Chapter 1

Introduction and Some Historical Background

"How I Lost a Billion Dollars in My Spare Time" is the partial title of (now Sir) Arthur C. Clarke's 1965 essay on how and why he did not (and probably could not) patent the idea of a geostationary communications satellite, which he detailed and publicized in 1945. For one thing, he expected it to be at least 50 years in the future! The marvel is that Sir Arthur (Fig. 1.1) survived to see his concept fulfilled by approximately 250 geostationary commercial communications satellites ringing the globe.

Most people consider Clarke to be the father of the communications satellite. He, however, considers himself the godfather, and considers the fathers to be the two scientists who more fully developed the technical concepts, Dr. John R. Pierce (Fig. 1.2) and Dr. Harold Rosen. Nonetheless, the unique orbit around our planet

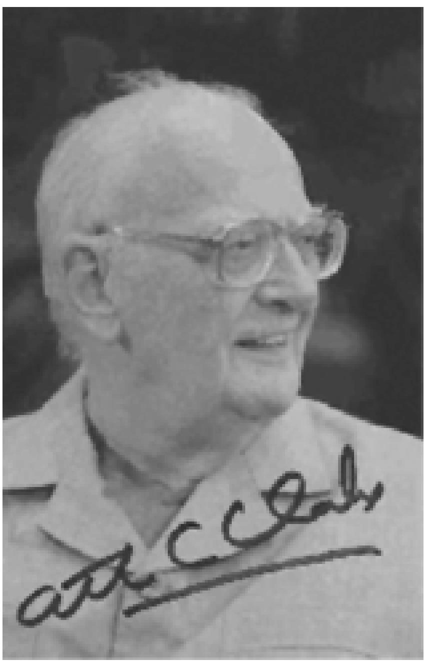

Figure 1.1 Sir Arthur C. Clarke (Photograph courtesy of the Arthur C. Clarke Foundation.)

Figure 1.2 John R. Pierce (Photograph courtesy of Lucent.)

where satellites seem to be stationary as seen from the surface is universally honored as the Clarke orbit.

As Clarke himself says, the concept is simple and capable of being understood through orbital physics. Although Newton could have come up with the idea, he doesn't seem to have done so. In the nineteenth century, a foresighted writer described a (brick!) satellite that communicated to Earth by having people on the satellite jump up and down (they didn't know much about the vacuum of space then). The brilliant and pioneering German, Hermann Oberth, wrote of communicating with manned satellites by mirrors and lights in 1923 when radio was still in its infancy. Other writers, including a little-known Austrian army officer named Hermann Potocnik (who also wrote science fiction under the pen name of Hermann Noordung) had proposed a manned space station in his 1928 book *The Problem of Spaceflight*, placing it in a geostationary orbit to facilitate radiocommunications with Earth. Finally, in 1942, engineer-writer George O. Smith proposed a radio relay satellite in Venus' orbit to permit communication between that planet and Earth when they were on opposite sides of the sun.

Clarke's contribution is his description of the technical characteristics of a geostationary communications satellite (Fig. 1.3). First published in 1945, his articles brought together his interests and technical knowledge of radio and space flight (not to mention science fiction, of which genre he is a master) with his ability to write. In fact, Clarke's article is still somewhat prescient: he not only suggested radio links with Earth, but also suggested what we call intersatellite links today. While some government satellites make use of intersatellite links in geostationary orbits, commercial satellites in geosynchronous orbit are just beginning to use them because they make the satellite system much more expensive. Some low-orbit satellites do use such links.

The major advantages of satellites in geostationary orbit, as we will detail more fully in later chapters, is twofold: coverage and simplicity. Each Clarke-orbit satellite sees about 44% of the total surface of the earth, which aggregates a huge

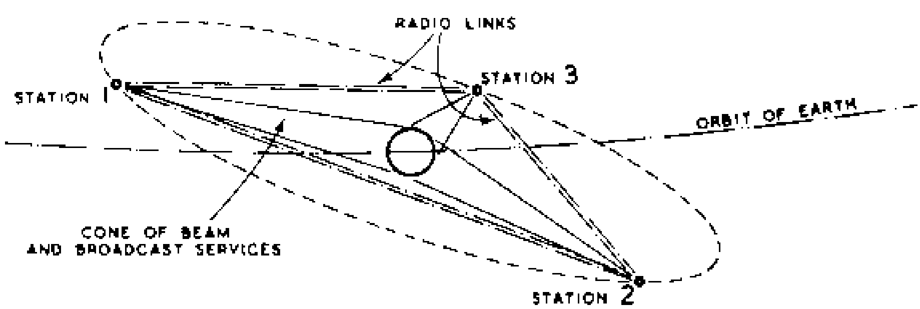

Fig. 3. Three satellite stations would ensure complete coverage of the globe.

Figure 1.3 Arthur C. Clarke's diagram from his seminal article in *Wireless World* magazine, October 1945, showing the concept of geostationary radio relay stations. (Photograph courtesy of Electronics World, Cambridge, U.K.)

market. Since the satellites appear stationary in the sky as seen from an earthstation, the stations can be simpler, and thus less expensive, as they can be pointed once at a satellite and not have to track it across the sky.

Rocketry and electronics progressed much faster than even futurists like Clarke foresaw. Twelve years after Clarke's article, on October 4,1957, the Soviet Union launched Sputnik-1 as the first artificial satellite. The first active communications satellite came only 14 months later. Note that by "active" we mean a satellite that has a transmitter aboard to relay a radio signal to Earth, not just a passive reflector like the Echo balloon satellite that came a couple of years later.

Project SCORE, which stood for "signal communications by orbital relay equipment," was a wire recorder in the nosecone of an Atlas missile, launched December 18, 1958, to an orbit just a few hundred miles up. It was battery-powered and broadcast holiday greetings recorded by President Dwight Eisenhower to the world. The mission lasted only a few weeks before the batteries ran out and the missile plunged back to Earth. Simple and crude, it was the first active commsat (as opposed to Comsat, which is a trademarked company name).

The next step in satellite communications was the Echo balloon, launched August 12, 1960. This 30-m-diameter aluminum-covered sphere reflected radio waves back to Earth. (It also reflected light well and was one of the visually brightest satellites ever to appear in our skies.) It stayed in orbit until 1968.

The first commercial satellite went into orbit on July 10, 1962, when AT&T launched Telstar-1 (Fig. 1.4). At that time, rockets still did not have the power to reach the geosynchronous orbit, and Telstar orbited only several hundred miles above

Figure 1.4 Telstar-1, the first commercial (but non-geostationary) communications satellite, built by AT&T. (Photograph courtesy of Lucent Technologies, Bell Labs.)

Earth. Because of its low altitude, like Echo and Project SCORE before it, it could link sites on Earth only a few thousand miles apart. (It's still up there, for another 100 centuries at least.) It required a huge tracking antenna to communicate with the satellite.

Finally, on February 14, 1963, the Syncom-1 ("synchronous communications") reached the geosynchronous altitude of roughly 36,000 km (23,000 miles). Although the satellite went around Earth in one day—and was therefore geosynchronous—its orbit was not over the equator so it was therefore not truly geostationary. It was followed later that year by Syncom-2, and the next year by Syncom-3, which finally achieved an almost perfectly circular orbit over the equator, making it the first geostationary commsat. Syncom-3 could carry only one television signal, and was used to relay the opening ceremonies of the 1964 Tokyo Olympics to North America.

On April 6, 1965, the Communications Satellite Corporation, later named Comsat, launched "Early Bird" (Fig. 1.5). At 8:40:25 EST, Early Bird was injected into the Clarke orbit, with a final small rocket firing to make it the first truly commercial geostationary communications satellite. Later renamed Intelsat-1, the 39-kg satellite could carry 240 telephone calls or 1 television signal. That may not sound like a lot of telephone circuits now, but at the time it was almost 10 times the number of telephone circuits available on the trans-Atlantic analog cables. Commercial users paid $4,200 per month ($23,000 in today's dollars) for a two-way leased telephone circuit on "Early Bird," and paid $2,400 for a half-hour television transmission.

The year 1965 also saw the launch of the U.S. Department of Defense's first military communications satellite and the first Molniya satellite from the Soviet Union.

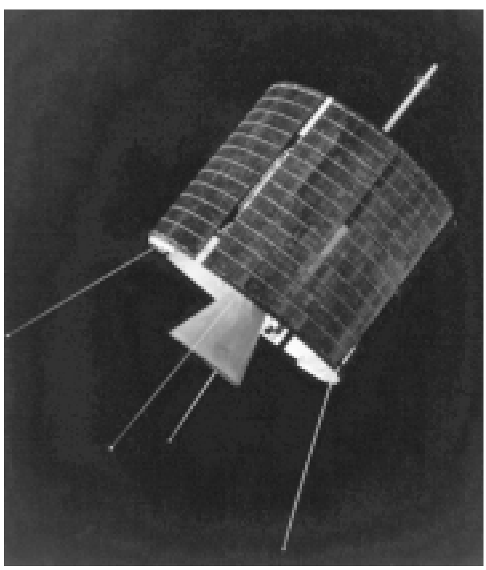

Figure 1.5 Intelsat-1, nicknamed "Early Bird." This was the first commercial geostationary communications satellite, launched in 1965. It could carry 240 telephone channels, or one television picture. (Photograph courtesy of Intelsat Global Service Corp.)

Chapter 11

Orbital Slots, Frequencies, Footprints, and Coverage

Since all GSO satellites are in an orbit lying over the earth's equator, the way to refer to such a satellite's orbital position is by the longitude over which it remains stationary. The location on Earth's surface directly below any satellite is called the *subsatellite point*. For GSO satellites, these are always on the equator. The position in orbit, denoted by its longitude, is called the *satellite slot*. See Fig. 11.1.

11.1 Satellite longitude and spacing

Confusingly, there are two common ways of measuring a satellite's longitude. The preferred method is to begin counting at the Greenwich Meridian of 0° longitude,

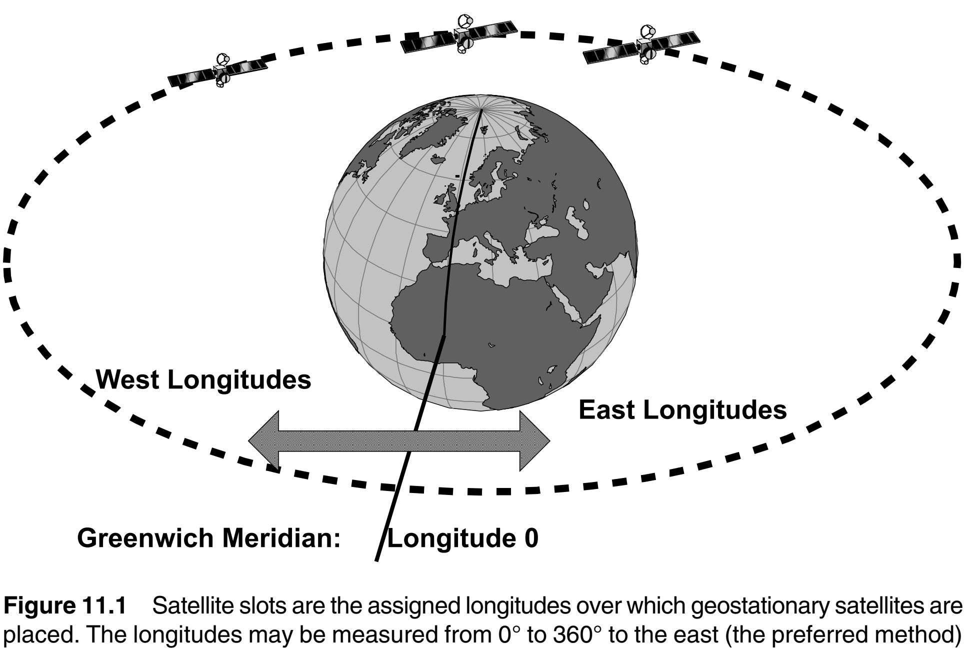

Figure 11.1 Satellite slots are the assigned longitudes over which geostationary satellites are placed. The longitudes may be measured from 0° to 360° to the east (the preferred method) or to the west, or from 0° to 180° east and west, measured from the Greenwich Meridian of 0° longitude.

and increase toward the east, all the way around to 360°. This is the method always used by the International Telecommunication Union, and by European and Asian nations. When it is not clear that such an east-going longitude is being used, the satellite's longitude is followed by the letter E. Thus the satellite PAS-4 is at longitude 64.5°E, over the Indian Ocean.

Many people in the Americas, however, prefer to measure from the Greenwich Meridian westward, and the satellite's longitude is followed by the letter W. To convert an east longitude to a west longitude, or vice versa, subtract from 360°. For example, Orion-1 is at 37.5°W, which is the same as 322.5°E, over the Atlantic Ocean.

Sometimes people measure only 180° both east and west. If you are compiling a list of GSO satellites visible from some earthstation, you have to be careful when using more than one source: you can erroneously end up with twice as many satellites as there really are.

Sometimes only an approximate location for a GSO satellite is all that is required to specify its area of service. One common group of abbreviations is to name the ocean over which the satellite orbits: *AOR* for Atlantic Ocean Region, *IOR* for Indian Ocean Region, and *POR* for Pacific Ocean Region. Sometimes these regions may be further subdivided, such as AOR-East and AOR-West.

Like frequencies, orbital slots are allocated by the ITU, and then assigned by individual nations. Because there is only a single Clarke Orbit, it is considered to be a limited natural resource and the "common heritage of mankind." There are no rights to ownership of orbital slots.

Each kind of satellite service—such as fixed services, mobile services, and broadcast services—is assigned specific ranges of frequencies to use. For instance, there are C-band fixed services, Ku-band for both fixed services and a different part of the Ku-band for broadcast services, and the newer Ka-band for fixed and mobile services. It would be a waste of valuable spectrum to allow a single satellite to exclusively use a specific frequency band, so all satellites operating in a given service and frequency band use the same range of frequencies.

This naturally means that satellites could potentially interfere with one another if an earthstation cannot distinguish between the signals from two satellites using the same frequencies, or if the uplink beam from an earthstation is so broad that it hits more than one satellite. It is important to remember that, with minor exceptions, *all satellites operating in a specific service are sharing the exact same frequencies.*

Some satellites operate in two or more frequency bands; these are often called *hybrid* satellites. For example, some mobile communications satellites connect to gateway stations in the C-band, but connect with the mobile users in L-band or S-band. Some fixed-service satellites have a mix of C-, Ku-, X-, L-, and/or Ka-band transponders for versatility. This adds to the difficulty of minimizing interference between satellites.

An analogous situation on Earth is that of broadcast radio and television stations. For example, all FM radio stations in the United States broadcast in the 88–108 MHz band of frequencies, each station's assigned frequency is centered on an odd decimal place (e.g., 101.1, 101.3, 101.5, etc.), and each has the same 0.2 MHz bandwidth as every other FM station. However, they may differ in transmitter power from one another. Television channels are always the same frequency, no matter what city the station is in. For example, every U.S. television channel 13 uses the frequency range of 210–216 MHz.

So—how to keep the stations from interfering with one another?

11.1.1 Orbital spacing

For both terrestrial stations and satellites sharing identical frequencies, the twofold answer is the same: limit the power transmitted, and keep a minimum physical separation between them. Thus, you can have a television station on Channel 2 in Miami and another on the same channel in Baltimore because their power is limited and they are well separated. Thus, you can have a C-band satellite located at orbital slot 221°E and at 223°E.

In orbit, the physical separation is termed *orbital spacing* (Fig. 11.2). The actual spacing between similar satellites varies greatly, and the minimum that can be tolerated without interference varies with the frequency, satellite power, satellite beam patterns, earthstation dish size, satellite polarization and orientation, and other

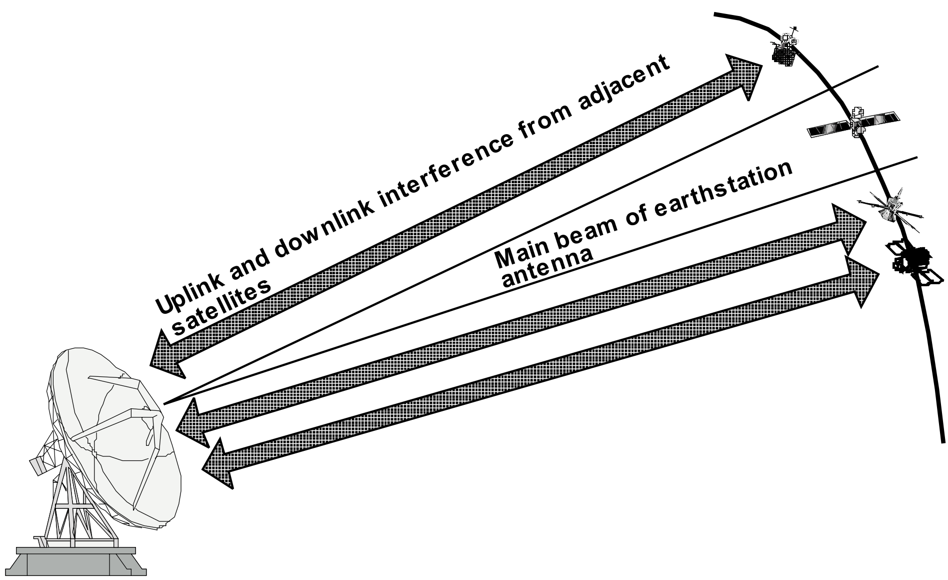

Figure 11.2 Satellite spacing. An antenna beam from an earthstation may be several degrees wide. If satellites are spaced too closely together in orbit, the beam may cover not only the intended satellite, but adjacent ones, creating interference. Note that the problem is one of electronic collision, not physical collision. The ITU suggests a spacing of 2°. Because beamwidth varies with frequency, satellites using the lower frequency bands need to be spaced farther apart than do ones using the higher-frequency bands.

factors. The complex and contentious topic of minimizing interference is called *frequency coordination.* (The problem of coordinating—minimizing interference—between GSO systems is bad enough; it is a much more complex task to coordinate problems between non-GSO systems and between non-GSO and GSO systems.)

The goal is to maximize the use of the Clarke orbit though control of the spacing of the satellites and their transmission characteristics. Proper choice of modulation, multiplexing, and error control affect how closely satellites may be spaced, and how strong their signals may be. For example, for analog signals, frequency modulation with a wide swing of frequencies around the center frequency (technically called a high-modulation index) promotes spectral efficiency in the GSO. For digital signals, using four- or eight-phase shift-keying is most efficient. Other techniques such as compression also affect how much total traffic a satellite can carry.

The problem is partially caused by the fact—as we will see in more detail in Chapter 16—that when an earthstation dish is pointed at a satellite, the beam or range of directions into which it sends a transmitted uplink radio signal, or from which it is sensitive to receive downlink radio signals, is not a perfectly cylindrical shape. Instead, it is actually a cone of directions that may be several degrees wide. This is called the antenna's *beamwidth*. If other satellites lie in this cone, the uplinked signal will be seen by the intended satellite and also by the nearby ones as well, causing them *uplink interference*. Similarly, the downlink signals from these nearby satellites will also be received by the earthstation along with the signal from the intended satellite, causing the earthstation *downlink interference*.

As an analogy, think of shining a flashlight on a wall. The lightbeam will be brightest in the center and drop off in intensity away from the center. If the flashlight was an earthstation, any satellite within the beam, not just at the center, would be getting some signal. The same is true in reverse, if the flashlight was a telescope receiving signals. All real-world transmitters and receivers, except for some lasers, have a range of angles into which they send and from which they can receive.

Another analogy may help explain this situation. You may have had the experience of driving a car at night on a long, straight, flat highway. Occasionally you see a light approaching you. If the other vehicle is very far away, you don't know if it is a motorcycle with a single headlamp or a car with two headlamps spaced a couple of meters apart. That is because there is a "beamwidth" for your eye, and if two objects are less than this angle apart, you cannot distinguish them as distinct objects. Only when the object gets closer do you discover if it was one light or two. To continue this analogy, assume it is a car with two headlamps, and now pretend that for some reason each light is sending you a message blinked in Morse code. Of course, when that car is close enough, you can focus on one or the other headlight and get the message; but when the car is too far away to distinguish between the two "signals," you get a mix of both and thus, your received signal is so noisy that you cannot tell one message from the other. The same thing happens if the receiving beam of an earthstation is so broad that two (or more) satellites are within the beam.

11.2 Once around the Clarke orbit

If we do a simple calculation to see just how much space we have available along the Clarke orbit, we have a circumference of about 265,000 km. Dividing by the 360° in a circle, we find that each degree along the orbit is about 740 km, or 460 miles. Since typical earthstation beamwidths are often a degree or more, we see that satellites at the same frequency must be typically spaced a few degrees apart along the orbit. If satellites are spaced a few degrees apart as seen from Earth, that means that their real physical separation in space is hundreds, even thousands, of kilometers. It is important to realize, then, that the need for satellite spacing comes about because of potential electronic interference between them, not because of possible collision of the satellites.

Another technique can be used to allow satellites to be spaced close together without interference. If two closely spaced satellites have same-frequency antenna beam patterns pointed at different regions of the earth, then they will not interfere, because an earthstation in one region will not be able to see the satellite beam pointed to the other region. This is called *frequency re-use*.

The problem with interference between satellites operating in the same band is that they all operate on exactly the same frequencies. However, satellites operating in different frequency bands, say C-band and Ku-band, will not interfere. Thus, they could be placed at approximately the same orbital slot. This is called *co-location.* It is conceptually equivalent to having the antennas of several radio stations attached to one tower; they don't interfere because each is on a separate frequency. By a combination of different frequencies and different beams, one orbital location can host several satellites.

The ITU suggests that ideally, FSS satellites should be able to be spaced 2° apart to maximize the number of satellites in the GSO. (National regulatory authorities, especially the FCC in the U.S., have also adopted their own spacing regulations for satellites.) This is not always possible for many reasons. But if it could be adhered to, this would mean that the maximum possible number of such satellites at a given frequency is 180. (The typical spacing is actually about 3°.)

This simplistic answer is totally pointless because we have not taken one paramount item into consideration: to be useful, a satellite has to be visible from an earthstation. Thus, a satellite over the Pacific Ocean is hardly useful for European communications. Therefore, there is a complex interrelationship between orbital slot, frequency, satellite spacing, and coverage of the earth's surface.

Obviously, there will be more satellites in those parts of the Clarke orbit that serve the most people. The most crowded portions of the arc are the longitude ranges 1°W to 35°W (serving trans-Atlantic communications), 87°W to 135°W (serving mostly North America), and 49°E to 90°E (covering the Indian Ocean and connecting Europe with Asia).

11.3 Satellite coverage

From the Clarke orbit, each satellite sees about 44% of the earth's surface, centered on its subsatellite point. If the antenna on the satellite covers this full area, this is said to be a *global beam* pattern. Sometimes it is desired to serve a smaller region of Earth with a *regional beam* or *spot beam*, which will limit the part of the earth served. This is done by limiting the range of directions to which the satellite's downlink antenna points.

With a global beam, a satellite can see a region of Earth's surface that extends along the equator to longitudes 77° on either side of the subsatellite point, and also 77° north and south of the equator. Because of the geometry of the cone-shaped beams from the satellite intersecting the sphere of the earth, the service region when drawn on the usual Mercator map projection looks like a big square with rounded corners, like that in Fig.11.3. This is somewhat misleading, however. Note that because the meridian lines of longitude on Earth converge toward the

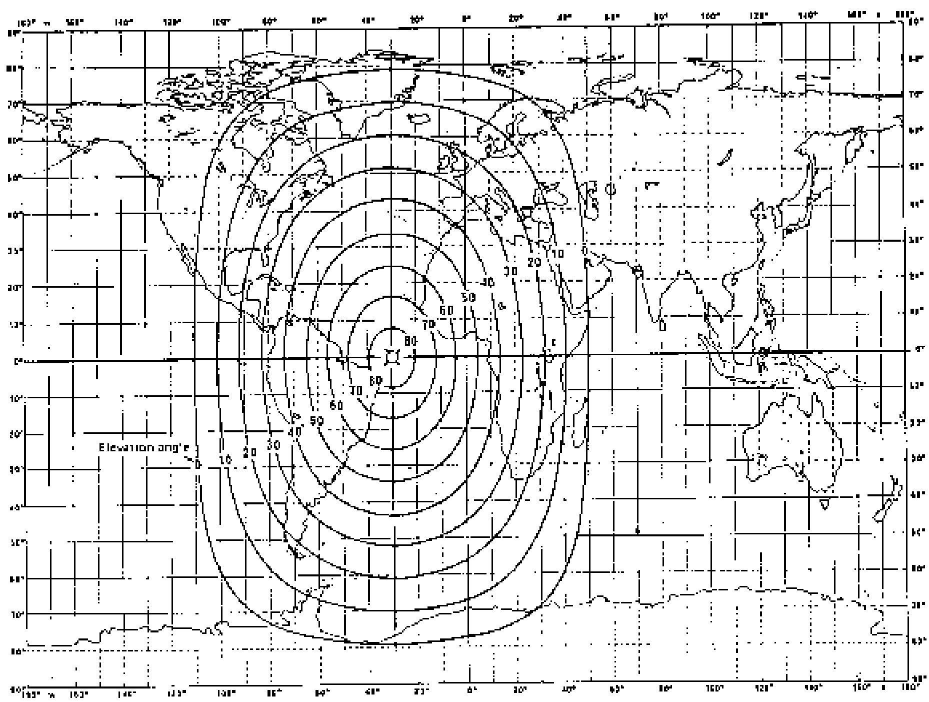

Figure 11.3 A single GSO satellite can see only about 44% of the surface of the Earth, and cannot see any areas with a latitude more than 77° north or south. The farther an earthstation is from the equator, the smaller the range of longitudes it can see along the Clarke orbit. An earthstation on the equator can see satellites about 77° to the east and west of its longitude, but an earthstation at latitude 77° can see on a satellite at its own longitude. (Guidelines suggest that an earthstation should not try to connect with a satellite that is less than 5° above the horizon.) (Source: ITU.)