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16 September 1960 to 15 September 1961

STUDY OF ELECTROMAGNETIC WINDOW DIELECTRIC TECHNIQUES

ANTENNA LABORATORY
DEPARTMENT OF ELECTRICAL ENGINEERING
THE OHIO STATE UNIVERSITY

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AERONAUTICAL SYSTEMS DIVISION
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Antenna Laboratory
Department of Electrical Engineering
The Ohio State University

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Reconnaissance Laboratory
Aeronautical Systems Division
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base
Ohio

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Aeronautical Systems Division
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base
Ohio

ABSTRACT

A study has been made of the performance of an electronic-scan antenna when mounted in a quadripod. Measurements have been obtained also of the diffraction by other metal objects in front of an antenna. Good agreement is observed between the measurements and theoretical results obtained with the aid of a digital computer. The computer program is designed to predict the effects of metal supporting structures, pitot booms, and infrared systems which may be mounted in front of a radar antenna.

Two techniques have been developed for the analysis and design of inhomogeneous radomes. Step-by-step numerical integration is used in cases where the permittivity gradient is large. The WKB method is more convenient and is accurate when the permittivity gradient is small. These techniques are useful in analysing the effects of thermal gradients on radome performance, and in designing broadband radomes with variable density or variable loading.

The factors affecting the power-handling capacity of a radome are considered briefly. The power-handling capacity is generally limited by thermal failure rather than voltage breakdown in the radome.

A survey of recent radome literature indicates the need for an up-to-date supplement to the report "Techniques for Airborne Radome Design".

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FOREWORD

This report was prepared by The Ohio State University Antenna Laboratory, on Air Force Contract AF 33(616)-7614, under Task Number 42039 of Project Number 1(670-4161), "Study of Electromagnetic Window Dielectric Techniques." The work was administered under the direction of Reconnaissance Laboratory, Aeronautical Systems Division, Air Force Systems Command, United States Air Force, Wright-Patterson Air Force Base, Ohio. The task engineer for the laboratory was

FINAL ENGINEERING REPORT

I. INTEGRATED RADOME-SCANNER TECHNIQUES

Under previous radome contracts, techniques were developed for the unified design of reinforced nose cones with mechanical-scan antennas. Now electronic-scan systems must be introduced as soon as possible to keep up with the increased speeds of our vehicles and their targets, and to reduce vulnerability to jamming. Therefore, the unified design of reinforced nose cones with electronic scanners was investigated.

A new nose cone structure was designed and built. Any number of metal ribs can readily be attached on the cone to form a tripod, quadripod or multipod structure. The ribs may help support a radome, convey cooling fluid to the radome surface, and provide connections to a pitot boom and infrared system. Furthermore, the metal frame of straight ribs and circular rings will simplify the problem of attaching the radome to the aircraft frame. It may even permit the radome to be fabricated in sections; these sections would be held in place by the metal frame.

Measurements were made to determine the effects of the quadripod on the pattern of an electronic-scan antenna. The antenna consists of an array of traveling-wave slots. Scanning is accomplished in one plane by varying the frequency.

It was found that the metal ribs of the quadripod introduced ripples in the pattern, but it is believed this effect can be reduced by an improved antenna design.

Another antenna was designed and is now under construction. It consists of a parallel-plate waveguide which radiates through arrays of holes in one plate. The parallel-plate region is fed by a single waveguide in a manner yielding a desirable input impedance match. The antenna beam will scan in one plane as the frequency is varied, and the parallel-plate region is dielectric filled to increase the angular scan per unit frequency change. When this antenna is completed, it is planned to mount it in the quadripod and measure the far-field patterns at various frequencies.

Some aspects of the study of integrated radome-scanner techniques are described in Report 1180-2.[2]

Much of the work outlined in the next Section, "Diffraction by Obstacles in the Fresnel-Zone", is directly applicable to integrated radome-scanner design.

II. DIFFRACTION BY OBSTACLES IN THE FRESNEL-ZONE

In the unified design of radome scanners, diffraction by various obstacles must be considered. The obstacles, including the metal quadripod or space-frame, the pitot tube, and perhaps an infrared system, are located in the near zone of the antenna. Some information has been obtained on the effects of these obstacles by experimental measurements, but a better understanding of the phenomenon might be provided by a theoretical analysis. The objective of the study is to produce design data on impedance, beamwidth, gain, sidelobe level, and boresight error as a function of antenna size, shape, and aperture distribution, and obstacle size, shape and position.

With this objective in mind, the calculation of obstacle diffraction patterns was programmed for an IBM 704 digital computer. The program permits calculations of the far-field pattern of an antenna in the presence of a metal object. The required input data are the aperture fields of the antenna and the location and cross-section shape of the obstacle. The IBM machine starts with the given antenna aperture fields and computes the field that would exist in the vicinity of the obstacle if the obstacle were absent. The near-zone integral formulas are used for this calculation. The resulting near-zone data may be printed out or stored. This part of the program has considerable interest because it permits a study of near-zone field distributions. The near-zone data can then be fed back into the IBM machine with a far-field pattern program to obtain the diffraction pattern.

To simplify the calculations it was assumed that a conducting obstacle forces the tangential electric field intensity to zero on the shadow side, and does not disturb the tangential electric field intensity elsewhere on a plane reference surface passing through the obstacle. To determine the conditions under which this simplified computer program is accurate, calculations were made for a square metal plate in front of a point source, an array of five point sources, a horn, and a paraboloidal antenna. Satisfactory agreement was obtained with experimental measurements.

This work is described in detail in Report 1180-5.[6]

Using a different formulation based on the reciprocity theorem, a desk machine was used to calculate the pattern of a small horn in the presence of a metal cylinder. Excellent agreement was found on comparison with experimental measurements, although the cylinder was only five wavelengths from the horn. Rather poor results were obtained for this problem on the computer program described above. This was to be expected, since the program was designed for thin, plane obstacles.

To analyse the effects of a radome supported by a metal quadripod, calculations and measurements were made of diffraction by a metal cylinder at the surface of a plane dielectric sheet. Good results were obtained with a simple theory which utilizes the transmission coefficient of the sheet. An attempt is being made to extend the technique to cases where the cylinder is embedded in the dielectric sheet.

A report will be issued to describe these developments.

III. ANALYSIS AND DESIGN OF INHOMOGENEOUS RADOMES

The permittivity of most radome materials changes by a significant amount when the temperature is increased by hypersonic flight through the atmosphere. The outer surface of the radome becomes hotter than the inner, resulting in a continuous variation in permittivity even if the radome was designed as a homogeneous structure.

Moreover, new techniques of radome fabrication may make it feasible to construct continuously inhomogeneous radomes. This can be accomplished with variable loading or with variable density foams. Alternatively, a multilayer sandwich having many thin laminations can form an adequate approximation. These structures may have a greater bandwidth or a greater range of incidence angles than conventional radomes.

Exact solutions in closed form are available only for a few special cases including the linear and exponential inhomogeneities. An exact solution for more general cases is available in the form of a power series expansion. The convergence is so slow, however, that this technique is not practical except for application to a thin layer.

A practical solution is given by step-by-step numerical integration. This involves simple, repetitive calculations, and it yields the phase as well as the amplitude of the field distribution in the inhomogeneous layer. When the solution for the field distribution has been completed, the transmission and reflection coefficients are readily determined. The necessary equations have been derived for both perpendicular and parallel polarization, and these were applied to layers having linear and exponential variations in permittivity. The results show excellent agreement with the exact solutions.

An equation was developed for the error in step-by-step numerical integration as a function of the step size. This is useful in selecting the step size when the allowable error is specified. If the fields and the transmission coefficient are to be calculated to an accuracy within one percent, only ten steps are needed for a half-wave sheet or radome.

The solution by step-by-step numerical integration is discussed in Report 1180-4 [4].

It is suggested that step-by-step numerical integration be reserved for problems involving large permittivity gradients, since the WKB solution is advantageous for small gradients. The WKB solution was employed to develop simple expressions for the field distribution in low-loss inhomogeneous layers. These expressions are accurate if the permittivity is a slowly varying function of the distance from the surface of the layer, and they reduce to the exact solution for a homogeneous layer.

The corresponding equation for the transmission coefficient of an inhomogeneous layer (or radome) was developed. It has the symmetry properties required to satisfy the reciprocity theorem for waves incident on opposite surfaces of the layer.

Equations were derived for the WKB solution for parallel and perpendicular polarization. Excellent agreement was obtained between the WKB solution and the rigorous solution for the field intensity in an inhomogeneous layer for oblique incidence, and for the transmission coefficient at normal incidence over a broad band of frequencies. Accurate results for a thin layer at low frequencies can be expected only if the initial, final and average permittivities in the layer do not differ greatly.

The WKB formulas are considerably more convenient than the exact solution (when available) or step-by-step numerical integration. They reduce the computation time and effort for an inhomogeneous layer to approximately the same as for a homogeneous layer.

The application of the WKB technique to the analysis and design of inhomogeneous radomes is discussed in Report 1180-7 [5].

IV. RADOME POWER-HANDLING CAPACITY

The object of this study is to determine the conditions that may lead to radome failure at high power levels. Under a previous contract it was found that the electric field intensity in a homogeneous radome will not exceed that at its surface, insofar as plane-sheet theory applies. (In practice, this result is modified by the effects of radome curvature, the presence of small voids in the radome, and surface-wave excitation.) Therefore, it is to be expected that corona will occur first in the air or plasma at the radome surface.

This is not always true for radomes having a sandwich construction, however, or for a solid wall with thermal gradients. In the A sandwich, the field intensity in the core generally exceeds that in the surrounding air. Furthermore, the dielectric strength of the core is relatively low.

An analysis was made of the maximum field intensity in A sandwiches. It was found that the worst case occurs under the following conditions: perpendicular polarization, air core, quarter-wave lossless skin, large angle of incidence. For example, the maximum electric field intensity in the air core is ten times the field intensity at the radome surface if the skin dielectric constant is four, the angle of incidence is eighty degrees, and the core is not so thin as to miss this maximum. The maximum field intensity is even greater if the skin dielectric constant or the angle of incidence is increased. However, these unfavorable conditions are seldom met in practice since the skin is ordinarily thinner than a quarter wavelength and the core dielectric constant is ordinarily greater than unity.

Techniques were also developed for calculating the maximum field intensity in continuously inhomogeneous layers, such as a radome with a thermal gradient. Examples were worked out using step-by-step numerical integration (Report 1180-4 [4]) and the WKB solution (Report 1180-7 [5]) in which it was found that the electric field intensity in an inhomogeneous radome may exceed the intensity at the surface by a large factor.

It appears, however, that the power handling capacity of a radome is ordinarily limited by thermal failure rather than voltage breakdown. (The power handling capacity of the radar system may be limited by corona or voltage breakdown in the waveguide which feeds the antenna or in the plasma sheath at the radome surface. The electric field intensity in the waveguide feed is usually much greater than its peak value in the radome. Furthermore, the radome generally has a greater dielectric strength than the surrounding plasma.) The heat input to a radome from the radar transmitter is of greatest concern when the radome is close to thermal failure as a result of high-velocity flight through the atmosphere. A few general rules for increasing the power handling capacity of a radome are listed below.

a. Use high-temperature radome materials.
b. Use low-loss radome materials to reduce the heat input.
c. Use radome materials having high thermal conductivity to avoid thermal gradients and to carry the heat to the surfaces.

It appears that the steady-state temperature of a radome can be calculated quite readily if data are available on the incident power density, the thermal conductivity, the loss tangent, the dielectric constant and the thickness.

V. TEMPERATURE-COMPENSATED RADOMES

The objective of this program is to determine those radome designs which are least critical with respect to temperature changes and thermal gradients.

The half-wave solid-wall radome was considered first. It was found that a radome can be designed for good performance at any given uniform temperature or temperature distribution. To accomplish this, a compromise must be made with respect to the performance at other temperatures. However, the radar frequency could be controlled automatically by thermal sensing elements in such a way as to maintain high radome performance over a large temperature range.

There does not appear to be any method of compensating for the increased loss in radome materials at high temperatures. The A sandwich with thin skins and foam core may be advantageous in this respect. The attenuation in such a structure remains small even when the loss tangent increases at high temperatures. The skins dissipate little power since they are thin, and the core dissipates little power since its dielectric constant is small.

Data were collected from several organizations on the dielectric constant and loss tangent of various materials as a function of temperature. It was noted with interest that General Electric has developed a mica laminate that is stable with respect to dielectric constant and loss tangent up to 1100°F or higher. It is possible that the problem of temperature compensation will be overcome by this material or another stable material that may be developed.

The techniques described in Section III, "Analysis and Design of Inhomogeneous Radomes", are applicable to the study of temperature compensation. Step-by-step numerical integration and the WKB solution are particularly useful when thermal gradients induce a significant inhomogeneity in the radome.

VI. A CIRCUIT ANALOG FOR RADOME STUDIES

Under a previous radome contract a circuit was developed, built, and partially tested to determine its possible usefulness in radome studies. The circuit consists of ten T sections in cascade, each section having a variable shunt capacitor and resistor and two series inductors. In the present contract period several additional radome problems were set up on the circuit analog. The measurements agreed well with theoretical calculations, and it was concluded that the circuit analog may be useful in many radome studies. In particular, it permits rapid measurements of the transmission coefficients of solid walls, sandwiches, and inhomogeneous radomes over a broad range of frequencies. Such data are obtained at a cost much less than that of digital calculations, without the necessity for fabricating test panels.

This circuit analog is described in Report 1180-3 [3].

VII. RADOME SURVEY

A survey was made of state-of-the-art advancements in radome design theory and techniques. Technical reports and the Proceedings of the OSU-WADD Radome Symposia were studied in this literature survey. It was found that significant developments have been made in this field since the issuance of "Techniques for Airborne Radome Design" (WADC-TR-57-67). It is, therefore, recommended that an up-to-date supplement be produced and distributed.

VIII. LUNEBERG LENSES FOR INTEGRATED RADOME-SCANNERS

The purpose of this study was to determine the applicability of two-dimensional Luneberg Lenses to radar and ECM systems.

A study was made of the radiation patterns of such lenses. The two dimensional lenses radiate a beam from a semicircular aperture. The beam may be described by the vertical beam cross-section and the beam cross-section through the beam maximum and orthogonal to the vertical beam cross-section. The phase distribution around the semicircular aperture is such as to give maximum radiation at a specified angle with respect to the plane of the lens rim.

The principal beam cross-sections were evaluated for two types of amplitude distributions around the semicircular aperture. In each type of distribution a family of patterns is obtained. Each particular pattern is derived by linear combination of a basic set of patterns.

Synthesis methods were developed to obtain a specified pattern in the vertical plane. It was shown that the focusing action of the lens fixes the phase distribution in the aperture. This in turn sets a restriction on the radiation patterns obtainable from the two-dimensional Luneberg lens. The significance of this limitation was considered.

This research will be described in a report now being written.

IX. REPORTS AND PUBLICATIONS ISSUED UNDER THIS CONTRACT

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3. Richmond, J.H., and Ryan, C.E., "A Circuit Analog for Radome Simulation", Report 1180-3, 15 March 1961.
4. Richmond, J.H., "Transmission Through Inhomogeneous Plane Layers", Report 1180-4, 15 July 1961.
5. Richmond, J.H., "The WKB Solution for Transmission Through Inhomogeneous Plane Layers", Report 1180-6, 15 September 1961.
6. Collier, J.R., "Digital Calculation of Diffraction from Aperture Blocking", Report 1180-5, 15 September 1961.
7. Final Engineering Report, Report 1180-6, 16 September 1961.

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1. Richmond, J.H., "The Numerical Evaluation of Radiation Integrals", I.R.E. Transactions on Antennas and Propagation, Volume AP-9, Number 4, July 1961.
2. Richmond, J.H., "A Reaction Theorem and Its Application to Antenna Impedance Calculations", I.R.E. Transactions on Antennas and Propagation, Volume AP-9, Number 6, November 1961.

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Investigator Robert Caldecott Date 17 Oct 1961

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