1

Introduction

The word *radome,* is an acronym of two words "radar" and "dome" and is a structural, weatherproof enclosure that protects the enclosed radar or communication antenna. The main objective of the radome is to be fully transparent to the electromagnetic energy transmitted/received by the enclosed antenna, and in this sense its objective is similar to that of a glass window for light in the optics spectrum. Radomes protect the antenna surfaces from weather and, in contrast to a glass window, can also conceal the antenna electronic equipment from the outside radome observer. Another benefit for using a radome is that it enables use of a low-power antenna rotating systems and weaker antenna mechanical design, followed by a significant price reduction, since the enclosed antenna is not exposed to the harsh outside weather. Radomes can be constructed in several shapes (spherical, geodesic, planar, etc.), depending on the particular application using various construction materials (e.g., fiberglass, quartz, polytetrafluoroethylene (PTFE)-coated fabric, closed cell foam (rohacell), honeycomb). The radomes are assembled on aircrafts, ships, cars, and in fixed ground-based installations. In case of high-speed moving platforms like aircrafts, another important consideration is related to the streamline shape of the radome to reduce its drag force.

The materials used to construct radomes are often used to prevent ice and freezing rain (sleet) from accumulating directly on its external surface to avoid extra losses of the communication link. In case of a spinning radar dish antenna, the radome also protects the antenna from debris and rotational problems due to wind. For stationary antennas, excessive ice accumulation on the radome surface can de-tune the antenna, causing extra losses and internal reflections, which may

Radome Electromagnetic Theory and Design, First Edition. Reuven Shavit.

go back to the transmitter and cause overheating. A good designed radome prevents that from happening by covering the exposed parts with a sturdy' weatherproof material like PTFE, which keeps debris or ice away from the antenna. One of the main driving forces behind the development of fiberglass as a structural material was the need for radomes during World War II. Sometimes radomes may be internally heated to melt the accumulated ice on their exterior surface. The most common shape of ground-based radomes is spherical because of the rotational symmetry such a radome offers. Large ground-based radomes are made of sandwich panels interconnected by seams or beams, which may affect the enclosed antenna radiation pattern as described in Chapter 6. Small or medium-sized radomes are usually made of one molded piece. In this case, only the transmission loss and boresight error caused by the radome need to be considered in the design as explained in Chapter 4.

Static electricity caused by air friction on the radome surface can present a serious shock hazard. Thin antistatic coatings are used to neutralize static charge by providing a conducting path to attached structures. Lightning strikes to aircraft are common, so metallic lightning-diverter strips are used to minimize structural damage to the radome. Diverters cause some increase in sidelobe levels; this effect can be estimated using the computational tools described in Chapter 5.

The US Air Force Aerospace Defense Command operated and maintained dozens of air defense radar stations in the United States, including Alaska, during the Cold War. Most of the radars used at these ground stations were protected by rigid or inflatable radomes. The radomes were typically at least 15 m (50 ft) in diameter, and the radomes were attached to standardized radar tower buildings that housed the radar transmitter, receiver, and antenna. Some of these radomes were very large. The CW-620 was a rigid space frame radome with a maximum diameter of 46 m (150 ft), and a height of 26 m (84 ft). This radome consisted of 590 panels and was designed for winds of up to 240 km/h (150 mph). The total radome weight was 92,700 kg (204,400 lb) with a surface area of 3680 m^2 (39,600 ft^2). The CW-620 radome was designed and constructed by Sperry-Rand Corp. for the Columbus Division of the North American Aviation. This radome was originally used for the FPS-35 search radar at Baker Air Force Station in Oregon. Two typical airborne radomes are shown in Fig. 1.1 and Fig. 1.2. Both of them are ogive type, but with different contours.

Figure 1.1 Tejas aircraft (India) radome picture.

Figure 1.2 Norton radome B787 dreamliner picture.

For maritime satellite communication service, radomes are widely used to protect dish antennas, which are continually tracking fixed satellites while the ship experiences pitch, roll, and yaw movements. Large cruise ships and oil tankers may have radomes over 3 m in diameter covering antennas for broadband transmissions for television, voice, data, and the internet, while recent developments allow similar services from smaller installations, such as the 85 cm motorized dish used in the ASTRA2 Connect Maritime Broadband system. Small private yachts may use radomes as small as 26 cm in diameter for voice and low-speed data transmission/reception.

1.1 History of Radome Development

The first radomes appeared in United States in 1940 with the introduction of the radar during the World War II when radars were installed on aircrafts and aerodynamics considerations were imposed to cover the radar antennas to reduce the drag forces on a high speed aircraft. The first reported aircraft radomes used simple, thin-wall designs. In 1941, the first in-flight radome was a hemispherical nose radome fabricated from plexiglass [1, 2]. It protected an experimental S-band, Western Electric radar flown in a B-18A aircraft. Beginning 1943, production airborne radars used plywood radomes [1].

In this period, plywood radomes also appeared on Navy PT boats and blimps, as well as in ground installations. Because plywood has moisture absorption problems and does not easily bend into doubly curved shapes, new radome construction techniques and materials were introduced. In 1944, the MIT Radiation Laboratory developed the three-layer *A-sandwich,* which used dense skins and a low-density core material. The skins were fabricated from fiberglass and the core from polystyrene. Since World War II, radome materials have developed in the following areas: ceramics for high-speed missile radomes, quartz, fiberglass, honeycomb, and foam for sandwich composites radomes. Today, the majority of aircraft radomes use sandwich-wall designs. Fig. 1.3 shows some typical radomes installed on ships.

Various authors have contributed to the literature describing the evolution, design, and manufacture of radomes. Cady [3] describes the electrical design of normal and streamlined radomes and their installation, together with the theory of reflection and transmission

Figure 1.3 Typical radomes installed on ships.

of electromagnetic waves through dielectric materials. The focus is on airborne radomes. Hansen [4] describes large ground radomes, their environmental, structural and design problems. Walton [5] describes advanced airborne radomes. Skolnik [6] and Volakis [7] gave theoretical electrical characteristics for sandwich panels and typical requirements for airborne and ground radomes. Chapters describing the radome theory and design rules can also be found in [8] and [9] and in books like [10].

The major electrical parameters that determine the radome performance are:

- Insertion loss (IL) due to the presence of the radome.
- Increased antenna sidelobe levels of the radiation pattern.
- Depolarization radiation pattern increase.
- Boresight error (BSE) and boresight error slope (BSES).

Insertion loss is a reduction in the signal strength as the electromagnetic wave propagates through the radome wall. Part of the loss is due to the reflection from the air/dielectric interface. Additional losses are due to internal and external diffraction, refraction effects, and polarization shift. The remainder is due to the dissipation within the dielectric layers. The computation of these parameters in multilayer radomes, including analysis in frequency selective surfaces (FSS), are described in Chapters 2 and 3.

The reflection and scattering from the radome also causes changes of the main beam-shape and increases the radiation pattern sidelobes. The scattering mechanism from a single beam in a space structure radome is described in Chapter 5 and the total effect of all beams array in front of the antenna is described in Chapter 6.

Depolarization is an energy diverted from the primary antenna polarization to the orthogonal polarization. This phenomenon occurs as a result of the radome wall curvature and the difference in complex transmission coefficient between orthogonal polarized vectors. Depolarization can be problematic, particularly with satellite communication (SATCOM) ground terminals that utilize frequency reuse with orthogonal polarization. In this application, two independent signals are transmitted or received within the same frequency channel, but in opposite polarization senses. This topic is discussed in Chapters 4 and 6.

BSE is caused by the distortion of the electromagnetic wavefront as it propagates through the radome wall and bends the angle of arrival of the received signal relative to its actual angle of arrival. For monopulse antennas, it is the shift that the radome causes in the direction of the difference mode pattern's deepest minimum, or the shift that is obtained by comparing the phases in a pair of antennas. The BSES is defined as the rate of change of BSE with respect to the angle between axes of the radome and the antenna. Radome's BSES can cause severe degradation for modern guidance systems as well as for classical proportional navigation systems. This topic is discussed in Chapter 4.

1.2 Types of Radomes

We will now introduce and briefly discuss some forms of the various radome types in order to familiarize ourselves with the types of radomes discussed in the rest of the textbook.

1.2.1 Solid Laminate

The solid laminate radome is made of doubly curved solid fiberglass panels in which for small radomes (less than 1 m in diameter) are made from one piece and in case of larger sizes are made of panels arranged in neat vertical and horizontal rows. A typical solid laminate radome is shown in Fig. 1.4.

Figure 1.4 Solid laminate radome of L-3 Communications-ESSCO, Concord, Massachusetts.

The radome exhibits excellent performance below 3 GHz or at higher frequencies when wall thickness is tuned for narrow bandwidths.

1.2.2 Inflatable

The inflatable radome is actually a truncated spherical balloon made of strong fabric, which keeps its shape since it is highly pressurized. In terms of electromagnetic performance, it is superior to other radome types due to its highly transmittance feature from low to high frequencies. Its drawback is its pressurizing system that is vulnerable to electricity breakdowns and the entire radome may collapse over the enclosed antenna. This deficiency may be ameliorated by backing up the main power supply by an uninterruptible power supply (UPS) system. The inflatable radome can't sustain extreme environment conditions like high winds. A typical inflatable radome is shown in Fig. 1.5.

Figure 1.5 A typical inflatable radome.

1.2.3 Sandwich

The sandwich radome is a multilayer structure doubly curved, which may be fabricated in one piece for small size radomes or as a multipanel geodesic form for larger size radomes with polygonal panels bolted together to form the radome. The radome shell is made of highly developed composites to obtain panel consistency and strength. The fiberglass skins fully enclose each panel core to make the panels weather tight. The sandwich radome exhibits very good performance over relatively narrow frequency bands or potentially at multiple discrete frequencies. A typical ground-based multipanel sandwich radome is shown in Fig. 1.6.

1.2.4 Metal Space Frame

The metal space frame (MSF) radome is made of triangular frames quasi-randomly oriented in space and bolted together to form a geodesic dome. The frames are usually made of metal aluminum extrusion. Thin membranes made of materials with low dielectric constant and low losses are bonded into the frames. To avoid rain and snow accumulation, a thin laminate based on PTFE is permanently bonded on the membranes. A typical MSF radome is shown in Fig. 1.7.

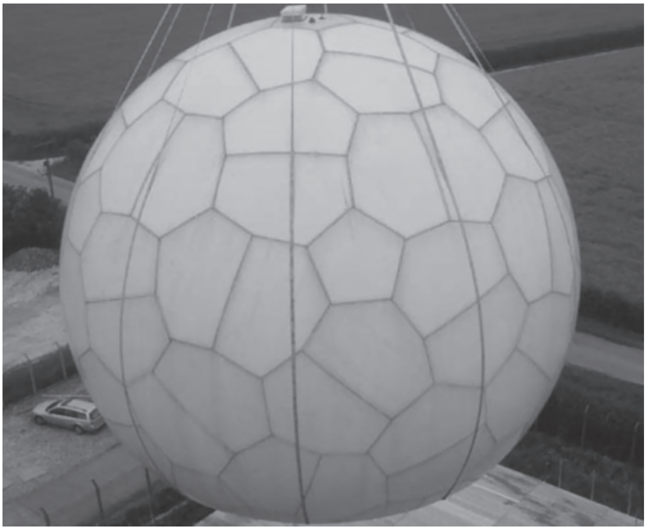

Figure 1.6 Multipanel sandwich radome of L-3 Communications-ESSCO, Concord, Massachusetts.

Figure 1.7 Metal space frame radome of L-3 Communications-ESSCO, Concord, Massachusetts.

The operational frequency of the MSF radomes is 1–20 GHz with an insertion loss lower than 0.6 dB.

1.2.5 Dielectric Space Frame

The dielectric space frame (DSF) radome is made of panel geometries available in both regular and quasi-randomized. It is similar in structure to the MSF with the difference being that its beams are made of pultruded fiberglass beams instead of metal. The DSF panels may be flat or double curved, yielding a faceted geodesic or spherical smooth appearance. This type of radome extends the operational frequency band of the MSF to lower frequencies than 1 GHz. For frequencies above 1 GHz, the DSF insertion loss is oscillating and increasing, making the MSF the correct choice for a radome. Fig. 1.8 shows a typical DSF from AFC, Florida.

1.3 Organization of the Book

The book is organized into seven chapters. Chapter 2 describes the analogy in the analysis of a multilayer sandwich radome and transmission line theory. This analogy enables an efficient analysis and use of all the tools developed in transmission line theory like matching techniques, Smith chart, scattering matrix, and more. It also describes and brings design data and graphs for various types of sandwich radomes, such as A-sandwich; B-sandwich; and C-sandwich.

Chapter 3 describes analysis techniques of an arbitrary type FSS element geometry using Floquet modes and numerical solution of the current distribution on the FSS unit cell element. It also describes simulation results of the transmission and reflection coefficients through an FSS as a function of frequency, incident angle, and polarization for different type of elements, such as square patch, circular patch, crossed dipole, Jerusalem cross slot, double square loops, and more. It analyzes the benefits and drawbacks of the various type of element geometries. In addition, it describes the scattering analysis techniques for multilayer FSS structures. It also describes a metamaterial-inspired radome with a narrow passband to allow the enclosed antenna transmission

Figure 1.8 Dielectric space frame radome of AFC, Ocala, Florida.

and reception and a wide band above the passband with maximum absorption.

Chapter 4 describes various techniques for the analysis of airborne radomes with conformal shape like ogive and conical. The basic analysis for relatively large aperture antennas enclosed in conformal radomes is based on ray tracing combined with physical optics to determine the radiation pattern of the antenna enclosed in the radome. The ray-tracing method is not accurate near tips and discontinuities in the radome. In these cases and for small antennas enclosed in conformal radomes, integral equations (surface or volume) are formulated and solved numerically with the method of moments. The alternative numerical solution of integral equations is a solution using the finite element method (FEM).

Chapter 5 describes various methods to compute scattering from infinite cylinders with arbitrary cross section, made of conductive, dielectric and composite mixture of dielectric material and conductive strips. This information is critical in the evaluation of the radiation pattern of the enclosed antenna in a ground-based space frame radome. The scattering analysis can be performed by solution of an integral equation (volume or surface) or by a differential equation formalism. The integral equation can be solved numerically by the method of moments, while the differential equation can be solved numerically by the FEM. The surface integral equation is numerically efficient but is limited to homogeneous and conductive cylinders analysis. On the other hand, the volume integral equation enables analysis of inhomogeneous cylinders but is more numerically involved.

Chapter 6 describes the computation of the scattering parameters of a ground-based space frame radome as a function of the scattering from a single beam and the array factor of all the beams present in front of the antenna. Design considerations and the trade-offs made in terms of minimal optical blockage to the antenna, amount of scattering of a single beam (tuned or untuned), and the beam geometry randomness are also described.

Chapter 7 describes various methods to measure the electrical parameters (insertion loss and reflection) of sandwich panels and the scattering parameters (forward scattering and scattering radiation pattern) of dielectric (tuned and untuned) and conductive cylinders with arbitrary cross section using near field and far field techniques.

References

1. Baxter, JP. Scientists against time. Boston: Little Brown and Company, 1952.
2. Tice, TE. Techniques for Airborne radome design. Air Force Avionics Laboratory, Wright Patterson AFB, Ohio, 1966.
3. Cady, W, Karelitz, M, and Turner, L. Radar scanners and radomes. New York: McGraw-Hill, 1948.
4. Hansen, RC. Microwave scanning antennas. New York: Academic Press, 1964.

5 Walton, JD. Radome engineering handbook. New York: Marcel DeKker, 1976.

6 Skolnik, M. Radar handbook. New York: Wiley, 1990.

7 Volakis, JL. Antenna engineering handbook. New York: McGraw-Hill, 2007.

8 Lo, YT, and Lee, SW. Antenna handbook: theory, applications, and design. New York: Van Nostrand Reinhold, 1988.

9 Rudge, AW, Milne, K, Olver, AD, and Knight, P. The handbook of antenna design. London: Peter Peregrinus, 1986.

10 Kozakoff, DJ. Analysis of radome-enclosed antennas. Boston: Artech House, 1997.