ROYAL SCHOOL OF ARTILLERY

BASIC SCIENCE & TECHNOLOGY SECTION

Radar Antennae

INTRODUCTION

The radar antenna is the part of the radar system through which the radar energy enters and leaves. It determines the direction (azimuth and elevation) in which the radar is making observations and its properties have a considerable affect on the ability of the radar to detect echoes from the target. The precision of any measurements made by the radar are also affected by the antenna.

This handout describes the basic properties of antennae that are important in radar and includes some formulae that you can use to calculate important properties of antennae. This will enable you to compare the performance of different designs of antennae and to describe how the choice of antenna affects the performance of a radar system.

The radar systems that we will use to illustrate the theory will be 'generic' surveillance-radar systems as this avoids including information above 'RESTRICTED' in the handout. The generic systems that we will describe will be similar to those used in the Rapier, MStar and Cobra Radars.

DIRECTIONAL PROPERTIES

Almost all radars measure the range to a target. Most radars are also required to obtain information about the direction to a target, by measuring its angles of azimuth and/or elevation. [MVMD is an example of a radar that does not measure range or bearing - it measures velocity only.]

Two-dimensional radars (e.g. MSTAR) measure range and azimuth but not elevation; three-dimensional radars (e.g. Rapier FSB2, FSC) measure range, azimuth and elevation. It is the directional properties of the antenna that determine the ability of the radar to measure the azimuth and/or elevation of the target. These directional properties depend on the dimensions of the antenna and the wavelength (λ) that the radar

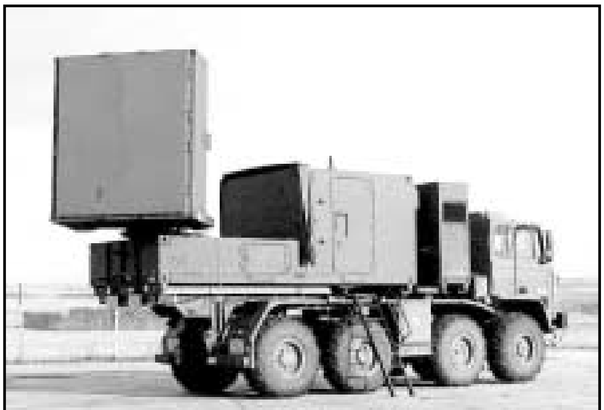


Figure 1: The COBRA Antenna

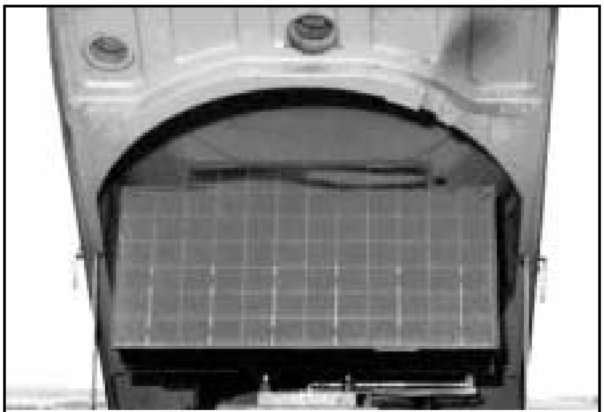


Figure 3: The Rapier FSB2 Antenna

uses. When considering the performance of any antenna then it is always necessary to know at least the dimensions of the antenna and the wavelength that is being used. [Remember that the wavelength (in cm) multiplied by the frequency (in GHz) is equal to 30.]

The Beam of a radar antenna: most people have seen the beam of light from a torch or searchlight and visualise a radar beam as being very similar. There are many similarities between the two types of beam but there are also some differences because the radar beam generally consists of a single frequency (or very narrow range of frequencies) of coherent waves, whereas most light sources (apart from lasers) produce a range of frequencies and are not coherent because the light is produced at random times, at random frequencies, individually, by millions of atoms that are heated in some way.

The meaning of beamwidth: when you shine a torch onto a distant object then you can often see a circle of light that the torch illuminates. In dusty air, the beam can often be seen directly. It seems to have sharply-defined edges but the sharpness of the edge is an illusion, as it is determined by the wavelength and, since the wavelength of light is less than 1 micron then

Figure 2: The MSTAR Antenna

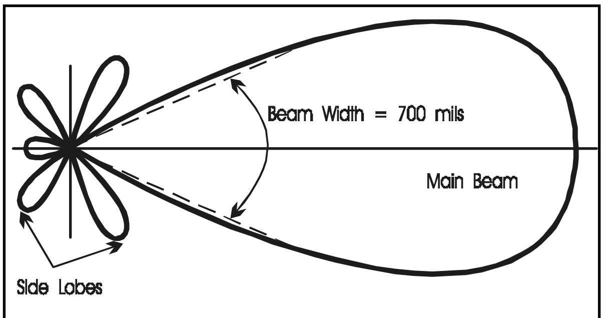


Figure 4: A Polar Diagram for a Radar Antenna

it merely seems sharp to the human eye. The wavelength of a radar wave is much longer than that of a light wave so the beam cannot have such a sharp edge.

Additionally, the sharpness of the beam is determined by the size of the lens or reflector that produces it. A torch reflector might be several centi-metres in diameter - perhaps 20,000 times bigger than the wavelength. The radar antenna would, typically, be only about twenty-times bigger than the wavelength and this also influences its ability to produce a narrow beam (see later for more details).

MEASURING BEAMWIDTH

To determine the directional properties of any antenna, it is connected to a source of EM energy and allowed to transmit the energy. By measuring the power levels at different azimuths (and elevations if required) around the antenna then its directional properties can be established. Since the power also varies with distance then all the measurements must be made at the same distance from the antenna.

The results are usually presented graphically, using polar coordinates. Each measurement of power is plotted at the azimuth where it was measured and marked at a distance from the centre of the graph that depends on the amount of power received along that azimuth. A typical graph showing the variation of power with azimuth, called a ‘polar diagram’, is illustrated in Figure Four. The diagram shows a ‘Main Lobe’, pointing to the right, showing where the majority of the power goes. It also shows a number of ‘Side Lobes’ that indicate additional directions, other than the main beam, into which the antenna also radiates power.

Any antenna has the same properties whether receiving or transmitting, so a polar diagram can also be produced by rotating a receiving antenna near a transmitter and monitoring the power that it receives in different orientations. The same diagram will be obtained..

Definition of Beam Edge: one feature of the radar beam is that it does not have an abrupt edge. The power in the beam fades way as you move away from its centre. The ‘edge’ of the beam is defined as the position where the power has reduced to one half of the power in the centre. (This is often expressed in deci-Bel units as the –3 db point, because –3 db represents half power in deci-Bels.) The beamwidth is the angle between the two points of half power.

An ideal antenna should emit all its energy into the main beam and no energy should go anywhere else. However, this is very difficult to implement and all antennae emit some energy in ‘side-lobes’. In the diagram of Figure Four, the main beam is pointing East but there are additional and much smaller beams (side-lobes) pointing North-East, North-West, etc.

For a simple dish antenna, the power level in a side-lobe is typically about $^1/_{20}$ of the power in the main beam. This creates severe problems in a radar if, as the antenna rotates, a side-lobe points towards the ground or a nearby metallic object. The radar echo from a side-lobe can reduce the efficiency of the radar by masking the weak echoes from real targets.

An additional problem with side-lobes is that they provide an entry point for enemy jamming signals. Any signal that enters the radar receiver via a side-lobe would be assumed to have come from the direction towards which the main beam was currently pointing.

Reducing side-lobe power: there are two methods that can be used to reduce the levels of power in the side-lobes:

- **mechanical design**: any object that lies in the path of the EM waves as they enter or leave the antenna could deflect energy away from the main beam and produce a side-lobe. This includes supports for the feed-horn and these are often placed below the beam (e.g. Radar Tracker of Rapier) to avoid this.
- **tapered illumination**: the worst side-lobes occur when the EM energy is emitted or received uniformly across the antenna. If the power levels are made higher in the centre part of the antenna and reduced (tapered) towards the edge of the antenna then the power in the side-lobes is much reduced. (The power must reduce in a very specific and precise way - not just a vague reduction near the edge.)

These features are relatively easy to implement in a phased-array antenna, such as Cobra, where the front of the antenna is completely clear and the power to each individual element can be precisely set to minimise side-lobes. It is possible, with careful antenna design, to reduce the sidelobe power to less than -50 dB, compared to the main lobe. This means that the power in a sidelobe is $^1/_{100,000}$, or 10^{-5}, of the power in the main beam.

BEAM SHAPE

A surveillance radar, that needs to measure the azimuth of a target, requires a beam that is relatively narrow in azimuth (e.g. two or three degrees) in order to measure the target’s bearing accurately, but relatively wide in elevation (e.g. ten degrees) in order to be sure of detecting targets at low and high altitude. The antenna required to achieve this is asymmetric: its width is greater than its height.

A tracking radar, that needs to measure the direction to a target, measures this by pointing directly at the target in azimuth and elevation. This requires a symmetrical antenna, with a beam narrow both in azimuth and elevation.

If you could see radar waves in a similar way to light, then just as shining a torch onto a wall produces a small, round spot of light so the tracking radar would produce a small round spot of light whereas a surveillance radar would produce a tall oval spot.

BEAMWIDTH FORMULAE

When the antenna uses uniform illumination, where the power is applied equally over its entire surface, then the beamwidth, Θ_b, is given by:

$$\Theta_b = \frac{60\,\lambda}{D} \text{ degrees} \qquad (1)$$

where 'λ' is the wavelength in use and 'D' is the distance across the antenna. For a circular antenna, 'D' is its diameter; for a square antenna, 'D' is the length of one side. When the antenna is oval or rectangular then there will be two values of 'D': the horizontal measurement (width) of the antenna will determine its beamwidth in azimuth and the vertical measurement (height) of the antenna will determine its beamwidth in elevation.

When the antenna uses tapered illumination then the beamwidth is increased because the surface of the antenna is not being fully utilised to produce the beam (the centre is used in preference to the edges). For a typical taper that makes the power at the edge of the antenna $^1/_{10}$ of the power in the centre then the beamwidth is given by:

$$\Theta_b = \frac{70\,\lambda}{D} \text{ degrees} \qquad (2)$$

In Formulae One and Two, the diameter 'D' and the wavelength 'λ' must be converted to the same unit of measurement. Use either metres for both or centimetres for both.

Remember that the beam does not have a clearly defined edge; the beam width is defined using the half-power points. There is still significant power beyond the nominal edge of the beam. The above formulae, therefore, give only an indication of the directional properties of an antenna. (See 'beam splitting', below.)

You should note that 'D' appears at the bottom of the above equations. This means that using an antenna of increased diameter (or height/width) of will cause a decrease in the beamwidth. The bigger the antenna then the narrower the beam. (E.g. the wide/narrow beam antennae of the Rapier command transmitter.)

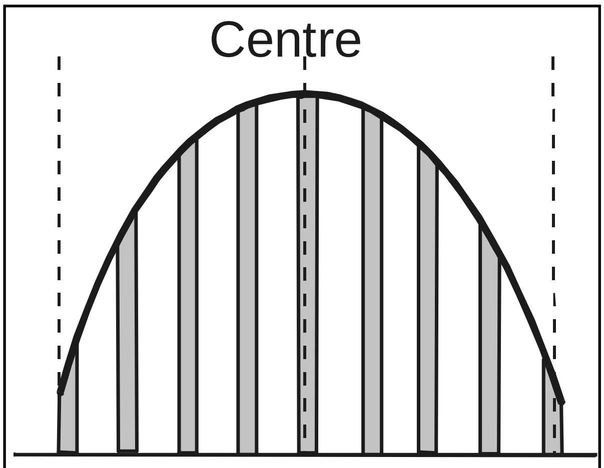


Figure 5: The Rise and Fall of the Radar Echo as the Antenna Scans Across a Target

Beam splitting: in a radar system, the echo that is received from a target will vary in intensity as the radar antenna rotates through the bearing to the target. The maximum return should be when the centre of the beam points towards the target. The strength of the echo should, therefore, increase and then decrease as the antenna rotates through the bearing to the target. A radar system which monitors this rise and fall in the strength of the echo can determine when the echo is greatest and measure the bearing at that exact point. This is illustrated in Figure Five. A beam of nominal width 2° could, therefore, be used to measure azimuths to an accuracy of at least $^1/_{10}$ of the beamwidth, or 0.2° (3 ₥). This technique is called 'Beam Splitting'. Note that a real radar signal would have noise and glint added to it and that the presence of these will cause a loss of accuracy in the angular measurement.

Examples

1. A circular antenna of diameter 60 cm (0.6 m) operates at a frequency of 10 GHz. Its beamwidth, when using uniform illumination, will be:

Ans: use the formula (1) above, where λ = 5 cm (0.05 m) and 'D' = 60 cm (0.6 m):

$$\Theta_b = \frac{60 \times 0.05 \text{ m}}{0.6 \text{ m}} \quad \text{or} \quad \frac{60 \times 5 \text{ cm}}{60 \text{ cm}}$$
$$= 5°$$

2. A rectangular antenna has a height of 40 cm (0.4 m) and a width of 1.5 m and it is used with tapered illumination at a frequency of 15 GHz. Its beamwidth in azimuth will be:

Ans: use the formula (2) above, where λ = 2 cm (0.02 m) and 'D' = 1.5 m (for the azimuth beamwidth use the width of the antenna):

$$\Theta b = \frac{70 \times 0.02}{1.5}$$
$$= 0.93°$$

ANTENNA GAIN

The antenna has the effect of concentrating the transmitted power into the beam. If we were to measure the power density (Watts per square metre) that reaches a distant point from an antenna and compare it with the power density that would reach the same distant point from a non-directional (isotropic) antenna then the power from a radar antenna will be greater. The power that would reach each square metre at a range 'R' from an isotropic radiator is given by the formula:

$$\text{Power Density} = \frac{\text{Transmitted Power}}{4\,\pi\,R^2}$$

The increase in power that we get from using the antenna is called the 'gain' of the antenna and can have a value in excess of 1,000 for a radar antenna. Of course, the thousand times increase in power only applies in the direction of the main beam – for other directions then the power is reduced practically to zero.

All antenna have the same properties for receiving as they do for transmitting. Consequently, when an antenna is used to receive a signal then the power that it receives is also increased by the same amount, compared to an isotropic antenna. This means that a high-gain antenna receives a much stronger signal than a low-gain antenna.

As with beamwidth, the gain of an antenna changes as its dimensions and the wavelength change. Unlike beamwidth, the gain is also affected by the any energy losses in the antenna, for example because the surface of the reflector is corroded. It is also affected by the use of tapered illumination, since the edges of the antenna are not fully utilised.

The gain of an antenna, compared to an isotropic antenna, is given by the formula:

$$G = \frac{4\,\pi\,A\,k}{\lambda^2} \qquad (3)$$

Where 'A' is the aperture of the antenna (the cross-sectional area that it uses to collect the EM waves), 'k' is its efficiency factor (typical values: about 0.7 for uniform illumination and about 0.5 for tapered illumination) and 'λ' is the wavelength in use. The value of the efficiency factor, 'k', cannot be calculated; instead, a value is found by testing the antenna to determine how much energy is wasted.

For a circular antenna, of radius 'r', 'A' is given by the formula for the area of a circle: $4\pi r^2$; For a rectangular antenna, of height 'h' and width 'w', 'A' is h × w; for an oval reflector (e.g. Mstar) of height 'h' and width 'w', 'A' is $\pi wh/2$.

You should note that 'A', the area of the aperture, appears in the top of this equation. This means that using an antenna of greater area will increase the gain. From the previous section, increasing the diameter of the antenna causes a decrease in the beamwidth. This means that an antenna of narrow beamwidth will also have high gain.

Effective Aperture: an antenna of aperture 1 m^2 in a power density of 1 Wm^{-2} should, in theory, collect 1 W of power. In practice, with a value of 'k' of 70%, the antenna would only collect 0.7 W. It is behaving as if its aperture were only 0.7 m^2, or 70% of its physical size. This is called its 'Effective Aperture' and it is often given the symbol 'A_e'. It can be calculated using the formula:

$$A_e = A \times k$$

Examples

1. A circular antenna of diameter 60 cm (0.6 m) operates at a frequency of 10 GHz. Its gain, when using uniform illumination, will be:

Ans: 'D' = 60 cm (0.6 m) means that the radius is 30 cm (0.3 m), so the area 'A' is $\pi r^2 = \pi \times 0.3^2$. Use the formula (3) above, where 'λ' = 3 cm (0.03 m), use the typical value for 'k' = 0.7 and 'A' = $\pi \times 0.3^2$:

$$G = \frac{4 \times \pi \times \pi \times 0.3^2 \times 0.7}{0.03^2}$$

$$= 2\ 763$$

2. A rectangular antenna has a height of 40 cm (0.4 m) and a width of 1.5 m and it is used with tapered illumination at a frequency of 15 GHz. Its gain will be:

Ans: The area, 'A' is 1.5 × 0.4 = 0.6 m^2. Use the formula (3) above, where 'λ' = 2 cm (0.02 m), use the typical value for 'k' = 0.5 and 'A' = 0.6 m^2:

$$G = \frac{4 \times \pi \times 0.6 \times 0.5}{0.02^2}$$

$$= 9\ 425$$

3. A rectangular antenna measures 0.5 m by 1.0 m and has an efficiency of 60%. Its effective aperture is:

Ans: the physical aperture, A', is 0.5 × 1.0 = 0.5 m^2. The effective aperture, A_e, is 70% of this or 0.35 m^2.

USE OF DECI-BELS FOR GAIN

The results for gain, above, are numerical values that compare two powers (from isotropic and directional antennae). Using the standard deci-Bel formula:

dB = 10 × Log (Gain)

the two gains in the examples on this page could be written as 34 dB (2 763) and 40 dB (9 425). Antennae gains are usually quoted in dBs.

CONVENTIONAL ANTENNAE

The standard radar antenna is a specially-shaped, metal dish that is designed to reflect the EM waves

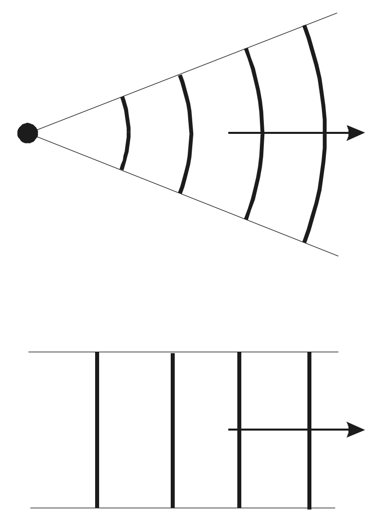


Figure 6:
Upper: Waves Spreading from a Point Source
Lower: Waves Forming a Beam

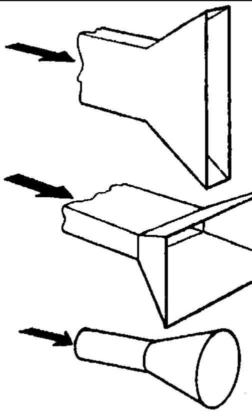


Figure 7: Examples of Horns

to form a beam. The upper part of Figure Six shows the radiation from a point source of EM waves, with some directional effects added - this looks very like part of the pattern of ripples that appears when a stone is dropped into a pond. The wavefronts are circular and they spread out. In order to form an effective beam then the wavefronts must be made parallel, as shown in the lower part of the Figure.

There are many forms of antennae that can produce beams: these include:

- **Horns**: to minimise the effects of the change from waveguide to free-space, the waveguide is formed into a horn. This produces a gradual change in impedance, over the length of the horn, and this reduces the reflection. Three types of horn are illustrated in Figure Seven. Horns do not produce a narrow beam because they act as a point source (at the narrow part of the horn) whose radiation is confined by the expanding edges of the horn. Their 'beam' resembles that shown in the upper part of Figure Six. Consequently, the horn is commonly used to direct energy onto the surface of a reflector dish and it is the dish that forms the narrow beam.
- **Parabolic dish**: energy that leaves a horn placed the focus of a parabola will reflect from the dish as a 'plane wavefront'. Along the line 'XY' in Figure Eight, each part of the wave that left the focus 'F' has travelled the same distance to reach the wavefront so all the waves arrive their at the same time (in phase). The principle drawback of such an arrangement is that the feed and its supports are in the path of the beam and deflect energy sideways and form side-lobes.

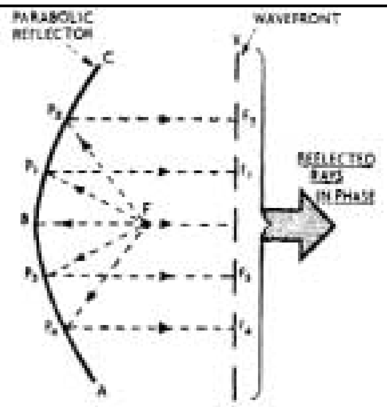


Figure 8: Paths in a Parabolic Reflector Antenna

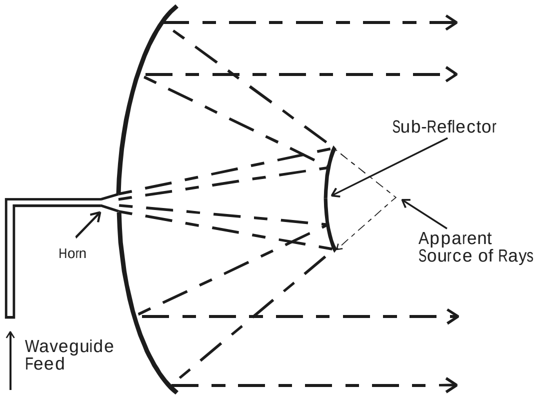


Figure 9: A Cassegrain Antenna

- **Cassegrain antenna**: this antenna has a horn feed in the centre of the dish and uses a sub-reflector to bend the EM waves back to the dish, as shown in Figure Nine. The depth of the antenna is reduced and some of the radar electronics can be placed behind the dish, rotating with it, to act as a counterweight. The length of waveguide required is much shorter than the conventional front-fed dish.
- **Cassegrain with offset feed**: Figure Ten shows a cassegrain antenna which is, effectively, just the top half of the antenna of Figure Nine. This antenna is designed to look upwards and the sub-reflector does not obstruct the path of the main beam. This arrangement is used in some tracking radars where the sub-reflector is moved rapidly from side to side, or up and down, in order to scan the beam across a small area of the sky to search for and to track a target. The main reflector would be too heavy to move so fast, but the small sub-reflector is light enough for such rapid movements. The absence of obstruction from support arms, etc., makes this antenna most suitable for angle tracking as it produces a symmetrical beam shape. (Compare the offset-feed antenna with the Command Transmitter's antenna of Rapier FSB - if one support leg were slightly different from another then this would produce a tracking bias.)

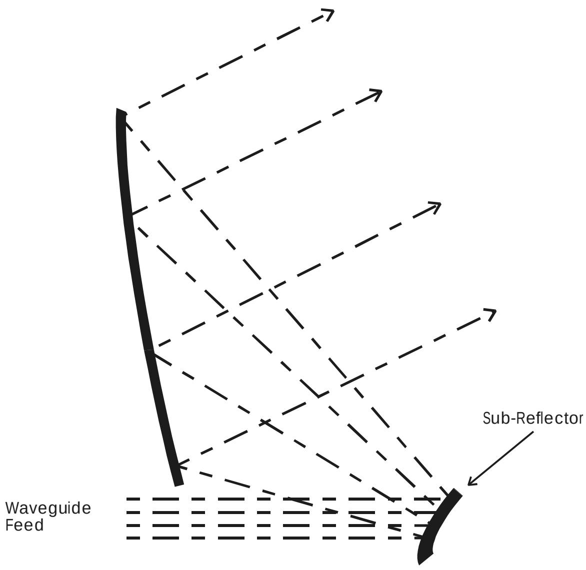


Figure 10: An Offset-Feed, Cassegrain Antenna

Movable feed horn(s): an alternative to moving the sub-reflector to produce a slight change in the direction of the beam is to change the position of the feed or to employ several feed-horns. Using an arrangement of movable waveguides, the radar waves are directed to the required feed. This allows the elevation of the beam to be changed very rapidly between two values as the switching mechanism can changeover the feed much more rapidly than a large parabolic reflector could be moved.

The type of movement of the beam differs between moving sub-reflector and switched feeds. The beam flips between the two or three alternative positions when the feed is switched; where the sub-reflector is moved then the beam scans steadily from one position to the other. The Cymbeline radar uses the moveable-feed technique to track mortar rounds at different heights - once the round is detected at low elevation then the feed-horns are switched over to direct the beam to a higher elevation for a second fix on the round. From these data, the trajectory of the round can be determined and, hence, its origin.

MULTI-FEED ANTENNAE

Some radar applications require information about both the azimuth and elevation of a target. This requires a number of independent elevation beams to be produced by the antenna. One very simple means of achieving this is to fit several feeds to the antenna, as shown in Figure Eleven. The reflection occurs such that the upper feed provides the lower beam and vice-versa.

This very simple arrangement can be used with reflector (dish) antennae but the side-lobe performance is generally poor, because the feed horns tend to obstruct the beam.

Each feed is connected to a separate radar receiver that detects echoes from that particular elevation. The beam pattern in elevation allows for some overlap between the beams and this allows a target on the boundary between two beams to be detected in both. The pattern shown in the Figure could be used to assign targets to one of five elevations. For example, an echo that appeared in both low and medium elevation beams could be assigned an elevation that was between the two of them.

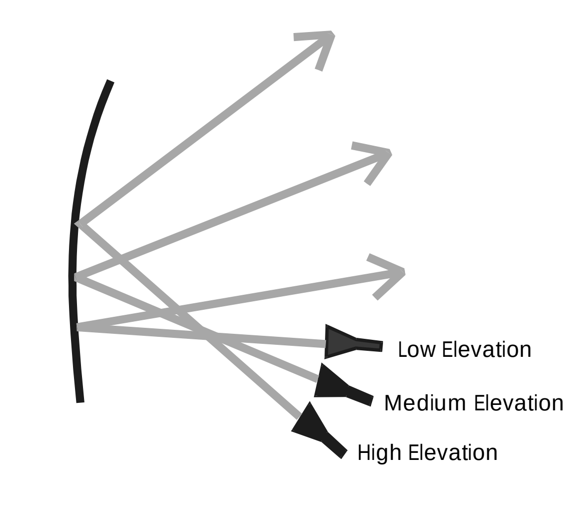


Figure 11: Using Three Feeds for Three Elevations

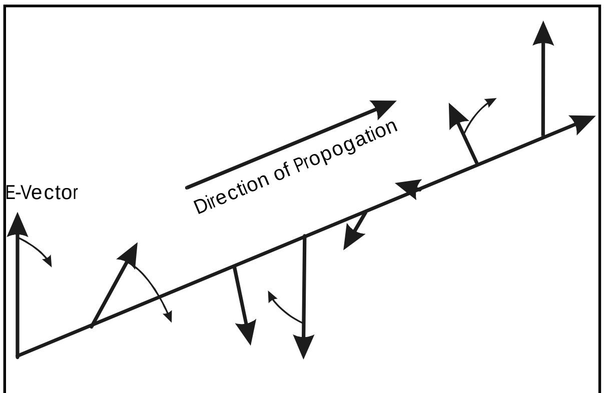


Figure 12: Illustrating Circular Polarisation

POLARISATION

The polarisation of an electro-magnetic wave is the orientation of its E-Field. In free space, this E-Field will always lie in a plane at right-angles to the direction of propagation. For radio and radar waves, the polarisation is determined by the antenna and the electric field is usually aligned parallel to the elements of the antenna (whip, dipole, Yagi) or aligned across the short dimension of the waveguide that feeds the antenna (dish, horn).

Wire Antennae: a wave produced by a half-wave dipole, whip or Yagi (ordinary TV antenna) has its E-Field oriented along the axis of one of the antenna elements - a vertical antenna produces vertical polarisation and a horizontal antenna produces horizontal polarisation. This is linear polarisation - orientated along a particular line. If the orientation of transmitting and receiving antennae differ then the reception of the E-Field will reduce by a factor Cosθ (where θ is the angle of mis-alignment) and a mis-alignment of 90^o will give zero reception. You might have noticed that some areas of the UK have their TV antenna oriented horizontally (e.g. HTV West) whilst adjacent areas, a few dozen miles away, (e.g. Meridian) might use vertically-oriented antennae. This is to reduce mutual interference.)

Dish Antennae: the polarisation produced by a dish antenna is generally determined by the orientation of the E-Field of its feeder waveguide. The BST Handout on Waveguides describes how the E-Field of a rectangular waveguide is oriented across the short dimension. An ordinary, dish antenna reflects the same polarisation. In a transmission link then the antennae at each end must use the same polarisation.

Plane Polarisation: the electric field might be aligned in a vertical or horizontal plane and this is called 'Plane Polarisation'. However, it is not always desirable to use plane polarisation at higher frequencies for the following reasons:

- **Rain**: liquid water is a (poor) conductor of electricity but it will reflect enough radar signal to register on a radar and this reflection might obscure military targets either within or on the other side of the rain.
- **Comms to Missile**: a missile rolls whilst in flight and it is not easy to keep its antenna in any particular orientation. If linear polarisation were used then communication would be lost whenever the antenna was oriented at right-angles to that of the transmitter. This would occur twice during each revolution of the missile.

The alternative form of polarisation is 'Circular Polarisation' and this can be used to reduce the effects of reflections from falling rain and to communicate with another antenna whose orientation is either unknown or varying with time.

CIRCULAR POLARISATION

Circular polarisation produces an E-Field whose orientation rotates once along the length of one cycle of the wave. For a wave that is polarised anti-clockwise and travelling away from you, if at the start of a cycle the E-Field is vertically up then after 1/4 cycle it will be horizontal-left, after 1/2 cycle it will be vertically down and 3/4 cycle sees it horizontal-right. Finally, it returns to vertically up at the end of the cycle. In effect, the E-Field performs a corkscrew-like movement along the direction of travel of the wave during each cycle. Of course, the E-Field could revolve in the opposite sense - so clockwise and anti-clockwise circular polarisations are possible. The H-Field also rotates, as it remains at right-angles to the E-Field. Figure Twelve illustrates this.

Circular polarisation is used in the signal from the command transmitter of Rapier. This is necessary because the missile spins in flight and its receiving antennae could be in any orientation. Circular polarisation ensures that the command signal can be received by the missile regardless of its roll angle.

A plane polarised wave can be converted to a circular polarised wave by passing it through a grid of metal wires that are set at 45° to the electric field of the original wave. Passing the wave through the grid for a second time will restore the original plane polarisation. Waves of opposite polarisation are reflected by the grid.

Circular polarisation is used in Radar to reduce the effects of falling rain and hail. Plane polarised and unpolarised waves are reflected from falling rain and the echoes from the rain hide echoes from targets located within the falling rain and on the other side of the shower. When circular polarisation is used, the reflections from target and raindrops occur as follows:

Raindrops: the raindrops are spherically symmetrical and reflect the waves equally throughout their cycle of rotation. This causes no change of polarisation but, as the waves are now travelling in the opposite direction (back to the radar), they appear, to the radar antenna, to have the opposite polarisation (i.e clockwise becomes anti-clockwise) and the echoes are rejected by the receiving antenna which is set to reject waves that have the opposite polarisation of the transmitted wave.

Target: The target will, generally, not be a sphere so its echoes will not be uniform throughout the cycle of rotation of the incoming wave. This distorts the circular polarised wave into an elliptically polarised wave that contains some energy that can be received by the system. However, the strength of the echo will be reduced as it passes through the falling rain and some of the echo will be rejected by the antenna, so the performance of the radar is generally impaired by the rain since the echo that it receives is reduced. However, without the polariser there would probably have been even less echo to receive so, overall, the system copes better with falling rain.

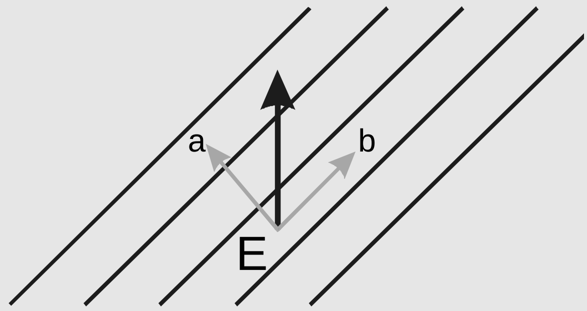


Figure 13: A Vertically Polarised Wave in a 45° Grid

PRODUCING CIRCULAR POLARISATION

When an antenna is fed using a circular waveguide and horn then the EM wave in the guide can be formed with circular polarisation which is retained during the beam forming process. When a rectangular guide is used then the electric field within the guide will be oriented across the short dimension and the wave will be linearly polarised. The conversion from linear to circular polarisation is achieved by placing a grid of wires or plates in the path of the beam, with the grid oriented at 45° to the linear polarised field, as illustrated in Figure Thirteen.

The electric field must be considered as two components: one parallel to the grid (marked 'b' in the Figure) and a second, at right-angles to the grid (marked 'a' in the Figure). The sum of these two components is equal to the field ('E') that is illustrated.

The component 'a' passes through the wires and is unaffected by them. Component 'b' lies parallel to the wires and induces currents along the wires as it passes through. The currents re-radiate the wave 's energy with a change of phase of 90° (λ/4) compared to component 'a'.

After emerging from the plates, the two components re-combine to produce the circular polarisation. This is illustrated in Figure Fourteen, where the tow components are shown both as sinusoids and as vectors. Over one cycle, as illustrated, the resultant vector 'E' rotates anti-clockwise by one revolution.

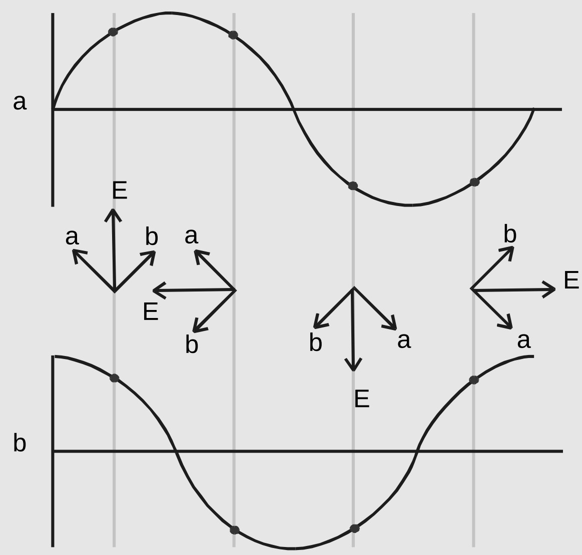


Figure 14: Two Sinusoids, at 90° Phase, Producing Circular Polarisation

ANTENNAE ARRAYS (PHASED ARRAYS)

An array antenna consists of a number of identical elements that operate as one large antenna. Each element is an antenna in its own right but the collective antenna – the array – has useful properties that are very difficult to produce from a single element. In other words, the array gives better performance than any single antenna could give. The Cobra antenna, for example, has over three-thousand individual elements.

The advantages of using an array antenna are particularly relevant to military applications as performance is enhanced under difficult conditions where targets are designed to reflect as little as possible and where there might be counter-measures such as jamming in operation.

This section describes the principles of operation of the array antenna and explains the significance of its operating features.

MULTI-ELEMENT ARRAY

In order to form a beam then an antenna must produce a plane wavefront (see Figure Six). The parabolic dish achieves a plane wavefront with its geometrical shape, but this can also be achieved by using a flat antenna. Each element on the flat antenna has its own, individual feed and all feeds are the same length. This means that the whole surface of the antenna radiates simultaneously and, since the elements radiate waves of the same phase, a plane wavefront is produced.

Figure Fifteen illustrates how a column of elements can be connected to a feed (waveguide or co-axial cable) with equal lengths. This is a parallel-fed array, since the feeders are in parallel. The Figure illustrates the feed to a single column of elements, most practical arrays are rectangular and would contain many such columns. This produces the plane wavefront directly, without the need for reflectors and dishes. For example, the Command Transmitter antenna of Rapier FSC has twenty-four elements, connected in parallel, in a 5 × 5 array (the centre element is a horn antenna that is used for the wide beam) with twenty-four separate co-axial feeders, each of exactly the same length (see side-bar).

Figure Sixteen illustrates how a row of elements can be connected to a feed in series. Provided that each loop of the series feed is exactly one wavelength long then the signal radiated from each element is in-phase with the others and a plane wavefront is produced.

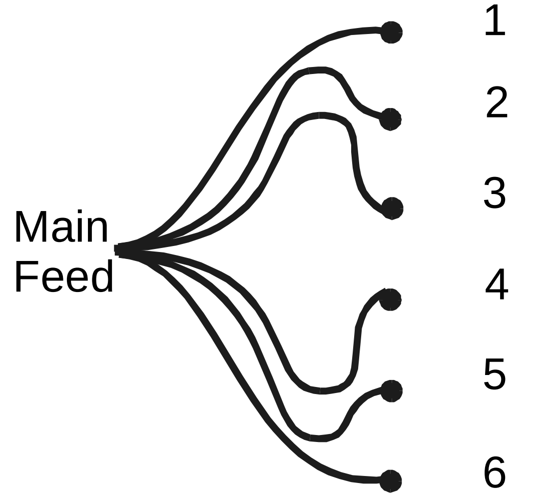


Figure 15: Using Feeds of Equal Length, in Parallel, to Feed the Elements of an Array

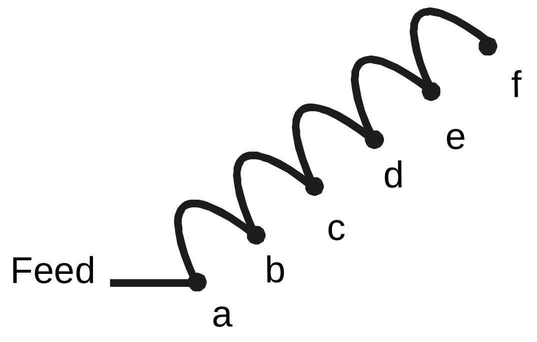


Figure 16: A Series-Fed Array, Using a Serpentine Feed, with Loops of Length 'λ'

Figure Seventeen shows an array antenna, of 36 elements, where the signal is applied to the end of each row in parallel and then fed along each row in series. This is a practical arrangement, since it minimises the length of feeder that is required.

Arrays have been constructed with many thousands of elements, some using as much as 30 km of waveguide to distribute the signal to the individual elements. The spacing between the elements of most phased arrays that radiate at right-angles to the antenna surface is $\lambda/2$, or an odd-numbered multiple (e.g. $7\lambda/2$) of half-wavelengths. This minimises radiation across the surface as adjacent elements will be in anti-phase.

TAPERED ILLUMINATION

One important feature of the array antenna is its ability to use tapered illumination to control sidelobes. Since each element has its own feed then this allows the feeds to be adjusted so that the central elements contribute more to the signal than the outer elements - and in a very precise way. The taper can be controlled much more effectively than that of a dish antenna. Additionally, the front of the array antenna is flat and there are no support arms, etc., that might obstruct or interfere with the radiation.

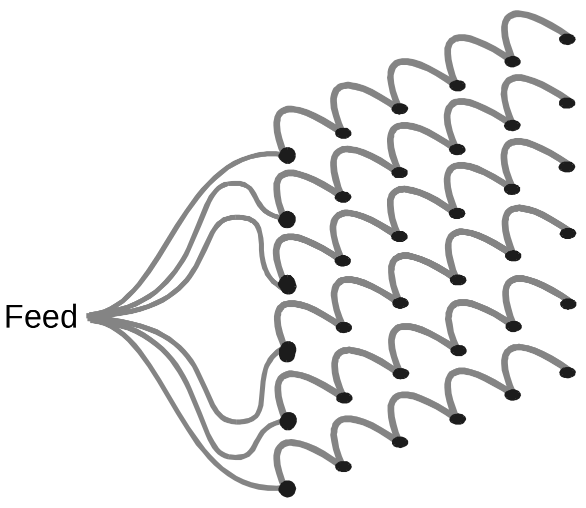


Figure 17: An Array, Using Parallel Feed to Each Row and Series Feed Across each Row

GAIN OF AN ARRAY

The gain of an array is calculated in the same way as that of any other antenna - and the same formula is used:

$$G = \frac{4 \pi A k}{\lambda^2}$$

The aperture, ‘A’, is the total area of the array which, if the elements are identical and contiguous, is equal to the aperture of one element multiplied by the number of elements. Thus, the gain of the array is also equal to the number of elements multiplied by the gain of one of the elements.

Note that the gain of an array cannot be greater than the gain of a dish antenna that has the same effective aperture (i.e. a dish antenna of the same size). If the system uses, say, just the central portion of the array then the gain would be less because the effective aperture would be reduced.

BEAMWIDTH OF AN ARRAY

This is governed by exactly the same rules as for parabolic (or any other shape) of radar antenna and the beamwidth is determined by the dimensions of the array. For a rectangular array, of height ‘H’ and width ‘W’ where all elements have equal weights (i.e. tapered illumination is not used):

- the beamwidth in azimuth is $60\lambda/W$
- the beamwidth in elevation is $60\lambda/H$

One common technique, that is applied to reduce sidelobes, uses tapered illumination. More power is fed to the central elements than is fed to those near the edges of the array. This dramatically reduces the effects of sidelobes whilst having only a moderate effect on other parameters. When tapered illumination is used then the ‘60’ in the above formulae should be replaced by ‘70’.

Note that the beamwidth of an array antenna cannot be any narrower than the beam of a dish antenna of the same size. However, if the array antenna has the ability to use just some of its elements, for example those near the centre, then its beamwidth can be varied during use. This is because the use of fewer elements will reduce the size of the region that is actually in use.

COMPARISON OF COMMAND TX ANTENNAE

The antenna used for the Command Transmitter of Rapier FSB is a conventional dish antenna and it is quite bulky and heavy. As this is not a radar antenna, but a communications antenna, then side-lobes are not particularly important. The small horn antenna, beneath the main dish, is the wide-beam antenna. (Remember that the beam width is narrower when the antenna is larger.) The dish antenna is pictured below.

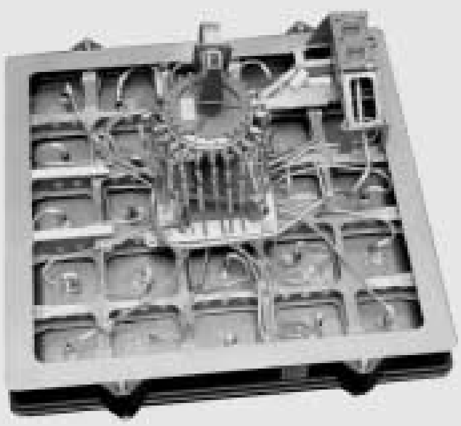
The Command Transmitter Antenna of Rapier FSB, with Separate Horn

Rapier FSC uses an array antenna, instead of the dish and horn that was used in FSB. The array antenna, pictured below, is much lighter than the dish antenna and also occupies less depth. There is a horn antenna fitted in the central position, to provide the wide beam. This antenna is pictured below.

The transmitter power that enters the antenna is split into twenty-four separate feeds which are connected to the elements of the array. It is essential that all the feeds are the same length , to ensure that all the elements radiate in phase.

The array antenna is much more difficult to manufacture than the dish and probably has a similar performance in terms of gain and beamwidth. However, the array antenna is considerably lighter and more compact than the dish that it replaces.

The face of the array antenna is fitted with a grid of wires, at 45°, to provide the necessary circular polarisation of the signal.



The Command Transmitter Antenna of Rapier FSC, with Equal-Length Feeds to Each Element of the Array

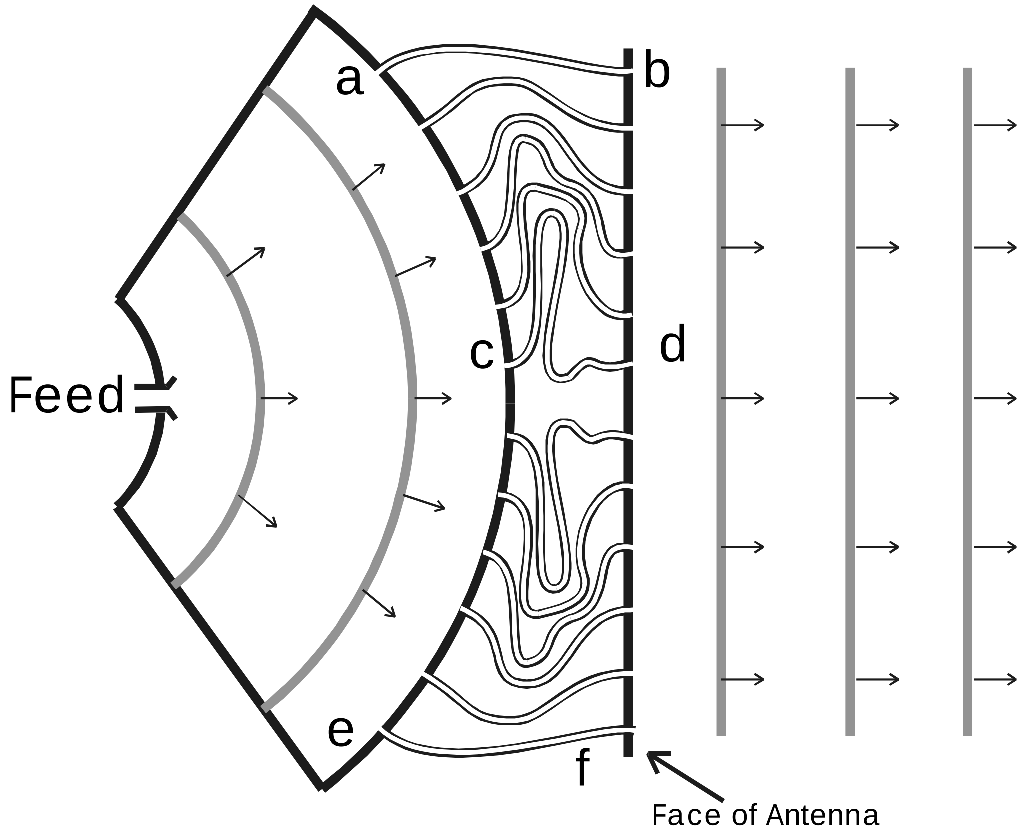


Figure 18: Schematic Diagram of Rotman Lens, Side View

THE ROTMAN LENS

This can be used to provide a parallel-feed, as an alternative to the arrangement shown in Figure Eighteen. It is illustrated in Figure Fifteen. The main feed enters from the left and forms curved wavefronts; the spread of the waves is limited by the enclosed body of the lens (shaped like a slice of cake). These wavefronts are shown leaving the feed point as grey curves, in Figure Fifteen.

On reaching the far side of the lens, the waves arrive at point ‘a’ and point ‘c’ (for example) where they are collected and passed into lengths of co-axial cable that carry the waves to the flat front of the antenna at points ‘b’ and ‘d’. The length of co-axial cable between points ‘a’ and ‘b’ is shorter than that between points ‘c’ and ‘d’ (the length increases, progressively, towards the middle of the lens) so that the waves arrive simultaneously at the flat front of the antenna. By delaying the central part of the wavefront, compared to the edges, then the curved wavefront is changed into a plane wavefront and a beam is formed.

The Rotman lens could be used, instead of the parallel feed, to feed the end of the antenna that is illustrated in Figure Fourteen. The Rotman Lens might also be used to feed the centre of an array, with series feeds running left and right, towards the outer edges of the antenna. This provides some degree of tapering, as the energy feed in the centre can be designed to provide more power there than at the edges.

The Rotman Lens has a relatively wide bandwidth and the beam direction remains constant as the frequency changes. [To discover more about the Rotman Lens then search the Internet for articles and web pages, using ‘Rotman Lens’ as keywords.]

VECTOR REPRESENTATION OF A WAVE

Ordinary vectors, such as displacement, force and velocity, have both magnitude (size) and direction. A wave has two properties that are similar to those of vectors: amplitude and phase. It is, therefore, possible to represent a sinusoidal wave in vector form - such vectors are called ‘Phasors’ to distinguish them from ordinary vectors. Phasors are particularly useful when considering the addition of waves. Figure Nineteen (a) shows two waves of amplitude three and four, respectively, with a phase of 90°. Their sum does not equal seven, because the values three and four do not occur simultaneously. The sum could be found by adding the two waves together on a point-by-point basis, taken over a whole cycle, but it is much easier to perform this addition by adding their phasors, as shown in Figure Nineteen (b).

This technique can be applied to an array antenna if the output from (or input to) each element is represented by a small phasor. Since all the elements act in-phase then all the phasors point in the same direction and, consequently, add up to form a large resultant, as shown in Figure Twenty. This represents the situation for an observer who is situated in the centre of the main beam (at right-angles to the flat surface of the antenna). In this position, all elements lie at the same distance from the observer, consequently, signals form all elements arrive in-phase.

However, for an observer who is situated outside the main beam, some of the elements are further away than

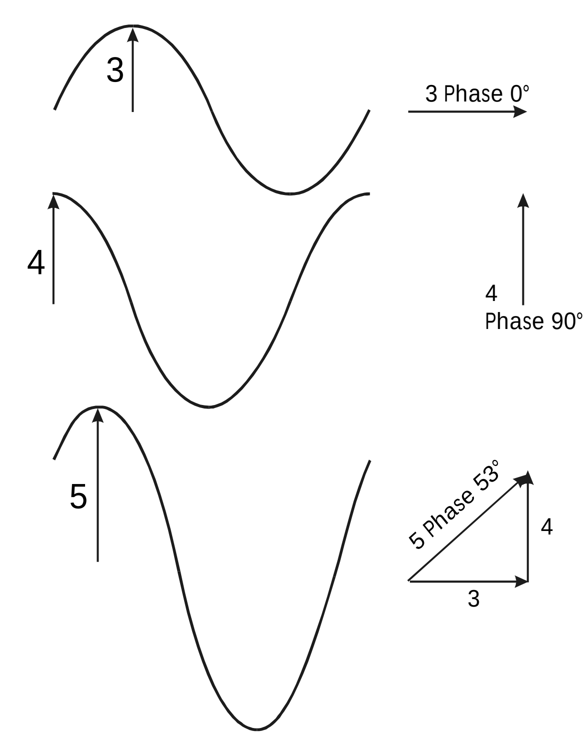


Figure 19:
a. (left) Addition of Sinusoids by Drawing Curves
b. (right) Addition of Sinusoids by Phasors

others. Signals from elements closest to the observer will arrive with a phase that is ahead of signals that have come from elements further away. This is illustrated in Figure Twenty-One - the end result is that the phasors do not form a large resultant, as they curl-up due to the progressive phase changes.

SIDELOBES

Sidelobes arise when the curled-up vectors, shown in Figure Twenty-One, do not form a closed circle. This means that full cancellation does not occur and that some power leaves the antenna in that particular direction. Theory indicates that the worst scenario for sidelobes is when each element radiates the same power. Although this arrangement gives the best main beam performance, it also gives the worst sidelobes. This result is true for any antenna, including parabolic dishes.

Figure 20: Sum of Phasors for an Observer Situated in the Centre of the Main Beam

Sidelobes significantly impair the performance of a radar system. For an air-defence radar, any sidelobe that is oriented downwards will illuminate the ground and, because some of this will occur at close range, the return signal is likely to be very strong indeed. As military aircraft are designed to be stealthy then the amount of radar echo that they produce is very small and can be masked by returns from sidelobes that illuminate the terrain. Sidelobes also provide a convenient entry point for noise, interference and any electronic jamming signals that the enemy employs in attempts to deceive the radar. Any such signals will appear to have come from the direction in which the main beam is pointing and not from their true direction.

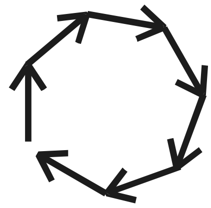


Figure 21: Sum of Phasors for an Observer Situated Away from the Centre of the Main Beam

Array antennae might be used in a radar solely because of their superior sidelobe performance. Because each element has its own feed from the radar transmitter, the amount of power to an element can be tightly controlled. This is the key to getting low sidelobes, by feeding maximum power to the central elements of the array and reducing this power gradually, according to a definite mathematical rule, for elements towards the edges. Current designs can produce sidelobes with powers better than 50 dB below the main beam (50 db below means 100 000 times less power) whereas a uniformly illuminated antenna would have sidelobes only about 13 dB below the main beam (1/20 power).

Sidelobes do not waste very much transmitter power - even in a worst case, at least 90% of the power leaves via the main beam. The problem with sidelobes is the vulnerability to jamming, false targets, noise and clutter that they cause.

The side-lobes for a receiving antennae are identical to the side-lobes that it has when transmitting. For an air defence radar, the main beam usually points into the sky - and noise levels tend to be low because the sky is cold. A sidelobe that received signals from the warmer ground would allow noise into the receiver and reduce the signal to noise ratio, masking echoes from stealthy targets.

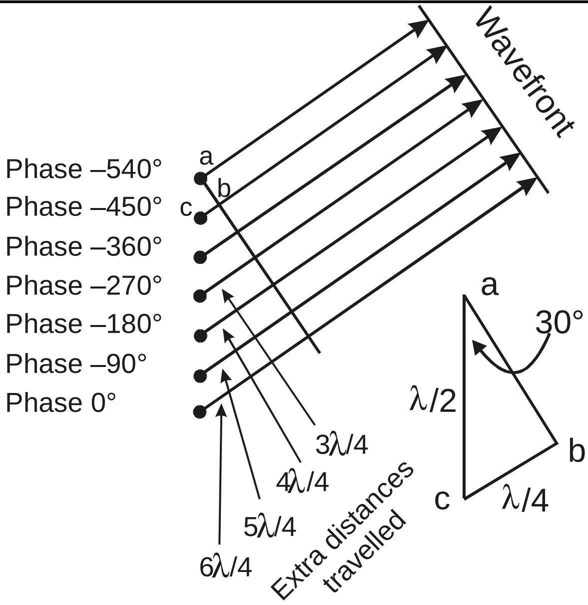


Figure 22: Beam Steering by Means of Progressive Phasing Across an Array

STEERING THE ARRAY

The beam from any antenna may be directed in a different direction by physically moving the antenna. For surveillance antennae, this is usually achieved by simple rotation of the antenna. The use of simple rotation implies that any space around the antenna is allocated equal priority with any other space as the antenna rotates uniformly, spending the same amount of time scanning any particular azimuth or elevation.

When it is necessary to scan a particular area or to scan several areas of high priority then this cannot easily be accomplished using an antenna that simply rotates. The antenna cannot move quickly enough to reach the areas of interest and might spend much of the time scanning areas of little interest.

An array antenna can be steered in a very short time - a few milli-seconds - to direct its beam to a new azimuth or elevation. This applies over a range of about ±50° from the broadside direction of the array. The beam is steered by changing the phase of the radiation from each element in a controlled way. When the elements radiate in phase then, as we have already seen, maximum power is radiated in the broadside direction. This is the direction in which the vectors arrive in phase and so they add up, as indicated in Figure Twenty.

Figure Twenty-Two shows an array of seven elements where the phase of the signal fed to each element has a progressive lag of 90° (or λ/4) for each element, starting from the bottom of the diagram and working upwards. The spacing between each element is λ/2 and, suing simple trigonometry, you should be able to calculate that the direction in which the vectors will align is now at 30° to the broadside line.

The angle is 30° because of the geometry of the array, and the triangle used is ‘abc’ as shown in the Figure. Consider the small triangle, abc, at the top of the array. This is a right-angled triangle whose hypotenuse is equal to the spacing between the array elements - λ/2. The phase angle that has been applied to the array is 90° from element to element - this corresponds to a distance of λ/4 and is the opposite side to the angle through which the beam has been deflected. So we have a right-angled triangle with opposite side of λ/4 and hypotenuse of λ/2 giving a Sine of 0.5 and angle of 30°, as shown in the inset to Figure Twenty-Two.

If this progressive change of phase (called a ‘Phase Gradient’) is applied from left to right across the antenna then the beam is steered in azimuth. If the phase gradient is applied from top to bottom of the antenna then the beam is steered in elevation. Both gradients can be applied simultaneously to direct the beam in any direction within the range of operation. The available beam directions seldom exceed ±50° in azimuth and elevation: some systems use much smaller deviations. Note that the number of degrees of phase change from element to element is not the same as the number of degrees through which the beam is steered (as this has to be worked out using trigonometry, as shown in the Figure).

The Cobra radar uses this technique to scan its observation area. Without moving the antenna, Cobra can scan the horizon over a wide front and direct extra pulses towards any target of interest.

There is a practical limit to the angle through which the beam can be steered. This is because the beam is skewed – rather than rotated – when steered and this causes the apparent aperture to reduce (by Cos θ, where ‘θ’ is the angle of skew) and the beamwidth to increase in the direction of skew. For example, the beam in the forward direction (at right-angles to the face of the antenna) might be circular in cross-section, but the effect of steering the beam to one side would be to make the beam oval in cross-section - and the distortion increases with the angle through which the beam is steered.

BEAM WIDTH CONTROL

The beamwidth of any antenna depends on its dimensions. A phased array can use all its elements - and full size - to obtain a narrow beam, but it can also use fewer elements (e.g. those near the centre) to operate from a smaller aperture and, hence, a larger beam.

This technique is used in the command transmitter of Rapier FSC, where one element (a horn) at the centre of the array is used for a wide beam transmission whilst the missile is gathered. Once the missile has been gathered then the remaining array of 24 elements is used to give a narrow beam.

Other phased-array radars can use a wider beam for surveillance and then switch to a narrow beam for tracking a particular target.

TRACKING WITH A PHASED ARRAY

The phased array can be used to track targets by splitting the array into left/right halves and comparing the signal in the two halves. When there is no difference between the signal received in the left half of the array and the signal received in the right half of the array then the target is directly in front of the antenna. If the signal in the left half has a phase that is ahead of the signal in the right half then the target is to the left of the centre line, The amount of phase difference indicates the angle between the centre line and the target’s azimuth.

THREE-DIMENSIONAL RADARS

Conventional surveillance radars have 'fan'-shaped beams that are broad in elevation and narrow in azimuth. Such radars cannot determine the angle of elevation (and the height) of a target and they are limited to measuring range, bearing and radial velocity.

For air defence, when a tracking radar is used during the engagement, the tracking radar can be brought onto the correct target much more quickly and reliably when the elevation of the target is known. This is because the tracking radar will have a narrow beam and, if given only the azimuth and range of the target, it will have to search in elevation to acquire the target. If it follows a simple search pattern, starting at low elevation and searching upwards, then the tracking radar might lock onto the lowest of several targets- as it would find that first.

The properties of a phased array antenna can be exploited to produce a radar that can determine elevation as well as azimuth. There are several ways of implementing this and the general concept is explained, below.

The transmitted beam remains the same, fan-shape, as before and the array is used to form multiple receive beams at different elevations. To produce a wider beam (in elevation) on transmit, only the central rows of the array would be used.

On receive, the EM energy from each row of the antenna is combined in-phase. To achieve this. the path lengths from each element to the combining point must be identical (with an accuracy of a small fraction of a wavelength). Since the wavelength used is likely to be only a few centi-metres then this requirement implies high precision during manufacturing. This is illustrated in Figure Twenty-Three where an arrangement such as that shown in Figure Sixteen has been used to sum the signals along each row and then the sum signals from each row are applied to an additional summing network that forms the beams.

In the diagram of Figure Twenty-Three, the outputs for each of the three beams are shown at the bottom of the diagram. For Beam One:

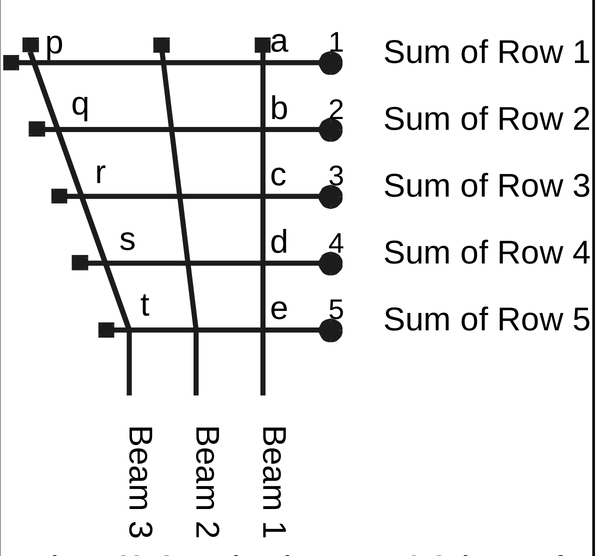


Figure 23: Summing the Rowns & Columns of an Array to Produce Three Elevation Beams

- EM energy from Row One passes via Point 'a' then down towards the output. The distance from Point 'a' to Point 'b' is exactly one wavelength.
- EM energy from Row Two passes via Point 'b' then down towards the output. It joins the energy from Row One in-phase because the energy from Row One has travelled exactly one wavelength further. The distance from Point 'b' to Point 'c' is exactly one wavelength.
- EM energy from Row Three passes via Point 'c' then down towards the output. It joins the energy from Rows One and Two in-phase because they have all travelled the same distance (plus one wavelength for Row Two and two wavelengths for Row One).
- The above pattern is followed by the remaining rows and they all arrive at the Beam One output in-phase.

Beam One will give maximum response to EM energy that arrives simultaneously at all rows. The waves will arrive at the output of Beam One in phase and add up as indicated in Figure Twenty. This corresponds to energy that arrives from a direction that is square-on to the antenna (at right-angles to the plane of the array).

At junctions such as Point 'a', there are directional couplers so that energy can pass in the required direction. Additionally, there will be a number of dummy loads and attenuators placed to intercept any 'stray' energy. These are indicated by black rectangles at the unused end of each waveguide (or coaxial cable).

Of course there is nothing to prevent this same energy from reaching the Beam Three output, but the path lengths are wrong for this to occur. Energy that travels from Row One, via Point 'p' to Beam Three's output will have travelled further than energy from Row Two, via Point 'q', and this is true for the remaining rows. Consequently, their phasors will arrive at Beam Three's output arranged as in Figure Twenty-One and they will cancel. Note that this does not waste any signal, because cancellation in this manner has the effect of eliminating the wave as if it never went in that direction.

Beam Three differs from Beam One in that the distance that the energy from each row has to travel is increased progressively from the bottom of the array. Beam Three gives maximum response to Em energy that arrives from a high angle of elevation. This energy will arrive at Row One before it arrives at Row Two and it will arrive at Row Five last of all. As the energy from Row One passes through the system to reach the Beam Three output then, because the channel to that output is angled, the energy from Row One is delayed by just the right amount, as it passes from Point '1' via Point 'p' to Point 'q' to put it in phase with the energy from Row Two that has travelled a slightly shorter distance from Point '2' to Point 'q'.

Receivers: this system requires three, separate radar receivers, one for each beam, but it can now determine the elevation of a target by comparing the strength of the echo in each beam. The amount of energy sent to each receiver is reduced because the received signal has been divided and this has an effect on the signal to noise ratio. Very low noise receivers are required (expensive) and one receiver is needed for each elevation channel (expensive). The receivers must act in step for frequency and PRF agility and, to ensure equal sensitivity, the system must inject test signals from time to time to ensure equality of response. Additionally, the antenna has to be built using very close tolerances (expensive).

Jamming: using a number of elevation beams in this type of 3-D radar introduces a degree of resistance to jamming. Any single jammer will only be able to jam one beam - the others will remain operational. If he changes his height (and elevation from the radar) to jam a higher beam then he will cease jamming the lower beam.

ELEMENT SPACING

The elements of a phased array antenna are often placed at half-wavelength intervals. This offers several advantages:

- Any build up of energy across the surface of the array is limited because the half-wavelength spacing causes a phase shift of 190° for any surface waves. This may be further improved by placing a thin, absorbent layer on the surface so that the main energy passes through the thin dimension whilst any unwanted surface waves would be travelling inside this layer and would, therefore, be absorbed.
- the elements are usually a little smaller than $\lambda/2$ and any smaller spacing would be impractical.
- Any larger spacing than λ will lead to additional main lobes (called 'grating lobes') of equal strength to the main lobe. This would be unworkable in a radar.

MULTIPLE BEAMS USING A ROTMAN LENS

A conventional, dish antenna can form multiple beams, as shown in Figure Eleven, by using a number of feeds in slightly different positions. An array antenna can also form multiple beams using many lengths of waveguide, co-axial cable or transmission line. The Rotman lens can also be used to produce an antenna with many beams.

The Rotman lens can be used to form several beams by adding feeds above and below the feed shown in Figure Eighteen. For example, a feed placed above that shown in the Figure would produce a wavefront within the lens that reached the top part of the output (at Point 'a') before it reached the bottom part of the output (at Point 'e'). This would cause the energy radiated from that feed to form a beam directed downwards. Such beams have a fixed orientation and can only be steered by physically moving the antenna.

CONNECTING TO THE ARRAY

Some arrays (e.g. Cobra) have as many as three thousand elements. These could be fed from one travelling-wave tube or klystron (valve) but that would require miles of waveguide to split the energy and there would be a single point of failure in the valve. Cobra uses solid-state devices in each individual element to generate the EM energy - each element is an individual radar system - and there is no big valve to fail.

For smaller arrays, a valve can be used in conjunction with many metres of waveguide or co-axial cable to divide the energy between the elements.

Space Fed Arrays: some designs of array use a horn or dish antenna to illuminate the back of the array with EM energy. This is received by each element, using a small antenna, processed as necessary (to phase-shift it by the correct amount) and then re-radiated from the front of the array.

End Fed Arrays: some designs use lengths of slotted waveguide to form each row of the array. The energy is fed in at the end of each row and passes, inside a waveguide, across the front of the array. Slots cut into the waveguide allow the energy to escape at intervals of $\lambda/2$ to form the array.

THERMAL SIGNATURE

Some designs of phase-shifter use electro-magnets to produce the phase shift and much heat is generated. Modular arrays, such as Cobra, generate heat in each element. The end result is an antenna that produces many kilo-Watts of heat and that has a significant thermal signature. As the antenna must be above ground so that it can 'see' its surroundings, then this heat makes it clearly visible to a thermal imager for quite some time after the radar is switched off.

The antenna of the US-THAAD System (Theatre High-Altitude Area-Defence System). The phased-array antenna has over 25 thousand elements and can detect ballistic missiles at 1 000 km range.

ALMAZ S-300 (SA-10 'GRUMBLE') FAMILY OF LOW- TO HIGH-ALTITUDE SURFACE-TO-AIR MISSILE SYSTEMS

The Russian `Almaz' Scientific Industrial Corporation S-300 designated (US/NATO code-named SA-10 `Grumble') missile system began development in 1967.

It was specifically designed as a semi-mobile all-weather strategic air defence system to replace the obsolete S-25 Berkut (US/NATO code-named SA-1 `Guild') missile network around Moscow and for use against low-altitude air breathing threats such as cruise missiles.

The engagement radar used was the 30N6 (NATO code-named `Flap Lid') I/J-band phased-array set. The usual battery configuration was three semi-trailer launchers and a single `Flap Lid' radar. The battery could simultaneously engage up to a maximum of three targets with six missiles under command guidance.

'Grumble' Radar Antenna Space-Fed Array

THOMSON-CSF AIRSYS CROTALE LOW-ALTITUDE SURFACE-TO-AIR MISSILE SYSTEM

Mounted on the top of the vehicle is a Thomson-CSF E-band Mirador IV pulse Doppler radar with fixed-echo suppression which rotates at 60 rpm and has a maximum detection range of 18.5 km against low-level targets with speeds of between 35 and 440 m/s and altitude limits between zero and 4,500 m. Thirty targets can be processed per antenna revolution with the 12 most dangerous targets automatically evaluated and tracked by the system.

The firing unit has a J-band monopulse 17 km range single target tracking radar mounted concentrically with the launcher turret, which carries four ready to launch missiles, two each side. The system also has an I-band 10º antenna beamwidth command transmitter, differential angle-error measurement infrared tracking and gathering system with a +-5º wide field of view, an integrated TV tracking mode as a low-elevation back-up, an optical designation tripod-mounted binocular device (which is controlled manually by a handlebar arrangement and used primarily in a heavy ECM environment or whenever passive operation is required).

Crotale Radar Antenna

RAYTHEON MIM-104 PATRIOT HIGH- TO MEDIUM-ALTITUDE AIR DEFENCE (HIMAD) SYSTEM

The AN/MPQ-53 G-band frequency-agile phased-array radar is automatically controlled from the ECS by the digital weapons control computer. Mounted on a trailer it has a 5161-HAWK platoon element array for the search and detection, target track and illumination and missile command and uplink beams. At any one time the system is able to handle between 100 target tracks and support up to nine missiles in their final moments of engagement using TVM terminal homing.

This technique involves the missile's passive monopulse seeker array being directed by the ECS to look in the direction of the target which then begins to intercept increasingly precise returns from the reflected electromagnetic energy signals. This in turn triggers the G/H-band onboard downward datalink which is offset in frequency from the target track and illumination beam and which transmits target data from the missile guidance package to the ECS computer via the circular 251-element TVM receive-only array at the lower right of the antenna group. The ECS uses this information to calculate guidance instructions which are passed to the missile by the radar's G/H-band command and uplink beam.

'Patriot' Phased Array Radar Antenna

[Pictures & text from Jayne's CD-ROM]

SUMMARY OF FORMULAE

Beam Width, when using unform illumination:

$$\Theta_b = \frac{60\,\lambda}{D} \text{ degrees} \qquad (1)$$

Beam Width, when using tapered illumination:

$$\Theta_b = \frac{70\,\lambda}{D} \text{ degrees} \qquad (2)$$

Gain of an antenna:

$$G = \frac{4\,\pi\,A\,k}{\lambda^2} \qquad (3)$$

The beam width and gains of array antennae are calculated using the same formulae as above.

When a number 'n' of antennae with individual gains of 'G' are made into an array then the total gain is n × G.

SELF ASSESSMENT QUESTIONS - ANTENNAE

1. A waveguide would have a horn at its open end in order to give:

   a. impedance matching.
   b. maximum reflection.
   c. a very narrow beam.
   d. resonance with the load impedance.

2. A waveguide ends with a conical horn that has a maximum diameter of 15 cm. What beamwidth would it give when used at a frequency of 6 GHz?

   a. 6°.
   b. 20°.
   c. 23.3°.
   d. 90°.

3. A parabolic antenna has an aperture of 0.75 m^2 and its efficiency is 70%. Its gain at an operating frequency of 3 GHz would be:

   a. 943
   b. 750
   c. 700
   d. 660

4. An antenna is 1 m wide and 0.25 m tall and operates with tapered illumination at a wavelength of 5 cm (6 GHz). This means that its beamwidths will be:

   a. 3.5° in azimuth and 14° in elevation.
   b. 14° in azimuth and 3.5° in elevation.
   c. 14° in both azimuth and elevation.
   d. 3.5° in both azimuth and elevation.

5. Compared to a conventional parabolic antenna, a Cassegrain antenna of the same diameter has:

   a. higher gain.
   b. less overall depth.
   c. narrower beam.
   d. higher efficiency factor.

6. To reduce the power in the side-lobes of the beam from any type of antenna, a designer should:

   a. use a co-axial feeder instead of a waveguide.
   b. establish uniform illumination.
   c. ensure that the impedances are matched.
   d. use tapered illumination.

7. Compared to a dish with uniform illumination, a parabolic dish that uses tapered illumination will have:

   a. more gain.
   b. a wider effective aperture.
   c. lower efficiency.
   d. a narrower beam.

8. Circular polarisation is used to reduce the effects of:

   a. jamming.
   b. falling rain.
   c. snow.
   d. side lobes.

9. One advantage of using a sub-reflector in a Cassegrain antenna is that it can be used to provide:

   a. a narrower beam.
   b. increased gain.
   c. a beam that can be rapidly scanned.
   d. circular polarisation of the beam.

10. A radar beam has a power level (intensity) at its centre of 10 Wm^{-2}. The ‘edge’ of this radar beam would be the point where the power level is:

    a. 5 Wm^{-2}.
    b. 9.9 Wm^{-2}.
    c. 7.1 Wm^{-2}.
    d. Zero.

11. A dish antenna might have two feed horns, one above the other in order to:

    a. reduce side-lobes.
    b. reduce beam width.
    c. produce two elevation beams.
    d. produce two azimuth beams.

Answers

1. Impedance matching, to reduce reflections (a)
2. BWdth = $60\lambda/D = 60 \times 5 \div 15 = 20°$ (b)
3. $G = 4\pi AK \div \lambda^2 = 4\times\pi\times0.75\times0.7\div(0.1)^2 = 660$ (d)
4. BW=$70\lambda/D$. $70\times5\div100=3.5°$Az; $70\times5\div25=14°$ El (a)
5. Cassegrain antenna is shorter (folded path) (b)
6. Tapered illumination reduces sidelobes. (d)
7. Tapered illumination reduces efficiency (c)
8. Circular polarisation hides reflections from rain (b)
9. Sub-reflectors can be moved easily to steer (c)
10. Edge of beam is the HALF POWER point. (a)
11. Horns stack vertically for elevation beams (c)

SELF-ASSESSMENT QUESTIONS - ARRAYS

1. Which one of the following is NOT an advantage of using an antenna array?

a. Lower operating voltages
b. Fast beam steering
c. High gain
d. All round coverage without moving the antenna

2. An array is built of 5 Yagi antennae, spaced at half-wavelength intervals. Each Yagi has a gain of 10. What will be the gain of the array of Yagis?

a. 5
b. 10
c. 15
d. 50

3. A sixteen-element, linear array is set up horizontally with half-wavelength spacing. The gain of each element is 4 Which one of the following statements is false?

a. The array aperture is eight wavelengths.
b. The gain is 8
c. The beamwidth in azimuth is approximately 8°
d. No appreciable energy is radiated along the line of the array.

4. An stacked-array has 20 elements horizontally and these are stacked in 5 rows, making 100 elements in all. Which statement is false?

a. The gain is 100 times the gain of an element
b. The beam cross-section is elliptical, taller than it is wide.
c. The azimuth beamwidth is approximately 6°
d. The beam has no side-lobes.

5. Which one of the following statements about side-lobes is false?

a. Side-lobes reduce the efficiency of the antenna.
b. Side-lobes are oriented at right-angles to the main beam
c. Side-lobes give rise to spurious radar echoes
d. Side-lobes increase vulnerability to ECM.

6. Tapered illumination is used in antennae in order to produce:

a. narrow beams.
b. fan-shaped beams.
c. reduced side lobes.
d. multiple-receive beams.

7. To steer the beam of a phased-array antenna to the left it is necessary to introduce a progressive phase shift such that the phase of the elements on the:

a. left are ahead of those on the right.
b. right are ahead of those on the left.
c. top are ahead of lower elements.
d. bottom are ahead of upper elements.

8. When an attempt is made to jam a 3-D radar then each individual jammer can jam:

a. only one elevation beam.
b. all elevation beams.
c. only one azimuth.
d. all azimuths.

9. A phased array antenna has the following advantage over a parabolic dish antenna:

a. cheaper.
b. smaller, for the same beamwidth.
c. much reduced sidelobes.
d. smaller, for the same gain.

10. One disadvantage of using a phased array antenna, compared to a parabolic dish is that the array antenna is:

a. much more expensive.
b. lighter.
c. smaller.
d. invisible to thermal imagers.

Answers

1. One array antenna limited to 1/3 horizon (d)
2. Gain of array increases by No of elements (d)
3. Gain is 64(16 x 4), not 8. (b)
4. All antennae have sidelobes (d)
5. Sidelobes might be at any angle (b)
6. Tapered illumination to reduce sidelobes (c)
7. Furthest away go first (b)
8. A jammer can have only one elevation (a)
9. Arrays have less sidelobes (c)
10. Arrays are expensive (but effective) (a)

Teaching Objectives		Comments
J.04.01 Calculate the basic parameters of an antenna		
J.04.01.01	Describe what is meant by Gain and use the formula: Gain = $4\pi Ak/\lambda$ (dish) or Gain = nG (array).	Quote typical values of 'k' as 0.7 (uniform illumination) and 0.5 (tapered).
J.04.01.02	Describe the meaning of Beamwidth and use the formula: Beamwidth = 60 λ/nd (70 for tapered illumination)	Where 'd' is the element spacing and 'n' is the number of elements in Az or El as required.
J.04.01.03	Describe the features o f a polar diagram.	
J.04.01.04	Describe the use of beam splitting.	Variation of echo strength during scan.
J.04.02 Describe the features of typical reflector antennae		
J.04.02.01	Describe the use of a horn as a feed to a reflector.	Include multi -feed.
J.04.02.02	Describe the features of a parabolic dish antenna	
J.04.02.03	Describe the features of a Cassegrain antenna	
J.04.03 Describe the basic operating principles of typical phased array antennae		
J.04.03.01	State that each individual element radiate s part of the total power.	Beamwidth same as dish of same size.
J.04.03.02	Describe how the individual fields combine in (a) the main beam and (b) near a null.	Hence, Gain = $n \times G_1$
J.04.03.03	Describe how a progressive phase change causes the beam to be deflected.	Use the term 'Phase Gradient'/
J.04.03.04	Calculate the deflection angle, θ, of the beam using the formula: Sin θ = Phase shift ÷ Element spacing.	When both phase shift and element spacing are expressed in fractions of a wavelength.
J.04.04 Describe the features of practical array antennae		
J.04.04.01	Describe the problems caus ed by side lobes and how tapered illumination is used to reduce their effects.	
J.04.04.02	Describe the distortion of the beam that occurs when it is deflected by a large angle from the broadside direction.	
J.04.04.03	Describe how using different groupi ngs of elements can change the properties of the array.	Fewer elements for wider beam, left/right split of azimuth tracking,
J.04.04.04	Explain the difference between the thermal signatures of the Rapier and Cobra antennae.	
J.04.04.05	State that the element spacing is usually $\lambda/2$, to reduce end-fire effects.	
J.04.04.06	Describe the various means of feeding power to the array's elements.	Space-fed (Grumble), in -element generation (Cobra), Rotman Lens (FSC) and use of power dividers (FSB2).
J.04.05 Describe the basic principles of a 3 -D radar		
J.04.05.01	State that a 3 -D radar needs to identify both the azimuth and elevation angles of a target.	
J.04.05.02	Describe how the feeds from each row of an array can be combined to p roduce multiple receive beams.	A single transmit beam, covering all required elevations, may be used.
J.04.05.03	State that a 3 -D radar with multiple receive beams can be jammed on one beam only by each jammer.	