CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Two developments in the twentieth century changed the way people lived: the automobile and telecommunications. Prior to the widespread availability of personal automobiles, individuals had to travel on foot, by bicycle, or on horseback. Trains provided faster travel between cities, but the lives of most people were centered on their hometowns and immediate surroundings. A journey of 100 miles was a major expedition for most people, and the easy mobility that we all take for granted in the twenty-first century was unknown. Before the telegraph and telephone came into widespread use, all communication was face-to-face, or in writing. If you wanted to talk to someone, you had to travel to meet with that person, and travel was slow and arduous. If you wanted to send information, it had to be written down and the papers hand carried to their destination.

Telecommunication systems have now made it possible to communicate with virtually anyone at any time. Early telegraph and telephone systems used copper wire to carry signals over the earth's surface and across oceans, and high frequency (HF) radio, also commonly called short wave radio, made possible intercontinental telephone links. Artificial earth satellites have been used in communications systems for more than 35 years and have become an essential part of the world's telecommunications infrastructure. Satellites allow people to talk by telephone and exchange electronic mail from anywhere in the world and to receive hundreds of TV channels in their homes.

The origins of satellite communications can be traced to an article written by Arthur C. Clarke in the British radio magazine *Wireless World* in 1945[1]. At the time, Clarke was serving in the British Royal Air Force, and was interested in long-distance radio communication. He later became famous as the author of *2001: A Space Odyssey*, and other science fiction books[2]. In 1945, HF radio was the only available method for radio communication over transcontinental distances, and it was not at all reliable. Sunspots and ionospheric disturbances could disrupt HF radio links for days at a time. Telegraph cables had been laid across the oceans as early as the mid-1800s, but cables capable of carrying voice signals across the Atlantic did not begin service until 1953. Clarke suggested that a radio relay satellite in an equatorial orbit with a period of 24 h would remain stationary with respect to the earth's surface and make possible long-distance radio links. At the time Clarke wrote, there were no satellites in orbit nor rockets powerful enough to launch them. But his ideas for what we now know as a geostationary satellite system were not science fiction, as the launch of the Russian satellite *Sputnik* in 1957 was to prove. In 1965 the first geostationary satellite, *Early Bird*, began to provide telephone service across the Atlantic Ocean, fulfilling Clarke's vision of 20 years earlier.

Satellite communication systems were originally developed to provide long-distance telephone service. In the late 1960s, launch vehicles had been developed that could place a 500 kg satellite in geostationary earth orbit (GEO), with a capacity of 5000 telephone circuits, marking the start of an era of expansion for telecommunication satellites. Geostationary satellites were soon carrying transoceanic and transcontinental telephone calls.

For the first time, live television links could be established across the Atlantic and Pacific oceans to carry news and sporting events.

The geostationary orbit is preferred for all high capacity communication satellite systems because a satellite in GEO appears to be stationary over a fixed point on the ground. It can establish links to one-third of the earth's surface using fixed antennas at the earth stations. This is particularly valuable for broadcasting, as a single satellite can serve an entire continent. Direct broadcast satellite television (DBS-TV) and the distribution of video signals for cable television networks are the largest single revenue source for geostationary satellites, accounting for $17 B in revenues in 1998. By year 2001, nearly 200 GEO communication satellites were in orbit, serving every part of the globe. Although television accounts for much of the traffic carried by these satellites, international and regional telephony, data transmission, and Internet access are also important. In the populated parts of the world, the geostationary orbit is filled with satellites every 2° or 3° operating in almost every available frequency band.

GEO satellites have grown steadily in weight, size, lifetime, and cost over the years. Some of the largest satellites launched to date are the KH and Lacrosse surveillance satellites of the U.S. National Reconnaissance Office weighing an estimated 13,600 kg (30,000 lb)[3]. By 2000, commercial telecommunications satellites weighing 6000 kg with lifetimes of 15 years were being launched into geostationary orbit at a typical cost around $125 M for the satellite and launch. The revenue earning capacity of these satellites must exceed $20 M per year for the venture to be profitable, and they must compete with optical fibers in carrying voice, data, and video signals. A single optical fiber can carry 4.5 Gbps, a capacity similar to that of the largest GEO satellites, and optical fibers are never laid singly but always in bundles. But GEO satellites can compete effectively on flexibility of delivery point. Any place within the satellite coverage can be served by simply installing an earth terminal. To do the same with a fiber-optic link requires fiber to be laid. Fiber-optic transmission systems compete effectively with satellites where there is a requirement for high capacity or, equivalently, when the user density exceeds the required economic threshold.

GEO satellites have been supplemented by low and medium earth orbit satellites for special applications. Low earth orbit (LEO) satellites can provide satellite telephone and data services over continents or over the entire world, and by 2000 three systems were in orbit or nearing completion, with a total of 138 LEO satellites. LEO satellites are also used for earth imaging and surveillance. Although not strictly a satellite communications system, the Global Positioning System (GPS), which uses 24 medium earth orbit (MEO)

SIDEBAR

The high capacity of both optical fibers and satellites, and the steady move of telecommunications traffic from analog signals to digital has lowered the cost of long-distance telephone calls and increased enormously the number of circuits available. In 1960, prior to the advent of satellite communications, the United States had 550 overseas telephone circuits. Calls to Europe cost more than $1 per minute at 1960 prices, and had to be placed through an operator, with delays of many hours being common. In 2000, virtually all international calls could be dialed by the end user, and rates to Europe had dropped to below $0.10 per minute.

To put the reduction in the cost of an international telephone call in perspective, we must remember that incomes have risen significantly over this time period. In the 1950s, a typical blue-collar wage was $1.50 per hour, so a blue-collar worker had to work for 40 min to pay for a call to Europe, ignoring any tax deductions. In 2000, the average worker in the United States earned $11.00 per hour, and had to work less than 1 min to pay for the international call. The United States now has hundreds of thousands of overseas telephone circuits, and video links daily carry live news reports from all over the globe.

satellites, has revolutionized navigation. GPS receivers have become a consumer product. Eventually every car and cellular telephone will have a GPS receiver built into it so that drivers will not get lost and emergency calls from cellular phones will automatically carry information about the phone's location.

1.2 A BRIEF HISTORY OF SATELLITE COMMUNICATIONS

Satellite communications began in October 1957 with the launch by the USSR of a small satellite called *Sputnik I*. This was the first artificial earth satellite, and it sparked the space race between the United States and the USSR. *Sputnik I* carried only a beacon transmitter and did not have communications capability, but demonstrated that satellites could be placed in orbit by powerful rockets. The first satellite successfully launched by the United States was *Explorer I*, lofted from Cape Canaveral on January 31, 1958 on a Juno I rocket. The first voice heard from space was that of President Eisenhower, who recorded a brief Christmas message that was transmitted back to earth from the Project Score satellite in December 1958. The *Score* satellite was essentially the core of the Atlas ICBM (intercontinental ballistic missile) booster with a small payload in the nose. A tape recorder on *Score* had a storage capacity that allowed a 4 min message received from an earth station to be retransmitted. The batteries on *Score* failed after 35 days in orbit.

After some early attempts to use large balloons (*Echo I* and *II*) as passive reflectors for communication signals, and some small experimental satellite launches, the first true communications satellites, *Telstar I* and *II*, were launched in July 1962 and May 1963. The Telstar satellites were built by Bell Telephone Laboratories and used C-band transponders adapted from terrestrial microwave link equipment. The uplink was at 6389 MHz and the downlink was at 4169 MHz, with 50-MHz bandwidth. The satellites carried solar cells and batteries that allowed continuous use of the single transponder, and demonstrations of live television links and multiplexed telephone circuits were made across the Atlantic Ocean, emphatically demonstrating the feasibility of satellite communications.

The Telstar satellites were launched into what is now called a medium earth orbit, with periods of 158 and 225 min. This allowed transatlantic links to operate for about 20 min while the satellite was mutually visible. The orbits chosen for the Telstar satellites took them through several bands of high energy radiation which caused early failure of the electronics on board. However, the value of communication satellites had been demonstrated and work was begun to develop launch vehicles that could deliver a payload to geostationary orbit, and to develop satellites that could provide useful communication capacity.

On July 24, 1961, U.S. President John F. Kennedy defined the general guidelines of U.S. policy in regard to satellite communications and made the first unambiguous references to a single worldwide system. On December 20, 1961, the U.S. Congress recommended that the International Telecommunications Union (ITU) should examine the aspects of space communications for which international cooperation would be necessary. The most critical step was in August 1962, when the U.S. Congress passed the *Communications Satellite Act*. This set the stage for commercial investment in an international satellite organization and, on July 19, 1964, representatives of the first 12 countries to invest in what became Intelsat (the International Telecommunications Satellite Organization) signed an initial agreement. The company that represented the United States at this initial signing ceremony was Comsat, an entity specifically created to act for the United States within Intelsat. It should be remembered that, at this point, the Bell System had a complete monopoly of all long-distance telephone communications within the United

States. When Congress passed the *Communications Satellite Act*, the Bell System was specifically barred from directly participating in satellite communications, although it was permitted to invest in Comsat.

Comsat essentially managed Intelsat in the formative years and should be credited with the remarkable success of the international venture. The first five Intelsat series of satellites (INTELSAT I through V) were selected, and their procurement managed, by teams put in place under Comsat leadership. Over this same phase, though, large portions of the Comsat engineering and operations groups transferred over to Intelsat so that, when the Permanent Management Arrangements came into force in 1979, many former Comsat groups were now part of Intelsat.

In mid-1963, 99% of all satellites had been launched into LEO. LEO, and the slightly higher medium earth orbit (MEO), were much easier to reach than GEO with the small launchers available at that time. The intense debate was eventually settled on launcher reliability issues rather than on payload capabilities. The first 6 years of the so-called space age was a period of both payload and launcher development. The new frontier was very risky, with about one launch in four being fully successful. The system architecture of the first proposed commercial communications satellite system employed 12 satellites in an equatorial MEO constellation. Thus, with the launch failure rate at the time, 48 launches were envisioned to guarantee 12 operational satellites in orbit. Without 12 satellites in orbit, continuous 24-h coverage could not be offered. Twenty-four hours a day, seven days a week—referred to as 24/7 operation—is a requirement for any successful communications service. A GEO systems architecture requires only one satellite to provide 24/7 operation over essentially one-third of the inhabited world. On this basis, four launches would be required to achieve coverage of one third of the earth; 12 for the entire inhabited world. Despite its unproven technological approach, the geostationary orbit was selected by the entities that became Intelsat.

The first Intelsat satellite, INTELSAT I (formerly *Early Bird*) was launched on April 16, 1965. The satellite weighed a mere 36 kg (80 lb) and incorporated two 6/4 GHz transponders, each with 25-MHz bandwidth. Commercial operations commenced between Europe and the United States on June 28, 1965. Thus, about 2 decades after Clarke's landmark article in *Wireless World*, GEO satellite communications began. Intelsat was highly successful and grew rapidly as many countries saw the value of improved telecommunications, not just internationally but for national systems that provided high quality satellite communications within the borders of large countries.

Canada was the first country to build a national telecommunication system using GEO satellites. Anik 1A was launched in May 1974, just 2 months before the first U.S. domestic satellite, WESTAR 1. The honor of the first regional satellite system, however, goes to the USSR Molniya system of highly elliptic orbit (HEO) satellites, the first of which was launched in April 1965 (the same month as INTELSAT I). Countries that are geographically spread like the USSR, which covers 11 time zones, have used regional satellite systems very effectively. Another country that benefited greatly from a GEO regional system was Indonesia, which consists of more than 3000 islands spread out over more than a thousand miles. A terrestrially based telecommunication system was not economically feasible for these countries, while a single GEO satellite allowed instant communications region wide. Such ease of communications via GEO satellites proved to be very profitable. Within less than 10 years, Intelsat was self-supporting and, since it was not allowed to make a profit, it began returning substantial revenues to what were known as its Signatories. Within 25 years, Intelsat had more than 100 Signatories[4] and, in early 2000, there were 143 member countries and Signatories that formed part of the international Intelsat community.

The astonishing commercial success of Intelsat led many nations to invest in their satellite systems. This was particularly true in the United States. By the end of 1983, telephone traffic carried by the U.S. domestic satellite systems earned more revenue than the Intelsat system. Many of the original Intelsat Signatories had been privatized by the early 1990s and were, in effect, competing not only with each other in space communications, but with Intelsat. It was clear that some mechanism had to be found whereby Intelsat could be turned into a for-profit, private entity, which could then compete with other commercial organizations while still safeguarding the interests of the smaller nations that had come to depend on the remarkably low communications cost that Intelsat offered. The first step in the move to privatizing Intelsat was the establishment of a commercial company called New Skies and the transfer of a number of Intelsat satellites to New Skies.

In the 1970s and 1980s there was rapid development of GEO satellite systems for international, regional, and domestic telephone traffic and video distribution. In the United States, the expansion of fiber-optic links with very high capacity and low delay caused virtually all telephone traffic to move to terrestrial circuits by 1985. However, the demand for satellite systems grew steadily through this period, and the available spectrum in C band was quickly occupied, leading to expansion into Ku band. In the United States, most of the expansion after 1985 was in the areas of video distribution and VSAT (very small aperture terminal) networks. By 1995 it was clear that the GEO orbit capacity at Ku band would soon be filled, and Ka-band satellite systems would be needed to handle the expansion of digital traffic, especially wide band delivery of high-speed Internet data. SES, based in Luxemburg, began two-way multimedia and Internet access service in western and central Europe at Ka band using the *Astra 1H* satellite in 2001[6]. Several Ka-band satellite systems are expected to be operational in the United States by 2003[7,8].

The ability of satellite systems to provide communication with mobile users had long been recognized, and the International Maritime Satellite Organization (Inmarsat) has provided service to ships and aircraft for several decades, although at a high price. LEO satellites were seen as one way to create a satellite telephone system with worldwide coverage; numerous proposals were floated in the 1990s, with three LEO systems eventually reaching completion by 2000 (Iridium, Globalstar, and Orbcomm). The implementation of a LEO and MEO satellite system for mobile communication has proved much more costly than anticipated, and the capacity of the systems is relatively small compared to

SIDEBAR

The first step in the move to privatizing Intelsat was the establishment of a commercial company called New Skies. New Skies is based in the Netherlands and, on 30 November 1998, six satellites were transferred from Intelsat ownership to New Skies. There was one INTELSAT V series satellite (*IS-513* at 183° E), one INTELSAT VII series satellite (*IS-703* at 57° E), two INTELSAT VIII series satellites (*IS-803* at 338.5° E and *IS-806* at 319.5° E), the INTELSAT-K satellite (in inclined orbit at 338.5° E), and a new satellite designed for direct broadcast services (*K-TV* at 95° E). New Skies has as their prime businesses plan the provisioning of TV services, both distribution and direct to home.

Intelsat is currently (2000) in the process of renewing its major assets through the purchase of up to seven INTELSAT IX satellites from SS-Loral to replace the current fleet of INTELSAT VI, and some of the INTELSAT VII, satellites. Each of these satellites carries the equivalent of 96 units of 36 MHz bandwidth. The satellites will be located at 62° E, 60° E, 335.5° E, 325.5° E, 332.5° E, 342° E, and 328.5° E. More details on the Intelsat fleet of satellites can be found at http://www.intelsat.int. Intelsat is moving forward with plans to privatize the remainder of the organization in the 2002/2003 time frame. Any reorganization will contain strong safeguards for smaller users to the system.

GEO satellite systems, leading to a higher cost per transmitted bit. Satellite telephone systems were unable to compete with cellular telephone systems because of the high cost and relatively low capacity of the space segment. The Iridium system, for example, cost over $5 B to implement, but provided a total capacity for the United States of less than 10,000 telephone circuits. Iridium Inc. declared bankruptcy in early 2000, having failed to establish a sufficiently large customer base to make the venture viable. The entire Iridium system was sold to Iridium Satellite LLC for a reported $25 M, approximately 0.5% of the system's construction cost. The future of the other LEO and MEO satellite telephone systems also seemed uncertain at the time this book was written.

Satellite navigation systems, notably the Global Positioning System, have revolutionized navigation and surveying. The Global Positioning System took almost 20 years to design and fully implement, at a cost of $12 B. By 2000, GPS receivers could be built in Original Equipment Manufacturer (OEM) form for less than $25, and the worldwide GPS industry was earning billions of dollars from equipment sales and services. In the United States, aircraft navigation will depend almost entirely on GPS by 2010, and blind landing systems using GPS will also be available. Accurate navigation of ships, especially in coastal waters and bad weather, is also heavily reliant on GPS. Europe is building a comparable satellite navigation system called Gallileo.

1.3 SATELLITE COMMUNICATIONS IN 2000

Tables 1.1, 1.2, and 1.3 list the majority of the GEO, MEO, and LEO communication satellites in orbit in 2000. The list is not exhaustive, and excludes satellites used solely for military communications and surveillance, and those used primarily for weather forecasting and earth imaging. Not all the communications satellites are included, and experimental and scientific satellites are omitted. In all, Tables 1.1 and 1.2 list a total of 172 geostationary communication satellites. When other satellites in geostationary orbit are considered, there were close to 200 GEO satellites in operation in 2000 (Table 1.4).

GEO satellites have always been the backbone of the commercial satellite communications industry. Large GEO satellites can serve one-third of the earth's surface, and can carry up to 4 Gbps of data, or transmit up to 16 high power direct broadcast satellite television (DBS-TV) signals, each of which can deliver several video channels. The weight and power of GEO satellites have also increased. In 2000 a large GEO satellite could weigh 10,000 kg (10 tons), might generate 12 kW of power, and carry 60 transponders, with a trend toward even higher powers but lower weight. For example, in 2001 Space System/Loral contracted with APT Satellite Company Ltd. in Hong Kong to build the Apstar-V satellite, a GEO satellite serving Asia with a mass of 4845 kg when injected into geostationary orbit and an expected lifetime of 13 years. Apstar-V will generate an initial power of 10.6 kW, and carry 38 C-band transponders with 60-W output power and 16 Ku-band transponders at 141 W each[5]. Satellites generating 25 kW and carrying antennas with hundreds of beams are planned for the time frame 2005–2010.

Television program distribution and DBS-TV have become the major source of revenue for commercial satellite system operators, earning more than half of the industry's $30 B revenues for 1998. By the end of 2000 there were over 14 million DBS-TV customers in the United States. The high capacity of GEO satellites results from the use of high-power terrestrial transmitters and relatively high gain earth station antennas. Earth station antenna gain translates directly into communication capacity, and therefore into revenue. *Increased capacity lowers the delivery cost per bit for a customer. Systems with fixed directional antennas can deliver bits at a significantly lower cost than systems using*

TABLE 1.1 GEO Satellite Systems: U.S. Operators (after 3, 6)

Organization	Satellites	Type	Transponders	Orbit location
American Mobile Satellite Corp., Reston, VA http://www.AmMobile.com	AMSC-1	Mobile land communications	16 L band	101° W
Columbia Communications Corp., Bethesda, MD http://www.tdrss.com	Columbia 515 (formerly Intelsat 515)	Telecommunications	12 C band 12 Ka band	37.7° W
	TDRSS-5, 6	Data relay	4, 12 C band	174.3° E, 47° W
Comsat Corp., Bethesda, MD http://www.comsat.com	Inmarsat 2F, 1–4	Mobile ship and aircraft communications	9 GEO satellites L band	Many locations
Comsat is the U.S. provider of Inmarsat and Intelsat services	Inmarsat 3F, 1–5		See Inmarsat entry	
	Intelsat	Telecommunications	19 GEO satellites C band and Ku band See Intelsat entry	Many locations
Directv Inc., El Segundo, CA http://www.directv.com	DBS-1, 2, 3, Directv-3R	Direct to home digital television broadcasting	Ku band BSS band DBS-1, 2, 3, 3R: 16 HP transponders	110° W 101° W
	Tempo 2		Tempo 2: 11 transponders	119° W
Echostar Communications Corp., Littleton, CO http://www.dishnetwork.com	Echostar 1–5	Direct to home digital television broadcasting	Ku band BSS band 16 transponders per satellite	Echostar 1, 2: 119° W Echostar 3: 61.5° W Echostar 4: 148° W Echostar 5: 110° W
GE Americom, Princeton, NJ http://www.geamericom.com	GE-1, 1A, 2–8	Telecommunications, video distribution, broadcasting, VSAT networks	24 C band Up to 28 Ku band	79° W through 139° W
	GE-1E		16 Ku band	5° E
	GE Gstar 4		16 Ku band	105° W

(continued)

TABLE 1.1 *(continued)*

Organization	Satellites*	Type	Transponders	Orbit location
	Satcom C-1, 3, 4, 5	GE-1A and GE-5 are designated for broadcasting only	24 C band	131° W through 139° W
	Satcom K-2		16 Ku band	85° W
	Spacenet 3, 4		18 C band 6 Ku band	85° W, 83° W
Loral Skynet, Bedminster, NJ http://www.loralskynet.com	Telstar 4, 5, 6, 7	Broadcasting, video distribution, telecommunications	24 C band 16 to 28 Ku band	89° W, 97° W, 93° W, 129° W
	Telstar 11, 12		34, 38 Ku band	37.5° W, 34° W
PanAmSat Corp., Greenwich, CT http://www.panamsat.com	Galaxy 1RR, 5, 6, 9	Telecommunications	24 C band	133° W, 125° W, 74° W, 123° W
	Galaxy 3R	Telecommunications	24 C band, 8 Ku band	95° W
	Galaxy 7	Telecommunications	8 C band, 32 Ku band	91° W
	Galaxy 8L	DBS-TV broadcasting to Latin America	Up to 24 C band Up to 36 Ku band	91° W
	PAS 1, 3R, 4, 5, 6B, 7	Telecommunications	16 C band, 16 Ku band 24 C band, 24 Ku band	43° W through 68.5° W
	PAS 2, 8	Telecommunications	36 Ku band	169° W, 166° W
	PAS 6	DBS-TV broadcasting to South America		43° W
	SBS-4, 5, 6	Telecommunications	14, 14, 19 Ku band	77° W, 123° W, 74° W
WorldSpace Corp., Washington, DC http://www.worldspace.com	AfriStar	Audio broadcasting	6 HP Ku band	21° E
	AmeriStar	Broadcasting		95° W
	AsiaStar	Broadcasting		105° E

* Telecommunications means any form of signal that can be sent through a satellite transponder, including analog and digital voice, data, and video.

For more complete information about these satellite systems consult reference 6.

There are 71 GEO satellites listed in the above table.

TABLE 1.2 GEO Satellite Systems: Non-U.S. and International Operators (after 3, 5)

Organization	Satellites	Type	Transponders	Orbit location
ACeS Asia Cellular Satellite, Indonesia www.acesinternational.com	Garuda 1	Mobile communications	140 with spot beams	123° E
Arab Satellite Communications Organization, Riyadh, Saudi Arabia www.arabsat.com	Arabsat 2A	Broadcasting	22 C band, 12 Ku band	26° E
	Arabsat 2B	Broadcasting, telecommunications	22 C band, 12 Ku band	30.5° E
	Arabsat 3A	Broadcasting	20 Ku band	26° E
Asia Broadcasting and Communications Network, Ltd., Bangkok, Thailand	L-Star 1	Broadcasting	32 Ku band	126° E
	L-Star 2	Telecommunications	32 Ku band	126° E
Asia Satellite Telecommunications Co. Ltd., Hong Kong, PRC www.asiasat.com	Asiasat 1	Broadcasting	24 C band	122° E
	Asiasat 2		24 C band, 9 Ku band	100.5° E
	Asiasat 3S	Telecommunications	28 C band, 16 Ku band	105.5° E
Broadcasting Satellite System Corp., Tokyo, Japan	BSat-1A, BSat-1B	DBS-TV	4 Ku band	110° E
	BS-3N	Broadcasting	3 Ku band	109.85° E
Deutsche Telekom Geschaftsbereich Rundfunk, Bon-Bad Godesburg, Germany www.dtag.de	DFS Kopernikus (1, 2)	Broadcasting, telecommunications	10 Ku band, 1 Ka band	23.5 ° E, 28.5° E
Embratel, Rio De Janiero, Brazil	Brasilsat A2	DBS-TV broadcasting	24 C band	92° W
	Brasilsat B1		28 C band, 1 X band	70° W
	Brasilsat B2		28 C band, 1 X band	65° W
	Brasilsat B3		28 C band	84° W

(continued)

TABLE 1.2 *(continued)*

Organization	Satellites	Type	Transponders	Orbit location
Eutelsat, Paris, France www.eutelsat.com	Eutelsat 1 F-4, F-5	Broadcasting, telecommunications	10 Ku band (+2 spare)	25.5° E, 21.5° E
	Eutelsat 2 F-1, F-2, F-3, F-4	Broadcasting, telecommunications	16 Ku band (+8 spare)	48° E, 12.5° E, 36° E 10° E 16° E, 7° E
	Eutelsat W2, W3	Broadcasting, telecommunications	24 Ku band	
	Hot Bird	DBS-TV	16 Ku band	13° E
	Hot Bird 2, 3, 4	DBS-TV	20 Ku band	All at 13° E
Inmarsat Ltd., London, UK www.inmarsat.org	Inmarsat 2F-1, 2F-2, 2F-3, 2F-4	Mobile telecommunications	L band, demand assigned	179° E, 98° W, 65° E 109° E
	Inmarsat 3F-1, 3F-2, 3F-3, 3F-4, 3F-5			64° E, 15.5° E, 178° E 54° W, 25° E
Intelsat, Washington, DC, USA www.intelsat.int	Intelsat 505	Broadcasting, telecommunications	21 C band, 6 Ku band	72° E
	Intelsat 510, 511		26 C band, 6 Ku band, 1 L band	33° E, 330.5° E
	Intelsat 601, 602, 603, 604, 605		64 C band, 24 Ku band	325.5° E, 62° E, 335.5° E 60° E, 332.5° E
	Intelsat 701, 702, 704, 705, 709		42 C band, 20 Ku band	180° E, 177° E, 66° E 342° E, 310° E
	Intelsat 706, 707	Broadcasting, telecommunications	42 C band, 28 Ku band	307° E, 359° E
	Intelsat 801, 802, 804		64 C band, 12 Ku band	328.5° E, 174° E, 64° E
	Intelsat 805		36 C band, 6 Ku band	304.5° E
Japan Satellite Systems Inc., Tokyo, Japan www.jcsat.co.jp	JCSat-1B, JCSat-2	Telecommunications	32 Ku band	150° E, 154° E
	JCSat-3	Broadcasting	12 C band, 28 Ku band	128° E
	JCSat-4A	Telecommunications	32 Ku band	124° E
Korea Telecom, Korea www.kt.co.kr	Koreasat 1, 2	Broadcasting	15 Ku band	116° E, 113° E
	Koreasat 3	Telecommunications	30 Ku band, 3 Ka band	116° E
Mabuhay Philippines Satellite Corp., Makati City, Philippines	Agila 2	DBS-TV, broadcasting, telecommunications	30 C band, 24 Ku band	146° E
NahuelSat, SA, Buenos Aires, Argentina www.nahuelsat.com.ar	Nahuel 1	Broadcasting	18 Ku band	71.8° W
	Nahuel 2	Telecommunications	46 C band, 36 Ku band	81° W
New Skies Satellites, N.V., The Hague, Netherlands www.newskiessat.com	NS 513	Telecommunications	42 C band, 12 Ku band	183° E
	NSS 703	Broadcasting, telecommunications	46 C band, 20 Ku band	57° E
	NSS 803	Broadcasting, telecommunications	64 C band, 12 Ku band	21.5° W
	NSS 806	Broadcasting, telecommunications	36 C band, 6 Ku band	40.5° W
	NSS K	Broadcasting, telecommunications	16 Ku band	21.5° W
PT Pasifik Satelit Nusantara, Bekasi, Indonesia www.psn.co.id	Garuda 1	Mobile communications	140 spot beams	123° E
	Palapa C1	Broadcasting, telecommunications	4 Ku band	113° E
Sino Satellite Communications Co., Ltd., Beijing, PRC www.sinosat.com	SinoSat 1	Broadcasting, telecommunications	24 C band, 14 Ku band	123° E
Societe Europenne des Satellites, SA (SES), Betzdorf, Luxembourg www.astra.lu	Astra 1A, 1B	DBS-TV, multimedia	16 Ku band	19.2° E
	Astra 1C, 1D	DBS-TV, multimedia	20 Ku band	19.2° E
	Astra 1E, 1F	DBS-TV, multimedia	20, 22 Ku band	19.2° E
	Astra 1G	DBS-TV, multimedia	30 Ku band	19.2° E
	Astra 2A, 2B	DBS-TV, multimedia	32, 30 Ku band	28.2° E
	Astra 2G	DBS-TV, multimedia	16 Ku band	28.2° E

(continued)

TABLE 1.2 *(continued)*

Organization	Satellites	Type	Transponders	Orbit location
Space Communications Corp., Tokyo, Japan www.superbird.co.jp	Superbird A	Broadcasting, telecommunications	23 Ku band, 2 Ka band	158° E
	Superbird B		23 Ku band, 2 Ka band	162° E
	Superbird C		23 Ku band, 2 Ka band	144° E
Spacecom Satellite Communication Services, Ramat-Gan, Israel www.spacecom.co.il	Amos 1	DBS-TV, telecommunications	7 Ku band	4° W
Swedish Space Corp., Solna, Sweden www.ssc.se	Sirius 1	DBS-TV	6 Ku band	5° E
	Sirius 2	DBS-TV, VSAT networks	32 Ku band	5° E
	Sirius 3	DBS-TV	15 Ku band	
Telenor Satellite Services AS, Oslo, Norway www.telenor.com	Thor 1	Broadcasting, telecommunications	5 Ku band	1° E
	Thor 2		15 Ku band	1° E
	Thor 3		14 Ku band	1° E
Telesat Canada, Gloucester, ON, Canada www.telesat.ca	Anik E1	Broadcasting, telecommunications	14 C band, 12 Ku band	111.1° W
	Anik E2		14 C band, 12 Ku band	107.3° W
TMI Communications, Ottawa, Canada www.tmisolutions.com	MSat 1	Mobile communications	16 L band, 1 Ku band	106.5° W
Turk Telekom, Ankara, Turkey	Turksat 1B, 1C	Broadcasting, telecommunications		31.3° E, 42° E

There are 101 satellites listed in Table1.2.

TABLE 1.3 LEO and MEO Satellite Systems (after 3, 5)

Organization	Satellites	Type	Transponders	Constellation orbit
Globalstar, San Jose, CA, USA www.globalstar.com	48 LEO satellites with four spares in orbit	Mobile communications, satellite telephones, all digital	16 spot beams within footprint. Each beam has multiple 1.25-MHz channels with 1 to 13 channels per beam. Multiple access through CDMA. L- and S-band links to mobiles	Six orbital planes inclined at 52°, eight satellites per plane 1413 km altitude (763 nm)
Iridium LLC, Washington, DC, USA www.iridium.com	66 LEO satellites with seven spares in orbit	Mobile communications, satellite telephones, all digital	48 spot beams with seven RF channels in 8 MHz. L-band links to mobiles. Ka-band links to Gateways. 22 GHz satellite cross links. Multiple access through FDMA/TDMA	Six orbital planes inclined at 84.6°, eleven satellites per plane 898 km altitude (485 nm)
Orbcomm Global L.P., Dulles, VA, USA www.orbcomm.com	28 LEO satellites	Data transmission to handheld and mobile terminals	Bent pipe transponder with earth coverage beams. Data rate up to 2400 bps in 0.1-s bursts vhf links to mobiles (uplink 148 MHz, downlink 137 MHz)	24 satellites in 45° inclined orbits. Two in 70° inclined orbits, two inclined 108°

TABLE 1.4 Other Satellite Systems

System	Satellites	Type and lifetime	Application	Orbits
Global positioning System (GPS), operated by U.S. Air Force	Navstar GPS 13 through 21	Design lifetime 7.5 years	Navigation, early warning	Six orbital planes with four satellites per plane at 20,200 km altitude. Inclination of orbital plane is 55°
	22 through 40	Design lifetime 10 years		
Useful web sites: www.navcen.uscg.mil www.laafb.af.mil/SMC/CZ/homepage/ http://gps.faa.gov/ http://www.spacecom.af.mil	43, 44, 45	Design lifetime 10 years		
		All satellites broadcast CDMA signals on two L-band frequencies		

low gain antennas, such as those designed for use by mobile users. Consequently, GEO satellites look set to be the largest revenue earners in space for the foreseeable future. Figure 1.1 shows the estimated growth in revenue from all satellite communication services, projected to 2010.

All radio systems require frequency spectrum, and the delivery of high-speed data requires a wide bandwidth. Satellite communication systems started in C band, with an allocation of 500 MHz, shared with terrestrial microwave links. As the GEO orbit filled up with satellites operating at C band, satellites were built for the next available frequency band, Ku band. There is a continuing demand for ever more spectrum to allow satellites to provide new services, with high speed access to the Internet forcing a move to Ka-band and even higher frequencies. Access to the Internet from small transmitting Ka-band earth stations located at the home offers a way to bypass the terrestrial telephone network and achieve much higher bit rates. SES began two-way Ka-band Internet access in Europe in 1998 with the Astra-K satellite, and the next generation of Ka-band satellites in the United States will offer similar services.

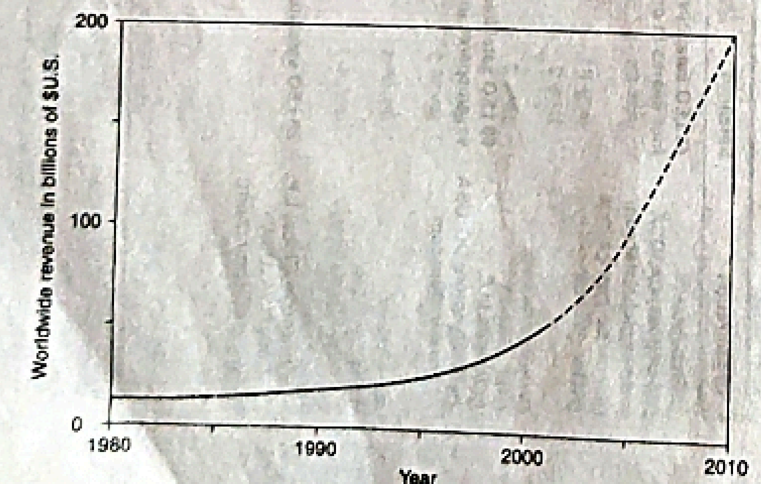

FIGURE 1.1 *Growth of worldwide revenues from satellite communications 1980 through 2010. Beyond 2000, the curve is a projection.*

Successive World Radio Conferences have allocated new frequency bands for commercial satellite services that now include L, S, C, Ku, K, Ka, V, and Q bands. Mobile satellite systems use vhf, uhf, L, and S bands with carrier frequencies from 137 to 2500 MHz, and GEO satellites use frequency bands extending from 3.2 to 50 GHz. Despite the growth of fiber-optic links with very high capacity, the demand for satellite systems continues to increase. Satellites have also become integrated into complex communications architectures that use each element of the network to its best advantage. Examples are VSAT/WLL (very small aperture terminals/wireless local loop) in countries where the communications infrastructure is not yet mature and GEO/LMDS (local multipoint distribution systems) for the urban fringes of developed nations where the build-out of fiber has yet to be an economic proposition.

1.4 OVERVIEW OF SATELLITE COMMUNICATIONS

Satellite communication systems exist because the earth is a sphere. Radio waves travel in straight lines at the microwave frequencies used for wideband communications, so a *repeater* is needed to convey signals over long distances. Satellites, because they can link places on the earth that are thousands of miles apart, are a good place to locate a repeater, and a GEO satellite is the best place of all. A repeater is simply a receiver linked to a transmitter, always using different radio frequencies, that can receive a signal from one *earth station*, amplify it, and retransmit it to another earth station. The repeater derives its name from nineteenth century telegraph links, which had a maximum length of about 50 miles. Telegraph repeater stations were required every 50 miles in a long-distance link so that the Morse code signals could be re-sent before they became too weak to read.

The majority of communication satellites are in geostationary earth orbit, at an altitude of 35,786 km. Typical path length from an earth station to a GEO satellite is 38,500 km. Radio signals get weaker in proportion to the square of the distance traveled, so signals reaching a satellite are always very weak. Similarly, signals received on earth from a satellite 38,500 km away are also very weak, because of limits on the weight of GEO satellites and the electrical power they can generate using solar cells. It costs roughly $25,000 per kilogram to get a geostationary satellite in orbit. This obviously places severe restrictions on the size and weight of GEO satellites, since the high cost of building and launching a satellite must be recovered over a 10 to 15 year lifetime by selling communications capacity.

Satellite communication systems are dominated by the need to receive very weak signals. In the early days, very large receiving antennas, with diameters up to 30 m, were needed to collect sufficient signal power to drive video signals or multiplexed telephone channels. As satellites have become larger, heavier, and more powerful, smaller earth station antennas have become feasible, and Direct Broadcast Satellite TV (DBS-TV) receiving systems can use dish antennas as small as 0.5 m in diameter.

Satellite systems operate in the microwave and millimeter wave frequency bands, using frequencies between 1 and 50 GHz. Above 10 GHz, rain causes significant attenuation of the signal and the probability that rain will occur in the path between the satellite and an earth station must be factored into the system design. Above 20 GHz, attenuation in heavy rain (usually associated with thunderstorms) can cause sufficient attenuation that the link will fail.

For the first 20 years of satellite communications, analog signals were widely used, with most links employing frequency modulation (FM). Wideband FM can operate at low carrier-to-noise ratios (C/N), in the 5 to 15 dB range, but adds a signal-to-noise improvement so that video and telephone signals can be delivered with signal-to-noise ratios (S/N) of 50 dB. The penalty for the improvement is that the radio frequency (RF) signal occupies a much larger bandwidth than the baseband signal. In satellite links, that penalty results because signals are always weak and the improvement in signal-to-noise ratio is essential.

The move toward digital communications in terrestrial telephone and data transmission has been mirrored by a similar move toward digital transmission over satellite links. In the United States, only TV distribution at C band remains as the major analog satellite transmission system. Even this last bastion of analog signaling seems destined to disappear as cable TV stations switch over to digital receivers that allow six TV signals to be sent though a single Ku-band transponder. More importantly, dual standards permitting the transmission of not only digital TV but also high definition TV (HDTV), will eventually remove analog TV from consideration.

Almost all other signals are digital—telephony, data, DBS-TV, radio broadcasting, and navigation with GPS all use digital signaling techniques. All of the LEO and MEO mobile communication systems are digital, taking advantage of voice compression techniques that allow a digital voice signal to be compressed into a bit stream at 4.8 kbps. Similarly, MPEG 2 (Moving Picture Coding Expert Group) and other video compression techniques allow video signals to be transmitted in full fidelity at rates less then 6.2 Mbps.

1.5 SUMMARY

Satellite communication systems have become an essential part of the world's telecommunications infrastructure, serving billions of people with telephone, data, and video services. Despite the growth of fiber-optic links, which have much greater capacity than satellite systems and a lower cost per bit, satellite systems continue to thrive and investment in new systems continues. Satellite services have shifted away from telephony toward video and data delivery, with television broadcasting directly to the home emerging as one of the most powerful applications. GEO satellites carry the majority of services, because the use of high gain fixed antennas at earth stations maximizes the capacity of the satellite. Over the years, there has been a trend away from trunk communications using very large earth station antennas toward delivery from more powerful satellites to individual users using much smaller antennas. LEO and MEO satellites are used for mobile communications and navigation systems and, as the need for Geographic Information Systems grows with a variety of applications, LEO earth imaging satellites have the potential to provide strong revenue streams.

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CHAPTER 2

ORBITAL MECHANICS AND LAUNCHERS

2.1 ORBITAL MECHANICS

Developing the Equations of the Orbit

This chapter is about how earth orbit is achieved, the laws that describe the motion of an object orbiting another body, how satellites maneuver in space, and the determination of the look angle to a satellite from the earth using ephemeris data that describe the orbital trajectory of the satellite.

To achieve a stable orbit around the earth, a spacecraft must first be beyond the bulk of the earth's atmosphere, i.e., in what is popularly called space. There are many definitions of space. U.S. astronauts are awarded their "space wings" if they fly at an altitude that exceeds 50 miles (~80 km); some international treaties hold that the space frontier above a given country begins at a height of 100 miles (~160 km). Below 100 miles, permission must be sought to over-fly any portion of the country in question. On reentry, atmospheric drag starts to be felt at a height of about 400,000 ft (~76 miles ≈ 122 km). Most satellites, for any mission of more than a few months, are placed into orbits of at least 250 miles (≈400 km) above the earth. Even at this height, atmospheric drag is significant. As an example, the initial payload elements of the International Space Station (ISS) were injected into orbit at an altitude of 397 km when the shuttle mission left those modules on 9 June 1999. By the end of 1999, the orbital height had decayed to about 360 km, necessitating a maneuver to raise the orbit. Without onboard thrusters and sufficient orbital maneuvering fuel, the ISS would not last more than a few years at most in such a low orbit. To appreciate the basic laws that govern celestial mechanics, we will begin first with the fundamental Newtonian equations that describe the motion of a body. We will then give some coordinate axes within which the orbit of the satellite can be set and determine the various forces on the earth satellite.

Newton's laws of motion can be encapsulated into four equations:

$$s = ut + (\tfrac{1}{2})at^2 \tag{2.1a}$$

$$v^2 = u^2 + 2at \tag{2.1b}$$

$$v = u + at \tag{2.1c}$$

$$P = ma \tag{2.1d}$$

where s is the distance traveled from time $t = 0$; u is the initial velocity of the object at time $t = 0$ and v the final velocity of the object at time t; a is the acceleration of the object; P is the force acting on the object; and m is the mass of the object. Note that the acceleration can be positive or negative, depending on the direction it is acting with respect to the velocity vector. Of these four equations, it is the last one that helps us understand the motion of a satellite in a stable orbit (neglecting any drag or other perturbing forces). Put into words, Eq. (2.1d) states that the force acting on a body is equal to the mass of