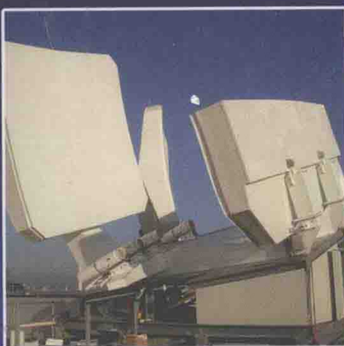
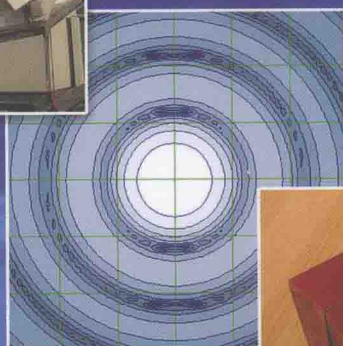
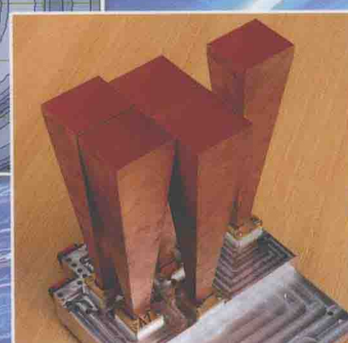
Trevor S. Bird







Fundamentals of APERTURE ANTENNAS and ARRAYS

From Theory to Design, Fabrication and Testing

with website

WILEY

FUNDAMENTALS OF APERTURE ANTENNAS AND ARRAYS

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Preface

Aperture antennas are a class of antennas in common daily use and some have even become synonymous with areas of science and technology. Typical examples include reflectors, horns, lenses, waveguides, slits, and slots. Other antennas can be conveniently described by means of aperture concepts. Some of these include microstrip patches and reflectarrays. In this book we describe the underlying theory and application of these antennas as well as their use in arrays.

The history of aperture antennas is inextricably linked with historical developments in wireless and also the verification of Maxwell's equations. The very first waveguide was demonstrated by Lodge in 1894 and in 1895 Bose used circular waveguides as an antenna along with pyramidal horns for experiments on the polarization properties of crystals. About thirty years later a 10 m diameter reflector became the first radiotelescope when it detected emissions from electrons in interstellar space. In the 1960s aperture antennas accompanied the first humans on the moon and more recently they have contributed to the wireless revolution that is presently underway.

Aperture antennas are normally associated with directional beams and, indeed, this is their role in many applications. They can also occur on non-planar or curved surfaces such as on aircraft or ground-based vehicles. These antennas may consist of a single radiator or in arrays. In this form they are often used to provide directional or shaped beams.

Directional beams are needed in terrestrial and satellite microwave links to efficiently use the available power as well as to reduce interference and noise. Radar systems also require directional antennas to identify targets. As well, arrays of aperture antennas can produce almost omnidirectional radiation.

A limitation of a directional planar antenna is that when it is scanned from broadside the beam broadens and the pattern deteriorates. When the antenna is conformal to a convex surface, such as a cylinder or a cone, the beam can be scanned in discrete steps through an arc while maintaining a constant pattern. Of importance in the design of low sidelobe antenna arrays, both planar and conformal, is predicting the effect of mutual coupling between the array elements. Maximum performance is achieved from arrays when the coupling between elements is fully taken into account.

This book gives an introduction to the techniques that are used to design common aperture antennas as well as some approaches to their fabrication and testing. The intention is for it to be a single textbook for a course in antennas in the final year undergraduate or in a master's degree by coursework. It assumes that the reader has undertaken a course on Maxwell's equations, fields and waves. Some of these topics are reviewed in the early few chapters to provide continuity and background for the remainder of the book. The antennas covered in later chapters include horns, reflectors and arrays. Some examples are pyramidal and corrugated horns, parabolic and spherical reflectors, reflectarrays, planar lenses and coaxial waveguide array feeds. To provide more than a simplified treatment of arrays, the topic of mutual coupling is covered in more detail than most similar books on this topic. Also included is an introduction to sources and arrays on non-planar surfaces, which is of importance for applications involving aerodynamic surfaces and for making aperture antennas unobtrusive. A chapter is included on modern aperture antennas that extend the concepts introduced in earlier chapters. This is to show where advances have been made in the past and how they could be made in the future. Also included are some topics of a practical nature detailing some techniques for fabrication of aperture antennas and their measurement.

Acknowledgement

The author thanks his many colleagues who have provided comments on some of the material and for their contribution to the projects described herein. In particular for this book, thanks are extended to colleagues Drs. Stuart Hay, Doug Hayman, Nasiha Nikolic, Geoff James, Stephanie Smith and Andrew Weily who readily gave up time to providing comments on early drafts of the chapters. Thanks are extended to members of the editorial staff at Wiley, in particular Anna Smart, Sandra Grayson and Teresa Nezler, and also to the SPi publications content manager Shiji Sreejish. The kind permission to use pictures by CSIRO Australia, the Institution of Engineering and Technology (IET), Engineers Australia, and SES ASTRA is gratefully acknowledged.

The author also wishes to acknowledge in particular several folk who provided mentorship and gave great support and encouragement during his early research career. To mention a few significant mentors by name: Prof. Peter Clarricoats, FRS gave the author a great start in the area of aperture antennas and arrays; the late Dr. George Hockham FRS, inspired the author and demonstrated the importance of some of the techniques described herein for applications and how practical antennas could be realised; Dr. Geoff Poulton provided a number of important opportunities for the author and long-term friendship and the many technical discussions during our working careers; and finally, the late Mr. David Hurst helped the author in his first attempts in the wireless area graciously and shared his wide knowledge and practical expertise. The author wishes to thank Ms. Dallas Rolph for assisting greatly in editing the text as well as general assistance when they worked together at CSIRO. Finally, the author is very grateful to his wife, Val, for her love and strong support over 40 years when many of the topics discussed herein were investigated.

Contents

1

Introduction

The topic of this book covers a class of antenna in common use today as well as a way of describing many others. Examples include waveguides, horns, reflectors, lenses, slits, slots and printed antennas. Some examples are illustrated in Figure 1.1. In the following chapters, the background theory and application of some basic forms of these antennas are described as well as how they can be designed, fabricated and tested. Additionally, detail will be provided on some of the individual antennas pictured in Figure 1.1.

Aperture antennas are normally associated with directional radiation beams and, indeed, this is their purpose in many applications. They can also create other types of beams such as shaped or contoured beams either separately or combined as arrays as will be shown. Aperture antennas can also occur on non-planar or conformal surfaces such as on aircraft or missile bodies where airflow and aerodynamic performance are paramount. Conformal antennas can consist of a single radiator or arrays in the surface where they can be used to provide directional and shaped beams.

Aperture antennas can be used to produce omnidirectional radiation patterns, which are important if the antenna platform is unstable or the user direction is unknown, for all-round electronic surveillance and monitoring or where the location of another user cannot be guaranteed such as in mobile radio systems. A 360-degree coverage can be achieved with a conformal antenna or with electronic switching between planar elements.

Directional beams are required in terrestrial and satellite microwave links to efficiently use the available power as well as to reduce interference and noise. Directional antennas are also required in radar systems to identify targets. A limitation of a directional planar antenna is that when it is scanned from broadside (typically boresight) the beam broadens and the pattern deteriorates. When the antenna is conformal to a convex surface, such as a cylinder or a cone, the

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Figure 1.1 Examples of aperture antennas. (a) Open-ended waveguide antennas (right to left) coaxial, circular and rectangular. (b) Circular waveguide (diameter 32.7 mm) with three ring-slots designed for operation at 9 GHz. (c) Feed array of pyramidal horns for 12.25–12.75 GHz. (d) 11–14.5 GHz high-performance circular corrugated feed horn, diameter 273 mm, and flare angle 11.8°. (e) Small paraboloidal reflector and rear waveguide feed designed for a 15 GHz microwave link. (f) 64 m Parkes radio telescope is a front-fed paraboloid ($f/D = 0.408$). This versatile instrument has been used for frequencies from 30 MHz to >90 GHz. *Source*: Reproduced with permission from CSIRO (a–f)

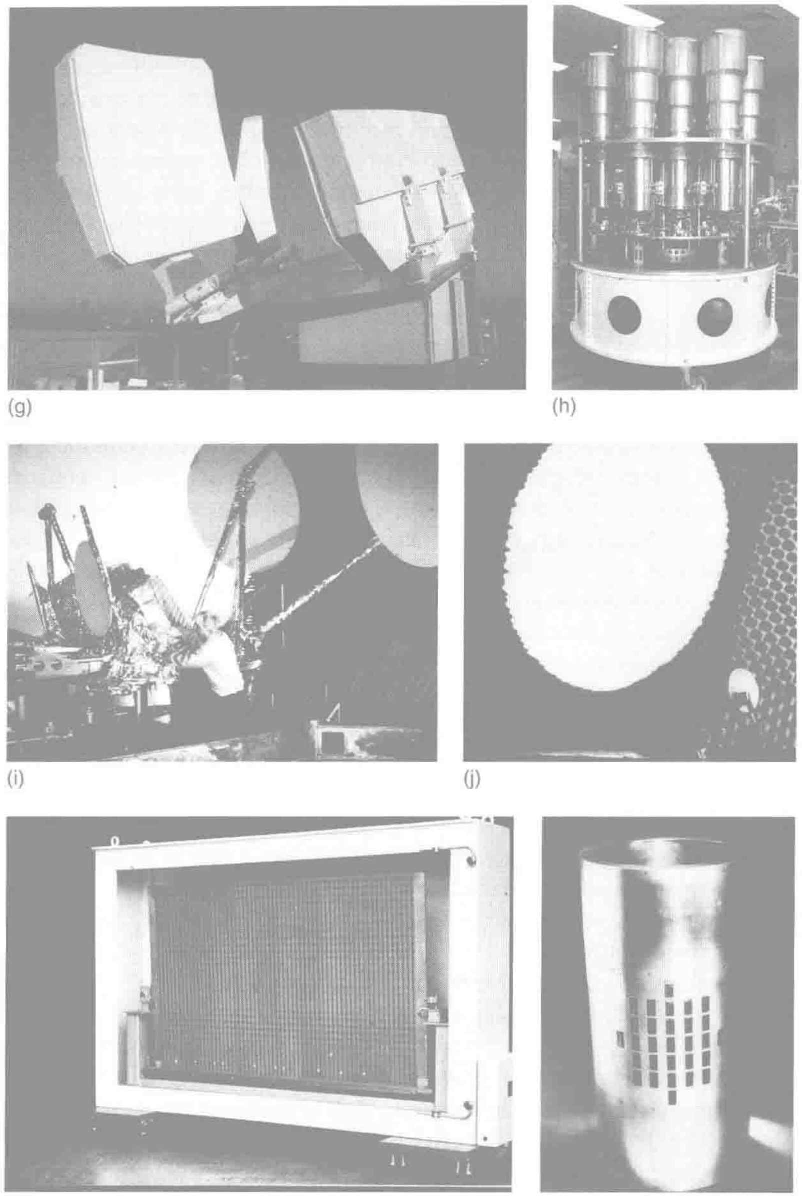

Figure 1.1 (*continued*) (g) Two multibeam earth station antennas at Danish Radio's multimedia house in Ørestad in Copenhagen, Denmark, covering different segments of the geostationary satellite arc. (h) Multibeam feed system for the Parkes radio telescope. *Source*: Reproduced with permission from CSIRO. (i) On-board Ku-band satellite antennas under test on an outdoor test range prior to launch. (j) Dual-offset Cassegrain antenna with a waveguide array feed cluster under test in anechoic chamber (Bird & Boomars, 1980). (k) Series-fed microstrip patch array for a microwave landing system. *Source*: Reproduced from INTERSCAN International Ltd. (l) Conformal array of rectangular waveguides (22.86 × 10.16 mm) on a cylinder of radius 126.24 mm. *Source*: Picture courtesy of Plessey Electronic Systems

beam can be scanned in discrete steps through an arc while maintaining a constant pattern. Recent developments in microwave and optical components have simplified the design of feed networks, thereby making conformal antennas and arrays attractive alternatives for directive applications as well as for scanned beam and in ultra-low sidelobe antennas. Of importance in the design of the latter, both planar and conformal antenna arrays are often employed, and in this application predicting the effect of mutual coupling between the array elements should be undertaken. Maximum performance is achieved from arrays when the effects of coupling are known and included in the design. Otherwise, the full potential of the array flexibility may not be realized.

Aperture antennas may be analysed in much the same way as the conceptually simpler wire antennas. First, the designer needs to find the currents on the conductors or in other materials from which the antenna is constructed. To do this exactly is usually impossible except in a few idealized cases, and numerical methods are required to obtain approximate solutions. After the currents are known, the radiated fields are obtained from Maxwell's equations. Sometimes, however, adequate design information may be obtained from simplified approximations to the current, similar in some regards to adopting a sinusoidal current approximation on a linear wire antenna. This approach is especially valuable for analysing the far-field radiation characteristics, which are relatively insensitive to second-order variations in the current distribution. However, for more detailed information or quantities such as the input impedance, reflection coefficient at the input of horns or the effects of mutual coupling from nearby antennas, an accurate representation of the currents is usually required to properly take account of the current variations and near-field behaviour.

The representation of actual currents on the antenna structure may be difficult, or impossible, to achieve analytically because of the geometry and materials involved. It is convenient, and also physically allowable, to replace the actual sources by equivalent sources at the radiating surface, the antenna 'aperture', which need not lie on the actual antenna surface but on another often fictitious surface close by. For example, the aperture of a paraboloid reflector may be the projection of the rim onto a suitable plane. These equivalent sources are used in the same way as actual sources to find the radiated fields. Once these fields are known, an assessment of the antenna's performance can be made.

For the engineer wishing to specialize in the area of communications systems, some knowledge is needed of the theory and design of aperture antennas. The intention of this book is to provide some of this basic information. Today, compared with prior to the 1980s and even earlier, a variety of full wave computer solvers are now available and are particularly valuable for final design and analysis. The fundamental material available in this book is important as a starting point and for understanding the physical nature of the antenna structure before more detailed design is undertaken. It is intended that readers should be able to move from the present material to more specialized topics and to the research literature. In addition, the details provided herein should help the non-specialist in antennas to critically assess aperture antenna specifications. Where possible, useful design information has also been included. An underlying assumption is that the reader is familiar with the basic concepts of electromagnetic fields, waves and radiation, as presented, in a variety of excellent textbooks (Harrington, 1961; Jones, 1964; Jordan & Balmain, 1968; Kraus & Carver, 1973; Johnk, 1975). Some topics of a more advanced nature have also been included here, beyond those of a typical introductory course. These are indicated by an asterisk (*) after the section heading. They have been included as possible extensions from standard material for more specialized courses, research or possibly part of a project.

The material included here is based on notes for several courses in antennas given to fourth year students in Electrical Engineering at James Cook University of North Queensland and also at the University of Queensland in the 1980s. At that time there was no suitable modern text-book available on antennas for undergraduate teaching. Since then, several excellent textbooks have appeared (Balanis, 1982). In addition, the notes were found useful over the years by members of my research group at CSIRO. Other relevant material had been developed on mutual coupling for presentation at several symposia held in the 1990s, and some of this information has been included here. As might be anticipated, practical topics of relevance that were encountered during my research career have been included as well.

The purpose of this book is to provide a stand-alone textbook for a course in antennas, possibly in the final undergraduate years or in a master's degree by coursework. It should also be useful for Ph.D. candidates and practising engineers. For continuity, some background electromagnetics, fields and waves are included.

The antennas described in detail include horns, reflectors, lenses, patch radiators and arrays of some of these antennas. Because of its importance and to provide more than a superficial treatment of arrays, the topic of mutual coupling is covered in greater detail than most similar books in the area. Also included is an introduction to sources and arrays on non-planar surfaces, which is important for applications involving aerodynamic surfaces and for making aperture antennas unobtrusive. An introduction to the fabrication and test of aperture antennas is included as well as some recent examples of them.

The theory needed for analysing aperture antennas is given in Chapter 3. Material is also included for handling conformal aperture antennas. Starting with the concept of equivalent sources, the equations for radiation from an aperture are developed from the fields radiated by a small electric dipole and a small loop of current. The basic theory that is needed for more detailed development is also provided. This includes details of the far-field radiation from uniformly illuminated rectangular and circular apertures and also how phase aberrations on the aperture impact the far-fields. The radiation from waveguide and horn aperture antennas are described in Chapter 4, and material is included for the radiation from rectangular waveguide antenna. This model is used as a basis for detailed description of the pyramidal horn. The radiation properties of circular waveguides and horns are reviewed in this chapter and details are provided on the corrugated horn. A simple model of the microstrip patch antenna is given in Chapter 5 along with details of the radiation properties of these antennas. The purpose is to describe another form of aperture antenna and as background for reflectarrays. The properties of reflector antennas in common use are described in Chapter 6, including the paraboloid the Cassegrain, and spheroid geometries as well as some offset counterparts. Planar arrays of aperture antennas and mutual coupling in arrays are detailed in Chapter 7. This is followed in Chapter 8 by similar details for apertures on conformal surfaces. The areas of arrays and reflectors come together in the reflectarray antenna, which is introduced in Chapter 9. This chapter also includes details of some other aperture antennas not treated elsewhere, in particular, lenses, and the Fabry-Pérot cavity antennas. Finally, some possible approaches for the fabrication and testing of aperture antennas are described in Chapter 10. In addition it includes examples of some aperture antennas that make use of many of the techniques covered earlier in the book. At all times, the intention is an emphasis on fundamentals and, where possible, practical information for design is also included.