Features of Comprehensive Coverage
Includes dedicated chapters on Earth Station Technology, Applications of Satellite Communication, and Modern Developments & Future Trends. It also discusses satellite systems and applications such as DTH, ISRO Distance Edu Program used in India, giving an Indian perspective to the subject.

Abbreviations
A list of abbreviations with their expansions at the beginning of the book facilitates easier understanding of standard abbreviations used throughout the book.

Tables and Figures
More than 300 interactive figures and tables aid the readers to visualize the concepts and principles of Satellite Communication.

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the Book

Appendices, Case Studies, and MATLAB Codes
The book has exciting introductory case studies on Indian space missions GSAT–16, Chandrayaan–1, and the very recent Mars Orbiter Mission spacecraft. Among the Appendices, the book also has appendices on Satellite Tests and Instruments, Earth Station Measurements, MATLAB codes, and Glossary.

Chapter-wise MATLAB codes are provided to help the students to compute various parameters discussed in the text. Comments provided at the beginning of each program and also in the program make it easy for the students to understand the program steps.

Solved Examples
Numerous solved examples interspersed throughout the chapters give readers the opportunity to understand the application of concepts in practical engineering problems.

Exhaustive Chapter-end Self-assessment Section
This section, at the end of each chapter, provides Multiple Choice Questions with answers; A mixed bag of critical-thinking and concept-based questions in Review Questions; and Numerical Problems for practice.

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Online Resources

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For Faculty
- Solutions Manual
- Chapter-wise PowerPoint Slides

For Students
- Test Generator (Additional MCQs)
- Answers to Review Questions

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Preface

Satellite communication has come a long way since its conception in 1945 by Sir Arthur C. Clarke, who envisioned that three satellites placed in a geostationary orbit would remain stationary to an observer on ground and could be used as repeaters in the sky providing communication to almost the entire globe. The technology development began with demonstration of space communication with data transmission from the SCORE satellite, launched by the US army in 1958, followed by Echo I, a simple reflecting balloon, launched by NASA in 1960. The true model of Sir Arthur Clarke was tested with the launch of Syncom-2, a geostationary satellite, by NASA in 1963. In 1964, International Telecommunication Satellite (Intelsat) organization was created, which started the commercial satellite communication by launching Intelsat-1 satellite, also called the Early Bird.

Intelsat has since then launched over ten series of satellites. Besides communication, satellites are also used for many applications such as audio and television broadcast, distance education, telemedicine, earth observation, disaster warning, search and rescue, and so on. Over the decades, the capacity of satellites has grown from single transponder to dozens of transponders, offering hundreds of TV channels and thousands of voice circuits. The weight of a satellite and the power handling capacity have also grown significantly. During recent years, there is a parallel trend of smaller and smaller satellites. These satellites, called micro, nano, and pico satellites, are being launched at lower costs for specific applications.

ABOUT THE BOOK

Satellite Communication—Principles and Applications provides an introduction to satellite communication for the graduate and undergraduate students studying communication engineering. As the title suggests, the book covers the fundamental concepts of satellite communication and their applications. The principles of satellite communication include the satellite, the earth stations, the earth–satellite link, access methods, and communication techniques employed. The traditional, recent, and modern applications are covered and so are the future trends in satellite systems.

Salient Features

- The content is designed to provide the basics of satellite systems in the first 10 chapters and the major applications in the following 4 chapters.
- Many new applications of satellite communication are covered in a separate chapter.

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Preface

- The new developments underway in communication satellite systems are provided in the last chapter.
- Some special techniques, such as the digital speech interpolation and echo cancellation, unique to satellite communication are discussed at length.
- Case studies are provided, with reference to recent Indian spacecrafts.
- Applications are described with the current standard systems.

Pedagogical Features

- A large number of diagrams (more than 275) are included in the text to clear the concepts
- Nearly 50 tables provide consolidated information
- Over 70 examples are provided in Chapters 2 to 10, which deal with the principles
- More than 90 numerical problems are provided for the students to practice
- Total number of review questions is more than 285 and multiple choice questions is more than 200
- A large number of references are provided, which help the students to get detailed information
- A glossary of terms used in the book provides a quick reference to students

Contents and Coverage

The entire content of this book is organized in 16 chapters and 7 appendices. Chapters 1–10 describe the principles of various aspects of satellite communication including the earth stations, satellites, orbits, communication links, and communication techniques. Chapters 11–15 cover the applications of satellite systems in communication, navigation, and broadcasting, and also describe some special applications. Chapter 16 describes the future trends and research taking place in the area of satellite systems. Each chapter and each appendix is briefly discussed in the following paragraphs:

Chapter 1 provides an introduction to satellite communication systems, types of satellites, and services provided by satellites. It states the frequency bands used and various configurations. The evolution of satellite communication in the world in general and particularly in India is described.

Chapter 2 describes the orbits, the launching, placing, and maintaining of the satellite in the orbit, the parameters defining an orbit, and the laws governing the motion of a satellite in orbit. It explains how the satellite position is defined. It prepares a student to calculate the velocity and period of a satellite in an orbit and the altitude of an orbit of a satellite.

Chapter 3 explains the sub-systems of a satellite. The antenna sub-system; transponder sub-system; attitude- and orbit-control sub-system; telemetry, tracking, and command sub-system; power sub-system; thermal sub-system; and the
satellite structure are described in detail. Also covered in this chapter are the reliability and quality assurance aspects of the spacecraft.

Chapter 4 describes all the sub-systems that go in an earth station. These include the antennas, antenna tracking system, high-power and low-noise amplifiers, up/down converters, IF equipment, and baseband equipment. Additionally, this chapter deals with the reliability issues, performance measures used in earth stations, and the master control facility.

Chapter 5 explains the propagation effects on the signals on the satellite links. It also covers the mitigation techniques employed to overcome the propagation effects.

Chapter 6 covers the most important topic of link design. Calculation of signal power in both up and down links, losses encountered by the signal, and the noise introduced at the receiver are discussed. This chapter enables the student to design the total link and provides examples of the same.

Chapter 7 describes the source coding techniques for speech, audio, and video signals carried over satellite channels. Different multiplexing techniques used with analog and digital signals and transcoding technique are discussed.

Chapter 8 covers the analog and digital modulation techniques used on satellite channels and the error control techniques employed for improving the performance.

Chapter 9 describes various multiple access techniques employed on satellite channels for sharing the resources of the satellite. These include frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), random access and demand assignment techniques.

Chapter 10 discusses some special techniques that are relevant on satellite channels. These include the echo control, speech interpolation, and encryption techniques.

Chapter 11 covers the VSAT system in depth, including the advantages, frequency bands used, network configuration, system elements, and access protocols.

Chapter 12 describes the satellite-based broadcast services offered for audio and video. Some recent standards used for different broadcast applications are described.

Chapter 13 explains the mobile satellite communication systems with emphasis on Inmarsat systems. The space segment and ground segment are described and the earth station standards employed in Inmarsat system are discussed. Some mobile satellite systems currently in use with non-geo satellites are described.

Chapter 14 covers the satellite navigation systems used over the world, and explains the GPS system, its principles of operation, the GPS receiver, the GPS message format, and applications.
Chapter 15 covers some recent applications of satellite systems including the disaster alert, search and rescue, telemedicine, distance education, and meteorological data collection.

Chapter 16 deals with some futuristic developments in the size of satellite, aircraft based launching, in-orbit refueling, deep space communication, use of higher bands and SDR technology.

Appendix A describes the tests carried out on the satellite and test instruments employed. High reliability of satellite system is ensured through rigorous testing of components, sub-assemblies, and the integrated units. This appendix familiarizes the students and professionals to the test philosophy adopted in the development of satellite systems.

Appendix B explains the performance measures of earth station systems. The parameters measured, the test procedures followed, and the test equipment used are described.

Appendix C summarizes the Inmarsat terminal standards and the applications.

Appendix D provides some case studies for satellite communication employed in the Indian satellites and spacecrafts. The communication system of GSAT-16 geostationary satellite, the planetary mission Chandrayaan-1, and the interplanetary mission Mars Orbiter Mission (MOM) are described.

Appendix E provides MATLAB codes with examples for the various computations discussed in the book.

Appendix F contains answers to MCQs.

Appendix G is glossary of important terms.

Online Resources
The following resources are available to support the faculty and students using this text:

For Faculty
- Solutions Manual
- Chapter-wise PowerPoint Slides

For Students
- Test Generator (Additional MCQs)
- Answers to Review Questions
Acknowledgements

This book is the result of my over thirty years of R&D experience in the Indian Space Research Organization (ISRO) and several Aerospace companies in Canada, notably the EMS Technologies, Inc., in Montreal. Through this book, I wish to share my experience with students and professionals in the satellite industry. Many people have contributed directly and indirectly to the preparation of this work, whose help I duly acknowledge. I am grateful to my colleague Ms Hansa Shigrakhia for designing the MATLAB codes. I thank all the reviewers whose constructive suggestions have helped in improving the content of the topics covered in this text.

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R.N. Mutagi
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CHAPTER FOUR

Earth Station Technology

Learning Objectives

After reading this chapter, you will be able to:

• Explain the elements of an earth station
• Describe different types of earth stations and their applications
• Differentiate between various types of antennas used in earth stations and their characteristics
• Explain the tracking requirements of the antenna and their implementation
• Describe the types of high-power amplifiers and low-noise amplifiers
• Explain how the earth station interfaces with terrestrial systems
• Describe the signal processing carried out at the earth station on the transmit and receive sides
4.1 INTRODUCTION

An earth station is a gateway to the terrestrial links; it is the link that connects the satellite to the users. All the signals from different sources that are to be transmitted to a satellite are brought to an earth station through terrestrial communication channels and processed there. Similarly, the signals received from a satellite are processed at the earth station before they are sent on terrestrial links to the users. An earth station may not be confined to ground. An aircraft can carry an earth station for aeronautical satellite communication. Similarly, a ship may carry an earth station for maritime communication. To distinguish various types of earth stations, those on the land are termed ground earth stations (GES), those on the aircraft are called aircraft earth stations (AES), and the ones carried on ship are known as ship earth stations (SES). However, for our discussion, we treat them simply as earth stations. An earth station comprises many sub-systems for processing the signals on either way; from satellite to ground or from ground to satellite. An earth station may be large or small, fixed, transportable, or mobile. Most of the communication sub-systems remain the same irrespective of the size or type of the earth station. This chapter describes different types of earth stations and sub-systems of an earth station.

4.2 ELEMENTS OF AN EARTH STATION

An earth station is used to transmit signals from a terrestrial source to a satellite and sends the signals received from a satellite to the terrestrial systems. Hence, the earth station has a transmitter and a receiver. As the communication to the satellite is through the radio media, an antenna is also a part of the station. On the terrestrial side, the earth station receives signals from various terrestrial systems and also sends signals that are received from the satellite back to the terrestrial systems. These signals include telephonic speech, audio, video, and television signals, and computer data. An earth station has proper interface equipment to deal with these systems. Figure 4.1 shows a simplified block diagram of a typical earth station. The signals received from a terrestrial system are formatted and modulated with an intermediate frequency (IF) in the baseband system, and the IF signal is sent to the transmit system where it is up-converted and amplified with a high-power amplifier. The high-power signal is sent to the antenna for transmission to the satellite. Similarly, the low-power signal received from the satellite is amplified with a low-noise amplifier, down-converted to an IF, and sent to the baseband system. Here, the IF signal is demodulated and the baseband signal is sent to the terrestrial interface unit. Besides the main communication sub-systems discussed, an earth station also has a power system to provide uninterrupted power to all the systems, a monitoring system to check the health of the communication system, and a control system to switch the main communication system to a redundant system in case of any problem in any of the sub-systems. In this way, uninterrupted service is provided to the users of the satellite link. Another function carried out by the control system is to rotate the antenna to
track the satellite so that the antenna beam is aligned with the satellite, thus maximizing the power transmitted to the satellite and that received from the satellite.

### 4.3 TYPES OF EARTH STATIONS

Earth stations may be classified into three groups based on the size of the antenna: large, medium, and small. The size of the antenna also has a direct bearing on the traffic-handling capacity (number of telephone channels or TV channels) of the earth station.

A large earth station is usually more complex catering to a variety of applications and has more sub-systems than a small earth station that is designed for a specific application. It has a fixed structure to support the large antenna and has a control room housing the equipment. The antenna itself is fully steerable in azimuth and elevation. The steering of the antenna is carried out with a servo system to automatically track a satellite. The location of the earth station is also carefully chosen to minimize the interference by ensuring that there are no ground systems radiating in the frequency bands used by the earth station. An ideal location would be the one in a valley surrounded by hills with altitudes not obstructing the path above the minimum elevation angle. Large earth stations are designed to carry high volume of domestic and international telephone traffic and television signals for broadcast or for program distribution to terrestrial broadcast stations. They may cater to many other special services such as disaster warning, data collection, and search and rescue. Hence, a large earth station comprises one or more transmit and receive chains depending on how many carriers are transmitted/received by it.

Medium-sized earth stations are used in fixed locations and also mounted on trucks, which can be transported for establishing temporary communication links with a satellite. For example, an earth station may be established to provide nationwide coverage of an important sport event.

A small earth station may have a small antenna and a single transmit and receive chain. Small earth stations are used by corporate offices to establish
their private VSAT networks; individuals to receive television receive-only (TVRO) channels and other services like digital broadcasting directly from satellite or to set up communication facility at short notice at inaccessible areas. As an example, a small earth station can be airlifted and taken to a disaster location, and installed quickly to provide communication for relief operations and gather news for news channels and papers. Table 4.1 lists the key features of different types of earth stations.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Large</th>
<th>Medium</th>
<th>Small</th>
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<tbody>
<tr>
<td>Antenna size (diameter)</td>
<td>15 m and above</td>
<td>5–15 m</td>
<td>Up to 5 m</td>
</tr>
<tr>
<td>Antenna tracking</td>
<td>Fully steerable, servo control</td>
<td>Limited steerability, step track control</td>
<td>Fixed, manual steering</td>
</tr>
<tr>
<td>Feed</td>
<td>Horn, sub-reflector</td>
<td>Sum mode</td>
<td>Prime focal</td>
</tr>
<tr>
<td>HPA</td>
<td>Klystron</td>
<td>TWT A</td>
<td>SSP A</td>
</tr>
<tr>
<td>Power</td>
<td>3 kW</td>
<td>100–400 W</td>
<td>1–10 W</td>
</tr>
<tr>
<td>LNA noise temperature</td>
<td>30 K</td>
<td>45 K</td>
<td>65 K</td>
</tr>
<tr>
<td>Redundancy</td>
<td>Full</td>
<td>HPA, LNA</td>
<td>No</td>
</tr>
<tr>
<td>Power system</td>
<td>No break</td>
<td>Standby redundancy</td>
<td>Battery, solar</td>
</tr>
<tr>
<td>Application</td>
<td>Fixed</td>
<td>Fixed, transportable</td>
<td>Transportable, emergency, VSAT</td>
</tr>
</tbody>
</table>

4.4 EARTH STATION TRANSMITTER

The transmitter section of a large earth station receives the user signals through terrestrial links, and after processing, transmits them to the satellite. Figure 4.2 shows the transmit side of a large-/medium-size earth station transmitting more than one carrier. It comprises several terrestrial interface modules (TIMs), modulators, equalizers, up-converters, frequency synthesizers, and power amplifiers. Additionally, the transmitter also has a standard frequency source, several IF modulators, waveguide switches, power combiner, and harmonic rejection filter.

The TIMs receive the user signals to be uplinked. These signals are received on terrestrial links from telephone exchanges, television studios, etc. These signals are amplified, filtered and if necessary, converted to digital format for digital transmission. The TIM may include equipments such as the multiplexers, circuit multipliers, and digital speech interpolation equipment. More on this digital equipment will be discussed in Chapters 7 and 10.

The type of modulator depends on the signal being transmitted on the carrier. Wideband FM modulators are used for modulating frequency division multiplexed (FDM) analog voice channels and analog television channels. Narrowband FM modulators are used for transmitting single channel per carrier (SCPC) analog voice. Phase shift keying (PSK) modulators are used for digital data such
Earth Station Technology

Fig. 4.2: Earth station transmit chain.

(TIM: Terrestrial Interface Module; Mod: Modulator; EQ: Equalizer; U/C: Up Converter; HPA: High Power Amplifier; FS: Frequency Synthesizer; WG: Waveguide).

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as time-division multiplexed pulse-code modulated (PCM-TDM) voice channels or digital television (DTV) signals. PSK modulators are also used with single digital voice channel per carrier.

Modulated signals go through an IF patch panel comprising switching arrangement for selection of carrier to be uplinked. In earlier days, the selection was carried out manually through cabling on the patch panel, where all the input/output connectors were placed. Modern earth stations have remote-controlled switches to carry out the selection, and an operator can switch the signal paths from a console.

Equalizers are placed on each path to compensate for spectral distortion and the group delay distortion in the IF path. An equalized signal is then up-converted to appropriate radio frequency (RF) by mixing with a frequency provided by a frequency synthesizer. A standard frequency source with high stability and accuracy provides the reference frequency for all carriers.

Output of each up-converter is applied to a high power amplifier (HPA). The power level in a large earth station can be in kilowatts due to the large bandwidth. The large and medium earth stations are provided with redundant stand-by HPA. A hot standby is provided to the power amplifier, where a second amplifier is kept in powered mode with its output terminated into a dummy load. When the stand-by mode is switched to normal mode, the output is connected to the antenna through a waveguide switch. The input to the power amplifier is also fed through a waveguide switch which acts as 2:1 multiplexers, allowing either the RF signal from the up-converter or an external signal applied from another source, such as a test signal generator. The power coupler at the input of the HPA allows monitoring of the input signal driving the HPA. The HPA is generally a cascade of a travelling wave tube amplifier (TWTA) driving a klystron amplifier. The TWTA is operated in linear mode, whereas the klystron is saturated to provide maximum output, up to 3 kW. The output power of the HPA is also monitored through a waveguide coupler with a typical coupling ratio of 56 dB. This output of the coupler at a low level can also be used for loop-back testing of transmit–receive chains of the earth station. The output of couplers is applied to waveguide switches to enable the selection of the carriers to be uplinked. Selection of the main or redundant transmit chains is also carried out through these switches. The selected outputs are combined in a high-power combiner, the output of which is applied to a harmonic rejection filter. This filter attenuates the harmonics generated due to the non-linear gain characteristics of the HPA. The final output is applied to the antenna feed through a test coupler and an azimuth rotary joint waveguide. The rotary joint permits the signal transmission to the feed when the antenna is rotated in azimuth.

### 4.5 EARTH STATION RECEIVER

The earth station receive chain is the reverse of the transmit chain. The signal on the downlink is received by the antenna and is passed through a noise rejection filter. The filtered signal is amplified by a wideband low-noise amplifier (LNA).
Fig. 4.3 Earth Station receive chain

(TIM: Terrestrial Interface Module; Mod: Modulator; EQ: Equalizer; U/C: Up Converter; HPA: High Power Amplifier; FS: Frequency Synthesizer; WG: Waveguide).

User signals

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This signal is divided into several channels and down-converted and separated into different frequency bands with the bandpass filters. The signals in different bands are sent to different demodulators. These demodulators depend on the type of the signals. The typical channels may include single channel per carrier (SCPC), frequency modulated TV (FM TV), frequency division multiplexed/ frequency modulated (FDM/FM), PCM/TDM/PSK, and multiple channel per carrier/motion pictures expert group (MCPC/MPEG) TV channels.

Figure 4.3 shows a typical major earth station receive system. The functional blocks of the earth station are described in the following sections.

4.6 ANTENNA AND FEED SYSTEMS

The antenna is a key element in the earth station and it decides the performance of the earth station. On the transmit side, the antenna determines the effective isotropic radiated power (EIRP) of the earth station and on the receive side, the figure of merit, gain-to-noise temperature ratio (G/T). The function of the antenna is to convert the electrical signal to electromagnetic waves and radiate them into space on the transmit side and intercept the electromagnetic radiation, and convert it to electrical signal on the receive side. There are several types of antenna configurations achieving this goal, and the most common ones are as follows:

- Prime focus aperture antenna
- Cassegrain antenna
- Dual-reflector antenna
- Multiple beam antenna

4.6.1 Prime Focus Antenna

Aperture antenna is invariably used in satellite communication both at the earth station and on the satellite. The radiated power along the main axis of the antenna, the boresight, and the power received by the antenna vary directly with the size
of the aperture. The antenna is basically a section of the parabola with a feed placed at the focal point. Such an antenna is termed as prime focus single-reflector antenna. Figure 4.4 shows a prime focus single-reflector antenna with the feed horn in the focal point. The energy radiated from the horn on the circular aperture is reflected as a parallel beam. Similarly, a parallel beam received by the circular aperture is focused on the feed horn at the focal point due to its parabolic curvature. The major problem with the prime focus antenna is the blockage of the aperture by the feed horn at the focus. This may not be a serious consequence with large antenna, where the size of the feed is a small fraction of the reflector size. However, with a small antenna, the size of the feed horn is relatively significant. Blocking of the aperture, therefore, reduces the illumination of the reflector by the received waves, thus reducing the received power. To overcome this problem, often the feed is offset from the beam axis of the main reflector. Such an antenna is known as offset antenna.

4.6.2 Cassegrain Antenna

An antenna with dual reflectors is often used to get certain advantages over single reflector antenna. Here, the main reflector is the paraboloid, and the secondary reflector is a small hyperboloid placed in such a way that the focal point of the main reflector and the virtual focal point of the secondary reflector coincide. When the sub-reflector is convex towards the main reflector, the antenna is known as Cassegrain antenna. If, on the other hand, the sub-reflector is concave towards the main reflector, the antenna is termed as Gregorian antenna. Figure 4.5 shows a Cassegrain antenna with a convex sub-reflector.

The Cassegrain antenna has a better mechanical stability, because the feed is now at the vertex of the main reflector. As a result, this antenna also has better pointing accuracy compared to the single reflector antenna, where the feed is suspended at the focus. In a single-reflector antenna, the energy from the feed
spills over the reflector towards the ground. Conversely, the feed also collects more noise from the ground due to spillover from the reflector. In Cassegrain antenna, the spillover of the feed from the sub-reflector is towards the sky. Consequently, the noise temperature of this antenna is low. Due to the relaxed pointing accuracy requirements on the feed, the feed design is simpler.

### 4.6.3 Offset Antenna

In prime focus antenna, the feed horn and its supporting struts block the waves reaching the main reflector. Similarly, in the dual-reflector Cassegrain antenna, the sub-reflector and its supporting struts block the waves. The blockage reduces the efficiency and the gain of the antenna. The blockage is more in Cassegrain antenna than in prime focus antenna. To overcome this problem, offset fed antennas are used, particularly, when the size is small as in TV receive only (TVRO) or direct-to-home (DTH) systems. In offset fed antenna, the feed horn is placed not on the main axis of the reflector but below it as shown in Figure 4.6(a). The reflector is a section of a paraboloid. The sub-reflector in the offset Cassegrain antenna is similarly placed below the main axis of the primary reflector as shown in Figure 4.6(b). The feed horn is part of the main reflector, as a result of which the effective size of the main reflector is slightly reduced.

![Fig. 4.6](image)

**Fig. 4.6** (a) Offset feed horn antenna with single reflector, and (b) Offset sub reflector antenna

### 4.6.4 Multiple-beam Antenna

When an earth station has to receive signals from multiple satellites, it is economical to use a multiple-beam antenna instead of using a separate antenna for each satellite. It results in significant reduction in cost and space. A typical application is in the reception of DBS signals from several satellites by a cable TV provider. Multiple beams are generated by placing multiple feed horns in the focal plane of the antenna. Each feed horn is directed to the reflector with different offset angles. The reflector then has beams in different directions.
4.7 ANTENNA TRACKING

With high-gain antennas, the beam width is small and it becomes necessary to track the satellite to minimize the pointing error. Geostationary satellites move within a window of ±3°. Hence, if the earth station beam is smaller than this, it is imperative to track the satellite. Also, a low-orbit satellite remains visible to the earth station for a short duration due to its motion. The earth station must acquire the satellite as it comes in the visible range and continuously tracks it until it moves out of the visible range. Large and medium earth stations have tracking systems for this purpose. The tracking system acquires the satellites and continuously tracks it using either open-loop or closed-loop tracking. The tracking is sometimes carried out manually using manual commands to steer the antenna in azimuth and elevation. Figure 4.7 shows the functional block diagram of an antenna-tracking system.

![Fig. 4.7 Antenna control system](image)

4.7.1 Types of Tracking Systems

Tracking systems can basically be grouped into three types as follows:

- Manual tracking
- Program tracking
- Autotracking

In the manual tracking system, the operator controls the movement of the antenna to align the major axis towards the satellite. This is done by manually feeding the values of the elevation and azimuth to the antenna control unit through the console. The control unit drives the motors through the servo amplifier to move the antenna in the desired direction. The actual position of the antenna is obtained through the shaft encoders, and the difference signal drives the antenna until the error is zero.

The program tracking is an open-loop system of control. The predicted path of the satellite with time tag is available from the satellite operators.
example, satellite local-position predictions are provided by Intelsat for its satel-
lites routinely as ephemeris data files. These files are loaded into the earth station
computer, which then controls the antenna to track the satellite. These files are
updated on weekly basis. The accuracy of the program tracking depends on the
accuracy of the ephemeris data and the alignment accuracy of the electrical and
mechanical axes of the antenna.

The most widely used tracking is the auto-tracking described in the following
section.

4.7.2 Autotracking
Autotracking is a closed-loop system and is carried out with the aid of the
beacon signal transmitted by the satellite. An earth station receives the beacon
signal with two antenna patterns that are symmetrically offset around the main
axis of the antenna. If the main axis, or the boresight, of the antenna coincides
with the satellite direction, then the beacon signals received by the two offset
patterns are equal. If the main axis has an angle with the satellite direction,
then the two patterns provide unequal signals for the beacon, and the differ-
ence between them indicates an angular error and also the sense of the error,
i.e., whether the antenna axis is above the satellite direction or below it. There
are two types of auto tracking: sequential lobing and simultaneous lobing.

Sequential Lobing In this method, the tracking error is obtained by comparing
the beacon signal received sequentially by two antenna patterns. There are sev-
eral methods of sequential lobing as follows:

- Beam switching
- Conical scanning
- Step tracking
- Electronic beam squinting
- Smoothed step tracking

Beam switching In this tracking technique, the antenna generates two patterns
symmetrically above and below the boresight. When the boresight is aligned to
the satellite direction, the received voltage from each pattern is equal and is the
same, as shown by the intersection point of the two radiation patterns and the
boresight. If the boresight has an angle with the satellite direction, as shown in
Fig 4.8, the received voltages by the two patterns are different. As the satellite
direction is above the boresight, the voltage $V_1$ received by Pattern 1 is larger
than the voltage $V_2$ received by Pattern 2 and their difference, $V_1 - V_2$, is positive.
If the satellite direction is below the boresight, then the situation is reversed; the
voltage $V_1$ will be smaller than the voltage $V_2$, and their difference, $V_1 - V_2$, will be
negative. The magnitude of the difference is proportional to the offset angle of
the antenna axis with the satellite direction.

Two beams in the same plane are switched to the tracking receiver alternately
to measure the voltages and to find the error voltage. Two orthogonal pairs of
beams are needed to get the error in azimuth and elevation.
**Fig. 4.8** Finding tracking error through beam switching

**Conical scanning** If the antenna is rotated around its axis with a small squint angle, the received beacon signal will be modulated in amplitude and phase. When the axis is aligned with the satellite axis, the modulation is zero. The conical scanning technique utilizes this principle in autotracking of satellite. The antenna beam is rotated by actually rotating the antenna in small antennas and rotating either the feed or the sub-reflector in case of large antennas (Skolnik, 2007). Figure 4.9 shows the conical beam scanning.

**Fig. 4.9** Conical beam scanning

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The full signal is received by the main antenna beam in conically scanned auto-tracking system. Hence, it is not necessary for the auto-tracking receiver to have high sensitivity. However, due to the mechanical rotation of the antenna or the sub-reflector, the tracking is slow. Also, amplitude modulation is introduced on the received signal until the tracking is in progress.

**Step tracking** In this method, the antenna is moved in small steps, alternately in azimuth and elevation, homing towards the satellite axis from an arbitrary axis. The signal strengths between successive positions of the antenna are compared after each step, and the difference gives the error voltage. The direction of motion is retained if the polarity of error is negative, that is, signal is stronger after movement than before. If the signal strength after the movement is lesser than the one measured before the movement, then error polarity is positive and the direction of motion is reversed in the next step.

The step track system comprises signal strength detector formed by the LNA, down converter, and the envelope detector, as shown in Figure 4.10. The decision circuit makes logical decision according to whether the signal strength for the current step was more or less compared to the previous step. A proper control signal is then generated to drive the appropriate azimuth or elevation stepper motor by one step in forward or reverse direction. As the control voltage is the function of the signal strength, any variation in the received signal strength due to the channel noise can mislead the decision circuit. Hence, for the proper operation of the step track system, the signal-to-noise ratio should be high.

![Fig. 4.10 Step-track antenna control system](image-url)

**Electronic beam squinting** Electronic beam squinting method of antenna tracking is being employed by large earth stations in recent times. In this method, multiple antenna squinted beams are generated by launching higher order modes of transmission in the waveguide. Higher order mode generators are coupled to the primary feed and are electronically switched to produce serial deviation in the secondary beam. Secondary beam is scanned in a pre-determined sequence without moving the antenna. Switching speed is kept high, up to 350 Hz.
Figure 4.11 shows the radiation patterns generated from beam squinting with a parabolic reflector in rectangular coordinates. Two beams, 1 and 2, are having a squint angle $\alpha$ from the boresight of the antenna. The boresight is deflected from the satellite axis by an angle $\theta$. The signal strengths of the beacon received from satellite by the two beams are shown as $G_1$ and $G_2$, respectively. For a parabolic reflector, the signal loss at an angle $\theta$ away from the boresight is given by (Hawkins, 1990): \[
G_i = 12 \left( \frac{\theta}{\theta_{3dB}} \right)^2 \]
where $\theta_{3dB}$ is the half-power beam width of the antenna. The half-power beam width is approximately given by the following equation: \[
\theta_{3dB} \approx \frac{75\lambda}{D} \text{ degrees} \]
where $\lambda$ is the wavelength of the signal and $D$ is the diameter of the antenna.

The gain loss at an angle $\alpha$ from the boresight is, therefore, given by \[
G_1 = 12 \left( \frac{\theta - \alpha}{\theta_{3dB}} \right)^2 \] \[
G_2 = 12 \left( \frac{\theta + \alpha}{\theta_{3dB}} \right)^2 \]

The differential gain is obtained by subtracting Eqn (4.3) from Eqn (4.4) as \[
\Delta G = G_2 - G_1 = 12 \frac{\theta_{3dB}}{\theta_{3dB}} \left[ (\theta + \alpha)^2 - (\theta - \alpha)^2 \right] \]
Rearranging Eqn (4.5) for the deflection angle $\theta$, we get

$$\theta = \frac{\Delta G \theta_{3\text{dB}}}{48\alpha} \quad (4.6)$$

From Eqn (4.6), we see that the error angle $\theta$ is proportional to the differential signal, the 3-dB beam width and the squint angle $\alpha$ being constants. Hence, the measurement of $\Delta G$ provides a means of tracking the satellite by minimizing $\theta$ in a closed loop.

As the beam switching is done electronically, this system is fast. Also, as the squint beam is receiving only the beacon signal and the main signal is received by the fixed reflector, there is no amplitude modulation of the received signal due to beam switching.

**Example 4.1**

A Standard A Earth station has the antenna diameter of 13 m. It is pointing to a geostationary communication satellite and uses electronic beam squinting method to align the antenna. The squint angle is 0.5°. The satellite transmits a beacon signal at 11 GHz. Find the error angle if the measured gain losses are 26.87 and 32.89 dB?

**Solution**

First, we find the 3 dB beam width of the receiving antenna.

$$\theta_{3\text{dB}} \approx \frac{75\lambda}{D} \text{ degrees} = \left(75 \times 3 \times 10^8\right)/\left(11 \times 10^9 \times 13\right) = 0.157^\circ$$

We have $G_1 = 26.87$, dB = 486.35, and $G_2 = 32.89$ dB = 1947.3

Hence, $\Delta G = 1947.3 - 486.35 = 1461$

Using Eqn (4.6), we get the error angle as

$$\theta = \frac{\Delta G \theta_{3\text{dB}}^2}{48\alpha} = \frac{1461 \times (0.157)^2}{48 \times 0.5} = 1.5^\circ$$

**Smoothed step tracking**  By combining the prediction data along with the closed-loop step tracking, a smoothed step tracking is achieved. For geostationary satellites, the orbital positions are predicted with high accuracy, and hence, a prediction model is easily generated. The satellite position is computed with microcomputer, optimally combining the estimate of the antenna position obtained from an accurate gradient tracking algorithm and the prediction data obtained from an adaptive satellite position model. The tracking algorithm can either switch between the two schemes as needed or optimally combine them. Thus, when there are large signal fluctuations, the antenna is updated with the
prediction data. The step tracking algorithm is used less frequently, minimizing the mechanical wear and tear in this tracking system.

**Simultaneous Lobing**  Simultaneous lobing, also called monopulse tracking, is a method employing multiple antenna beams to receive the signals simultaneously and continuously comparing them to derive error signals. There are different versions of monopulse techniques: amplitude comparison, phase comparison, and amplitude and phase comparison types. In the amplitude comparison type of monopulse tracking described here, the RF signals received from the two orthogonal sets of offset antenna beams are combined to simultaneously obtain the sum and difference signals.

![Diagram](image)

**Fig. 4.12** Arrangement to obtain sum and difference signals from the horns

Figure 4.12 shows the arrangement to obtain the sum and difference signals for azimuth and elevation. The beam horns are arranged as A, B, C, and D as shown on the left. The sum of the RF signal from all four beams gives the sum signal, which acts as reference signal in the receiver operation. The difference of the signals from A, B and C, D gives the error signal in the elevation. The difference of signals from A, C and B, D gives the error in azimuth. These signals are used by the receiver in Figure 4.13 to derive the driving signals for the motors controlling the direction of the antenna in azimuth and elevation.

The sum and the two orthogonal error signals are amplified and down-converted to an IF. They are amplified with automatic gain-controlled (AGC) IF amplifiers. The sum signal output level is detected and used to control the gain of all the three IF amplifiers. The AGC removes the effects of the propagation medium on the signal-level variation. The sum signal also provides a reference to the phase detectors
providing the angle-tracking error voltages from the difference signals in azimuth and elevation. Phase detector using the sum (Σ) and the elevation difference signal (ELΔ) as input provides an output proportional to the angular error in the elevation. Similarly, the phase detector using the sum (Σ) and the azimuth difference signal (AZΔ) as inputs provides an output proportional to the angular error in the azimuth. The product of these two signals provides the magnitude and direction of the angular error signal as shown in the block diagram of Fig. 4.13.

4.8 HIGH-POWER AMPLIFIERS

The EIRP requirement of earth station is higher than that of satellite to ensure that the uplink does not limit the overall C/N at the receiver, which is the combination of uplink C/N and downlink C/N. HPAs are used along with large high-gain antenna at the earth station to obtain the desired EIRP. The power requirements depend upon the size of the earth station. A large earth station with high amount of data, such as trunk telephone channels or television channels, needs to transmit power in the order of several kilowatts to the satellite. Small earth stations, such as the VSATs, typically handle small amount of data, catering to one voice channel, and transmit a few watts of power to the satellite. The power amplifiers used in the earth stations correspondingly are different. Typical power amplifiers employed in the earth station belong to the following classes:

- Travelling wave tube amplifier (TWTA)
- Klystron tube amplifier
- Solid-state power amplifier (SSPA)
- Cross-field electron tube amplifier
4.8.1 Travelling Wave Tube Amplifier
TWTA is the most widely used power amplifier as it delivers very high power, in the order of kW. Additionally, it has a wide bandwidth, typically 10% of the carrier. Hence, at 6 GHz uplink frequency, it can have well over 500 MHz bandwidth. The TWTA works on the principle of velocity modulation. Figure 4.14 shows the construction of a TWTA.

![Fig. 4.14 Travelling wave tube amplifier](image)

The TWTA comprises a tube with a cathode placed on one side and an anode on the other side. A helix is placed along the tube through which the electrons emitted from the cathode travel and are collected by the anode at the other end. The cylindrical magnets placed around the tube focus the electrons into a beam going through the helix. RF signal is applied to the helix end at the cathode and taken out from the end of the helix at the anode end. As the RF signal travels along the helix, the electron beam imparts energy to the RF field, and hence, to the RF signal. The propagation velocity of the RF signal is slowed down by the helix to match the velocity of the electron beam. The electron beam generated by the cathode is controlled by the DC voltage of the cathode. The energy of the electron beam is transferred to the RF signal amplifying it as it travels along the helix.

4.8.2 Klystron Tube Amplifier
Klystron tube amplifier has higher efficiency and gain. However, the bandwidth is small, typically 2% of the signal frequency, which does not cover the entire band but may be used in C-band transponder with 36 MHz bandwidth or a Ku-band transponder with 72 MHz bandwidth. A klystron tube has a cathode and an anode at the two ends inside a glass tube, as shown in Figure 4.15, the cathode acting as an electron gun producing an electron beam when the heater heats it. The beam is captured by the anode. It has two cavities called buncher cavity and catcher cavity. A pair of electrodes near the cathode and a magnet around the tube keeps the electron beam focused and at the centre of the tube. When an RF signal is applied to the buncher cavity, during the negative half-cycle, negative charges will develop around the buncher cavity and reduce the speed.
of the electron beam, resulting in velocity modulation. This causes the electron concentration forming a bunch resulting in density modulation of the beam. This bunch moves towards the anode. During the positive half-cycle of the RF signal, the electrons speed up and join the previous bunch, increasing the field strength of the field of the bunch. When the bunch is near the catcher cavity, the strong field strength excites the cavity and an amplified output will be obtained from the catcher cavity. Typical power outputs are 3 kW at C-band and 2 kW at Ku band (Nelson, 1998).

### 4.8.3 Solid-state Power Amplifier

Solid-state power amplifiers made their entry in the late seventies and featured low-power capability. However, over the decades, much advancement has taken place in the solid-state technology, and currently, SSPA modules producing several kilowatts of output power are available (Turner, 2012). SSPA has higher reliability than TWTA, which is the major advantage in satellite communications (Turner).

Gallium Arsenide Field-Effect Transistors (GaAs FETs) are used in SSPAs. However, due to lower thermal conductivity and lower breakdown voltage, the output power generated is limited to several tens of watts. At C-band, the GaAs SSPA may provide 30–45 W and at Ku-band only 15 W. Higher power is obtained by connecting several amplifiers in parallel and combining their outputs. SSPAs are commercially available with rated powers up to about 500 W at C-band or 100 W at Ku-band using the paralleling technique. Figure 4.16 shows how high power is generated by combining the power output from multiple...
low-power amplifiers. Here, the input power is applied to two SSPAs through a power divider. The output of each amplifier is divided into two branches through power dividers, and the signal in each branch is applied to an SSPA. The outputs of two SSPAs are combined through a power combiner. The outputs of two combiners again combined through another power combiner to obtain the final output.

The advent of Gallium Nitride high electron mobility transistors (GaN HEMT) for use in SSPA has brought in tremendous advantage of SSPA over the TWTA. GaN SSPA outperforms SSPA employing GaAs devices. Currently, GaN SSPAs are available in all the bands like L, S, C, X, and Ku bands (Damian, 2012). GaN technology features very high breakdown voltage (in excess of 100 V), high electron mobility, and saturation velocity. GaN HEMT devices have high power efficiency (up to 48% at C-band), can operate at higher voltage (50 VDC compared to 10 V DC for GaAs), and have higher reliability due to higher breakdown voltage (mean time before failure (MTBF) exceeding millions of hours). Using multiple GaN amplifiers in parallel, very high power is generated as shown in Figure 4.16. GaN SSPAs are poised to replace the TWTA completely.

### 4.8.4 Cross-field Electron Tube Amplifier

In TWTA and klystron amplifiers, the DC magnetic field in parallel with the DC electrical field is used for focussing the electron beam. In cross-field electron tube amplifier (CFA), however, the magnetic and electric fields are perpendicular to each other. The CFAs are available in two types: forward wave cross-field tube amplifier and backward wave cross-field amplifier. The CFAs have low or moderate gain, moderate bandwidth, high efficiency, small size, and low weight, and hence, are used in space applications.
4.9 LOW-NOISE AMPLIFIER

Low-noise amplifier is the most important element on the receive side of the earth station. Its noise temperature decides the overall performance of the receiver. The desirable characteristics for an LNA are its gain and noise temperature. In fact, to achieve a certain performance of the downlink, the noise figure of the LNA can be traded with the size of the antenna. By choosing an amplifier with lower noise figure or noise temperature, the size of the antenna can be reduced. Although the cost of the amplifier increases with decreasing noise figure, it is more than offset by the reduction in the antenna size.

Several amplifier technologies are used for the LNA. GaAs FET amplifier, parametric amplifier, and cooled parametric amplifier are the examples of an LNA.

4.9.1 GaAs Field-Effect Transistor

At frequencies of several GHz, the GaAs exhibits superior performance than silicon, because the electron drift mobility in GaAs is several times higher than in silicon. GaAs FET is also known as metal semiconductor FET (MESFET). Figure 4.17(a) shows the cross section of the GaAs FET structure.

![GaAs FET structure](image)

**Fig. 4.17** (a) GaAs FET structure

The structure consists of a semi-insulating GaAs substrate, a buffer layer, and the n-type layer, which has a doping density of $8 \times 10^{16}$ to $2 \times 10^{17}$/cm$^3$ with an electron mobility of 3,000–4,500 cm$^2$/V s. The depletion region formed in the n-layer is modulated by the reverse bias between the gate and source, and the
forward bias between the gate and drain accelerates the electrons. As the reverse bias increases, the depletion region increases, decreasing the channel-opening height and reducing the drain current. The gate voltage, thus, modulates the drain current. A typical drain-source voltage ($V_{ds}$) and current ($I_{ds}$) is shown in Fig. 4.17(b).

**4.9.2 Parametric Amplifier**

Generally in an amplifier, the power supply voltage is converted into amplified output voltage. In a parametric amplifier, a high-frequency source, called the pump, provides the amplified output. In the parametric amplifier, two resonant circuits are coupled through a varactor diode. One resonant circuit is tuned to input frequency $\omega_1$ and the second to the output frequency $\omega_2$, called the idler frequency. The sum frequency of input and output is applied to the varactor, which is known as the pump frequency $\omega_p$. Thus,

$$\omega_p = \omega_1 + \omega_2$$  \hspace{1cm} (4.7)
Figure 4.18 shows the equivalent circuit of the parametric amplifier (Ha, 1990). The capacitance of the varactor diode varies non-linearly with the sinusoidal pump frequency. When the input and output frequencies are different, the amplifier is termed non-degenerative type. The input signal is applied to Port 1 of a circulator, which is applied to the resonant circuit resonant to $\omega_1$ through Port 2. The reflected signal on Port 2 is output on Port 3. The equivalent noise temperature of the amplifier is given by

$$T_v = \frac{\omega_1}{\omega_2} T_v$$

(4.8)

where $T_v$ is the noise temperature of the varactor diode. In the degenerative case, where $\omega_1 = \omega_2$, the equivalent noise temperature is equal to that of the varactor diode.

### 4.9.3 High Electron Mobility Transistor

HEMT is similar to an FET with source, drain, and gate but has a junction formed by two different materials that have different band gaps. The layers are typically formed with GaAs and GaAlAs (Gallium Aluminium Arsenide) materials. The hetero-junction formed between these layers provides a low-resistance channel for the electron carriers, thus increasing the electron mobility.

### 4.10 UP CONVERTER

The baseband signal usually modulates a carrier at IF. The IF is generally chosen as 70 MHz for C-band uplink and 140 MHz for higher bands. This is the centre frequency of the uplink spectral band of 36 MHz. An up-converter translates the IF spectrum to an RF frequency of the uplink. When an earth station transmits multiple signals on different carriers, they are placed in the IF band. That is, each
baseband signal modulates a carrier that lies in the 36 MHz band around the centre frequency of 70 MHz as shown in Fig. 4.19(a). The entire IF spectrum is translated to an RF at 6 GHz for uplinking as shown in Fig. 4.19(b).

Here, three modulated carriers at 59, 70, and 82 MHz with the bandwidths of 8, 8, and 10 MHz within the overall transponder bandwidth of 36 MHz are shown. The 36-MHz IF spectrum is raised to the uplink frequency of 6718 MHz with the same bandwidth. This is achieved by mixing the IF signal with a local oscillator (LO) frequency of 6788 MHz in a mixer. The mixer is a non-linear circuit with two inputs and one output. It generates the sum and difference of the two input frequencies and their harmonics. For example, if input frequencies are $f_1$ and $f_2$, then the output contains the frequencies such as $f_1 + f_2$, $2f_1 + f_2$, $f_1 + 2f_2$, . . . An output filter would select the desired component from this set. If $f_1 - f_2$ is the desired signal then $f_1 + f_2$ is the mirror frequency. Figure 4.20 shows a typical up-converter using a single-mixer stage with $f_{IF}$ as the input and $f_{LO}$ as the LO frequency. The LO frequency is obtained with a crystal oscillator followed by a frequency multiplier. The crystal oscillator is usually at a low frequency, as it is not feasible to get crystals at high frequencies in GHz range. The oscillator frequency is multiplied using a chain of harmonic generators, amplifiers, and filters, or a phase-locked loop. The bandpass filter following the mixer has a passband equal to the signal bandwidth and high attenuation outside this band, rejecting the mirror frequency and other undesired components present in the output of the mixer.

**Example 4.2**

An Earth station employs a 70 MHz modulator and the modulated signal occupies the complete transponder bandwidth of 36 MHz. A single up-converter is used to raise the spectrum to an uplink frequency of 6350 MHz. Find
Often, it is difficult to get the desired rejection characteristics from the band-pass filter resulting in adjacent channel interference or presence of unwanted components from the mixer. Double-conversion technique with two-stage mixing is employed to get rid of these problems. Figure 4.21 shows a double conversion up-converter employing two mixer stages. The first mixer up-converts the modulated input signal to an IF, 770 MHz in this case by mixing with a LO frequency of 700 MHz. The sum frequency is selected by the bandpass filter following the first mixer. This signal, after amplification in the IF amplifier, is applied to a second mixer.

**Solution**

An up-converter mixer generates sum and difference frequencies from the LO frequency and the input frequency. Hence, the LO frequency should be lower or higher than the RF output frequency from the mixer by the signal frequency. Therefore, the LO frequency is obtained as

$$f_{LO} = f_{RF} \pm f_{IF}$$

Hence

$$f_{LO} = (6350 + 70) \text{ MHz} = 6420 \text{ MHz or}$$

$$f_{LO} = (6350 - 70) \text{ MHz} = 6280 \text{ MHz}$$

The multiplication factor $n$ required to obtain the LO frequency from a crystal oscillator of 10 MHz is obtained from

$$f_{LO} = n \times 10 \text{ MHz}$$

Hence, the multiplication factor $n = 6420/10 = 642$, or $n = 6280/10 = 628$.
mixer. The mixing frequency is derived from a frequency synthesizer, which can be set to generate any desired frequency. The synthesizer uses a reference oscillator that is crystal controlled. In the example here, the mixing frequency is at 5948 MHz. The sum of these two frequencies, 6718 MHz, is selected by the second bandpass filter and amplified before it is sent to the power amplifier.

By comparing the frequency separation between the desired and mirror frequencies, we can see the advantage of dual conversion. In the single-conversion technique, the desired and image frequencies were separated by 140 MHz around 6 GHz. Realization of bandpass filter is difficult with this requirement. In the dual conversion technique, the frequency at the output of the first mixer is 140 MHz around 700 MHz. The frequency separation at the output of second mixer is 1540 MHz at 6 GHz. In both these cases, the separation is sufficient enough for easy realization of bandpass filters.

4.11 DOWN CONVERTER

The high-frequency signal on the receive side is amplified with a wideband LNA and then down-converted to an IF at which the demodulation takes place. The conversion can be in either a single stage or two stages. Figure 4.22 shows a down-converter with dual-stage mixer.
The input C-band downlink signal at 4 GHz is mixed with a LO frequency of 3 GHz resulting in the difference frequency of 1 GHz. This signal, after bandpass filtering and amplification, is fed to the second mixer which is driven by an oscillator of 930 MHz. The output of the mixer contains 70 MHz difference frequency and 1930 MHz sum frequency. The second bandpass filter extracts the 70 MHz signal, which is amplified and fed to the demodulator.

### 4.12 IF EQUIPMENT

The IF equipment at the earth station comprises modulators and spectral shaping bandpass filters on the transmit side, and noise-restricting bandpass filters and demodulator on the receive side. In analog satellite communication system, FM modulator and demodulator are used. In digital satellite communication system, PSK modulator and demodulator are used. In FDMA system, continuous-type modulator and demodulator (FM or PSK) are employed and burst-type modulators and demodulators in a TDMA system. The output of a modulator is passed through spectral shaping bandpass filter and a group-delay equalizer. The group-delay equalizer compensates the phase non-linearity introduced by the filter. It is an all-pass network with phase characteristics opposite to that of the filter. Figure 4.23 shows a typical IF system in a large earth station.

### 4.13 BASEBAND EQUIPMENT

Baseband equipment consists of TIMs, coders/decoders, and multiplexers/demultiplexers. An earth station interfaces to a terrestrial telephone exchange from where analog and digital voice signals are received for transmission over satellite channel, and received voice signals are sent to the exchange. If the earth station operates with few voice channels in SCPC mode, individual voice signals are received from the users. In case of digital SCPC, the voice signals are coded and modulated by the SCPC channel unit. In case of multichannel system, FDM analog voice channels in the form of super group are received from terrestrial trunk exchanges. The PCM/TDM signals at 2.048 Mb/s are received from terrestrial digital network. Figure 4.24 shows baseband equipment at transmit and receive sides of a typical earth station.

### 4.14 EARTH STATION PERFORMANCE

Earth station performance is measured in terms of how much signal power it can transmit and how much lower power it can receive. The parameter used to specify the transmitted power is the EIRP, which is the product of the actual power generated by the output power amplifier and the gain of the transmit antenna. Thus, if the transmitter power amplifier output is $P_T$ W and the gain of the transmit antenna gain is $G_T$, then
The gain of an aperture antenna, from the antenna theory, in terms of area and wavelength is given by [Kraus]

\[
G = \frac{4\pi A}{\lambda^2}
\]

where \( A \) is the aperture area in \( \text{m}^2 \) and \( \lambda \) is the wavelength of the signal in metres.

\[
\text{EIRP} = P_T \cdot G_T \cdot W \quad (4.9)
\]

The gain of an aperture antenna, from the antenna theory, in terms of area and wavelength is given by [Kraus]

\[
G = \frac{4\pi A}{\lambda^2}
\]

where \( A \) is the aperture area in \( \text{m}^2 \) and \( \lambda \) is the wavelength of the signal in metres.

Fig. 4.23 (a) IF equipment at transmit side (b) IF equipment at receive side
In practice, the power amplifier output is applied to the antenna feed through a waveguide which may have certain loss at the operating frequency. If this loss is \( L_{\text{wg}} \) (\( L_{\text{wg}} < 1 \)), then Eqn (4.9) is modified as
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\[ \text{EIRP} = P_T G_{\text{T}} L_{\text{WG}} \text{ W} \]  

(4.11)

If all parameters are expressed in dB, EIRP is given by

\[ \text{EIRP (dB)} = P_T(\text{dB}) + G_{\text{T}}(\text{dB}) - L_{\text{WG}}(\text{dB}) \text{ dBW} \]  

(4.12)

The receive-side performance of the earth station is measured in terms of the ratio of the antenna gain and the receive-system noise temperature, \( G_R / T_S \). The gain of the receive antenna is a function of its size and the operating temperature. Thus, even when the same antenna is used for transmitting and receiving signals, the gain differs for both as transmit and receive frequencies are different. The system noise temperature is the effective temperature at the input of the first amplifier. This is the sum of the temperature of the antenna, temperature of the first amplifier which usually is low, and the effective temperatures of all the succeeding stages reflected at the input. An expression for the effective system temperature is provided in the next chapter.

**Example 4.3**

An earth station employs a power amplifier providing an output power of 100 W and an antenna of 5 m diameter for both transmission and reception. The transmit frequency is 6.25 GHz and the receive frequency is 4.5 GHz. System noise temperature is 140 K. Find the EIRP and G/T for this station.

**Solution**

The gain of the antenna for transmit and receive frequencies is obtained using Eqn (4.10)

\[ G = \left( \frac{4\pi A}{\lambda^2} \right) \]

The area of the antenna with circular aperture of diameter \( D \) is \( A = \pi D^2/4 \). Hence, the gain is

\[ G = \left( \frac{\pi^2 D^2}{\lambda^2} \right) = \left( \frac{\pi D}{\lambda} \right)^2 = \left( \frac{\pi f}{c} \right)^2 \]

where \( \lambda \) is the wavelength in metres, \( f \) is the frequency in Hz, and \( c \) is the velocity of light. Hence, the transmit side gain is

\[ G_T = \left( \frac{\pi f T}{c} \right)^2 = \left( \frac{\pi \times 5 \times 6.25 \times 10^9}{3 \times 10^8} \right)^2 = 107092 = 50.3 \text{ dB} \]

and, the gain for the received signal is

\[ G_R = \left( \frac{\pi f R}{c} \right)^2 = \left( \frac{\pi \times 5 \times 4.5 \times 10^9}{3 \times 10^8} \right)^2 = 55516.5 = 47.44 \text{ dB} \]
The noise temperature in dBK is \( T = 10\log(140) = 21.46 \text{ dBK} \)
And, the power output in dB is \( PT = 10\log(100) = 20 \text{ dBW} \).
Hence, EIRP = 20 + 50.3 = 70.3 \text{ dBW} and,
\[ G/T = 47.44 - 21.46 = 26 \text{ dB/K} \]

4.15 REDUNDANCY AND RELIABILITY

Reliability was defined in Chapter 3.10 for satellite systems. As we have seen that reliability of a system can be improved at a cost, use of high-reliability components and redundant sub-systems increases the cost of the system. In satellite systems, the increased cost for improving the reliability is justified because the system cannot be repaired. This is not so in case of earth station. The cost of earth station is also of importance, particularly, in case of small earth terminals owned by individuals. Hence, the cost and the reliability are balanced in earth station design.

In large earth stations carrying high traffic and many channels, the reliability is critical. Hence, in large earth stations, the reliability is improved by providing redundancy in all the critical sub-systems which are prone to failure. These include the power amplifiers, LNAs, up/down converters, and modulators/demodulators, and others. The probability of failure is high for sub-systems employing active devices, and hence, they have redundancy. In medium earth stations, the redundancy is provided for only few critical sub-systems like power amplifier and LNAs. In small earth stations, like VSATs, no redundancy is provided to keep the terminal cost low. The reason we afford to accept low reliability in earth stations is because the sub-systems are accessible and can be repaired or replaced when they fail. Hence, in earth stations, we are interested in mean time to repair (MTTR) rather than meantime to failure (MTTF). MTTR is defined as the MTTR a system. The availability, \( A \), of the system is then defined as

\[
A = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \tag{4.13}
\]

Example 4.4
The MTBF for an Earth station is found to be 2400 hr. Find the availability of the Earth station if the MTTR is 3 hr. If the availability is to be increased to 0.999, how much the MTTR be reduced?

Solution
Using Eqn (4.13), the availability is found as
\[
A = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} = \frac{2400}{2400 + 3} = 0.99875
\]
If the availability is to be increased to 0.999, we can calculate the MTTR as

\[
0.999 = \frac{2400}{2400 + \text{MTTR}}
\]

\[
1 + \left(\frac{\text{MTTR}}{2400}\right) = 1/0.999
\]

\[
\text{MTTR} = 2400(0.001/0.999) = 2.4 \text{ hr}
\]

### 4.16 MISSION CONTROL FACILITY

During all stages of a satellite mission, the satellite is controlled from a mission control facility (MCF) comprising one or more earth stations, either functioning dedicatedly for this purpose or sharing this function along with communication functions. The phases during which the satellite needs support from the MCF include the launch stage, pre-orbit phase, initial phase, payload check-out phase, normal operation phase, and end of life phase. The MCF has two components: a TT&C earth station and a Satellite Control Center (SCC) (Elbert, 2008). A single earth station or several earth stations in network mode are employed for these tasks. Figure 4.25 shows a typical MCF comprising TT&C and SCC.

![Mission control facility](image)

**Fig. 4.25** Mission control facility

U/C: Up-converter; D/C: Down-converter.

A TT&C earth station may have more than one antenna to point towards multiple satellites. It is necessary to have at least one fully tracking antenna to support a satellite in transfer orbit, while others can have limited tracking capability for GEO satellites. For LEO satellites, all the antennas must have full tracking capability. Tracking type communication antennas are employed to support communication functions.

The telemetry carrier received on the downlink is down-converted to IF, and demodulated and telemetry data is extracted. A baseband ranging signal is modulated in the command sub-system at IF, and after up-conversion to an RF carrier, transmitted to the satellite on uplink. The ranging data received on the downlink carrier is compared to the data transmitted on the uplink to measure the delay from which the computer calculates the range of the satellite.
The telemetry data received from the satellite also contains information on the status of all the sub-systems of the satellite. This data obtained from the telemetry receiver are decoded and processed by the computer in the SCC. If something is not right, the computer along with the operator decides the necessary action, and the control signals are generated and transmitted to the satellite after formatting and modulation on an uplink carrier through the command sub-system.

**SUMMARY**

- An earth station acts as a gateway between terrestrial systems and satellite, transmitting the terrestrial signals to satellite on the uplink, and receiving the signals from the satellite on the downlink, and sending them to the terrestrial systems.
- An earth station can be on the land, sea, or air. An earth station on the land is called GES, the one on the ship is termed as SES, and the one the aircraft is called AES.
- An earth station comprises baseband equipment, IF equipment, RF equipment, and antenna.
- Transmit side of the earth station has coder, multiplexer, modulator, up-converter, IF amplifier, bandpass filter, RF amplifier, and power amplifier.
- Receive side of the earth station has LNA, bandpass filter, down converter, IF amplifier, demodulator, demultiplexer, and decoder.
- Earth stations are classified as large, medium, and small earth stations based on the size of the antenna used.
- Large earth stations are designed to carry large telephone traffic, video signals, and high-rate data, and are fixed at a location.
- Medium earth stations are used both at fixed locations and mounted on trucks for relocation to set up communication links in an emergency. The traffic is moderate, single video, or medium-rate data.
- Small earth stations are used in emergency situations to set up a communication link at short notice, in corporate networks, and in receive-only terminals for direct reception of TV signals from satellite to home.
- Different types of modems are employed in earth stations to carry different types of signals, SCPC modems, wideband FM modems, and continuous and burst-mode PSK modems.
- Large earth stations employ klystron amplifiers to deliver output power in the range of kWs, and medium earth stations employ TWTAs to deliver output power in the range of hundreds of watts, and small earth stations employ SSPAs delivering a few watts.
- GaAs FET amplifier, parametric amplifier, HEMT amplifier, and cooled parametric amplifier are used as LNAs.
- Baseband signals are modulated at IF of 70 MHz and up-converted to RF at the transmit side, and down-converted from RF to IF and demodulated on the receive side.
- Several types of antenna configurations are used at the earth station including prime focus aperture antenna, Cassegrain antenna, dual-reflector antenna, and multiple-beam antenna.
- High-gain antennas used in large earth station have small beam width necessitating tracking the satellite to minimize the pointing error.
• Tracking is carried out manually, or using program tracking or autotracking.
• Performance of an earth station is measured in terms of the EIRP and G/T, EIRP indicating the power transmitted and G/T is the receiver performance.
• Redundancy is used at the earth station to improve the system reliability; critical elements like HPA and LNA are used in multiple numbers, and faulty units are replaced with working units using RF switches.
• MCF comprising TT&C earth station and SCC supports all the control functions needed during launch, initial orbit phase, check-out phase, operation phase, and the end-of-operation phase.

REFERENCES


EXERCISES

Multiple Choice Questions

1. A bandpass filter is used after the power amplifier on the transmit side of an earth station for the purpose of:
   (a) Limiting the noise  (c) Limiting the signal spectrum
   (b) Limiting the interference (d) For all the above

2. A bandpass filter is used at the input of the receiver in an earth station for the purpose of:
   (a) Shaping the signal spectrum  (c) Eliminating in-band interference
   (b) Limiting the noise (d) For all the above
3. For transmitting an analog voice signal, the following modulator may be used at the earth station:
   (a) Wideband FM modulation
   (b) Narrowband FM modulator
   (c) BPSK modulator
   (d) QPSK modulator

4. An equalizer is placed on the transmit path to:
   (a) Provide gain
   (b) Compensate for spectral distortion
   (c) Shape the noise spectrum
   (d) Shape the signal spectrum

5. In an offset-fed antenna, the feed is placed:
   (a) At the focal point of the reflector
   (b) On the main axis of the reflector
   (c) Below the main axis of the reflector
   (d) Behind the reflector

6. In a large earth station where the beam width is small, tracking is:
   (a) Not necessary
   (b) Necessary
   (c) Not necessary for geo satellites
   (d) Necessary for only low orbit satellites

7. EIRP of an earth station depends on:
   (a) The size of the antenna
   (b) Frequency of the signal
   (c) Output power of final amplifier
   (d) All the above

8. Figure of merit of an earth station depends on:
   (a) The size of the antenna
   (b) Frequency of the signal
   (c) Noise figure of LNA
   (d) All the above

9. A bandpass filter is invariably placed after the mixer to:
   (a) Select the desired frequency signal
   (b) Remove the thermal noise
   (c) Eliminate IM products in the band
   (d) Eliminate the harmonics

10. Redundant power amplifier is used at the earth station:
    (a) To increase the output power level
    (b) Because they are inexpensive
    (c) To increase the reliability
    (d) To increase the output bandwidth

11. Redundant LNA is used at the earth station:
    (a) To reduce the total noise power
    (b) To increase the reliability
    (c) To increase the input bandwidth
    (d) To reduce the system noise temperature
12. An MCF is required during:
   (a) Launching phase of the satellite
   (b) Orbit check-out phase
   (c) Operational phase
   (d) All the above phases

**Review Questions**

1. What are the functions of an earth station? What are the different types of earth stations?
2. Describe the functional blocks of the transmit side of a typical earth station.
3. Describe the functional blocks of the receive side of a typical earth station.
4. Which are the different types of antennas used at an earth station?
5. What parameter is used to describe the performance of an earth station and why?
6. What types of power amplifiers are used in earth stations?
7. What types of LNAs are used in earth stations?
8. Why is it necessary to employ antenna tracking in large earth stations?
9. What techniques are employed for antenna tracking?
10. How is the reliability of an earth station improved?

**Numerical Problems**

1. An earth station has antenna of 13 m diameter with the efficiency of 55% and transmits 14 GHz signal to a satellite in geostationary orbit. Find the EIRP of the antenna if the transmitted power is 20 W.
   
   \( \text{(Ans: 76 dBW)} \)

2. An earth station is operating in C band with the transmit frequency of 6.2 GHz and receives frequency of 4.2 GHz. The transmit power is 100 W and the EIRP is 70 dBW. Find the gain of the antenna for the received signal. Assume the efficiency of the antenna as 75%.

   \( \text{(Ans: 46.61 dB)} \)

3. If the gain of the antenna of an earth station for the uplink frequency of 6 GHz is 55dB and the system noise temperature is 120 K, find the G/T of the earth station.

   \( \text{(Ans: 30.68 dB/K)} \)

4. The figure of merit of an earth station is given as 25.5 dB/K at the receive frequency of 3.8 GHz. The EIRP is 57 dBW for a transmitted power of 100W at the transmit frequency of 5.8 GHz. What is the system noise temperature of the Earth station?

   \( \text{(Ans: 121 K)} \)

5. What is the 3-dB beam width for the antenna in Problem 4.

   \( \text{(Ans: 2.47°)} \)
6. An earth station transmits a signal with 36 MHz bandwidth at an uplink frequency of 5945 MHz. The IF used for modulation is 70 MHz. Find the LO frequency required if single conversion is employed. What is the guard band available for the design of image rejection bandpass filter?

*(Ans: LO frequency is 5875 or 6015 MHz, Guard band is 104 MHz)*

7. In the earlier problem, if the earth station employs dual conversion with a second IF of 1 GHz, what are the LO frequencies needed? What is the spectral gap between the desired and image signals at the output of second mixer?

*(Ans: LO₁ = 930 or 1070 MHz and LO₂ = 4945 or 6945 MHz. Guard band = 1974 MHz)*

8. An earth station transmits 1 kW of signal power at C band. It employs solid-state amplifiers with a gain of 20 dB, and power dividers and combiners. Draw the SSPA configuration to generate 1 kW power from an input power of 1 W. Assume the insertion loss of combiners and dividers as 0 dB.

9. An earth station with an antenna having 10 m diameter employs electronic beam squinting technique for tracking the satellite. The gain losses measured with the two beams with a squint angle of 0.3° are 14.9 dB and 19.35 dB with a carrier frequency of 4 GHz. What is the error angle between the satellite direction and the antenna boresight?

*(Ans: 1.2°)*

10. The availability required for a large earth station is 0.999. If the MTTR is 2 h, what MTBF should be achieved?

*(Ans: 2000 hr)*