Chapter 16

Direct Broadcast Satellite Services

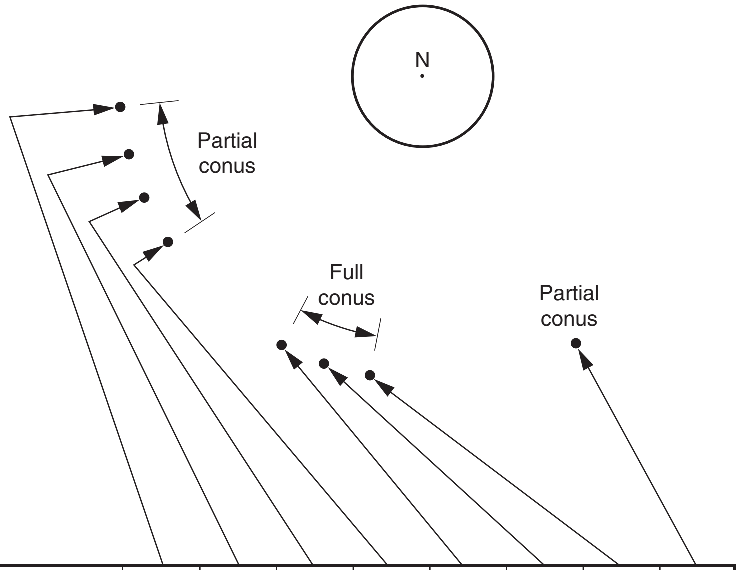
16.1 Introduction

Satellites provide *broadcast* transmissions in the fullest sense of the word, since antenna footprints can be made to cover large areas of the earth. The idea of using satellites to provide direct transmissions into the home has been around for many years, and the services provided are known generally as *direct broadcast satellite* (DBS) *services.* Broadcast services include audio, television, and Internet services. Internet services are covered in Chap. 15, and this chapter is concerned mainly with television.

A comprehensive overview covering the early years of DBS in Europe, the United States, and other countries is given in Pritchard and Ogata (1990). Some of the regulatory and commercial aspects of European DBS will be found in Chaplin (1992), and the U.S. market is discussed in Reinhart (1990). Reinhart defines three categories of U.S. DBS systems, shown in Table 1.4. Of interest to the topic of this chapter is the high power category, the primary intended use of which is for DBS .

16.2 Orbital Spacings

From Table 1.4 it is seen that the orbital spacing is 9° for the high-power satellites, so adjacent satellite interference is considered nonexistent. The DBS orbital positions along with the transponder allocations for the United States are shown in Fig. 16.1. It should be noted that



Satellite location	175°	166°	157°	148°	119°	110°	101°	61.5°
Company	Transponder totals							
Continental		11						11
DBSC	11							11
DirecTV			27				27	
Dominion		8						8
Echostar				24				
Echostar/Directsat	11	11			21	1		
MCI						28		
TCI/Tempo					11			
USSB				8		3	5	
Unassigned	10	2	5					2

Figure 16.1 DBS orbital positions for the United States.

although the DBS services are spaced by 9°, *clusters of satellites* occupy the nominal orbital positions. For example, the following satellites are located at 119°W longitude: EchoStar VI, launched on July 14, 2000; EchoStar IV, launched on May 8, 1998; EchoStar II, launched September 10, 1996; and EchoStar I, launched on December 28,1995 (source http://www.dishnetwork.com/).

16.3 Power Rating and Number of Transponders

From Table 1.4 it will be seen that satellites primarily intended for DBS have a higher [EIRP] than for the other categories, being in the range 51 to 60 dBW. At a Regional Administrative Radio Council (RARC) meeting in 1983, the value established for DBS was 57 dBW (Mead, 2000). Transponders are rated by the power output of their high-power amplifiers. Typically, a satellite may carry 32 transponders. If all 32 are in use, each will operate at the lower power rating of 120 W. By doubling up the high-power amplifiers, the number of transponders is reduced by half to 16, but each transponder operates at the higher power rating of 240 W. The power rating has a direct bearing on the bit rate that can be handled, as described in Sec. 16.8.

16.4 Frequencies and Polarization

The frequencies for direct broadcast satellites vary from region to region throughout the world, although these are generally in the Ku band. For region 2 (see Sec. 1.2), Table 1.4 shows that for high-power satellites, whose primary use is for DBS, the uplink frequency range is 17.3 to 17.8 GHz, and the downlink range is 12.2 to 12.7 GHz. The medium-power satellites listed in Table 1.4 also operate in the Ku band at 14 to 14.5 GHz uplink and 11.7 to 12.2 GHz downlink. The primary use of these satellites, however, is for point-to-point applications, with an allowed additional use in the DBS service. In this chapter only the high-power satellites intended primarily for DBS will be discussed.

The available bandwidth (uplink and downlink) is seen to be 500 MHz. A total number of 32 transponder channels, each of bandwidth 24 MHz, can be accommodated. The bandwidth is sometimes specified as 27 MHz, but this includes a 3-MHz guardband allowance. Therefore, when calculating bit-rate capacity, the 24 MHz value is used, as shown in the next section. The total of 32 transponders requires the use of both right-hand circular polarization (RHCP) and left-hand circular

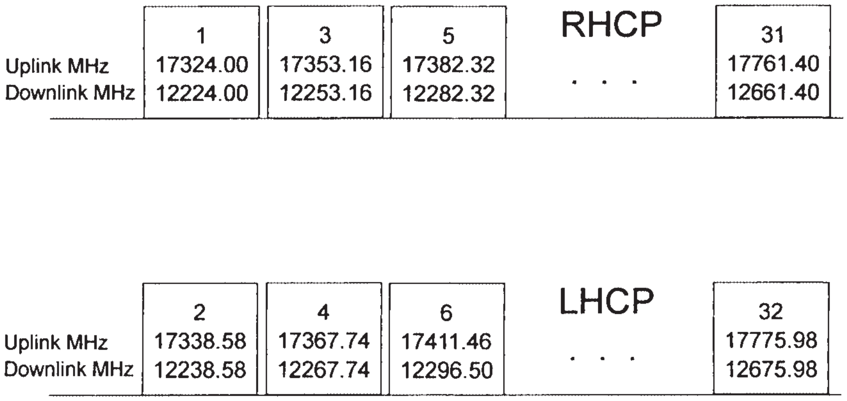


Figure 16.2 The DBS frequency plan for Region 2.

polarization (LHCP) in order to permit frequency reuse, and guard bands are inserted between channels of a given polarization. The DBS frequency plan for Region 2 is shown in Fig. 16.2.

16.5 Transponder Capacity

The 24-MHz bandwidth of a transponder is capable of carrying one analog television channel. To be commercially viable, direct broadcast satellite (DBS) television [also known as direct-to-home (DTH) television] requires many more channels, and this requires a move from analog to digital television. Digitizing the audio and video components of a television program allows *signal compression* to be applied, which greatly reduces the bandwidth required. The signal compression used in DBS is a highly complex process, and only a brief overview will be given here of the process. Before doing this, an estimate of the bit rate that can be carried in a 24-MHz transponder will be made.

From Eq. (10.16), the symbol rate that can be transmitted in a given bandwidth is

$$R_{\text{sym}} = \frac{B_{\text{IF}}}{1 + \rho} \tag{16.1}$$

Thus, with a bandwidth of 24 MHz and allowing for a rolloff factor of 0.2, the symbol rate is

$$R_{\text{sym}} = \frac{24 \times 10^6}{1 + .2}$$

$$= 20 \times 10^6 \text{ symbols/s}$$

Satellite digital television uses QPSK. Thus, using $M = 4$ in Eq. (10.3) gives $m = 2$, and the bit rate from Eq. (10.5) is

$$R_b = 2 \times R_{\text{sym}}$$

$$= 40 \text{ Mb/s}$$

This is the bit rate that can be carried in the 24-MHz channel using QPSK.

16.6 Bit Rates for Digital Television

The bit rate for digital television depends very much on the picture format. Some values are shown in Table 16.1.

It can be seen, therefore, that the bit rate ranges from 118 Mb/s for standard television at the lowest pixel resolution to 995 Mb/s for high-definition TV at the highest resolution. Although HDTV is "on its way," this chapter will be limited to the bit rates encountered with SDTV. As a note of interest, the broadcast raster for studio-quality television, when digitized according to the international CCIR-601 television standard, requires a bit rate of 216 Mb/s (Netravali and Lippman, 1995). Therefore, considering an uncompressed bit rate of around 200 Mb/s for the video signal alone gives some idea of the magnitudes involved.

TABLE 16.1 ATSC Television Formats

Format	Name	Screen	Resolution, Pixels	Bit Rate, Mb/s at 60/30/24 Frames per Second
HDTV	1080i	16:9	1920 × 1080	N.A./995/796
HDTV	720p	16:9	1280 × 720	885/442/334
SDTV	480p	16:9	704 × 480	324/162/130
SDTV	480p	4:3	640 × 480	295/148/118

NOTE: ATSC, Advanced Television Systems Committee; HDTV, high-definition television; SDTV, standard definition television; p, progressive scanning; i, interlaced scanning; N.A., not applicable to format.

SOURCE: Booth, 1999.

A single DBS transponder has to carry somewhere between four and eight TV programs to be commercially viable (Mead, 2000). The programs may originate from a variety of sources, film, analog TV, and videocassette, for example. Before transmission, these must all be converted to digital, compressed, and then time-division multiplexed (TDM). This TDM baseband signal is applied as QPSK modulation to the uplink carrier reaching a given transponder.

The compressed bit rate, and hence the number of channels that are carried, depends on the type of program material. Talk shows where there is little movement require the lowest bit rate, while sports channels with lots of movement require comparatively large bit rates. Typical values are in the range of 4 Mb/s for a movie channel, 5 Mb/s for a variety channel, and 6 Mb/s for a sports channel (Fogg, 1995). Compression is carried out to MPEG standards.

16.7 MPEG Compression Standards

MPEG stands for Moving Pictures Expert Group, a group within the International Standards Organization and the International Electrochemical Commission (ISO/IEC) that undertook the job of defining standards for the transmission and storage of moving pictures and sound. The standards are concerned only with the bit-stream syntax and the decoding process, not with how encoding and decoding might be implemented. Syntax covers such matters as bit rate, picture resolution, time frames for audio, and the packet details for transmission. The design of hardware for the encoding and decoding processes is left up to the equipment manufacturer. Comprehensive descriptions of the MPEG can be found at the Web site http://www.mpeg.org and in Sweet (1997) and Bhatt et al. (1997). The MPEG standards currently available are MPEG-1, MPEG-2, MPEG-4, and MPEG-7. For a brief explanation of the "missing numbers," see Koenen (1999).

In DBS systems, MPEG-2 is used for video compression. As a first or preprocessing step, the analog outputs from the red (R), green (G), and blue (B) color cameras are converted to a luminance component (Y) and two chrominance components (Cr) and (Cb). This is similar to the analog NTSC arrangement shown in Fig. 9.7, except that the coefficients of the matrix **M** are different. In matrix notation, the equation relating the three primary colors to the Y, Cr, and Cb components is

$$\begin{bmatrix} Y \\ Cr \\ Cb \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.169 & -0.331 & 0.500 \\ 0.500 & -0.419 & -0.081 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{16.2}$$

The Y, C, and Cb signals are sampled in the digitizer shown in Fig. 16.3. It is an observed fact that the human eye is less sensitive to resolution in the color components (Cr and Cb) than the luminance (Y) component. This allows a lower sampling rate to be used for the color components. This is referred to as *chroma subsampling,* and it represents one step in the compression process. For example, in the CCIR-601-1 standard, sampling along the horizontal axis for the color components is less by a factor 2 compared with the luminance sampling. This is written as 4:2:2 sampling.

Following the digitizer, difference signals are formed, and the discrete cosine transform (DCT) block converts these to a "spatial frequency" domain. The familiar Fourier transform transforms a time signal $g(t)$ to a frequency domain representation $G(f)$, allowing the signal to be filtered in the frequency domain. Here, the variables are time t and frequency f. In the DCT situation, the input signals are functions of the x (horizontal) and y (vertical) space coordinates, $g(x, y)$. The DCT transforms these into a domain of new variables u and v, $G(u, v)$. The variables are called *spatial frequencies* in analogy with the time-frequency transform. It should be noted that $g(x, y)$ and $G(u, v)$ are *discrete functions.* In the

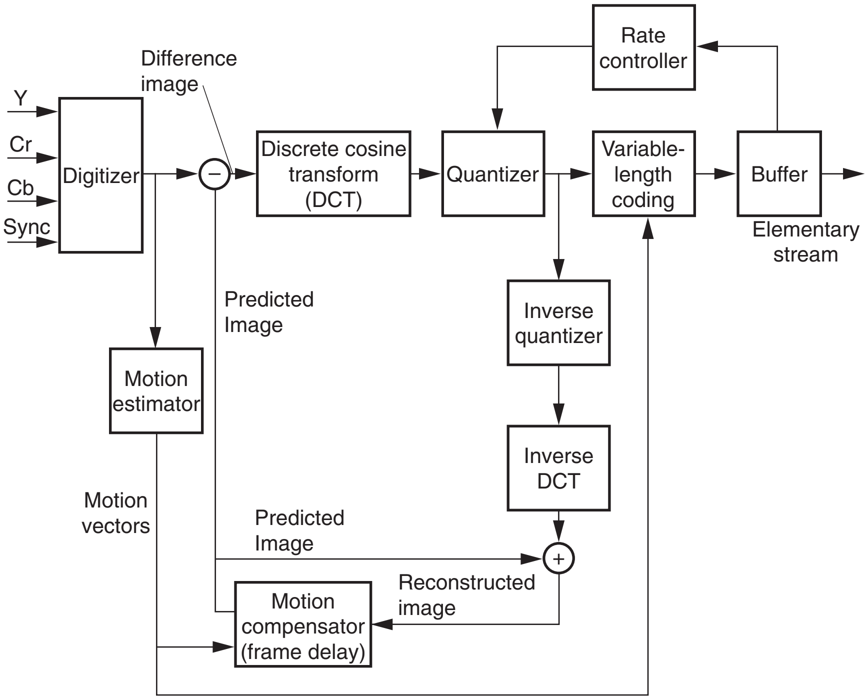


Figure 16.3 MPEG-2 encoder paths. (*From Bhatt et al., 1997. IEEE.*)

quantizer following the DCT transform block, the discrete values of $G(u, v)$ are quantized to predetermined levels. This reduces the number of levels to be transmitted and therefore provides compression. The components of $G(u, v)$ at the higher spatial frequencies represent finer spatial resolution. The human eye is less sensitive to resolution at these high spatial frequencies; therefore, they can be quantized in much coarser steps. This results in further compression. (This step is analogous to the nonlinear quantization discussed in Sec. 10.3.)

Compression is also achieved through *motion estimation.* Frames in MPEG-2 are designated *I, P,* and *B* frames, and motion prediction is achieved by comparing certain frames with other frames. The *I* frame is an independent frame, meaning that it can be reconstructed without reference to any other frames. A *P* (for previous) frame is compared with the previous *I* frame, and only those parts which differ as a result of movement need to be encoded. The comparison is carried out in sections called *macroblocks* for the frames. A *B* (for bidirectional) frame is compared with the previous *I* or *P* frame and with the next *P* frame. This obviously means that frames must be stored in order for the forward comparison to take place. Only the changes resulting from motion are encoded, which provides further compression. Taking the 200 Mb/s deduced in Sec. 16.6 as the uncompressed rate, and taking 5 Mb/s as typical of that for a TV channel, the compression needed is on the order 200/5 = 40:1. The 5 Mb/s would include audio and data, but these should not take more than about 200 kb/s. Audio compression is considered later in this section.

The whole encoding process relies on digital decision-making circuitry and is computationally intensive and expensive. The decoding process is much simpler because the rules for decoding are part of the syntax of the bit stream. Decoding is carried out in the *integrated receiver decoder* (IRD) unit. This is described in Sec. 16.8.

In DBS systems, MPEG-1 is used for audio compression, and as discussed earlier, MPEG-2 is used for video compression. Both of these MPEG standards cover audio and video, but MPEG-1 video is not designed for DBS transmissions. MPEG-1 audio supports mono and two-channel stereo only, which is considered adequate for DBS systems currently in use. MPEG-2 audio supports multichannel audio in addition to mono and stereo. It is fully compatible with MPEG-1 audio, so the integrated receiver decoders (IRDs), which carry MPEG-2 decoders, will have little trouble in being upgraded to work with DBS systems transmitting multichannel audio.

The need for audio compression can be seen by considering the bit rate required for high-quality audio. The bit rate is equal to the number of samples per second (the sampling frequency f_s) multiplied by the number of bits per sample n:

$$R_b = f_s \times n \tag{16.3}$$

For a stereo CD recording, the sampling frequency is 44.1 kHz, and the number of bits per sample is 16:

$$\begin{aligned} R_b &= 44.1 \times 10^3 \times 16 \times 2 \\ &= 1411.2 \text{ kb/s} \end{aligned}$$

The factor 2 appears on the right-hand side because of the two channels in stereo. This bit rate, approximately 1.4 Mb/s, represents too high a fraction of the total bit rate allowance per channel, and hence the need for audio compression. Audio compression in MPEG exploits certain *perceptual phenomena* in the human auditory system. In particular, it is known that a loud sound at one particular frequency will mask a less intense sound at a nearby frequency. For example, consider a test conducted using two tones, one at 1000 Hz, which will be called the *masking tone,* and the other at 1100 Hz, the *test tone.* Starting with both tones at the same level, say, 60 dB above the threshold of hearing, if now the level of the 1000-Hz tone is held constant while reducing the level of the 1100-Hz tone, a point will be reached where the 1100-Hz tone becomes inaudible. The 1100-Hz tone is said to be *masked* by the 1000-Hz tone. Assume for purposes of illustration that the test tone becomes inaudible when it is 18 dB below the level of the masking tone. This 18 dB is the *masking threshold.* It follows that any noise below the masking threshold also will be masked.

For the moment, assuming that only these two tones are present, then it can be said that the *noise floor* is 18 dB below the masking tone. If the test-tone level is set at, say, 6 dB below the masking tone, then of course it is 12 dB above the noise floor. This means that the signal-to-noise ratio for the test tone need be no better than 12 dB. Now in a pulse-code modulated (PCM) system the main source of noise is that arising from the quantization process (see Sec. 10.3). It can be shown (see, for example, Roddy and Coolen, 1995) that the signal-to-quantization noise ratio is given by

$$\left(\frac{S}{N}\right)_q = 2^{2n} \tag{16.4}$$

where n is the number of bits per sample. In decibels this is

$$\begin{aligned} \left[\frac{S}{N}\right]_q &= 10 \log 2^{2n} \\ &\cong 6n \text{ dB} \end{aligned} \tag{16.5}$$

This shows that increasing n by 1 bit increases the signal-to-quantization noise ratio by 6 dB. Another way of looking at this is to say that a 1-bit decrease in n increases the quantization noise by 6 dB. In the example above where 12 dB is an adequate signal-to-noise ratio, Eq. (16.5) shows that only 2 bits are needed to encode the 1100-Hz tone (i.e., the levels would be quantized in steps represented by 00, 01, 10, 11). By way of contrast, the CD samples taken at a sampling frequency of 44.1 kHz are quantized using 16 bits to give a signal-to-quantization noise ratio of 96 dB.

Returning to the example of two tones, in reality, the audio signal will not consist of two single tones but will be a complex signal covering a wide spectrum of frequencies. In MPEG-1, two processes take place in parallel, as illustrated in Fig. 16.4. The filter bank divides the spectrum of the incoming signal into subbands. In parallel with this the spectrum is analyzed to permit identification of the masking levels. The masking information is passed to the quantizer, which then quantizes the subbands according to the noise floor.

The masking discussed so far is referred to as *frequency masking* for the reasons given above. It is also an observed phenomenen that the masking effect lasts for a short period after the masking signal is removed. This is termed *temporal masking,* and it allows further compression in that it extends the time for which the reduction is quantization applies. There are many more technical details to MPEG-1 than can be covered here, and the reader is referred to Mead (2000), which contains a detailed analysis of MPEG-1. The MPEG Web page at http://www.mpeg.org/MPEG/audio.html also provides a number of articles on the subject. The compressed bit rate for MPEG-1 audio used in DBS systems is 192 kb/s.

16.8 Forward Error Correction

Because of the highly compressed nature of the DBS signal, there is little redundancy in the information being transmitted, and bit errors

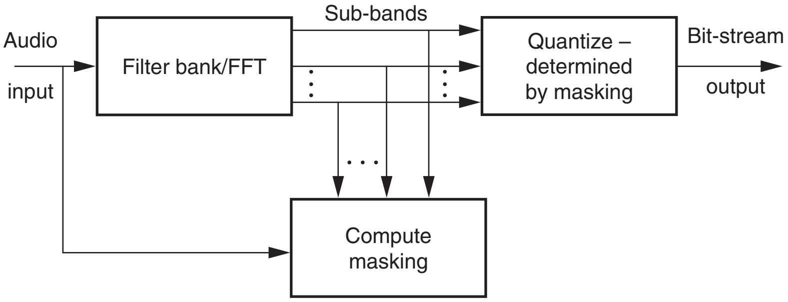


Figure 16.4 MPEG-1 block schematic.

affect the signal much more severely than they would in a noncompressed bit stream. As a result, forward error correction is a must. Concatenated coding is used (see Sec. 11.6). The outer code is a Reed-Solomon code that corrects for block errors, and the inner code is a convolution code that corrects for random errors. The inner decoder utilizes the Viterbi decoding algorithm. These FEC bits, of course, add overhead to the bit stream. Typically, for a 240-W transponder (see Sec. 16.3), the bit capacity of 40 Mb/s (see Sec. 16.5) may have a payload of 30 Mb/s and coding overheads of 10 Mb/s. The lower-power 120-W transponders require higher coding overheads to make up for the reduction in power and have a payload of 23 Mb/s and coding overheads of 17 Mb/s. More exact figures are given in Mead (2000) for DirecTV, where the overall code rates are given as 0.5896 for the 120-W transponder and 0.758 for the 240-W transponder.

Mead (2000) has shown that with FEC there is a very rapid transition in BER for values of $[E_b/N_o]$ between 5.5 and 6 dB. For $[E_b/N_o]$ values greater than 6 dB, the BER is negligible, and for values less than 5.5 dB, the BER is high enough to render the system useless.

Advances in coding techniques promise a further increase in transponder capacity. A system patented by France Telecom (see Vollmer, 2000), when used with 8-PSK, should realize a 50 percent increase in the bit rate capacity of a transponder. The new codes are called *Turbo codes,* and details will be found in Hewitt and Thesling (2000).

16.9 The Home Receiver Outdoor Unit (ODU)

The home receiver consists of two units, an outdoor unit and an indoor unit. Commercial brochures refer to the complete receiver as an *integrated receiver decoder* (IRD). Figure 16.5 is a block schematic for the outdoor unit (ODU). This will be seen to be similar to the outdoor unit shown in Fig. 8.1. The downlink signal, covering the frequency range 12.2 to 12.7 GHz, is focused by the antenna into the receive horn. The horn feeds into a polarizer that can be switched to pass either left-hand circular to right-hand circular polarized signals. The low-noise block that follows the polarizer contains a low-noise amplifier (LNA) and a downconverter. The function of the LNA is described in Sec. 12.5. The downconverter converts the 12.2- to 12.7-GHz band to 950 to 1450 MHz, a frequency range better suited to transmission through the connecting cable to the indoor unit.

The antenna usually works with an offset feed (see Sec. 6.14), and a typical antenna structure is shown in Fig. 16.6. It is important that the antenna have an unobstructed view of the satellite cluster to

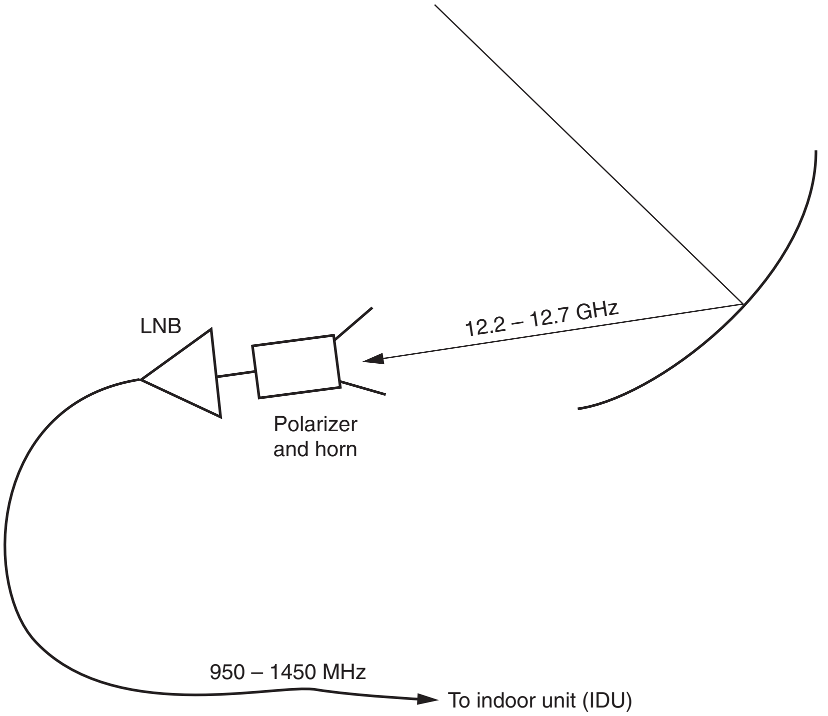


Figure 16.5 Block schematic for the outdoor unit (ODU).

which it is aligned. Alignment procedures are described in Sec. 3.2. The size of the antenna is a compromise among many factors but typically is around 18 in (46 cm) in diameter. A small antenna is desirable for a number of reasons. Small antennas are less intrusive visually and also are less subject to wind loading. In manufacture, it is easier to control surface irregularities, which can cause a reduction in gain by scattering the signal energy. The reduction can be expressed as a function of the root-mean-square (rms) deviation of the surface, referred to an *ideal parabolic surface.* The reduction in gain is given by (see Baylin and Gale, 1991)

$$\eta_{\text{rms}} = e^{8.8\sigma/\lambda} \tag{16.6}$$

where σ is the rms tolerance in the same units as λ, the wavelength. For example, at 12 GHz (wavelength 2.5 cm) and for an rms tolerance of 1 mm, the gain is reduced by a factor

$$\begin{aligned}\eta_{\text{rms}} &= e^{(8.8\times\ 0.1)/2.5} \\ &= 0.7\end{aligned}$$

Figure 16.6 A typical DBS antenna installation.

This is a reduction of about 1.5 dB.

The isotropic power gain of the antenna is proportional to $(D/\lambda)^2$, as shown by Eq. (6.32), where D is the diameter of the antenna. Hence, increasing the diameter will increase the gain (less any reduction resulting from rms tolerance), and in fact, many equipment manufacturers provide signal-strength contours showing the size of antenna that is best for a given region. Apart from the limitations to size stated above, it should be noted that at any given DBS location there are *clusters* of satellites, as described in Sec. 16.2. The beamwidth of the antenna must be wide enough to receive from all satellites in the cluster. For example, the Hughes DBS-1 satellite, launched December 18, 1993, is located at 101.2°W longitude; DBS-2, launched August 3, 1994, is at

100.8°W longitude; and DBS-3, launched June 3, 1994, is at 100.8°W longitude. There is a spread of plus or minus 0.2° about the nominal 101°W position. The −3-dB beamwidth is given as approximately $70\lambda/D$, as shown by Eq. (6.33). A 60-cm dish at 12 GHz would have a −3-dB beamwidth of approximately $70 \times 2.5/60 = 2.9°$, which is adequate for the cluster.

16.10 The Home Receiver Indoor Unit (IDU)

The block schematic for the indoor unit (IDU) is shown in Fig. 16.7. The transponder frequency bands shown in Fig. 16.2 are downconverted to be in the range 950 to 1450 MHz, but of course, each transponder retains its 24-MHz bandwidth. The IDU must be able to receive any of the 32 transponders, although only 16 of these will be available for a single polarization. The tuner selects the desired transponder. It should be recalled that the carrier at the center frequency of the transponder is QPSK modulated by the bit stream, which itself may consist of four to eight TV programs time-division multiplexed. Following the tuner, the carrier is demodulated, the QPSK modulation being converted to a bit stream. Error correction is carried out in the decoder block labeled FEC^{-1}. The demultiplexer following the FEC^{-1} block separates out the individual programs, which are then stored in buffer memories for further processing (not shown in the diagram). This further processing would include such things as conditional access, viewing history of pay-per-view (PPV) usage, and connection through a modem to the service provider (for PPV billing purposes). A detailed description of the IRD will be found in Mead (2000).

16.11 Downlink Analysis

The main factor governing performance of a DBS system will be the $[E_b/N_o]$ of the downlink. The downlink performance for clear-sky conditions can be determined using the method described in Sec. 12.8 and illustrated in Example 12.2 that follows. The effects of rain can be calculated using the procedure given in Sec. 12.9.2 and illustrated in Example 12.3 that follows. These examples are worked in Mathcad (see Appendix H). In calculating the effects of rain, use is made of Fig.16.8, which shows the regions (indicated by letters) tabulated along with rainfall in Table 16.2.

Example 16.1 A ground station located at 45°N and 90°W is receiving the transmission from a DBS at 101°W. The [EIRP] is 55 dBW, and the downlink frequency may be taken as 12.5 GHz for calculations. An 18-in-diameter antenna is used, and an efficiency of 0.55 may be assumed. Miscellaneous transmission losses of 2 dB also may be assumed. For the IRD, the equivalent

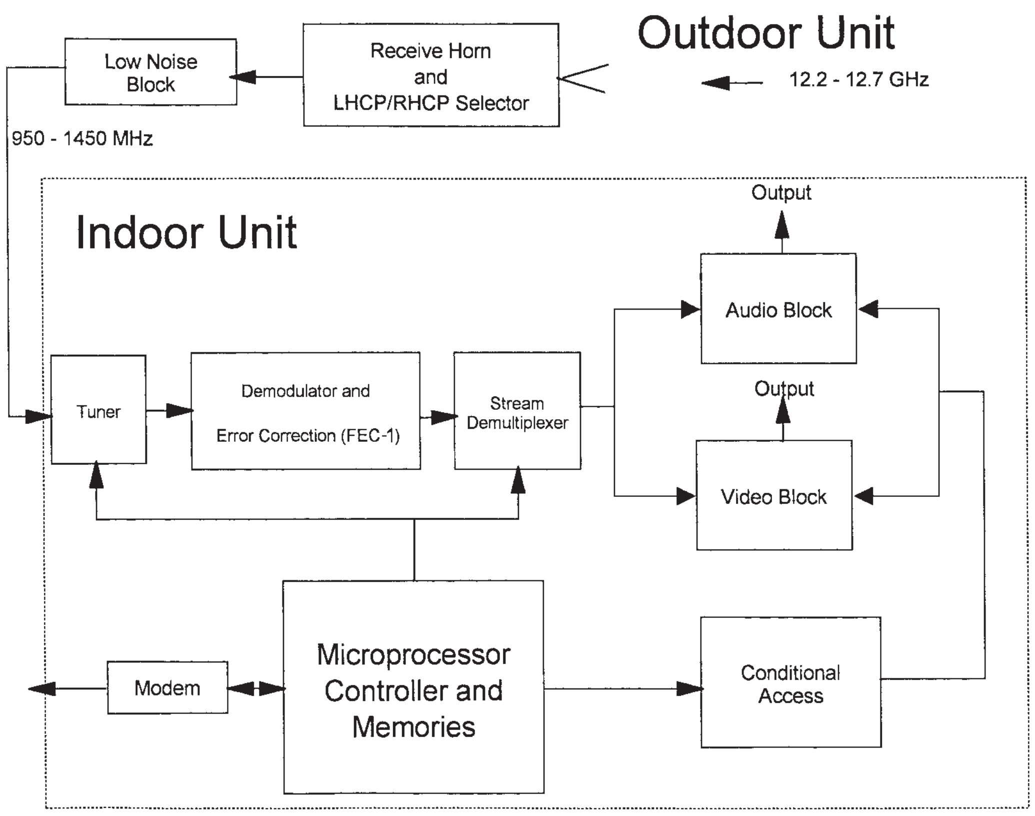


Figure 16.7 Block schematic for the indoor unit (IDU).

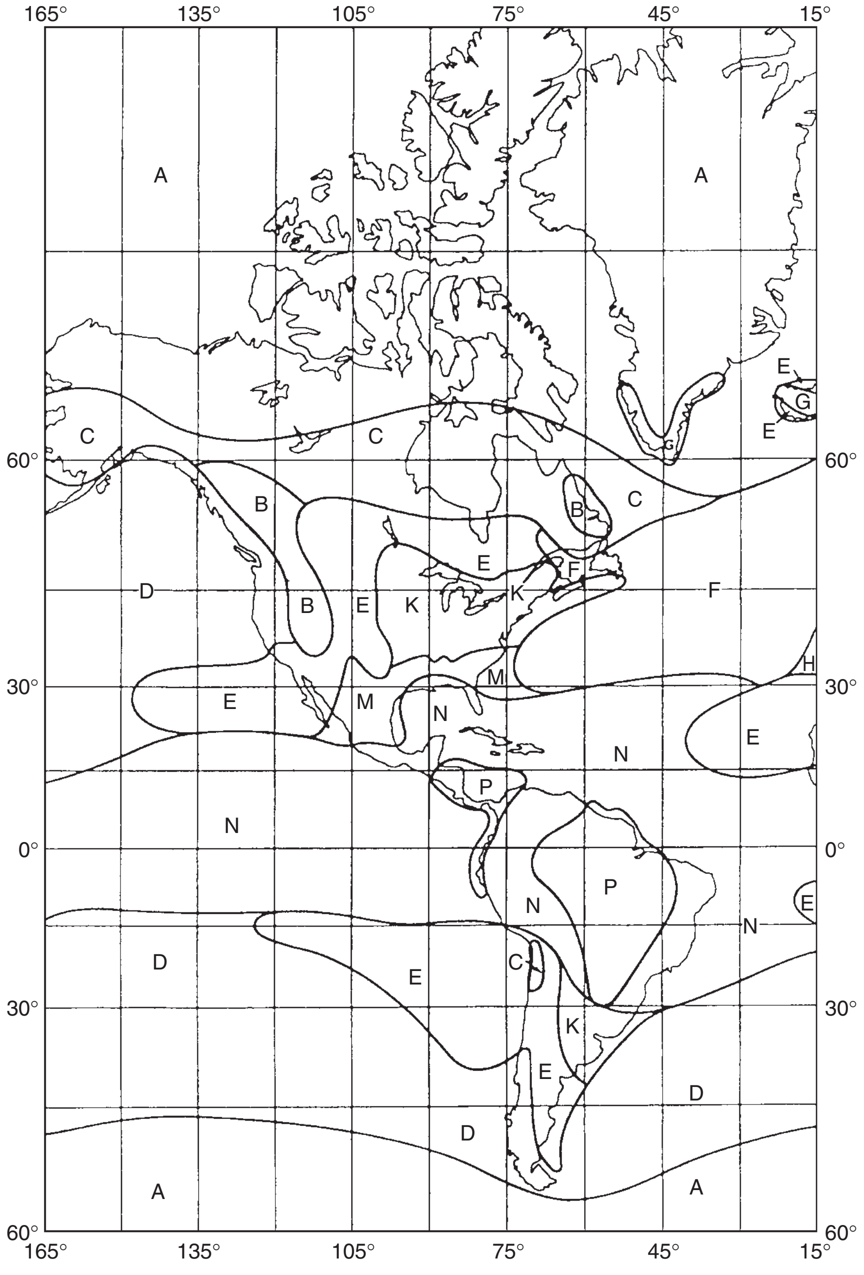


Figure 16.8 Rain climatic zones. Refer to Table 16.2. (*From Rec. ITU-R PN.837-1, with permission from the copyright holder ITU. Sole responsibility for the reproduction rests with the author. The complete volume of the ITU material from which the material is extracted can be obtained from the International Telecommunication Union, Sales and Marketing Service, Place des Nations–CH-1211, Geneva 20, Switzerland.*)

TABLE 16.2 Rainfall Intensity Exceeded (mm/h) (Refer to Fig. 16.8)

Percentage of Time	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q
1.0	<0.1	0.5	0.7	2.1	0.6	1.7	3	2	8	1.5	2	4	5	12	24
0.3	0.8	2	2.8	4.5	2.4	4.5	7	4	13	4.2	7	11	15	34	49
0.1	2	3	5	8	6	8	12	10	20	12	15	22	35	65	72
0.03	5	6	9	13	12	15	20	18	28	23	33	40	65	105	96
0.01	8	12	15	19	22	28	30	32	35	42	60	63	95	145	115
0.003	14	21	26	29	41	54	45	55	45	70	105	95	140	200	142
0.001	22	32	42	42	70	78	65	83	55	100	150	120	180	250	170

SOURCE: Table 16.2 and Fig. 16.8 reproduced from ITU Recommendation ITU-R PN.837-1 (1994), with permission.

noise temperature at the input to the LNA is 100 K, and the antenna noise temperature is 70 K. Calculate the look angles for the antenna, the range, and the $[E_b/N_o]$ at the IRD and comment on this.

solution Given data:

For the satellite:

$$\text{EIRPdBW}: = 55 \qquad f_D := 12.5 \cdot \text{GHz} \qquad \phi_{SS} := -101 \cdot \text{deg}$$

and it may be assumed that it is transmitting at full capacity:

$$\text{Rb} := 40 \cdot 10^6 \cdot \text{sec}^{-1}$$

For the IRD:

$$D := 18 \cdot \text{in} \qquad \eta := .55 \qquad T_{ant} := 70 \cdot \text{K} \qquad T_{eq} := 100 \cdot \text{K}$$

For the transmission path, the mean earth radius is used:

$$R := 6371 \cdot \text{km}$$

and the miscellaneous losses are

$$\text{LdB} := 2$$

Geostationary radius:

$$a_{GSO} := 42164 \cdot \text{km}$$

Boltzmann's constant in dB units:

$$\text{kdB} := -228.6$$

For the earth station:

$$\phi_E := -90 \cdot \text{deg} \qquad \lambda_E := 45 \cdot \text{deg}$$

Calculations:

Equation (3.8):

$$B := \phi_E - 1\, \phi_{SS} \qquad B = 11 \cdot \text{deg}$$

Equation (3.9):

$$b := \text{acos}\,(\cos(B) \cdot \cos(\lambda_E)) \qquad b = 46 \cdot \text{deg}$$

Equation (3.10):

$$A := \text{asin}\left(\frac{\sin(|B|)}{\sin(b)}\right) \qquad A = 15.4 \cdot \text{deg}$$

By inspection, $\lambda_E > 0$ and $B > 0$; therefore, Fig. 3.3*d* applies, and

$$A_z := 180 \cdot \mathrm{deg} + A$$

The required azimuth angle is

$$\underline{\underline{A_z = 195.4 \cdot \mathrm{deg}}}$$

Equation (3.11):

$$d := \sqrt{R^2 + a_{GSO}{}^2 - 2 \cdot R \cdot a_{GSO} \cdot \cos(b)}$$

The range is

$$\underline{\underline{d = 38019 \cdot \mathrm{km}}}$$

Equation (3.12):

$$El := \mathrm{acos}\left(\frac{a_{GSO}}{d} \cdot \sin(b)\right)$$

The required antenna angle of elevation is

$$El = 37 \cdot \mathrm{deg}$$

As noted in Sec. 3.2, the calculated values for azimuth and elevation provide a guide. Practical adjustments would be made to maximize the received signal.

Equation (12.10):

$$FSLdB := 32.4 + 20 \cdot \log\left(\frac{d}{km}\right) + 20 \cdot \log\left(\frac{f_D}{MHz}\right) \qquad FSLdB = 205.9$$

Equation (12.12):

$$LOSSESdB := FSLdB + LdB \qquad LOSSESdB = 207.9$$

Equation (12.23):

$$T_S := T_{eq} + T_{ant} \qquad T_S = 170 \cdot K$$

$$TdB := 10 \cdot \log\left(\frac{T_S}{K}\right) \qquad TdB = 22.3$$

Equation (12.5):

$$G := \eta \cdot \left(3.192 \cdot \frac{f_D}{GHz} \cdot \frac{D}{ft}\right)^2 \qquad GdB := 10 \cdot \log(G) \qquad GdB = 32.9$$

Equation (12.35):

$$GTdB := GdB - TdB \qquad GTdB = 10.6$$

Equation (10.53):

$$\mathrm{CNodB} := \mathrm{EIRPdBW} + \mathrm{GTdB} - \mathrm{LOSSESdB} - \mathrm{kdB} \qquad \mathrm{CNodB} = 86.3$$

The downlink bit rate in dB relative to 1 bps is

$$\mathrm{RbdB} := 10 \cdot \log\left(\frac{\mathrm{Rb}}{\mathrm{sec}^1}\right) \qquad \mathrm{RbdB} = 76$$

Equation (10.24):

$$\mathrm{EbNodB} := \mathrm{CNodB} - \mathrm{RbdB} \qquad \mathrm{EbNodB} = 10.3$$

As noted in Sec. 16.8, a $[E_b/N_o]$ of at least 6 dB is required. The value obtained provides a margin of 4.3 dB under clear-sky conditions.

Example 16.2 Table 16.2 and Fig. 16.8 show the rainfall intensity in mm/h exceeded for given percentages of time. Calculate the upper limit for $[E_b/N_o]$ set by the rainfall for the percentage of time equal to 0.01 percent. The earth station is at mean sea level, and the rain attenuation may be assumed entirely absorptive, and the apparent absorber temperature may be taken as 272 K.

solution It is first necessary to calculate the attenuation resulting from the rain. The given data are shown below. Because the CCIR formula contains hidden conversion factors, units will not be attached to the data, and it is understood that all lengths and heights are in km, and rain rate is in mm/h. The elevation angle, however, must be stated in degrees in order for Mathcad to correctly evaluate the sine and cosine functions.

From Fig. 16.8, the earth station is seen to be located within region K. From the accompanying Table 16.2, the rainfall exceeds 42 mm/h for 0.01 percent of the time.

$$R_{01} := 42$$

Table 4.2 does not give the coefficients for 12.5 GHz; therefore, the values must be found by linear interpolation between 12 and 15 GHz. Denoting the 12-GHz values with subscript 12 and the 15-GHz values with subscript 15, then from Table 4.2,

$$f_{12}{:=}12\cdot\mathrm{GHz} \qquad a_{h12}{:=}.0188 \qquad a_{v12}{:=}.0168 \qquad b_{h12}{:=}1.217 \qquad b_{v12}{:=}1.2$$

$$f_{15}{:=}15\cdot\mathrm{GHz} \qquad a_{h15}{:=}.0367 \qquad a_{v15}{:=}.0335 \qquad b_{h15}{:=}1.154 \qquad b_{v15}{:=}1.128$$

Using linear interpolation, the values at 12.5 GHz are found as

$$a_h := a_{h12} + \frac{a_{h15} - a_{h12}}{f_{15} - f_{12}} \cdot (f_D - f_{12}) \qquad a_h = 0.022$$

$$b_h := b_{h12} + \frac{b_{h15} - b_{h12}}{f_{15} - f_{12}} \cdot (f_D - f_{12}) \qquad b_h = 1.207$$

$$a_v := a_{v12} + \frac{a_{v15} - a_{v12}}{f_{15} - f_{12}} \cdot (f_D - f_{12}) \qquad a_v = 0.02$$

$$b_v := b_{v12} + \frac{b_{v15} - b_{v12}}{f_{15} - f_{12}} \cdot (f_D - f_{12}) \qquad b_v = 1.188$$

Since circular polarization is used, the coefficients are found from Eq. (4.8):

Equation (4.8a):

$$a_c := \frac{a_h + a_v}{2} \qquad a_c = 0.021$$

Equation (4.8b):

$$b_c := \frac{a_h \cdot b_h + a_v \cdot b_v}{2 \cdot a_c} \qquad b_c = 1.198$$

Using the Method 3 curves in Fig. 4.4 for $p = 0.01$ percent and earth station latitude 45°, the rain height is approximately 3.5 km, and as stated in the problem, at mean sea level $h_o = 0$,

$$h_R := 3.5 \qquad h_o := 0$$

Equation (4.4):

$$L_S := \frac{h_R - h_o}{\sin(El)} \qquad L_S = 5.8$$

Equation (4.6):

$$L_G := L_S \cdot \cos(El) \qquad L_G = 4.6$$

From Table 4.3,

$$r_{01} := \frac{90}{90 + 4 \cdot L_G} \qquad r_{01} = 0.8$$

Equation (4.5):

$$L := L_S \cdot r_{01} \qquad L = 4.8$$

Equation (4.2):

$$\alpha := a_c \cdot {R_{01}}^{b_c} \qquad \alpha = 1.819$$

Equation (4.3):

$$AdB_{01} := \alpha \cdot L \qquad AdB_{01} = 8.8$$

The effect of rain is calculated as shown in Sec. 12.9.2. This requires the attenuation to be expressed as a power ratio:

$$A := 10^{\frac{AdB_{01}}{10}} \qquad A = 7.5$$

Given:

$$T_a := 272 \cdot K$$

Equation (12.58):

$$T_{RAIN} := T_a \cdot \left(1 - \frac{1}{A}\right) \qquad T_{RAIN} = 235.9 \cdot K$$

For Eq. (12.60), the noise-to-signal ratios are required. These are denoted here as NoC along with the appropriate subscript:

$$NoC_{CS} := 10^{\frac{-CNodB}{10}} \qquad NoC_{CS} = 2.3 \cdot 10^{-9}$$

The system noise temperature under clear-sky conditions is just T_S, but the subscript will be changed to conform with Eq. (12.60):

$$T_{SCS} := T_S$$

Equation (12.60):

$$NoC_{RAIN} := NoC_{CS} \cdot \left(A + (A - 1) \cdot \frac{T_a}{T_{SCS}}\right)$$

In dB, this is

$$CNodB_{RAIN} := -10 \cdot \log\left(NoC_{RAIN}\right) \qquad CNodB_{RAIN} = 73.8$$

Recalculating the $[E_b/N_o]$ ratio:

Equation (10.24):

$$EbNodB_{RAIN} := CNodB_{RAIN} - RbdB \qquad \underline{\underline{EbNodB_{RAIN} = -2.3}}$$

Thus the rain will completely wipe out the signal for 0.01 percent of the time. It is left as an exercise for the reader to find the size of antenna that would provide an adequate signal under these rain conditions.

16.12 Uplink

Ground stations that provide the uplink signals to the satellites in a DBS system are highly complex systems in themselves, utilizing a wide range of receiving, recording, encoding, and transmission equipment. Signals will originate from many sources. Some will be analog TV received from satellite broadcasts. Others will originate in a studio, others from video cassette recordings, and some will be brought in on cable or optical fiber. Data signals and audio broadcast material also may be included. All of these must be converted to a uniform digital format, compressed, and time-division multiplexed (TDM). Necessary service additions which must be part of the multiplexed stream are the program guide and conditional access. Forward error correction (FEC) is added to the bit stream, which is then used to QPSK modulate the carrier for a given transponder. The whole process, of course, is duplicated for each transponder carrier.

Because of the complexity, the uplink facilities are concentrated at single locations specific to each broadcast company. The uplink facilities for Echostar's DISH network is shown in Fig. 16.9. The four uplink facilities in operation as of 1996, as given in Mead (2000), are shown in Table 16.3.

TABLE 16.3 Uplink Facilities in Operation as of 1996

Company	Location
AlphaStar	Oxford, Connecticut
DirecTV	Castle Rock, Colorado
EchoStar	Cheyenne, Wyoming
U.S. Satellite Broadcasting	Oakdale, Minnesota

Figure 16.9 Uplink facilities for Echostar's DISH network. (*From* http://www.dishnetwork.com/profile/third_level_content/uplink_center/index.asp.)

16.13 Problems

16.1. Referring to Fig. 16.1, calculate (*a*) the total number of transponders broadcasting from each of the orbital positions shown and (*b*) the total number of transponders in use by each service provider.

16.2. The [EIRP] of a 240-W transponder is 57 dBW. Calculate the approximate gain of the antenna.

16.3. The transponder in Prob. 16.2 is switched to 120 W. Calculate the new [EIRP], assuming that the same antenna is used.

16.4. Draw accurately to scale the transponder frequency plan for the DBS transponders 5, 6, and 7 for uplink and downlink.

16.5. Calculate the total bit rate capacity available at each of the orbital slots for each of the service providers listed in Fig. 16.1. State any assumptions made.

16.6. Calculate the bandwidth required to transmit a SDTV format having a resolution of 704 × 480 pixels at 30 frames per second.

16.7. The R, G, and B colors in Eq. (16.2) are restored by the matrix multiplication (Mead, 2000):

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.000 & 0 & 1.404 \\ 1.000 & -0.3434 & -0.712 \\ 1.000 & 1.773 & 0 \end{bmatrix} \begin{bmatrix} Y \\ Cr \\ Cb \end{bmatrix}$$

Using Eq. (16.2), verify that this equation is correct.

16.8. Briefly describe the video compression process used in MPEG-2.

16.9. Explain what is meant by *masking* in the context of audio compression. Describe how MPEG-1 utilizes the phenomenon of masking to achieve compression.

16.10. Using the overall codes rates (Mead, 2000) given in Sec. 16.8 and assuming a 40-Mb/s transponder, calculate the payload bit rate and the overhead for the low-power and high-power transponders.

16.11. Plot antenna gain as a function of diameter for a paraboloidal reflector antenna for antenna diameters in the range 45 to 80 cm. Use a frequency of 12.5 GHz.

16.12. Assuming that the rms tolerance can be held to 0.2 percent of the diameter in antenna manufacture, calculate the reduction in gain that can be expected with antennas of diameter (*a*) 46 cm, (*b*) 60 cm, and (*c*) 80 cm.

16.13. Calculate the gain and −3-dB beamwidth for antennas of diameter 18, 24, and 30 in at a frequency of 12.5 GHz. Assume that the antenna efficiency is 0.55 and that the rms manufacturing tolerance is 0.25 percent of diameter.

16.14. A DBS home receiver is being installed at a location 40°N, 75°W to receive from a satellite cluster at 61.5°. Calculate the look angles for the antenna. It is hoped to use an 18-in antenna, the antenna efficiency being 0.55, and the effect of surface irregularities may be ignored. The system noise temperature is 200 K. The downlink frequency may be taken as 12.5 GHz, the [EIRP] as 55 dBW, and the transponder bit rate as 40 Mb/s. Miscellaneous transmission losses may be ignored. Calculate the received clear sky $[E_b/N_o]$, and state whether or not this will make for satisfactory reception.

16.15. Following the procedure given in example 16.2, calculate the rain attenuation for 0.01 percent of time and the corresponding $[E_b/N_o]$ for the system in Prob. 16.14. The ground station may be assumed to be at mean sea level. State if satisfactory reception occurs under these conditions.

16.16. A DBS home receiver is being installed at a location 60°N, 155°W to receive from a satellite cluster at 157°. Calculate the look angles for the antenna. It is hoped to use an 18-in antenna, the antenna efficiency being 0.55, and the effect of surface irregularities may be ignored. The system noise temperature is 200 K. The downlink frequency may be taken as 12.5 GHz, the [EIRP] as 55 dBW, and the transponder bit rate as 40 Mb/s. Miscellaneous transmission losses may be ignored. Calculate the received clear sky $[E_b/N_o]$, and state whether or not this will make for satisfactory reception.

16.17. Following the procedure given in Example 16.2, calculate the rain attenuation for the 0.01 percent of time, and the corresponding $[E_b/N_o]$ for the system in Prob. 16.16. The ground station may be assumed to be at mean sea level. State if satisfactory reception occurs under these conditions.

16.18. A DBS home receiver is being installed at a location 15°S, 50°W to receive from a satellite cluster at 61.5°. Calculate the look angles for the antenna. Calculate also the diameter of antenna needed to provide a 5-dB margin approximately on the received $[E_b/N_o]$ under clear-sky conditions. An antenna efficiency of 0.55 may be assumed, and the effect of surface irregularities may be ignored. The antenna noise temperature is 70 K, the equivalent noise temperature at the input of the LNA is 120 K, and miscellaneous transmission losses are 2 dB. The downlink frequency may be taken as 12.5 GHz, the [EIRP] as 55 dBW, and the transponder bit rate as 40 Mb/s.

16.19. For the system described in Prob. 16.18, determine the rainfall conditions that will just cause loss of signal. The ground station may be assumed to be at mean sea level.

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Chapter
17

Satellite Services

17.1 Introduction

The idea that three geostationary satellites could provide communications coverage for the whole of the earth, apart from relatively small regions at the north and south poles, is generally credited to Arthur C. Clarke (1945). The basic idea was sound, but of course the practicalities led to the development of a much more complex undertaking than perhaps was envisioned originally. Technological solutions were found to the many problems that were encountered, and as a result, satellite services expanded into many new areas. Geostationary satellites are still the most numerous and well in excess of three! If an average of 2° spacing is assumed, the geostationary orbit could hold 180 such satellites. Of course, the satellites are not deployed evenly around the orbit but are clustered over regions where services are most in demand. Direct-to-home broadcasting, referred to as *direct broadcast satellite* (DBS) service in the United States, represents one major development in the field of geostationary satellites. Another is the use of *very small aperture terminals* (VSATs) for business applications. A third geostationary development is *mobile satellite service* (MSAT), which extends geostationary satellites services into mobile communications for vehicles, ships, and aircraft.

Rapid development also has been taking place in services using nongeostationary satellites. *Radarsat* is a large polar-orbiting satellite designed to provide environmental monitoring services. Possibly the most notable development in the area of nongeostationary satellites is the *Global Positioning Satellite* (GPS) system which has come into everyday use for surveying and position location generally.

Although the developments in satellites generally have led to a need for larger satellites, a great deal has been happening at the other end of the size spectrum, in what is referred to as *microsats* (see, for example, Sweeting, 1992, and Williamson, 1994). In this chapter, brief descriptions are given of some of these services to illustrate the range of applications now found for satellites.

17.2 Satellite Mobile Services

Although countries in the developed world are well served by global communications, there remain large areas and population groups that have very limited access to telecommunications services. In the United States and some European countries, telephone landline density, measured by the number of phone lines per 100 people, is as much as 30 times higher than in China, India, Pakistan, and the Philippines, and an estimated 3 billion people have no phone at home (Miller, 1998). Developing a telephone network on the ground, whether wired or cellular, is time-consuming and expensive. Civil infrastructure may need to be installed or upgraded, including roads and utilities such as water and electricity. Once satellites are deployed in orbit, they can provide wide-area service for telephone, facsimile, and Internet on an as-needed basis without the need for extensive ground facilities. Table 17.1 lists some satellite mobile services. Most of the systems that offer telephone services provide the users with dual-mode phones that operate to GSM standards. GSM stands for *Global System for Mobile Communications* (originally Groupe Spe’cial Mobile); it is the most widely used standard for cellular and personal communications. A number of these systems are in the initial, setting-up stages, and network configuration and coverage may change as operating experience is gained. The Web site addresses given below should be consulted for most recent information. As shown in Table 17.1, the user frequencies are in the L and S bands. This requires the use of large antennas in the range 100 to 200 m^2 aboard the geostationary satellites.

The Global Positioning Satellite (GPS), which system provides position and location services, is covered in Sec. 17.5, and Orbcomm, which provides mainly data services, is covered in Sec. 17.6.

Asian Cellular System. The Asian Cellular System, or AceS, utilizes one Garuda geostationary satellite covering the Asia Pacific area. A second satellite will be employed to expand the service into western and central Asia, Europe, and northern Africa. Each satellite has capacity for at least 11,000 simultaneous telephone channels, servicing up to 2 million subscribers. The satellites utilize two 12-m antennas that generate 140 spot beams, with onboard digital switching and routing of calls between beams. Subscribers are provided with a dual-mode phone that can be switched between satellite and the GSM

TABLE 17.1 Satellite Mobile Services

		User Frequency Range, MHz		Feeder Frequency, GHz	
Name	Orbit	Uplink	Downlink	Uplink	Downlink
AceS	GEO	1626.5–1660.5	1525.0–1559.0	6.425–6.725	3.400–3.700
Ellipso	MEO	1610.0 –1621.5	2483.5–2500.0		
Globalstar	LEO	2483.5–2500.0	1610.0–1626.5	5.025–5.225	6.875–7.055
MSAT	GEO	1626.5–1660.5	1550.0–1559.0		
New ICO	MEO	1985.0–2015.0	2170.0–2200.0		
Thuraya	GEO	1625.5–1660.5	1525.0–1559.0	6.425–6.725	3.400–3.625

modes of operation. Services include voice telephony, Internet connectivity, data, and alerting and paging. Further information can be obtained from the Web site at http://www.aces.co.id.

Ellipso. Ellipso is designed on the basis that the population density to be served is concentrated in the northern hemisphere, with very low population density below 50°S latitude. The system uses a combination of medium earth orbits (MEOs) consisting of an equatorial orbit at height 8040 km and two elliptical orbits with apogee height 7846 km and perigee height 520 km. The equatorial orbit has the trademark name Concordia, and it will be noted that although it is equatorial, it is not geostationary. Satellites in Concordia orbit serve the region between the 50°N and 50°S latitudes. The elliptical orbits, which have the trademark name Borealis, have their apogees over the northern hemisphere. As noted in Sec. 2.3, the orbital velocity is lowest at apogee, and this provides for longest visibility over the northern hemisphere. No onboard signal processing takes place, the satellites operating in the bent pipe mode. CDMA is used. Services include voice telephony, Internet, data, and alerting and paging. Further information can be obtained from the Web site at http://www.ellipso.com/.

Globalstar. Globalstar employs 48 satellites in circular low earth orbits (LEOs) in eight planes at a height of 1414 km. There are also 4 in-orbit spares. Several satellites carry a call simultaneously, thus providing path diversity, which minimizes the danger of a signal being blocked by buildings, trees, or other objects. A range of services is offered, including voice telephony, mobile (hands-free), and two-way short messaging service (SMS). Service is also provided to fixed telephone sites, bringing telephone services to underserved and developing economies without the need for extensive infrastructure on the ground. Globalstar handsets are multimode, allowing selection between GSM, AMPS (analog mobile phone service), and CDMA. Switching and routing take place in the gateway ground stations, obviating the need for switching facilities aboard the satellites. Further information can be obtained from the Web site at //www.globalstar.com/.

MSAT. Operated by Telesat Mobile Inc., in Ottawa, the MSAT-1 satellite covers the primary service area of Canada and the United States. A variety of services are offered, including tracking and managing trucking fleets, wireless phone, data and fax, dispatch radio services, and differential GPS. Further information can be obtained from the Web site at http://www.msat.tmi.ca/.

New ICO. The space segment consists of 12 satellites in medium earth orbits (MEOs). Two orbits are used, at inclinations of 45° and 135° (i.e., the orbits are at right angles to each other). Orbital height is 10,390 km. Ten of the satellites are active, and 2 are in-orbit spares. The satellites operate in the "bent pipe" mode, the switching and routing being carried out at the ground stations. Services being offered or anticipated include voice telephony, Internet connectivity, data, and fax using the GSM standard. Further information can be obtained from the Web site at http://www.ico.com/.

Thuraya. The Thuraya satellite is in geostationary orbit located at 44°E and serving an area between about 20°W to 100°E longitude and 60°N to 2°S latitude. A 12.25 × 16 m antenna is employed providing 250 to 300 spot beams, with onboard beam-switching. The system operates with a 10-dB fade margin to allow for shadowing of handheld units. The network capacity is about 13,750 telephone channels. QPSK modulation is used, with FDMA/TDMA. Dual-mode handsets are used that can be switched between GSM mode and satellite mode. Service features include voice telephony, fax, data, short messaging, location determination, emergency services, and high-power alerting. Further information can be obtained from the Web site at http://www.thuraya.com/.

17.3 VSATs

VSAT stands for *very small aperture terminal* system. This is the distinguishing feature of a VSAT system, the earth station antennas being typically less than 2.4 m in diameter (Rana et al., 1990). The trend is toward even smaller dishes, not more than 1.5 m in diameter (Hughes et al., 1993). In this sense, the small TVRO terminals described in Sec. 16.9 for direct broadcast satellites could be labeled as VSATs, but the appellation is usually reserved for private networks, mostly providing two-way communications facilities. Typical user groups include banking and financial institutions, airline and hotel booking agencies, and large retail stores with geographically dispersed outlets.

The basic structure of a VSAT network consists of a hub station which provides a broadcast facility to all the VSATs in the network and the VSATs themselves which access the satellite in some form of multiple-access mode. The hub station is operated by the service provider, and it may be shared among a number of users, but of course, each user organization has exclusive access to its own VSAT network. Time-division multiplex is the normal downlink mode of transmission from hub to the VSATs, and the transmission can be broadcast for reception by all the VSATs in a network, or address coding can be used to direct messages to selected VSATs.

Access the other way, from the VSATs to the hub, is more complicated, and a number of different methods are in use, many of them proprietary. A comprehensive summary of methods is given in Rana et al. (1990). The most popular access method is frequency-division multiple access (FDMA), which allows the use of comparatively low-power VSAT terminals (see Sec. 14.7.12). Time-division multiple access (TDMA) also can be used but is not efficient for low-density uplink traffic from the VSAT. The traffic in a VSAT network is mostly data transfer of a bursty nature, examples being inventory control, credit verification, and reservation requests occurring at random and possibly infrequent intervals, so allocation of time slots in the normal TDMA mode can lead to low channel occupancy. A form of demand-assigned multiple access (DAMA) is employed in some systems in which channel capacity is assigned in response to the fluctuating demands of the VSATs in the network. DAMA can be used with FDMA as well as TDMA, but the disadvantage of the method is that a *reserve channel* must be instituted through which the VSATs can make requests for channel allocation. As pointed out by Abramson (1990), the problem of access then shifts to how the users may access the reserve channel in an efficient and equitable manner. Abramson presents a method of code-division multiple access (CDMA) using spread-spectrum techniques, coupled with the Aloha protocol. The basic Aloha method is a random-access method in which packets are transmitted at random in defined time slots. The system is used where the packet time is small compared with the slot time, and provision is made for dealing with packet collisions which can occur with packets sent up from different VSATs. Abramson calls the method *spread Aloha* and presents theoretical results which show that the method provides the highest throughput for small earth stations.

VSAT systems operate in a star configuration, which means that the connection of one VSAT to another must be made through the hub. This requires a double-hop circuit with a consequent increase in propagation delay, and twice the necessary satellite capacity is required compared with a single-hop circuit (Hughes et al., 1993). In Hughes, a proposal is presented for a VSAT system which provides for *mesh connection,* where the VSATs can connect with one another through the satellite in a single hop.

Most VSAT systems operate in the Ku band, although there are some C-band systems in existence (Rana et al., 1990). For fixed-area coverage by the satellite beam, the system performance is essentially independent of the carrier frequency. For fixed-area coverage, the beamwidth and hence the ratio λ/D is a constant (see Eq. 6.33). The satellite antenna gain is therefore constant (see Eq. 6.32), and for a given high-power amplifier output, the satellite EIRP remains constant. As shown in Sec. 12.3.1, for a given size of antenna at the earth station and a fixed EIRP from the satellite, the received power at the earth station is independent of frequency. This ignores the propagation margins needed to combat atmospheric and rain attenuation. As shown in Hughes et al. (1993), the necessary fade margins are not excessive for a Ka-band VSAT system, and the performance otherwise is comparable with a Ku-band system. (From Table 1.1, the K band covers 18 to 27 GHz and Ka band covers 27 to 40 GHz. In Hughes, 1993, results are presented for frequencies of 18.7 and 28.5 GHz.)

As summarized in Rana et al. (1990), the major shortcomings of present-day VSAT systems are the high initial costs, the tendency toward optimizing systems for large networks (typically more than 500 VSATs), and the lack of direct VSAT-to-VSAT links. Technological improvements, especially in the areas of microwave technology and digital signal processing (Hughes et al., 1993), will result in VSAT systems in which most if not all of these shortcomings will be overcome.

17.4 Radarsat

Radarsat is an earth-resources remote-sensing satellite which is part of the Canadian space program. The objectives of the Radarsat program, as stated by the Canadian Space Agency, are to

Provide applications benefits for resource management and maritime safety

Develop, launch, and operate an earth observation satellite with synthetic aperture radar (SAR)

Establish a Canadian mission control facility

Market Radarsat data globally through a commercial distributor

Make SAR data available for research

Map the whole world with stereo radar

Map Antarctica in two seasons

The applications seen for Radarsat are

- Shipping and fisheries
- Ocean feature mapping
- Oil pollution monitoring
- Sea ice mapping (including dynamics)
- Iceberg detection
- Crop monitoring
- Forest management
- Geological mapping (including stereo SAR)
- Topographic mapping
- Land use mapping

Radarsat is planned to fly in a low-earth near-circular orbit. The orbital details are given in Table 17.2.

It will be seen from the orbital parameters that Radarsat flies in an orbit similar to the NOAA satellites described in Chap. 1; in particular, it is sun-synchronous. There are fundamental differences, however. Radarsat carries only C-band radar as the sensing mechanism, whereas the NOAA satellites carry a wide variety of instruments, as described in Secs. 1.5 and 7.11. Even though it is known that C-band radar is not the optimal sensing mechanism for all the applications listed, the rationale for selecting it is that it does penetrate cloud cover, smoke, and haze, and it does operate in darkness. Much of the sensing is required at high latitudes, where solar illumination of the earth can be poor and where there can be persistent cloud cover.

It also will be seen that the orbit is described as *dawn to dusk*. What this means is that the satellite is in view of the sun for the ascending and descending passages. With the radar sensor it is not necessary to have the earth illuminated under the satellite; in other words, the sun's rays reach the orbital plane in a broadside fashion. The main operational advantage, suggested in Raney et al. (1991), is that the radar becomes fully dependent on solar power rather than battery power for both the ascending and descending passes. Since there is no operational need to distinguish

TABLE 17.2 Radarsat Orbital Parameters

Geometry	Circular, sun-synchronous (dawn–dusk)
Altitude (local)	798 km
Inclination	98.6°
Period	100.7 min
Repeat cycle	24 days

between the ascending and descending passes, nearly twice as many observations can be made than otherwise would be possible. Also, as Raney et al. point out, the downlink periods for data transmission from Radarsat will take place at times well-removed from those used by other remote-sensing satellites. Further advantages stated by the Canadian Space Agency are that the solar arrays do not have to rotate, the arrangement leads to a more stable thermal design for the spacecraft, the spacecraft design is simpler, and it provides for better power-raising capabilities. With this particular dawn-to-dusk orbit, the satellite will be eclipsed by the earth in the southern hemisphere from May 15 to July 30. The eclipse period changes gradually from zero to a maximum of about 15 minutes and back again to zero, as shown in Fig. 17.1. The battery backup consists of three 50 Ah nickel-cadmium batteries.

Radarsat, shown in Fig. 17.2, is a comparatively large spacecraft, the total mass in orbit being about 3100 kg. The radar works at a carrier frequency of 5.3 GHz, which can be modulated with three different pulse widths, depending on resolution requirements. The SAR operating modes are illustrated in Fig. 17.3. The swath illuminated by the radar lies 20° to the east and parallel to the subsatellite path. As shown, different beam configurations can be achieved, giving different resolutions. The mode characteristics are summarized in Table 17.3.

The satellite completes $14 + 7/24$ revolutions per day. The separation between equatorial crossings is 116.8 km. According to Raney et al. (1991), the scanning SAR is the first implementation of a special radar technique. In summary, Radarsat is intended as a rapid response system providing earth imagery for a range of operational applications and is intended to complement other earth resources satellites.

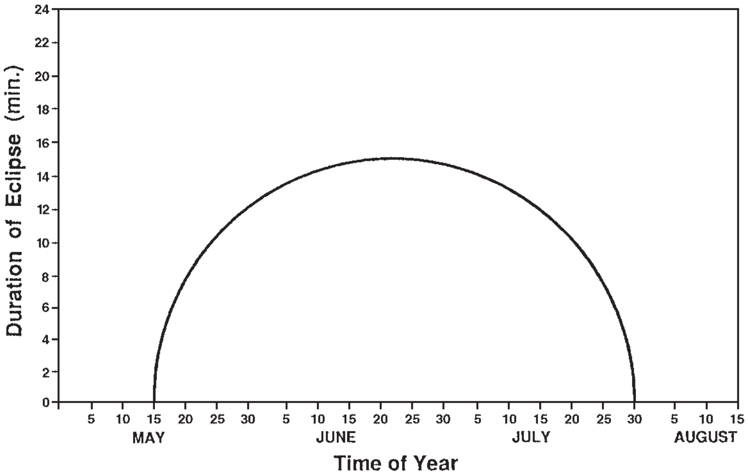

Figure 17.1 Duration of eclipse versus time of year, dawn–dusk orbit. (*Courtesy Canadian Space Agency*.)

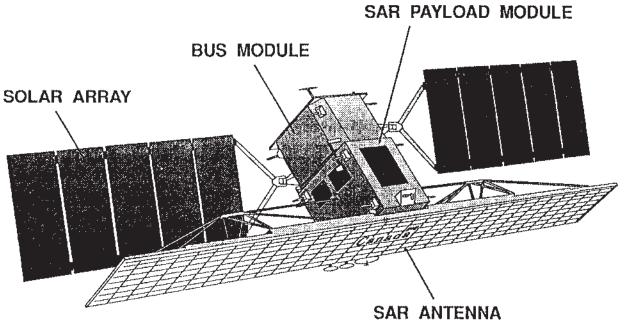

Figure 17.2 Spacecraft configuration. *(Courtesy Canadian Space Agency.)*

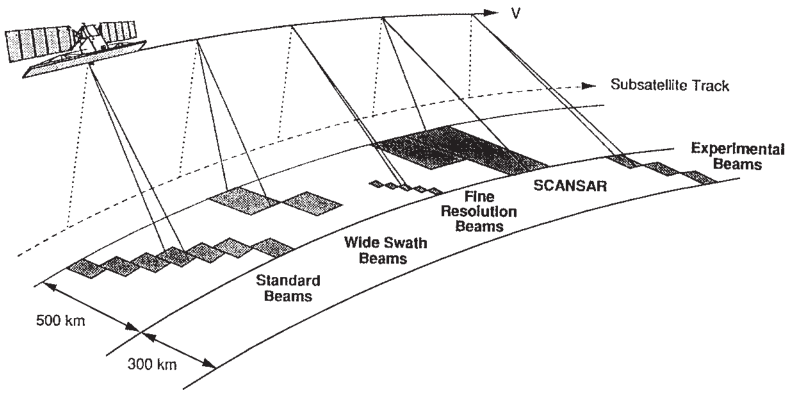

Figure 17.3 SAR operating modes. (*Courtesy Canadian Space Agency.*)

TABLE 17.3 SAR Modes

	Swath, km	Resolution	Incidence angle, degrees
Operational	1	28 m × 30 m (4 looks)	20–50
High resolution	50	10 m × 10 m (1 look)	30–50
Experimental	100	28 m × 30 m (4 looks)	50–60
Scan SAR	500	100 m × 100 m (6 looks)	20–50

17.5 Global Positioning Satellite System

In the Global Positioning Satellite (GPS) system, a constellation of 24 satellites circles the earth in near-circular inclined orbits. By receiving signals from at least four of these satellites, the receiver position (latitude, longitude, and altitude) can be determined accurately. In effect, the satellites substitute for the geodetic position markers used in terrestrial surveying. In terrestrial surveying, it is only necessary to have three such markers to determine the three unknowns of latitude, longitude, and altitude by means of triangulation. With the GPS system, a time marker is also required, which necessitates getting simultaneous measurements from four satellites.

The GPS system uses one-way transmissions, from satellites to users, so that the user does not require a transmitter, only a GPS receiver. The only quantity the receiver has to be able to measure is time, from which propagation delay, and hence the range to each satellite, can be determined. Each satellite broadcasts its ephemeris (which is a table of the orbital elements as described in Chap. 2), from which its position can be calculated. Knowing the range to three of the satellites and their positions, it is possible to compute the position of the observer (user). The geocentric-equatorial coordinate system (see Sec. 2.9.6) is used with the GPS system, where it is called the *earth-centered, earth-fixed* (ECEF) *coordinate system*.

As mentioned above, if the positions of three points relative to the coordinate system are known and the distance from an observer to each of the points can be measured, then the position of the observer relative to the coordinate system can be calculated. In the GPS system, the three points are provided by three satellites. Of course, the satellites are moving, so their positions must be tracked accurately. The satellite orbits can be predicted from the orbital parameters (as described in Chap. 2). These parameters are continually updated by a master control station which transmits them up to the satellites, where they are broadcast as part of the navigational message from each satellite.

Just as in a land-based system, better accuracy is obtained by using reference points well separated in space. For example, the range measurements made to three reference points clustered together will yield nearly equal values. Position calculations involve range differences, and where the ranges are nearly equal, any error is greatly magnified in the difference. This effect, brought about as a result of the satellite geometry, is known as *dilution of precision* (DOP). This means that range errors which occur from other causes, such as timing errors, are magnified by the geometric effect. With the GPS system, dilution of position is taken into account through a factor known as the *position dilution of precision* (PDOP) *factor*. This is the factor by which the range errors are multiplied to get the position error. The GPS system has been designed to keep the PDOP factor less than 6 most of the time (Langley, 1991*c*).

The GPS constellation consists of 24 satellites in six near-circular orbits, at an altitude of approximately 20,000 km (Daly, 1993). The ascending nodes of the orbits are separated by 60°, and the inclination of each orbit is 55°. The four satellites in each orbit are irregularly spaced to keep the PDOP factor within the limits referred to above.

It was stated earlier that three satellites are needed to fix position. In the GPS system, a minimum of four satellites must be observed, for reasons which will be explained shortly. Where more than four satellites are in view, the additional data are used to minimize errors by using the method of least squares.

Each satellite broadcasts its *ephemeris,* which contains the orbital elements needed to calculate its position, and as previously mentioned, the ephemerides are updated and corrected continuously from an earth control station. It should be mentioned that the GPS system is first and foremost intended for military use. However, civilian applications have now become quite extensive and are an accepted part of the GPS program.

Time enters into the position determination in two ways. First, the ephemerides must be associated with a particular time or epoch (as described in Chap. 2). The standard timekeeper is an atomic standard, maintained at the U.S. Naval Observatory, and the resulting time is known as *GPS time.* Each satellite carries its own atomic clock. The time broadcasts from the satellites are monitored by the control station which transmits back to the satellites any errors detected in timing relative to GPS time. No attempt is made to correct the clocks aboard the satellites; rather, the error information is rebroadcast to the user stations, where corrections can be implemented in the calculations.

Second, time markers are needed to show when transmissions leave the satellites so that, by measuring propagation times and knowing the speed of propagation, the ranges can be calculated. Therein lies a problem, since the user stations have no direct way of telling when a transmission from a satellite commenced. The problem is overcome by having the satellite transmit a continuous-wave carrier which is modulated by a clocking signal, both the carrier and the clocking signal being derived from the atomic clock aboard the satellite. At a user station, the receiver generates a replica of the modulated signal from its own atomic clock. The satellite signal and its replica are compared in a correlator at the receiver, and the replica is shifted in time until exact correlation is achieved. If the receiver clock kept exactly the same time as the satellite clock, the time shift as measured by the correlator would give the propagation delay. However, the receiver clock in general will be offset from the satellite clock (which is synchronized to GPS time) by an unknown amount. This offset will be the same for the signals received from the four satellites, and hence by obtaining four range measurements, four equations can be set up in terms of the x,y,z position vectors for the user and the time offset. The four equations can then be solved for these four unknowns. All this requires quite sophisticated microprocessing in the receiver. Also, the composition of the GPS signal is much more complex than indicated here, utilizing spread-spectrum techniques. The reader is referred to the following for details: Langley (1990*a,* 1991*b,* 1991*c*), Kleusberg and Langley (1990), and Mattos (1992, 1993*a,* 1993*b,* 1993*c,* 1993*d,* 1993*e*).

17.6 Orbcomm

The Orbital Communications Corporation (Orbcomm) system is a low earth orbiting (LEO) satellite system intended to provide two-way message and data communications services and position determination. In the Orbcomm submission to the FCC (Orbcomm, 1993), the planned launch dates extend from about mid-1994 to early 1998, with near-full availability expected by December 1995, contingent on licensing factors.

There are to be four main orbital planes, each containing eight satellites spaced from each other by 45° ± 5°. The inclination of each of the main planes is 45°, and the altitude is 775 km (424 nautical miles, or 482 statute miles). The main plane orbits are circular (eccentricity zero). Two supplemental orbits at 70° inclination, each having two satellites, will complete the constellation. The latter two orbits are intended to provide enhanced polar coverage. The satellites and their orbital parameters are listed in Table 17.4.

The ground segment consists of the subscribers (mobile or stationary), gateway earth stations (GES) which provide access to terrestrial systems such as the public switched telephone network and other mobile systems, a network control center (NCC), and a satellite control center (SCC). The network control center and the satellite control center are collocated at the Dulles, Virginia, Orbcomm facility, and the four gateway earth stations for the U.S. services are located near the corners of the contiguous United States (CONUS) in Washington state, Arizona, Georgia, and New York state. Figure 17.4 illustrates the system.

The satellites are small compared with the geostationary satellites in use, as shown in Fig. 17.5. The VHF/UHF antennas are seen to extend in a lengthwise manner, with the solar panels opening like lids top and bottom. Before launch, the satellites are in the shape of a disk, and the launch vehicle, a Pegasus XL space booster [developed by Orbital Sciences Corporation (OSC), the parent company of Orbcomm] can deploy eight satellites at a time into the same orbital plane. For launch, the satellites are stacked like a roll of coins, in what the company refers to as "an eight-pack."

Attitude control is required to keep the antennas pointing downward and at the same time to keep the solar panels in sunlight (battery backup is provided for eclipse periods). A three-axis magnetic control system, which makes use of the earth's magnetic field, and gravity gradient stabilization are employed. A small weight is added at the end of the antenna extension to assist in the gravity stabilization. Thus the satellite antennas hang down as depicted in Fig. 17.4. At launch, the initial separation velocity is provided by springs used to separate the satellites, and a braking maneuver is used when the satellites reach their specified 45° in-plane separation. Intraplane spacing is maintained by a proprietary station-keeping technique which, it is claimed, has no cost in terms of fuel usage (Orbcomm, 1993). Because no onboard fuel is required to maintain the intraplane spacing between satellites, the satellites have a design lifetime of 4 years, which is based on the projected degradation of the power subsystem (solar panels and batteries).

The messaging and data channels are located in the VHF band, the satellites receiving in the 148- to 149.9-MHz band and transmitting in the 137- to 138-MHz band. Circular polarization is used, and a summary of the frequencies and polarization plans is given in Table 17.5.

TABLE 17.4 Constellation Orbital Parameters

Sat. no.	Alt, km	Inc, deg	Ecc, deg	ArgP, deg	Ra, deg	M, deg	S, deg
1	775	45	0	0	0	0	360
2	775	45	0	0	0	45	360
3	775	45	0	0	0	90	360
4	775	45	0	0	0	135	360
5	775	45	0	0	0	180	360
6	775	45	0	0	0	225	360
7	775	45	0	0	0	270	360
8	775	45	0	0	0	315	360
9	775	45	0	0	135	0	360
10	775	45	0	0	135	45	360
11	775	45	0	0	135	90	360
12	775	45	0	0	135	135	360
13	775	45	0	0	135	180	360
14	775	45	0	0	135	225	360
15	775	45	0	0	135	270	360
16	775	45	0	0	135	315	360
17	775	45	0	0	270	0	360
18	775	45	0	0	270	45	360
19	775	45	0	0	270	90	360
20	775	45	0	0	270	135	360
21	775	45	0	0	270	180	360
22	775	45	0	0	270	225	360
23	775	45	0	0	270	270	360
24	775	45	0	0	270	315	360
25	775	45	0	0	405	0	360
26	775	45	0	0	405	45	360
27	775	45	0	0	405	90	360
28	775	45	0	0	405	135	360
29	775	45	0	0	405	180	360
30	775	45	0	0	405	225	360
31	775	45	0	0	405	270	360
32	775	45	0	0	405	315	360
33	775	70	0	0	0	0	360
34	775	70	0	0	0	180	360
35	775	70	0	0	180	90	360
36	775	70	0	0	180	270	360

Abbreviations: Alt = altitude; Ecc = eccentricity; M = mean anomaly; S = service arc; Inc = inclination; ArgP = argument of perigee; Ra = right ascension of the ascending node.
SOURCE: Orbcomm, 1993.

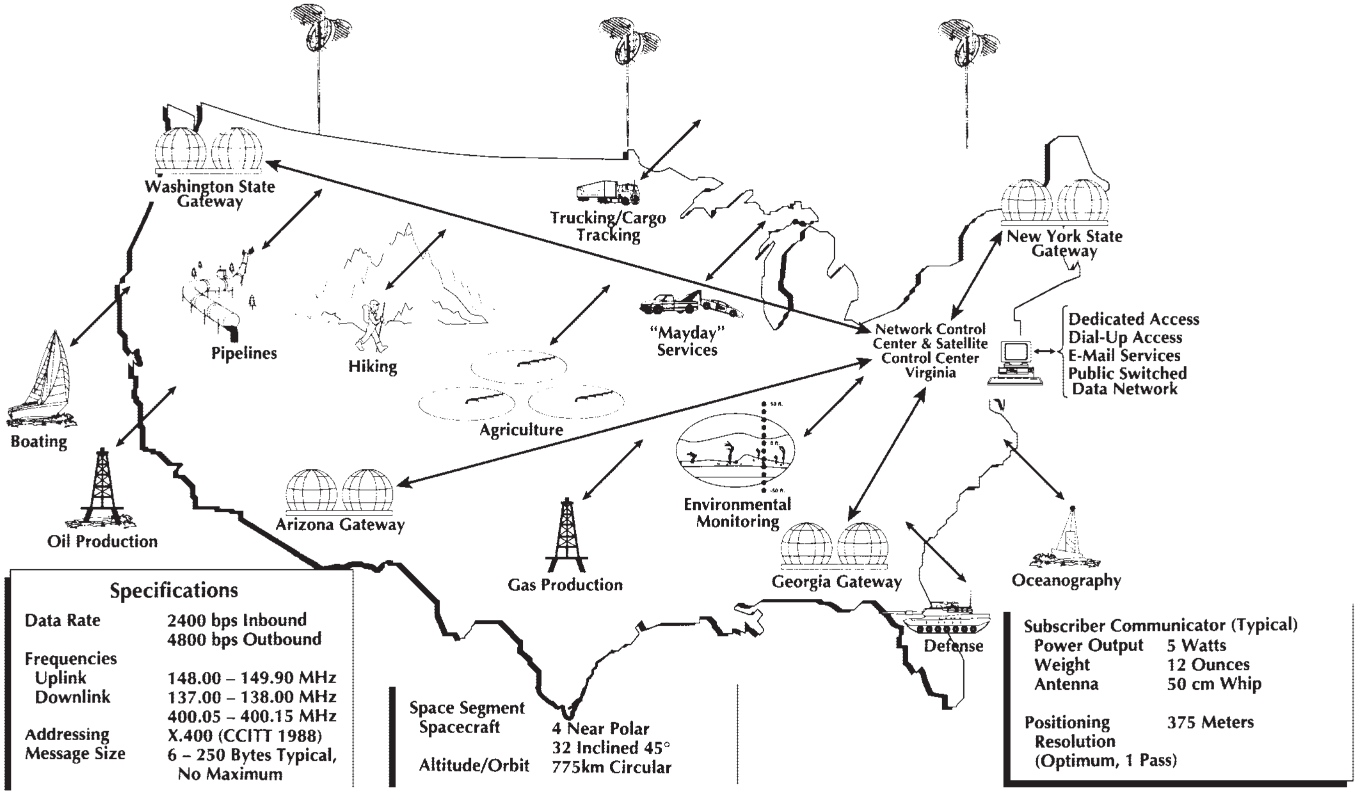

Figure 17.4 The Orbcomm system. (*Courtesy Orbital Communications Corporation.*)

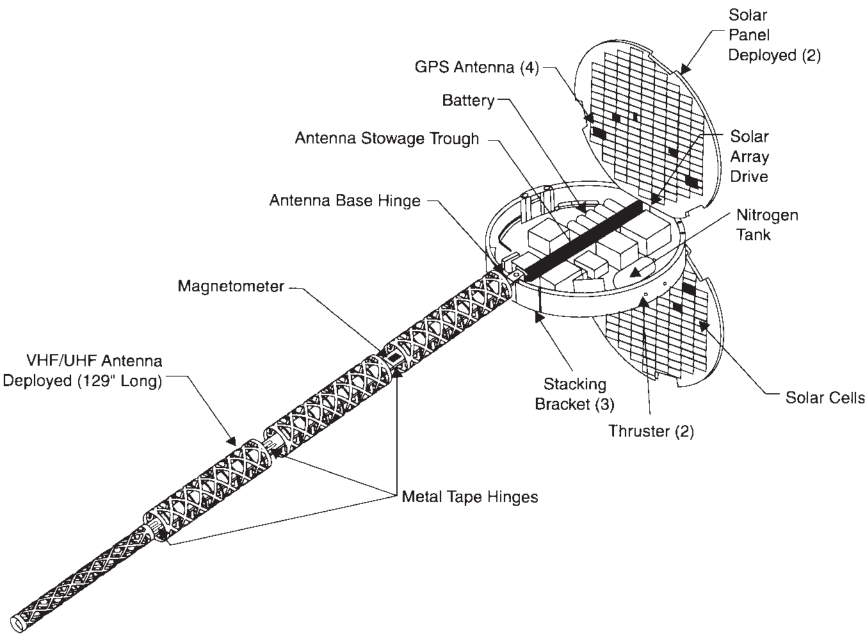

Figure 17.5 Orbcomm/Microstar satellite. (*Courtesy Orbital Communications Corporation.*)

In planning the frequency assignments, great care has been taken to avoid interference to and from other services in the VHF bands; the reader is referred to Orbcomm (1993) for details. In particular, the subscriber-to-satellite uplink channels utilize what is termed a *dynamic channel activity assignment system* (DCAAS), in which a scanning receiver aboard the satellite measures the interference received in small bandwidths, scanning the entire band every 5 s or less. The satellite receiver can then prepare a list of available channels (out of a total of 760) and prioritize these according to interference levels expected. A summary of the link budget calculations for the uplinks and downlinks is given in Tables 17.6 to 17.11.

The Orbcomm system is capable of providing subscribers with a basic position determination service through the use of Doppler positioning, which fixes position to within a few hundred meters. The beacon signal at 400.1 MHz is used to correct for errors in timing measurements introduced by the ionosphere (these errors are also present in the GPS system described in Sec. 17.5, and two frequencies are used in that situation for correction purposes). When used in conjunction with the VHF downlink signal, the beacon signal enables the effects of the ionosphere to be removed. The link budget figures for the

TABLE 17.5 137-MHz Downlink Channelization and Polarization Plan

Subscriber channel number	Lower band edge, MHz	Upper band edge, MHz	Center frequency, MHz	Bandwidth, kHz	Polarizaiton*	Comment
1	137.1927	137.2075	137.200	15	RHCP, LHCP	
GES	137.2075	137.2575	137.235	50	RHCP	GES Downlink
2	137.2575	137.2725	137.265	15	RHCP, LHCP	
3	137.2725	137.2875	137.280	15	RHCP, LHCP	
4	137.2875	137.3025	137.295	15	RHCP, LHCP	
5	137.3025	137.3175	137.310	15	RHCP, LHCP	
6	137.3175	137.3325	137.325	15	RHCP, LHCP	
7	137.3675	137.3825	137.375	15	RHCP, LHCP	
8	137.3825	137.975	137.390	15	RHCP, LHCP	
9	137.3975	137.4125	137.405	15	RHCP, LHCP	
10	137.4125	137.4275	137.420	15	RHCP, LHCP	
11	137.4275	137.4425	137.435	15	RHCP, LHCP	
12	137.4425	137.4575	137.450	15	RHCP, LHCP	
13	137.4575	137.4725	137.465	15	RHCP, LHCP	
14	137.5175	137.5325	137.525	15	RHCP, LHCP	
15	137.5325	137.5475	137.540	15	RHCP, LHCP	
16	137.5475	137.5625	137.555	15	RHCP, LHCP	
17	137.5626	137.5775	137.570	15	RHCP, LHCP	
18	137.5775	137.5925	137.585	15	RHCP, LHCP	
UHF	400.075	400.125	400.100	18	RHCP	

*RHCP = right hand circular polarization, LHCP = left hand circular polarization.
SOURCE: Orbcomm, 1993.

TABLE 17.6 148-MHz Uplink Channelization and Polarization Plan

Channel number	Lower band edge, MHz	Upper band edge, MHz	Center frequency, MHz	Bandwidth, kHz	Polarization	Comment
1	149.585	149.635	149.610	50	LHCP	GES uplink
2	148.000	149.900	Dynamic*	10	LHCP	760-channel uplink, DCAAS subscriber channels

*The DCAAS system will operate within the 148–149.9-MHz band, autonomously selecting unused channels.

SOURCE: Orbcomm, 1993.

TABLE 17.7 Gateway Earth Station-to-Satellite Uplink Link Budget (Edge of coverage, minimum elevation)

General information			Comments
Satellite altitude	775	km	
Elevation angle to satellite	5	deg	
Satellite angle from nadir	62.5	deg	
Range to earth	2730	km	
Data rate	57.6	kb/s	
Uplink frequency	149.4	MHz	
Uplink:			
Transmit EIRP	40.0	dBW	
Spreading loss	−139.7	dB/m^2	
Pointing loss	0.2	dB	
Atmospheric losses	2.0	dB	
Polarization losses	0.1	dB	GES axial ratio 1.2 dB, *S/C* 2.0 dB
Multipath fade losses	5.0	dB	
Area of an isotrope	−4.9	dB/m^2	
Power at satellite antenna	−112.0	dBW	
Satellite antenna G/T	−33.3	dBK^{-1}	
Received C/N_0	83.3	dBHz	
Data rate	47.6	dBHz	57.6 kb/s
Received E_b/N_0	35.7	dB	
Ideal E_b/N_0	10.6	dB	BER at 1:10^{-6}
Implementation loss	3.0	dB	
Interference margin	20.0	dB	
Remaining margin	3.1	dB	

SOURCE: Orbcomm, 1993.

400.1-MHz channel are summarized in Table 17.11. It will be observed from Fig. 17.5 that the satellites carry GPS antennas which enable onboard determinations of the positions of the satellites. This information can then be downloaded on the VHF subscriber channel and used for accurate positioning. Recently, Orbcomm announced an agreement with Trimble Navigation to develop hybrid GPS/Orbcomm user equipment for position and navigation purposes (Orbcomm, 1993). The system also can be used for search and rescue and may well be a strong competitor to the search and rescue service described in Sec. 1.5.

One significant advantage achieved with low earth orbits is that the range is small compared with geostationary satellites (the altitude of the Orbcomm satellites is 775 km compared with 35,876 km for geostationary satellites). Thus the free-space loss (FSL) is very much less. Propagation delay is correspondingly reduced, but this is not a significant factor where messaging and data communications, as compared to real-time voice communications, are involved.

The Orbcomm system will provide a capacity of more than 60,000 messages per hour. By using digital packet switching technology, and confining the system to nonvoice, low-speed alphanumeric transmissions, Orbcomm calculates that the service, combined with other LEO

TABLE 17.8 Satellite-to-Subscriber Downlink Link Budget
(Edge of coverage, minimum elevation)

General information			Comments
Satellite altitude	775	km	
User elevation angle	5	deg	
User data rate	4800	b/s	
Downlink frequency	137.5	MHz	Midrange
Downlink:			
Transmit EIRP	12.5	dBW	
Spreading loss	−139.7	dB/m^2	
Atmospheric losses	2.0	dB	
Polarization losses	4.1	dB	*S/C* 2-dB axial ratio, subscriber linear
Multipath fade losses	5.0	dB	
Satellite pointing loss	0.2	dB	5° off-nadir pointing
Area of an isotrope	−4.2	dB/m^2	
Power at user antenna	−143.8	dBW	
Subscriber antenna G/T	−28.6	dBK^{-1}	
Received C/N_0	57.2	dBHz	
Data rate	36.8	dBHz	4.8 kb/s
Received E_b/N_0	20.4	dB	
Ideal E_b/N_0	10.3	dB	BER at 10^{-5}
Implementation loss	9.0	dB	Blockage, implementation and system
Remaining margin	1.1	dB	

SOURCE: Orbcomm, 1993.

systems, will be able to provide for 10,000 to 20,000 subscribers per kilohertz of bandwidth, which is probably unmatched by any other two-way communications service. Although it is a U.S.-based system, because of the global nature of satellite communications, Orbcomm has signed preliminary agreements with companies in Canada, Russia, South Africa, and Nigeria to expand the Orbcomm service (Orbcomm, 1994). The Orbcomm website is *http:www.orbcomm.com*

17.7 Problems

17.1. Write brief notes on the advantages and disadvantages of using satellites in LEOs, MEOs, and GEOs for mobile satellite communications.

17.2. Write brief notes on the advantages and disadvantages of onboard switching and routing compared to the "bent pipe" mode of operation for satellite mobile communications.

17.3. Describe the operation of a typical VSAT system. State briefly where VSAT systems find widest application.

17.4. Describe the main features of Radarsat. Explain what is meant by a "dawn to dusk" orbit and why the Radarsat follows such an orbit.

TABLE 17.9 Subscriber-to-Satellite Uplink Link Budget
(Edge of coverage, minimum elevation)

General information			Comments
Satellite altitude	775	km	
User elevation angle	5	deg	
User data rate	2400	b/s	
Uplink frequency	148.95	MHz	
Uplink budget:			
Transmit EIRP	7.5	dBW	
Spreading loss	−139.7	dB/m^2	
Atmospheric losses	2.0	dB	After Ippolito
Polarization losses	4.1	dB	*S/C* 2-dB axial ratio, subscriber linear
Multipath fade losses	5.0	dB	After Krauss
Satellite pointing loss	0.2	dB	5° off-nadir pointing
Area of an isotrope	−4.9	dB/m^2	
Power at satellite antenna	−148.5	dBW	
Satellite G/T	−26.0	dBi	
Received P_r/N_0	53.3	dBHz	
Data rate	33.8	dBHz	2.4 kb/s
Received E_b/N_0	19.5	dB	
Ideal E_b/N_0	10.3	dB	BER at 10^{-5}
Implementation loss	2.0	dB	
Required link margin	3.0	dB	
Remaining margin	4.2	dB	

SOURCE: Orbcomm, 1993.

TABLE 17.10 Satellite-to-Gateway Earth Station Downlink Link Budget
(Edge of coverage, minimum elevation)

General information			Comments
Satellite altitude	775	km	
Earth station elevation angle to satellite	5	deg	
Data rate	57,600	b/s	
Downlink frequency	137.2	MHz	
Downlink budget:			
Transmit EIRP	6.5	dBW	
Spreading loss	−139.7	dB/m^2	
Pointing loss	0.2	dB	5° off-nadir pointing
Atmospheric losses	2.0	dB	
Polarization losses	0.1	dB	*S/C* 2-dB axial ratio, GES 1.2 dB
Multipath fade losses	5.0	dB	
Area of an isotrope	−4.2	dB/m^2	
Power at satellite antenna	−144.8	dBW	
Gateway antenna G/T	−12.8	dBK^{-1}	
Received C/N_0	71.0	dBHz	
Data rate	47.6	dBHz	57.6 kb/s
Received E_b/N_0	23.4	dB	
Ideal E_b/N_0	10.6	dB	OQPSK at 1:10^{-6}
Implementation loss	3.0	dB	
Required link margin	3.0	dB	
Interference margin	3.0	dB	
Remaining margin	3.8	dB	

SOURCE: Orbcomm, 1993.

TABLE 17.11 UHF-to-Subscriber Downlink Link Budget
(Edge of coverage, minimum elevation)

General information			Comments
Satellite altitude	775	km	
User elevation angle	5	deg	
Downlink frequency	400.1	MHz	
Downlink budget:			
Transmit EIRP	2.5	dBW	
Spreading loss	−139.7	dB/m^2	
Atmospheric losses	2.0	dB	
Polarization losses	4.1	dB	*S/C* 2-dB axial ratio, subscriber linear
Multipath fade losses	4.0	dB	
Area of an isotrope	−13.9	dB/m^2	
Receiver gain	0.0	dBi	
Antenna-to-receiver losses	−1.0	dB	
Received signal level	−162.5	dBW	
Receiver noise temp.	24.6	dBK^{-1}	(3-dB noise figure)
Receiver loop bandwidth	20.0	dBHz	
Boltzmann's constant	−228.6	dBW/Hz·K	
Receiver noise power	−184.0	dBW	
Received signal-to-noise	21.5	dB	

SOURCE: Orbcomm, 1993.

17.5. Explain why a minimum of four satellites must be visible at an earth location utilizing the GPS system for position determination. What does the term *dilution of position* refer to?

17.6. Describe the main features and services offered by the Orbcomm satellite system. How do these services compare with services offered by geostationary satellites and terrestrial cellular systems?

17.7. Using the range and frequency values given in Table 17.7, calculate the free-space loss. Explain how this differs from the spreading loss listed in the table.

17.8. Using the free-space loss calculated in Prob. 17.9, calculate the received $[C/N_o]$ value and the received $[E_b/N_o]$ and compare with the values given in Table 17.7

17.9. Using the range value given in Table 17.7, and the frequency given in Table 17.8, calculate the free-space loss, the received $[C/N_o]$ value, and the received $[E_b/N_o]$, and compare with the values given in Table 17.8.

17.10. Using the range value given in Table 17.7, and the frequency given in Table 17.9, calculate the free-space loss, the received $[C/N_o]$ value, and the received $[E_b/N_o]$, and compare with the values given in Table 17.9.

17.11. Using the range value given in Table 17.7, and the frequency given in Table 17.10, calculate the free-space loss, the received [C/N_o] value, and the received [E_b/N_o], and compare with the values given in Table 17.10.