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PREFACE

Communications satellites play a major role in telephone transmission, television and radio program distribution, computer communications, maritime navigation, and military command and control. The current strong demand for electrical engineers originates from all segments of the industry, ranging from satellite and earth station manufacturers to lessors of satellite channels. This book was written as a text for a one-semester senior or beginning graduate level course to provide these engineers with an appropriate background in satellite technology, link design, and operations. We hope that graduate engineers will also find it useful as a reference.

Satellite communications engineering combines such diverse topics as radio wave propagation, antennas, orbital mechanics, modulation, detection, coding, and radio electronics. Each of these is a major field of study, and each has its own extensive literature. In preparing this text we emphasized the material from these areas that is important to satellite communications and derived those equations that a beginning engineer might reasonably be expected to know and to understand. We have tried to make our coverage as practical as possible, stressing those techniques that are or soon will be in use.

We assume that our readers will have completed the usual undergraduate courses in physics (to provide a background for orbital mechanics), electromagnetic fields (to understand wavelength, power density, and electromagnetic radiation), and communications theory (for a background in modulation, detection, noise, and spectra). Although some familiarity with microwaves and radio electronics would be useful, these are not required.

Although later chapters build upon material covered in earlier ones, we have made each chapter reasonably self-contained for practicing engineers who are seeking information about a particular topic. To help with this process we have provided an end-of-book glossary and a list of symbols.

Chapter 1 introduces satellite communications and provides a brief history of the subject. Chapter 2 is a detailed discussion of orbital mechanics and orbital considerations in satellite launches and satellite link design. So far as we are aware, it is the first treatment of the subject for electrical engineers that covers everything from Newton's laws of motion to look angles. Chapter 3 presents a review of those aspects of spacecraft design and organization that are important in communications satellites. Chapter 4 derives the equations needed for calculating the carrier-to-noise ratio (C/N) of a link and discusses techniques for achieving a specified (C/N). Chapter 5 reviews digital and analog modulation and multiplexing techniques and provides the necessary information for determining the (C/N) requirement that links designed by the procedure of Chapter 4 must meet. Chapter 6 discusses multiple access, and Chapter 7 presents error detection and correction, applications of coding theory that are particularly important to satellite systems. Chapter 8 presents propagation effects and their impact on system design; these are severe at frequencies above 10 GHz. Chapter 9 discusses earth station technology, emphasizing antennas. Chapter 10 describes Intelsat (The International Telecommunications Satellite Organization) and Inmarsat (The International Maritime Satellite Organization). Chapter 11 is about television distribution and satellite broadcasting, topics that the general public most strongly associates with satellite communications. The appendix provides background information on how decibels are used in communications engineering and on the effect of bandlimiting on digital radio signals.

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Initial word processing of this manuscript was by Cynthia Will Dettmer and Linda White Kipps. All later drafts were prepared by Patricia Wojciechouski, who completed the book via a long-distance telephone hookup to our computer. We appreciate their contributions and their struggles with our handwriting and notation.

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T. P.
C. W. B.

CONTENTS

1 INTRODUCTION

In less than 20 years communications satellites have become the dominant carriers of long distance communications. From the first commercial launch of INTELSAT I[1] (also called EARLY BIRD) on April 6, 1965, the satellite industry has grown until it handles most international telephone traffic, all international and almost all domestic long-distance television program distribution, and a rapidly growing proportion of new domestic voice and data channels. Direct satellite broadcasting will soon begin, and proposals for electronic mail and personal two-way satellite radios are under discussion. Satellites have significantly improved the reliability and the accuracy of aviation and maritime communications and navigation, removing these functions from the high-frequency (HF) portion of the spectrum. The International Telecommunication Satellite Organization (*Intelsat*) has grown at a rate of 20 percent per year since 1965 and, as of 1984, it operated over 35,000 two-way traffic links. United States domestic satellite use is expected to grow at an annual rate of 15 percent until the end of this century [2].

These changes have occurred because the technology is now available to put large *spacecraft* into synchronous orbit where, to an observer on the ground, they remain permanently at the same place in the sky. At an altitude of about 35,870 km (22,291 miles), the satellites can receive, amplify, and retransmit radio signals for most of a hemisphere. Thus, with one relay via a satellite, a single transmitter on the ground can reach nearly half the world. With three relays it can reach all of it.

[1] In this text we have followed the conventional practice of printing the names of individual spacecraft and families of spacecraft in capital letters. Individual members of multiple families are generally identified by Roman numerals, for example, INTELSAT III, except for those cases like the COSMOS series, where there have been over 1300 launches [1].

As satellites have grown larger and more powerful, the cost of required terrestrial equipment has fallen. Where once an earth terminal was a multimillion dollar proposition, receive-only stations are now available for under $1500. The result is that satellites are the cheapest way to send information reliably over a long distance, particularly if that information is intended for a large number of receivers, who may not always be in the same places.

1.1 THE ORIGIN OF SATELLITE COMMUNICATIONS

Most authorities credit Arthur C. Clarke, famous British science fiction writer and author of *2001: A Space Odyssey* [3], with originating the idea of a synchronous communications satellite. In 1945 Clarke noted [4] that a satellite in a circular equatorial orbit with a radius of about 42,242 km would have an angular velocity that matched the earth's. Thus it would always remain above the same spot on the ground, and it could receive and relay signals from most of a hemisphere. Three satellites spaced 120 degrees apart could cover the whole world (with some overlap); provided that messages could be relayed between satellites, reliable communication between any two points in the world would be possible.

As is appropriate for a science fiction writer, Clarke had ideas ahead of their time. It was not until the USSR launched SPUTNIK I on October 4, 1957, that rocket technology was available to put a satellite into even a low orbit; synchronous orbit was not achieved until 1963.

1.2 A BRIEF HISTORY OF SATELLITE COMMUNICATIONS [5]

The 1957 launch of SPUTNIK I was followed by the "space race" and a sustained effort by the United States to catch up with the USSR. This was reflected in SCORE (Signal Communicating by Orbiting Relay Equipment) launched by the U.S. Air Force on December 18, 1958. Essentially an Atlas 10B missile with a modified upper stage, SCORE was placed in a low elliptical orbit with a period of 101 min. It broadcast a taped message from President Eisenhower, but it was also the first successful "bent pipe in the sky" satellite repeater. Its normal operating mode was to record an uplink transmission while passing over one earth station and to play it back when requested by another earth station. The maximum message length was 4 min, and the spacecraft's capacity was either one voice channel or seventy 60-words-per-minute teletype channels. SCORE's transponder was a marvel of "quick and dirty" engineering; the receiver was a modified FM pocket pager and the transmitter was a "handy-talkie" with an outboard amplifier to boost transmitter power to 8 W. The uplink frequency was 150 MHz and the downlink frequency was 132 MHz, and the spacecraft carried a tracking beacon at 108 MHz. SCORE's batteries failed after 35 days in orbit.

The first communications satellites to draw widespread popular interest (because on clear nights they were visible to the naked eye) were ECHO I and II, launched by *AT&T* on August 12, 1960, and January 25, 1964. These were orbiting balloons 100 ft in diameter which served as passive reflectors. As such, they