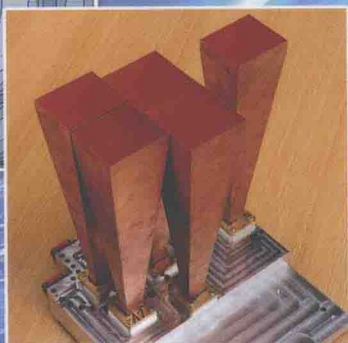
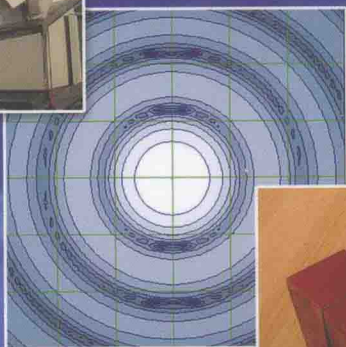
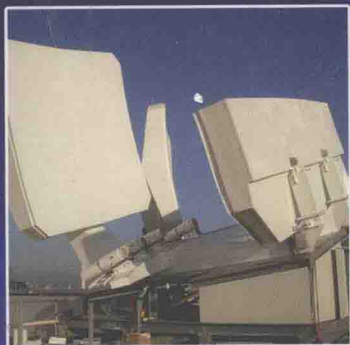


Trevor S. Bird



Fundamentals of **APERTURE ANTENNAS** and **ARRAYS**

From Theory to Design, Fabrication and Testing



WILEY

FUNDAMENTALS OF APERTURE ANTENNAS AND ARRAYS

FROM THEORY TO DESIGN,
FABRICATION AND TESTING

Trevor S. Bird PhD, FTSE

*Principal Antengenuity, Adjunct Professor Macquarie University &
Honorary CSIRO Fellow, Australia*

WILEY

This edition first published 2016
© 2016 John Wiley & Sons, Ltd

Registered Office

John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. It is sold on the understanding that the publisher is not engaged in rendering professional services and neither the publisher nor the author shall be liable for damages arising herefrom. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

The advice and strategies contained herein may not be suitable for every situation. In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of experimental reagents, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each chemical, piece of equipment, reagent, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. The fact that an organization or Website is referred to in this work as a citation and/or a potential source of further information does not mean that the author or the publisher endorses the information the organization or Website may provide or recommendations it may make. Further, readers should be aware that Internet Websites listed in this work may have changed or disappeared between when this work was written and when it is read. No warranty may be created or extended by any promotional statements for this work. Neither the publisher nor the author shall be liable for any damages arising herefrom.

Library of Congress Cataloging-in-Publication Data

Bird, Trevor S. 1949–

Fundamentals of aperture antennas and arrays : from theory to design, fabrication and testing / Trevor S. Bird.
pages cm

Includes bibliographical references and index.

ISBN 978-1-118-92356-6 (cloth : alk. paper) I. Aperture antennas. I. Title.

TK7871.6.B49 2016

621.3841'35–dc23

2015021598

A catalogue record for this book is available from the British Library.

Set in 10/12pt Times by SPi Global, Pondicherry, India

Printed and bound in Singapore by Markono Print Media Pte Ltd

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

Preface	xiii
Acknowledgement	xv
1 Introduction	1
References	6
2 Background Theory	7
2.1 Maxwell's Equations for Time-Harmonic Fields	7
2.1.1 <i>Field Representation in Terms of Axial Field Components in Source-Free Regions</i>	9
2.1.2 <i>Boundary Conditions</i>	10
2.1.3 <i>Poynting's Theorem</i>	11
2.1.4 <i>Reciprocity</i>	11
2.1.5 <i>Duality</i>	13
2.1.6 <i>Method of Images</i>	13
2.1.7 <i>Geometric Optics</i>	13
2.2 Equivalent Sources	15
2.2.1 <i>Aperture in a Ground Plane</i>	17
2.2.2 <i>Conformal Surfaces</i>	17
2.3 Radiation	18
2.3.1 <i>Near-Field</i>	21
2.3.2 <i>Far-Field</i>	21
2.3.3 <i>Mutual Coupling Between Infinitesimal Current Elements</i>	23
2.4 Problems	26
References	27

3	Fields Radiated by an Aperture	29
3.1	Radiation Equations	29
3.2	Near-Field Region	32
3.3	Fresnel Zone	32
3.4	Far-Field Region	33
3.4.1	<i>Example of a Uniformly Illuminated Rectangular Aperture</i>	38
3.5	Radiation Characteristics	40
3.5.1	<i>Radiation Pattern</i>	41
3.5.2	<i>Half-Power Beamwidth</i>	42
3.5.3	<i>Front-to-Back Ratio</i>	42
3.5.4	<i>Polarization</i>	42
3.5.5	<i>Phase Centre</i>	44
3.5.6	<i>Antenna Gain and Directivity</i>	44
3.5.7	<i>Effective Aperture</i>	46
3.5.8	<i>Radiation Resistance</i>	47
3.5.9	<i>Input Impedance</i>	47
3.5.10	<i>Antenna as a Receiver</i>	48
3.6	Aberrations	48
3.7	Power Coupling Theorem	50
3.8	Field Analysis by High-Frequency Methods	52
3.8.1	<i>Asymptotic Physical Optics</i>	53
3.8.1.1	<i>Example: Scattering Radiation from Large Conducting Wire Loop</i>	55
3.8.1.2	<i>Special Case: APO in Two Dimensions</i>	57
3.8.2	<i>Geometrical Theory of Diffraction</i>	61
3.9	Problems	67
	References	70
4	Waveguide and Horn Antennas	71
4.1	Introduction	71
4.2	Radiation from Rectangular Waveguide	72
4.3	Pyramidal Horn	74
4.3.1	<i>Design of a Standard Gain Pyramidal Horn</i>	79
4.3.2	<i>Dielectric-Loaded Rectangular Horn</i>	81
4.4	Circular Waveguides and Horns	85
4.4.1	<i>Circular Waveguide</i>	86
4.4.1.1	<i>Matching at a Circular Aperture</i>	90
4.4.2	<i>Coaxial Waveguide</i>	91
4.4.2.1	<i>Matching of a Coaxial Aperture</i>	95
4.4.2.2	<i>Coaxial Apertures with an Extended Central Conductor</i>	97
4.4.3	<i>Conical Horn</i>	101
4.4.4	<i>Corrugated Radiators</i>	105
4.4.5	<i>Cross-Polarization</i>	110
4.5	Advanced Horn Analysis Topics	114
4.5.1	<i>Flange Effects</i>	114
4.5.2	<i>Mode Matching in Horns</i>	115

4.5.3	<i>Profiled Horns</i>	123
4.5.3.1	<i>Optimization</i>	126
4.5.3.2	<i>Parametric Profiles</i>	126
4.6	Problems	131
	References	133
5	Microstrip Patch Antenna	137
5.1	Introduction	137
5.2	Microstrip Patch Aperture Model	138
5.3	Microstrip Patch on a Cylinder	143
5.4	Problems	146
	References	147
6	Reflector Antennas	149
6.1	Introduction	149
6.2	Radiation from a Paraboloidal Reflector	150
6.2.1	<i>Geometric Optics Method for a Reflector</i>	152
6.2.1.1	<i>Dipole Feed</i>	154
6.2.1.2	<i>Circular Waveguides and Horn Feeds</i>	157
6.2.2	<i>Edge Taper and Edge Illumination</i>	160
6.2.3	<i>Induced Current Method</i>	162
6.2.3.1	<i>Radiation from Symmetrical Reflectors with General Profile</i>	164
6.2.3.2	<i>Spherical Reflector</i>	167
6.2.4	<i>Receive-Mode Method</i>	168
6.3	Focal Region Fields of a Paraboloidal Reflector	172
6.3.1	<i>Asymptotic Representation of the Scattered Field</i>	176
6.4	Blockage	181
6.5	Reflector Antenna Efficiency	183
6.6	Reflector Surface Errors	188
6.7	Offset-fed Parabolic Reflector	189
6.8	Cassegrain Antenna	196
6.8.1	<i>Classical Cassegrain</i>	196
6.8.2	<i>Offset Cassegrain Antenna</i>	198
6.9	Shaped Reflectors	202
6.9.1	<i>Reflector Synthesis by Geometric Optics</i>	203
6.9.2	<i>Reflector Synthesis by Numerical Optimization</i>	209
6.10	Problems	213
	References	217
7	Arrays of Aperture Antennas	219
7.1	Introduction	219
7.2	Two-Dimensional Planar Arrays	219
7.2.1	<i>Rectangular Planar Array</i>	221
7.2.2	<i>Hexagonal Array</i>	223
7.3	Mutual Coupling in Aperture Antennas	228
7.3.1	<i>Infinite Periodic Arrays</i>	230

7.3.2	<i>Finite Arrays</i>	235
7.3.3	<i>Mutual Impedance and Scattering Matrix Representation</i>	239
7.3.4	<i>Analysis of Arrays of Aperture Antennas by Integral Equation Methods</i>	242
7.3.4.1	<i>Moment Method Approach</i>	245
7.3.4.2	<i>Mode Matching in Arrays</i>	247
7.3.5	<i>Mutual Coupling Analysis in Waveguide Apertures</i>	249
7.3.5.1	<i>Rectangular Waveguide Arrays</i>	249
7.3.5.2	<i>Self-Admittance of TE_{10} Mode</i>	253
7.3.5.3	<i>Arrays of Circular and Coaxial Waveguides</i>	257
7.3.5.4	<i>Self-Admittance of TE_{11} Mode in Circular Waveguide</i>	262
7.3.5.5	<i>Mutual Coupling in Other Geometries</i>	266
7.3.5.6	<i>Waveguide-Fed Slot Arrays</i>	269
7.3.5.7	<i>Arrays of Microstrip Patches</i>	273
7.3.5.8	<i>A Numerical Formulation of Coupling in Arbitrary Shaped Apertures</i>	278
7.3.6	<i>An Asymptotic Expression for Mutual Admittance</i>	281
7.3.7	<i>Radiation from Finite Arrays with Mutual Coupling</i>	284
7.4	<i>Techniques for Minimizing Effects of Mutual Coupling</i>	286
7.4.1	<i>Element Spacing</i>	286
7.4.2	<i>Aperture Field Taper</i>	287
7.4.3	<i>Electromagnetic Fences</i>	287
7.4.4	<i>Mutual Coupling Compensation</i>	287
7.4.5	<i>Power Pattern Synthesis Including the Effect of Mutual Coupling</i>	289
7.5	<i>Low-Sidelobe Arrays and Shaped Beams</i>	289
7.6	<i>Problems</i>	300
	<i>References</i>	302
8	Conformal Arrays of Aperture Antennas	307
8.1	<i>Introduction</i>	307
8.2	<i>Radiation from a Conformal Aperture Array</i>	308
8.2.1	<i>Waveguide with E-Field Polarized in Circumferential Direction</i>	308
8.2.2	<i>Waveguide with E-Polarized in Axial Direction</i>	315
8.2.3	<i>Historical Overview of Asymptotic Solutions for Conformal Surfaces</i>	317
8.3	<i>Mutual Coupling in Conformal Arrays</i>	319
8.3.1	<i>Asymptotic Solution for Surface Dyadic</i>	322
8.4	<i>Coupling in a Concave Array: Periodic Solution</i>	325
8.5	<i>Problems</i>	331
	<i>References</i>	331
9	Reflectarrays and Other Aperture Antennas	335
9.1	<i>Introduction</i>	335
9.2	<i>Basic Theory of Reflectarrays</i>	337
9.3	<i>Extensions to the Basic Theory</i>	341
9.4	<i>Other Aperture Antennas</i>	344
9.4.1	<i>Lenses</i>	344
9.4.2	<i>Fabry-Pérot Resonator Antennas</i>	352

9.5 Problems	354
References	356
10 Aperture Antennas in Application	357
10.1 Fabrication	357
10.1.1 Machining	357
10.1.2 Printing	358
10.1.3 Mould Formation	358
10.1.4 Electroforming	358
10.1.5 Lightweight Construction	358
10.1.6 Pressing and Stretch Forming of Reflector Surfaces	359
10.1.7 Assembly and Alignment	360
10.2 Measurement and Testing	361
10.2.1 Far-Field Measurement	361
10.2.2 Near-Field Measurement	364
10.2.3 Intermediate-Field Measurement	369
10.3 Modern Aperture Antennas	371
10.3.1 Compact Low-Sidelobe Horns	371
10.3.2 Multibeam Earth Station	375
10.3.3 Radio Telescopes	379
10.4 Problems	387
References	388
Appendix A: Useful Identities	391
A.1 Vector Identities	391
A.2 Geometric Identities	392
A.3 Transverse Representation of the Electromagnetic Field	393
A.4 Useful Functions	394
References	394
Appendix B: Bessel Functions	395
B.1 Properties	395
B.2 Computation of Bessel Functions	400
References	401
Appendix C: Proof of Stationary Behaviour of Mutual Impedance	403
Appendix D: Free-Space Dyadic Magnetic Green's Function	405
Reference	406
Appendix E: Complex Fresnel Integrals	407
References	409
Appendix F: Properties of Hankel Transform Functions	411
References	412

Appendix G: Properties of Fock Functions for Convex Surfaces	413
G.1 Surface Fock Functions	413
<i>G.1.1 Soft Surface Functions ($m > 0$)</i>	414
<i>G.1.2 Hard Surface Fock Functions ($m < 0$)</i>	415
G.2 Acoustic Fock Functions	417
<i>G.2.1 Soft Acoustic Fock Function</i>	418
<i>G.2.2 Hard Acoustic Fock Function</i>	419
References	421
Index	423

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



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)

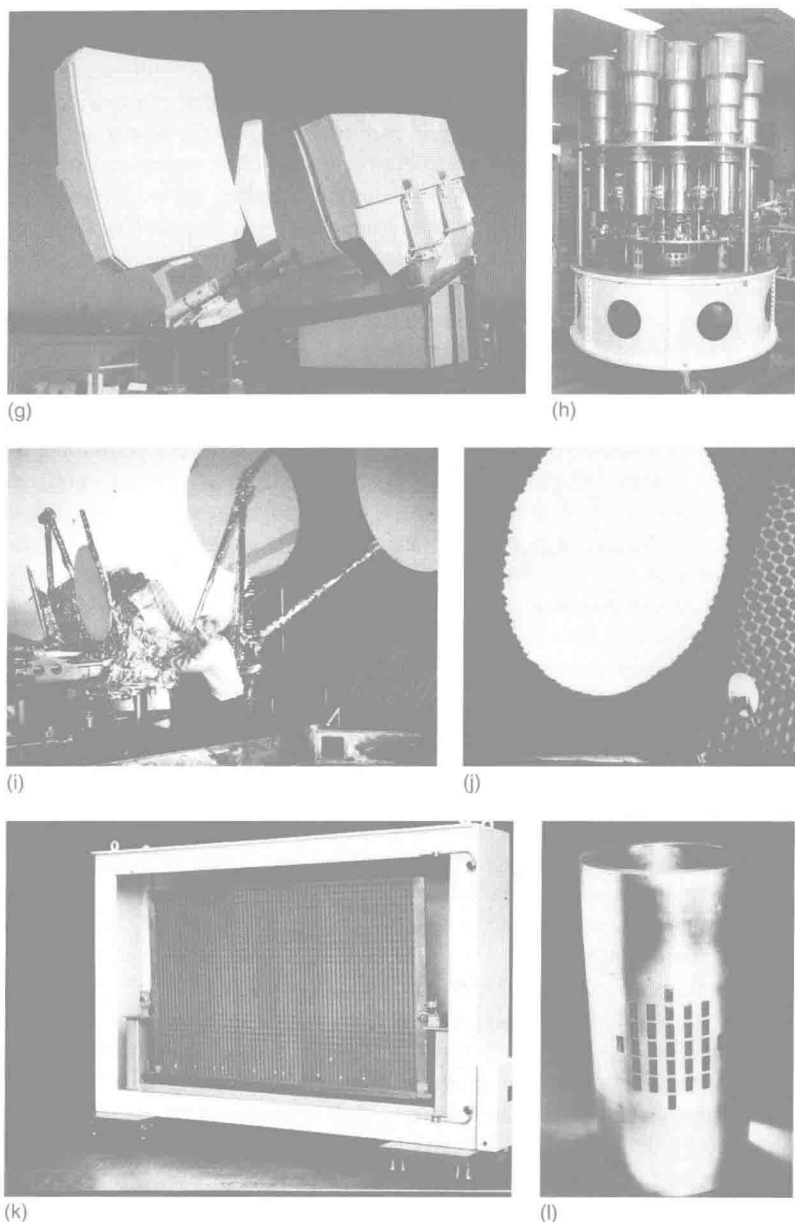


Figure 1.1 (continued) (g) Two multibeam earth station antennas at Danish Radio's multimedia house in Ørestad in Copenhagen, Denmark, covering different segments of the geostationary satellite arc. (h) Multibeam feed system for the Parkes radio telescope. *Source:* Reproduced with permission from CSIRO. (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 textbook 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.