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RADAR ANTENNAS

Although the principle of radar has been known and advocated by many scientists since the early 1900s, it did not come into its own until its widespread development and application in World War II when the word RADAR was coined. Since then, the use of radar has expanded prodigiously. Important applications are found not only in numerous military problems but also in many public and commercial areas (e.g., civil air-traffic control, aircraft navigation, ship safety, spacecraft, ground detection, and remote sensing of the environment). It is even applied to law enforcement when police use radar to check the speed of cars.

The major types of radar are pulse radar, high-range-resolution radar, continuous waveform (*CW*) radar, moving target indication (*MTI*) radar, airborne radar, tracking radar, pulse Doppler radar, ground penetrating radar, synthetic aperture radar (*SAR*), and inverse SAR. Each of these radar types employs a different characteristic waveform, which is determined by the corresponding radar antenna and signal-processing method.

The radar antenna is an important component of radar. For different radar types, the requirement for antenna performances and functions is varied. Because the subject of radar antennas is very extensive, only selected types and performances of radar antennas are discussed in this article. The reader should consult the bibliography for further details (1,2,3,4,5).

Radar antennas serve as transduces to couple electromagnetic (*EM*) energy into the atmosphere. A simple description of the antenna in a radar system is shown in Fig. 1. The functions of the antenna when transmitting are to concentrate the radiated energy from the transmitter into a shaped directive beam in a predetermined direction. When receiving, the antenna again forms a beam in a particular direction and collects the energy contained in the reflected target echo signals. Received energy is sent to the receiver via transmission lines. Therefore, the primary purpose of the antenna is to determine accurately the angular direction of the target in both transmit and receive modes. For this purpose, a highly directive beamwidth is required, not only to achieve accurate angular targets but also to resolve closely located targets. This important feature of radar antennas can be quantitatively expressed in terms of the beamwidth, gain, and sidelobes.

Generally, the functions of radar antennas can be classified into beam scanning and target tracking. Beam scanning fulfills the search or surveillance function of a radar. It requires that the narrow directive beam be scanned rapidly and repeatedly over the region where the detected target may appear. Target tracking, however, requires that the narrow beam follow the target once it has been detected. In some radar systems, particularly airborne radars, the antenna is designed to perform both searching and tracking functions.

The preceding functional description of radar antennas implies that a single antenna is used for both transmitting and receiving via the duplexer, a device that permits both transmission and reception of EM waves with the single antenna. This is true for most radar systems, but there are exceptions (e.g., the bistatic radars in which separate transmit and receive antennas are used). This article considers only the single antenna.

Radar antennas are mainly classified into two types: quasi-optical antennas, which can be analyzed by optics methods like geometrical optics and physical optics, and array antennas. In some cases, small antennas are used (e.g., in ground-penetrating radars). Quasi-optical antennas include reflector antennas and lens antennas. The former are still widely used for radar, whereas lens antennas, although still used in some

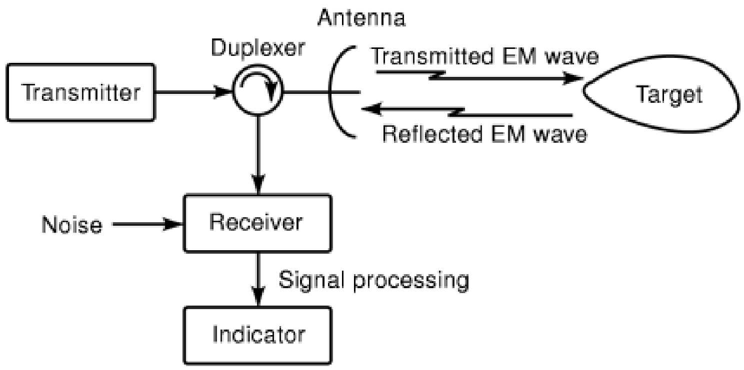

Fig. 1. Basic elements in a radar system in which the antenna is an important part. It can be served as transmitting and receiving.

communication and military applications, are no longer used in modern radar systems. Therefore, because of limited space, we discuss only reflector antennas and array antennas.

Basic Parameters and Requirements

Consider a radar antenna located at the origin of a spherical coordinate system as shown in Fig. 2. The observation point is on a sphere having a very large radius R, which is located in the far field of the antenna. Assuming that the antenna is reciprocal, so that the transmit and receive patterns are identical. When the antenna is transmitting, its radiation efficiency is defined as

$$\eta = \frac{P_\mathrm{r}}{P_0} \tag{1}$$

where P_0 is the total power consumed by the antenna, and P_r is the power radiated by the antenna. The later can be expressed by the radiation intensity $\Phi(\theta, \phi)$

$$P_\mathrm{r} = \int_0^{2\pi} \int_0^{\pi} \Phi(\theta, \phi) \sin\theta \, d\theta \, d\phi \tag{2}$$

in which ϕ is the azimuth angle and θ is the elevation angle, as shown in Fig. 2. From Eq. (2), the average radiation intensity is easily obtained

$$\langle\Phi\rangle = \frac{P_\mathrm{r}}{4\pi} [\text{watts/steradian}] \tag{3}$$

From Eqs. (1)–(3), we can define some basic parameters of an antenna. Directivity is a measure of the ability of the antenna to concentrate the radiated power in a particular direction. Thus it can be defined as the

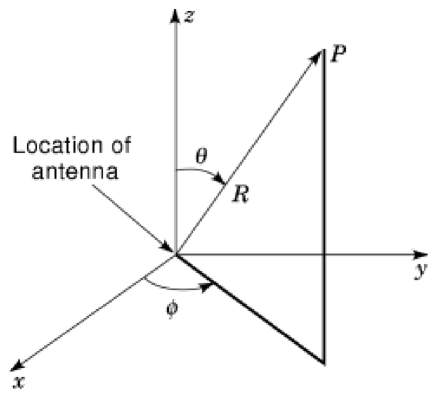

Fig. 2. Spherical coordinate system. The azimuth angle ϕ and elevation angle θ are adopted by most antennas.

ratio of the achieved radiation intensity in the direction to the average:

$$D(\theta,\phi)=\frac{\Phi(\theta,\phi)}{\langle\Phi\rangle} \tag{4}$$

In practice, one is usually interested in the maximum directivity of the main lobe.

Gain is another important parameter of an antenna. It represents the ability to concentrate the power accepted by the antenna in a particular direction:

$$G(\theta,\phi)=\frac{\Phi(\theta,\phi)}{P_0/4\pi}=\eta D(\theta,\phi) \tag{5}$$

Thus antenna gain is always less than directivity except for a lossless and reflectionless antenna ($\eta=1$). Again, the peak value of the gain, G_0, is of more interest in practice.

The aperture of an antenna is its physical area projected on a plane perpendicular to the desired direction. If the antenna is lossless and the aperture of area A is uniformly illuminated with equiphase, the directivity is given by

$$D_0=\frac{4\pi A}{\lambda^2} \tag{6}$$

which is the maximum available gain from an aperture A. Practical antennas are not uniformly illuminated, but they have a maximum in the center of the aperture and are less tapered toward the edges in order to reduce the sidelobes of the pattern. In this case, an effective aperture is defined from the directivity

$$A_e(\theta,\phi)=\frac{\lambda^2}{4\pi}D(\theta,\phi) \tag{7}$$

The concept of effective aperture is very useful when considering the antenna in its receiving mode, which measures the effective absorption area of the antenna to an incident plane wave. Let A_e be the peak value of

$A_e(\theta, \phi)$. Clearly, the effective aperture A_e is always less than the physical aperture A by a factor η_a

$$A_e = \eta_a A \tag{8}$$

which is usually called the aperture efficiency. From the definitions in Eqs. (6)–(8), we can see that the aperture efficiency measures only how effectively a given aperture is used, but does not involve the EM energy loss. Therefore, the efficiency of the antenna should be the multiplication of η_a and antenna losses η_L.

When the power radiation intensity $\Phi(\theta, \phi)$, the directivity $D(\theta, \phi)$, the gain $G(\theta, \phi)$, and the effective aperture $A_e(\theta, \phi)$ are normalized to their peak values, they will be identical and are called the antenna radiation pattern, which in fact represents the EM-energy distribution in three-dimensional (*3-D*) angular space. There are several ways to plot the radiation pattern: rectangular or polar, voltage intensity or power density, absolute value or dB value, or power per unit solid angle. However, the 3-D plots of radiation pattern require extensive data. Thus two-dimensional (*2-D*) plots are usually adopted as a result of the ease in measurement and plotting. Generally, the two cuts of 3-D plots in the principal elevation and azimuth planes are sufficient to describe the pattern performance of an antenna, which is much less costly.

Instead of azimuth and elevation, *E*- and *H*-plane patterns are usually used in actual radar antennas because the terms *azimuth* and *elevation* imply the earth-based reference coordinates, which are not applicable to some space-based systems like airborne and satellite.

The main lobe of the radiation pattern is in the direction of maximum gain; all other lobes are called sidelobes. In addition to the peak gain of the main lobe, two other important features of an antenna pattern are the beamwidth of the main lobe, which is usually specified at the half-power level (3 dB), and the maximum sidelobe level. The half-power beamwidth (*HPBW*) is usually a measure of the resolution of an antenna. Therefore, if two identical targets at the same range can be separated by the HPBW, they are said to be resolved in angle.

The beamwidth of an antenna is determined by the size of the antenna aperture as well as the amplitude and phase distributions across the aperture. For a given distribution, the half-power beamwidth in a particular plane is inversely proportional to the size of the aperture in that plane

$$\mathrm{HPBW} = K\frac{\lambda}{L} \tag{9}$$

where L is the aperture dimension and K is a constant for the given distribution, which is known as the beamwidth factor. Accurate estimate of the beamwidth factor must take into account the aperture illumination function. However, $K = 70^\circ$ can give a rough estimate in most cases. For reflector-type antennas, a good estimation to K is given by (6)

$$K = 1.05238I + 55.9486\,(\mathrm{deg}) \tag{10}$$

in which I is the absolute value of edge illumination in decibels.

From the half-power beamwidths in two orthogonal principle planes, one can obtain a practical formula for predicting the gain of a relatively lossless antenna

$$G_0 = \frac{C}{\theta_1\theta_2} \tag{11}$$

where C is a unitless constant and θ_1 and θ_2 are HPBWs in degrees. The accurate value of C depends on the antenna efficiency, but the rough estimate can be taken from 26,000 to 35,000 (1,7).

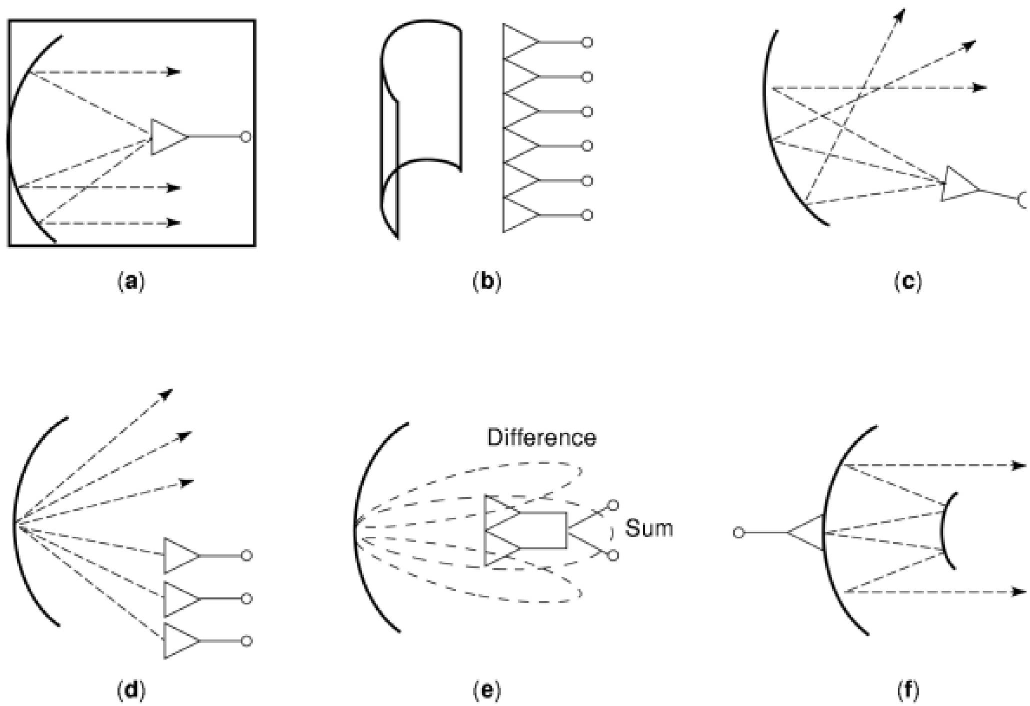

Fig. 3. Common reflector antenna types. (a) Paraboloid; (b) parabolic cylinder; (c) shaped reflector; (d) multiple beam; (e) monopulse; (f) cassegrain.

Ideally, an antenna radiation pattern would consist of a single main lobe and no sidelobes. However, for all practical radar antennas, it contains numerous sidelobes. These sidelobes can be a source of problems for the radar system. For example, a radar for detecting low-flying aircraft targets can receive strong ground or ocean echoes, which is called the clutter, through the sidelobes. This signal will interfere with the desired echoes coming from the low radar cross-section targets through the main lobe. Another fatal problem of the sidelobes is coming from jamming, which threatens most military radars. Therefore, it is often (but not always) desirable to design radar antennas with sidelobes as low as possible to minimize such problems. However, low sidelobes and high gain are competing requirements. Thus, the trade-off between sidelobes level, gain, and beamwidth is an important consideration for designing radar antennas.

Reflector Radar Antennas

Reflector antennas are one of the most important radar antennas and are widely used in practical radar systems. They provide an economical way to distribute energy over a large aperture area and produce shaped or pencil beams with high gain. In accordance with different demands, there are many types of reflector antennas with different shapes and feed systems.

Types of Reflectors. A wide variety of reflector antennas have been used in radar system. Figure 3 shows the most common reflector antennas.

Paraboloidal Reflector Antennas. The paraboloidal reflector antenna shown in Fig. 3(a) is a classical one with a round aperture. The theory and design of this kind have been well developed and discussed in the literature (1,5). In this antenna, the feed is placed at the focus of the paraboloid. Then the spherical wave emerging from the feed strikes on the reflector and is transformed into a plane wave after reflection to form a pencil beam. Usually, the paraboloidal antenna provides a high gain and a minimum beamwidth with the simplest and smallest feed.

An important parameter for this paraboloid is the ratio of the focal length f to the aperture diameter D. For fixed aperture, when f increases, the reflector becomes flatter and introduces less distortion for polarization and off-axis beam. However, a narrow primary beam that leads to a larger feed is also required. For example, the size of the horn to feed a reflector of $f/D = 1.0$ is approximately four times that of $f/D = 0.25$. In general, most reflectors are chosen to have a ratio between 0.25 and 0.5.

Besides the round aperture, a variety of reflector outlines are also used in practice (2,5). For example, an oblong shape is chosen when the azimuth and elevation beamwidths have different requirements.

Parabolic-Cylinder Antennas. It is very common that only one of the azimuth and elevation beams must be steerable or shaped while the other is not. In this case, a parabolic-cylinder reflector fed by a line source shown in Fig. 3(b) can meet the requirement at a modest cost. The line source feed may be a parallel-plate lens, a slotted waveguide, a phased array, etc. (1). Of course, the parabolic-cylinder antenna is not limited to these applications. It can even be applied when both patterns are fixed in shape (e.g., the AN/TPS-63).

Parabolic cylinders suffer from large blockage if they are symmetrical, thus they are often built off-set. Properly designed, however, a cylinder fed by an offset multiple-element line source can have excellent performance (8).

Shaped-Reflector Antennas. A good method of shaping the beam in one plane is using shaped reflectors (9), as shown in Fig. 3(c), in which the surface itself is no longer a paraboloid. From Fig. 3(c), each portion of the reflector is aimed in a different direction, making the analysis complicated. However, with modern computers, arbitrary beam shapes can be approximated accurately by direct integration of the reflected primary pattern.

A disadvantage of the shaped reflector is that its effective aperture is very small because a large fraction of its energy is radiated to a wide angle. However, it can reduce the blockage from the feed. In most shaped reflectors, the feed is usually placed outside the secondary beam. Then the blockage can be virtually eliminated even though the feed appears in front of the reflector, as shown in Fig. 3(c).

Comparing shaped-reflector antennas with parabolic-cylinder antennas, the shaped reflector is cheap and simple to construct. But it has less control over the beam shape because only the phase of the wave across the aperture is changed, whereas both phase and amplitude can be adjusted in the linear array for the parabolic cylinder.

Multiple-Beam Reflector Antennas. Very often the radar designer needs multiple beams to provide extended coverage. This requirement can be achieved by using a reflector with multiple feeds (10), as shown in Fig. 3(d). As we know, a feed at the focal point of a paraboloid forms a beam at the direction parallel to the focal axis. The feeds displaced from the focal point, however, will form additional beams at distinct angles from the axis with nearly full gain. Therefore, the coverage range of the radar can be increased. However, when the feed is off the focus, a distortion occurs on the antenna pattern. As the angular displacement increases, the beamwidth becomes larger, and additional sidelobes arise. The other limitation of this kind of antennas is that the extended feeds increase the blockage of the aperture.

Monopulse Reflector Antennas. An especially common multiple-beam radar antenna is the monopulse reflector illustrated in Fig. 3(e). In fact, the illustration shows an amplitude comparison system, which is far more prevalent than the phase comparison system. In the amplitude system, the sum of the even-numbered source outputs fed by a single pulse forms a high-gain and low-sidelobe beam, and the difference forms a precise deep null at the peak-value direction of sum pattern. The sum beam is used on bolt transmit and receive to detect the target, whereas the difference beams provide angle determination in both azimuth and elevation angles. Therefore, the monopulse reflector is normally used in tracking systems in which the antenna is removable and keeps the target near the null in difference pattern.

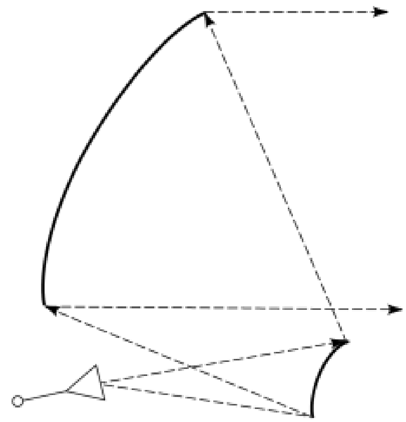

Fig. 4. Offset dual reflector. The blockage of the subreflector can be virtually eliminated.

A trade-off to design the monopulse radar antenna is the choice of feed size. The conflict arises between the goals of high sum-beam gain and large difference-beam slopes. For example, for a four-horn feed, the former requires a small overall horn size to reduce the blockage, whereas the latter requires large individual horns. Also, high difference sidelobes are required for tracking purpose in the design. To overcome these problems, many methods have been presented and several suggested configurations of the feed are given in Ref. (11).

Multiple-Reflector Antennas. Multiple-reflector systems can offer more degrees of flexibility by shaping the primary beam and then overcoming some of the shortcomings of single reflector. Figure 3(f) shows the most common type of multiple reflector, the Cassegrain antenna (12), in which the feed system is conveniently located behind the main reflector. In the Cassegrain system, the subreflector is a hyperboloid. The feed is placed at the left focus of the hyperboloid, and the paraboloid focus coincides with the right focus. From geometry optics, the spherical wave radiated by the feed and then reflected to the main reflector by the hyperboloid is equivalent to the one emerging directly from the right focus. Therefore, the wave reflected from the main reflector is also a plane wave that forms a pencil beam. A similar antenna to Cassegrain is the Gregorian antenna, which uses an ellipsoidal subreflector rather than a hyperboloidal one.

Aperture blockage can be very large for symmetrical Cassegrain antennas, as illustrated in Fig. 3(f). There are two ways to reduce blockage. The first method is to make the diameter of the subreflector equal to that of the feed, but the reduction is limited. The second method, which is generally used, is achieved by offsetting both the feed and subreflector. For example, Fig. 4 shows an offset dual reflector with blockage and supporting struts virtually eliminated. This antenna usually has very low sidelobes.

The geometry of the Cassegrain antenna is especially attractive for monopulse tracking radar because the radiofrequency (*RF*) plumbing can be placed behind the reflector to avoid blocking of the aperture. Also, the long runs of transmission line out to the feed at the focus of a conventional monopulse reflector are avoided. Therefore, the Cassegrain antennas have usually a low noise temperature.

Feeds for Reflector Antennas. In the previously discussed antennas, a spherical wave from the focus of the paraboloidal reflectors will be transferred into a plane wave to form a pencil beam at the transmit mode, while the incoming plane wave will be converted into spherical phase fronts centered at the focus on their receive mode. Thus the feeds for reflector antennas must be point-source radiators so that they can radiate spherical waves. Other requirements for reflector feeds include the proper illumination of the reflector with a prescribed amplitude distribution, a minimum spillover, and the correct polarization with no or minimum cross polarization. These are the basic factors chosen to design a feed. For a different application of the antennas, other considerations must be included.

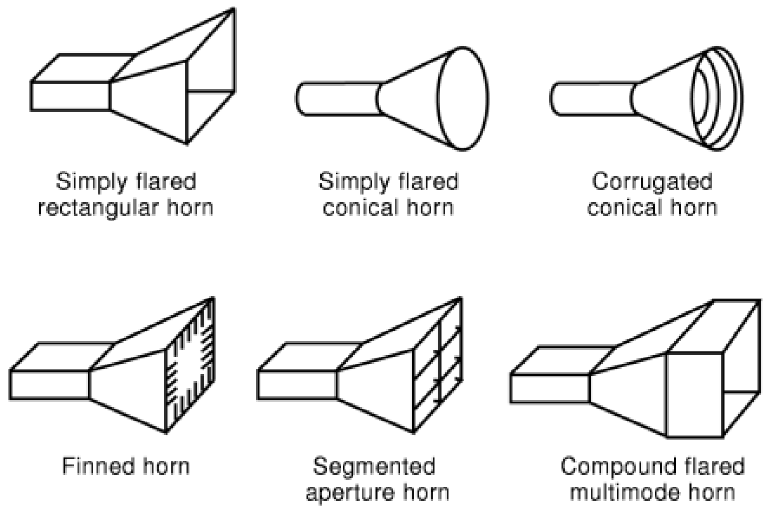

Fig. 5. Various types of feeds used in radar antennas.

The most common feeds for reflector antennas are the flared waveguide horns, which are very suitable for microwave-frequency radar systems (L band and higher). At lower frequencies, dipole feeds, Yagi-Uda or log-periodic feeds are sometimes used. For example, a linear array of dipoles can feed a parabolic-cylinder reflector. Rectangular waveguide horns propagating the dominant TE_{01} mode are widely adopted because they meet the high power and other requirements, although in some cases circular waveguide horns propagating TE_{11} mode have also been used. These single-mode horns provide just one linear polarization. When such additional requirments as polarization diversity, multiple beams, high beam efficiency, or ultralow sidelobes are needed, the design for feeds becomes more complicated. In these cases, segmented horns, finned horns, multimode horns, and corrugated horns must be used. Figure 5 illustrates some of the types, which have been well studied (1,13).

In addition, the sitting of the feeds has also a great influence to the performance of the reflector antennas. Figure 6 shows several placement styles of the feeds.

Reflector Antennas Design and Analysis. The analysis and design of conventional paraboloidal reflectors are well developed (1,5) and not stated here. However, most of the rotating search radars require that the antenna patterns have a narrow azimuth beamwidth for angular resolution and a shaped elevation beam for multiple requirements, for example, the ARSR-3 radar for air-traffic control and the AN/TPN-19 for ground control. Thus, a shaped reflector is nearly always the practical choice. In this section, we will consider the analysis and design of such kinds of antennas.

Requirements. When a search radar works, small nearby targets like birds and insects may clutter the output of the radar because of the inverse fourth-power variation of signal strength with range. For example, the radar that can detect a 1 m^2 target at 100 nmi can detect a 10^{-4} m^2 target at 10 nmi. [Nautical mile (nmi) where 1 nmi = 1852 m is usually used as the range unit.] To avoid the clutter, the receiver gain should be reduced at short range and increased at distant range so that the received signal from a target of constant size remains unchanged with range. The programmed control of the receiver gain to keep a constant echo signal strength is called sensitive time control (*STC*), which is an effective method of eliminating the radar echoes from unwanted objects. Therefore, STC is the usual requirement for designing the search radar.

A typical range coverage requirement for the rotating search radars is shown in Fig. 7, which is an idealized simplification of the STC requirement (14). It gives a relationship between the radar range, height,

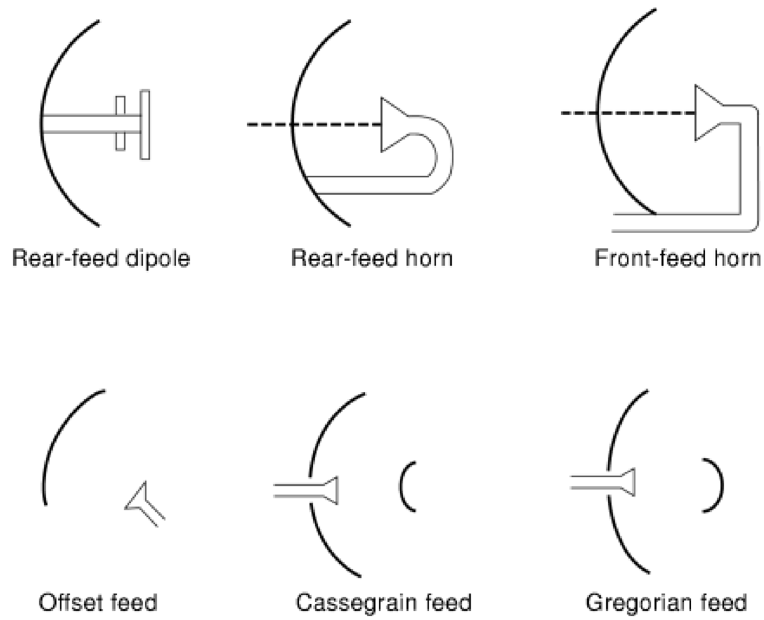

Fig. 6. Various placements of the feeds in radar antennas.

and elevation angle. From Fig. 7, at low elevation angles (0.5° to 3.5°), the maximum range is the critical requirement. When the elevation angle increases (3.5° to 9.5°), however, the height becomes the governing requirement. In this period, the corresponding pattern is a cosecant square. At high elevation angles (9.5° to 30°), the STC is used.

The two-way coverage requirement shown in Fig. 7 is inconvenient for antenna design. It can be converted into a pattern requirement if we plot only the range against angle because the range is directly proportional to the pattern amplitude, as shown in Fig. 8 (the solid line).

Analysis. Antenna analysis is very important not only in analyzing a given antenna but also in antenna design. Because the accurate design is usually an iterative procedure, in each iterative cycle, an analysis is needed.

There are two methods to analyze a given antenna: current-distribution method and aperture-field method (5). For shaped antennas, however, the first one is more suitable. From the magnetic field $\boldsymbol{H}$ radiated by the feed, one can get the induced current on the reflector surface $\boldsymbol{J} = 2\hat{I} \times \boldsymbol{H}$. Then the radiated fields by the reflector can be obtained by integration.

This type of accurate analysis is quite time consuming. In practical design, the antenna pattern and gain are usually approximated in the first several iterative cycles. For rotating search radars, the antenna pattern can be obtained directly from the coverage requirement; however, the designer must realize that the range-angle plot represents the minimum range requirement. If some ripple is anticipated (normally about ±1 dB), the design curve should be raised 1 dB in the height limit and STC coverage regions. For the range limit region, a reasonable situation is achieved by assuming that a section or several sections of the reflector are shaped so that the −3 dB points of the resulting pattern will coincide with the two corners of the range limit portion, as shown in Fig. 8 (dashed line), which is just the realizable elevation pattern of the antenna.

For the gain of shaped beam considered here, we assume that the azimuth and elevation power patterns are separable. Then using the definition in Eq. (5), the maximum gain (in main beam direction) can be expressed

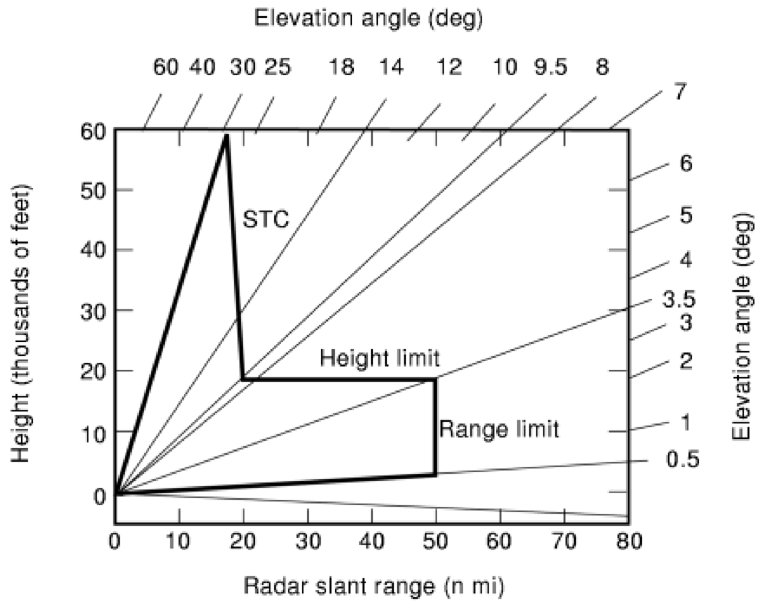

Fig. 7. Typical two-way coverage requirement of the search radar, in which a relationship between the radar range, height, and elevation angle is given.

as

$$G = \frac{4\pi}{\iint f_{az}(\phi) f_{el}(\theta)\, d\phi\, d\theta} = \frac{4\pi}{\int f_{az}(\phi)\, d\phi \int f_{el}(\theta)\, d\theta} \qquad (12)$$

where $f_{az}(\phi)$ and $f_{el}(\theta)$ are azimuth and elevation power patterns. For simplicity, the azimuth power pattern can be approximated by a Gaussian function: $f_{az}(\phi) = \exp[-2.7726(\phi/\text{BWAZ})^2]$. Then

$$\int f_{az}(\phi)\, d\phi = 1.0645\text{BWAZ} \qquad (13)$$

in which *BWAZ* is the azimuth half-power beamwidth. For the other integral in Fig. 8.

Design. For shaped-beam antennas, the shaping is generally in one plane (elevation), with a narrow pattern of conventional design in the orthogonal plane (azimuth). The parabolic-cylinder antenna fed from a line source is convenient for obtaining independent control of the patterns. However, it is much more expensive and heavier than a reflector fed from a point source. In order to obtain a shaped beam, the antenna with a point-source feed requires a reflector surface with double curvature. An easy but efficient way to do this is to use an offset paraboloidal antenna by adding several shaped sections. Each successive section points slightly higher than the preceding section, as shown in Fig. 9. Clearly, the projections of added sections are virtually missing the feed. So there is no feed blockage. The design of the added sections can be done iteratively by using a computer. However, the antenna's width and height can be directly approximated from the antenna patterns (14)

$$\text{Width} = \frac{65\lambda}{\text{BWAZ}} \qquad (14)$$

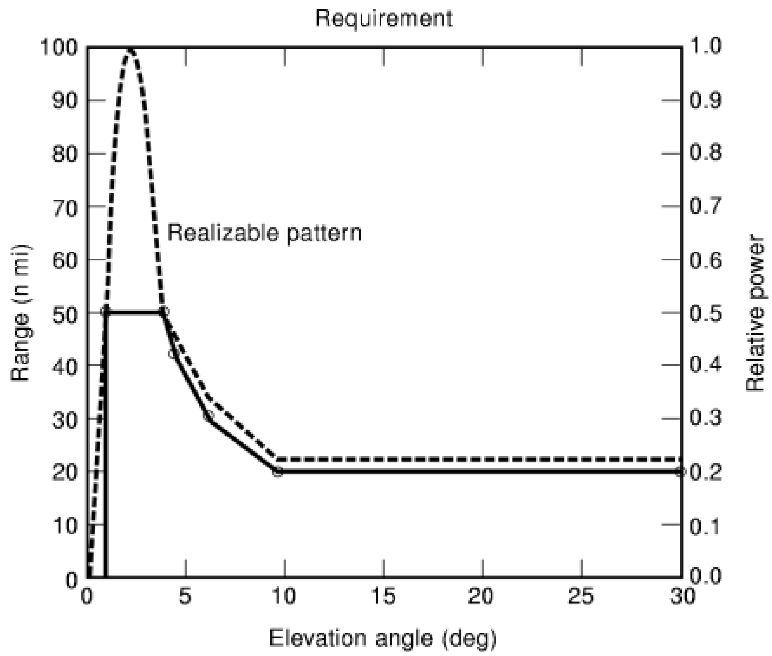

Fig. 8. Coverage requirement (solid line) and realizable pattern (dashed line).

$$\text{Height} = \frac{65\lambda}{\text{BWEL}} \frac{\int f_{\text{el}}(\theta)\,d\theta}{\Delta \int f_{\text{el}}(\theta)\,d\theta} \qquad (15)$$

in which *BWEL* is the elevation half-power beamwidth, and $\Delta\int$ is the integral in the range-limit region.

Practical Consideration. In the analysis and design of radar antennas, some practical considerations must be taken into account because they can affect the performances of the antennas. There are a lot of practical details for different radar antennas, but here we consider only four common effects: feed-support blockage, surface leakage, surface tolerance, and radomes.

Feed-Support Blockage. No matter whether the feed is placed in the front or rear, there is always blockage from the feed supports. In the case of Cassegrain or Gregorian, the blockage comes from the support of the subreflector. Like the blockage of feeds, the supports have two effects on the antenna's performance: they put a shadow in the desired distribution, and they scatter the intercepted power. Both effects can reduce the gain and increase the sidelobe level.

The effective size of the blockage may be larger than its projected area depending upon the material and polarization. For conducting supports, the effective size equals the actual dimension in the E plane, whereas the effective width becomes $W + \sqrt{0.5\lambda d}$ (where W and d are the width and thickness of a strut) in the H plane (15). Therefore, the blockage of a strut of 0.125λ square in cross section will be three times larger when it is parallel to the E field than when it is parallel to the H field. In addition, various ways of sitting the supports have different effects. Figure 10 shows three common ways of supporting the feeds. Note that the tripod arrangement produces sidelobe ridges that are broader but 6 dB lower than those of the quadrapods (15). The feed-support blockage can be reduced by using a dielectric strut.

Surface Leakage. Many reflectors are designed with a tubular grid or a wire-mesh instead of a solid-metal surface in order to reduce the wind resistance and the antenna's weight. To accomplish this, the opening

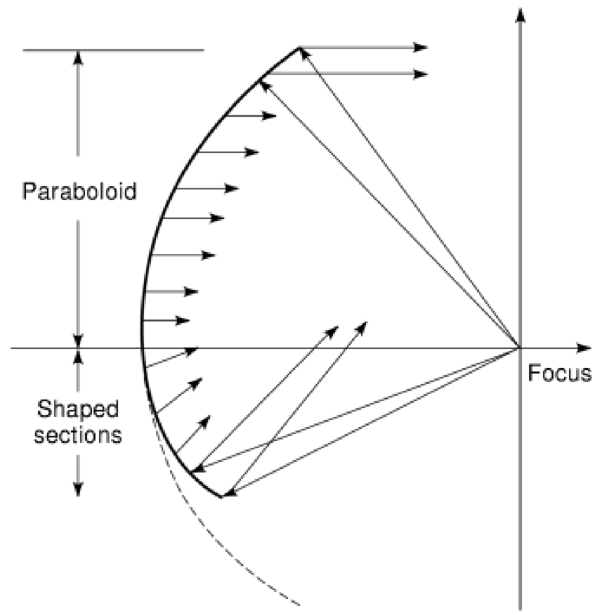

Fig. 9. An example of shaped-beam antenna design.

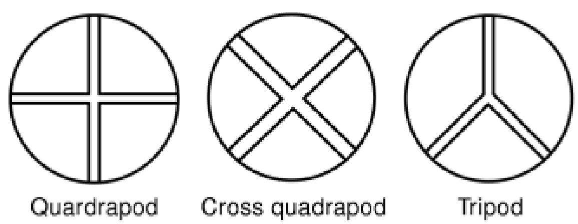

Fig. 10. Some common feed supports used in radar antennas.

area in the structure should be as large as possible. However, the openings lead to surface leakage, from which backlobe is produced. The larger the area of the opening is, the higher the backlobe is. Therefore, a suitable design of the surface structure is important to the antenna's performance. Figure 11 illustrates some of the common reflector surfaces, in which the gap S between conductors must be much smaller than half wavelength in the H plane so that the passage of EM energy will be below cutoff (14).

Surface Tolerance. Mechanical consideration to design reflector antennas is very important in a radar system. In most cases, it is even more difficult and complicated than the electrical design, especially for a high-performance radar. The surface tolerance is one important part of the mechanical design. The reflector surface must be smooth enough so that it remains within close tolerances of the ideal surface. Typically, the surface error must be less than $\lambda/28$.

The roughness of reflector surface can cause small phase error on the aperture. From the antenna tolerance theory, the loss of gain due to phase error is approximated by Eq. (16):

$$\frac{G_1}{G_0} \approx 1 - \bar{\delta}^2 \tag{16}$$

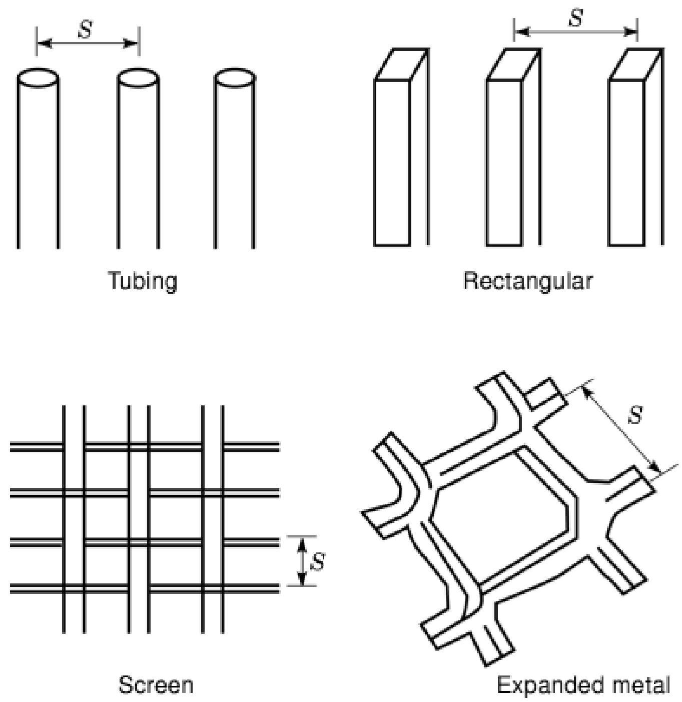

Fig. 11. Common types of reflector surfaces that can reduce the wind resistance.

where G_1 and G_0 are gains with and without phase error, and $\bar{\delta}^2$ is the mean square phase error. From Eq. (16), one clearly sees that for 1 dB loss of gain the phase error $\sqrt{\bar{\delta}^2}$ must be less than 0.45 rad, which means the reflector surface error must be less than $\lambda/28$.

Radomes. Antennas for ground-based radars are often subjected to high winds, icing, and temperature extremes so they must be sheltered if they are to survive and perform under adverse weather conditions. The shelter to protect antennas is called a radome. Antennas mounted on aircraft must also be housed within a radome to offer protection from large aerodynamic loads. An ideal radome should be perfectly transparent to the rf radiation from (or to) the antenna but mechanically strong if they are to provide the necessary protection. These two requirements are usually competing, thus the design of radomes must be compromised (17).

The design of radomes for antennas can be divided into two separate classes, depending upon whether the antenna is for airborne or ground-based (or ocean-based) applications. The airbone radome is characterized by smaller size than ground-based radomes because the antennas that can be carried in an aircraft are generally smaller. The airborne radome must be strong enough to form a part of the aircraft structure and usually it is designed to conform to the aerodynamic shape of the aircraft, missile, or space vehicle in which it is to operate. If the antenna scans inside the streamlined radome, the incident angle may be varied around the normal direction. This will lead to great degradation of antenna performance.

A properly designed radome should distort the antenna pattern as little as possible. The presence of a radome can affect the gain, beamwidth, sidelobe level, beam direction, the voltage standing-wave ratio (*VSWR*), and antenna noise temperature. Sometimes in tracking radars, the change rate of the beam direction can be very important.

Phased-Array Radar Antennas

Besides reflectors, phased-array antennas are also important in radar systems. An attractive advantage of the phased-array antenna for radar applications is that it can steer a beam without having to move a large mechanical structure. For example, when a single radar simultaneously carries out the functions of surveillance and tracking, it must pause for an instant to confirm or disprove a possible alert as a surveillance radar, however, it is required to follow several targets by pointing at each of them successively without any loss of time as a tracking radar. In this case, a phased-array antenna is the best choice because it can steer the beams rapidly by means of electronic control.

The first large steerable directive phase-array antenna for the reception of transatlantic shortwave communication was developed and installed by the Bell Telephone Laboratories in the late 1930s. However, it was limited because the beam was scanned by mechanically actuated phase shifters. A major advance in phased-array technology was made in the early 1950s with the replacement of the mechanically actuated phase shifters by electronic phase shifters, from which the scanning in one angular coordinate can be electronically controlled. The introduction of digitally switched phase shifters employing either ferrites or diodes in the early 1960s made a significant improvement in the practice use, in which a phased array could be electronically steered in two orthogonal angular coordinates. With the development of modern computer and solid-state microwave devices, multifunction phased-array antennas have been developed.

Array antennas can take many different forms for various applications. However, they always include some common components. Figure 12 shows a basic schematic of the phased-array antennas. Clearly, a phased-array system contains an element array composed of many similar radiating elements, a power splitter, the phase shifters, the transmitter and receiver, and a central computer. The radiating elements might be dipoles, open-ended waveguides (or small horns), slots cut in waveguide, printed-circuit patches, or any other type of antennas. On its transmission mode, the power splitter divides the energy from the transmitter to the various elements of the array via the phase shifters. Then the phases and amplitudes of the array can be controlled by the computer. Generally, the amplitude characteristic does not vary during scanning except for adaptive and optimum arrays. Therefore, one can adjust the phase and amplitude taper on array by using the phase distribution and the amplitude distribution to meet different uses.

Basic Characteristics. See Antenna arrays for a detailed analysis of phased-array antennas. Here we give only some general characteristics important to the analysis and design of radar antennas.

For a general planar array, when the elements are spaced by half wavelength to avoid the generation of grating lobes, the number of the radiating elements N for a pencil beam can be approximated from the broadside beamwidth by (18)

$$N \approx \frac{10000}{\mathrm{HPBW}^2} \quad \text{or} \quad \mathrm{HPBW} \approx \frac{100}{\sqrt{N}} \tag{17}$$

where HPBW is the 3 dB beamwidth (in degree) of the antenna pattern. When the beam points in the broadside direction to the aperture, the corresponding antenna gain is

$$G_0 \approx N\pi\eta \tag{18}$$

where η is the antenna efficiency, which accounts for antenna losses (η_{L}) and reduction in gain caused by weighting the elements with a nonuniform amplitude distribution (η_{a}).

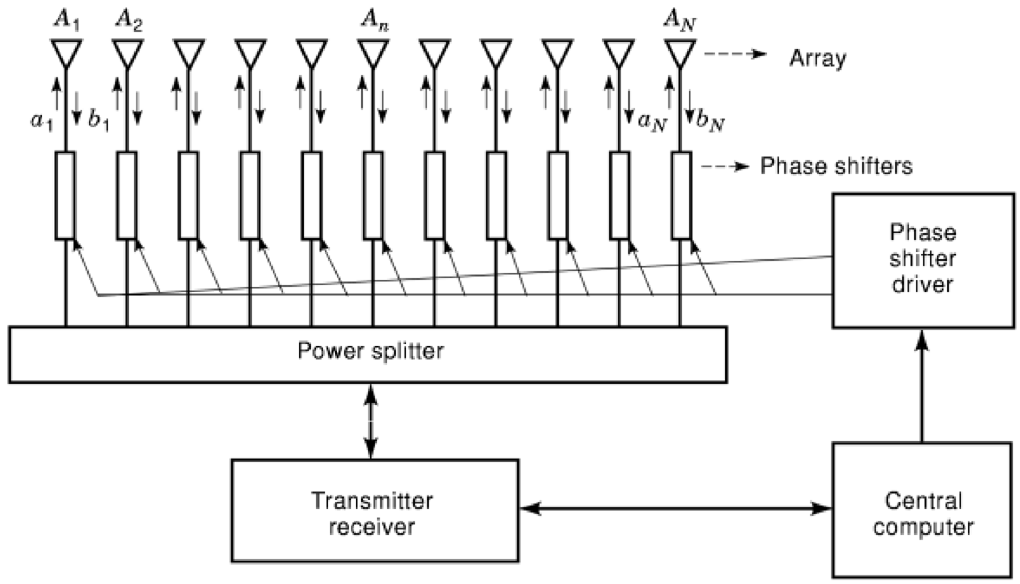

Fig. 12. General structure of a phased array in which the phase shifter driver provides different phases to the array.

When the antenna is scanning to an angle θ_0, the scanned beamwidth is increased from the broadside beamwidth

$$\mathrm{HPBW}(\theta_0) \approx \frac{\mathrm{HPBW}}{\cos\theta_0}(\theta_0 \neq 90^\circ) \tag{19}$$

whereas the gain of the planar array is reduced to that of the projected aperture

$$G_0(\theta_0) \approx N\pi\eta\cos\theta_0 \tag{20}$$

These characteristics can provide an easy way to estimate quickly when analyzing and designing array antennas.

Types of Arrays. The arrays used in radar systems can be classified by such different means as geometry and functions. This subsection will discuss several typical arrays.

Linear Arrays. The linear array generates a fan beam when the phase relationships are such that the radiation is perpendicular to the array. If the radiation is at some other angles, the antenna pattern is a conical-shaped beam. The broadside linear-array antenna may be used where broad coverage in one plane and a narrow beamwidth in the orthogonal plane are required. An active application of linear array is that it can act as the feed for a parabolic-cylinder antenna, as discussed earlier.

Planar Arrays. The two-dimensional planar array is capable of steering the beams in two angular coordinates. It is probably the array of most interest in radar applications because of its versatility. Generally, a rectangular aperture can produce a fan-shaped beam, whereas a square or a circular aperture can generate a pencil beam. The array may also be made to produce simultaneously many search and or tracking beams with the same aperture. Most of arrays discussed later will be the planar arrays.

Conformal Arrays. Sometimes, a radar designer is required to place array elements on an arbitrary surface to achieve a directive beam with good sidelobe level and efficiency, which can be easily scanned electronically. For example, on an aircraft, arrays arranged along the nose, on the wings, or on the fuselage would be attractive options. In this case, a conformal array, which conforms to the geometry of a nonplanar surface, should be used (1).

In principle, the array on any surface can be made to radiate a beam in some given direction by applying the proper phase, amplitude, and polarization at each element. In practice, however, it is very difficult to control the beam shape and obtain low sidelobes from an arbitrary surface when the beam is electronically scanned. Furthermore, the mechanisms for feeding the elements and generation of the phase-shifter command are also more complicated than those of a planar array. Therefore, the application of conformal array is only possible for some simple shapes like cylinder and cones.

Most of the work on conformal arrays has been with the cylinder because it has a geometry suitable for antennas that scan 360° in azimuth. Although it is of a relatively simple shape compared with others, the properties of the cylindrical array are not as suitable as those of planar array. In the cylindrical array, the radiation pattern cannot be separated into an element factor and an array factor as they can in the planar array. Considering the additional difficulties in the practical control, the conformal arrays are not widely used in the radar systems.

Thinned Arrays. Most array antennas have equal spacings between adjacent elements. In order to obtain a given beamwidth with considerably fewer elements, a thinned array has sometimes been considered. Generally, the shape of the main beam has little distortion after thinning. However, the average sidelobes are degraded in proportion to the number of elements removed. Figure 13 shows an example of thinned arrays, in which 77.5% of the elements are randomly removed from a regular grid (19). Then the gain, which is caused by the actual element number, will drop by 6.5 dB, while almost 77.5% of the power is delivered to the sidelobes because the main beam is nearly unchanged.

Therefore, the design of a thinned array consists of selecting the size of the aperture to give the desired beamwidth, selecting the number of actual elements to give the desired gain, and arranging the element distribution to obtain some required properties of the sidelobes.

The thinned arrays have seen only limited applications in radar system because of the reduction in gain and the increases in sidelobes. Instead of thinning elements, the number of phase shifters can also be thinned, in which some of the phase shifters in the array can be used to adjust the phase of more than one element. A 50% saving of the phase shifters might be possible (20).

Phase-Scan Arrays. The beam of an antenna points to the direction perpendicular to the phase front. In phase-scan arrays, the phase front is adjusted by controlling the phase of each radiating element to steer the beam, as shown in Fig. 14(a). The phase shifters are electronically actuated to perform rapid scanning and are adjusted in phase to a value between 0 and 2π rad. If the spacing between two adjacent elements is S, the incremental phase shift ψ will be $\psi = (2\pi/\lambda)S \sin \theta_0$, in which θ_0 is the scan angle. Because the phase shifters have phase shift that is virtually independent of frequency, the scan angle θ_0 is frequency-dependent.

Time-Delay-Scan Arrays. Phase scanning was seen to be frequency-sensitive. Time-delay scanning provides a way that is independent of frequency. Instead of the phase shifters, delay lines are used in the time-delay-scan arrays, as illustrated in Fig. 14(b). For the spacing distance between two adjacent elements S, the incremental time delay from element to element is $t = (S/c) \sin \theta_0$, in which c is the velocity of propagation of wave and θ_0 is again the scan angle. The time-delay circuits accompanied by all radiating elements are normally too cumbersome. A reasonable compromise solution is sharing one time-delay network by a group of elements in which each element has its own phase shifter. However, this will cause a grating lobe problem.

Frequency-Scan Arrays. A change in frequency of an EM signal propagating along a transmission line produces a change in phase. This provides a simple way for obtaining the electronic phase shift, as shown in Fig. 14(c). In this case, the incremental phase shift is

$$\psi = (2\pi/\lambda)l = (2\pi/\lambda)S \sin\theta_0 + 2\pi m \qquad (21)$$

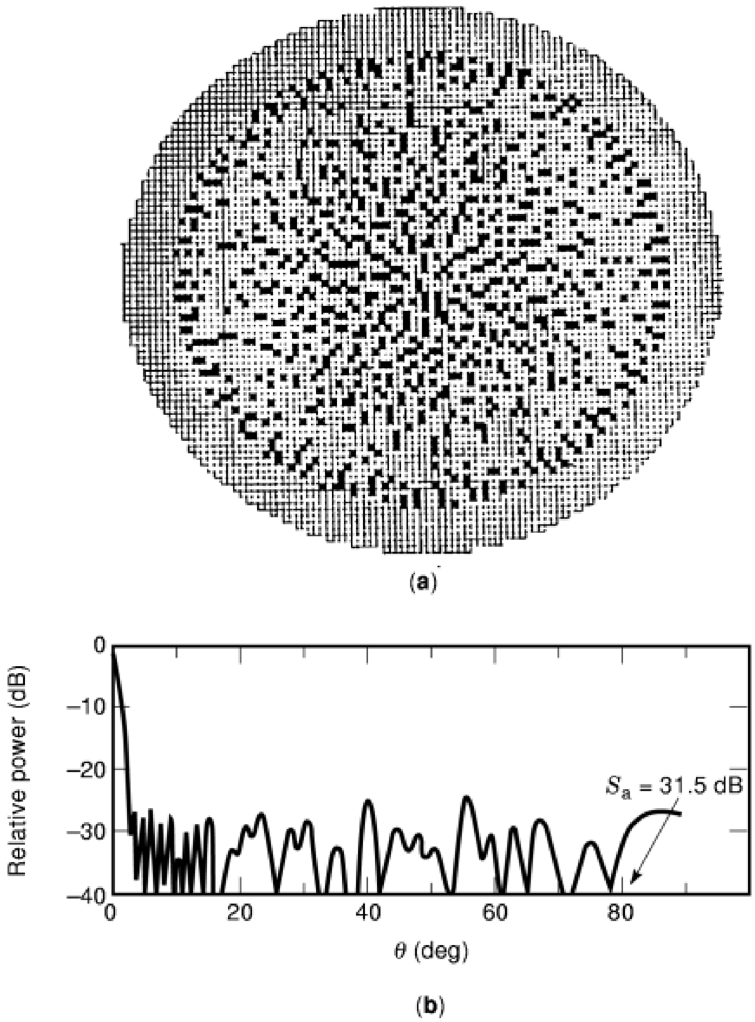

Fig. 13. (a) Thinned array with a 4000-element grid containing 900 elements; (b) typical pattern for a thinned array in which S_A is the average sidelobe level. [From Willey (15, Figs. 5 and 6) courtesy of Bendix Radio Div., Bendix Corporation.]

in which l is the length of line connecting adjacent elements. When the beam points broadside ($\theta_0 = 0$), Eq. (21) yields $m = l/\lambda_0$, where λ_0 is the wavelength corresponding to the beam position at broadside. Then the direction of beam pointing can be obtained from Eq. (21)

$$\sin\theta_0 = \frac{l}{S}\left(1 - \frac{\lambda}{\lambda_0}\right) \tag{22}$$

Comparing with other ways, the frequency-scanning system is relatively inexpensive and easy to implement. Frequency-scan arrays have been developed and used to provide elevation-angle scanning. Combined with the mechanical horizontal rotation, it served as 3-D radars in the past.

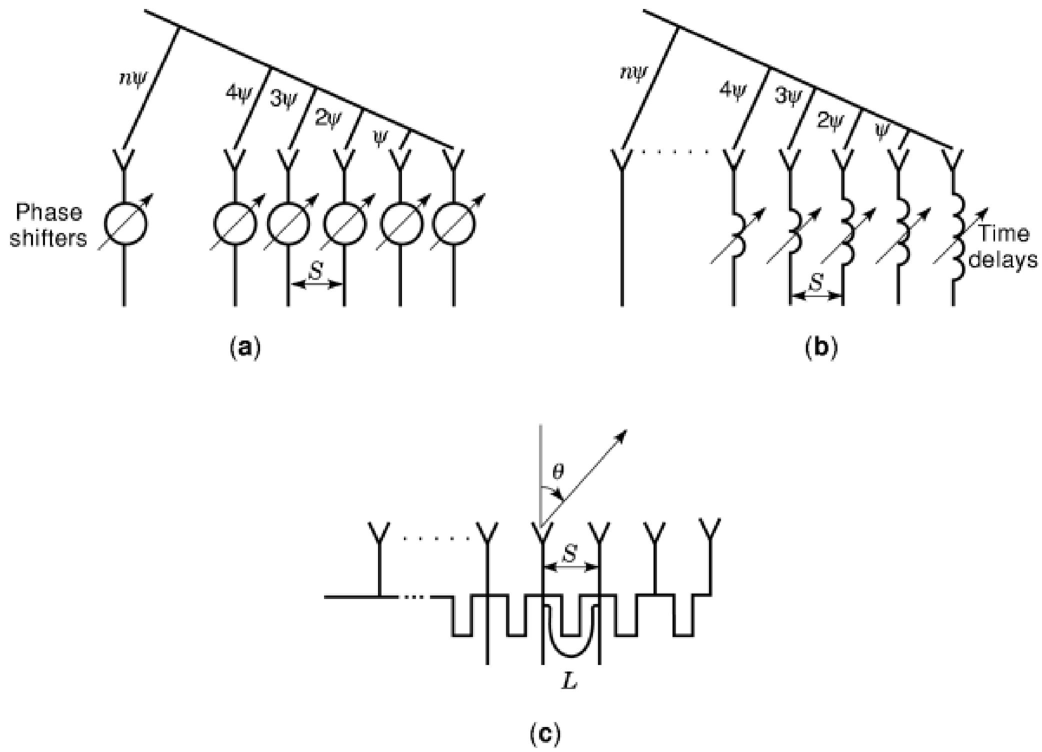

Fig. 14. Scanning of arrays. (a) Phase scan; (b) time-delay scan; (c) frequency scan.

Multiple-Beam-Forming Arrays. One of the properties of the phased array is the ability to generate multiple independent beams simultaneously from a single aperture. In principle, an N-element array can generate N independent beams. Multiple beams allow parallel operation and can obtain a higher data rate than a single beam. The multiple beams may be fixed in space, steered independently, or steered as a group. In some applications, multiple beams are generated on receive and connected to separate receivers, whereas only one wide radiation pattern is needed on transmit so that it can cover all the received beams. Such multibeam systems have found application with mechanical rotation for 3-D coverage.

Low-Sidelobe Arrays. A low sidelobes level is one of the most important requirements for the radar antennas, especially for military radars that may be threatened by the jamming. Therefore, the low sidelobe level has been and will be of great interests to radar designers. By modern technology, an ultralow sidelobe has been achieved in the Airborne Warning and Control System (*AWACS*) radar, which now supports sidelobe levels of more than 50 dB below the main-beam peak (21). However, as mentioned earlier, the low sidelobe and high gain are competing requirements. Thus the cost to achieve low sidelobe is a reduction in gain and an increase in beamwidth. Considering the practical implementation, the low sidelobes also require a high-tolerance control and a good environment free from obstructions that could increase the sidelobes so low-sidelobe antennas are usually expensive. In spite of these drawbacks, the trend to low-sidelobe arrays has accelerated because low sidelobes provide an excellent deterrent to electronic countermeasures (*ECM*).

From the aperture theory, antenna sidelobes are related to the aperture amplitude distribution. For phased arrays, the amplitude taper is generally fixed and does not change. However, the amplitude of each radiating element can be controlled individually by the computer, which makes it possible to achieve very low sidelobes.

The relation between the antenna pattern and the aperture illumination has been studied extensively in many literatures. It has been shown that the far-field pattern is just the Fourier transform of the aperture distribution. Some typical illumination functions and their corresponding gains, sidelobes, and beamwidths can be found in Refs. 5 and 18. For low-sidelobe arrays, the Taylor illumination for the sum patterns and the Bayliss illumination, a derivative form of the Taylor illumination, for the difference patterns are usually chosen because they can provide low sidelobes at a minimum loss in gain. Note that the sidelobes predicted by the aperture illuminations are suitable for perfect phase and amplitude distributions (error free). In practice, aperture illuminations must be chosen to provide peak sidelobes below the requirements to allow for errors. The effect of errors on the design will be mentioned next.

Practical Considerations. The array theory gives only the theoretical analysis and design of the phased arrays. For practical use in radar systems, a lot of details must be considered. In this subsection, some important considerations are addressed.

Phase Shifters. As already stated, there are three basic techniques to steer the beam electronically: frequency scanning, time-delay scanning, and phase scanning with phase shifters. In practice, the use of phase shifters is the most popular technique, but many other techniques have been developed for a variety of phase shifters (22). Generally, the phase shifters can be classified into two categories: reciprocal and nonreciprocal. For reciprocal phase shifters, the phase change does not depend on the direction of propagation. Therefore, it is not needed to switch the phase states between transmit and receive if the reciprocal phase shifters are used. For a nonreciprocal phase shifter, however, it is necessary to change the phase states between transmit and receive. Typically, it takes a few microseconds to switch the nonreciprocal phase shifters. During this period, the radar cannot detect targets.

A perfect phase shifter could change its phase rapidly; handle high power; require control signals of little power; be of low loss, light weight, small size, and reasonable cost; and have a long life. But in practice, no one device is universal enough to meet all the requirements. Various phase shifters possess these properties in varying degrees. Presently, three types of phase shifters are used in the phased-array antennas: the diode phasers which are all reciprocal, the nonreciprocal ferrite phasers, and the reciprocal ferrite phasers. Each of the three types has its own advantage. The choice of phase shifters is highly dependent on the radar requirements.

Array Elements and Matching. Almost any type of radiating antenna element can be considered for an array antenna. In practice, the dipole, open-ended waveguide (or small horn) and slotted waveguide have found wide applications. Detailed descriptions of these antennas have been investigated in the standard textbooks (1,5). However, note that the properties of a radiating element in an array is significantly different from its properties when in free space. For example, the radiation resistance of a half-wavelength dipole in free space is 73 Ω, but when it is in an infinite array with half-wavelength spacing and a back screen of quarter-wave separation, it will be 153 Ω when the beam is broadside. The impedance also varies with scan angles.

The change of impedance with scan angle makes the matching of an array antenna difficult. There are conditions where an antenna that is well matched at broadside may have some angles at which most of the power is reflected. Unlike a conventional antenna, the mismatch of array antennas will affect both the level of the radiated power and the shape of the antenna pattern.

Mutual Coupling. If two radiating elements are widely separated, the energy coupled between them is small, and the influence of one to the other on the current excitation and pattern can be negligible. However, when the elements are placed closer, their coupling will increase. Generally, the strength of the coupling in a phased array is related to the distance between elements, the pattern of the elements, and the structure of the array. For example, the radiation pattern of a dipole has a null at $\theta = \pm 90^\circ$ and a peak value at $\theta = 0^\circ$. Thus, the dipoles in a straight line are loosely coupled, whereas the dipoles parallel to each other have a strong coupling.

For a phased array, the effect of coupling between elements in mainly focused on the pattern and impedance of the element, which are usually called the active element pattern and the active element impedance. The exact analysis of coupling in practical arrays is rather complicated. A convenient way is to assume that the array is infinite in extent and has a uniform amplitude distribution and a linear phase taper from element to element. Under such an assumption, every element in the array has the same environment; thereby a significant simplification in the calculations can be made. It has been shown that the infinite-array model has a good prediction to the actual arrays. Even for a modest array that has fewer than 100 elements, the predicted results can also give reasonable agreement (23).

Errors in Arrays. As indicated in the section entitled "Low-Sidelobe Arrays," the errors in the amplitude and phase of the current at individual elements of the array may cause distortion of the radiation pattern. Additional factors of the error include the missing or inoperative elements, rotation or translation of an element from its correct position, and variations in the individual element patterns. These errors can result in a decrease in gain, increase in sidelobes, and shift in the direction of the main beam.

When errors occur in the phase and amplitude of the aperture, the energy will be removed from the main beam and distributed to the sidelobes. If the errors are purely random, they will produce random effects on the main beam and all sidelobes. When the errors are correlated, the sidelobe energy will be lumped at discrete locations in the far field. Usually, the correlated errors provide higher sidelobes than the random errors, but they are located at some certain directions only. Both of the correlated and random errors should be considered in the practical design of phased arrays (18,24).

Applications. In many cases, the phased-array antennas have been of considerable interest in the radar systems because they have different properties from those of reflector antennas. Hence, a number of phased-array radar systems have been built for different use (18,25). Examples include the AN/SPS-33 radar for the purpose as aircraft surveillance from on-board ship; the AN/FPS-85 for satellite surveillance; the PAR and MSR for ballistic missile defense; the AN/SPY-1 and PATRIOT for air defense; the *EAR* (Electronically Agile Radar) for airborne bomber; the AN/TPN-19 and AN/TPS-32 used in aircraft landing systems; the AWACS and AN/TPS-70 for airborne warning and control systems; the MESAR as a multifunction electronically scanned adaptive radar; the AN/TPQ-37 Firefinder radar; the PAVE PAWS for providing early warning of ballistic missiles and performing satellite tracking; the COBRA DANE for tracking of ballistic missile; and the COBRA JUDY for collecting data on foreign ballistic missile tests (18,25).

Although the array antennas have many unique characteristics that make them candidates for use in radar systems, they are expensive. As technology advances, the costs can be reduced, particularly in the areas of phase shifters and drivers. In the meantime, the high demand for better performance with lower sidelobes and wider bandwidth makes the costs high. In the future, the great potential for cost reduction may be the application of solid-state systems with a transmit/receive module at each element.

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