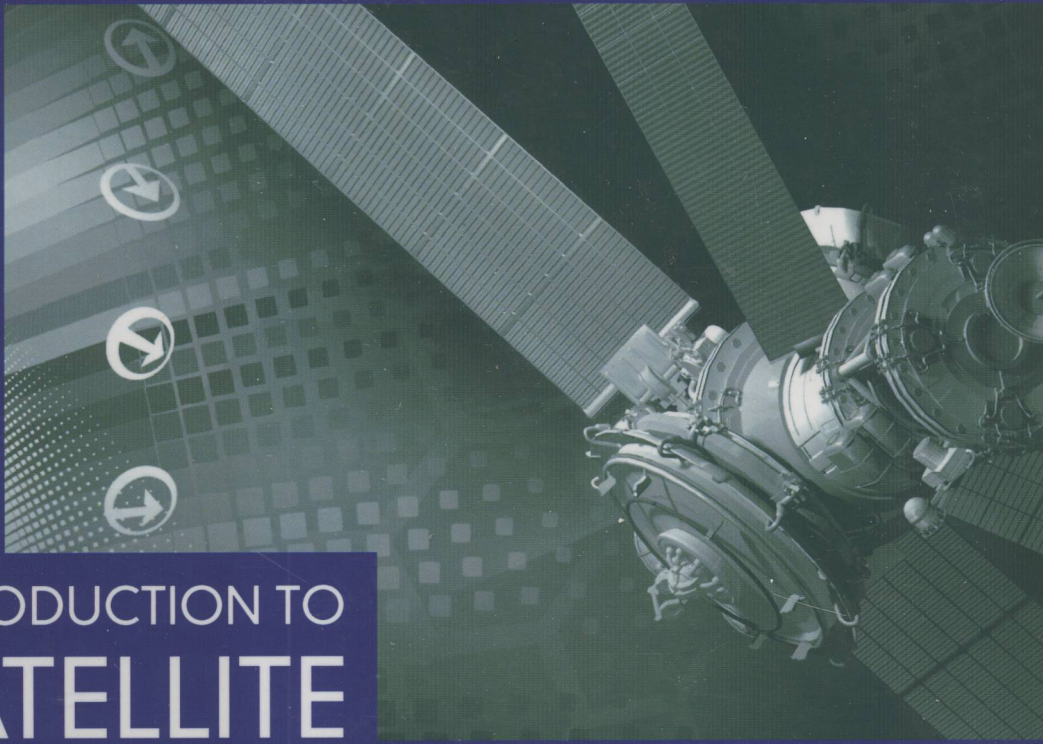


Bruce R. Elbert



INTRODUCTION TO
SATELLITE

COMMUNICATION

THIRD EDITION

TN927
E37
E-3

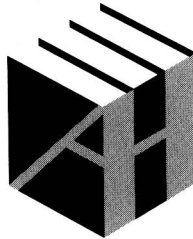
Introduction to Satellite Communication

Third Edition

Bruce R. Elbert



E2009000934



**ARTECH
HOUSE**

BOSTON | LONDON
artechhouse.com

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the U.S. Library of Congress.

British Library Cataloguing in Publication Data

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

ISBN-13: 978-1-59693-210-4

Cover design by Yekaterina Ratner

© 2008 ARTECH HOUSE, INC.

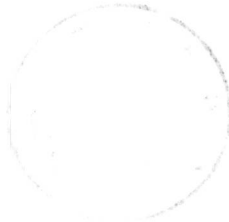
685 Canton Street

Norwood, MA 02062

All rights reserved. Printed and bound in the United States of America. No part of this book may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying, recording, or by any information storage and retrieval system, without permission in writing from the publisher.

All terms mentioned in this book that are known to be trademarks or service marks have been appropriately capitalized. Artech House cannot attest to the accuracy of this information. Use of a term in this book should not be regarded as affecting the validity of any trademark or service mark.

10 9 8 7 6 5 4 3 2 1



Introduction to Satellite Communication

Third Edition

For a listing of recent titles in the *Artech House Space Application Series*,
turn to the back of this book.

Preface

Introduction to Satellite Communication is designed to meet the needs of working professionals and students. The first edition was a response to a request by many friends and associates for a basic and clear book that provides newcomers with an accessible way to gain knowledge and become productive. The second edition followed the same approach, updating the older and dated material and adding background in newer systems, particularly the global mobile personal communications systems introduced worldwide. This third edition brings the text in line with industry and technology trends. Whether the reader is technically trained or not, the need exists for an authoritative guidebook to the construction and usage of satellite networks.

This book is designed to give you, the reader, an understanding that should permit you to begin work as a satellite professional or as a user of satellite communication. Sufficient technical information has been included to instill a feeling for how systems are designed and operate. Many categories of professionals and students should profit from a significant portion of the material. The book's explanatory nature and broad coverage make it suitable as a textbook for university programs and internal training in communication systems design and planning. Nontechnical professionals in associated business management, contracts, legal, and financial fields will find the book particularly helpful when they must deal with telecommunication projects and issues.

The book is organized into 12 chapters to correspond to the major areas of commercial satellite communication systems. Chapter 1, "Fundamentals of Satellite Systems," identifies the structure and key features of satellite communication and reviews some of the more basic concepts in a nontechnical style. It is understandable to all readers, including high school students. Likewise, Chapter 2, "Evolution of Satellite Communication," provides an easy-to-understand history of the technology and its applications. It begins with geostationary Earth orbit (GEO) systems, which are the foundation of the industry, and moves into non-GEO systems used in mobile applications. Another purpose of Chapter 2 is to capture in one place the background with which many newcomers otherwise would not be acquainted (e.g., how we got from Arthur C. Clarke's concept in 1945 to the present day). Chapter 3, "Satellite Network Architectures," covers the ways in which satellite links can be applied to practical communication problems. It gives the reader an appreciation for the variety of uses in which satellites have gained a stronghold. Technologists involved with spacecraft or communication systems will find that Chapter 3 explains many of the mysteries surrounding the business of using satellites.

The next two chapters begin the core technical material, focusing on the engineering and design of radio transmissions to and from satellites. Chapter 4, "Microwave Link Engineering," gives the reader a basic understanding of the physics of the radio link between the Earth station and the satellite and covers the factors that are under the designer's control as well as those that are not. It is assumed that the reader has little or no technical training, so the only form of mathematics used is arithmetic. Chapter 5, "Modulation, Multiple Access and Impairments," rounds out the basic theory of communication as it relates to efficient satellite transmission. The chapter is fairly compact and may be helpful for interested readers to supplement their study with a basic textbook on communication engineering. Nontechnical readers can examine Chapters 4 and 5 but not delve deeply into the engineering details (which are more important to technical professionals, who need to understand features and trade-offs).

Chapters 6, 7, and 8 provide a comprehensive review of the functional elements of all communication satellites. The objective here is to aid readers in understanding the key issues in satellites and is not appropriate for the detailed engineering design of satellite components and subsystems. As is customary, the physical piece of hardware is referred to as the spacecraft, which becomes an artificial Earth satellite (or just satellite) when in orbit. The major elements of the spacecraft are the repeater (bent-pipe and digital processor), the antennas, and the spacecraft bus (the supporting vehicle), which are covered in Chapters 6, 7, and 8, respectively. While those chapters are not essential to understanding how to use satellite communications, they will be of general benefit because the actual operation of a spacecraft affects the performance of the services rendered.

The complementary topics for the ground facilities used in conjunction with the satellite are reviewed in Chapter 9, "Earth Stations and Terrestrial Technology." Care has been taken to include only current classes of Earth stations, particularly those used for satellite control, television broadcasting, fixed and mobile very small aperture terminal (VSAT) applications, and mobile satellite services (GEO and non-GEO). Chapter 9 will be useful for those readers who plan to use satellite transmission, since ground facilities fundamentally are under the control of the user rather than the satellite operator.

Chapter 10, "Launch Vehicles and Services," covers topics that are of great concern to operators and major users of satellites alike. The chapter is a complete review of the alternatives for placing satellites into Earth orbit and emphasizes that particular launch vehicle choices change over time. However, because reliability is based on a consistent experience record, much of the change is evolutionary rather than revolutionary. Chapter 10 also discusses the planning and operation of the mission, which is the sequence of events of launch and placement into operating orbit. Risk management is addressed as well.

Chapter 11, "Satellite Operations and Organization," addresses the special needs of this type of business. In some detail, it reviews the complete satellite control system, the communication network needed to support such a system, and the human resources that are appropriate to those functions. Chapter 12, "Economics of Satellite Systems," provides the underlying characteristics of satellites and Earth stations that are related to the cost of implementing and operating satellite networks. Our perspective is that of a commercial operator who is in

business to make money (or reduce costs). The framework is useful for analyzing the economics of either a complete system or a portion of a system (e.g., one or a few Earth stations). Chapter 12 is expanded to address the overall systems engineering process in satellite communication. This is based on the structured approach found in the aerospace industry adapted to the needs of commercial applications. From this, we move into the topic of engineering economics and overall development of the entire satellite program.

The book can be read sequentially from cover to cover because the material follows a consistent thread. All the elements and uses of spacecraft and Earth stations are covered. Chapters also can be read out of sequence, if necessary, because each chapter explains the concepts relevant to it. References to other chapters are provided throughout. The material is completely current as of the time of publication (circa 2008), but care has been taken to emphasize concepts that are not likely to change quickly. That is the same approach taken in the first edition, a book that remained in print (and in demand) for 12 years. Once read, this book can be used as a reference because most of the terminology in current usage is defined and illustrated. This book is a mate to the author's previous work, *The Satellite Communication Applications Handbook, Second Edition*, and *The Satellite Communication Ground Segment and Earth Station Handbook*.

Acknowledgments

I wish to acknowledge my friends and associates in the industry and around the world whom I have helped put satellite communication into practical use. My first introduction to satellites came at COMSAT Laboratories, where we examined many concepts and systems well before they were applied commercially. My subsequent 25 years with Hughes provided the experience to examine the entire satellite system at the depth needed to write these books and teach this technology to students and working professionals. Since 1990, I have been affiliated with UCLA Extension, and I wish to express my special appreciation to Dr. Bill Goodin, manager of the Engineering Short Course Program, for his continued support. My technical editor, Ray Sperber, made countless contributions to the quality and accuracy of this material (something he also did so ably in every prior edition). Finally, I wish to acknowledge my wife, Cathy, who provided the support and motivation necessary to start and complete the revision of this book, and my daughters, who every day make a dad proud.

**Recent Titles in the Artech House
Space Technology and Applications Series**

Bruce R. Elbert, Series Editor

Business Strategies for Satellite Systems, D. K. Sachdev

Gigahertz and Terahertz Technologies for Broadband Communications,
Terry Edwards

Ground Segment and Earth Station Handbook, Bruce R. Elbert

Introduction to Satellite Communication, Third Edition, Bruce R. Elbert

Laser Space Communications, David G. Aviv

Low Earth Orbital Satellites for Personal Communication Networks,
Abbas Jamalipour

Mobile Satellite Communications, Shingo Ohmori, et al.

Satellite Broadcast Systems Engineering, Jorge Matos Gómez

The Satellite Communication Applications Handbook, Second Edition,
Bruce R. Elbert

Satellite Communications Fundamentals, Jules E. Kadish and Thomas W. R. East

The Satellite Communication Ground Segment and Earth Station Handbook,
Bruce Elbert

Understanding GPS: Principles and Applications, Second Edition, Elliott D. Kaplan
and Christopher J. Hegarty, editors

For further information on these and other Artech House titles, including
previously considered out-of-print books now available through our In-Print-
Forever® (IPF®) program, contact:

Artech House
685 Canton Street
Norwood, MA 02062
Phone: 781-769-9750
Fax: 781-769-6334
e-mail: artech@artechhouse.com

Artech House
46 Gillingham Street
London SW1V 1AH UK
Phone: +44 (0)171-973-8077
Fax: +44 (0)171-630-0166
e-mail: artech-uk@artechhouse.com

Find us on the World Wide Web at: www.artechhouse.com

Contents

Preface	<i>xi</i>
---------	-----------

CHAPTER 1

Fundamentals of Satellite Systems	1
1.1 Basic Characteristics of Satellites	1
1.1.1 Advantages of Satellite Communication	7
1.1.2 Use of Microwave Frequencies	11
1.1.3 Digital Transmission, Compression, and Routing	12
1.1.4 Improved Space Platforms and Launching Systems	13
1.1.5 Integration with Terrestrial Wired and Wireless Networks	14
1.2 System Elements	15
1.2.1 Space Segment	15
1.2.2 Ground Segment	17
1.2.3 Overall System	20
1.3 Satellite Orbit Configurations	20
1.4 Frequency Spectrum Allocations	22
1.4.1 ITU Spectrum Allocations and Regions	24
1.4.2 VHF and UHF Frequency Ranges	26
1.4.3 Microwave Bands: L and S	27
1.4.4 Microwave Bands: C, X, and Ku	31
1.4.5 Millimeter Wave and Higher: Ka-, Q-, and V-Bands	35
1.4.6 Guided and Unguided Optical Properties	36
References	38

CHAPTER 2

Evolution of Satellite Communication	39
2.1 Source of the Original Idea	39
2.1.1 SYNCOM	40
2.1.2 COMSAT	41
2.2 Evolving Satellite Coverage	42
2.2.1 Global Service: INTELSAT, PanAmSat, and Orion	42
2.2.2 Regional Coverage: EUTELSAT and SES	50
2.2.3 Domestic Systems: Telesat, Westar, and Palapa	51
2.3 Specialized Systems: DTH and Mobile	60
2.3.1 DTH Development	61
2.3.2 MSS Development	62
2.3.3 Digital Information Broadcasting	64

2.4	Expansion at Higher Frequency Bands: Ka-Band	66
	References	68
CHAPTER 3		
	Satellite Network Architectures	69
3.1	General Features of Satellite Networks	69
3.1.1	Dedicated Bandwidth Services	71
3.1.2	Circuit-Switched Services	75
3.1.3	Packet-Switched Services	77
3.1.4	Flexibility Features	78
3.1.5	Reliability of Satellites and Links	81
3.1.6	Quality Features and Issues	82
3.2	Point-to-Multipoint (Broadcast) Networks	88
3.2.1	Video Distribution	89
3.2.2	Direct-to-Home Television	96
3.2.3	Content Distribution Networks	97
3.2.4	Mobile Satellite Communications	99
3.3	Point-to-Point Networks	104
3.4	VSAT Networks	105
	References	107
CHAPTER 4		
	Microwave Link Engineering	109
4.1	The Decibel	109
4.2	Propagation on the Earth-Space Link	111
4.2.1	Basic Microwave Propagation	112
4.2.2	Isotropic Radiator	113
4.2.3	Directional Properties of Antennas	115
4.2.4	Polarization (Linear and Circular)	119
4.2.5	Propagation Losses	123
4.3	Microwave Transmitters and Receivers	133
4.3.1	Transmitting Station	133
4.3.2	Receiving Station	139
4.3.3	Definition of a Transponder	140
4.4	Overall Link Quality	142
4.4.1	How Noise and Interference Affect a Microwave Link	142
4.4.2	Carrier-to-Noise Ratio	144
4.4.3	Link Budget Analysis	146
4.4.4	Link Margin	148
	References	149
CHAPTER 5		
	Modulation, Multiple Access, and Impairments	151
5.1	Digital Baseband Signals and Hierarchies	151
5.1.1	Digital Information Sources and Bandwidth Requirements	153
5.1.2	Analog-to-Digital Conversion	156

5.1.3	Compression	158
5.1.4	Error Detection and Correction	159
5.1.5	Scrambling and Encryption	162
5.2	Digital Modulation	165
5.2.1	Frequency Shift Keying	169
5.2.2	Phase Shift Keying	169
5.2.3	Amplitude and Phase Shift Keying	171
5.3	Multiple Access Methods	172
5.3.1	Frequency Division Multiple Access	173
5.3.2	Time Division Multiple Access	175
5.3.3	ALOHA Packet Multiple Access	177
5.3.4	Code Division Multiple Access	179
5.3.5	RF Bandwidth Utilization in Multiple Access	181
5.4	Distortion and Impairments	183
5.4.1	Digital Signal Impairments	183
5.4.2	Transponder Intermodulation Impairment	185
5.4.3	Uplink and Downlink RF Interference	189
	References	193

CHAPTER 6

	Spacecraft and Repeater	195
6.1	Overview of Communications Spacecraft	195
6.1.1	Overall Payload Requirements	198
6.1.2	Transmit Effective Isotropic Radiated Power (EIRP)	199
6.1.3	Receive Gain-to-Noise Temperature Ratio (G/T)	203
6.1.4	Bent-Pipe Transponder Filtering	204
6.1.5	Linearity	205
6.1.6	Frequency Translation Effects	206
6.2	Analog Bent-Pipe Repeaters	208
6.3	Digital Processing Repeaters	208
6.3.1	Multiple Beam Switching and Routing	209
6.3.2	Digital Processor Architecture	212
6.3.3	Demod-Remod Repeater	215
6.4	Standard Repeater Elements	216
6.4.1	Wideband Receiver	217
6.4.2	Redundancy Switching	219
6.4.3	Waveguide Filters and Multiplexers	224
6.4.4	Traveling Wave Tube Amplifiers	228
6.4.5	Solid-State Power Amplifiers	232
6.4.6	Transponder Gain Control and Linearization	234
	References	236

CHAPTER 7

	Spacecraft Antennas	237
7.1	Horn Antennas	237

7.2	Reflector Antennas	243
7.2.1	Center-Fed Parabolic Reflectors	246
7.2.2	Offset-Fed Parabolic Reflectors	249
7.3	Antenna Patterns	251
7.4	Direct Radiating Array Antennas	255
	References	256

CHAPTER 8

	Spacecraft Mission and Bus Subsystems	257
8.1	Mission Summary	257
8.1.1	GEO Mission Profile	257
8.1.2	On-Station Operation Requirements	258
8.1.3	Non-GEO Requirements	259
8.2	Spacecraft Configuration	260
8.3	Spacecraft Bus Subsystems	262
8.3.1	Attitude-Control Subsystem	262
8.3.2	Solar Cells and Panels	268
8.3.3	Battery Design and Configuration	271
8.3.4	Liquid Propulsion System	274
8.3.5	Electric and Ion Propulsion	278
8.3.6	Solid-Fuel Rocket Motors	279
8.3.7	Tracking, Telemetry, and Command (TT&C)	280
8.3.8	Thermal Control	286
8.3.9	Structural Arrangements	289
	References	289

CHAPTER 9

	Earth Stations and Network Technology	291
9.1	Basic Earth Station Configuration	291
9.2	Performance Requirements	294
9.2.1	Transmit EIRP	294
9.2.2	Receive G/T	295
9.2.3	Location and Platform Requirements	297
9.3	Radio Frequency Equipment	299
9.3.1	Antennas for Earth Stations	300
9.3.2	Antenna Beam Pointing	302
9.3.3	High-Power Amplifiers	302
9.3.4	Upconverters and Downconverters	304
9.3.5	RF Combining	305
9.3.6	Uplink Power Control	305
9.4	Intermediate Frequency and Baseband Equipment	306
9.4.1	Modulators, Demodulators, and Modems	306
9.4.2	Multiplexing and Packet Processing	307
9.5	Tail Links and Terrestrial Interface	307
9.5.1	Terrestrial Tail Options	308
9.5.2	Terrestrial Network Interfaces	310

9.6	Earth Station Facility Design	311
9.7	Major Classes of Earth Stations	313
9.7.1	TT&C Ground Facilities	314
9.7.2	TV Uplinks and Broadcast Centers	319
9.7.3	FDMA Digital Communications Service	322
9.7.4	Full-Mesh TDMA Earth Station	324
9.7.5	VSAT Star Network Terminal	326
9.7.6	TV Receive-Only Design	330
9.7.7	MSS User Terminals	334
	References	336

CHAPTER 10

	Launch Vehicles and Services	337
10.1	The Launch Mission	338
10.1.1	The Boost Phase	339
10.1.2	Non-GEO Missions	341
10.1.3	Geostationary Transfer Orbit	342
10.1.4	Drift Orbit for GEO Operation	343
10.1.5	Deployments and In-Orbit Testing	345
10.1.6	RCS Fuel Allocation	346
10.2	Launch Technology and Systems	349
10.3	Typical Launch Vehicles	351
10.3.1	Ariane	352
10.3.2	Atlas	353
10.3.3	Delta	354
10.3.4	H-1 and H-2	354
10.3.5	Long March	355
10.3.6	Proton	356
10.3.7	Zenit	358
10.4	Launch Interfaces	359
10.4.1	Physical Launch Interfaces	359
10.4.2	Management Interfaces	360
10.5	Risk Management in Launch and Operation	361
10.5.1	Launch Insurance	362
10.5.2	Backup and Replacement Satellites	364

CHAPTER 11

	Satellite Operations and Organization	367
11.1	The Satellite Control System	367
11.1.1	GEO Satellite Control	369
11.1.2	Non-GEO Satellite Control	371
11.2	Intercommunication Networks	372
11.2.1	Backbone Communications	373
11.2.2	Alternate Routing for High Reliability	374
11.2.3	Network Management	375

11.3 Network Operations	375
11.3.1 Standard GEO Transponder Services	376
11.3.2 User Network Monitor and Control	379
11.3.3 Payload Configuration Management	381
11.4 Human Resources for Satellite Operations	382
References	387
CHAPTER 12	
Satellite Systems Engineering and Economics	389
12.1 Satellite Systems Engineering Principles	389
12.1.1 Fixed Satellite Systems and Services	392
12.1.2 Mobile Satellite Systems and Services	393
12.2 Satellite System Economic Principles	393
12.3 System Development Methodology	395
12.4 Space Segment Economics	398
12.4.1 Space Segment Investment Cost Elements	401
12.4.2 Annual Space Segment Costs	405
12.5 Earth Station Economics	407
12.5.1 Earth Station Investment Cost Elements	408
12.5.2 Annual Costs for Earth Station Networks	410
12.5.3 Teleport Earth Stations	411
12.6 Analysis of Network Economics	412
12.6.1 Determining Traffic Requirements	412
12.6.2 Laying Out the Network	415
12.6.3 Total Network Evaluation	417
12.6.4 Optimizing the Space and Ground Segments	418
12.7 Satellite Communications: Instant Infrastructure	419
12.7.1 Satellites Versus Fiber Optics	420
12.7.2 Emphasis on the Broadcast Feature	420
12.7.3 Paralleling the Terrestrial Networks	421
12.7.4 Mobility Enhancements	422
12.7.5 Creating the Future	424
12.7.6 Advancing Technology	424
12.8 Conclusions for the Next Generation	425
References	427
About the Author	429
Index	431

Fundamentals of Satellite Systems

Satellite communications¹, no longer a marvel of human space activity, have evolved into an everyday, commonplace thing. By 2010, satellite systems will represent well over \$100 billion of investment and provide an essential ingredient to many businesses and governments worldwide. Nearly all television coverage travels by satellite, today reaching directly to the home from space. Even in the age of wide-band fiber optic cables and the Internet, satellites still serve the basic telecommunication needs of a majority of countries around the world. For example, domestic satellites have greatly improved the quality of service of the public telephone system and brought nations more tightly together. Satellites are adapting to developments in multimedia information and personal communication, with the cost of one-way and two-way Earth stations now within the reach of many potential users. A unique benefit has developed in the area of emergency preparedness and response. When a devastating earthquake hit Mexico City in September 1985, the newly launched Morelos 1 satellite maintained reliable television transmission around the nation even though all terrestrial long-distance lines out of the city fell silent. Similarly, communications were restored to facilitate disaster relief on the island of Sumatra after the December 2004 earthquake and subsequent tsunami.

To provide an overview of the field, the remainder of this chapter describes the features of satellite communication networks as well as the principal elements of an overall system. The brief history in Chapter 2 is intended to explain how the satellite industry developed and why things are the way they are. Chapter 2 can be read in sequence or deferred until other chapters have been read, to get a better feel for the technology and terms.

1.1 Basic Characteristics of Satellites

A communications satellite is a microwave repeater station that permits two or more users with appropriate earth stations to deliver or exchange information in various forms. As discussed later in this chapter and again in Chapter 6, a satellite in a geostationary Earth orbit (GEO) revolves around the Earth in the plane of the equator once in 24 hours, maintaining precise synchronization with the Earth's rotation. There are two other classes of 24-hour orbits: the geosynchronous orbit and the highly elliptical synchronous orbit. Both involve satellites that appear to

1. *Satellite communication* and *satellite communications* are used interchangeably throughout.

move relative to a fixed point on the Earth. It is well known that a system of three satellites in GEO each separated by 120 degrees of longitude, as shown in Figure 1.1, can receive and send radio signals over almost all the inhabited portions of the globe. (The small regions around the North and South Poles—above 81° NL and below 81° SL—are not covered.) A given GEO satellite has a coverage region, illustrated by the shaded oval, within which Earth stations can communicate with and be linked by the satellite. The range from user to satellite is a minimum of 36,000 km, which makes the design of the microwave link quite stringent in terms of providing adequate received signal power. Also, that distance introduces a propagation delay of about one-quarter of a second for a single hop between a pair of users.

The GEO is the ideal case of the entire class of geosynchronous (or synchronous) orbits, which all have a 24-hour period of revolution but are typically inclined with respect to the equator and/or elliptical in shape. As viewed from the Earth, a synchronous satellite in an inclined orbit appears to drift during a day above and below its normal position in the sky. While ideal, the circular GEO is not a stable arrangement, and inclination naturally increases in time. As discussed in Chapter 8, inclination is controlled by the use of an onboard propulsion system with enough fuel for corrections during the entire lifetime of the satellite. A synchronous satellite not intended for GEO operation can be launched with considerably less auxiliary fuel for that purpose. Orbit inclination of greater than 0.1 degree usually is not acceptable for commercial service unless the Earth station antennas can automatically repoint toward (track) the satellite as it appears to move. Mechanical tracking is the most practical (and cumbersome) approach, but electrical beam steering systems are available for specialized applications such as aeronautical mobile.

Orbits that are below a mean altitude of about 36,000 km have periods of revolution shorter than 24 hours and hence are termed non-GEO. As illustrated

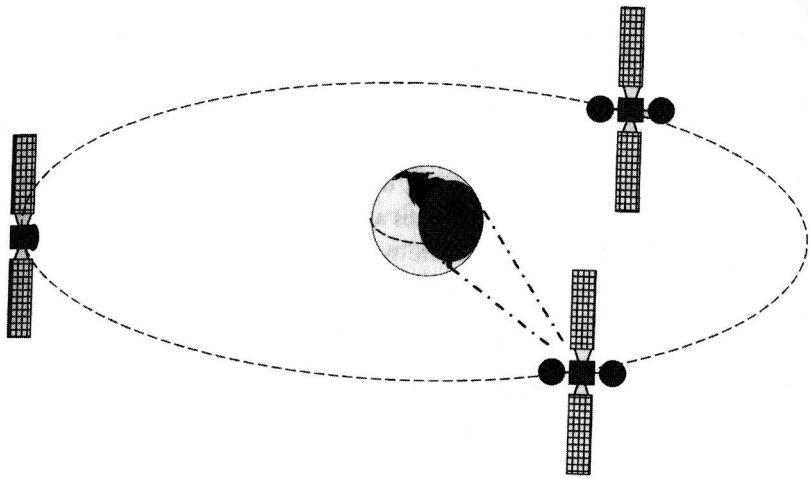


Figure 1.1 A system of three geostationary communication satellites provides nearly worldwide coverage.