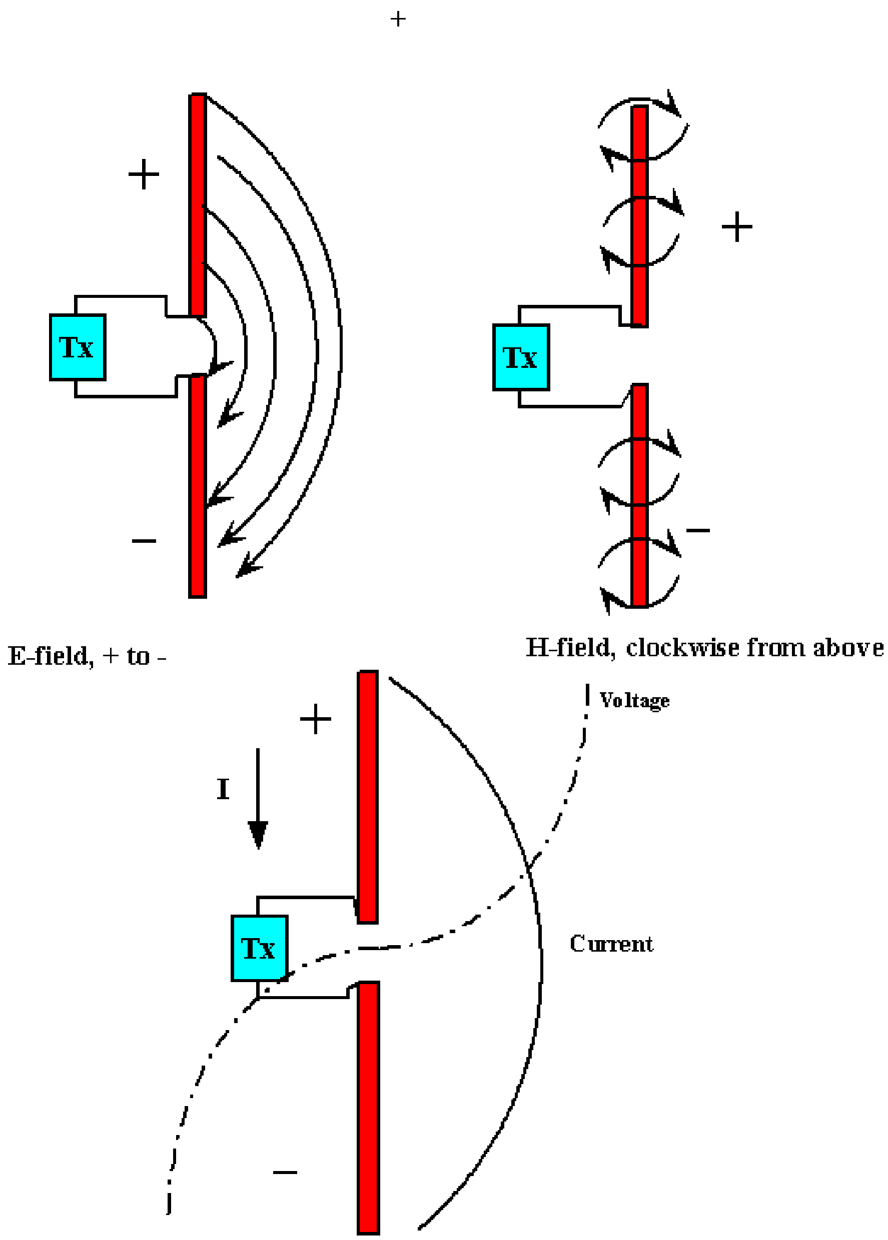


Fig.5

If an **alternating current** is applied the to the flared out wires, called a dipole, then the fields generated also alternate, as you might expect.

When the charges at the ends of the dipole are at a maximum the current is at a minimum. As these charges collapse, the current flows back along the wire element, bringing with it the electric field lines. Since this occurs at both ends of the antenna a situation if reached, where the charges cross over at the mid-point of the antenna, where the field line detaches and propagates away from the antenna at the speed of light. **Fig.7** shows the sequence of events.

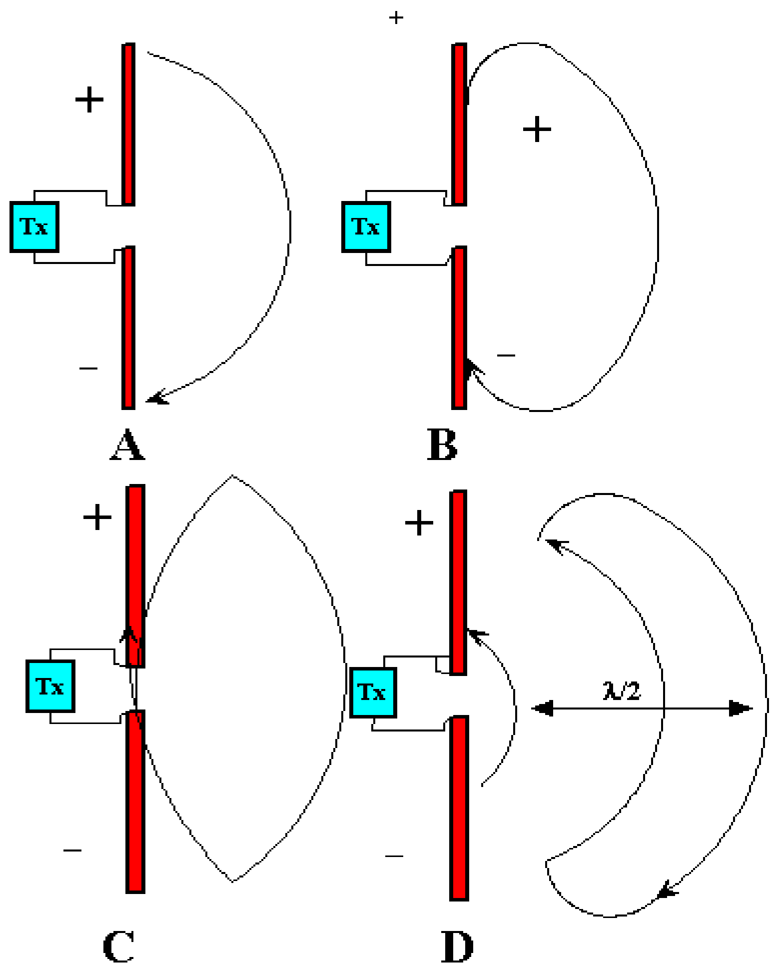


Fig.7 Formation of field lines

In the case where the dipole is exactly λ/2 long (ie: each element is λ/4 long) then standing waves are created on the elements, this condition is called **resonance**. It occurs because the current falls to zero at the ends of the dipole elements and is a maximum at the centre, conversely the voltage is at its maximum at the ends of the elements and therefore total reflection occurs at the element ends. If the antenna is not exactly λ/2, then it will still work, but will not be as efficient as a resonant antenna.

Just a brief word about **Maxwell's Equations.**

In order to understand the interaction between magnetic and electric fields, a model was devised to predict the existence of the observed phenomenon of electromagnetic waves. It takes the form of 4 equations derived from ideas put forward by Faraday, Ampere and Gauss. These equations are shown below and are in the form of vector differential equations in the time-domain.

$\nabla \bullet \mathbf{D} = \rho$	Gauss' electric law
$\nabla \bullet \mathbf{B} = 0$	Gauss' magnetic law
$\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$	Faraday's law
$\nabla \times \mathbf{H} = \mathbf{J} + \partial \mathbf{D}/\partial t$	Ampere's law

Where:-

ρ = volume charge density [C/m^3]

E = electric field intensity [V/m]

B = magnetic flux density [Wb/ m^2 or T] $\mathbf{B} = \mu_0\mathbf{H}$

t = time [s]

D = electric flux density [C/m^2]

H = magnetic field intensity [A/m]

J = electric current density [A/m^2]

∇ = divergence operator (div)

ie: $\nabla \bullet \mathbf{D} = \partial D_x/\partial x + \partial D_y/\partial y + \partial D_z/\partial z$

$\nabla \times \mathbf{E}$ = the curl of the electric field (curl ***E***)

ie: $\nabla \times \mathbf{E} = \mathbf{a}_x(\partial E_z/\partial y - \partial E_y/\partial z) + \mathbf{a}_y(\partial E_x/\partial z - \partial E_z/\partial x) + \mathbf{a}_z(\partial E_y/\partial x - \partial E_x/\partial y)$

Maxwell equations are fundamental to the analysis of electromagnetic waves. However, the scope of this course does not really allow for further examination of the detail of the equations and we shall not be pursuing them any further. If you wish to investigate Maxwell's equations in detail, then there are many very good references available.

Most sophisticated antenna calculations are done using an electromagnetic field solver program on a computer. (Which almost always use Maxwell's equations for the analysis).

The near and far field regions.

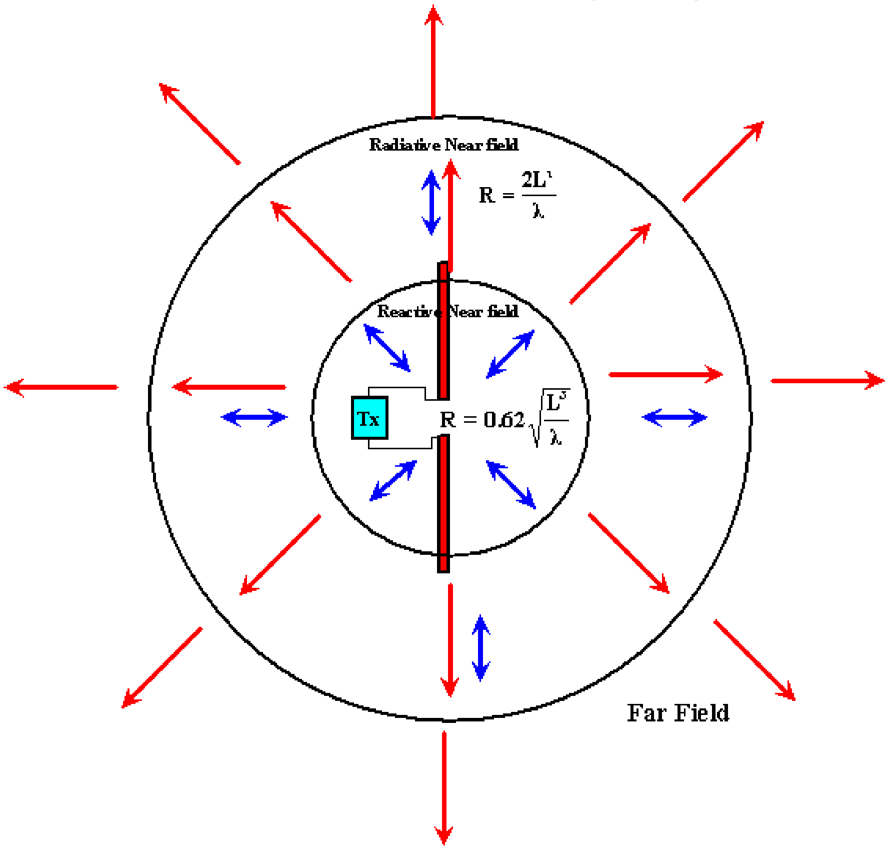
Very near an antenna, the electric and magnetic fields change rapidly depending on the exact distance from the antenna. This energy takes the form of both radiating energy and reactive energy.

The term reactive refers to the fact that the mutual coupling that occurs, between a transmitting and receiving antenna when they are very close, can be either capacitive or inductive.

This reactive near field is sometimes called the **induction field**, meaning that the magnetic field usually is predominant over the electric field in this region. The antenna acts as though it were a rather large, lumped-constant inductor or capacitor, storing energy in the reactive near field (like a transformer) rather than propagating it into space.

For simple wire antennas, the reactive near field is considered to be within about a half wavelength from an antenna's radiating centre. The strength of the reactive near field decreases in an inverse cube law as you increase the distance from the antenna.

Beyond the reactive near field, the antenna's radiated field is divided into two other regions: the radiating near field and the radiating far field, these have proper names which are the **Fresnel** and **Fraunhofer** regions, respectively. The figure below shows the near and far fields around a simple dipole.



Even inside the reactive near-field region, both radiating and reactive fields coexist, although the reactive field predominates very close to the antenna and decays with a $1/r^3$ law, whereas the radiating near field decays with a $1/r^2$.

The reactive near field extends to a distance given by the equation:

$$\mathbf{R = 0.62\sqrt{\frac{L^3}{\lambda}}}$$

Because the boundary between the fields is rather "fuzzy," there is debate as to where one field begins and another. However the generally accepted definition of where the near field finishes and the far field starts is based on the equation:

$$\mathbf{R = \frac{2L^2}{\lambda}}$$

Where **R** is the distance from the antenna, **L** is the largest dimension of the antenna in the same units as λ the wavelength. In the far field region the radiation decays with a 1/r law.

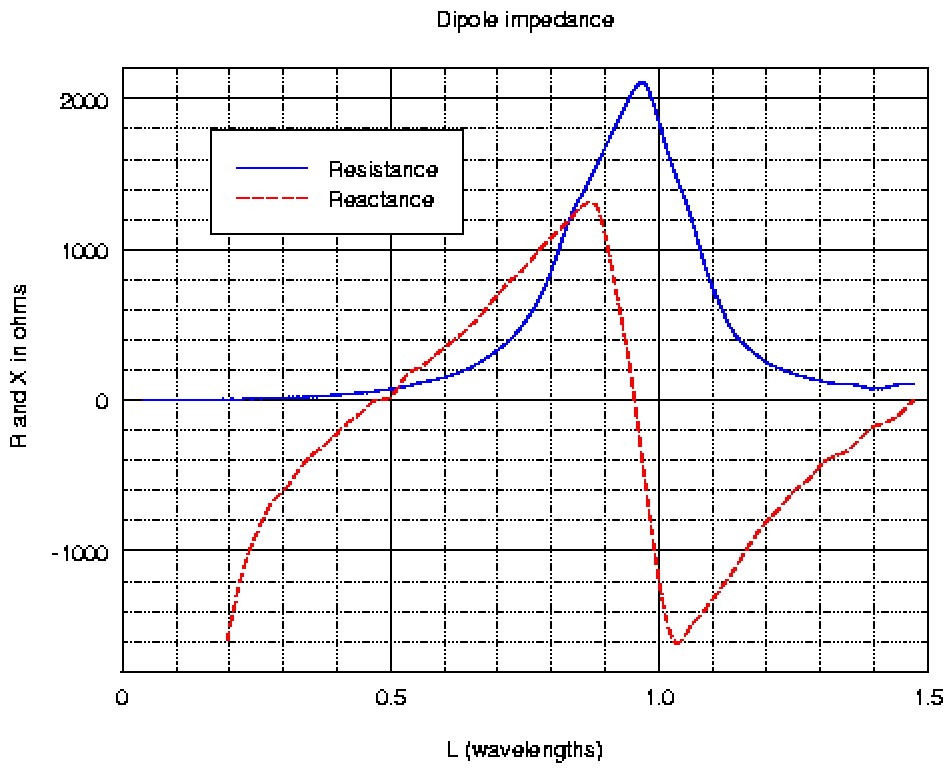
In all subsequent considerations of antennas we shall only be considering the radiating far fields.

It is interesting to note that in the reactive near field, the loading of the receiver antenna will determine how much power is ‘drawn’ from the transmit antennas. However, in the radiating field this is not the case, since the energy is completely released by the antenna and no matter how many receivers collect that signal, it will have no effect whatsoever on the transmitter output.

Input impedance and radiation resistance.

If you consider an antenna as being a component bolted onto an RF system, then there will be certain characteristics which will directly affect the amount of power transferred to the antenna and then radiated away.

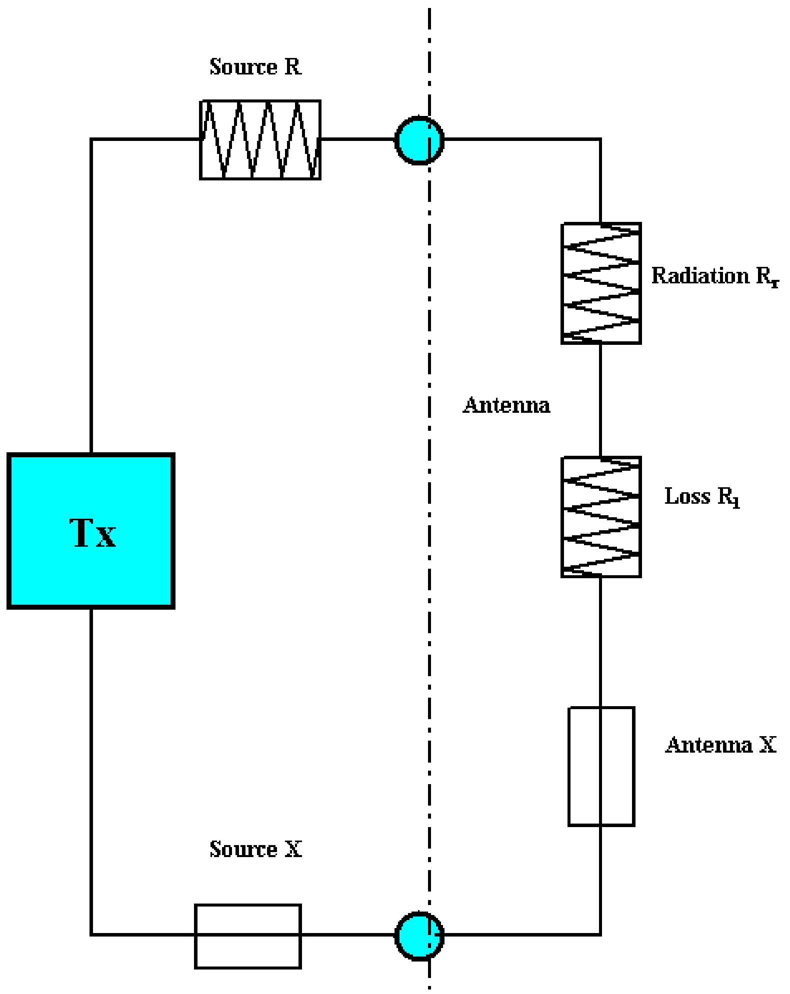
The current supplied to an antennas terminals must be supplied at a finite voltage. This means that the **input impedance** of the antenna, is simply the voltage divided by the current. The figure below shows a typical input impedance graph for a dipole antenna.



Where the current and voltage are exactly in phase, the impedance is purely resistive, with zero reactive component.
In this particular case the antenna is termed resonant. However, you should be aware that an antenna does not have to be resonant in order to radiate. But if it isn't, then some form of impedance matching circuit will be required. This can sometimes be beneficial since the antenna can be used on multiple frequency bands.

It is important to consider an antenna and its feed line as a system, in which all losses should be kept to a minimum.
At all frequencies except one, where it is truly resonant, the current in an antenna is at a different phase compared to the applied voltage. In other words, the antenna exhibits a feed-point impedance, not just a pure resistance.

The feed-point impedance is composed of either capacitive or inductive reactance in series with a resistance. The figure below shows the equivalent circuit of an antenna connected to an RF system.



The resistive part of the antenna impedance is split into two parts, a **radiation resistance** R_r and a loss resistance R_l. The power dissipated in the radiation resistance is the power actually radiated by the antenna, and the loss resistance is power lost within the antenna itself. This may be due to losses in either the conducting or dielectric parts of the antenna.

Since only the radiated power normally serves a useful purpose, it is useful to define the radiation efficiency **e** of the antenna as:

$$e = \frac{Power\_radiated}{Power\_accepted} = \frac{R_r}{R_r + R_l}$$

An antenna with high radiation efficiency therefore has high associated radiation resistance compared with the losses. The antenna is said to be resonant if its input reactance $X_a = 0$.

If the source impedance, $Z_s = R_s + j X_s$ and the total antenna impedance, $Z_a = R_r + R_l + j X_a$, are complex conjugates, then the source is matched to the antenna and a maximum of the source power is delivered to the antenna. If the match is not ideal, then the degree of mismatch can be measured using the voltage standing wave ratio (VSWR), or by the reflection coefficient, Γ, defined by:

$$\Gamma = \frac{V_r}{V_i} = \frac{Z_a - Z_s}{Z_a + Z_s}$$

where V_r and V_i are the amplitudes of the waves reflected from the antenna to the transmitter and incident from the transmitter onto the antenna terminals, respectively.

It is therefore not suprising that it is common practice to design antennas to have an input impedance of either 50 Ω or 75 Ω, to match commonly available coaxial feed cables.

Antenna height

Whenever we consider the impedance and radiation characteristics of an antenna, we always make the assumption that the antenna is in *Free Space.* That is, the antenna is a very large distance away from any other large object, particularly the ground.

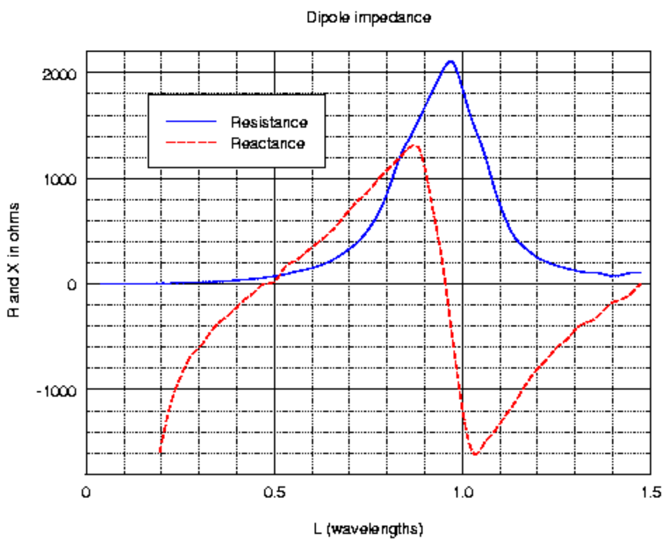
This is because close proximity to a large object such as the ground, will have a major effect on the aforementioned characteristics, and thus will be unrepresentative in terms of characterisation for a particular antenna.

This is a rather complicated field and is well documented in most text books for further reading. However, in simple terms, it can be stated that to sure that an antenna is in free space it should be at least 10λ away from (above) the ground, hence the expression *antenna height.*

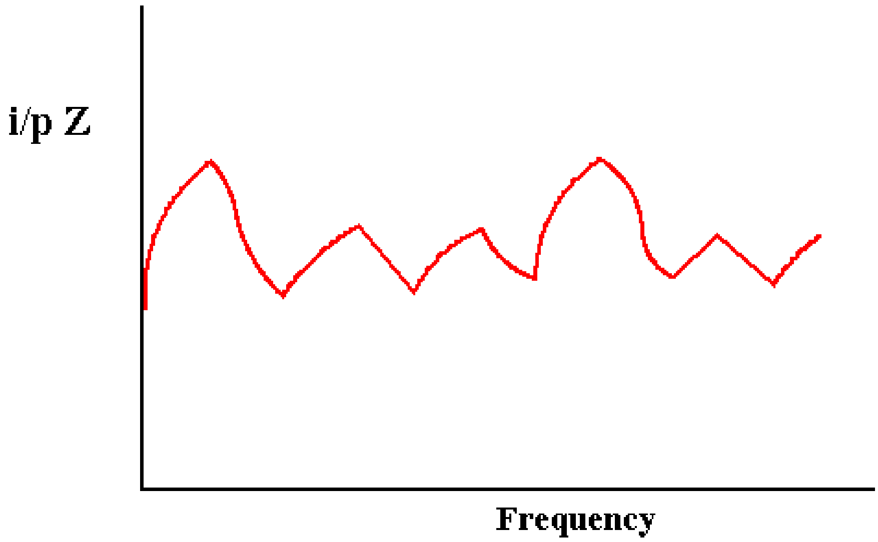
Bandwidth, matching and frequency dispersion.

The principle characteristic in determining the bandwidth of an antenna is the input impedance. It is usually desirable to have this at a value of either 50 Ω or 75 Ω, making it easy to connect to an RF system which has the same input or output impedance.

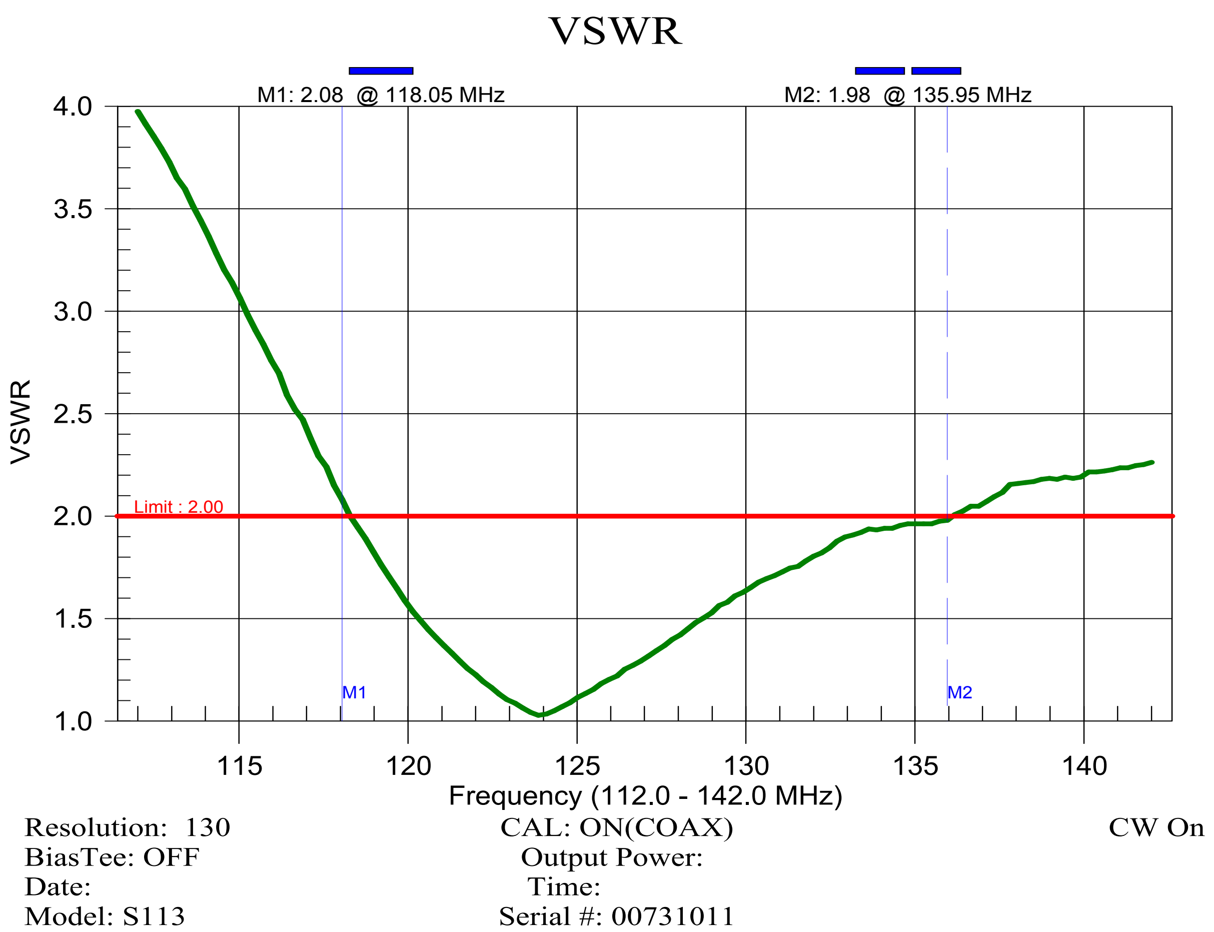
In the case of a dipole, the input impedance is only close to 75 Ω over a very narrow band, as seen in the impedance plot below and corresponding to half a wavelength.



A broadband antenna (by design) such as the log-periodic has an impedance plot, which is a lot like (not suprisingly) a train of dipole impedance peaks.



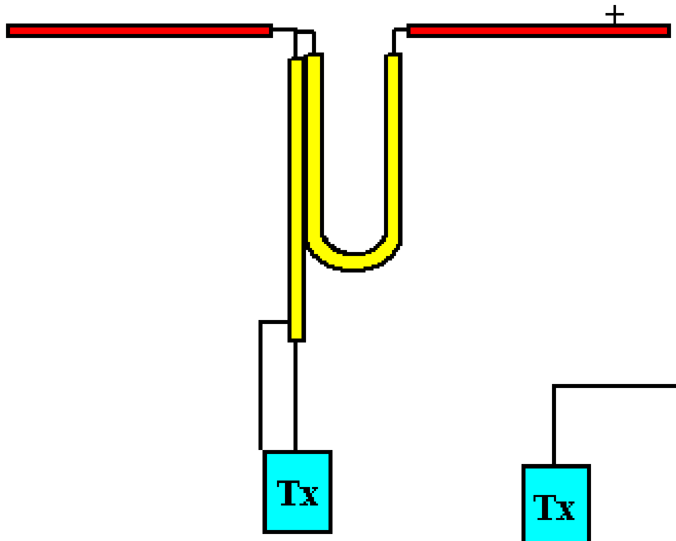
The impedance plots show the resistance and reactance characteristics at a given frequency, but do not directly indicate how well the antenna is matched to the system. In order to obtain a numerical value of the quality of the match, direct measurements are made of the antenna using an impedance analyser, which would typically give a graph as shown below; in this case it is showing VSWR (voltage standing wave ratio).

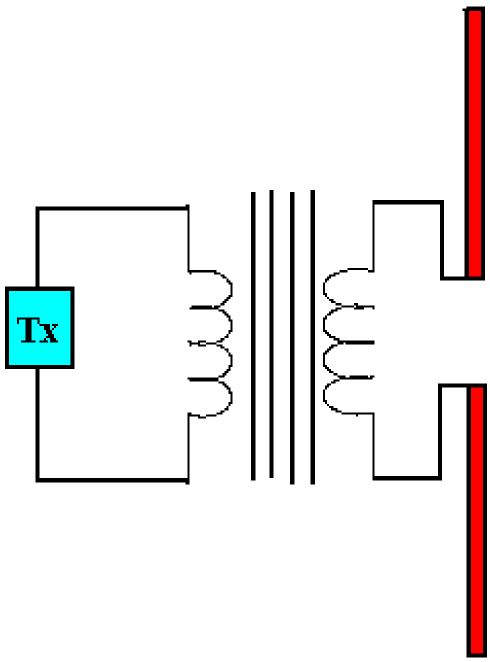


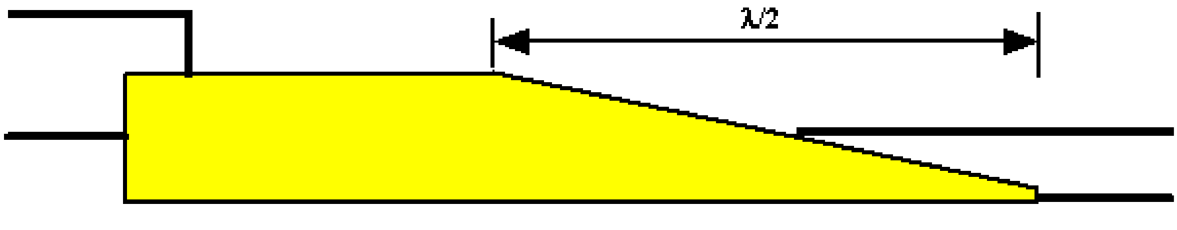
It is generally accepted that and antenna is reasonably well matched if the WSWR is less than 2; which in return loss terms means smaller than -10dB.

This figure means that 90% of the signal being applied to the antenna would be absorbed (though not necessarily radiated), with only 10% being reflected back to the source.

If antenna match is 'worse' than the figure indicated above (VSWR larger than 2), then you would need a matching network in order to have reasonable power coupling into the antenna. There are various techniques for matching antennas, some of which are shown below, the most common being stubs and transformers. However a tapered transmission line can be used for very broadband applications. Matching circuits often perform two functions, 1/ to match the transmitter and antenna impedances, 2/ to transition from unbalanced (coaxial cable) to balanced (antenna) transmission and is called a BALUN.



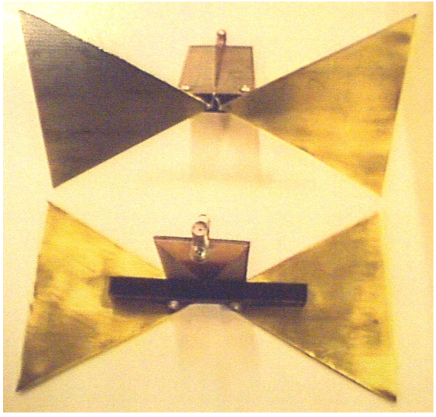


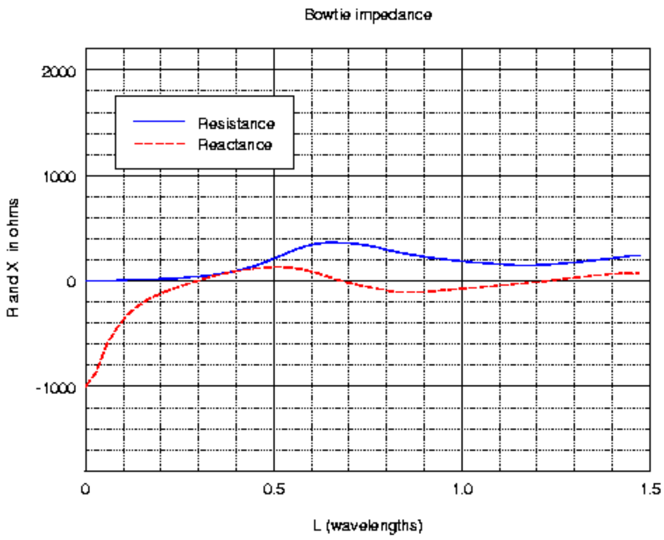


The reason that a single dipole has such a narrow bandwidth is because of the very high Q (reactance divided by resistance), and it is also the reason why it is very efficient.

There are two main ways increase the bandwidth of an antenna:

Decrease the Q, in the case of a dipole by making the elements larger in diameter or expanding them into triangles ie: the bow-tie configuration, giving the impedance plot as shown below.

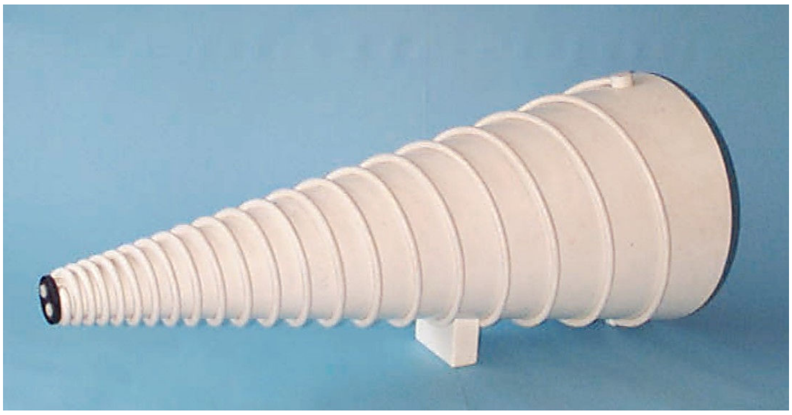


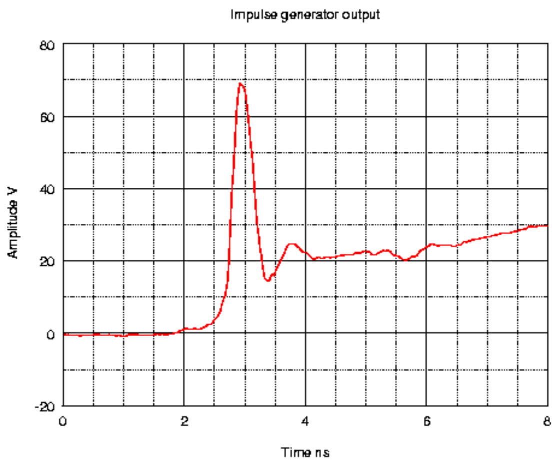


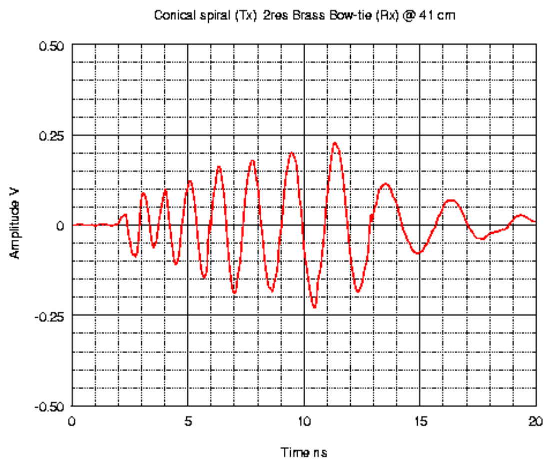
This particular antenna has a bandwidth approaching two octaves (600 MHz to 2400 MHz) however it is quite inefficient, about 45%, compared to a conventional dipole with 98%. This due to the fact that the radiation resistance is a lot lower in comparison to the loss resistance.

The other main way to increase the bandwidth of an antenna design the antenna to work at multiple bands, as with the log-periodic, or the ridged horn. However, it should be borne in mind that this type of antenna is really only designed to work with one frequency at once. When using a multi-element wideband antenna for propagating a signal with a very high spectral content, such as a narrow pulse, you get an effect called **frequency dispersion**. Dispersion occurs when components of an electromagnetic wave have different delays when passing through a media. A classic example of this is the optical prism, in this case the spectral components with a shorter wavelength (blue) are refracted more than are those with a long wavelength (red).

In the case of antennas the effect is to break apart the pulse into its spectral components, with different components arriving at different times. A good example of this is the use of a log conical spiral antenna used to propagate an impulse, as shown below. First is shown the impulse and then the received signal after having been transmitted by this antenna.







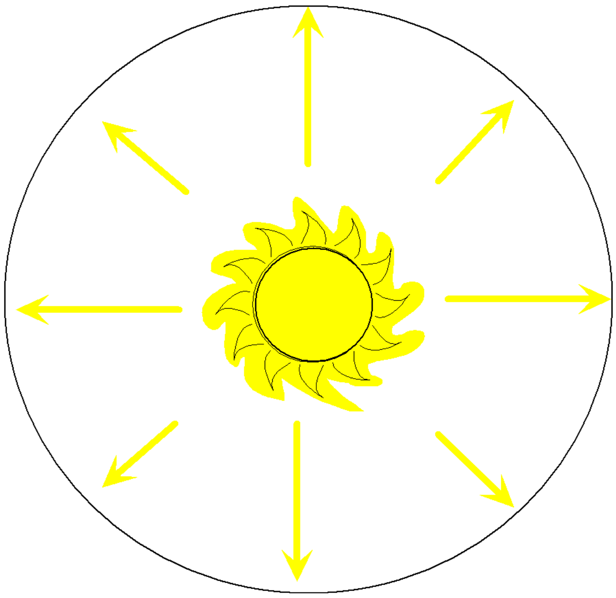
Frequency dispersion in antennas is almost always due to the physical geometry of the antenna and it is usually possible to predict the degree of dispersion by making some accurate measurements of the antenna's dimensions.

In general use however, dispersion is not a problem since the antenna will only be operating at one frequency at any particular time.

Antennas *Lecture 3*

Why do antennas radiate in certain directions and not in others ?

If we think about a point source of radiation, for example the sun, we find that it radiates in all directions with equal intensity, as shown in the figure below.



This type of radiator is termed an **isotropic radiator** and the radiated power density (W / m^2) is solely dependent on the distance away from the radiator with the relationship $\mathbf{P_r = P / 4\pi r^2}$.

In reality is impossible to construct an isotropic antenna, however it is a very useful starting point when considering the radiating properties of antennas in general, since it provides a reference point by which other antennas can be compared.

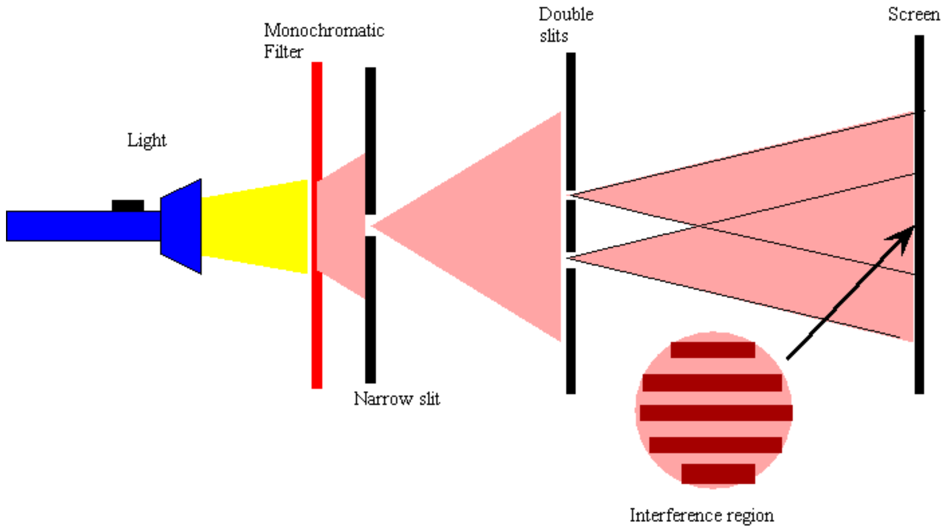
Every type of practical antenna has a **radiation pattern** associated with it. This is a graph of radiated power (ie: field strength) against angle. Almost always the pattern for an antenna is a **far field** pattern and is completely independent of the distance from the antenna, therefore representing a relative measurement.

There are normally two patterns, one for the **E** plane and one for the **H** plane.

For any practical antenna there are two ways of obtaining the radiation patterns. The first one is measure the pattern with purpose made test rig. The other way is analyse the antenna mathematically then to calculate the radiation pattern.

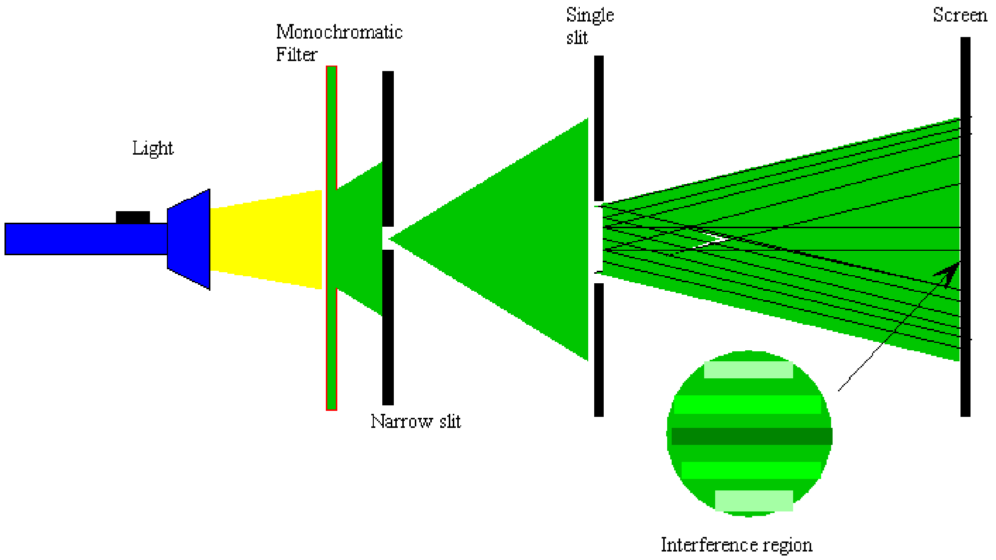
We shall look at the radiation from an antenna in two ways, the first, is in terms of optical diffraction and the second, is a more analytical approach.

The figure below shows a typical Young's double slit experiment

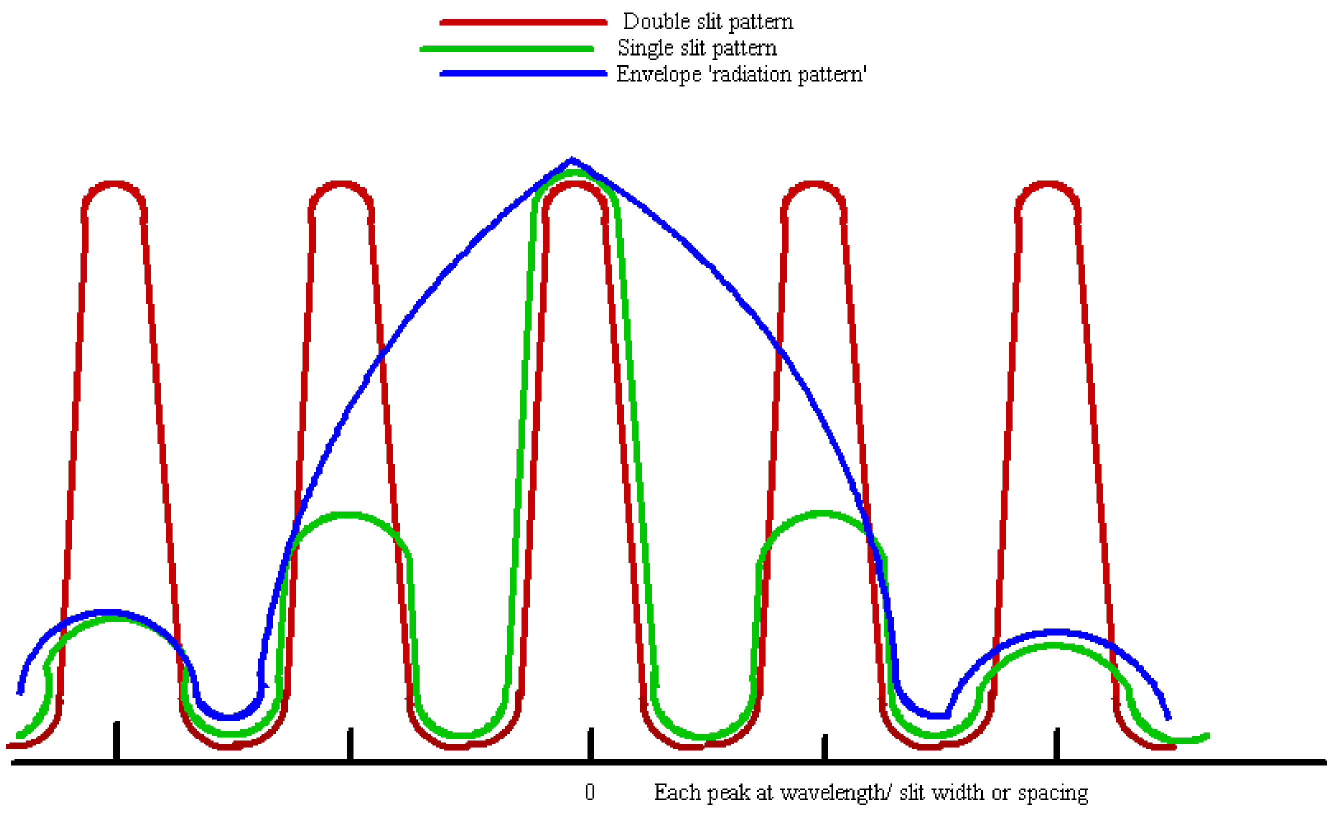


producing fringe patterns on the screen. The spacing and intensity of the fringes is entirely dependant on the spacing of the slits, since it is this that determines where the constructive or destructive interference occurs at a particular point on the screen. It is noticeable that in this case the fringe intensity will remain largely uniform.

If we now consider a situation where instead of having two slits, we only have one, but with a width the same as the spacing of the two slits, then we get a different effect. This is because the radiation can effectively come from any part of the wide slit and therefore produce an interference pattern with a varying intensity.



The figure below shows the difference in patterns obtained by using two slits (red line) and by using one wide slit (green line). The graph is scaled in terms of relative intensity against the angle of the radiation (ie: deviation from a line which is at right angles to the slit)



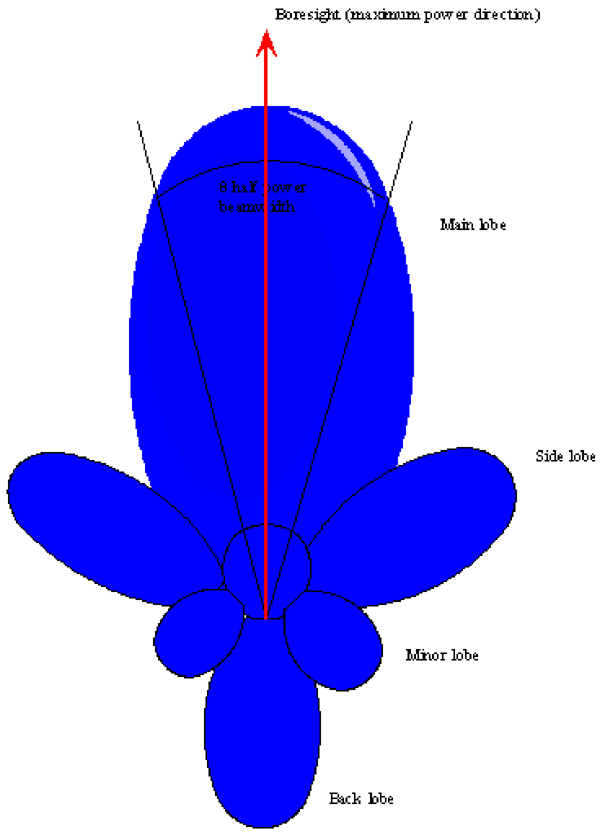
This single slit distribution is called **Huygens' Principle** and it is clear that the analogy with an antenna is actually quite close. If you imagine that the width of the slit is the length of an antenna, it is easy to see why changing this dimension will affect the radiation characteristics.

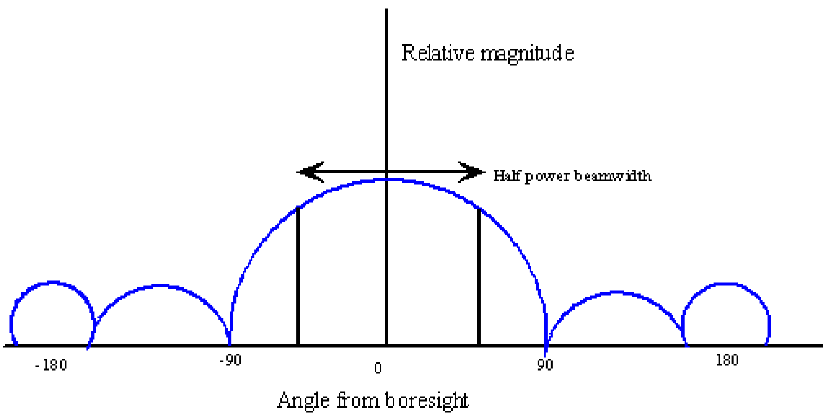
The most obvious changes occur when the distance d (or l in the case of an antenna) becomes larger than half a wavelength, the effect then is that you would get more than just getting one main peak (lobe).

This optical model is very useful in visualising the radiation from antenna and the blue line is in fact a crude **radiation pattern**, which is the subject of the next section.

How do you make sense of radiation patterns and what do they tell you?

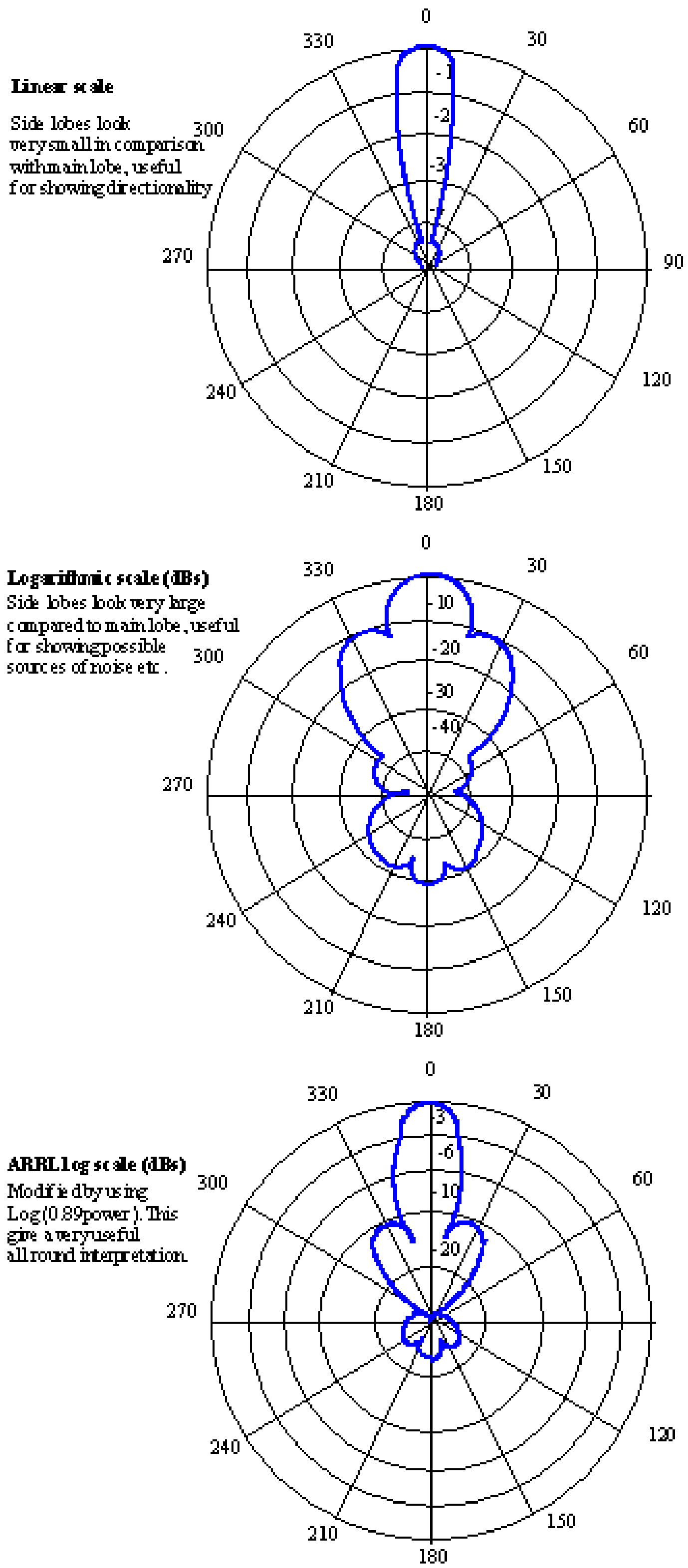
As described earlier the radiation pattern is a graph of the magnitude of radiated power against angle. The figure below shows a 3D representation of the radiation from an antenna (top) and one form of radiation pattern (bottom), which is plotted on conventional rectangular axes. It is noticeable that the pattern consists of a main lobe and several minor lobes. With all antennas (except monopoles and dipoles) you get sidelobes and backlobes and they are always undesirable because they represent wasted energy for transmitting antennas and potential noise sources for receiving antennas.



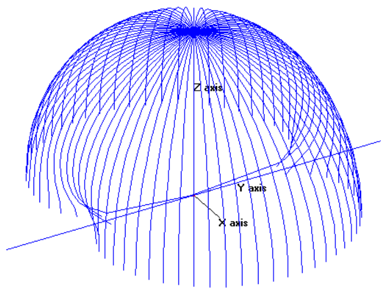


With a radiation pattern, as with any graph it is important to have the correct scaling. Additionally it is often useful for these to be plotted on polar coordinates rather than rectangular, since this give a better idea of the radiation characteristics.

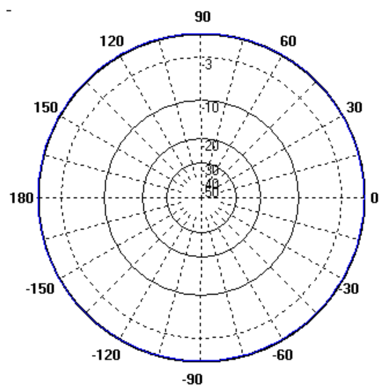
The figure below shows polar plots with different scaling.

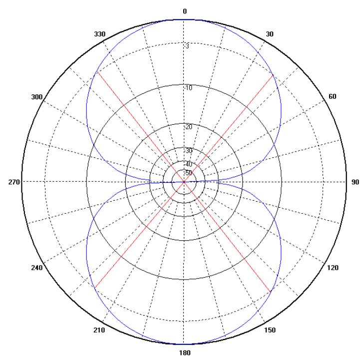


It is conventional to show both the both the horizontal and vertical radiation patterns for a particular antenna, since most antennas have a completely different pattern depending on which ‘slice’ through the radiation field is taken. A good example of this is the half wavelength dipole, which has radiation characteristics like a doughnut, as shown below.



When plotted in 2 dimensions you can clearly see the vertical pattern (zenith) is a circle and the horizontal pattern (azimuth) is a figure of eight.

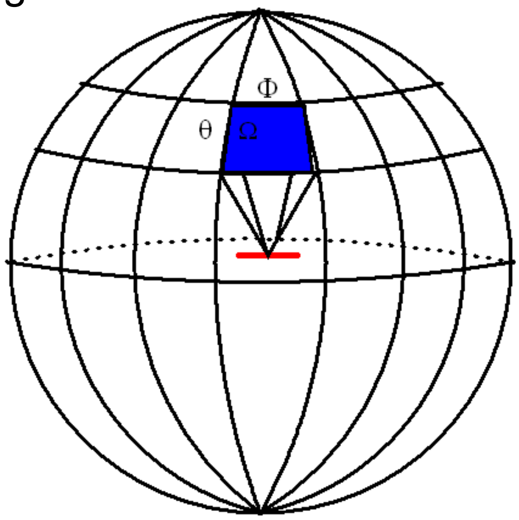




Now we’ve seen how radiation patterns are formed and what they actually are, it would be useful to see what information can be extracted from them.

The radiation patterns show the proportion of the surface of a sphere that has power passing through it. In the case of an isotropic radiator, it is the whole of the surface of the sphere. However, if the antenna has any directionality at all, it will radiate through less than the whole surface. The smaller the area of the sphere surface that is radiated through, the higher the directionality of the antenna. This is something that is very easy to visualise from polar form radiation patterns, since they effectively show slices through the sphere.

The figure below shows a sphere, with antenna in the centre, which radiates out through the surface.



If we can quantify the proportion of the sphere that is being radiated through, we can then establish a value for the directionality of the antenna. There are two ways of doing this.

a) An approximate way is to use the fact that there are 41,253 'square degrees' (360x360/π) on the surface of a sphere. If you know how many square degrees are contained within the radiation beam area (the blue patch on the diagram), which is known as Ω, then you can work out the proportion of the sphere surface being radiated through.

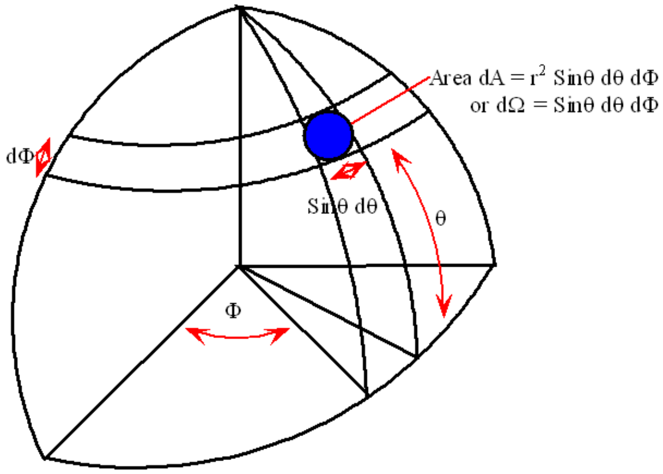
It would be usual to get these values from the two half power beamwidth figures obtained from the radiation patterns. These are known as θ_{HP} (vertical or zenith) and Φ_{HP} (horizontal or azimuth) and quite simply the beam are $\Omega_A = \theta_{HP}\Phi_{HP}$.

Eg: HP beamwidth in both planes = 90 degrees, therefore, the directionality value, called the **directivity** would be 41253/90x90 = 5.1, which can be converted to dBs and is 7dBi.

In the case of the dipole who's radiation patterns are on the previous page, the value for Ω_A is 360x70 = 25,200 and therefore has a linear gain of 1.64, or 2.15dBi.

b) Again using the radiation patterns, a more accurate method of calculating the directivity is to numerically integrate the radiation pattern to work out its area.

Looking at the beam area again there is an important thing to be notice.



The area is dependent on the elevation angle θ therefore becomes a function on Sinθ.

Since the area of a sphere is well known as $4\pi r^2$, it can also be evaluated (assuming Φ = 360) using.

$$\mathbf{2\pi r^2 \int_0^{\pi} \sin\theta \, d\theta,}$$

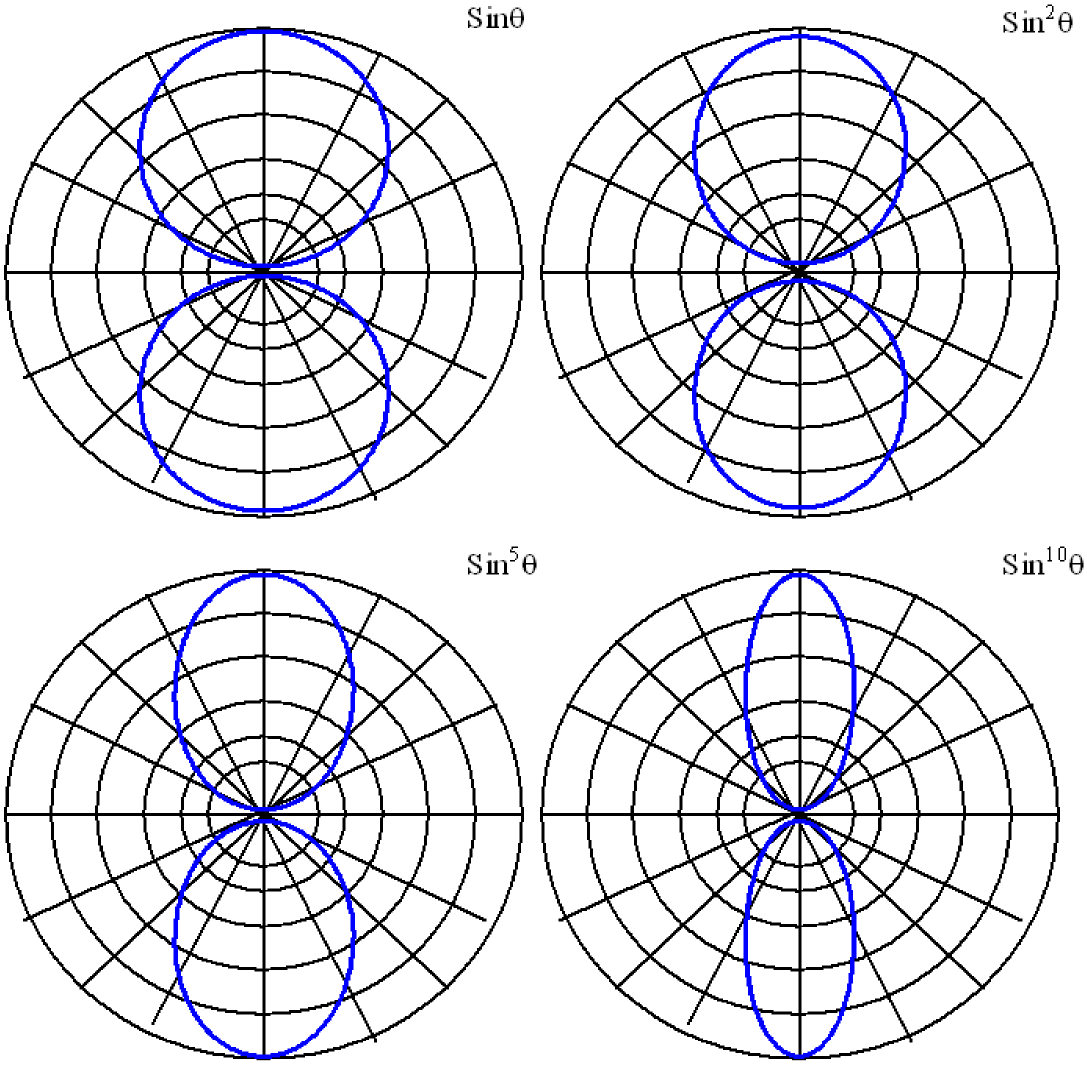
Therefore, taking our beam area on the sphere, we can produce an expression which describes how to calculate this, which includes the Φ term to allow for antennas which are not omni-directional in one plane:

$$\mathbf{\Omega_A = \int_0^{2\pi} \int_0^{\pi} P(\theta,\Phi)\sin\theta \, d\theta \, d\phi}$$

In order to be able to use this expression we need P(θ,Φ), this is obtained from the radiation pattern for each of the axes.

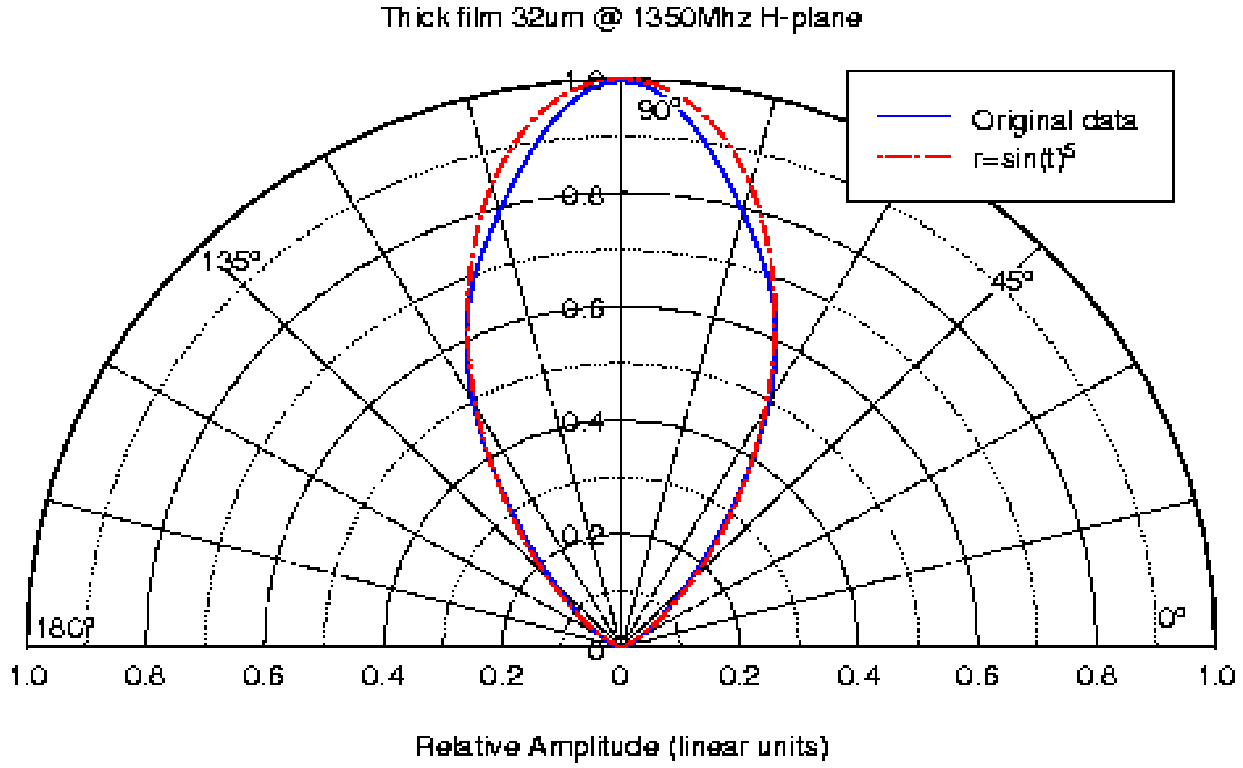
We shall start with the dipole, since it is relatively simple. In the Φ plane we have a complete circle as seen in the earlier radiation pattern (horizontal doughnut), but in the θ plane we have our figure of eight. We need to establish a function for this shape to use in the expression above.

If you plot the sinθ functions at various powers on a polar plot, you will get a figures of eight, starting with two perfect circles as shown below.



So if you can establish which sinθ function maps onto your radiation pattern, you can then use this to calculate the directivity of the antenna.

The example below shows a real antenna’s radiation pattern, but only the top half is shown.



The directivity of the antenna can be found by integrating for the volume of revolution determined by the radiation pattern, in this case the value for $P(\theta,\Phi)$ is $\sin^5\theta$ therefore the complete expression for Ω_A is:

$$\int_0^{2\pi}\int_0^{\pi} \sin^6\theta \, d\theta \, d\phi = \tfrac{5}{8}\pi^2$$

The solution to the integral can be found from a table of definite integrals, hence the solution shown.

The value of directivity is obtained by dividing **4π** (for the isotropic radiator) by the value obtained hence:

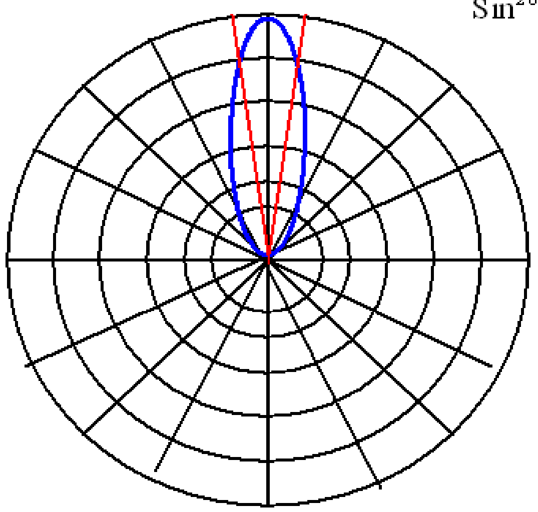
$$D = 4\pi / \Omega_A$$

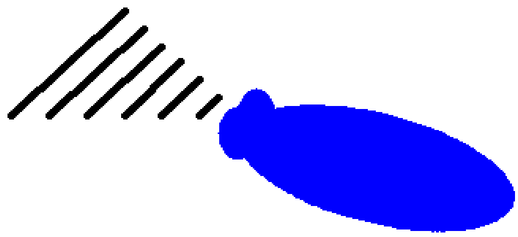
Therefore the directivity equal to **$32/5\pi$ = 2.04** linear units**,** which converts to **3.1dBi** in conventional units.

The directivity of an antenna is usually stated in dBi, which gives the directivity relative to that of an isotropic radiator. (directivity of 0dBi).

In actual practice the generation of radiation patterns and hence the calculation of antenna directivity is usually done with software. Here is an example for you to try to calculate the directivity using both the methods described.

The antenna is a high gain Yagi-Uda with the same radiation pattern in both horizontal and vertical planes.





A: Ω = Dir =

B: Given $\int_0^{\pi} \sin^n\theta \, d\theta = \int_0^{\pi} \cos^n\theta \, d\theta = \frac{(n+1)!!}{n!!}(\pi)$, n = 3,5…

$= \frac{(n-1)!!}{n!!}(\pi^2)$, n = 4,6…

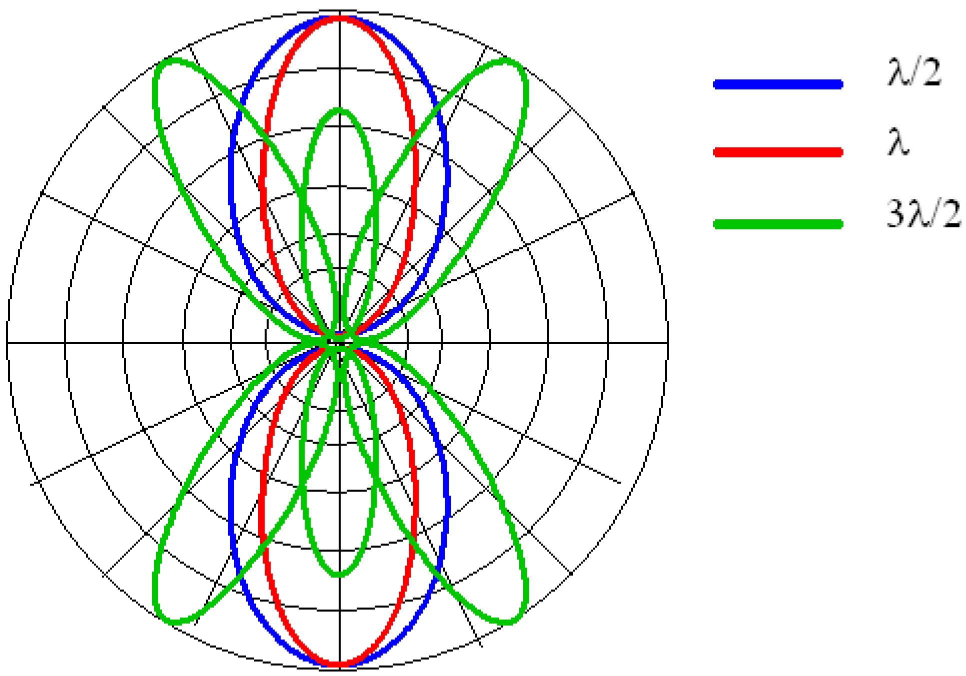
Dir =

Efficiency as described earlier, is $\xi = R_{rad}/R_{rad} + R_{loss}$

Antenna Gain simply the product of efficiency and directivity.
So an antenna that has a directivity of 12dBi and an efficiency of 50% will have again of 9dBi.

Just to finish off this section:

We have looked at the radiation patterns for the standard λ/2 dipole antenna, who's the radiation pattern is slightly narrower than for an electrically short dipole (Hertzian) but still has a figure of eight pattern and an input impedance of 72 ohms. As the antenna length increases past l = λ the main radiation lobe splits, also the input impedance changes rapidly, and it is not surprising that dipoles of above about 5/8 λ are hardly ever used. The figure below shows some examples of the radiation patterns for a selection of dipoles.



Antennas *Lecture 4*

What is the 'aperture' when used in relation to receiving antennas ?

The analysis we have done so far has been on antennas used as radiators. We shall now look at antennas when used to receive a signal ie: extracting energy from an incident wave and delivering it to a receiver. (It is worth pointing out that all antennas have an aperture which can be calculated. However, there is, as was mentioned before a category of antennas called aperture antennas, whose aperture can be directly measured.)

If the incident wave has a power density of S_i W/m^2 and the antenna receives a proportion of this power ie: the intercepted power P_{int} (W) then the capture ability of the antenna is termed the effective area or **aperture** of the antenna and is designated A_e where:

$$A = \frac{P_{int}}{S_I} \qquad (m^2)$$

If we consider the short dipole again where λ is large compared to the length then the aperture is:

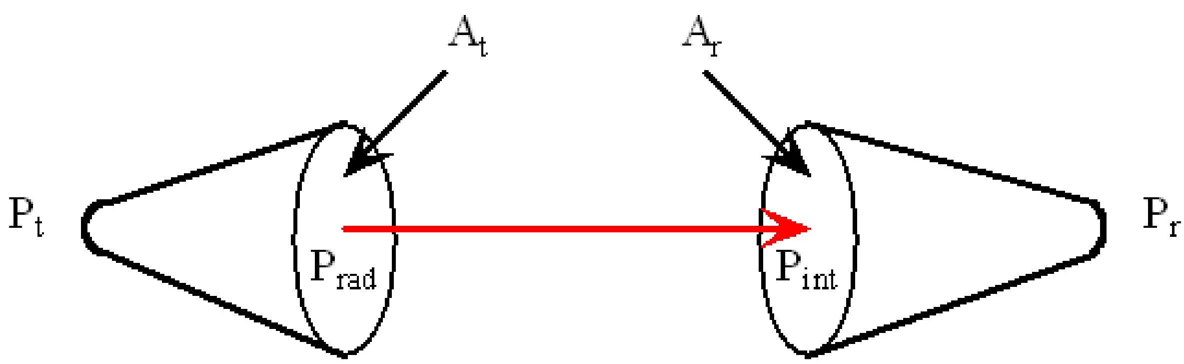
$$A = \frac{3\lambda^2}{8\pi}$$

and it can be shown that for **any antenna**:

$$\mathbf{A = \frac{\lambda^2 D}{4\pi}}$$

Where D is the measured or calculated directivity of the antenna.

If two antennas are used in a communications system, eg: one for transmit and one for receive as shown below.



Assuming that they are both operating in the far field region we can then work out how much of the power that is transmitted from one antenna, is received by the other.

Let's start by thinking of the transmit antenna as an isotropic radiator then the power density at the receive antenna will be:

$$S_{iso} = \frac{P_t}{4\pi R^2}$$

However since the transmit antenna is neither lossless or isotropic then the power density of the real antenna S_t is given by:

$$S_t = G_t S_{iso} = \xi_t D_t S_{iso} = \frac{\xi_t D_t P_t}{4\pi R^2}$$

Where ξ_t is the efficiency (<1), D_t is the directivity and G_t is the gain of the transmit antenna. Expressed in terms of the aperture (area) of the transmit antenna we get:

$$S_t = \frac{\xi_t A_t P_t}{\lambda^2 R^2}$$

{The general rule is that the gain of an antenna is the directivity multiplied by the efficiency and therefore the terms are not directly interchangeable. When aperture is used in the context of gain rather than directivity, the term **effective aperture** is often used and is designated A_{eff} or $\mathbf{A_e}$}

On the receiving side, the power intercepted by the receive antenna is therefore:

$$S_r = A_r S_t = \frac{\xi_t A_t A_r P_t}{\lambda^2 R^2}$$

The received power P_{rec} delivered to the receiver is equal to the intercepted power P_{int} multiplied by the radiation efficiency of the receive antenna ξ_r. Thus, $P_{rec} = \xi_r P_{int}$, hence:

$$\frac{P_{rec}}{P_t} = \frac{\xi_t \xi_r A_t A_r}{\lambda^2 R^2} = G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2$$

This equation is known as the **Friis transmission formula** and is a fundamental in antenna and communications calculations. It also shows the relationship between the aperture of an antenna and its gain/directivity ie: they are in direct proportion to each other.

Effective Isotropic Radiated Power

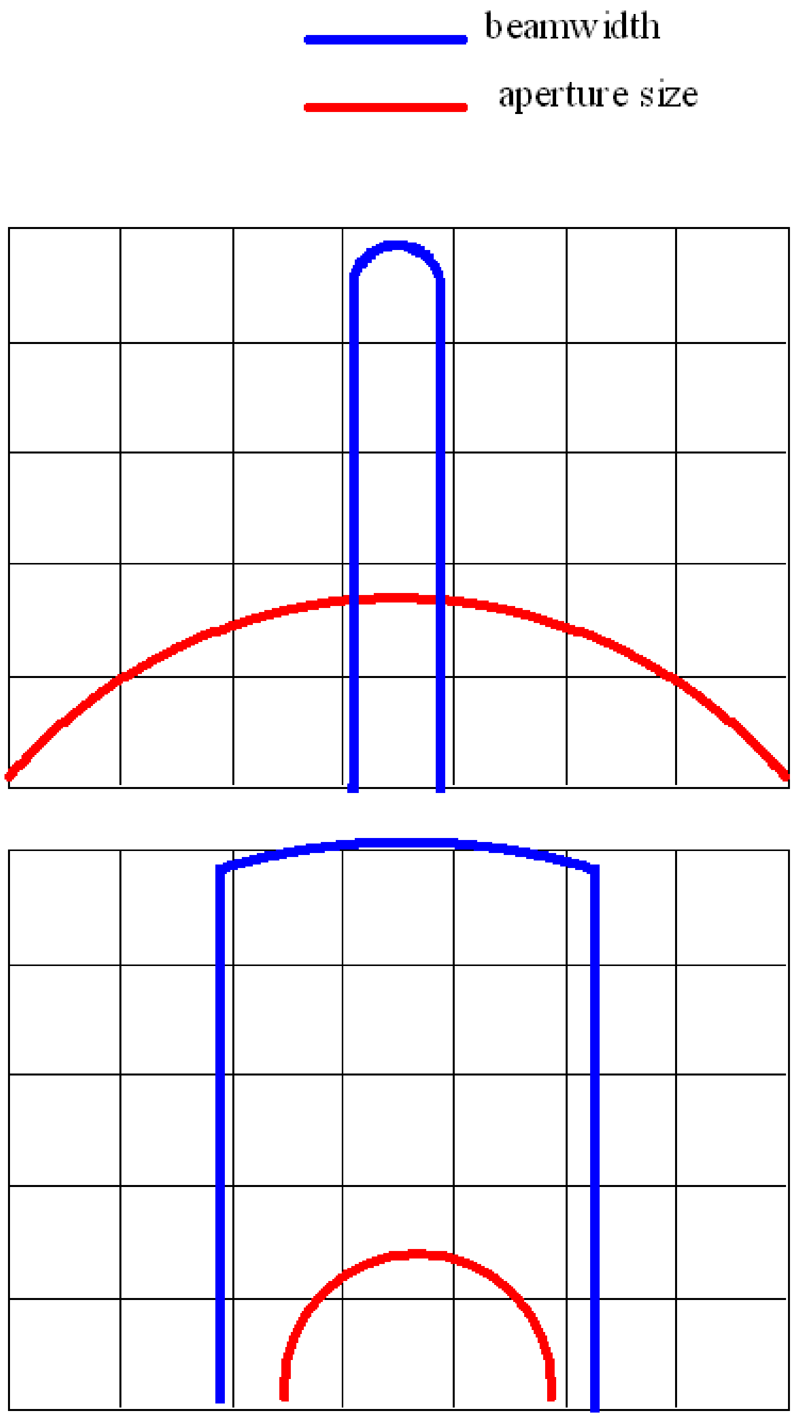
Since all practical antennas have directivity (gain) of some sort it is sometimes useful to state the radiated power and the gain of an antenna as a single value. The EIRP is the power that would have to be produced by an isotropic radiator if it were to give the same power at the point at the receive end, as the antenna being used.

EIRP = $P_t G_t$

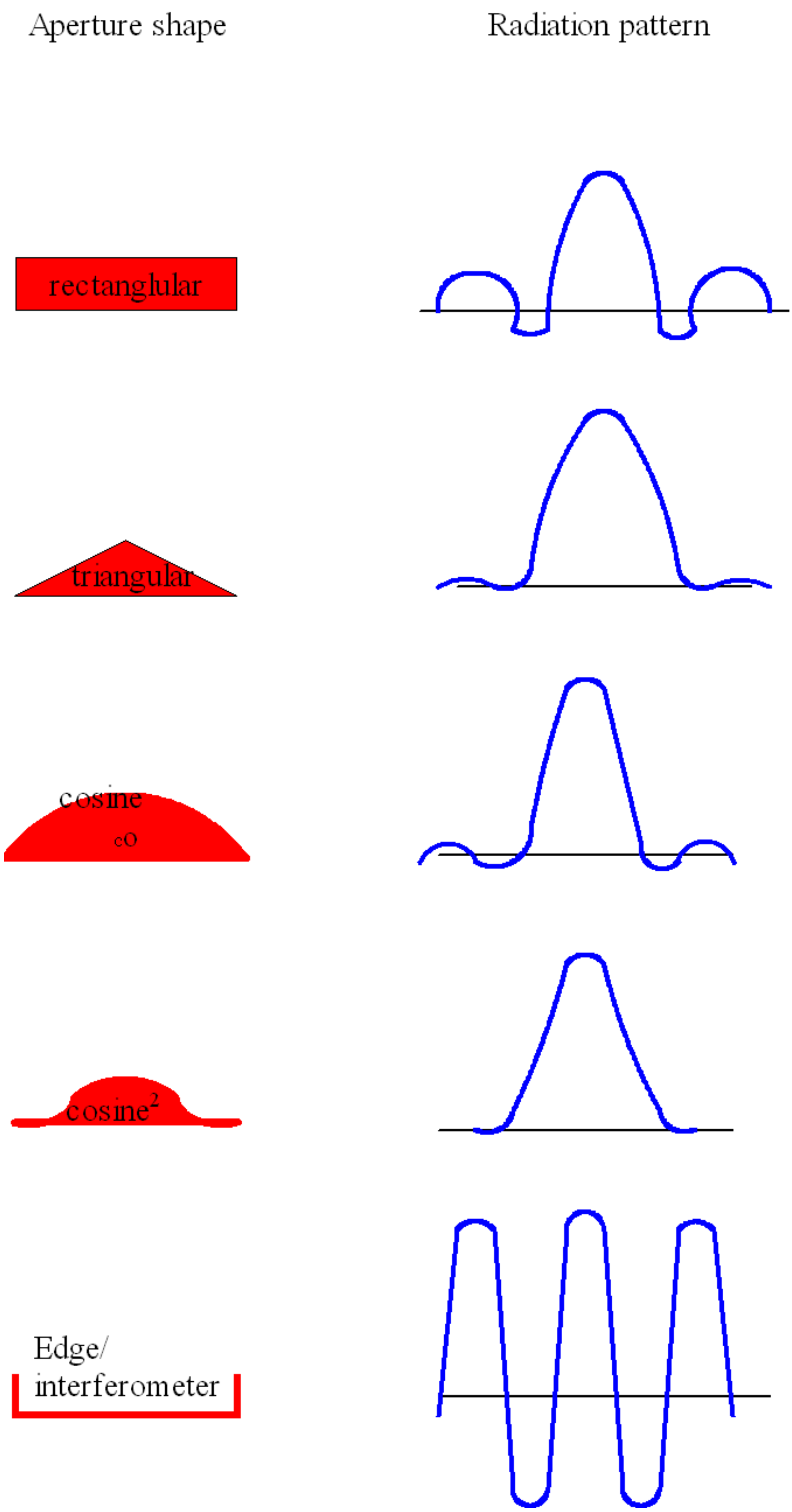
The EIRP is commonly used is the specification of satellite transponders eg: 52 dBW. (An isotropic radiator would have to be transmitting at a power of 100,000,000 watts to give the same power flux density).

EIRP is useful for comparing the power available at a specific point on the earths surface from satellites in the same location.

We have seen that the gain/directivity is inversely proportional to the beamwidth of the antenna ie: a large aperture and hence high gain antenna (in relation to λ) has a very narrow beamwidth. This may seem to be counter intuitive. However, if we consider this in terms of the **Fourier Transform** which effectively converts from one domain to the other then we get a transformation as shown in the figure below.



The figure below shows a selection of antenna aperture profiles and their associated radiation patterns. The important point to remember here, is that it's not just the aperture size that determines the radiation pattern characteristics, but the aperture profile as well.



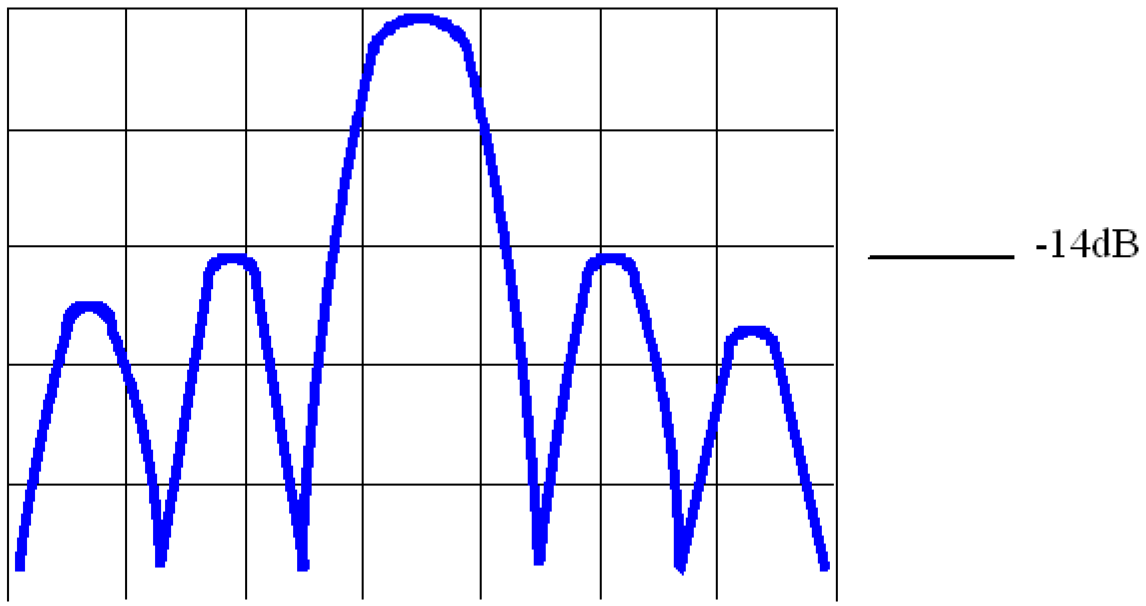
The patterns show that there is an optimum aperture shape, namely the cosine^2 aperture. However, the cost of achieving this profile on a real antenna may well be prohibitive in terms of cost/ benefit ratio.

It is also easy to see why the interferometer arrangement is would only have very specialised applications, such as radio-astronomy, due to its odd radiation pattern.

These aperture/ pattern correlations explain why in another way, why you get an omnidirectional radiation pattern from an isotropic radiator and a very narrow beam from a large aperture antenna such a parabolic dish or an antenna array, and suggests that you would need an infinitely large antenna to get an infinitely narrow beam.

From the uniform (rectangular) distribution diagram, you can see why large high gain antennas tend to have large sidelobes whose amplitude can be predicted and calculated. There is a distinct tradeoff between the width of the main lobe and the height of the sidelobes.

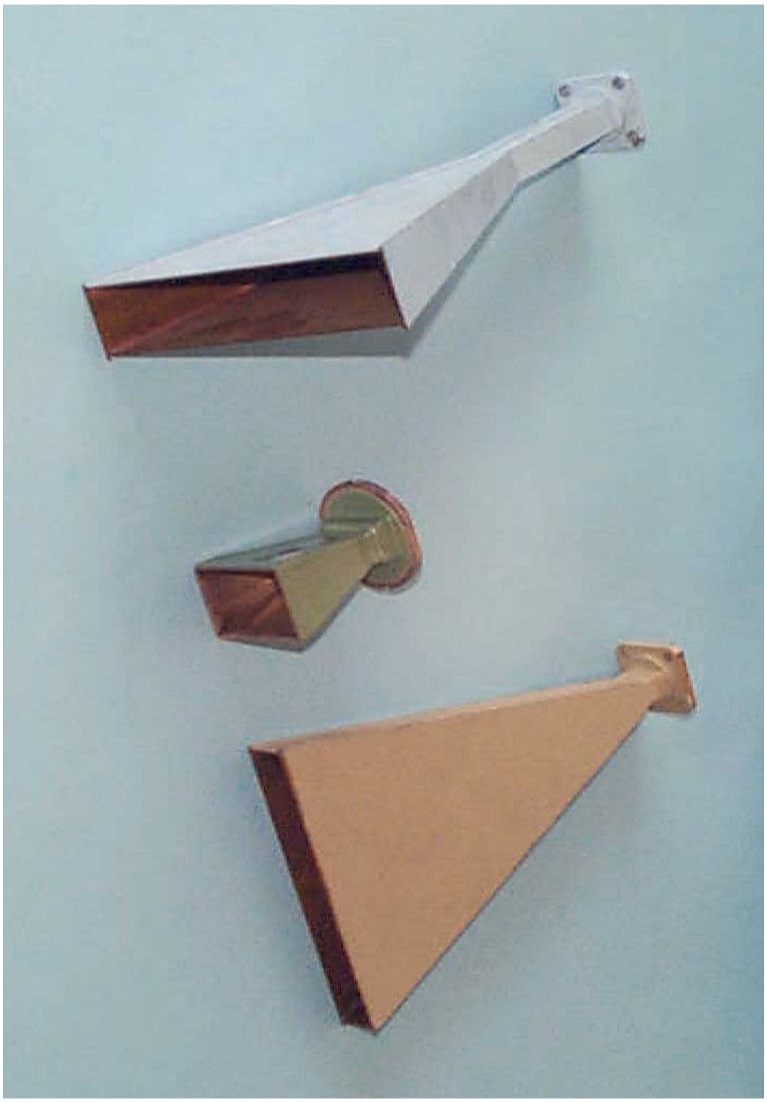
The figure below shows a rectangular aperture distribution with the corresponding field pattern, giving an indication of the height of the sidelobes. In order to reduce the height of the sidelobes, you would have to modify the aperture distribution (ie: taper the gain) so that it is a maximum in the centre and a minimum at the ends. This will be discussed again in reflector antenna section later on.



Aperture antennas

So far we have seen that antennas radiate power according to their associated radiation pattern. The beamwidth of the antenna is directly related to its aperture. For simple wire antennas the aperture can be calculated. However, there are antennas where the aperture can be directly measured, not surprisingly these are called aperture antennas. Horns and dishes fall into this category and the physical size of the antenna is closely related to it's aperture and hence its gain.

We shall start by looking at horn antennas. The figure below shows a range of horn antennas.



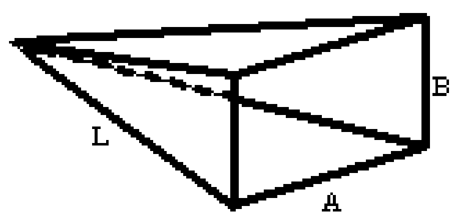
Any horn antenna may be considered to be a piece of flared out waveguide. Its function is to produce a uniform plane wave with high

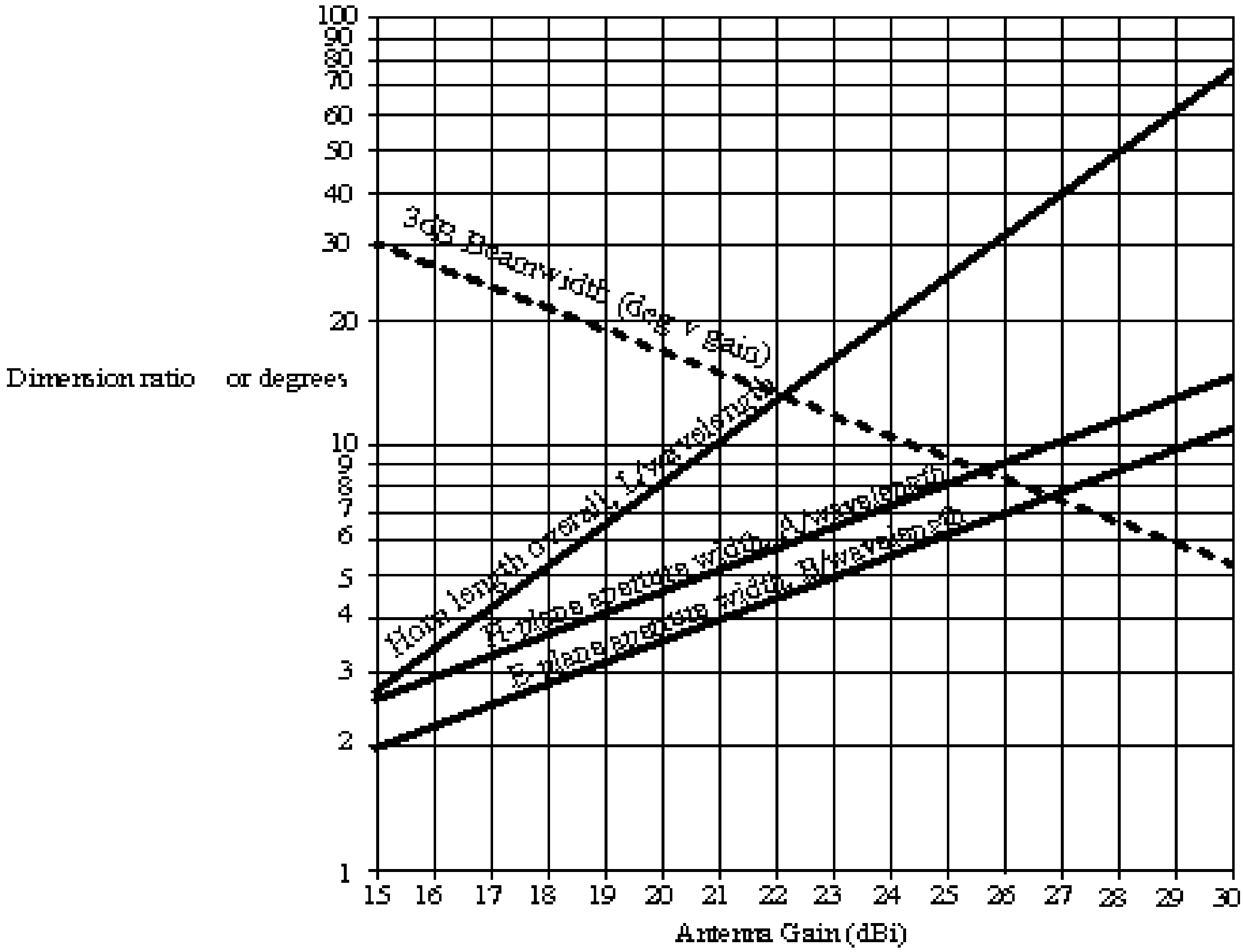
directivity, which is determined by the physical size of the aperture (opening). The most common type of horn is the rectangular pyramidal and the figure below shows the main dimensions a simple instructions on how work out the gain for any
frequency.

Designing a microwave horn antenna for a specified gain

Establish the wavelength of your signal, in cm, and using the chart below work out the values for L, A and B.

Eg: signal at 18GHz has wavelength of 1.67cm and you require a gain of 18dBi. So from the chart L/wavelength = 5.3, therefore L = 5.3x1.67 = 8.85cm. For A and B you get values of 6.18cm and 4.68cm respectively.





An alternative way of calculating the horn gain is ie: to determine the actual dimensions required for a practical horn, we can use either the directivity or the required beamwidth.

If we want to use directivity as the design factor, then we can use the equations below to determine the size of the horn.

$$\mathbf{D = 10\log(7.5A_p/\lambda^2)\ dBi}$$

Where A_p is the physical aperture size and is obtained by multiplying together a_E (E plane of the horn, B in the above diagram) and a_H (H plane of the horn, A in the above diagram).

It should be noted that physical aperture is actually slightly larger that the **effective aperture,** this is because a typical horn antenna is only about 60% efficient.

In terms of beamwidth, the horn can be designed by using the following equations:

HPBW (E plane) = 56°/ $a_{E\lambda}$
HPBW (E plane) = 67°/ $a_{H\lambda}$

Where $a_{E\lambda}$ = E plane aperture in wavelengths
Where $a_{H\lambda}$ = H plane aperture in wavelengths

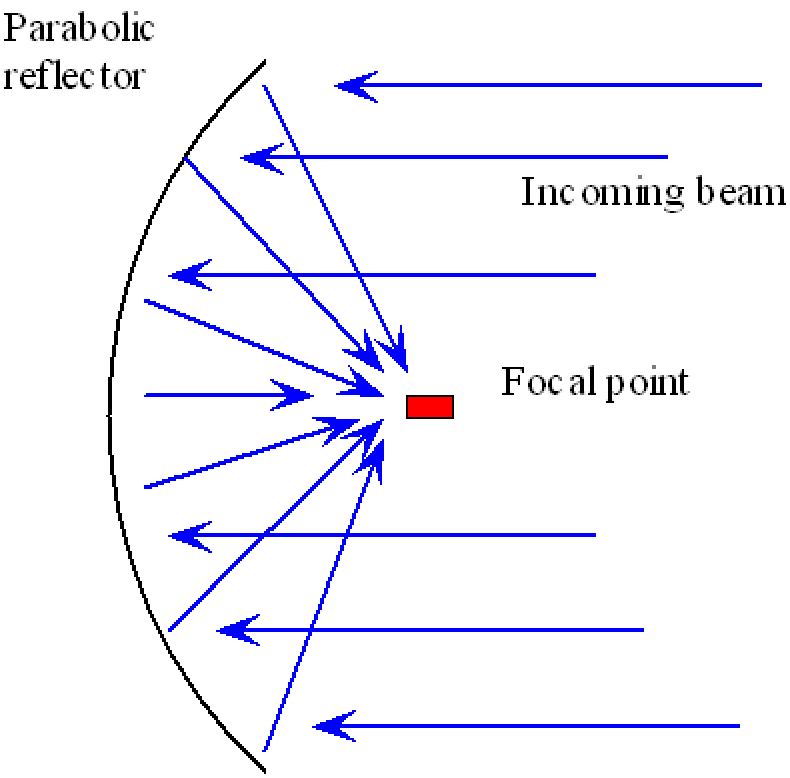
It should be noted that if it is required that the horn is designed in such a way as to provide a very narrow beam in one plane and a very wide beam in the other, such as for a surveillance radar, then the wide dimension of the horn should be in the H plane ie: dimension A in the diagram above. If it is done the other way round ie: a wide E plane dimension, the result will be a bifurcated main lobe.

Parabolic reflector antennas.

These antennas commonly known 'dishes', even though they are categorised as reflector antennas, they are another obvious example of an aperture antenna.

In principle, the dish consists of a parabolic reflector of certain dimensions, on which a feed antenna is placed at the primary focal point.

The advantage of a parabola, over a hemispherical reflector is that any EM waves arriving parallel to each other from a point source, ie: exactly that from a satellite, will always be focused to the same point as shown in the diagram below.



Because of the aperture effect, the main factor determining the gain of the dish is its area. However, the quality and surface finish of the dish can also play an important part. Typically, for a satellite dish, the feed antenna in a monopole (actually two monopoles, one for H pol, the other for V pol, switched inside the LNB). $\lambda/4$ Monopoles are generally very efficient, however the dish itself is typically only 60-70% efficient and therefore has to be factored in.

The main equation for calculating the gain of a parabolic dish is shown below.

$$G= 10 \log[\pi^2\eta(D/\lambda)^2] \text{ dBi}$$

It is easy to see that the main part of the relationship is the area of a circle calculated on the basis of the signal wavelength, multiplied by the efficiency and then converted to dBs.

A typical example would be the standard Sky dish, which has a diameter of 48cm (D), and is about 65% efficient (η). The wavelength to be used is the middle of the Ku band, which is 11.7GHz, hence a wavelength (λ) of 2.6cm. Therefore, applying the equation above we get:

$$G= 10 \log[\pi^2 0.65(0.48/0.026)^2] = 33\text{dBi}$$

An approximation to this, assuming that λ is constant at 2.6cm (any Ku band satellite dish), with the dish size in metres, would be:
$G =39.2 + 20 \log D$, which gives a value very close to the one above.

It stands to reason therefore that if you need a dish with twice the gain at a given frequency, you will need a dish with twice the area (aperture) or $\sqrt{2}$ times the diameter. It comes as no surprise therefore that dishes for satellite reception come in 3dB (double the gain) steps ie: 48cm, 60cm, 80cm etc.

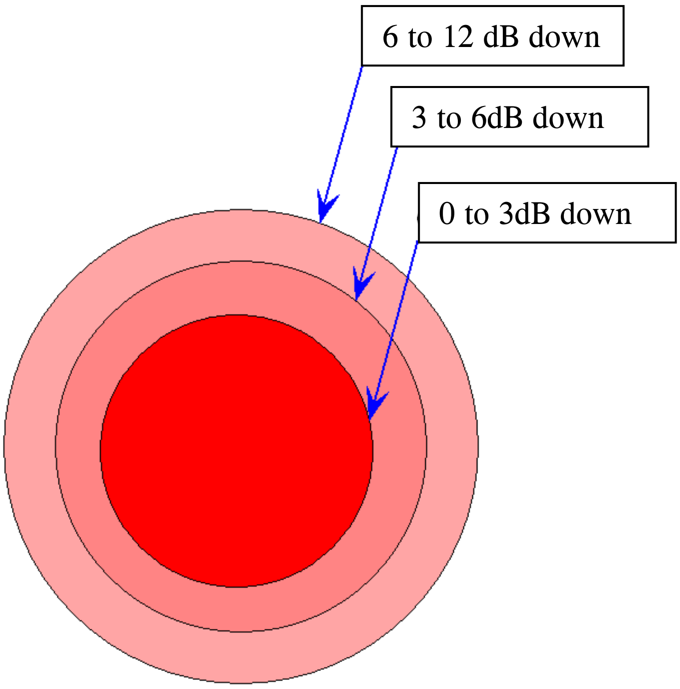
Parabolic dishes, like any other high gain antenna are plagued by sidelobes, even to the extent that sometimes it is possible to see different satellite signal from the one you want, because a sidelobe is pointing straight at the unwanted satellite. This will inevitably cause interference, even to the extent of disrupting the signal that you actually want

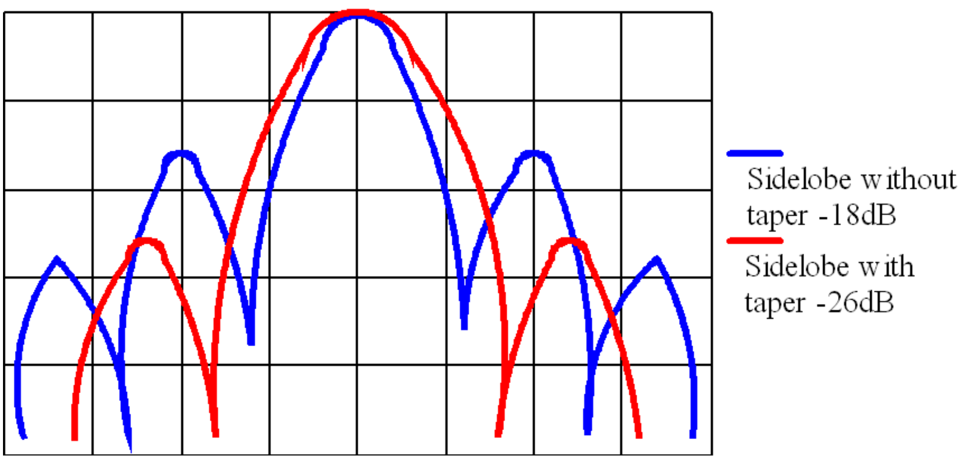
Manufacturers go to quite a lot of trouble to minimise sidelobes for this very reason. Quite a simple way to solve the problem, at the expense of some gain, is to use gain taper.

We saw in the previous section how changing the aperture profile makes a great deal of difference to the radiation patterns, and more specifically to the sidelobes. On a parabolic dish, it would be very difficult to reshape the reflector. However, it is possible to produce ‘gain taper’ by using the fact that the monopole described earlier is contained within a conical horn.

The horn (part of the LNB), because it is an antenna in its own right also has its own radiation pattern, with a single main lobe. If the position of the horn (at the focal pint of the dish) is adjusted slightly towards the dish, it tends to ‘under illuminate’ the dish and only look at the innermost 80%, hence the power coming from the edge of the dish is lower than that from the centre. This in effect changes the rectangular aperture distribution to more of a cosine distribution, hence reducing the sidelobes.

The diagram below shows the illumination of the dish and its corresponding radiation patterns.

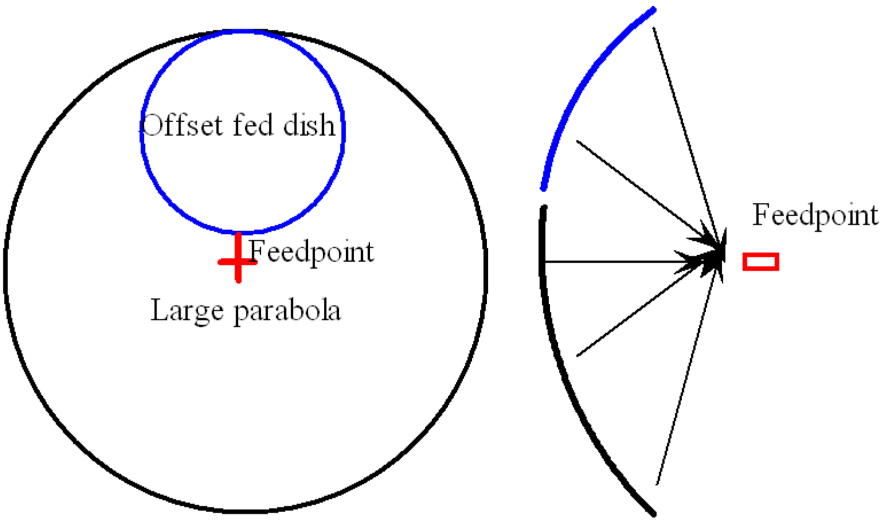




However, you will notice that in the again taper version, the main lobe is wider, representing a slight loss of gain.

On inspection of a sky dish there is a feature, which is now quite common on small (and some large) dishes. This is the position of the feedhorn (LNB).

You will notice that the feedhorn does not appear to be anywhere near the focal point of the dish. In fact it is, it is just that the shape of the dish is such that it appears to have been cut out of a much larger parabola, on which the feedpoint would be exactly over the centre of the dish. This arrangement is called an **offset feed**.



The offset fed dish has two main advantages:

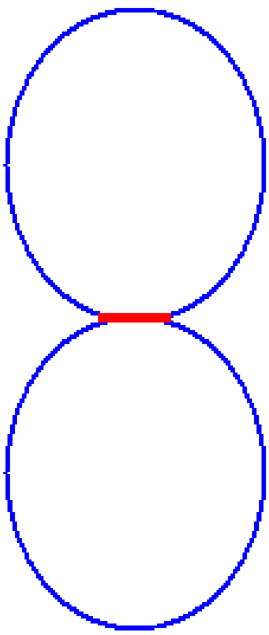
i) There is negligible aperture blockage (literally, the LNB/feedhorn blocking the incoming signal to the dish. This would be a particularly acute problem on a very small dish such as a domestic satellite dish.

ii) For high elevation angles, eg 25°, it allows the dish to appear to be almost vertical and fit flush against the wall. This offset angle has to be borne in mind when aligning a dish, typically the offset angle in the UK is 23°.

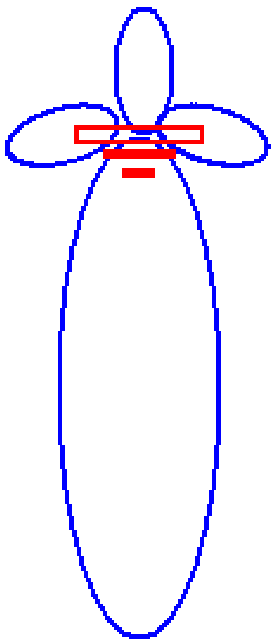
There is, as you might expect, a slight downside to having an offset feed, and that is that the feedhorn/LNB support arm has to be longer and hence heavier, also they are not as robust as centre fed dishes.

Antenna arrays

So far we have looked at the properties of single antennas and their applications. However, there are situations where the requirements in performance or cost terms cannot be met by a single antenna. Fortunately there are some well established techniques for combining single antennas such a way that a significant performance enhancement can be obtained. The figure below shows this more clearly:



Radiation pattern for single element antenna

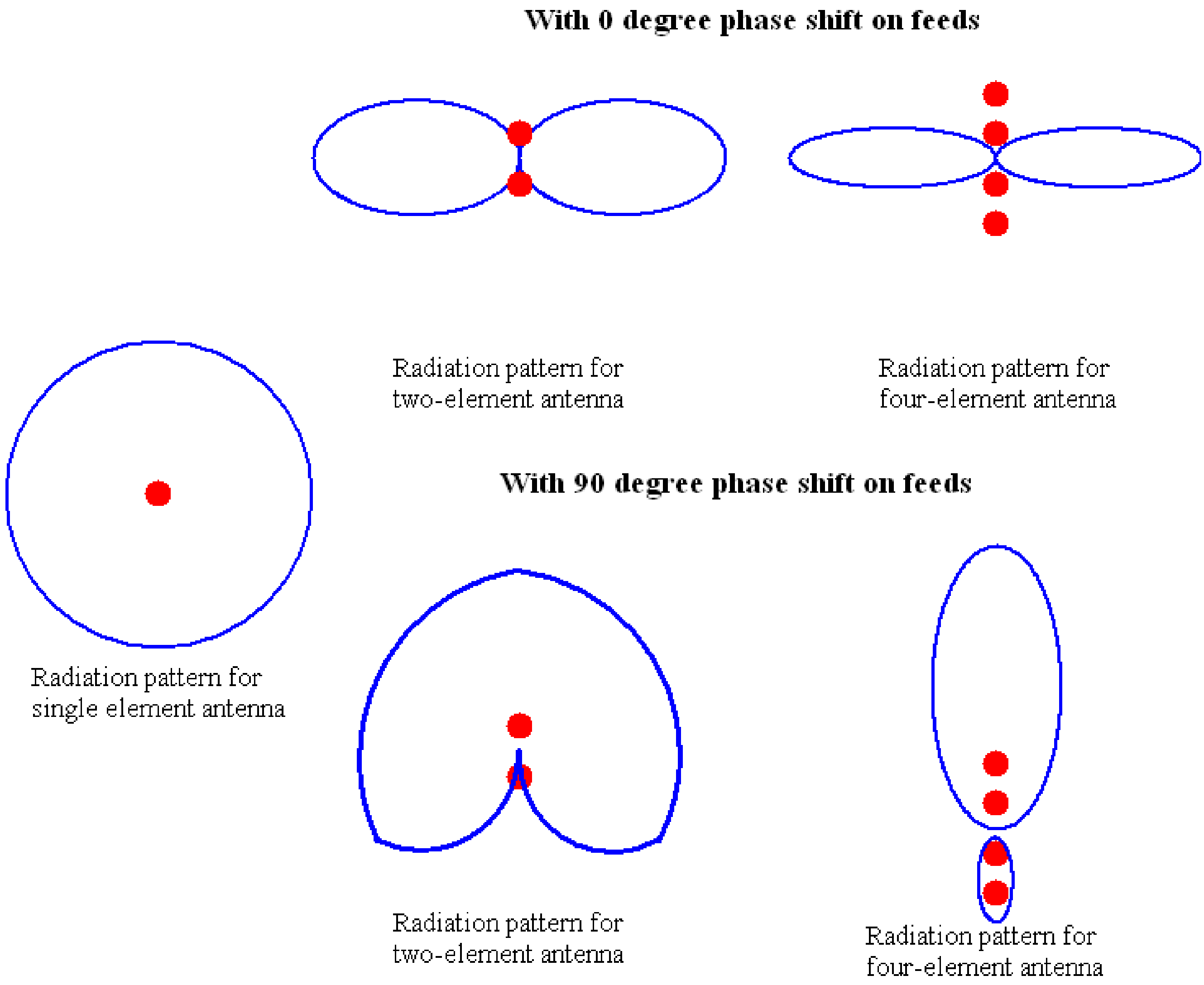


Radiation pattern for array (multi-element) antenna

The most basic array is one consisting of dipoles which are arranged either in parallel or stacked vertically.

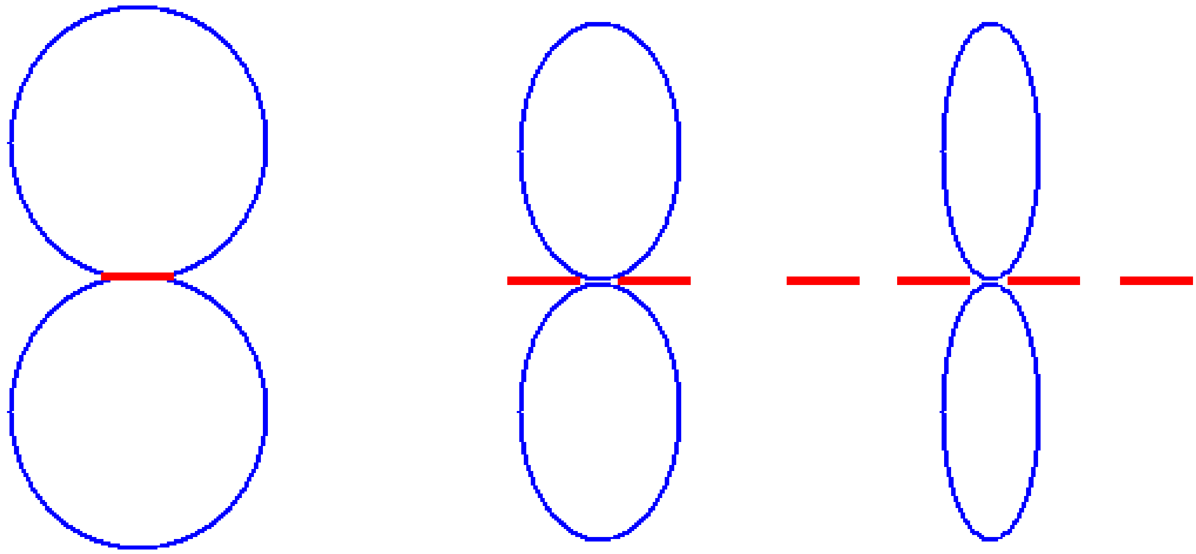
Lets look at the effect of such an arrangement of dipoles: in the first case with a parallel configuration, and the second stacked vertically (called a **collinear array**).

The figure below shows the arrangement and characteristic of two and four dipoles and in parallel.



As can be seen, with a phase shift of 0° the radiation pattern is different from that of a single dipole in that the radiation is not omnidirectional in the vertical plane, but in the horizontal plane in is broadly similar. Using more dipoles exaggerates this effect as can be seen in the 4 element case. However, as a 90° phase shift is introduces, the effect is dramatic, in that the whole radiation pattern swings round by 90° and thus gives what is called an '**end fire** effect', rather than a '**broadside** effect' as in the 0° phase shift case.

If we examine vertically stacked dipoles we find that we get exactly the opposite effect, in that the radiation pattern in the H-plane remains unchanged (ie: omnidirectional) but in the horizontal plane, the beamwidth becomes narrower with added elements, so rather than a doughnut you get a thin disk, as shown in the figure below.



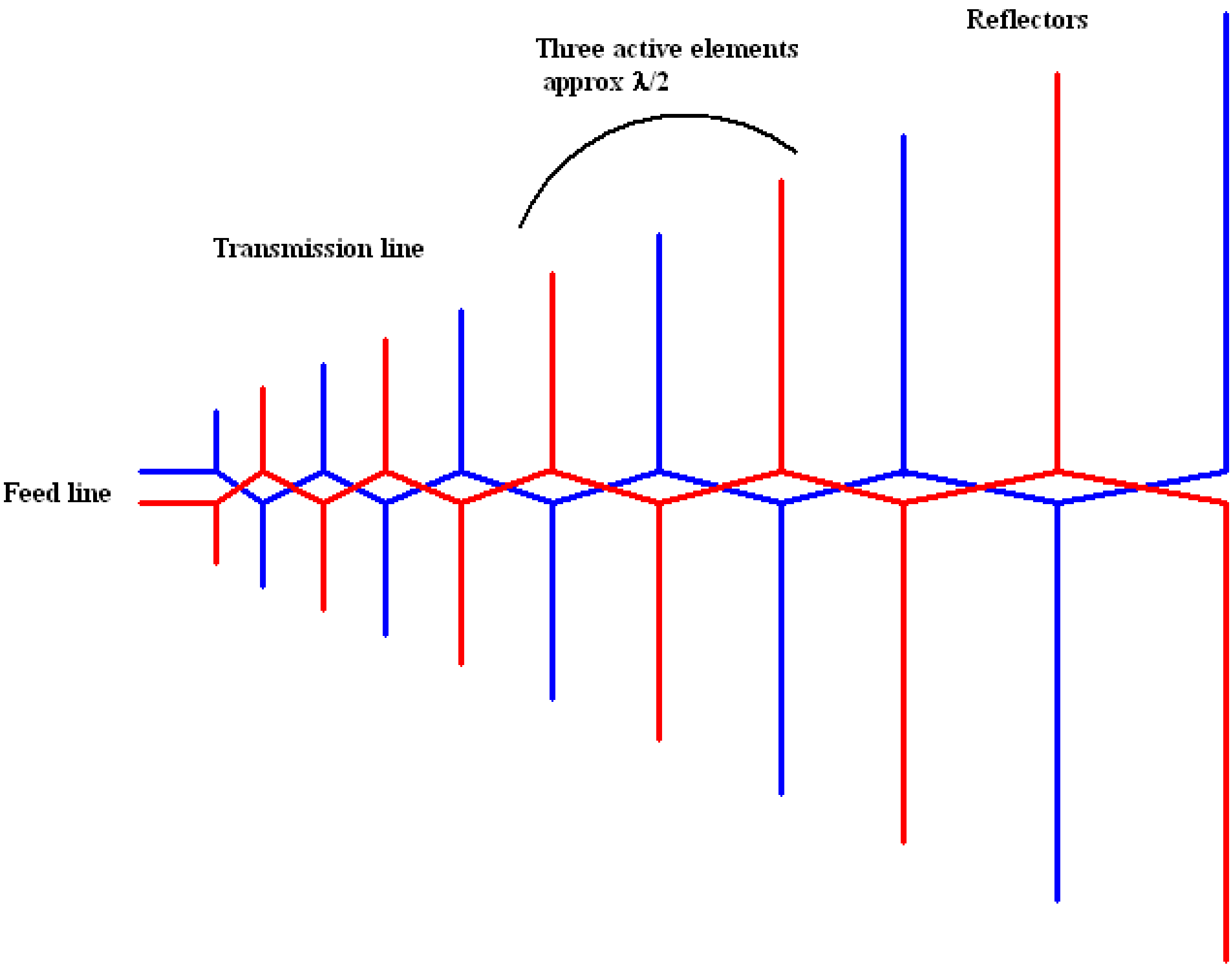
Radiation pattern for single element antenna | Radiation pattern for two-element antenna | Radiation pattern for four-element antenna

The vertically stacked collinear array is widely used in broadcasting, particularly on cellular telephone transmitter masts, where there is a requirement for omni-directionality in the horizontal plane, but a narrow beamwidth in the vertical plane, TV broadcast antennas use a similar arrangement.

Both parallel and collinear arrangements can be used in the same antenna array, this forms a two-dimensional array or planar array, and combines the characteristics of both types of array, we shall look at an example of that later on.

We shall look in more detail first at well known examples of parallel arrays: the **log periodic** and the **yagi-uda** antennas.

Starting with the log periodic, or to give it it's full title the Log Periodic Dipole Array (LPDA), is a parallel array of dipoles each of a different length to give an antenna with good directional properties ie: one main lobe 'end-firing' with very broadband characteristics. An example of a log-periodic is shown below.



This particular antenna is designed to have again of 7dBi using 11 elements with a bandwidth of about 2 octaves.

You will note that the elements in adjacent dipole pair are fed out of phase, this causes the antenna to end fire as described earlier. If they were fed in phase, the antenna would 'backfire' with very poor radiation characteristics. As it is, at any given frequency within the operating range on about 3 dipole pairs are actually behaving as antennas.

To give you an idea of how to design an log-periodic the following procedure can be followed, since it is clear that the element lengths and spacing cannot just be guessed.

The **design procedure** for the antenna for a directivity specified by D_0 dBi, is as follows:

i) Determine σ (relative element spacing) and τ (scale factor) from the table below which shows the optimum values.

Required gain dB	***σ (element spacing)***	***τ (scale factor)***
6.5	**0.133**	**0.76**
7	**0.14**	**0.780**
7.5	**0.15**	**0.822**
8	**0.16**	**0.853**
8.5	**0.166**	**0.888**
9	**0.172**	**0.908**
9.5	**0.175**	**0.925**
10	**0.179**	**0.943**
10.5	**0.182**	**0.957**
11	**0.185**	**0.964**

ii) Determine α (apex angle) from the equation below:

$$\alpha = \tan^{-1} [(1-\tau)/4\sigma]$$

iii) Determine B_{ar} (active region bandwidth) and B_s (designed bandwidth) with B (desired bandwidth) using the equations below:

$$B_{ar} = 1.1 + 1.7(1-\tau)^2 \cot \alpha$$
$$B_s = BB_{ar}$$

iv) Find L (total length of antenna) with l_{max} (the length of the longest element) and N (number of elements)using the equations below:

$$L = \lambda_{max}/4\ [1-(1/B_s)] \cot \alpha, \quad \text{where } \lambda_{max} = 2l_{max} = v/f_{min}$$

$$N = 1+[\ln(B_s)/\ln(1/\tau)]$$

v) Determine Z_a (average characteristic impedance) with l/d (length to diameter ratio of the elements eg: 200:1) and n using the equation below and $\sigma' = \sigma / \sqrt{\tau}$

$$Z_a = 120[\ln(l_n/d_n) - 1.25]$$

vi) Determine Z_0 / R_{in} using the table below:

Z_a/R_{in}	Z_o/R_{in} (σ' = 0.06)	Z_o/R_{in} (σ' = 0.10)	Z_o/R_{in} (σ' = 0.16)	Z_o/R_{in} (σ' = 0.24)
0.15			**10**	**6**
0.2			**8**	**5.3**
0.3		**8**	**5.3**	**3.8**
0.4	**10**	**6**	**4**	**3**
0.5	**8**	**5**	**3.5**	**2.6**
0.6	**7**	**4.3**	**3**	**2.3**
0.7	**6**	**3.8**	**2.7**	**2**
0.8	**5.5**	**3.5**	**2.4**	**1.8**
0.9	**4.8**	**3**	**2.2**	**1.7**
1	**4.4**	**2.8**	**2**	**1.65**
2	**2.6**	**1.8**	**1.5**	**1.4**
3	**1.9**	**1.6**	**1.35**	**1.3**
4	**1.7**	**1.4**	**1.3**	**1.2**
5	**1.6**	**1.35**	**1.25**	**1.15**
6	**1.5**	**1.3**	**1.2**	**1.15**
7	**1.4**	**1.25**	**1.2**	**1.1**
8	**1.35**	**1.2**	**1.15**	**1.1**
9	**1.3**	**1.2**	**1.1**	
10	**1.3**	**1.2**		
12	**1.3**			

vii) Find s (element spacing) using the equation below:

$S = d\cosh(Z_0/120)$

These equations give you a complete set of dimensions enabling you construct log-periodic antenna.

There are two types one dimensional array antenna that are very often confused with each other, we've looked at the log-periodic, now we're going to look at other which is called the Yagi-Uda.

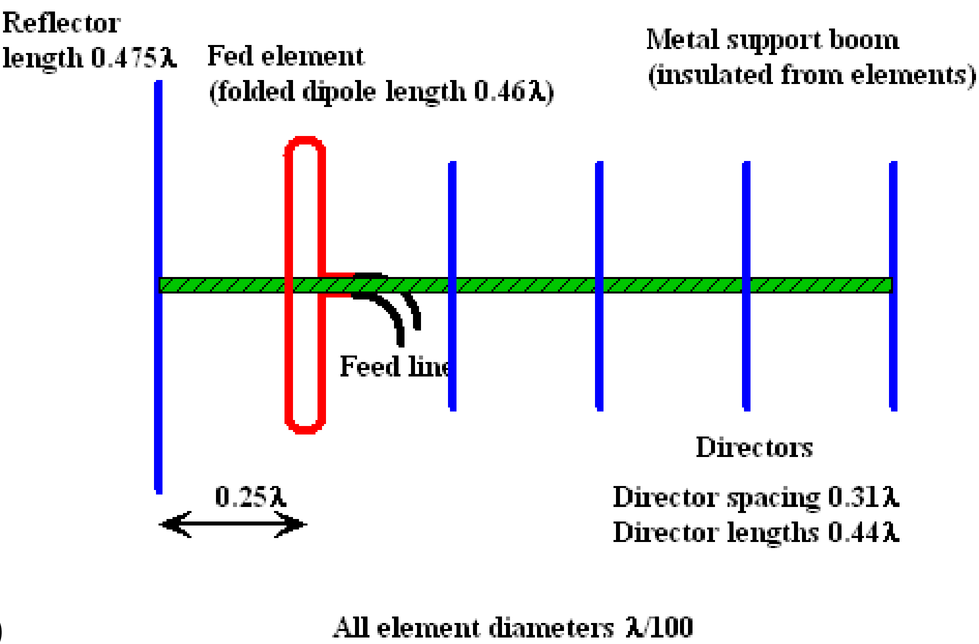
These two antennas mentioned differ in several respects

- In the case of the log-periodic all the elements are active, that is they are all fed with the signal. However with the Yagi-

Uda only one element is directly fed, all the others elements are ‘parasitic’.

- For a given number of elements a Yagi-Uda will have much higher directivity (gain) but a much narrower bandwidth than the Log-periodic.

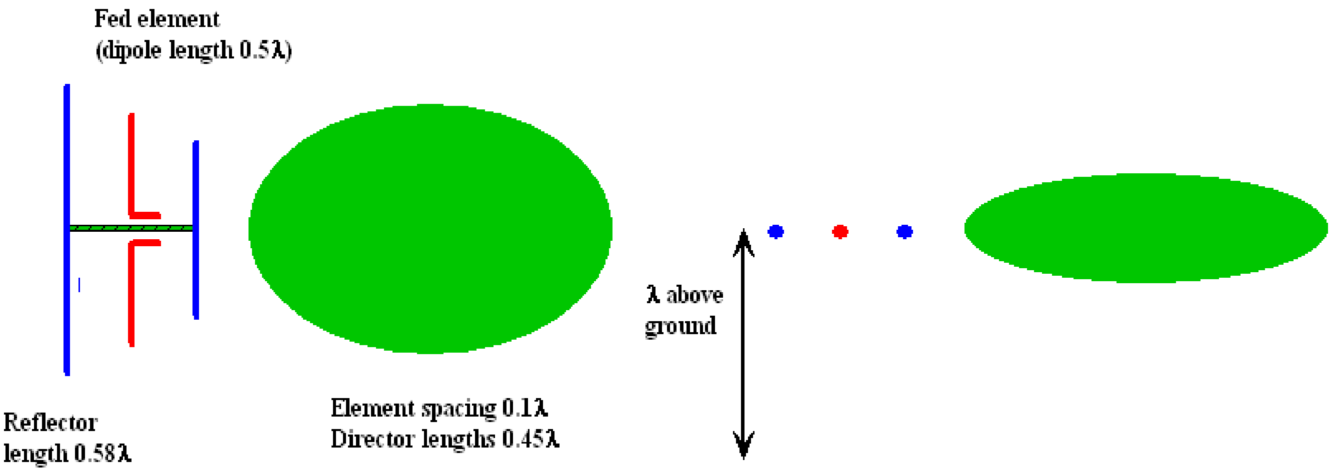
The figure below shows the configuration of a 6 element Yagi-Uda antenna with all the dimensions, this configuration would give a maximum directivity of about 12 dBi (compare this with the log-periodic shown



earlier)

The Yagi-Uda makes use of the guided wave effect to increase the directivity by using elements of the correct length. In particular, the length of the reflector which is made slightly longer then the driven element, as such having slightly inductive properties and therefore reflecting the EM energy, and the directors which are slightly shorter than the driven element and therefore are slightly capacitive, attracing the EM energy.

The simplest form of a Yagi-uga is the 3 element version shown below, along with its associated radiation pattern.



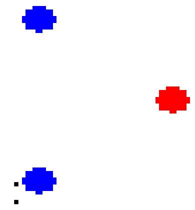
It is not surprising that the element spacing and lengths are critical (as with the log-periodic) in order to get a specified performance. However unlike the log-periodic, the element spacing is more or less equal throughout the antenna and is normally about 0.2λ between directors. However, the reflector/ driven element spacing has quite a large effect on the feed-point impedance as shown in the example table below.

Reflector spacing (λ)	***Feedpoint impedance***
0.25	**62**
0.18	**50**
0.15	**35**
0.13	**22**
0.1	**12**

With regard to the element lengths, it is usual to have the driven element at 0.48λ (same as a dipole) with the reflector length at +10% and the directors at –10% that of the driven element.

In general terms, doubling the number of directors will double the gain, but this becomes less and less worthwhile as you approach 12 directors, and in fact the largest TV antennas have 24 elements, but this is mostly to reduce 'ghosting', a problem associated with having large sidelobes.

Backlobes and sidelobes are always an issue with Yagi-Udas as they are with any high gain antenna. Reduction in backlobe radiation is usually accomplished by using more that one reflector element , which can sometimes look just like a corner reflector. However considerable improvements can be obtained just by using two reflectors as shown below in end view.



Sidelobes can be reduced by using gain tapering techniques. In terms of a Yagi-Uda this takes the form of increasing the number of directors, but changing the spacings and lengths, so that you don't increase the overall gain, but change the guiding properties of the antenna, thus reducing the sidelobes.

So far we have looked at dipole arrays which are one dimensional are give very well characterised performance. The logical extension of this would be, that it should be possible to use a combination of parallel and collinear arrays to form a two dimensional array with highly directional properties: not only that, but by adjusting the phase of the signal to each element (assuming that all elements can be independently driven) it would be possible to electronically steer the main antenna lobe, without physically having to move the antenna. This type of antenna is called a phased array and the procedure involved is called **pattern synthesis** .

Clearly the issues in terms of designing a phased array are numerous and involve principally:

- The size of the array in terms of the number of elements horizontally and vertically. This will determine the directivity/beamwidth.

- The distance between the elements. With a spacing of $\lambda/2$ to λ, you will get one main lobe and smaller sidelobes. With a larger spacing than λ you will get the same number of main lobes as the number of $\lambda/2$s eg: a spacing of $7\lambda/2$ will give 7 main lobes.

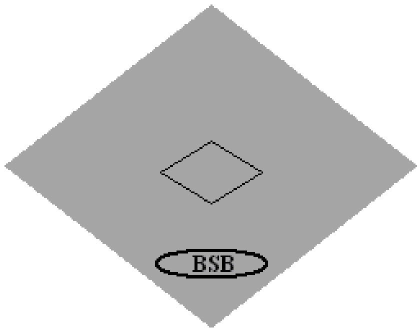
- The phase adjustment for feeding each element. This determines the way the array radiates in terms of the direction of the main lobe.

♦ The type of elements to use (frequency, bandwidth etc:)

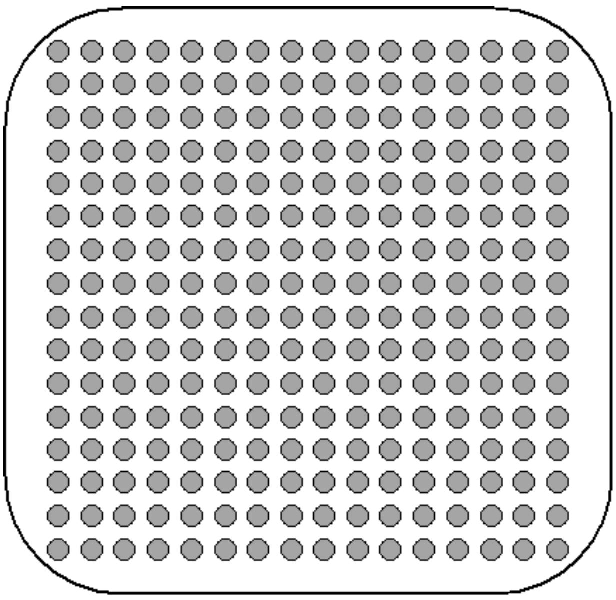
Electronically steerable phased array are almost exclusively the preserve of the military for target tracking purposed and are not likely to make an appearance on the domestic market due to the cost. However fixed 2 dimensional phased arrays have been available for some time, a classic example of which is readily identifiable but now obsolete, the B.S.B 'Squarial'. There are similar antennas available which are in direct competition to the parabolic dish for satellite broadcast receiving.

The 'Squarial' design gives a good insight into the complexity of making a phased array antenna actually work.

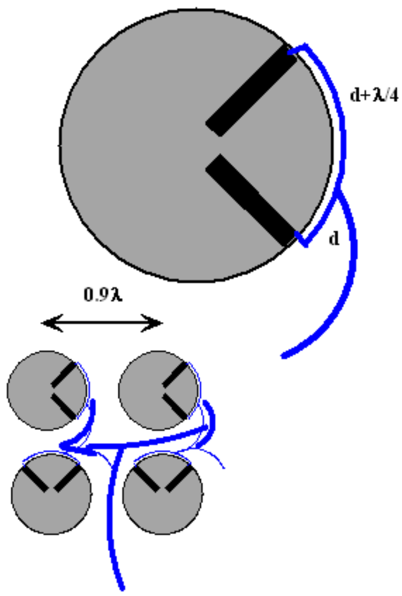
The Squarial is slightly smaller than a conventional sat dish and can still occasionally be seen on house walls.



Inside, it consists of a 2 dimensional array (16x16) of orthogonally disposed monopole pairs (for right hand circular polarisation) with an appropriately phased feed arrangement.



16x16 array



The feed arrangement allows all the elements to receive the signal in-phase so that they can be combined to give a total gain of about 33dBi (beam width 4°). However, because the distribution of elements is uniform across the array and the array is completely 'filled', the physical size of the array is considerably smaller than the 60cm diameter parabolic dish, which would be required to give the same gain at the same frequency.

The effect if of this rectangular aperture distribution is that the antenna has very large side lobes, because there is no gain taper.

To get round this problem, the antenna is diagonally oriented, as show in the top picture. With this orientation, the sidelobes are not pointing towards the satellite, but are above and below the line of satellite thus negating their effect.

With the phased array, like any other high gain antenna, the law of diminishing returns applies. So, just by increasing the number of elements ie: the physical size of the array, will increase the gain, but only up to a certain point (around 40dBi) this is because of the losses occurring in the feed network.

It is actually quite interesting to compare the **gain of an array antenna**, by measuring the aperture, to the theoretical gain figure obtained by counting the number of elements.

If we take the Squarial as an example. We can have a good idea of the gain by using the physical dimensions. The array is square with a side length of 36 cm and we shall assume 80% efficiency (better than a parabolic dish).

Since $\mathbf{D = \frac{4\pi A}{\lambda^2}}$

Then $D = \frac{0.365 \times 0.365 \times 4 \times \pi}{0.0256 \times 0.0256} = 2550$

Therefore the gain is 2550 x 80% = **33dBi**

We can now do the same exercise by knowing the gain of each element in the array and then ‘multiplying’ it by the number of elements.

Each element has gain of approx 8dBi (x2, due to the pair of monopoles) and there are 256 monopole pairs.
When the number of elements doubles, the gain goes up by 3dB, as shown in the table below.

No of elements	Gain increases by	Total gain
1	0dB	8dBi
2	3dB	11dBi
4	6dB	14dBi
8	9dB	17dBi
16	12dB	20dBi
32	15dB	23dBi
64	18dB	26dBi
128	21dB	29dBi
256	24dB	32dBi

Hence overall gain is 8 + 24 = **32 dBi**

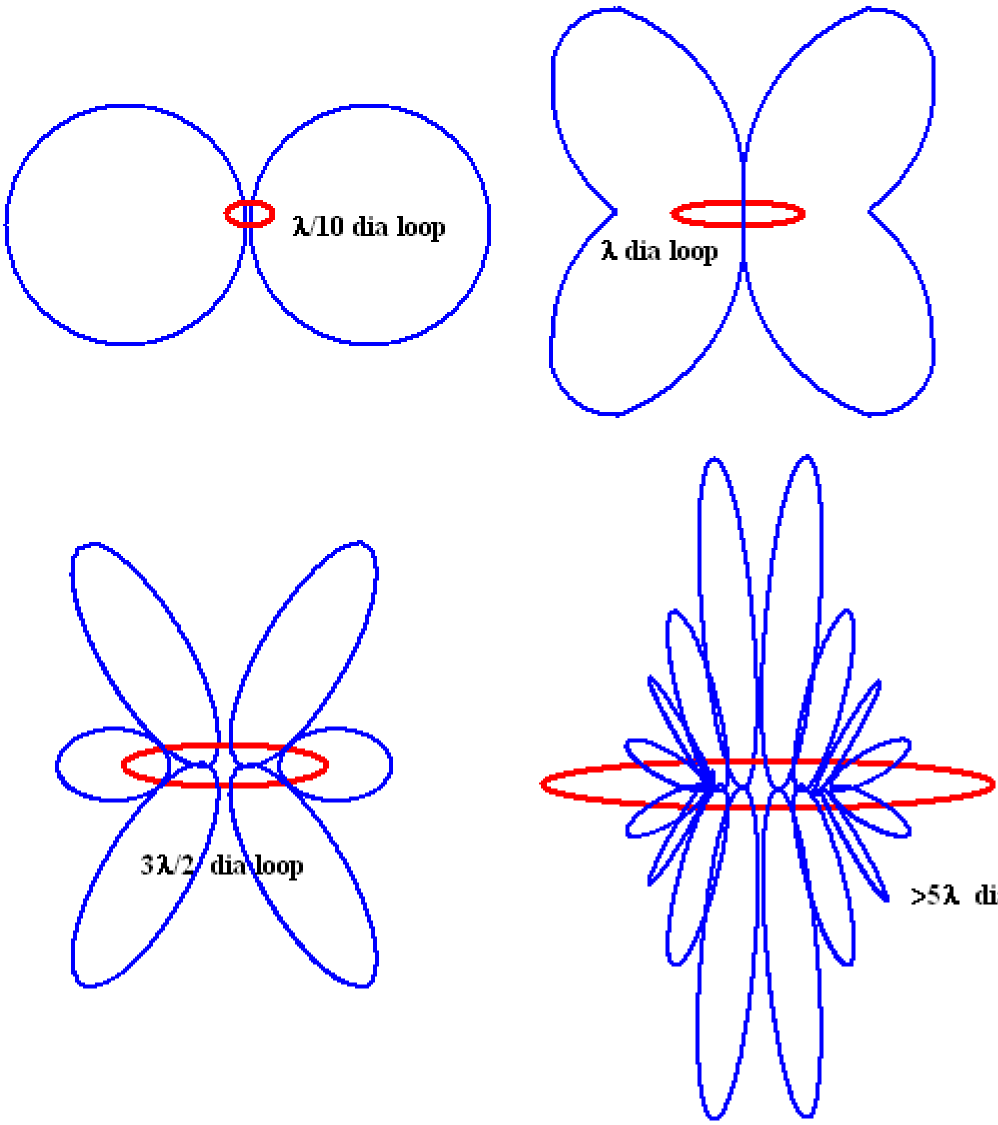
The figures are fairly close, but not exact due to an array being ‘more than the sum of its parts’. However, provided you have access to the array panel, counting the number elements is a very quick way of obtaining an approximate gain value for the array.

The main reason that parabolic dishes dominate the satellite communications business, is that they are relatively low cost, and they don’t have the same gain limitations. However, the phased array antenna is a compact and discrete antenna and is now finding its way into the domestic market, from purely aesthetic terms this, is to be welcomed.

Element antennas other than the dipole.

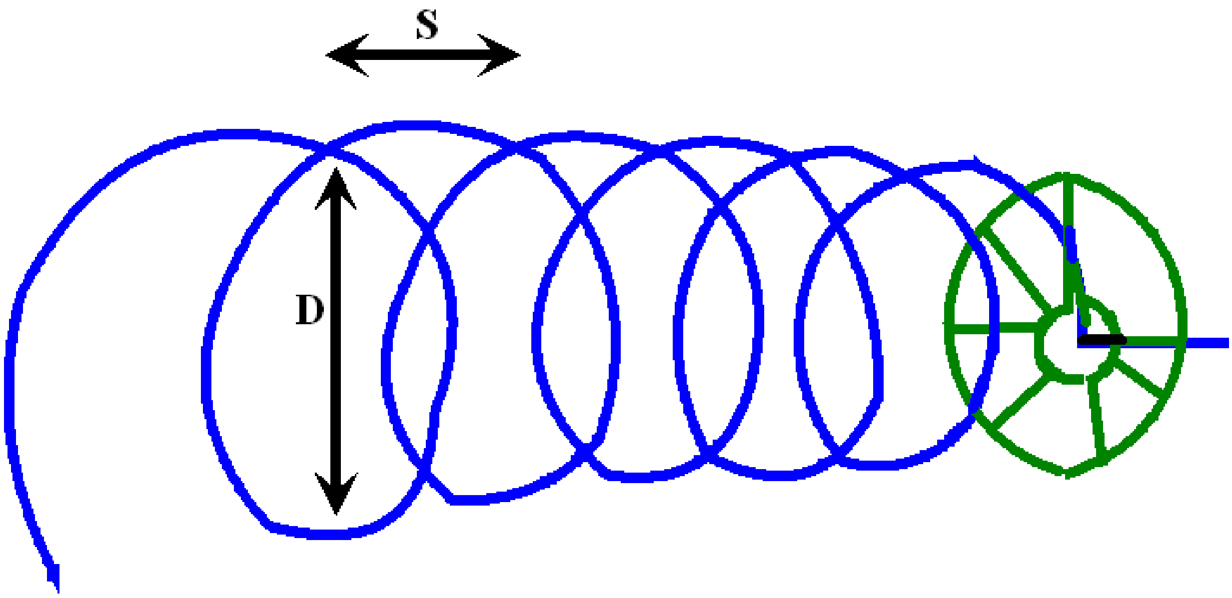
Whilst the dipole and its derivatives seem ubiquitous, there are other very distinct types of elements antennas, which justify closer examination. The first of these are the loops and helixes.

Starting with the simple small loop antenna. This antenna behaves similarly to the Hertzian dipole in terms of its general characteristics and has radiation characteristics as shown in the diagram below.



It is noticeable that as the loop becomes larger than a wavelength, the region of high radiation intensity migrates from the horizontal towards the vertical.

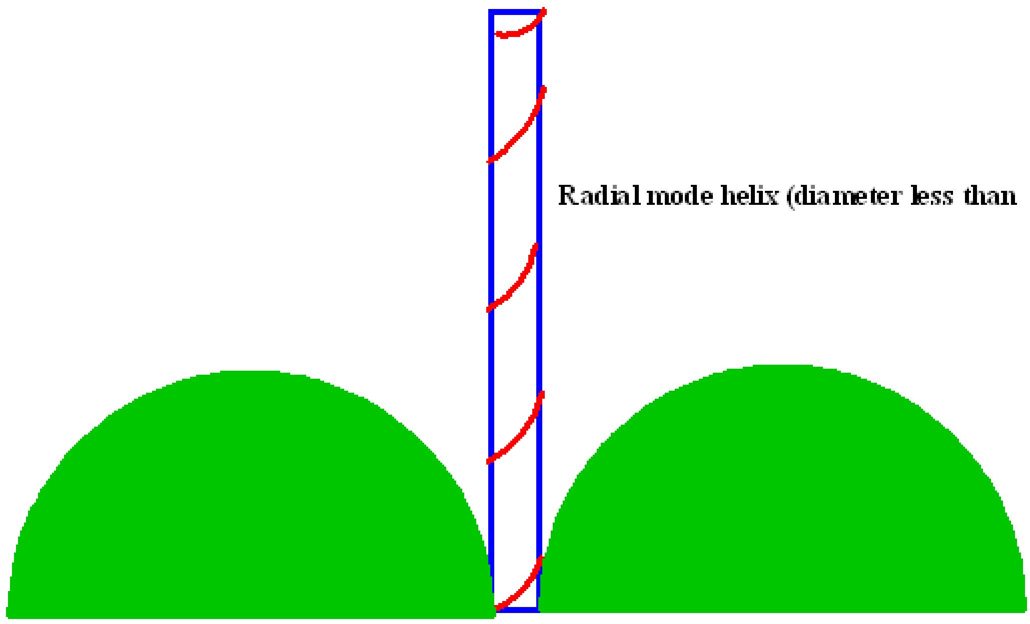
The logical extension to the loop antenna, is the helix or helical antenna. This is similar to a series of equally spaced loops and has characteristics, which in certain modes have highly directional properties. The figure below shows the general arrangement of a helical antenna with its principle dimensions.

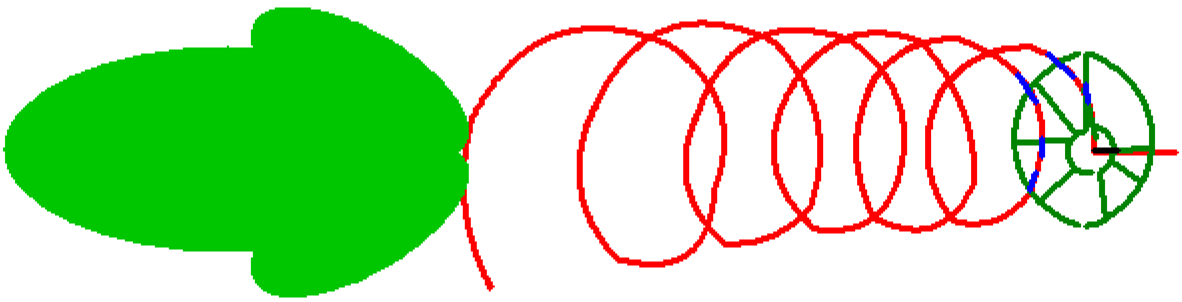


Helices have two main modes of operation: the first is the radial mode, which is similar to that of a monopole. The helix operates in this mode when the diameter D is less than about 1/10 λ. In this mode the helix often finds an application in for example the mobile phone, replacing a ¼ λ monopole, because it is very compact in comparison.

The other mode of operation for a helical antenna is called the axial mode and occurs when the diameter of each turn is greater than 1/3 λ. The figure below shows the antenna in its axial (end-fire mode).

With antenna in this mode, polarisation is circular and the directivity can be increased just by increasing the number of turns, and is commonly used at VHF and UHF as a transmitting antenna on weather satellites.





The equations which follow enable an axial mode helical antenna to be designed.

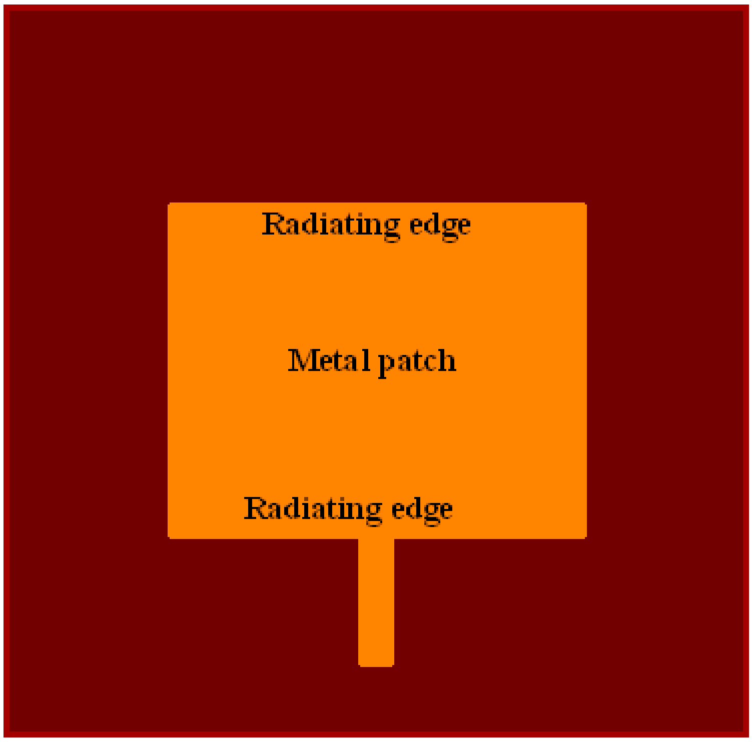
The Helix can be specified in terms of spacing between turns **S** (where $S = C \sin\alpha$) and **N**, which is the number of turns.

Assuming that: a) the pitch angle α (i.e.: the slope of the spiral) is between 12 and 14 degrees. b) the circumference C, of each turn is such that $3/4 < C/\lambda < 4/3$.

Input impedance, resistive: $\mathbf{R = 140(C/\lambda)}$
Half-power beam-width: $\mathbf{HPBW = 52\lambda^{3/2}/(C\sqrt{NS})}$
Directivity: $\mathbf{D_0 = 15N(C^2S/\lambda^3)}$
Axial ratio: $\mathbf{AR = (2N+1)/2N}$

Patch antennas

Microwave patch antennas usually take the form of metallisation deposited onto an insulating substrate. The geometry of patches is extremely varied and is a separate field of study in its own right. However, we shall look at the basics and concentrate on rectangular patches, as shown below. These patches tend to radiate from the 'long edges', due to it being a major discontinuity.

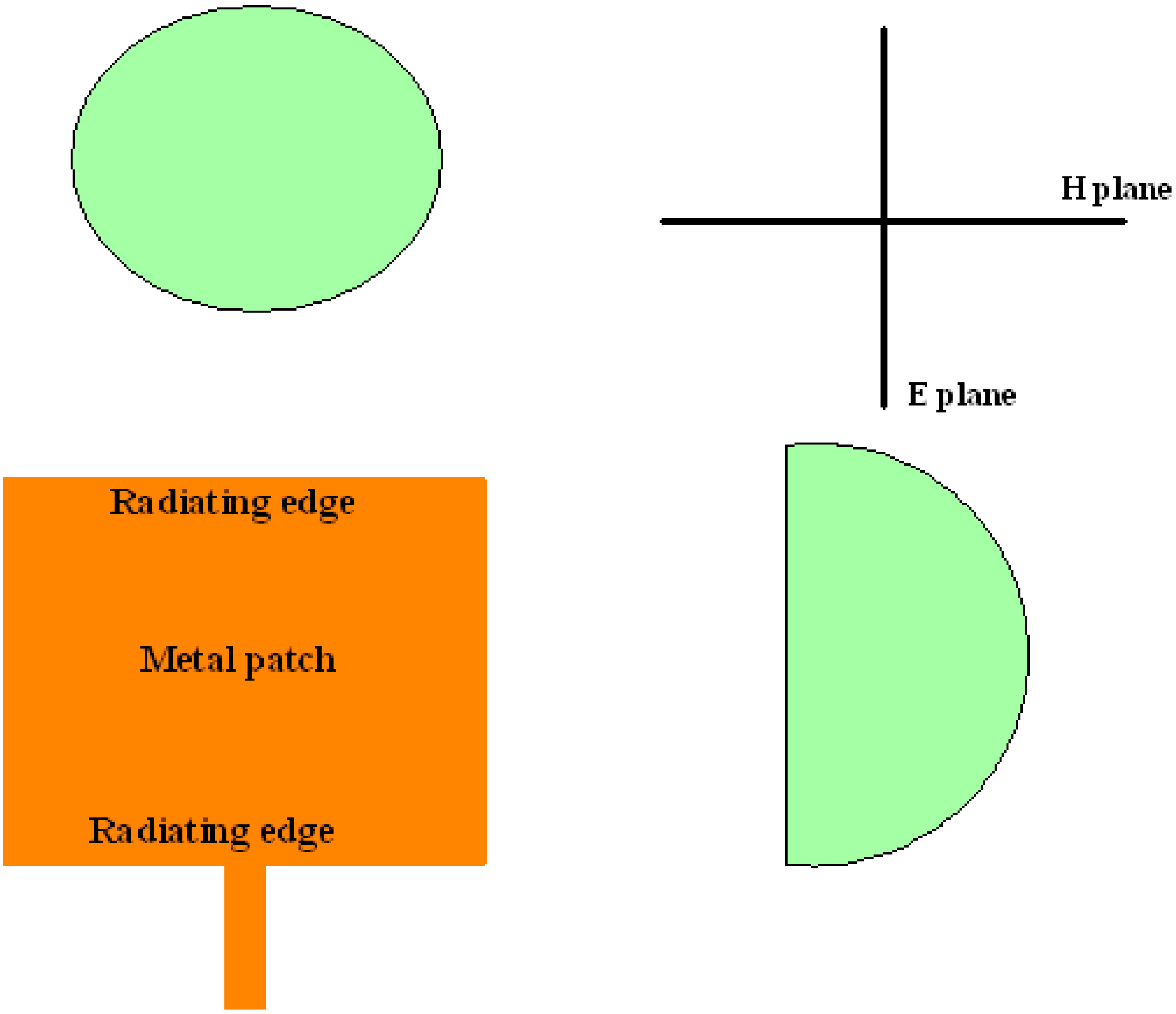


It can be seen that the patch antenna can almost be viewed as part of a transmission line structure with the antenna part being designed specifically to radiate. The equations below relate to the rectangular patch, and give an indication as to the approximate dimensions required of a patch to operate a particular frequency.

$\mathbf{A = \lambda_0/2}$ and $\mathbf{B = \lambda_d/2}$ where $\lambda_d = \lambda_0/\sqrt{\varepsilon_r}$

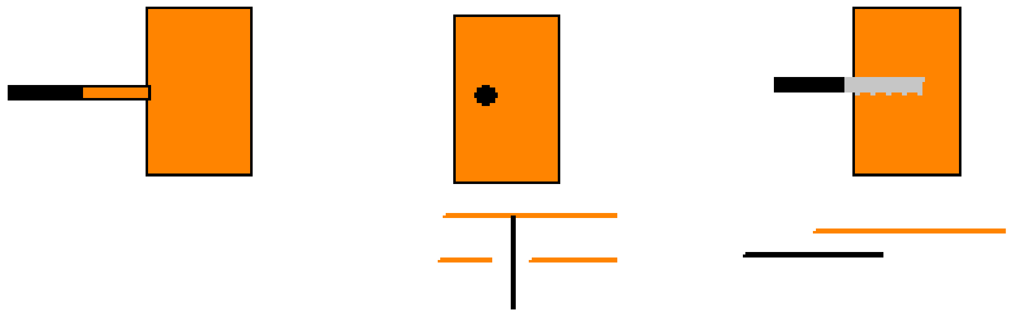
Where **A** and **B** are the dimensions of the patch, λ_0 is the free space wavelength and ε_r is the dielectric constant of the substrate. However these are very approximate.

The diagram below shows the orientations of the **E** and **H** plane and shows a typical radiation pattern for a patch.



The radiation pattern shows that the patch has a radiation pattern not dissimilar to a horizontal dipole, but because of the ground plane, the 'bottom half' is not present.

There are 3 main ways of feed arrangements of feeding patches each with its own advantages and disadvantages:



Microstrip:
Advantages: single layer ,good polarisation
Disadvantages: needs matching (inset feed), unwanted coupling

Coaxial cable:
Advantages: variable modes, better impedance matching
Disadvantages: poor polarisation purity

Capacitive coupling:
Advantages: flexibility with substrates, no dc contact from feed
Disadvantages: difficult fabrication

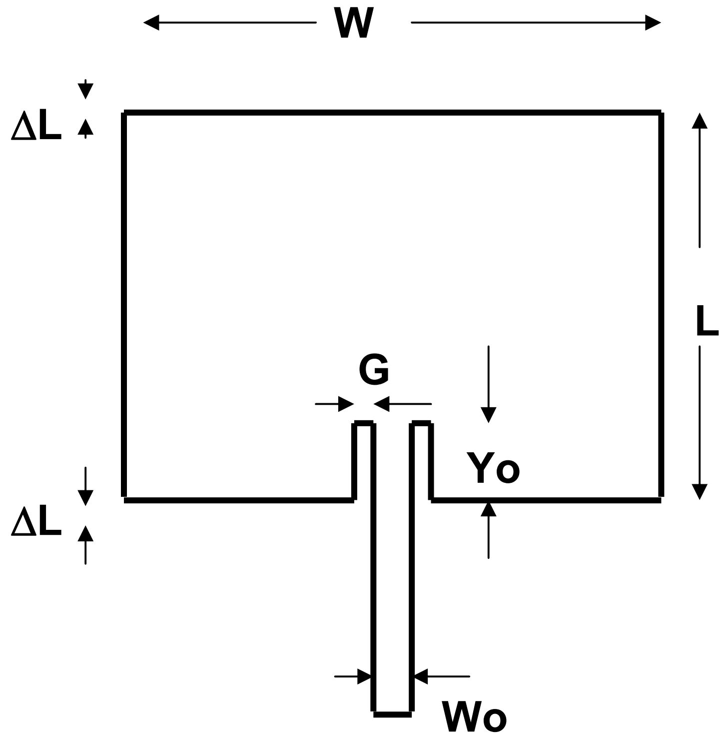
The properties of the substrate on which the patch is fabricated has a bearing on the performance of the patch. In general, the substrate should have as low a dielectric constant as possible. However, the patch can be miniaturised by using a high ε_r at the expense of efficiency.

Using thin substrates gives low dielectric losses, however thick substrates are preferred since they give good radiation efficiency and wider bandwidth. Typically the substrate thickness will be $\lambda/100$.

There are some clear advantages in using microstrip patch antennas over conventional wire antennas, such as very low profile, ease of integration into other RF circuits, low cost and simplicity in creating arrays: but also some disadvantages, such as poor efficiency, narrow bandwidth, poor polarisation purity and spurious radiation.

Design example for a rectangular patch antenna to operate at 11.7 GHz, utilising an inset microstrip line feed.

The arrangement of the patch is shown below, with parameters.



Other parameters which have to be considered, are the substrate thickness **h,** which is normally of the order of 0.025 λ and the dielectric constant of the substrate ε_r.

In order to calculate the patch dimensions it is also necessary to consider the 'fringing effect', which actually has the effect of making the physical patch slightly smaller than might be imagined.

Step 1: Calculate patch width, **W**

$$= \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{\upsilon_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}}$$

Where: $\nu = 3 \times 10^8$ ms^{-2}, $\varepsilon_r = 2.33$ and $f_r = 11.7$ GHz

Then **W** = 9.9 mm

Step 2: Calculate effective dielectric constant, ε_{eff}

$$= \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right)$$

Where substrate thickness, h = 0.8mm

Then ε_{eff} = 2.14

Step 3: Calculate actual patch length **L** and the extension length Δ**L**, (due to the fringing effect), which combined give the effective length

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{eff}}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L$$

$$\Delta L = 0.412h\frac{\left((\varepsilon_{eff} + 0.3)\left(\frac{W}{h} + 0.264\right)\right)}{\left((\varepsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.8\right)\right)}$$

Using previously calculated and known values:
Δ**L** = 0.4mm
Therefore **L** = 8.7 mm – 0.8mm = 7.9mm

Step 4: Find inset feed-point distance $\mathbf{Y}_o$, to get desired i/p impedance of 50 Ω.

$$Z_{in} = R_i \cos^2\left(\pi/L\right)Y_0$$

Where required $\mathbf{Z}_{in}$ = 50 Ω,

$\mathbf{R_l}$ = impedance of patch edge

$$= \frac{1}{2(G_1 \pm G_{12})}$$

With $\mathbf{G_{12}}$ being negligible and

$$G_1 = \frac{1}{90}\left(\frac{W}{\lambda}\right)^2$$

Using previously obtained values, $\mathbf{G_1}$=0.0017

Therefore $\mathbf{R_i}$ = 294 Ω
Now, using

$$Z_{in} = R_i \cos^2 (\pi/L) Y_0$$

We get , $\mathbf{Y_0}$ = 2.9 mm

Finally, the last two dimensions, $\mathbf{W_0}$ and **G**
$\mathbf{W_0}$ is simply the width of a 50 Ω transmission line in microstrip on a 0.8mm substrate with an ε_r of 2.33. This can be calculated using RF software or looked up in any good RF engineering book. In this case, $\mathbf{W_0}$ is calculated as being 2.33mm.

G, for the sake of simplicity can be assumed to be approx $\mathbf{W_0}/2$, Hence = 1.15 mm.

So, the patch antenna is now completely specified in terms of its dimensions for a given substrate.

It hardly needs to be said, but the reverse side of the substrate would be covered in copper, to produce the ground plane.

The radiation pattern has been shown previously and is somewhat similar to that of a horizontal dipole, (slightly narrower main lobe due to a larger effective aperture) this, combined with the ground plane (+3dBi) would give an overall gain for the patch of 6–7 dBi.

Ground planes

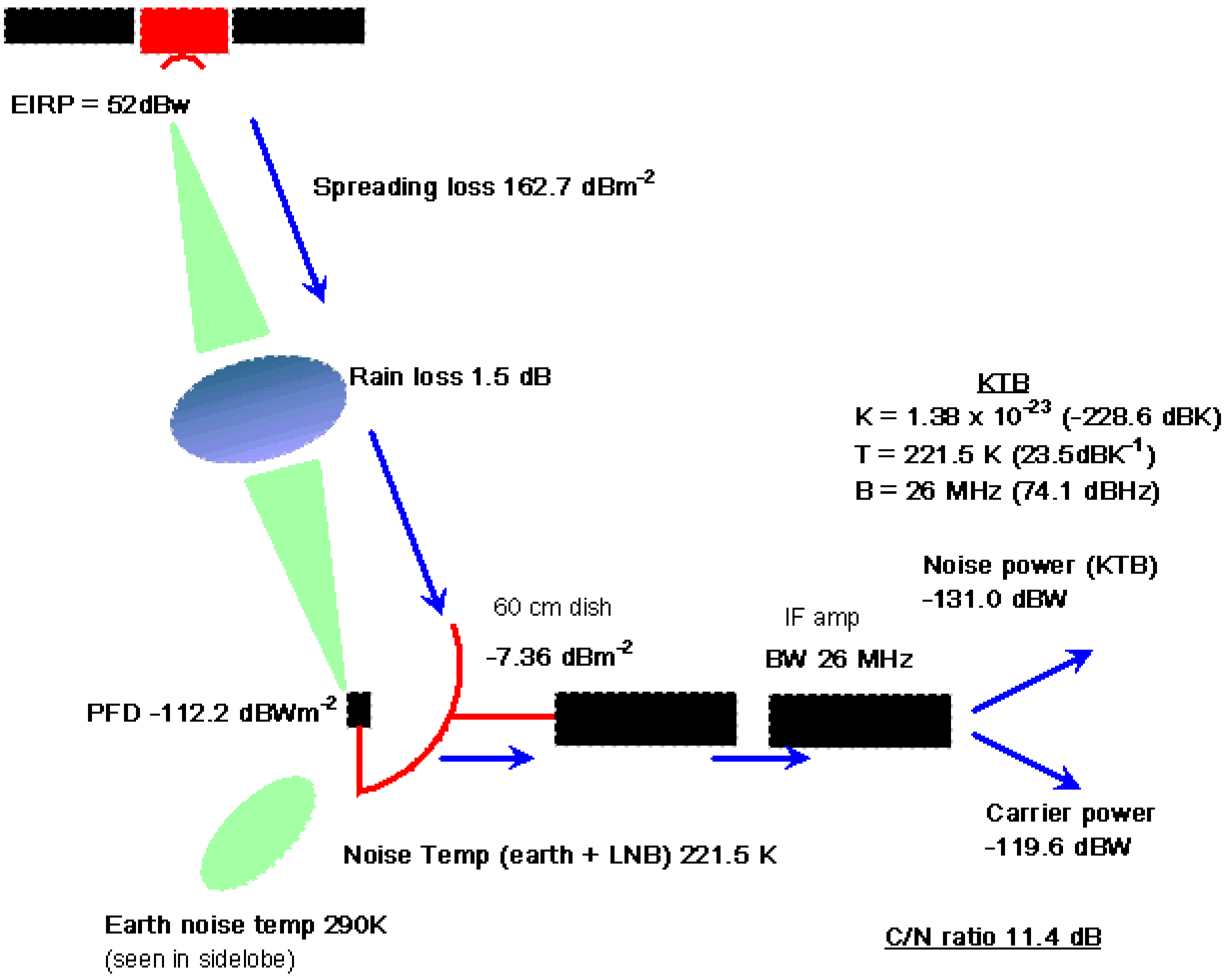
You will have noticed that patch antennas (mostly) have a ground plane (GP). This effectively forces the patch to radiate forwards, (broadside from the patch surface) since the ground plane acts as a reflector. The GP size is matched to the patch antenna using optimisation, but is typically slightly larger that the patch itself.

We have already discussed the principle of ‘antenna height’, that is, the effect of the real ground on the behaviour of an antenna. But there are other situations however, where GPs have to be considered. The most obvious of these is where an antenna is fitted to a metal skinned vehicle (car, aeroplane etc). Typically a λ/4 monopole will be fitted in a perpendicular position to the metal skin (ground plane) and will work quite well, provided the metal skin is large enough. This is not usually a problem, since the antennas are typically in the VHF or UHF bands and therefore have wavelengths in the region of 3m to 30cm. In vehicle applications, the requirement of the ground plane being at least 1λ in diameter will be easily met and therefore the antennas can be fitted and expected to work quite well. This large GP can be treated as an infinite GP.

What happens if the GP is too small ? eg, it is less than 1λ in diameter. Well, for a standard λ/4 monopole fitted to, for example to a ground plane of λ/2 diameter, the impedance will not be the same as it would be if fitted to an infinite GP, and the antenna length would have to be adjusted to give an appropriate impedance match. In a situation where the antenna length could not be adjusted, for instance a fin type antenna used for aircraft transponders, then you would have to get as close as possible to an infinite GP if you don’t have a metal skinned vehicle, which could be achieved by using a 1λ diameter metal plate. For applications where you could ‘tune’ the monopole, then a λ/2 GP would be ok, but no smaller. However, the metal disk could be replaced by wire radials, minimum of 4, better with 8. These are rods in the same plane as the ground and are spaced at equal angles to each other (90° in the case of 4 rods)

It would be expected that the effect on the radiation pattern of fitting a monopole to a finite GP, would be to eliminate any radiation below. This is not the case, and in fact the RF energy ‘leaks’ round the GP and gives what appears to be smallish lobes underneath, somewhere between 10 and 20 dBs below the maximum. The half doughnut above the GP is also somewhat distorted, with ‘waisting’ at the point where the radiation should be at a maximum.

Link budgets, or how much power will be available at the receive end, and therefore how much antenna gain will be required?



Given certain pieces of information it is possible find out whether the antenna specified is big enough for the application. This is because the primary problem in any reception system is obtaining a good enough signal to noise ratio, to be able to have signal with usable information when decoded, data, TV picture etc.

This set of calculations is called a link budget and the following example is for analogue satellite TV reception.

So, what do we need ?

Since we are working out the S/N ratio (actually carrier to noise), we need the carrier power and the noise power.

Lets start with the information available !

The signal is coming from Astra1 and the system parameters are as follows:

EIRP, **52 dBW** (assuming that the receiver is in the middle of the footprint ie: on boresight of satellite antenna)
Slant distance to satellite D_s, **38670 km**
Rain attenuation (rain also raises noise temperature), **1.5 dB**
Parabolic dish size, **60 cm**
Receiver IF bandwidth, **26 MHz**

It is very helpful to convert everything into dBs

1/ Calculate carrier power

EIRP = **52 dBW**
Spreading loss = $1/4\pi D_s^2$ (spherically) = 5.3×10^{-17} = **-162.7 dBm^{-2}**
Rain attenuation = **1.5 dB**

Power flux density (PFD) is 52 + (-162.7) –1.5 = **-112.2 dBWm^{-2}**

Effective capture area of antenna $A_e = \pi(d/2)^2\eta$, assume 65% eff.
$A_e = 0.184\ m^2$ = **-7.36 dBm^2**

<u>Therefore, carrier power available is –122.2 + (-7.36) = **-119.6 dBW**</u>

2/ Calculate noise power

Noise power, KTB where
Total system temperature T =173.9 k + 47.6 k = 221.6k = **23.5 dBk**
Boltzmann's constant K = 1.38×10^{-23} = **-228 dBk**
Receiver IF bandwidth B = 26 MHz = **74.1 dBHz**

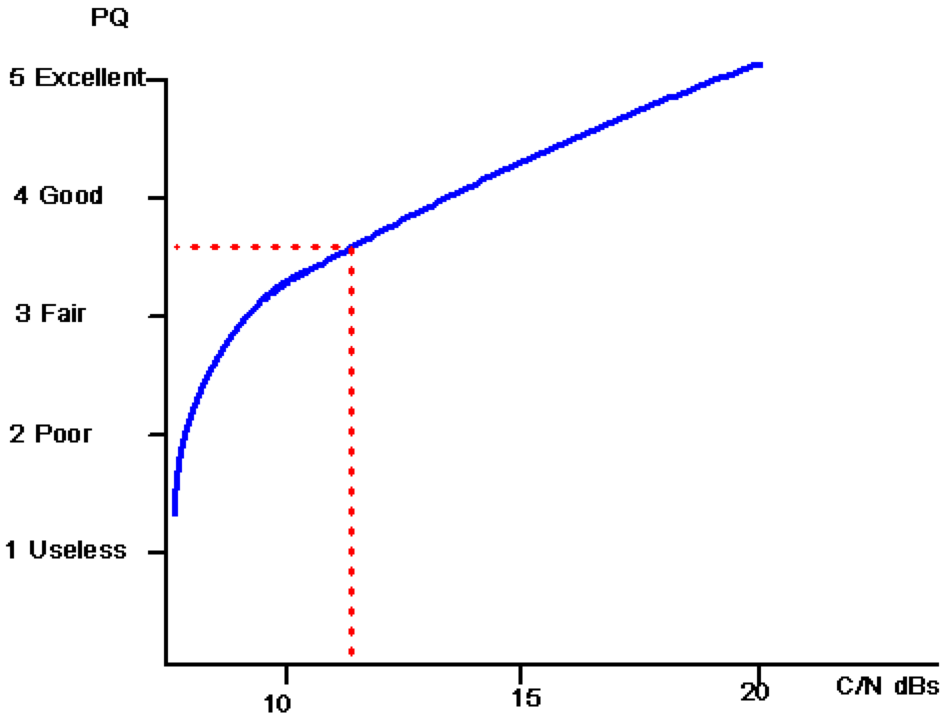
<u>Therefore, Noise Power = 23.5 = (-228) +74.1 = **-131.0 dBWHz^{-1}**</u>

3 Calculate carrier to noise ratio

<u>In dBs = -119.6 - (-131.0) = **11.4 dBs**</u>

This corresponds to a signal to noise ratio of about 43 dBs.

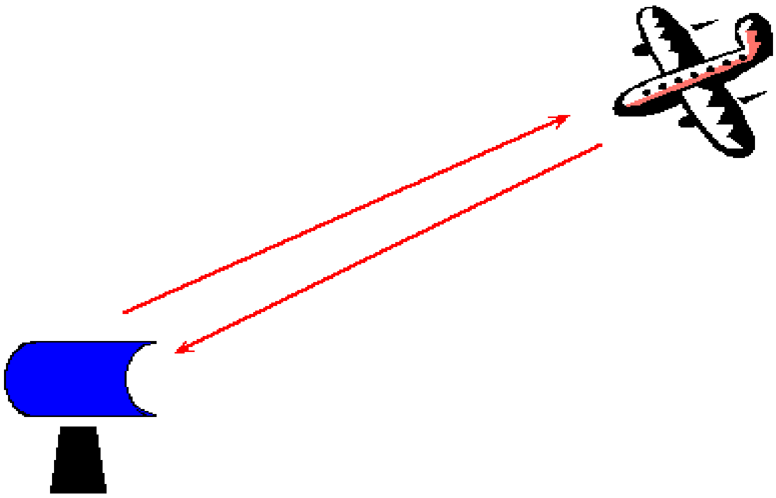
The question is, is this enough to ensure a good TV picture. Well, the graph below shows C/N ratio against picture quality and as you can see, anything above 10 dBs is watchable.



A similar system exists for working out link budgets for **digital** systems, which uses the Bit Error Rate (BER), which for a C/N ratio of 11.4 dBs would be around 10^{-6} and therefore provide a picture in the Excellent category, rather that Fair/Good, as it is in the analogue case.

Hence, one of the reasons for going over to digital, smaller dishes required (actually about half the size).

Another example of link budgets, although not exactly obvious, is calculating the range of a radar system, such as the one below.



Given the radar equation:

$$R^4 = \left(\frac{P_t G_t G_r \sigma \lambda^2 L_s}{(4\pi)^3 N.(SNR)} \right)$$

R = range in m, P_t = transmitter power
G = antenna gain (Tx & Rx)
σ = Radar cross section in m^2
λ = signal wavelength in m
L_s = system loss factor
N = noise power
SNR = signal/ noise ratio

> Some forms of the radar equation use received power P_r instead or N.(SNR), since they are equivalent, but in real situations you need to factor in the noise.

With the following parameters;

Transmitter power =10kW
Frequency 2.8GHz, and hence λ = 0.11m
Aircraft radar cross section(RCS) $\sigma = 10^2\ m^2$
Noise power = -140 dBW
SNR = 10dB
Antenna diameter equiv =$2.5m^2$, and hence gain (at 70 % efficiency) = 35 dBi
System loss factor = 0.3

First convert everything into dBs: and remember the antenna gain has to be counted twice (used for transmit and receive)

P_t = 40dBW
G_t = 35 dBi
G_r = 35 dBi
λ^2 = -19 dB
σ = 20 dBm^2
L_s = -5.2 dB
$1/(4\pi)^3$ = -33 dB
1/N = 140 dBW
1/SNR = -10dB

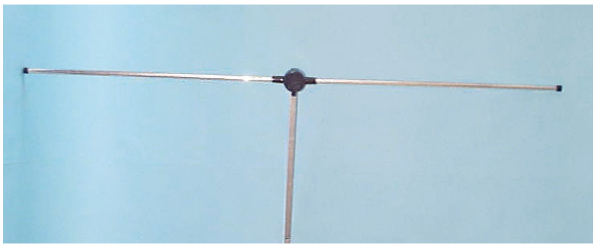
Then add them all up: Giving R^4 = 202.8 dBm^4

Therefore, range R = 202.8/4 = 50.7 dBm = 117490m or **117km**

It is easy to see that the radar range can be increased, by using a larger antenna (rather than using a higher power transmitter).

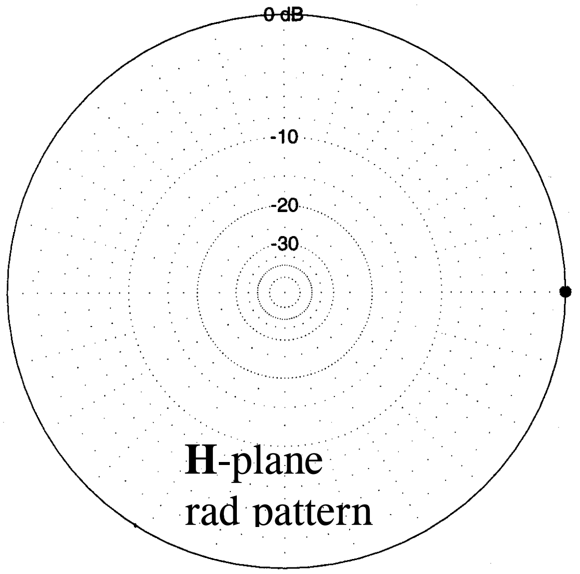
In fact to double the range of the radar, the antenna would have to have 4 times the gain (4 times larger in terms of area) to achieve this, and this is true for any ‘monostatic’ radar.

Antenna # 1 **_The $\lambda/2$ Dipole_**



Main Characteristics:

- Element type antenna
- Linear polarization
- Low gain ~ 2.15dBi
- Narrow bandwidth < 5%
- Non – dispersive
- Z_{in} = 73 Ω @ 1st resonance
- Omni-directional in **H** plane
- 3dB beamwidth in **E** plane 78°
- Very high efficiency >98%
- Virtually infinite scaleability
- Simple to fabricate



Dipole in free space

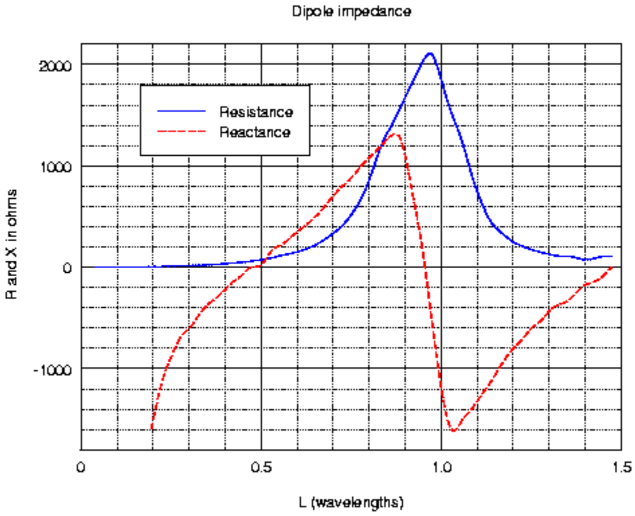
Applications:

- Long range communications
- **E**-field probes
- General radio & TV reception

Variants:

- Cylindrical dipole (wideband)
- Biconical (very wideband)
- Bow-tie (planar biconical)

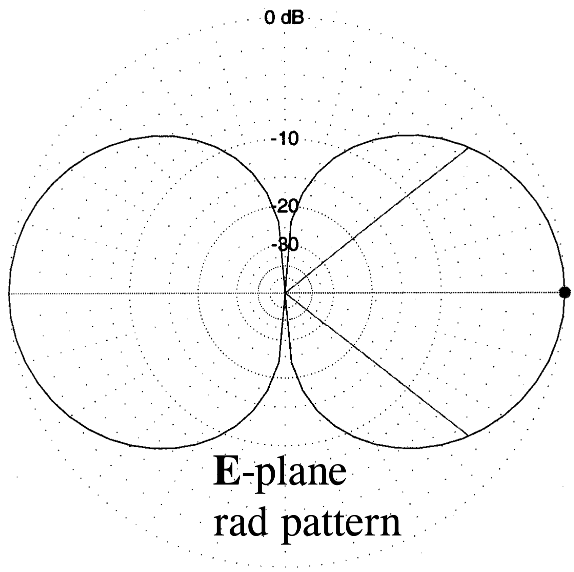
Input impedance



Useful Information:

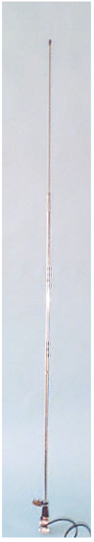
Overall length = 0.48λ

Element diameter ~ 0.005λ



Dipole in free space

Antenna # 2 *The λ/4 Monopole*



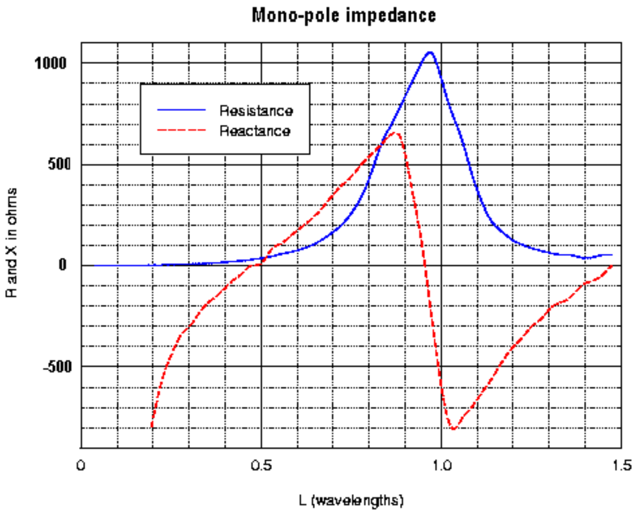
Applications:

- Radio and TV broadcasting
- General radio & TV reception
- Mobile phones

Main Characteristics:

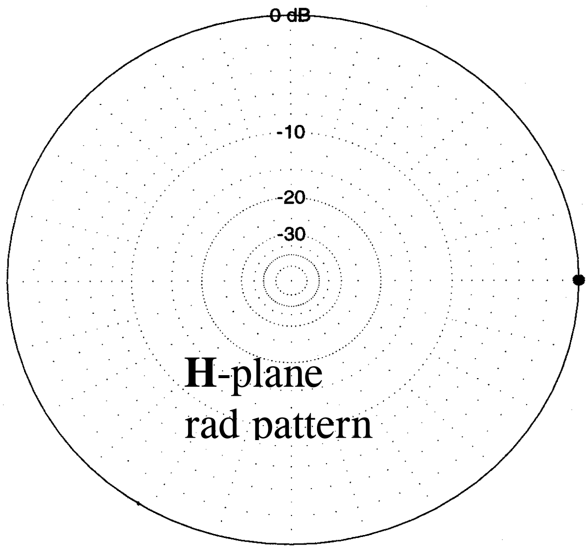
- Element type antenna
- Linear polarization (vertical)
- Low gain ~ 2.15dBi
- Narrow bandwidth < 5%
- Non – dispersive
- $Z_{in} = 37 + j0\ \Omega$ @ 1st resonance
- Omni-directional in **H** plane
- 3dB beamwidth in **E** plane 39°
- Very high efficiency >98%
- Very good scaleability
- Simple to fabricate

Input impedance

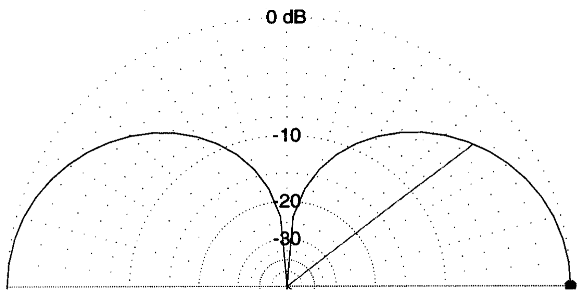


Useful information:

Length = 0.24λ

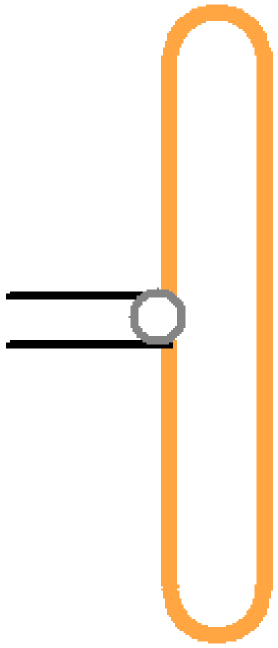


H-plane
rad pattern



E-plane
Rad pattern

Antenna # 3 ***The Folded Dipole***

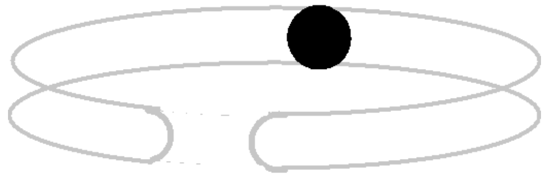


Applications:

- Used in arrays, particularly at UHF for mobile comms
- General radio & TV reception

Variants:

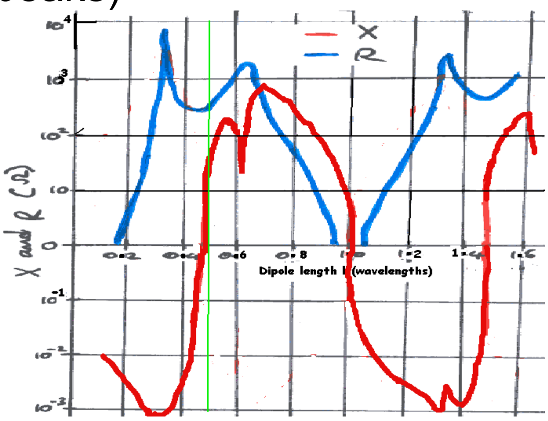
- The Omni-directional Antenna (very low gain ~ --5 to –2dBi)

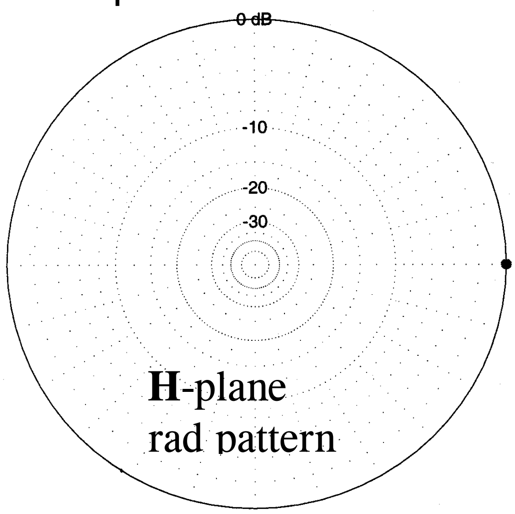


Main Characteristics:

- Element type antenna
- Linear polarization
- Low gain ~ 2.0dBi
- Fairly wide bandwidth ~ 20%
- Non – dispersive
- $Z_{in} = 288 + j0\ \Omega$ @ 1^{st} resonance
- Omni-directional in **H** plane
- 3dB beamwidth in **E** plane 80°
- Very high efficiency >98%
- Very good scaleability
- Simple to mount & robust

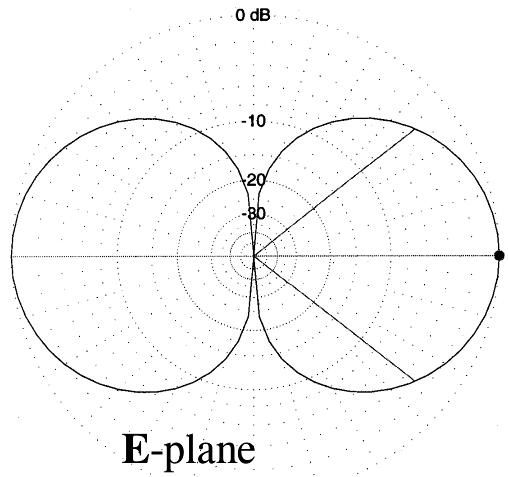
Input impedance (note double peaks)





H-plane rad pattern

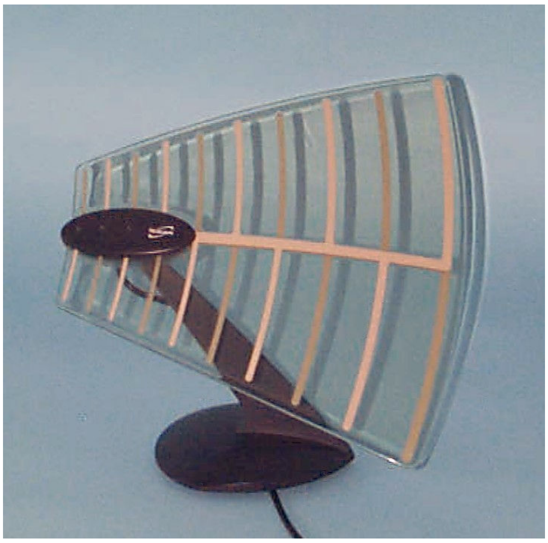
Dipole in free space



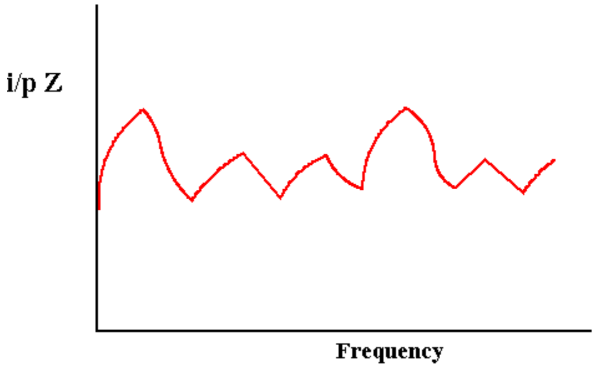
E-plane rad pattern

Dipole in free space

Antenna # 4 ***The Log-periodic Dipole Array***



Input impedance

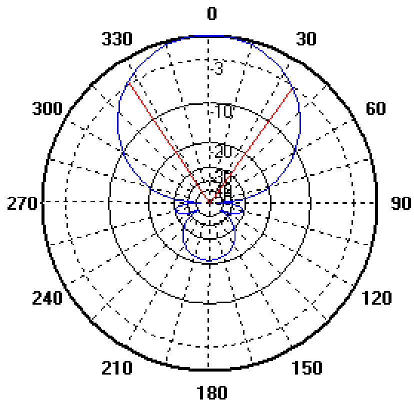


Main Characteristics:

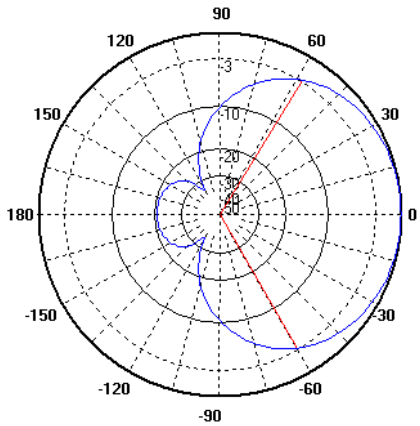
- Array antenna
- Linear polarization
- Moderate gain ~ 4 to 8 dBi
- Very wide bandwidth > 150%
- Very dispersive
- Z_{in} = 50 to 100 Ω
- 3db beamwidth in **H** plane 80° to 160°
- 3dB beamwidth in **E** plane 60° to 80°
- High efficiency >90%
- Scaleability factor 1000
- Complicated to fabricate

Radiation patterns

E plane



H plane



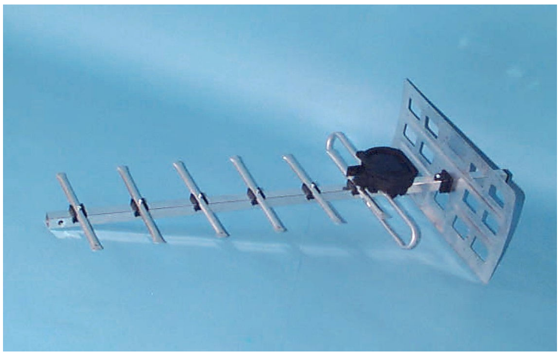
Applications:

- EMC testing
- General radio & TV reception

Variants:

- Planar toothed array

Antenna # 5 ***The Yagi-Uda***



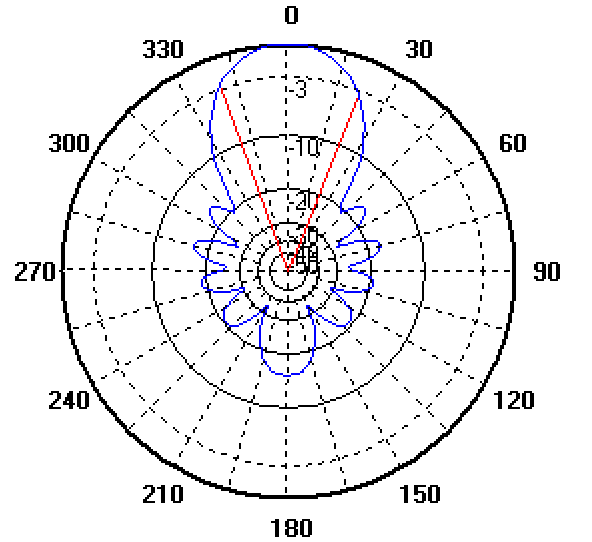
Main Characteristics:
- Array antenna
- Linear polarization
- High gain ~ 5 to 18 dBi
- Narrow bandwidth ~ 5 to 10%
- Non dispersive
- Z_{in} = 50 to 300 Ω
- 3db beamwidth in **H** plane 30° to 90°
- 3dB beamwidth in **E** plane 30° to 90°
- High efficiency >90%
- Scaleability factor 200
- Complicated to fabricate

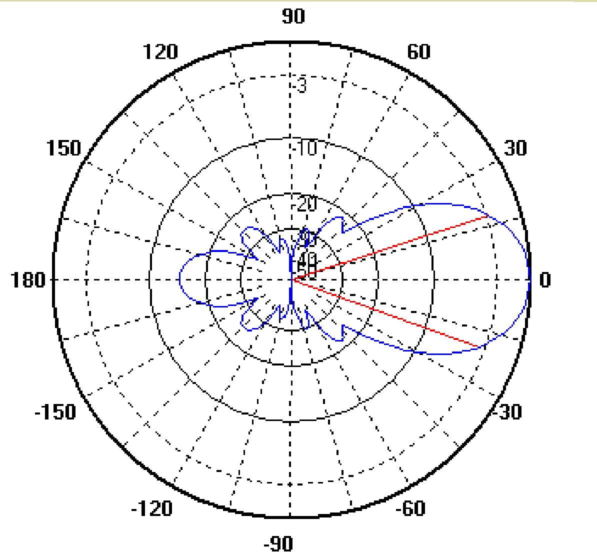
Applications:
- Satellite communications
- General radio & TV reception

Variants:
- Loop yagi

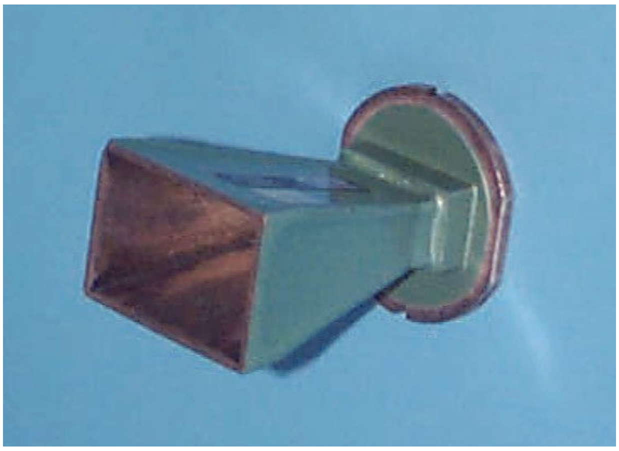
Impedance characteristic similar to that for a folded dipole, but with adjustable i/p impedance.

Radiation pattern, **H** plane (top) and **E** plane (bottom)





Antenna # 6 ***The Rectangular Horn***



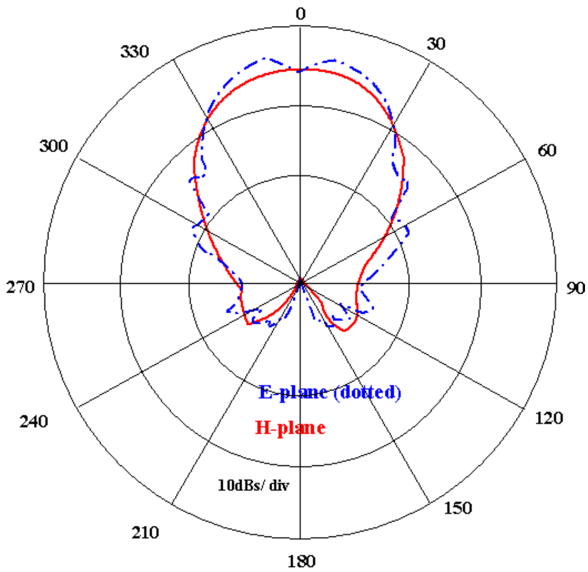
Variants:

- Conical horn
- Ridged horn (very wide bandwidth)

Main Characteristics:

- Aperture antenna
- Linear polarization
- High gain ~ 5 to 20 dBi
- Wide bandwidth ~ 67%
- Quite dispersive
- Z_{in} = 216 Ω (TE_{10} mode)
- 3db beamwidth in **H** plane 20° to 120°
- 3dB beamwidth in **E** plane 20° to 120°
- Moderate efficiency ~50%
- Scaleability factor 1000
- Simple to fabricate

Radiation pattern, **E** and **H** plane superimposed.



Applications:

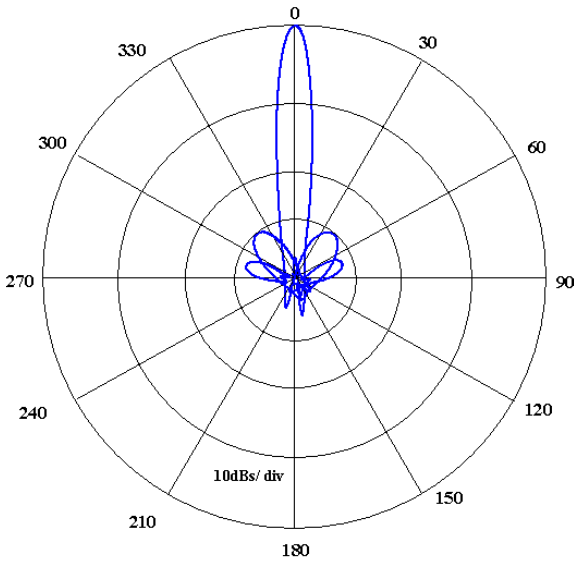
- Satellite communications
- Radio astronomy
- Microwave radar
- Gain standards
- Parabolic dish feed

Antenna # 7 ***The Parabolic Dish***

- Point to point links

Variants:
- Prime focus feed
- Offset feed
- Cassergrain feed
- Gregorian feed
- Hemispherical dish

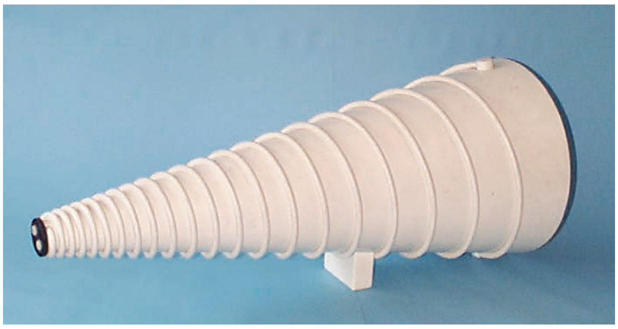
Typical radiation pattern, **E** and **H** plane superimposed.



Main Characteristics:
- Reflector antenna
- Polarization dependant on feed type.
- Very high gain ~ 10 to 60 dBi
- Wide bandwidth ~ 67%
- Non dispersive
- Z_{in} = Depends on feed type
- 3db beamwidth in **H** plane 0.25° to 30°
- 3dB beamwidth in **E** plane 0.25° to 30°
- Fairly good efficiency ~ 70%
- Scaleability factor 1000
- Difficult to fabricate

Applications:
- Satellite communications
- Radio astronomy
- Microwave radar

Antenna # 8 ***The Axial-mode Helix***

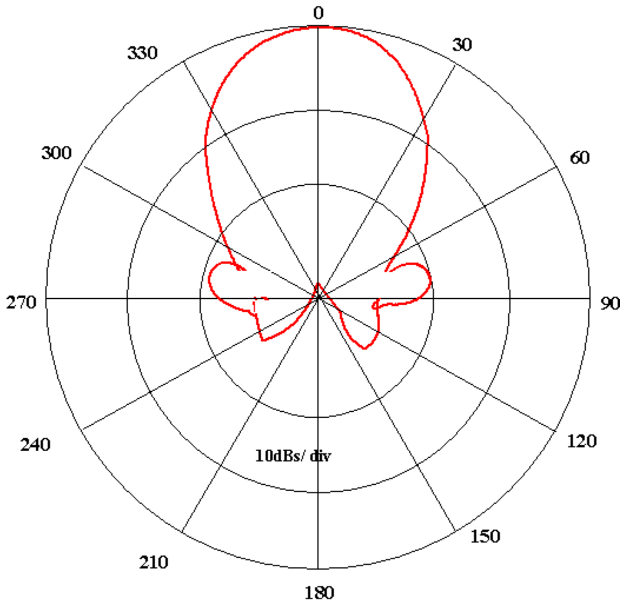


Variants:
Log conical spiral as seen in photo (very wide bandwidth)

Main Characteristics:

- Element antenna
- Circular polarization
- High gain 10 to 35 dBi
- Wide bandwidth ~ 60%
- Quite dispersive
- Z_{in} = 110 to 180 Ω
- 3db beamwidth in **H** plane 2° to 30°
- 3dB beamwidth in **E** plane 2° to 30°
- Moderate efficiency ~ 50%
- Scaleability factor 1000
- Simple to fabricate

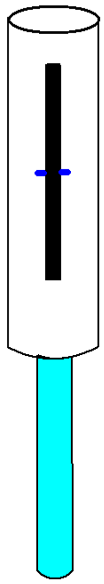
Radiation pattern,

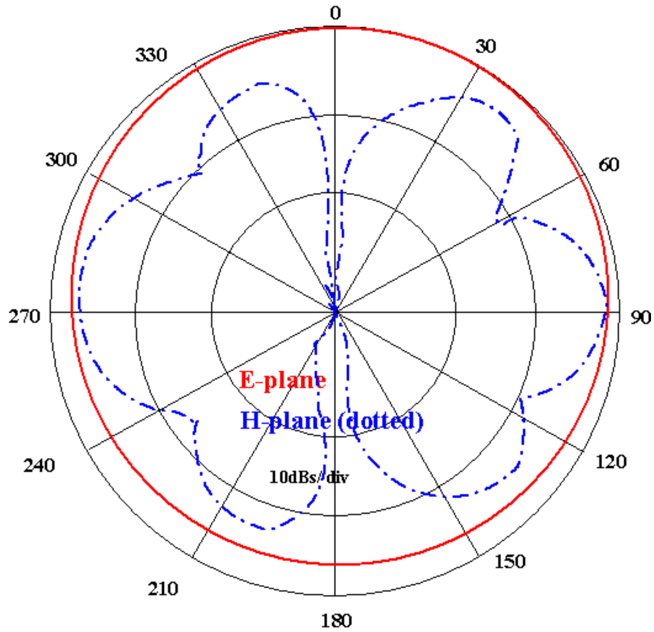


Applications:

- Satellite communications
- Parabolic feeds

Antenna # 9 ***The Alford Slot***





Main Characteristics:

- Slot antenna
- Linear polarization

  (with the antenna vertically oriented, E field is horizontally polarised)
- Low gain ~ 5 dBi
- Narrow bandwidth < 5%
- Non – dispersive
- $Z_{in} = 73\ \Omega$ @ 1st resonance
- Omni-directional in **E** plane
- 3dB beamwidth in **H** plane 78°
- High efficiency >90%
- Scaleability factor 10
- Difficult to fabricate

Applications:

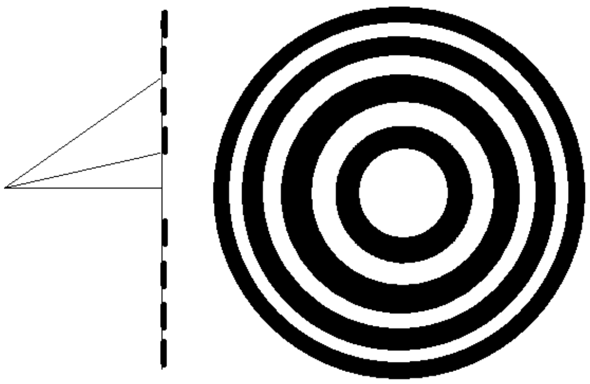
- UHF and microwave broadcasting

Useful data:

For resonance:
Diameter = 0.125λ
Length of slot = 0.75λ
Width of slot = 0.02λ

Antenna # 10 ***The Zone Plate***

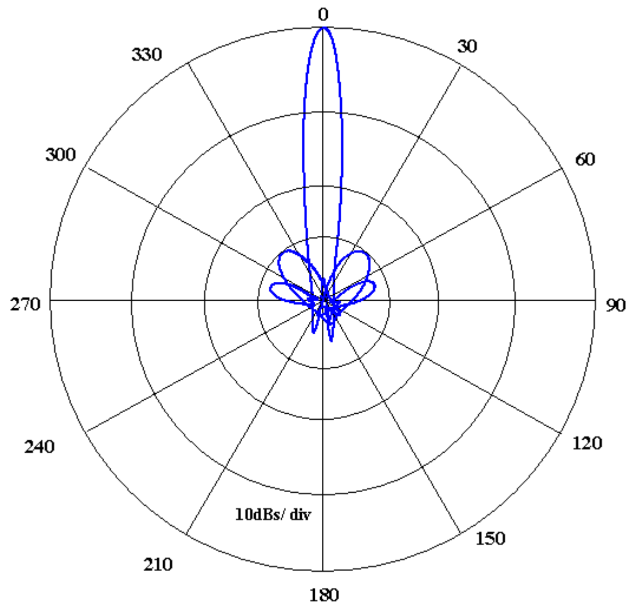
In essence, the lens antenna would have broadly the same characteristics as a similarly sized parabolic



Variants:

- Prime focus feed
- Elliptical zone plate
- Zone plate with reflective sheet (higher gain)

Radiation pattern, **E** and **H** plane superimposed.



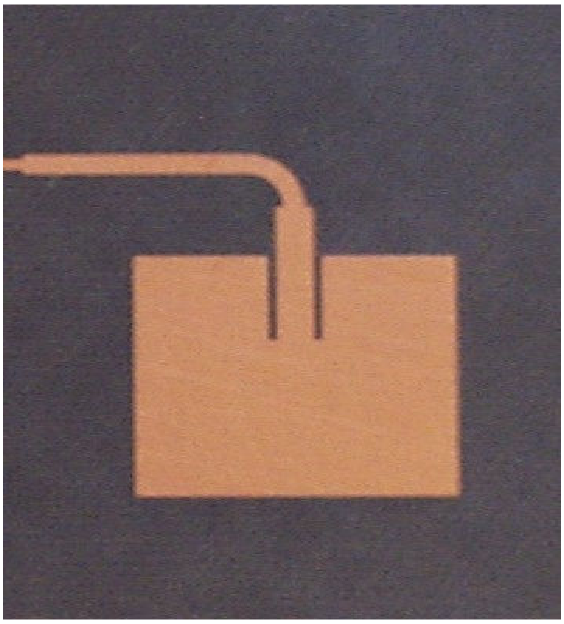
Main Characteristics:

- Refractor (lens) antenna
- Polarization dependant on feed type.
- Very high gain ~ 10 to 60 dBi
- Wide bandwidth ~ 67%
- Non dispersive
- Z_{in} = Depends on feed type
- 3db beamwidth in **H** plane 0.25° to 30°
- 3dB beamwidth in **E** plane 0.25° to 30°
- Fairly good efficiency ~ 70%
- Scaleability factor 10+
- Very difficult to fabricate

Applications:

- Satellite communications

Antenna # 11 ***The Microstrip Patch***

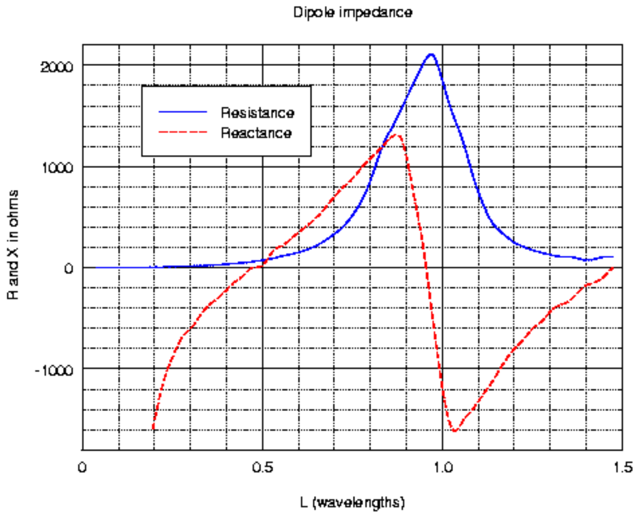


Main Characteristics:
- Element type antenna
- Linear or circular polarization depending on feed
- Moderate gain ~ 6dBi
- Very narrow bandwidth < 5%
- Non–dispersive
- Z_{in} = 50-200 Ω
- High efficiency 80-90%
- Very limited scaleability
- Simple to fabricate and integrate

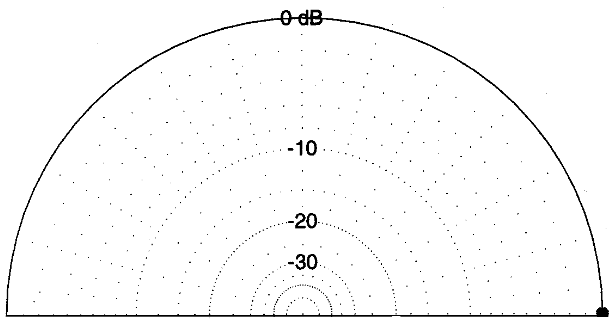
Applications:
- Cellular phones
- W-LANS
- Radar antennas

Variants:
- Too many to list

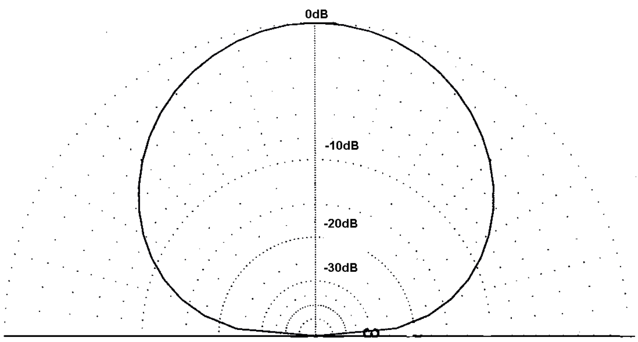
The Z plot shows that for a dipole and is broadly similar to that for a rectangular patch.



Useful Information:
Overall length and width ~ 0.5λ
Optimum spacing when part of multi-element array ~ 0.9λ
Almost always use ground plane

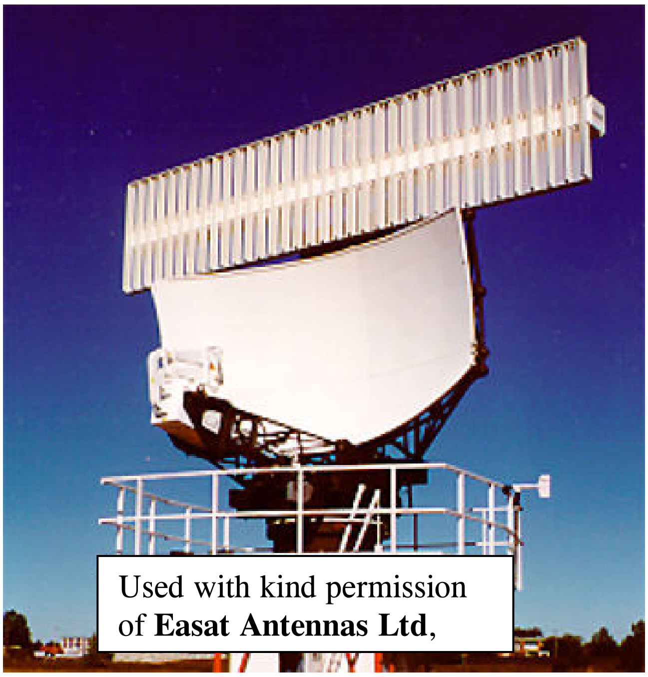


E-plane
rad pattern



H-plane
rad pattern

Antenna #12 **_Radar antennas_**



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The picture above shows a typical airport radar installation. This type of surveillance radar consists of two antennas, each of which has a specific purpose. However, they are rotated (scanned) on the same axis, with a rational speed of 1 revolution every few seconds.

1) The **primary radar** (PSR) has a horn fed parabolic reflector antenna (the lower antenna in the picture). This radar operates at 2.7-2.9 GHz and is designed to detect every aircraft within a 60 nautical mile (nm) radius and requires a very high power transmitter to do this. However, the information provided by this type of radar is somewhat limited, since it can only detect the distance and bearing of an aircraft and provides no identification data.

2) The **secondary radar** (SSR), has a broadside firing parallel element array type antenna (the upper antenna in the picture). Unlike the PSR, this type of radar can only 'see' aircraft fitted with a transponder and operates at around 1.0-1.1 GHz. However, because the transponder consists of a transmitter and receiver, the power required for SSR is very much lower than for PSR, additionally the information transmitted from the transponder on the aircraft also provides altitude and identification information with a range of up to 120 nm.

It is apparent from the **Radar Equation** below, that the gain characteristics of a radar antenna have a lot to do with the maximum range of a radar installation. The equation also shows two values for antenna gain, namely G_t and G_r. However, in most radar systems there is only one antenna (a mono-static radar), and in this case G_t and G_r would have exactly the same value.

$$R^4 = \frac{P_t G_t G_r \sigma \lambda^2 L_s}{(4\pi)^3 P_r}$$

R = range in m, P_t = transmitter power
G = antenna gain (Tx & Rx)
σ = radar cross section in m^2
λ = signal wavelength in m
L_s = system loss factor
P_r = received signal power

<u>Antennas: P&P/ M.P.</u>
Bibliography/ Recommended Reading

i) **The ARRL Antenna Book** 19th Ed. Pub: ARRL

ii) **Antennas** 3rd Ed. *G.Kraus, R.Marhefka*. Pub: McGraw-Hill

iii) **Antenna Theory** 2nd Ed. *C.Balanis.* Pub: Wiley

iv) **Applied Electromagnetics** 1999 Ed. *F.Ulaby.* Pub: Prentice-Hall

v) **Practical Antenna Handbook** 2nd Ed. *J.Carr.* Pub: McGraw-Hill

vi) **Antennas and Propagation** *S.Saunders.* Pub: Wiley

vii) **Printed Antennas for G.P.R** Ph.D 2000. *R.Clarke.* Pub: UoB

viii) **The Satellite Book** 5th Ed. *J.Breeds.* Pub: Swift TV Publications

ix) **Understanding Physics** 3rd Ed. *J.Breithaupt.* Pub: Stanley Thornes

x) **UHF/Microwave Experimenters Manual**. Pub: ARRL

xi) **Handbook of Microstrip Antennas** *J.R.James, P.S.Hall.* Pub: IEE

xii) **Radio Antennas and Propagation** *W.Gosling.* Pub: Newnes

Antennas: P&P/M.P

(University of Bradford ENG4002M & ENG3023M)

Web links

The following list gives the web links to useful sources of supporting material.

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www.tpub.com/content/neets/14182/css/14182_167.htm

www.ece.mcmaster.ca/faculty/georgieva/antennas.htm

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