Contributions to the Antenna Field During World War II*

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Summary—**During World War II intensive efforts of radio engineers and physicists resulted in the invention of many new types of antennas and in advances in fundamental antenna theory. The paper presents the results of this work in relation to the principal problem areas that were recognized during that period: 1) sidelobe suppression; 2) beam-shaping techniques; 3) beam-scanning techniques; 4) broadbanding; 5) antenna siting. In each of these areas major advances were made, both in operating hardware and in theoretical understanding.**

I. Introduction

THE developments in the antenna field during World War II, the result of intensive and combined efforts of radio engineers and physicists, were marked by the invention of many new types of antennas, and also by advances in fundamental antenna theory. Indeed, the whole subject of microwave optics was born and grew to maturity during the war years. A review of the field leads us into many different directions. In choosing the subjects for this short résumé we have arranged the material, including theoretical considerations, according to certain operational developments. Because the achievements were so largely the result of the combined efforts of many people in the United Kingdom, Canada, and the United States, we have avoided ascribing any development to a particular person, even though in a few instances this would have been possible.

The review is divided into five sections: 1) sidelobe suppression, which relates to developments based on the concept of flat phase fronts; 2) beam-shaping techniques, which utilized new developments in microwave optics; 3) beam-scanning techniques; 4) broadbanding; 5) antenna siting, a subject of great importance in realizing the optimum performance of the systems and in measuring the characteristics of antennas.

II. Pencil Beams and Sidelobe Suppression

The first operational concept in the design of antennas for radar applications was that of providing a narrow beam whereby targets could be located with high precision in azimuth and elevation. The pulse technique of radar, of course, provides the range information, and the combination of beam and pulse techniques yields the three coordinates of the target in space. The operational requirement, based on the searchlight concept of optics, required not only that the main beam be narrow, but also that the sidelobe structure be kept low to avoid the ambiguity of targets detected on the sidelobes. Two main approaches were taken to achieve a narrow beam: the use of optical devices, lenses and reflectors, having the property of transforming a family of rays from a point source into a family of parallel rays; and the use of discrete arrays of elements based on the principle of interference.

The directive antennas to produce a main beam circularly symmetric about the axis utilized a paraboloid of revolution with a primary feed at the focus. In order to achieve maximum forward gain out of a given aperture the distribution in the field over the aperture should be uniform in both amplitude and phase. However, the sidelobe structure is determined by the distribution of amplitude within the uniform phase constraint, and a major aspect of the theoretical work in this field was the study of the interrelation between the aperture distribution and the entire radiation pattern of the system. This greatly enlarged the understanding of diffraction theory over what had been available prior to the war. It also led to a rediscovery of long forgotten monumental contributions made to the field of optics over a hundred years ago.

Much effort was devoted to the realization of a feed system having, on the one hand, the characteristic of a point source, that is, generating a spherical phase front, and, on the other hand, a power pattern which would properly illuminate the paraboloid. When the coaxial line was the preferred form of transmission line, the natural choice of primary radiator was the dipole and, in particular, the reflector-backed dipole. Dipole feeds did only a fair job of illuminating the reflector since they produced unequal illumination in the orthogonal planes, and hence asymmetry in the mainlobe. In addition, their considerable backlobe radiation had deleterious effects on gain and near-in sidelobe characteristics of the final pattern.

As was indicated, it is necessary to trade sharpness of the main beam for sidelobe reduction. The general result established was that the aperture illumination should be tapered by some 15 db between the center of the aperture and the edge. The half-power width of the main beam is given by $\theta = k\lambda/D$, where λ = free-space wavelength, D = diameter of the aperture; designs were developed for circular apertures which yield values of k in the range $1.2 \leq k \leq 1.5$ with near-in sidelobes down 20 to 25 db from the peak intensity of the mainlobe.

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The availability of higher power, the move toward higher frequency and the toleration of heavier antenna structures, especially airborne, led to the use of rectangular uniconductor waveguides and compatible feed systems. The development of these waveguides and horns is certainly an outstanding feature of antenna work during World War II. Sectoral horns derived from rectangular waveguides by flaring in one or the other of the two principal planes of the guide, composite sectoral horns derived by flaring first in one plane and then in the orthogonal plane, and pyramidal horns derived by flaring simultaneously in both principal planes were developed for various applications. By virtue of the flexibility available in the design of a horn feed, it was possible to illuminate a reflector more effectively and to achieve improved performance with respect to backlobe and sidewise radiation. Three horn-feed types are shown in Fig. 1.

A major development in reflector design that accompanied the use of horn feeds was that of directing the axis of the horn pattern onto the reflector at an angle to the reflector axis. The reflector is then cut along an equi-intensity contour, again at an edge illumination some 15 db below the peak value over the aperture. Since the phase center of the horn remains at the focus, the phase distribution over the aperture remains plane yielding a directive beam. The importance of the technique is its flexibility in controlling sidelobe levels while retaining the required mainlobe characteristics. Such an antenna is shown in Fig. 2.

Operational needs arose for beams having mainlobes not circularly symmetric but of different beamwidths in two orthogonal planes, one very narrow to retain high resolution in the plane of scan, and the other relatively large to give extended coverage in the orthogonal direction. Such beams are known as *fanned* beams, and basic diffraction theory shows that they can be obtained by using rectangular or elliptical apertures with a corresponding ratio of their principal dimensions. The aperture illumination problem remains that of providing a uniform phase and a tapered amplitude distribution to control the sidelobe level; the horn feed solved this problem. Fig. 3 shows a paraboloid of revolution cut into an elongated elliptical shape and fed by a flared horn.

Another family of antennas designed to produce fanned beams consists of a parabolic cylindrical reflector between parallel plates illuminated by a sectoral horn feed at the focus. The exit pupil of the system is then a narrow rectangular aperture. Such antennas, known variously as cheese or pillbox antennas, served as ends in themselves or as line sources for illuminating larger parabolic cylinders, as shown in Fig. 4.

Microwave lenses were used in Germany prior to the war and were investigated extensively in the United States during the latter years of the war. In most military applications, however, lenses were not competitive with reflectors because of such factors as reduced gain, higher sidelobes, frequency sensitivity, greater weight and unfavorable shape. One development of note, however, must be mentioned in this survey. It was recognized that the dispersive property of a waveguide could be used in creating a medium having an effective index of refraction less than unity. The waveguide or metal-plate lens thus came into being but did not find actual application during the war. Fig. 5 shows an early type of waveguide lens.

Linear arrays also received a great deal of attention. The designs which were built around the coaxial line utilized dipole radiators, and there were many ingenious configurations devised for beacon antennas and related operational systems. Basically, however, these antennas were adaptations of ideas and developments already in use in radio-communications and direction-finder systems before the war. The distinct war-period contribution to the array system was the slotted waveguide array. The theory of slot radiators was developed extensively, and here it is appropriate to state that the basic work was largely provided by groups in the United Kingdom and Canada.

The excitation of a slot in the wall of a rectangular waveguide can be controlled by its position on the wall and the orientation of the axis of the slot with respect to the axis of the waveguide. It is this flexibility that makes possible the relatively easy control of excitation along the array. Of the many developments that were made in this field, the so-called Dolph-Tchebycheff array deserves special recognition. In this type of array the amplitude distribution along the array is related to the coefficients of a Tchebycheff polynomial. The result is a beam having all sidelobes of equal amplitude and therefore the narrowest beamwidth consistent with a prescribed sidelobe level. Sidelobe levels 30 db below the mainlobe peak were obtained, and in later developments following the war even lower sidelobe levels were achieved.

III. Beam Shaping

The operational requirements that motivated the design of fanned-beam antennas became rather quickly more demanding with respect to the more efficient utilization of the available power in air-search systems and more uniform ground illumination in airborne navigational and bombing antennas. One solution to the problem was obtained by the use of an extended feed in the focal plane of a paraboloid reflector. Each element of the feed produces a beam displaced from the axis by an angle proportional to the displacement of the element from the focal point. The resultant of the overlapping beams is a flared beam. High resolution in the transverse aspect is preserved until the coma aberration overrides the collimating property of the reflector. The theory of aberrations was advanced markedly in the course of this developmental program. The antenna on the left in Fig. 7 achieves a shaped beam by means of a three-horn distributed feed.

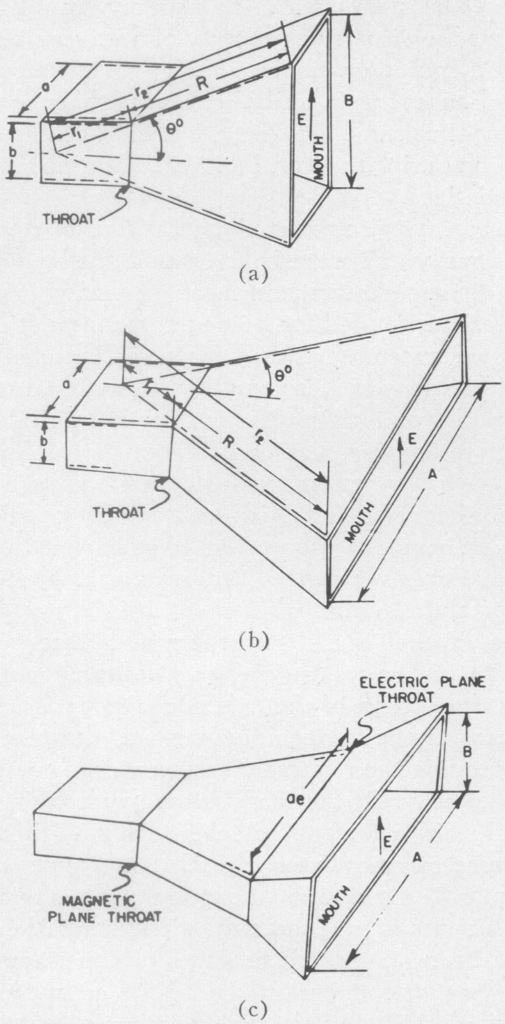

Fig. 1—Horn-feed types. (a) Electric-plane horn. (b) Magnetic-plane horn. (c) Compound horn.

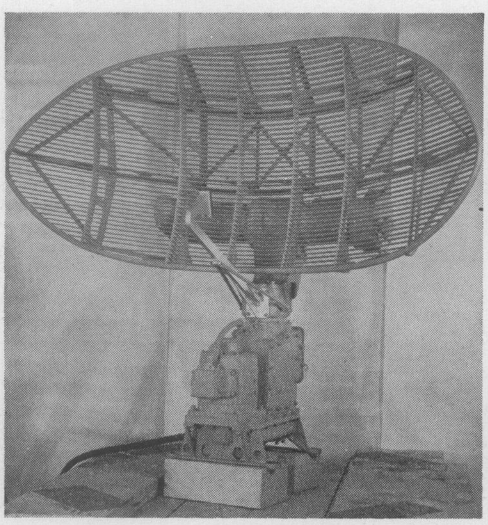

Fig. 2—Antenna with asymmetrically cut reflector.

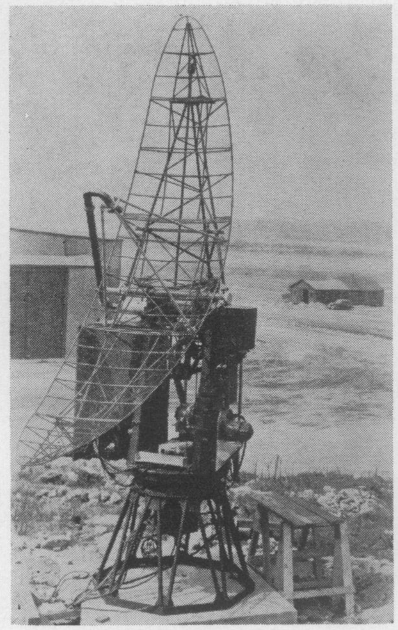

Fig. 3—Fanned-beam antenna.

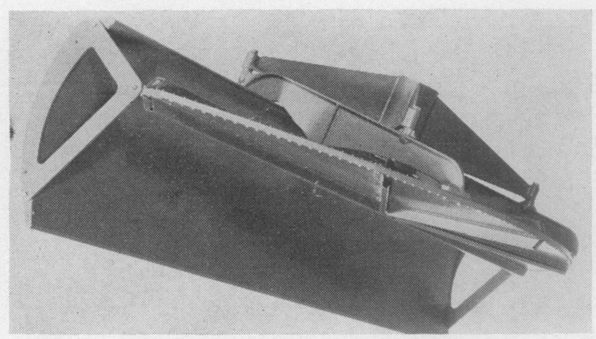

Fig. 4—Pillbox antenna feeding a cylindrical reflector.

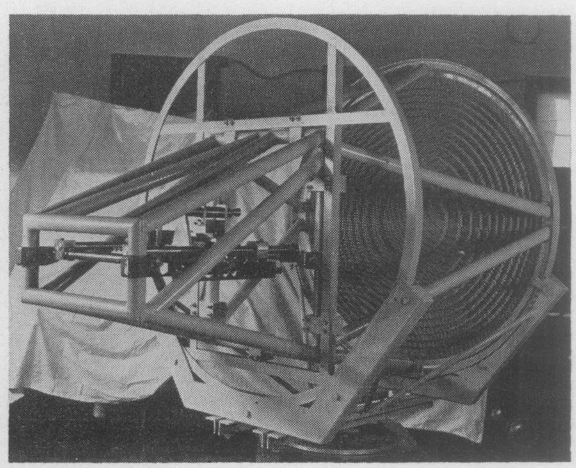

Fig. 5—Waveguide lens antenna.

The outstanding development, however, was the production of cylindrically curved phase fronts over the aperture of the antenna. By developing a phase front which is a section of a generalized cylinder, it is possible to obtain a flared beam which, in the transverse aspect, retains sharpness over large flare angles. The coma effect is eliminated since the rays are necessarily perpendicular to the generator of the cylinder. Both the underlying concepts and the realization of the system were major advances in microwave optics.

The requisite phase front was realized in several ways. One system utilized a line source feeding a cylindrical reflector whose cross section was designed to produce the dispersion of the ray system required for the flaring of the beam. The line source was aligned to be parallel to the generator of the reflecting cylinder. The sidelobe level in the transverse planes is determined entirely by the amplitude distribution along the line source. Both pillboxes and arrays were used as line sources, and all of the techniques for controlling sidelobe levels derived from flat phase fronts can be used in the design of the feed. (Fig. 4 represents this type of antenna.)

A second type of system utilized a point source feed with a modified paraboloidal reflector. The earliest form was made up of a split paraboloid of revolution with one section displaced relative to the other, so that the resulting phase front had a large amount of third-degree phase error. Advances in theory, however, led to a new type of reflector whose curvature varied from point to point so as to fit the ray requirements completely over the entire range of the beam. The complexity of the resulting surface was more than balanced by the simplicity inherent in the point source feed. This type of reflector, referred to as the doubly curved reflector, was used increasingly toward the end of the war. Fig. 6 shows an operational antenna of this class.

IV. Beam Scanning

A radar system must be able to scan its directive beam at a rate compatible with information rate called for by operational requirements. This must be accomplished while preserving resolving power and an effective SNR. Among the outstanding contributions made to the antenna art during World War II, were the developments in scanning techniques.

The obvious method of scanning by moving the entire antenna had soon to be superseded by other techniques as antennas became larger, and as higher scanning rates and complex scanning patterns became needed. In essence, the scanning problem is one of changing the orientation of the phase front at the aperture of the antenna. This must be done with minimum distortion of the phase front to preserve the structure of the beam. The various rapid-scanning techniques which were invented can be designated by the war-time categories as optical scanning, phase-shift scanning, and frequency-shift scanning.

In optical scanning only a part of the antenna is moved. For example, the feed of a parabolic reflector can be moved off axis in the focal plane to obtain a limited angle of scan. In particular, the feed may be displaced slightly and then spun about the axis to achieve a conical scan. The differential signal from either side of the cross-over point yields a high accuracy of pointing and a convenient tracking signal.

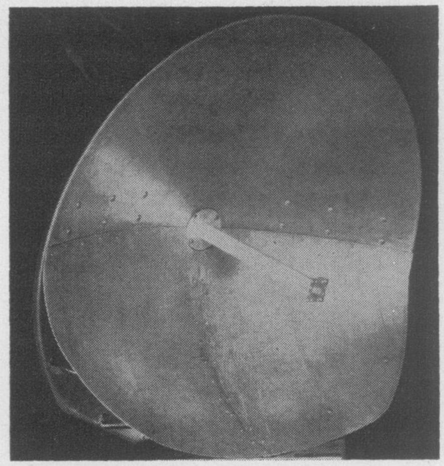

Fig. 6—Shaped-beam antenna employing a modified paraboloidal reflector.

The Robinson Roll antenna (right-hand antenna in Fig. 7) was the most ambitious application of the displaced-feed technique. The reflector had a long focal length in one plane and a relatively short focal length in the other. The feed was located at the far focal point, but was confined in one plane between parallel plates to meet the short-focus requirement. Moving the feed between the plates and parallel to the aperture then provided a scan in one plane. The final invention was to fold the plates in such a way that the oscillatory feed motion was replaced by a circular motion.

One system which was developed to effect the same purpose as conical scanning is essentially a data-processing technique. It uses a stationary feed system comprised of four feeds clustered in a square about the axis. These, when fed all in-phase and in out-of-phase pairs, form a central or sum lobe and two split or difference lobes in orthogonal planes, respectively. By using the sum lobe in transmission and the difference lobes and the sum lobe simultaneously on reception and comparing signals, one obtains a superior tracking antenna.

Three different examples of phase-shift scanning deserve mention. The Navy Mark 8 fire-control antenna (Fig. 8) scanned in an azimuth sector the beam formed by a two-dimensional array of "polyrod" endfire radiators, by separately controlling the phase to each vertical bank of radiators. This control was accomplished by rotating impedance elements in the circularly polarized field of cylindrical waveguide sections. In the Foster scanner a linear variation in phase was accomplished by control of physical path length; a wave between parallel plates was conducted around a variable portion of the circumference of a cone. The Eagle antenna was a

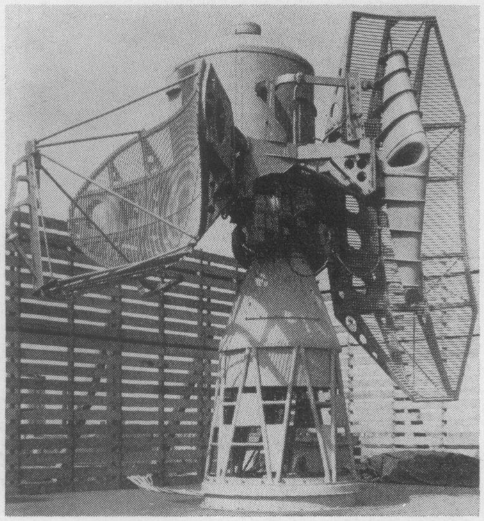

Fig. 7—Shaped-beam antenna (on the left) and Robinson Roll scanning antenna (on the right).

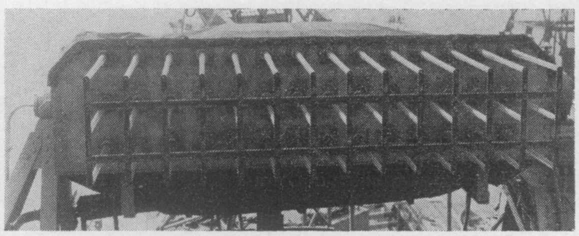

Fig. 8—Mark 8 "polyrod" scanning antenna.

linear array of dipole elements fed from rectangular waveguide. A linear-phase variation was obtained in this case by varying the major dimension of the waveguide and, hence, the optical path length between radiating elements.

Frequency-shift scanning makes use of the fact that the wavelength, and therefore the phase, along an array of radiators fed from a waveguide depends upon the frequency of the radiation. The scanning effect can be amplified by using a frequency-sensitive waveguide and by wrapping or folding the guide between radiators. This technique was explored during the war but did not find extensive application until later because of lack of frequency flexibility in available radio-frequency power sources.

V. Broadbanding

In the early days microwave power sources, even though designed for a spot frequency, came off the line with a spread in frequency. Later an even greater spread in frequency was required to reduce friendly jamming and to make enemy jamming more difficult. For these reasons the RF system, including the antenna, had to perform satisfactorily over a band of frequencies. Studies of a large variety of systems led to a clearer understanding of the factors limiting impedance bandwidth and of the methods of combining mismatches to cancel one another.

In the case of the antenna, satisfactory performance required that any of the essential antenna characteristics be maintained within certain limits over the specified band. These characteristics included power gain, beam-width, sidelobe level and, in the conical scan pattern, the cross-over level. The characteristic of greatest concern, however, in those days of the sensitive magnetron was the impedance of the antenna.

A constant impedance mismatch, even if large, could be corrected by a transformer at the magnetron, but a mismatch that varied widely and rapidly with frequency had to be eliminated or compensated at the point of origin. Frequency-sensitive mismatches resulted primarily from the combined effect of a series of discontinuities distributed along the RF line. Antenna mismatch was most serious since the antenna was farthest from the RF source.

Feeds for paraboloid reflectors were matched first independently of the reflector. Dipole feeds from coaxial lines, with their associated chokes and directive dipoles or plates, were relatively frequency sensitive with many critical dimensions requiring elaborate adjustments. Horn feeds from waveguides were basically better matched with fewer critical dimensions and were more susceptible to calculation.

The art of horn design reached an advanced state during the war years. If the waveguide was flared in both dimensions, the flare angles and their positions in the guide were chosen so that their discontinuities tended to compensate each other and also that caused by the mouth of the horn (see Fig. 1). Final correction was accomplished by capacitive or inductive strips at or near the mouth of the horn, or better, in some cases, by the thickness and placement of a plastic cover over the horn.

When the feed was placed in the reflector, an additional discontinuity resulted from reflection back into the feed. In some cases this discontinuity was corrected by a small plate placed a fraction of a wavelength in front of the vertex of the reflector. The size and placement of the vertex plate could be calculated from the geometry and the feed pattern. The vertex plate saw limited use, however, because it disturbed the aperture illumination and increased sidelobes. The ideal solution was found in the asymmetrically cut reflector (see Section II) which took the feed out, or almost out, of the reflected beam. In this case the feed was located at the focal point but directed off-axis approximately toward the center of the reflector area.

The reflector mismatch was much more serious in cylindrical reflectors, such as pillboxes fed by horns or long cylindrical reflectors fed by linear arrays. For these antennas it was essential that the feed be removed from the reflected beam. This was accomplished for the pillbox by the use of the folded pillbox or by the "hoghorn." In the folded pillbox the feed at one level was connected to the linear aperture at another level by a parabolic bend. In the hoghorn the feed, still at the focus, illuminated half a pillbox with the aid of a guiding horn. Both of these pillbox modifications, however, introduced additional weight and a less satisfactory form factor. In the case of a cylindrical reflector illuminated by a long linear array, the reflected wave striking the array seriously disturbed both the impedance and the radiation characteristics of the array. Therefore the array had to be kept well out of the path of the reflected wave.

The long linear array, in which only a small fraction of the incident power reached the far end of the array, was usually terminated in a load. This so-called nonresonant array provided a relatively good impedance match since the reflections from successive elements could be made to curl up into a small resultant mismatch at the input to the array. Short arrays, operated resonantly with a short-circuit termination, were more frequency sensitive in their impedance. In both cases, of course, well-matched or individually compensated radiating elements greatly improved the over-all performance.

VI. Antenna Siting

An antenna tested under relatively "free" conditions was found to perform quite differently under operating conditions because of reflection of its radiation by the surroundings. Reflection back into the antenna affected its impedance match; forward reflection affected the mainlobe or sidelobe characteristics of its radiation pattern. Toward the end of the war great strides were made in understanding and solving the complex problems created by the installation of many antennas on a single ship or aircraft.

A shipborne antenna with a horizontal beam had its elevation pattern sharpened and split into multiple lobes, and its gain increased by reflection of half of the mainlobe by the sea surface. The over-all effect was not simple since the reflectivity of the sea surface depends on wavelength and polarization of the radiation, angle of incidence, and sea state, and the combined pattern depends on height and orientation of the antenna.

A more complex installation problem was created aboard ship because many antennas were competing with each other in the presence of stacks, masts and superstructure for some semblance of free-space conditions. This so-called antenna-system problem was particularly severe for omnidirectional antennas. In the case of HF communication antennas, intercoupling between transmitting and receiving antennas and the sharply lobed patterns of individual antennas were known only through operational experience, so that maintaining satisfactory HF communications required black art of a high order. Radars were frequently installed in pairs with their antennas fore and aft or port and starboard in order to achieve complete azimuthal coverage.

Military aircraft also presented a serious antenna-system problem. Antennas for navigation, short- and long-range communication, and radar competed for favorable sites in the face of increasingly severe aerodynamic restrictions as aircraft speeds increased. The radar antennas, aircraft intercept or bombing and navigation, had the additional problem of operating through a radome, a plastic housing necessary for aerodynamic reasons.

The radome problem first presented itself dramatically when a naval aircraft search radar was found to be blanked out in certain sectors. This was found to be due to reflections from the radome back into the RF system pulling the frequency of the magnetron out of the pass band of the receiver. This impedance effect continued to be the most serious consideration. Under certain conditions, however, refractions and forward reflections could distort the mainlobe and introduce objectionable sidelobes.

Radome wall designs included the thin wall (zero-thickness approximation), the sandwich wall (two thin skins spaced a quarter wavelength apart by plastic foam), and the half-wave wall (a solid, high-density wall, one-half wavelength thick). During the war much attention was given to the sandwich wall, but shorter radar wavelengths, higher temperature requirements, and more severe microwave optical requirements eventually favored the half-wave wall.

Antenna siting problems were first encountered in connection with measurements made in the course of antenna development and test. With directive microwave antennas, measurements of the pattern and impedance were normally handled separately. For impedance measurements, satisfactory results could be obtained merely by pointing the antenna out through a large open window. For pattern measurements, especially since there was considerable interest in measuring low-level sidelobes, it was necessary to have transmitting and receiving antennas facing each other across a considerable distance from elevated vantage points, so that reflecting surfaces were well out of both beams. As antenna apertures increased, the minimum pattern range also had to be increased according to the relation $R_{\min}=2D^2/\lambda$, where D was the maximum dimension of either transmitting or receiving antenna.