

## 1

## Introduction to Satellite Communications

A communications satellite is an orbiting artificial earth satellite that receives a communications signal from a transmitting ground station, amplifies and possibly processes it, then transmits it back to the earth for reception by one or more receiving ground stations. Communications information neither originates nor terminates at the satellite itself. The satellite is an active transmission relay, similar in function to relay towers used in terrestrial microwave communications.

The commercial satellite communications industry had its beginnings in the mid 1960s, and in less than 50 years has progressed from an alternative exotic technology to a mainstream transmission technology, which is pervasive in all elements of the global telecommunications infrastructure. Today's communications satellites offer extensive capabilities in applications involving data, voice, and video, with services provided to fixed, broadcast, mobile, personal communications, and private networks users.

Satellite communications are now an accepted fact of everyday life, as evidenced by the antennas or "dishes," which dot city and country horizons, or the nearly instantaneous global news coverage that is taken for granted, particularly in times of international crises.

The communications satellite is a critical element in the overall telecommunications infrastructure, as represented by Figure 1.1, which highlights, by the shaded area, the communications satellite component as related to the transmission of information. Electronic information in the form of voice, data, video, imaging, and so on, is generated in a user environment on or near the earth's surface. The information's first node is often a terrestrial interface, which then directs the information to a satellite uplink, which generates a RF (radio frequency) radiowave, which propagates through the air link to an orbiting satellite (or satellites). The information-bearing radiowave is amplified and possibly processed at the satellite, then reformatted and transmitted back to a receiving ground station through a second RF radiowave propagating through the air link. Mobile users, indicated by the vehicle and handheld phone on the figure, generally bypass the terrestrial interface only for direct mobile to mobile communications.

Communications by satellite offers a number of features that are not readily available with alternative modes of transmission, such as terrestrial microwave, cable or fiber networks. Some of the *advantages* of satellite communications are:

- **Distance Independent Costs** The cost of satellite transmission is basically the same, regardless of the distance between the transmitting and receiving earth

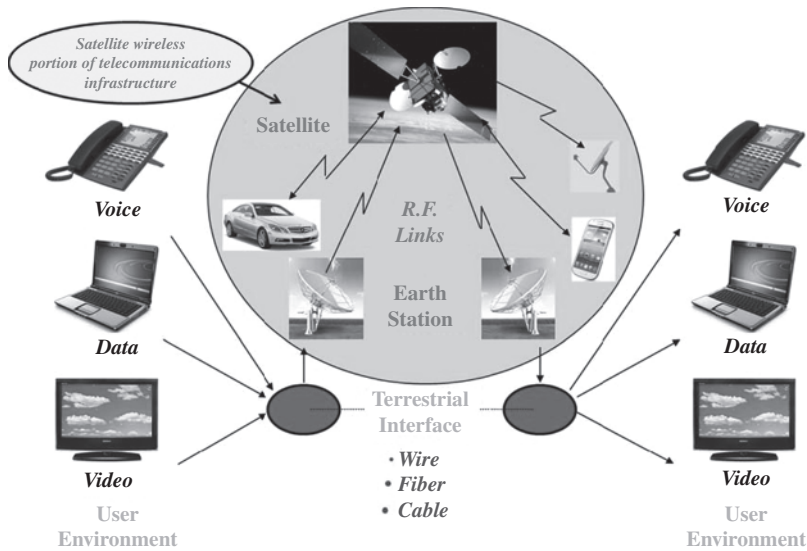


Figure 1.1 Communications via satellite in the telecommunications infrastructure.

stations. Satellite-based transmission costs tend to be more stable, particularly for international or intercontinental communications over vast distances.

- **Fixed Broadcast Costs** The cost of satellite broadcast transmission, that is, transmission from one transmit ground terminal to a number of receiving ground terminals, is independent of the number of ground terminals receiving the transmission.
- **High Capacity** Satellite communications links involve high carrier frequencies, with large information bandwidths. Capacities of typical communications satellites range from 10s to 100s of Mbps (megabits per second), and can provide services for several hundred video channels or several tens of thousands of voice or data links.
- **Low Error Rates** Bit errors on a digital satellite link tend to be random, allowing for statistical detection and error correction techniques to be utilized. Error rates of one bit error in  $10^6$  bits or higher can be routinely achieved efficiently and reliably with standard equipment.
- **Diverse User Networks** Large areas of the earth are visible from the typical communications satellite, allowing the satellite to link together many users simultaneously. Satellites are particularly useful for accessing remote areas or communities not otherwise accessible by terrestrial means. Satellite terminals can be on the surface, at sea, or in the air, and can be fixed or mobile.

The successful implementation of satellite wireless communications requires robust air links providing the uplink and downlink paths for the communications signal. Transmission through the atmosphere will degrade signal characteristics, however, and under some conditions can be the major impediment to successful system performance. A detailed knowledge of the types of atmospheric effects that impact satellite communications and the means to predict and model them for application to communications link design and performance is essential for wireless satellite link engineering. The effects of the atmosphere are even more significant as current and planned satellites move up

to higher operating frequencies, including the Ku-band (14 GHz uplink/12 GHz downlink), Ka-band (30 GHz/20 GHz), and V-band (50 GHz/40 GHz), where the effects of rain, gaseous attenuation, and other effects will increase.

## 1.1 Early History of Satellite Communications

The idea of a synchronous orbiting satellite capable of relaying communications to and from the earth is generally attributed to Arthur C. Clarke. Clark observed in his classic 1945 paper [1] that a satellite in a circular equatorial orbit with a radius of about 23,000 miles (42,000 km) would have an angular velocity matching that of the earth, thus it would remain above the same spot on the earth's surface. This orbiting artificial satellite could therefore receive and transmit signals from anywhere on earth in view of the satellite to any other place on the surface in view of the satellite.

The technology to verify this concept was not available until over a decade later, with the launch in 1957 of SPUTNIK I by the former USSR. This launch ushered in the 'space age' and both the United States and the USSR began robust space programs to develop the technology and to apply it to emerging applications. A brief summary of some of the early communications satellites programs, and their major accomplishments, follows.

### 1.1.1 SCORE

The *first communications by artificial satellite* was accomplished by SCORE (Signal Communicating by Orbiting Relay Equipment), launched by the Air Force into a low (100 by 800 nautical mile) orbit in December 1958. SCORE relayed a recorded voice message, on a delayed basis, from one earth station to another. SCORE broadcast a message from President Eisenhower to stations around the world, giving the first hint of the impact that satellites would have on point to point communications. The maximum message length was 4 minutes, and the relay operated on a 150 MHz uplink and 108 MHz downlink. SCORE, powered by battery only, operated for 12 days before its battery failed, and decayed out of orbit 22 days later [2].

### 1.1.2 ECHO

The first of several efforts to evaluate communications relay by passive techniques was initiated with the ECHO satellites 1 and 2, launched by the National Aeronautics and Space Administration, NASA, in August 1960 and January 1964, respectively. The ECHO satellites were large orbiting spheres of aluminized Mylar, over 100 ft in diameter, which served as passive reflectors for signals transmitted from stations on the earth. They caught the interest of the public since they were visible from the earth with the unaided eye under the right lighting conditions, usually just as the sun was rising or setting. The ECHO relays operated at frequencies from 162 MHz to 2390 MHz, and required large ground terminal antennas, typically 60 ft. or more, with transmit powers of 10 kW. ECHO 1 remained in orbit for nearly eight years, ECHO 2 for over five years [3].

### 1.1.3 COURIER

Launched in October 1960, COURIER extended SCORE delayed repeater technology and investigated store-and-forward and real-time capabilities from a low orbiting satellite. COURIER operated with an uplink frequency of 1.8 to 1.9 GHz, and a downlink of 1.7 to 1.8 GHz. It was all solid state except for the two-watt output power tubes, and was the first artificial satellite to employ solar cells for power. The satellite performed successfully for 17 days, until a command system failure ended operations [4].

### 1.1.4 WESTFORD

WESTFORD was the second technology employed to evaluate communications relay by passive techniques, with a first successful launch by the U.S. Army in May 1963. WESTFORD consisted of tiny resonant copper dipoles dispersed in an orbital belt, with communications accomplished by reflection from the dispersed dipole reflectors. The dipoles were sized to the half wavelength of the relay frequency, 8350 MHz. Voice and frequency shift keyed (FSK) transmissions up to 20 kbps were successfully transmitted from a ground station in California to one in Massachusetts. As the belt dispersed, however, the link capacity dropped to below 100 bps. The rapid development of active satellites reduced interest in passive communications, and ECHO and WESTFORD brought passive technology experiments to an end [5].

### 1.1.5 TELSTAR

The TELSTAR Satellites 1 and 2, launched into low orbits by NASA for AT&T/Bell Telephone Laboratories in July 1962 and May 1963, respectively, were the *first active wideband communications satellites*. TELSTAR relayed analog FM signals, with a 50 MHz bandwidth, and operated at frequencies of 6.4 GHz on the uplink and 4.2 GHz on the downlink. These frequencies led the way for 6/4 GHz C-band operation, which currently provides the major portion of fixed satellite service (FSS) throughout the world. TELSTAR 1 provided multichannel telephone, telegraph, facsimile, and television transmissions to stations in the United States, Britain, and France until the command subsystem failed in November 1962 due to Van Allen belt radiation. TELSTAR 2, redesigned with radiation resistant transistors and launched into a higher orbit to decrease exposure in the Van Allen belts, operated successfully for two years [6].

### 1.1.6 RELAY

RELAY 1, developed by RCA for NASA, was launched in December 1962 and operated for fourteen months. RELAY had two redundant repeaters, each with a 25 MHz channel and two 2 MHz channels. It operated with 1725 MHz uplink and 4160 MHz downlink frequencies, and had a 10-watt TWT (traveling wave tube) output amplifier. Extensive telephony and network television transmissions were accomplished between the United States, Europe, and Japan. RELAY 2 was launched in January 1964 and operated for 14 months. The RELAY and TELSTAR programs demonstrated that reliable, routine communications could be accomplished from orbiting satellites, and further indicated that satellite systems could share frequencies with terrestrial systems without interference degradations [7].

### 1.1.7 SYNCOM

The SYNCOM satellites, developed by Hughes Aircraft Company for NASA GSFC, provided the *first communications from a synchronous satellite*. SYNCOM 2 and 3 were placed on orbit in July 1963 and July 1964, respectively (SYNCOM 1 failed at launch). SYNCOM, with 7.4 GHz uplink and 1.8 GHz downlink frequencies, employed two 500 kHz channels for two-way narrowband communications, and one 5 MHz channel for one-way wideband transmission. SYNCOM was the first testbed for the development of station keeping and orbital control principles for synchronous satellites. It was the first satellite to employ range and range-rate tracking. NASA conducted voice, teletype and facsimile tests, including extensive public demonstrations to increase the base of satellite communications interest. The U.S. Department of Defense also conducted tests using SYNCOM 2 and 3, including transmissions with a shipboard terminal. Tests with aircraft terminals were also conducted with the SYNCOM VHF command and telemetry links [8].

### 1.1.8 EARLYBIRD

The *first commercial operational synchronous communications satellite* was EARLYBIRD, later called INTELSAT I, developed by COMSAT for INTELSAT, and launched by NASA in April 1965. The communications subsystem, very similar to the SYNCOM 3 design, had two 25 MHz transponders and operated at C-band, with uplinks at 6.3 GHz and downlinks at 4.1 GHz. It had a capacity of 240 two-way voice circuits or one two-way television circuit. TWT output power was 6 watts. Operations between the U.S. and Europe began on June 28, 1965, a date that many recognize as the birth date of commercial satellite communications. EARLYBIRD remained in service until August 1969, when it was replaced by later generation INTELSAT III satellites [9].

### 1.1.9 APPLICATIONS TECHNOLOGY SATELLITE-1, ATS-1

The ATS-1, first of NASA's highly successful series of Applications Technology Satellites, was launched in December 1966 and demonstrated a long list of "firsts" in satellite communications. ATS-1 included an electronically despun antenna with 18-dB gain and a 17° beamwidth. It operated at C-band (6.3 GHz uplink, 4.1 GHz downlink), with two 25 MHz repeaters. ATS-1 provided the *first multiple access communications from synchronous orbit*. ATS-1 had VHF links (149 MHz uplink, 136 MHz downlink) for the evaluation of air to ground communications via satellite. ATS-1 also contained a high-resolution camera, providing the *first photos of the full earth from orbit*. ATS-1 continued successful operation well beyond its three year design life, providing VHF communications to the Pacific basin region until 1985, when station keeping control was lost [7].

### 1.1.10 ATS-3

The ATS-3, launched in November 1967, continued experimental operations in the C and VHF bands, with multiple access communications and orbit control techniques. ATS-3 allowed, for the first time, "cross-strap" operation at C-band and VHF; the signal received at VHF could be transmitted to the ground at C-band. ATS-3 provided the *first color high-resolution pictures* of the now familiar "blue marble" earth as seen

from synchronous orbit. ATS-3, like ATS-1, far exceeded its design life, and providing VHF communications to the Pacific and continental United States for public service applications for over a decade [7].

#### 1.1.11 ATS-5

ATS-5 had a C-band communications subsystem similar to its predecessors, but did not have the VHF capability. Instead it had an L-band (1650 MHz uplink, 1550 MHz downlink) subsystem to investigate air to ground communications for navigation and air traffic control. ATS-5 also contained a millimeter wave experiment package that operated at 31.65 GHz (uplink) and 15.3 GHz (downlink), designed to provide propagation data on the effects of the atmosphere on earth-space communications at these frequencies. ATS-5 was designed to operate as a gravity gradient stabilized satellite, unlike the earlier spin-stabilized ATS-1 and -3 satellites. It was successfully launched in August 1969 into synchronous orbit, but the gravity stabilization boom could not be deployed because of the satellite's spin condition. ATS-5 was placed into a spin-stabilized condition, resulting in the satellite antennas sweeping the earth once every 860 milliseconds. Most of the communications experiments performed with limited success in this unexpected "pulsed" operation mode. The 15.3 GHz millimeter wave experiment downlink, however, was able to function well, after modifications to the ground terminal receivers, and extensive propagation data were accumulated at over a dozen locations in the United States and Canada [7].

#### 1.1.12 ANIK A

ANIK A (initially called ANIK I), launched in November 1972 by NASA for Telsat Canada, was the *first domestic commercial communications satellite*. Two later ANIK As were launched in April 1973 and May 1975. The satellites, built by Hughes Aircraft Company, operated at C-band and had 12 transponders, each 36 MHz wide. The primary services provided were television distribution, SCPC (single channel per carrier) voice, and data services. The transmit power was 5 watts, with a single beam covering most of Canada and the northern United States. The antenna pattern for ANIK A was optimized for Canada, however, sufficient coverage of the northern United States was available to allow leased service by U.S. communications operators for domestic operations prior to the availability of U.S. satellites. The ANIK A series continued in service until 1985, when they were replaced by ANIK D satellites [10].

#### 1.1.13 ATS-6

ATS-6, the second generation of NASA's Applications Technology Satellite program, provided major advancements in communications satellite technology and in new applications demonstrations. ATS-6 consisted of a 30 ft diameter deployed parabolic antenna, earth viewing module, two sun-seeking solar arrays, and the supporting structures [11]. It was launched in May 1974 and positioned at 94° W longitude, where it remained for one year. In July 1975 it was moved to 35° E longitude for instructional television experiments to India. After one year it was again relocated to 140° W longitude and used for several experimental programs until it was moved out of synchronous orbit in 1979. ATS-6 had eight communications and propagation experiments that

covered a frequency range from 860 MHz to 30 GHz. The communications subsystems on ATS-6 included four receivers; 1650 MHz (L-band), 2253 MHz (S-band), 5925–6425 (C-band), and 13/18 GHz (K-band). Transmitter frequencies were; 860 MHz (L-band), 2063 MHz (S-band), 3953–4153 MHz (C-band), and 20/30 GHz ( $K_a$ -band). The ATS-6 provided cross strapping at IF between any receiver to any transmitter (except for the 13/18 GHz receiver, which operated with a 4150 MHz transmitter only), allowing a wide range of communications modes. Major experiments [12] were:

- **Position Location and Aircraft Communication Experiment (PLACE)** – consisted of voice and digital data transmissions and four-tone ranging for aircraft position location. The system allowed multiple access voice from up to 100 aircraft, operating in 10 KHz channels.
- **Satellite Instructional Television Experiment (SITE)** – a cooperative experiment between NASA and the government of India to demonstrate direct broadcast satellite television for instructional purposes. Satellite signals at 860 MHz were received at over 2000 villages, using simple 10 ft parabolic antennas.
- **Television Relay Using Small Terminals (TRUST)** – evaluated hardware and system performance for 860 MHz satellite broadcast television, using the same general configuration as the SITE.
- **Health Education Experiment (HEW)** – provided satellite distribution of educational and medical programming, primarily to Alaska, the Rocky Mountain states, and Appalachia. Two independent steerable beams, operating through the 30 ft reflector, were available, with the uplink at C-band (5950 MHz) and the downlink at S-band (2750 and 2760 MHz).
- **Radio Frequency Interference Experiment (RFI)** – monitored the 5925 to 6425 MHz band with a sensitive on-board receiver to measure and map radio frequency interference sources in the continental United States (CONUS). The minimum detectable source EIRP was 10 dBW, with a frequency resolution of 10 kHz.
- **NASA Millimeter Wave Propagation Experiment** – designed to provide information on the communications and propagation characteristics of the atmosphere at 20 and 30 GHz ( $K_a$ -band). Two modes of operation were available; 1) downlink beacons at 20 and 30 GHz for measurement of rain attenuation, atmospheric absorption, and other effects, and 2) a communications mode, with a C-band (6 GHz) uplink, and simultaneous downlinks at 20, 30, and 4 GHz, for the evaluation of millimeter wave communications in a 40 MHz bandwidth. Extensive measurements were obtained in the U.S. and Europe, providing the first detailed information on  $K_a$ -band satellite communications performance.
- **COMSAT Millimeter Wave Experiment** – consisted of 39 uplinks, 15 at 13.19 GHz, and 24 at 17.79 GHz, which were received by ATS-6 and retransmitted to the ground at C-band (4150 MHz). About one year of measurements were accumulated on rain attenuation statistics, joint probability distributions and required rain margins, for links operating at K-band.

The accomplishments of ATS-6 have been extensively documented, and have provided a wide range of valuable design and performance information for virtually every application implemented in current satellite communications systems.

### 1.1.14 CTS

The Communications Technology Satellite, CTS, was a joint program between NASA and the Canadian Department of Communications, to evaluate high power satellite technology applicable to broadcast satellite service (BSS) applications at  $K_u$ -band. A 12 GHz, 200-watt output TWT on CTS, provided by NASA, allowed reception of television and two-way voice with small (4 ft diameter) ground terminal antennas [13]. A continuously operating 11.7 GHz propagation beacon was also included, and long-term (36 month) propagation statistics were developed for several locations in the United States [14]. CTS was launched in January 1976, and provided extensive experimental tests and demonstrations in the U.S. and Canada until operations ended in November 1979.

Three important events that helped to shape the direction and speed of satellite communications development in its early years were;

**1961 UNITED NATIONS INITIATIVE** – stated that “communications by means of satellite should be available to the nations of the world as soon as practicable ...”

**COMSAT ACT OF 1962** – The Congress of the United States created an international communications satellite organization, COMSAT. COMSAT was incorporated in 1963 and served as the primary commercial provider of international satellite communications services in the United States.

**Creation of INTELSAT** – In August 1964 INTELSAT becomes the recognized international legal entity for international satellite communications. COMSAT is the sole United States conduit organization to INTELSAT.

These early accomplishments and events lead to the rapid growth of the satellite communications industry beginning in the mid 1960s. INTELSAT was the prime mover in this time period, focusing on the first introduction of the benefits of satellite communications to many nations across the globe.

The decade of the 1970s saw the advent of domestic satellite communications (i.e., the provision of satellite services within the domestic boundaries of a single country), led by the rapid reduction in the cost of satellite equipment and services. The technology of the 1970s also allowed the first consideration of regional satellite communications, with antennal coverage areas over several contiguous countries with similar communications interests.

The 1980s began the rapid introduction of new satellite services and new participants in satellite communications. Nearly 100 countries were involved in satellite communications - providing either satellite systems or satellite based services. This decade also saw the advent of new and innovative ways to pay for the high costs of satellite systems and services, including lease/buy options, private networks (often referred to as VSATs - very small antenna terminals) and private launch services.

The 1990s introduced mobile and personal communications services via satellite. This era also saw the move to higher RF frequencies to support the increasing data rate requirements in the midst of bandwidth saturation in the lower allocated frequency bands. “Smart satellites” also were introduced, providing on-board processing and other advanced techniques on the satellite itself, morphing the satellite from a mere data relay to a major communications processing hub in the sky.

The new millennium has seen the rapid introduction of new services, including direct to the home video and audio broadcasting and cellular mobile satellite communications



networks. The preferred orbit for communications satellites, the geosynchronous (GSO) orbit, now shared the spotlight with low orbit non-GSO (NGSO) networks, particularly for global cellular mobile communications. Two new designations of satellites have appeared, based on their increased data transmission rates and capacity over previous generation systems – **broadband satellites** and **high throughput satellites, HTS**.

The satellite communications industry, since its inception, has been characterized by a vigorous expansion to new markets and applications, which exploit the advantages of the satellite link and provide cost effective alternatives to the traditional modes of telecommunications transmission.

Satellite networks have been a part of the evolution of cellular communications, beginning with 3G/4G implementations and moving now into the 5G era.

## 1.2 Some Basic Communications Satellite System Definitions

This section provides some of the basic definitions and parameters used in the satellite communications industry, which will be utilized throughout the book in the evaluation and analysis of satellite communications systems design and performance. The relevant sections in the book where the parameters are discussed more fully are also indicated where appropriate.

### 1.2.1 Satellite Communications Segments

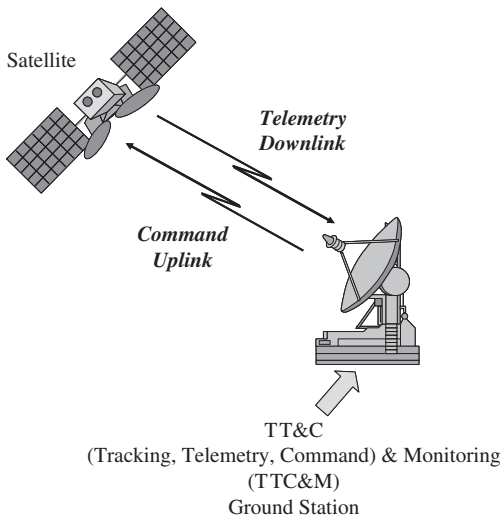
We begin with the communications satellite portion of the communications infrastructure, shown by the shaded oval in Figure 1.1. The satellite communications portion is broken down into two areas or segments, the *space segment* and the *ground (or earth) segment*.

#### 1.2.1.1 Space Segment

The elements of the space segment of a communications satellite system are shown on Figure 1.2. The space segment includes the satellite (or satellites) in orbit in the system, and the ground station that provides the operational control of the satellite(s) in orbit. The ground station, variously referred to as the *Tracking, Telemetry Command (TTC&C)* or the *Tracking, Telemetry, Command & Monitoring (TTC&M)* station. The TTC&M station provides essential spacecraft management and control functions to keep the satellite operating safely in orbit. The TTC&M links between the spacecraft and the ground are usually separate from the user communications links. TTC&M links may operate in the same frequency bands or in other bands. TTC&M is most often accomplished through a separate earth terminal facility specifically designed for the complex operations required to maintain a spacecraft in orbit. The TTC&C functions and subsystems are described in more detail in Chapter 3.

#### 1.2.1.2 Ground Segment

The ground segment of the communications satellite system consists of the earth surface area based terminals that utilize the communications capabilities of the Space Segment.



**Figure 1.2** The space segment for a communications satellite network.

TTC&M ground stations are not included in the ground segment. The ground segment terminals consist of three basic types;

- fixed (in-place) terminals
- transportable terminals
- mobile terminals

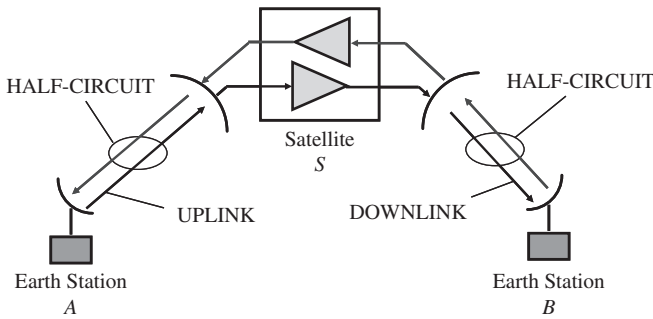
Fixed terminals are designed to access the satellite while fixed in-place on the ground. They may be providing different types of services, but they are defined by the fact that they are not moving while communicating with the satellite. Examples of fixed terminals are small terminals used in private networks (VSATs), or terminals mounted on residence buildings used to receive broadcast satellite signals.

Transportable terminals are designed to be movable, but once on location remain fixed during transmissions to the satellite. Examples of the transportable terminal are satellite news gathering (SGN) trucks, which move to locations, stop in place, then deploy an antenna to establish links to the satellite.

Mobile terminals are designed to communicate with the satellite while in motion. They are further defined as land mobile, aeronautical mobile, or maritime mobile, depending on their locations on or near the earth surface. Mobile satellite communications are discussed in detail in Chapter 12.

### 1.2.2 Satellite Link Parameters

The communications satellite link is defined by several basic parameters, some used in traditional communications system definitions, others unique to the satellite environment. Figure 1.3 summarizes the parameters used in the evaluation of satellite communications links. Two one-way free-space or *air links* between Earth Station's *A* and *B* are shown. The portion of the link from the earth station to the satellite is called the *uplink*, while the portion from the satellite to the ground is the *downlink*. Note that either station has an uplink and a downlink. The electronics in the satellite that receives the uplink signal, amplifies and possibly processes the signal, then reformats and transmits the signal back to the ground, is called the *transponder*, designated by the triangular amplifier




- CHANNEL - one way link from  $A \rightarrow B$  or  $B \rightarrow A$   
 CIRCUIT - full duplex link -  $A \leftrightarrow B$   
 HALF CIRCUIT - two way link -  $A \leftrightarrow S$  or  $S \leftrightarrow B$   
 TRANSPONDER -  basic satellite repeater electronics,  
 usually one channel

Figure 1.3 Basic link parameters in the communications satellite link.

symbol in the diagram (the point of the triangle indicates the direction of signal transmission). Two transponders are required in the satellite for each two-way link between the two ground stations as shown. The antennas on the satellite that receive and transmit the signals are usually not included as a part of the transponder electronics – they are defined as a separate element of the satellite payload (see Chapter 3).

A **channel** is defined as the one way total link from  $A$ -to- $S$ -to- $B$ , OR the link from  $B$ -to- $S$ -to- $A$ . The duplex (two-way) links  $A$ -to- $S$ -to- $B$  AND  $B$ -to- $S$ -to- $A$  establishes a **circuit** between the two stations. A **half-circuit** is defined as the two links at one of the earth stations, that is  $A$ -to- $S$  AND  $S$ -to- $A$ ; OR  $B$ -to- $S$  AND  $S$ -to- $B$ . The circuit designations are a carry-over from standard telephony definitions, which are applied to the satellite segment of the communications infrastructure.

### 1.2.3 Satellite Orbits

The characteristics of satellite orbits in common use for a vast array of satellite communications services and applications are discussed in detail in Chapter 2. We introduce here the satellite orbit terms for the four most common types of orbits used in satellite communications. Figure 1.4 shows the four most commonly used orbits for satellite communications applications. The basic orbit altitude(s) and the one way delay times are shown for each orbit, along with the common abbreviation designations.

#### 1.2.3.1 Geosynchronous Orbit (GSO or GEO)

The GSO orbit is by far the most popular orbit used for communications satellites. A GSO satellite is located in a circular orbit in the equatorial plane, at a nominal distance of 36,000 km, at a stable point, which maintains the satellite at a fixed location in the sky. This is a tremendous advantage for satellite communications, because the pointing direction remains fixed in space and the ground antenna does not need to track a moving satellite. A disadvantage of the GSO is the long delay time of  $\sim 260$  ms, which can affect

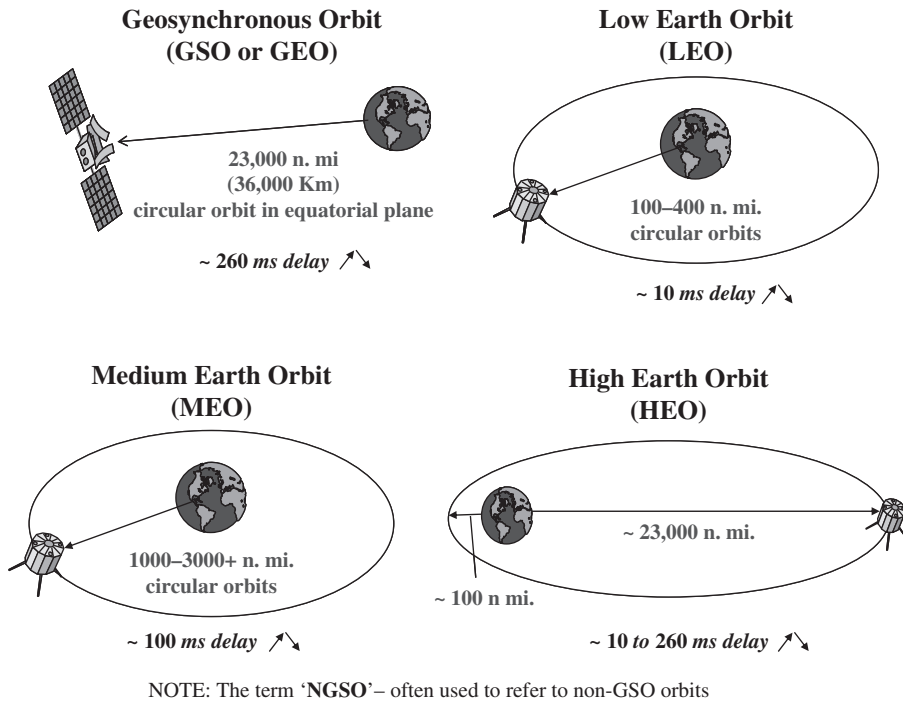


Figure 1.4 Satellite orbits.

network synchronization or impact voice communications. The GSO is described in detail in Chapter 2, Section 2.3.1.

#### 1.2.3.2 Low Earth Orbit (LEO)

The second most common orbit is the low earth orbit, LEO, which is a circular orbit nominally 100 to 400 n. miles above the earth. The delay is low, ~10 ms, however the satellite moves across the sky, and the ground station must actively track the satellite to maintain communications. The LEO is described in Section 2.3.2.

#### 1.2.3.3 Medium Earth Orbit (MEO)

The MEO is similar to the LEO, however the satellite is in a higher circular orbit – 1000 to 3000+ n. miles. It is a popular orbit for navigation satellites such as the GPS constellation. The MEO is described I Section 2.3.3.

#### 1.2.3.4 High Earth Orbit (HEO)

The HEO is the only non-circular orbit of the four. It operates with in an elliptical orbit, with a maximum altitude (apogee) similar to the GSO, and a minimum altitude (perigee) similar to the LEO. The HEO, used for special applications where coverage of high latitude locations is required, is discussed in Section 2.3.4.

Satellite orbits which are not synchronous, such as the LEO or the MEO or the HEO, are often referred to as non-geosynchronous orbit, **NGSO**, satellites.

### 1.2.4 Frequency Band Designations

The frequency of operation is perhaps the major determining factor in the design and performance of a satellite communications link. The wavelength of the free space path signal is the principal parameter which determines the interaction effects of the atmosphere, and the resulting link path degradations. Also, the satellite systems designer must operate within the constraints of international and domestic regulations related to choice of operating free space path frequency [15].

Two different methods of designation have come into common use to define radio frequency bands. Letter band designations, derived from radar applications in the 1940s, divide the spectrum from 1 to 300 GHz into eight bands with nominal frequency ranges, as shown on Figure 1.5. The K-band is further broken down into  $K_U$ -band (K-lower) and  $K_A$ -band (K-above). The boundaries of the bands not always followed, and often some overlap is observed. For example, some references consider C-band as 3.7-6.5 GHz, and  $K_U$ -band as 10.9-12.5 GHz. The bands above 40 GHz have seen several letter designations used, including Q-band, W-band, U-band and W-band. The ambiguity in letter band designations suggests that they should be used with caution – particularly when the specific frequency is an important consideration.

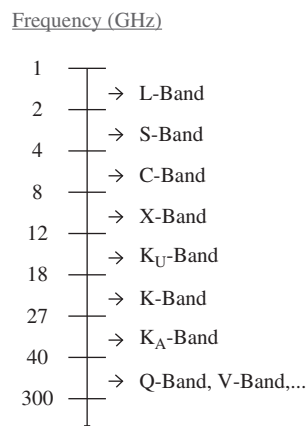
A second designation divides the spectrum from 3 Hz to 300 GHz into bands based on decade steps of nominal wavelength, as shown in Figure 1.6. This designation is less ambiguous than the letter designation, however, as we shall see in later chapters, most satellite communications links operate within only three or four of the bands, VHF through EHF, with the vast majority of systems in the SHF band.

In general, the frequency band designations are useful when general characteristics of satellite communications systems are of interest, however, when the specific operating carrier frequency or specific frequency band are important, the best solution is to specify the frequency directly, rather than using frequency band designations.

## 1.3 Overview of Book Structure and Topics

The material in this book begins with a discussion of some of the basic background disciplines and subsystems inherent in all satellite communications systems. **Chapter 2**

Figure 1.5 Letter band frequency designations.



Frequency	Wavelength		
3 Hz	$10^8$ m	→ VLF	Very Low Frequency
30 kHz	$10^4$ m	→ LF	Low Frequency
300 kHz	$10^3$ m	→ MF	Medium Frequency
3 MHz	$10^2$ m	→ HF	High Frequency
30 MHz	10 m	→ VHF	Very High Frequency
300 MHz	1 m	→ UHF	UltraHigh Frequency
3 GHz	10 cm	→ SHF	Super High Frequency
30 GHz	1 cm	→ EHF	Extremely High Frequency
300 GHz	1 mm		

**Figure 1.6** Frequency band designations by wavelength.

covers satellite orbits, general orbital mechanics, and focuses on orbits in common use. The parameters required for analysis of the geosynchronous orbit, the most prevalent orbit for current communications satellites, are developed. **Chapter 3** introduces the subsystems present in communications satellites, including power, attitude and orbital control, thermal control, and tracking, telemetry, command and monitoring. The basic elements of the communications satellite payload, the transponder and antenna systems, are introduced.

The next two chapters begin the discussion of the RF link. Transmission fundamentals, system noise and link performance parameters are developed in **Chapter 4**. **Chapter 5** focuses on link performance for specific types of links, and introduces the concept of percent of time performance specifications for the evaluation of communications satellite systems and networks.

The critical area of transmission impairments introduced to the RF link by the atmosphere is discussed in **Chapter 6**. Propagation effects on satellite communications are discussed in the context of the frequency band of operation – those operating below about 3 GHz, and those operating above 3 GHz. Topics covered include ionospheric and tropospheric scintillation, rain attenuation, clouds and fog, and depolarization. Radio noise from a wide range of sources is also covered in detail. **Chapter 7** then builds on the discussions of Chapter 6 with a presentation of current modeling and prediction techniques applicable to the evaluation of atmospheric impairments. Most of the models and prediction procedures are presented in step-by-step solution format, with all of the required information in one place, allowing the reader to obtain results directly. **Chapter 8** moves to a detailed discussion of modern mitigation techniques available to reduce the impact of rain fading on system performance. Topics discussed include; power control, site diversity, orbit diversity, and adaptive coding and modulation.

**Chapter 9** puts together all of the pieces from previous chapters to analyze the composite link, which includes the complete end-to-end satellite network. Both frequency translation and on-board processing satellite transponders are included, along with other important subjects such as intermodulation noise and the effects of atmospheric degradations on link performance.

**Chapter 10** discusses satellite communications signal processing, tracing the communications signal from baseband elements through source combining, carrier modulation, and transmission.

**Chapter 11** covers the important topic of satellite multiple access, MA, presented in the context of system performance and the inclusion of critical factors produced on the RF link. Key parameters such as frame efficiency, capacity, and processing gain are developed for the three basic multiple access techniques.

**Chapter 12** presents a detailed evaluation of the mobile satellite channel. The unique characteristics of the RF channel environment, and their effects on system design and performance, are highlighted. This chapter is similar in objective and outlook to the composite link evaluation of Chapter 9, but in the context of special considerations unique to the mobile satellite channel.

**Chapter 13** provides an overview of the important area of spectrum management in satellite communications. International and domestic organizations involved in spectrum management are discussed, with emphasis on the impact of frequency allocations and regulations on satellite system performance and design. Methods of radio spectrum sharing and spectrum efficiency metrics are developed and described.

**Chapter 14** covers interference mitigation in satellite communications. Interference modes and propagation mechanisms are discussed. Prediction methods for single interferer and multiple interferer scenarios are evaluated. Finally the important process of coordination for interference mitigation, at the national and international level, is described, including ITU-R coordination procedures for frequency sharing between satellite and terrestrial services.

**Chapter 15**, the final chapter, discusses the rapidly growing area of high throughput satellite (HTS) technology. HTS implementation is centered on multiple-beam antennas and frequency reuse, which are discussed in detail regarding antenna array design and adjacent beam interference considerations. Finally the extension of HTS networks into the 5G (fifth generation) global cellular infrastructure is reviewed.

**Appendix A** provides important mathematical functions used throughout the book.

## References

- 1 Clarke AC. Extraterrestrial relays. *Wireless World* 1945;51:305-308.
- 2 Davis MI, Krassner GN. SCORE First Communications Satellite. *Journal of American Rocket Society* 1959;4.
- 3 Jaffe L, Project Echo results. *Astronautics* 1961;6(5).
- 4 Imboldi E, Hershberg D. Courier satellite communications system. *Advances in the Astronautical Sciences* 1961;8.
- 5 Special Issue on Project West Ford, *Proceedings of the IEEE*, Vol. 52, No. 5, May 1964.
- 6 Gatland KW, *Telecommunications Satellites*, Prentice Hall, New York, 1964.
- 7 Martin DH, *Communications Satellites 1958-1988*, The Aerospace Corporation, December 31, 1986.
- 8 Jaffe L, "The NASA Communications Satellite Program Results and Status," *Proceedings of the 15th International Astronautical Congress*, Vol. 2: Satellite Systems, 1965.

- 9 Alper J, Pelton JN, eds., *The INTELSAT Global System*, Progress in Astronautics and Aeronautics. Vol. 93, AIAA, New York, 1984.
- 10 Almond J, *Commercial communications satellite systems in Canada*. IEEE Communications Magazine 1981;19(1).
- 11 Redisch WN, Hall RL. "ATS 6 Spacecraft Design/Performance," EASCON'74 Conference Record, October 1974.
- 12 *Special Issue on ATS 6*, IEEE Transactions on Aerospace and Electronics Systems, 1975;11(6).
- 13 Wright DL, Day JWB. "The Communications Technology Satellite and the Associated Ground Terminals for Experiments, AIAA Conference on Communications Satellites for Health/Education Applications, July 1975.
- 14 Ippolito LJ. "Characterization of the CTS 12 and 14 GHz Communications Links Preliminary Measurements and Evaluation," *International Conference on Communications: ICC'76*, June 1976.
- 15 *Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook)*, NTIA. Available at: [www.ntia.doc.gov/files/ntia/publications/redbook/2014-05/Manual\\_2014\\_Revision.pdf](http://www.ntia.doc.gov/files/ntia/publications/redbook/2014-05/Manual_2014_Revision.pdf) [accessed 5 October 2016].