EARTH STATION

TECHNOLOGY

Revision 5, June 1999

FOREWORD

This handbook has been prepared under INTELSAT's Assistance and Development Program (IADP). It is also used as a reference handbook for courses on Earth station communications technology organized under the INTELSAT Signatory Training Program (ISTP).

The handbook is updated from time to time. Address any questions or suggestions to:

Manager
Application Support and Training (IADP/ISTP)
Mail Stop 20B
INTELSAT
3400 International Drive, NW
Washington, DC 20008-3098

Telephone:	+1 202 944 7070
Facsimile:	+1 202 944 8214
Telex:	(WUT) 89-2707
International Telex:	(WUI) 64290

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CHAPTER 1

SATELLITE ORBITS

1.1 Introduction

The concept of a global telecommunications system using satellites was put forward first in an article for the British Magazine "Wireless World" in May 1945 by the science fiction author, Arthur C. Clarke. A brief extract from this article addressing the issue of orbital location for geostationary communications satellites is quoted below.

"All these problems can be solved by the use of a chain of space-stations with an orbital period of 24 hours, which would require them to be at a distance of 42,000 Km from the center of the Earth. There are a number of possible arrangements for such a chain but that shown (Figure 1.1) is the simplest. The stations would lie in the Earth's equatorial plane and would thus always remain fixed in the same spots in the sky, from the point of view of terrestrial observers. Unlike all other heavenly bodies they would never rise nor set. This would greatly simplify the use of directive receivers installed on the Earth."

"The following longitudes are provisionally suggested for the stations to provide the best service to the inhabited portions of the globe, though all parts of the planet will be covered.

30° E - Africa and Europe

150° E - China and Oceania

90° W - The Americas

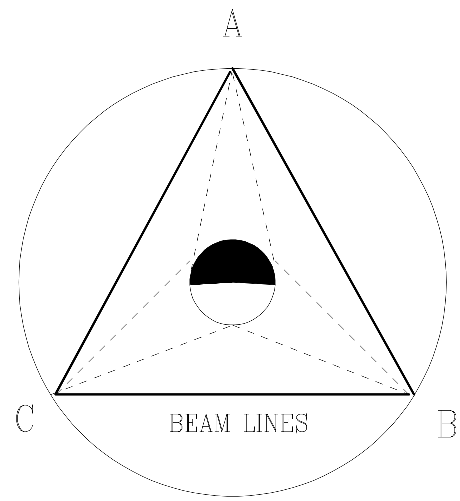


Figure 1.1 Arthur Clark’s View of a Global Communications System

Each station would broadcast programs over about a third of the planet. Assuming the use of a frequency of 3,000 megacycles, a reflector only a few feet across would give a beam so directive that almost all the power would be concentrated on the Earth. Arrays a meter or so in diameter could be used to illuminate single countries if a more restricted service was required."

1.2 Orbits

Before discussing satellite orbits in more general terms, it is important to understand the natural laws that control the movement of satellites. These are based on Kepler’s Laws and state that:

1. The orbital plane of any Earth satellite must bisect the Earth centrally.
2. The Earth must be at the center of any orbit.

There are basically three orbits: polar, equatorial, and inclined. The shape of the orbit is limited to circular and elliptical. Any combination of type and shape is possible but our discussions are concerned only with the circular polar, the elliptically inclined, and the circular equatorial orbit as used by INTELSAT, and shown in Figure 1.2.

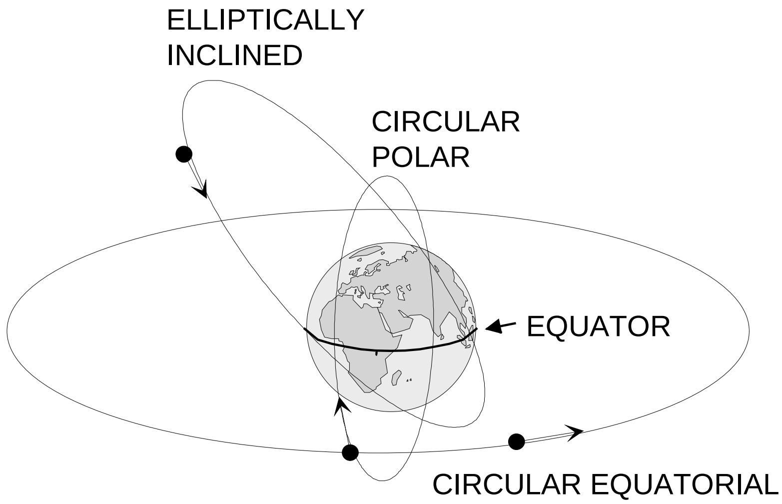


Figure 1.2 Three Basic Orbits

Circular Polar Orbit

This is the only orbit that can provide full global coverage by one satellite, but requires a number of orbits to do so. In the field of communications where the instantaneous transfer of information is required, full global coverage could be achieved with a series of satellites, where each satellite is separated in time and angle from its orbit. However, because of economic, technical, and operational drawbacks, global coverage is not used for telecommunications, though it is favored for some navigation, meteorological, and land resource satellite systems.

Elliptically-Inclined Orbit

An orbit of this type has unique properties that have been successfully used by some communications satellite systems, notably a Soviet domestic system. For this system, the elliptical orbit has an angle of inclination of 63° and a 12-hour orbit period. By design, the satellite is made to be visible for eight of its 12-hour orbit periods to minimize the handover problem while providing substantial coverage of the Earth's surface. By using three satellites, suitably phased, continuous coverage of the polar region that would not be covered by other orbits can be provided.

Circular Equatorial Orbit (Geostationary)

A satellite in a circular orbit at 35,800 km has a period of 24 hours, and consequently appears stationary over a fixed point on the Earth's surface. This orbit is known as the geostationary orbit. The satellite is visible from one-third of the Earth's surface, up to the Arctic Circle, and this orbit is used for the INTELSAT satellite communications system. Figure 1.3 shows typical coverage areas for different geostationary satellites.

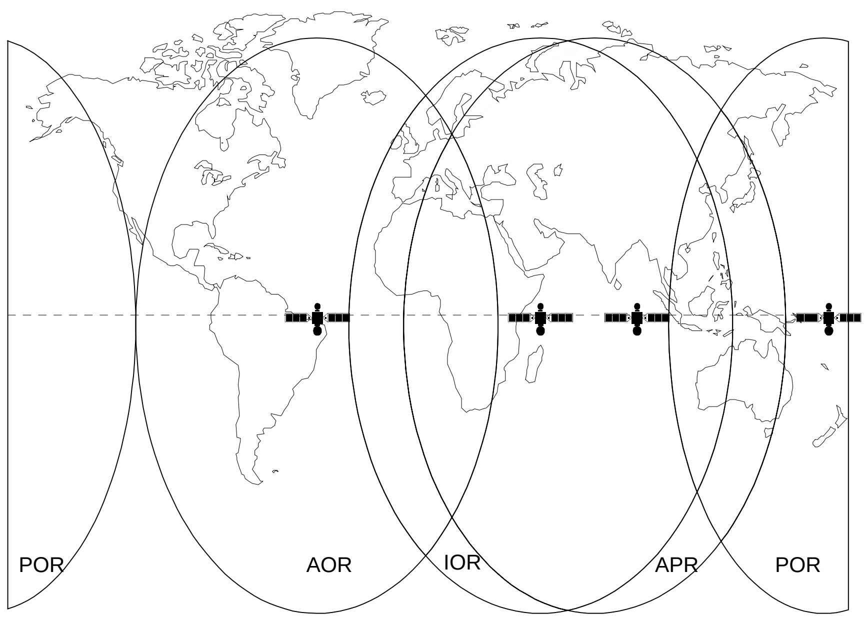


Figure 1.3 INTELSAT Global Network and Coverage Areas

As shown in Figure 1.3, there is a satellite positioned over each ocean region. In fact, INTELSAT has 19 satellites in the geostationary orbit, grouped into four regions. There is a considerable overlap of some of the beams that enables some countries to look at satellites in two or three different regions.

1.3 Stabilization

Stabilization of the satellite is necessary because the Earth is not truly spherical. The Earth's tidal motion, the Moon and the Sun have gravitational effects on the satellite, which tends to make it drift from its correct position. An orbit that is inclined towards the equatorial plane produces a sinusoidal variation in longitude, seen from Earth as motion around an ellipse once every 24 hours. Incorrect velocity results in incorrect altitude and a drift to the east or to the west.

1.4 Position

The satellite must be maintained in position for its required lifetime (typically 10 to 15 years). This positioning is regularly corrected to within ±0.10°. To extend the life of the satellites, less frequent corrections may be made. For example, keeping the satellite in its current North-South position is particularly demanding on satellite fuel reserves. If the North-South positioning is left unchecked, the satellite will tend to move to a natural position (Inclination) of 15° away from the geostationary orbit. INTELSAT allows some of its satellites to increase inclination up to about ± 3 degrees, which extends the operational life up to 3 years or more. These satellites are said to be in "inclined orbit".

1.5 Frequency Bands

A communication satellite is basically an electronic communication package placed in orbit around the Earth. Its prime objective is to facilitate communications transmission from one point on Earth to another. The satellite collects the electromagnetic field, and retransmits the modulated carriers as a downlink.

As the signal levels from the satellite are expected to be very low, any natural phenomena to facilitate the reception of the incoming signal must be exploited. Note in Figure 1.4 that between the frequencies of 2 GHz to 10 GHz the level of the sky noise diminishes, and this band is known as the "microwave window."

The frequencies allocated to satellite communications are in this band. Those initially used by INTELSAT were 6 GHz and 4 GHz (C-band). Due to the increased demand for more bandwidth, higher frequencies of 14 GHZ and 11/12 GHZ (Ku-band) are now being used. Also, new extensions to the existing bands were required. Tables 1.1 and 1.2, show the satellite frequency bands, and Figure 1.5 shows the different downlink frequencies for Ku-band according to the region.

The operational frequency band of the satellite is divided into small portions called transponders (it transmits the downlink by responding to the uplink).

A transponder receives the uplink carriers, amplifies them, converts them to the correct downlink frequency band and then transmits them, via high-powered amplifiers, back to Earth.

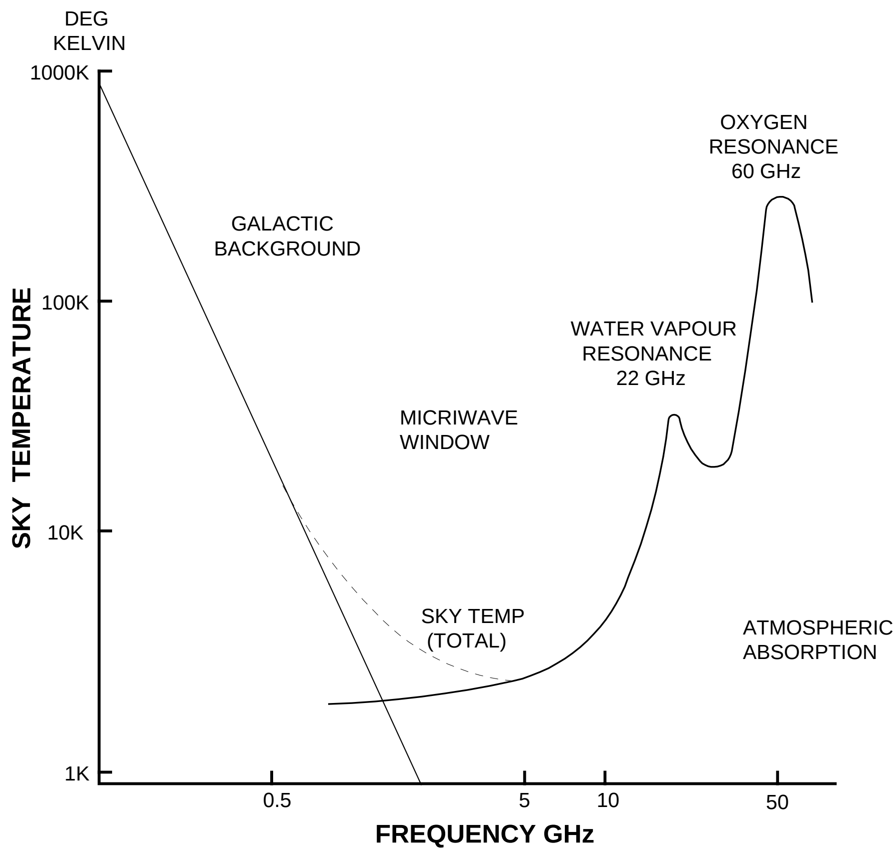


Figure 1.4 Sky-Noise and Frequency Bands

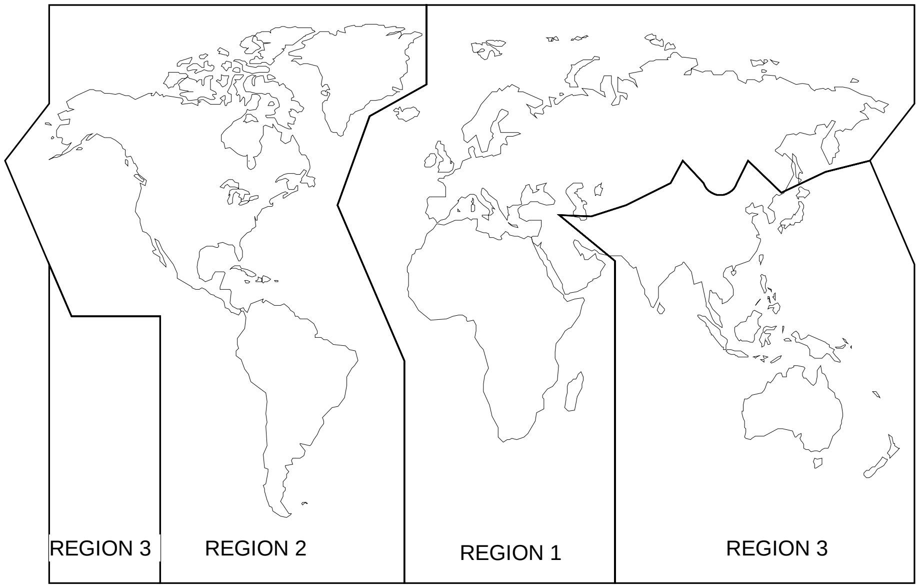
Table 1.1 INTELSAT Satellite Frequency Bands and Nomenclature (Ku-band)

FREQUENCY BANDS (GHz)			TYPICAL UTILIZATION	Shorthand Nomenclature
CURRENT DENOMINATION	UPLINK BANDWIDTH	DOWNLINK BANDWIDTH		
14/11 GHz Ku-band	13.75 – 14.50 (750 MHz) @	10.95 - 11.20 (250 MHz)	Satellite series INTELSAT V, V-A, V-A(IBS) VI, VII, VII-A, VIII, and IX	Lower 11GHz band Ku-band or Band A
		11.45 - 11.70 (250 MHz)	Satellite series INTELSAT V, V-A, V-A(IBS) VI, VII, VII-A, VIII, and IX	Upper 11GHz band Ku-band or Band B
14/12 GHz Ku-band	13.75 – 14.50 (750 MHz) @	11.70 - 11.95 (250 MHz)	Satellite series INTELSAT V-A (IBS), VII VII-A, VIII	Lower 12 GHz band Ku-band or Band C
		12.50 - 12.75 (250 MHz)	Satellite series INTELSAT V-A (IBS), VII VII-A, VIII	Upper 12 GHz band Ku-band or Band D

@ The frequency band 13.75 - 14.00 GHz was allocated to Fixed Satellite Service by WARC - 92 Resolution 112.

Table 1.2 INTELSAT Satellites Frequency Bands and Nomenclature (C-band)

FREQUENCY BANDS (GHz)			TYPICAL UTILIZATION	Shorthand Nomenclature
CURRENT DENOMINATION	UPLINK BANDWIDTH	DOWNLINK BANDWIDTH		
6/4 GHz C-band	5.925 – 6.425 (500 MHz)	3.700 - 4.200 (500 MHz)	At present the most widely used band all INTELSAT series.	C – band
	5.850 – 6.425 (575 MHz)	3.625 - 4.200 (575 MHz)	75 MHz of band extension, to nominal C-band. Satellite series INTELSAT VI, VIII, IX & APR-1.	C – band
	6.425 – 6.650 (225 MHz)	3.400 - 3.625 (225 MHz)	Extended C – Band Added to the nominal C – band in APR-1 and VIII-A.	C – band extended band



	REGION 1	REGION 2	REGION 3
FREQUENCY	10.7 - 11.7	10.7 - 11.7	10.7 - 11.7
BAND	11.7 - 12.5	11.7 - 12.2	
(GHZ)	12.5 - 12.75	12.2 - 12.75	12.5 - 12.75

Figure 1.5 Chart of Regions as defined by the ITU for Ku-band Downlink

1.6 Time Delay

The total Earth-satellite-Earth path length may be as much as 84,000km thus giving a one-way propagation delay of 250ms. The effect of this delay on telephone conversations, where a 500ms gap can occur between one person asking a question and hearing the other person reply, has been widely investigated, and found to be less of a problem than had been anticipated. This phenomenon is minimized with the use of "Echo cancelers". With geostationary satellites, a two-hop operation is sometimes unavoidable and results in a delay of over 1 second.

1.7 Geographical Advantage

A station which is located near the center of a satellite beam (footprint), will have an advantage in the received signal compared to another located at the edge of the same beam of the satellite.

The satellite antenna pattern has a defined beam edge to which the values of the satellite Equivalent Isotropically Radiated Power (EIRP), Gain-to-Noise Temperature ratio (G/T), and flux density are referenced. Therefore, a footprint as shown in Figure 1.6 will have lines of contours representing a 1 dB incremental toward the beam center.

1.8 Path Loss

The total path loss for satellites in geostationary orbit depends on the distance and frequency of operation but is in the order of 200 dB in C-band and 206 dB in Ku-band.

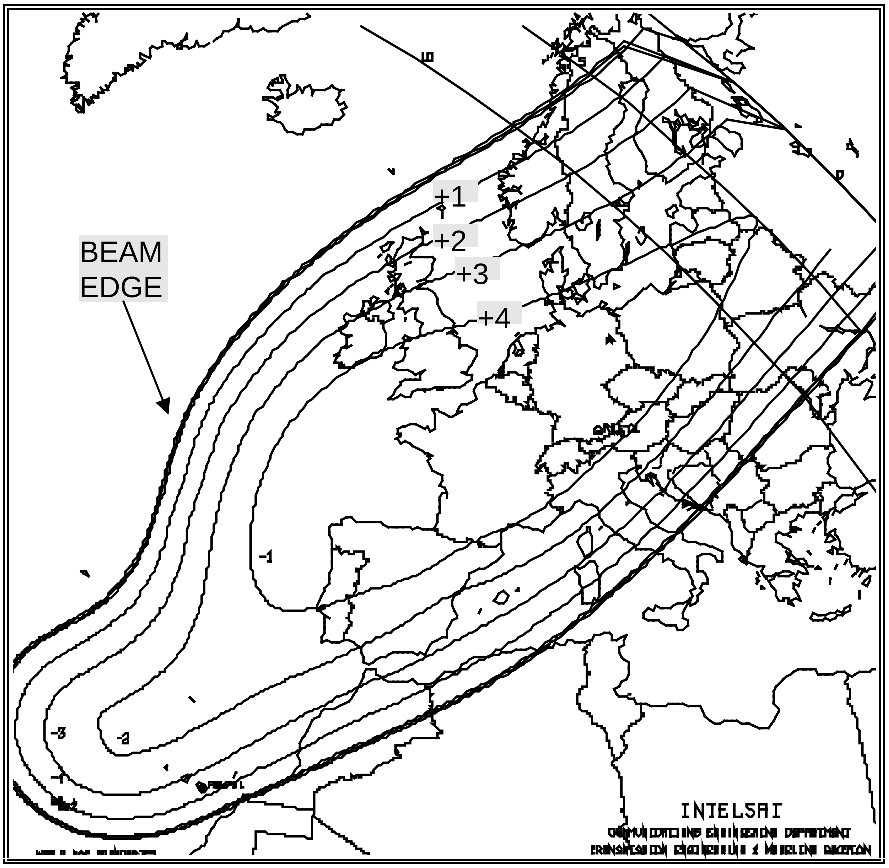


Figure 1.6 Example of Geographical Advantage

1.9 Sun Interference

Sun interference is due to the satellite, the Sun, and the Earth station antenna being aligned, causing the antenna to receive solar noise, as shown in Figure 1.7.

The Sun represents a transmitter with significantly more power than the satellite, and the solar noise will overwhelm the signals coming from the satellite, causing a total loss of traffic.

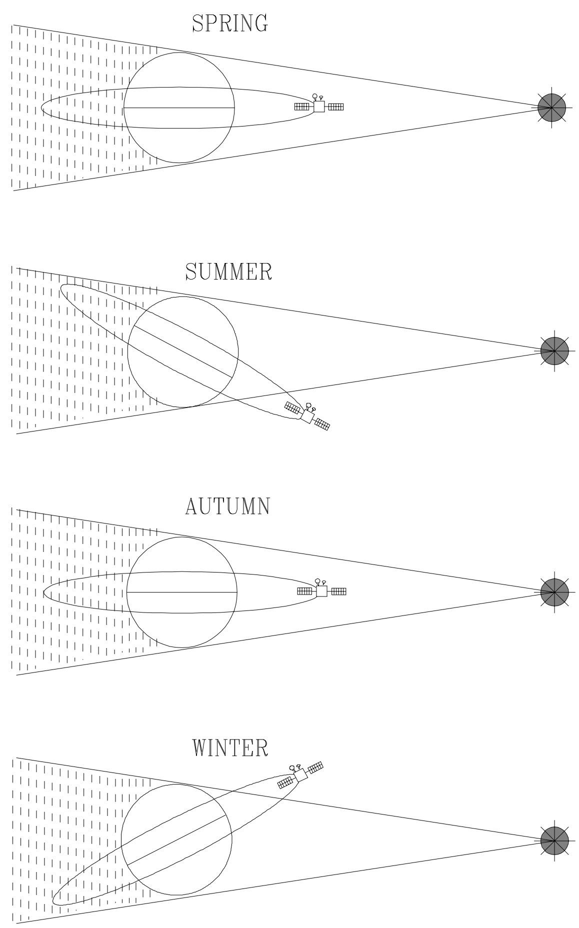


Figure 1.7 Sun Interference

This degradation occurs twice a year during the spring and autumn and lasts for 5 to 6 days, with the degradation on the first and last days lasting for a few minutes but no more than 15, depending on location. INTELSAT advises each station of when Sun interference can be expected and its duration as calculated for each day.

If continuous tracking is used at the Earth station, it is the duty of the technician to deactivate the continuous tracking during the periods of interference to ensure that the dish does not track the Sun instead of the satellite.

It is normal policy to advise priority customers whose traffic is susceptible to disturbances, i.e., banks, airline offices etc., well in advance to minimize the effects of the outage.

1.10 Tropospheric Scintillation

At unpredictable times the levels of receive signals from the satellite rapidly fluctuate up and down. This is called scintillation. Scintillation is brought about by the turbulent mixing of air mass at different temperatures and humidities, and by the random addition of particles such as rain, ice, and moisture. Changes of up to 12 dB have been recorded across the 500 MHz satellite band for up to 2 or 3 hours, and may be observed at one Earth station while a neighboring Earth station at a distance of 200km is not being affected.

Scintillation is caused by variations in amplitude and phase of the microwave signal as it propagates along the slant path through the atmosphere. The air masses that comprise the atmosphere are not homogenous causing the radio refractive index of the air mass to vary with time and position within the mass.

Severe scintillations can adversely affect the tracking capabilities of the Earth station and preventive action (such as program or memory tracking) may have to be taken.

CHAPTER 2

INTELSAT SATELLITES

2.1 INTELSAT SYSTEM

Satellites' Deployment

INTELSAT space segment currently comprises 19 satellites in orbit, making the INTELSAT system the most comprehensive system for global communications. It currently includes INTELSAT V/VA, VI, VII/VIIA, and VIII series satellites. In the near future, the system will also have APR-1 and INTELSAT IX.

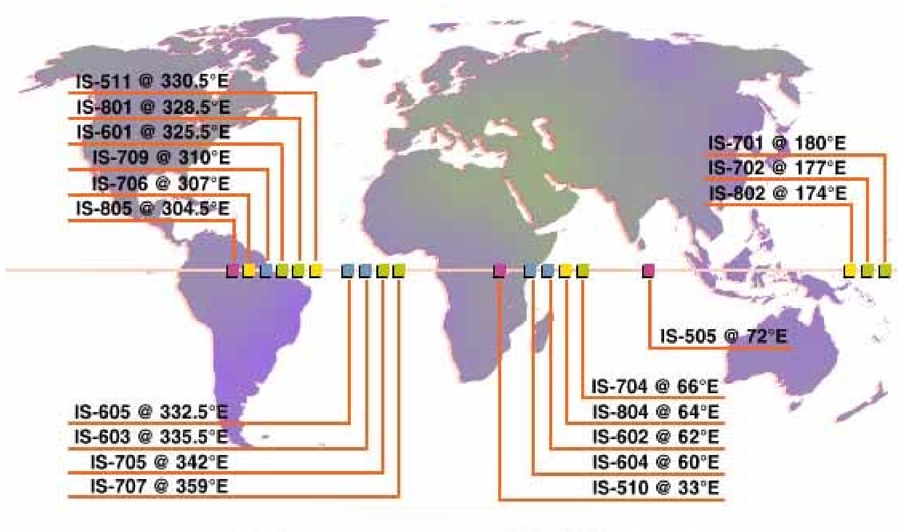


Figure 2.1 Deployment of INTELSAT Satellites

Coverage Areas

Atlantic Ocean Region (AOR): Covers the Americas, the Caribbean, Europe, the Middle East, India, and Africa with satellites at orbital locations ranging from 304.5° E to 359° E.

Indian Ocean Region (IOR): Covers Europe, Africa, Asia, the Middle East, India, and Australia with satellites at orbital locations ranging from 33° E to 66° E.

Pacific Ocean Region (POR): Covers Asia, Australia, the Pacific Rim, and the Western part of North America with satellites at orbital locations ranging from 174° E to 180° E.

Asia Pacific Region (APR): As three ocean regions no longer meet customer demand, a fourth region, Asia Pacific, was introduced and began service in 1993 using INTELSAT 501. This new region, highlighted in Figure 2.2, provides an improved connectivity for the western Pacific Rim and the Asian land mass as well as for all parts of Central and Eastern Europe, Japan, and Australia with one satellite, currently located at 72° E. A new satellite, APR1 at 83° E will be available for operation in 1999.

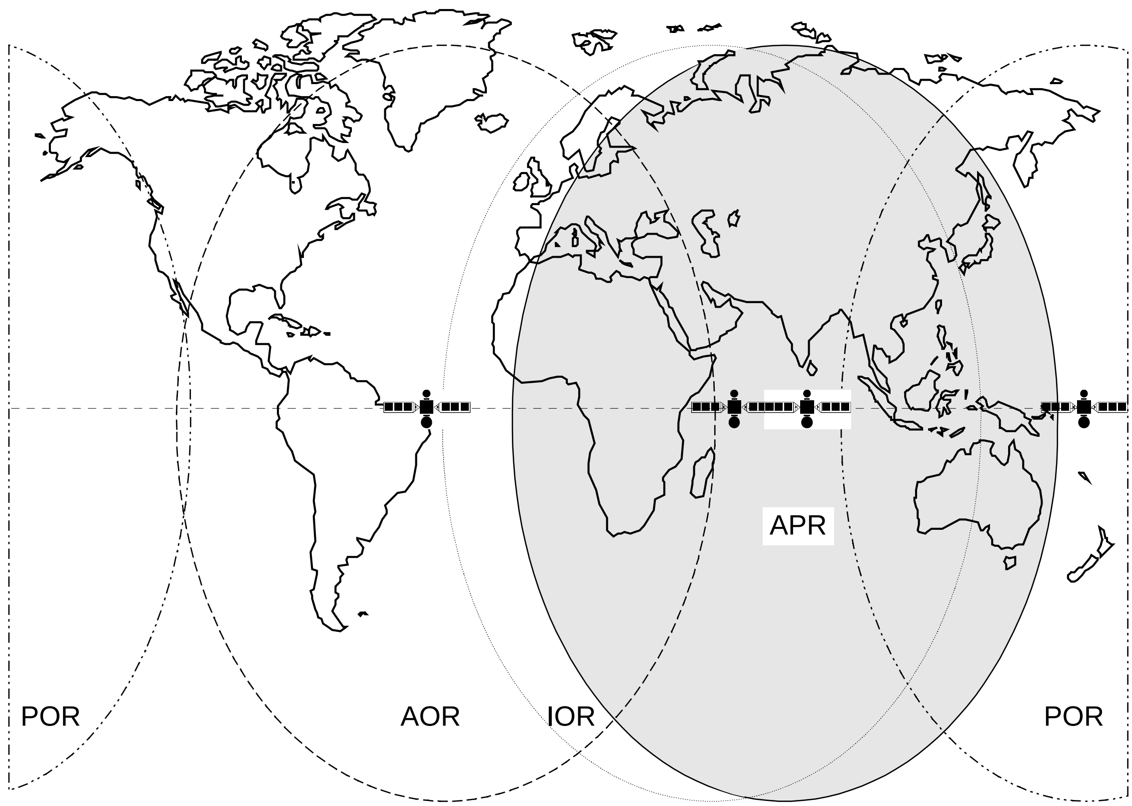


Figure 2.2 INTELSAT Coverage Areas

Upcoming Launches

The following satellites will be deployed in the near future to replace the satellites ending their projected lifetime.

Table 2.1 Upcoming Launches

New Satellite	Replaced Satellite	Launch Window
APR-1 @ 83°E	-	1999
IS-901 @ 60°E	IS-604 @ 60°E	2000
IS-902 @ 62°E	IS-902 @ 62°E	2000
IS-903 @ 335.5°E	IS-603 @ 335.5°E	2001
IS-904 @ 325.5°E	IS-601 @ 325.5°E	2001

2.2 SATELLITE DESIGN

Satellites-Series Overview

Figure 2.3 displays INTELSAT communications satellites. Since INTELSAT's inception in 1965, traffic growth has been extremely rapid. Invariably, the capacity offered by any individual satellite has been filled quickly, resulting in the requirement for larger satellites with increased capacity every few years. This has meant that INTELSAT has only just been able to keep pace with demand, but to do this each successive satellite has had to use a new technique to obtain increased channel capacity within the limitations imposed by satellite design.

Some of the limitations affecting the design include:

1. A maximum weight that a particular launch vehicle can carry into orbit.
2. Bandwidth allocated by the ITU for satellite communications. This is presently 875 MHz in the C-band and 750 MHz in the Ku-band.
3. A maximum radiofrequency (RF) power such that terrestrial microwave links using the same frequencies are not affected, but one that still provides sufficient power for realistic signal-to-noise ratios at the receiving Earth stations.

Table 2.2 shows INTELSAT satellites since Early Bird. A brief description of each type of satellite used by INTELSAT follows, showing the continuous improvements in design and capacity.

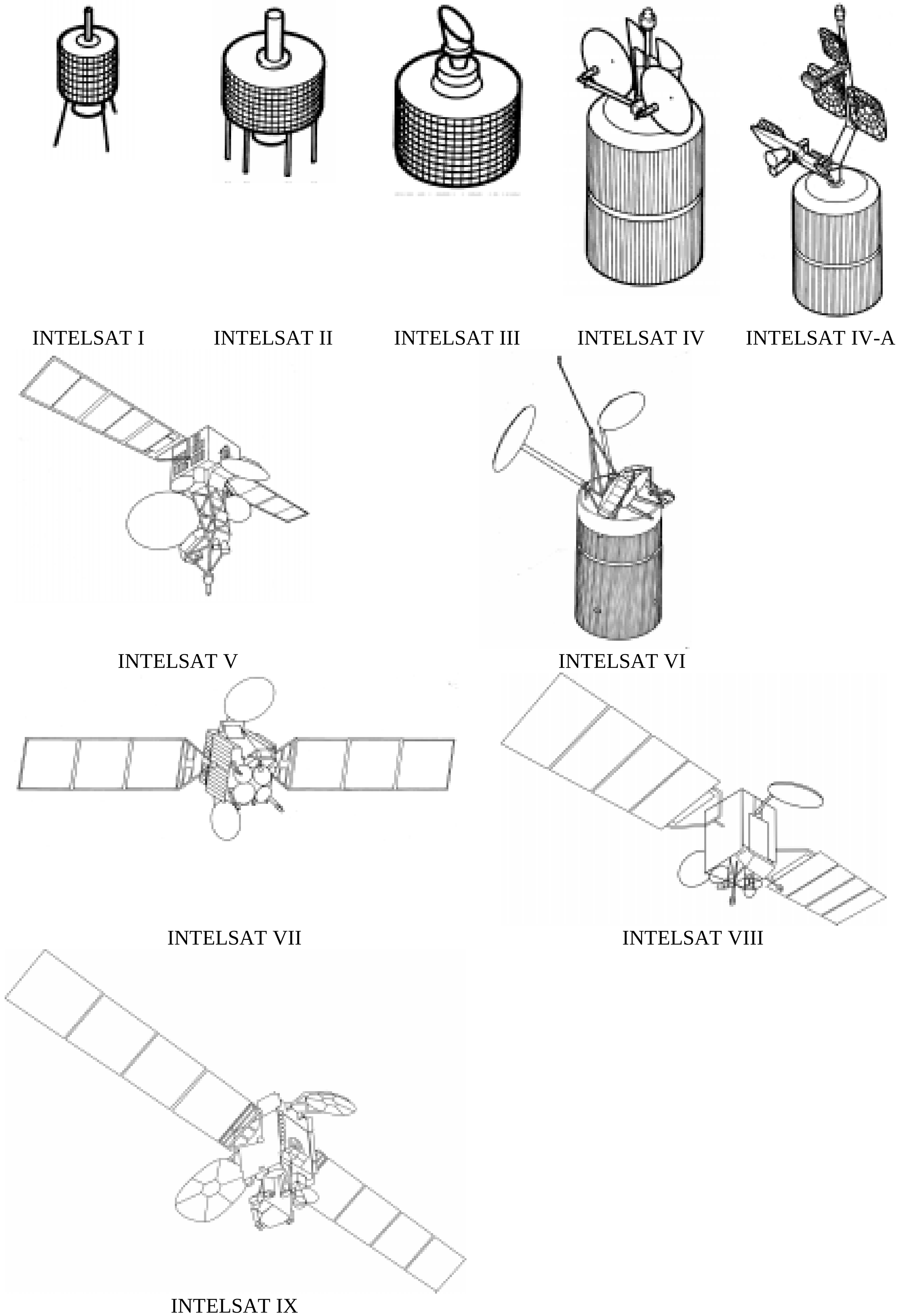


Figure 2.3 INTELSAT Satellite Series

Table 2.2 Summary of INTELSAT Satellites' Features

INTELSAT Satellite Series	TOTAL RF BW (MHz)	RF BAND	PRIME POWER (Watts)	WEIGHT (Kg).	STABILI-ZATION TYPE	Design LIFE (years)	NEW FEATURE
I	50	C	45	45	SPIN	1.5	First satellite for international telephony services
II	125	C	75	45	SPIN	3	Telephony plus TV capacity.
III	450	C	120	300	SPIN	5	The first global satellite system.
IV	480	C	460	720	SPIN	7	SCPC service and the RF band divided into 36 MHz transponders.
IV-A	800	C	595	795	SPIN	7	Frequency reuse by spatial isolation
V	2200	C and Ku	175	970	3-AXES	7	Frequency reuse by polarization isolation, Ku-band package and cross-strapped operation.
V-A	2250	C and Ku	1475	970	3-AXES	7	Frequency reuse for global beams and steerable spot beams
VI	3300	C and Ku	2100	1800	SPIN	10	SS-TDMA operation and Solid State Power Amplifiers (SSPAs) as output amplifiers in some beams.
VII	2432	C and Ku	4000	1437	3-AXES	10.9	SSPAs in all C-band transponders; switchable transponder and enhanced U/L connectivity in Zone Beams; 12 GHz D/L capability; enhanced Ku-Spot 2 coverage for POR
VII-A	3160	C and Ku	5000	1823	3-AXES	10.9	Linearized Traveling Wave Tube Amplifiers (LTWTAs) and paralleled LTWTAs in Ku-band for a high power mode; Ku- to C-band connectivity
VIII	2550	C and Ku	5100	1587	3-AXES	10	Polarization reversal option in Ku-band; TV Broadcast mode in Zone Beams for a West Quasi-Hemi coverage; flexible transponder activation for 6 out of 10 Channels in Ku-band
APR	396	Extended C	2200	1118	3-AXES	12	Linear polarization, extended C-band, higher EIRP
IX	3456	C and Ku	8085	1900	3-AXES	13	Selectable split uplink in Global Channel 12 for SNG; selectable split uplink in Hemi Channel 9 for DAMA. Flexible transponder activation for 12 out of 16 channels in Ku-band. Equipped with an overdrive control for Ku-band transponders.

Satellite Stabilization

INTELSAT communication satellites use two basic designs:

1. Cylindrical spin-stabilized
2. 3-Axes stabilized

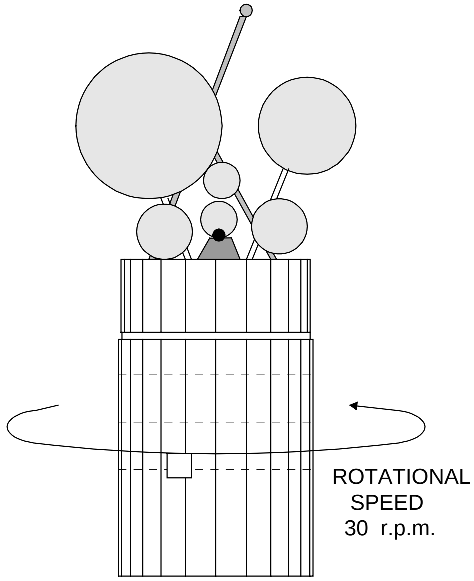


Figure 2.4 Cylindrical Spin-Stabilized

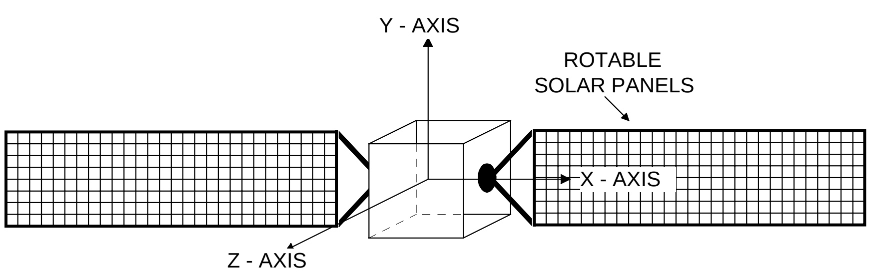


Figure 2.5 Three-Axes Stabilized

Cylindrical Spin-Stabilized

The satellite in Figure 2.4 is cylindrical in shape, and is made to rotate at approximately 30 rpm to maintain orbital stability.

The antennas used are directive and are mounted on a de-spun subassembly. Earth and Sun sensors control the subassembly to ensure that the main beams from the antennas are always pointing towards the Earth. The outer skin of the cylinder is covered in solar cells to provide the necessary power for the communication packages. Orbital corrections are performed by a series of small motors mounted on the main body.

The Satellite main engine, or Apogee Motor, is normally used to accelerate the satellite into its geostationary orbit, and also to remove the satellite from its geostationary 'slot' at the end of its useful life.

Three – Axes Stabilized

This design is radically different from the cylindrical type. The body of the satellite remains stationary, with its fixed antennas pointing towards Earth. A series of onboard gyroscopes maintain orbital stability in the three axes, X, Y, and Z, as shown in Figure 2.5.

The advantage of this construction mode is that complicated de-spinning machinery is not required. As a result, the satellite is lighter to launch, and a greater number of solar cells can be mounted on the extendible panels attached to the main body. These panels can be rotated to maximize illumination from the Sun.

Transponders

The basic building block of any satellite communications package is the transponder. This device receives the uplink carriers, amplifies them, converts them to the correct downlink frequency band, and then transmits them, via a high-powered amplifier, back to Earth.

EIRP

In the early satellites, few transponders were used. Those used had a relatively low output power. As the demand for circuits grew, the design of the communications packages changed to offer more transponders, each covering a small portion of the available band, thus providing better linearity and a higher output power capability.

For example, INTELSAT IV satellites contained twelve 40 MHz transponders (36 MHz usable bandwidth and 4 MHz guard band). These satellites had a total communications bandwidth of 432 MHz. The "guard bands" at each end of the C-band allocated frequencies took 48 MHz, and the remaining 20 MHz (500 MHz - {40 x 12}MHz) were taken up by the flight beacons.

The INTELSAT IV-A satellite series introduced the concept of shaped beams to cover selected areas of the Earth's surface. In this way different beams could be directed at the required areas and, as long as the beams did not overlap, a frequency band could be used for more than one beam, thereby increasing satellite capacity. This technique is known as Spatial Separation Frequency Reuse. The transponder capacity has grown with every satellite series. Table 2.2 shows the available and planned transponder power for INTELSAT satellites. This increase in power combined with the use of the latest output amplifiers, either Solid State Power Amplifiers (SSPAs) or Linearized Traveling Wave Tube Amplifiers (LTWTAs), make it possible for these satellites to carry more traffic. Also, more power is available for the downlink to reach very small antennas.

Table 2.3 Satellite Transponder EIRP Comparison Table

INTELSAT Satellite	Transponder Saturation EIRP at Beam Edge (dBW)							
	V	V-A	VI	VII	VII-A	VIII	IX	APR
C-band GLOBAL	23.5; 26.5 in channels 7-8	23.5; 26.5 in channels 7-8	26.5; 23.5 in channel 9	26.0/29.0 in channel 12(1)	29.0(1)	29.0	31.0	N/A
C-band SPOT	N/A	32.5/35.5	N/A	33.3; 36.3 in channels 7-8	36.1(2)	N/A Channel 12(2)	N/A	N/A
C-band HEMI and Zone	29.0; 26.0 in channel9	29.0; 26.0 in channel 9	31.0; 28.0 in channel 9	33.0	33.0	36.0/34.5*	37.0 to 40.0(4)	N/A
Ku-SPOT 1 or East Spot	41.1	41.1	44.7(3)	45.4/43.4* at 35W	47.0/44.7* at 49W 46.7/44.6* at 50W	47.0/44.0* 49.5/47.2* at 2x49W	49.0/47.0*	N/A
Ku-Spot 1X	N/A	N/A	N/A	N/A	47.1/44.8* at 49 W	N/A 49.4/47.1* at 2x49W	N/A	N/A
Ku-Spot 2 or West Spot; (NA)	44.0	44.0	44.7/41.7*(3)	44.5/41.4* at 35W 45.8/42.6* at 50W	47.0/43.7* at 73W 49.4/46.1* at 2x73W	47.0/44.0*	49.0/47.0*	N/A
Ku-Spot 2X	N/A	N/A	N/A	N/A	46.7/43.4* at 73W 48.9/45.6* at 2x73W	N/A	N/A	N/A
Enhanced Ku-Spot 2/2A	N/A	N/A	N/A	44.1/41.2* at 50W	45.2/42.2* at 73W 47.6/44.3* at 2x73W	N/A	N/A	N/A
Ku-Spot 3; (SA)	N/A	N/A	N/A	46.0/43.0* at 35W	42.8/41.0* at 49W 47.5/44.5* at 50W	N/A 44.5/42.7* at 73W 45.0/43.2* at 2x49W 46.7/44.9* at 2x73W	N/A	N/A
Wide and Zone Beam	N/A	N/A	N/A	N/A	N/A	N/A	N/A	36.0

Notes:

* EIRP values are for inner and outer coverage.

(1) INTELSAT VII/VIIA Global Transponder EIRP in Channel 9A is 28.5/28.0 dBW, and in Channel 9B is 26.0/26.0 dBW.
(2) INTELSAT VII and VIIA C-Spot transponder EIRP in Channel 9A is 35.2 dBW and in Channel 9B is 33.2 dBW.
(3) The INTELSAT VI EIRP for Channels (9-12) is 3 dB higher.
(4) The INTELSAT IX combined Zone Beams (4-Zone Mode) in the IOR have a minimum beam edge EIRP of 35 dBW.

Transponder Numbering

With the introduction of the IVA satellites, which featured spatial frequency reuse, it became necessary to devise a numbering system for the transponders, as two transponders could now occupy the same frequency slot. This numbering scheme was modified for use with the later series of satellites.

Each transponder is numbered according to the beam connectivity and the frequency slot it occupies. The number, normally shown in brackets, indicates the satellite channel or channels that are occupied in the transponder. The 500 MHz bandwidth is divided into 12 slots of 40 MHz each. These slots are known as satellite channels. Transponders on the INTELSAT satellites have bandwidth ranging from 34 to 241 MHz.

The first number is a one- to two-digit number indicating the beam to which the transponder is connected as shown in Table 2.4a. The last digit(s) indicates the transponder number within that beam (Table 2.4b).

Table 2.4a Transponder First Digit(s) Numbering

First Digit(s)	Beams	Frequency Band
1	West Hemi (A pol.)	C
2	East Hemi (A pol.)	C
3	Global (A pol.)	C
4	North West Zone (B pol.)	C
5	North East Zone (B pol.)	C
6	West Spot (Linear pol.)	Ku
7	East Spot (Linear pol.)	Ku
8	Global (B pol.)	C
9	South West Zone (B pol.)	C
10	South East Zone (B pol.)	C
11	Spot 3 (Linear pol.)	Ku
12	Mid West Zone (B pol.)	C
13	Spot (A pol.)	C
16	West Spot (Linear pol.)	Ku (12 GHz)
17	East Spot (Linear pol.)	Ku (12 GHz)
18	Spot (B pol.)	C

Table 2.4b Transponder Last Digit Numbering

Last Digit	Frequency Slot
0	1'-2' (ISVI & VIII)
1	1-2
2	3-4
3	5-6
3a	5 (IS VII upwards)
3b	6 (IS VII upwards)
4	7-8
5	9
6	10
7	11
8	12
9	7-12/10-12 etc

A Polarization is Left Hand Circular Polarization Uplink and Right Hand Circular Downlink.
B Polarization is Right Hand Circular Polarization Uplink and Left Hand Circular Downlink.
Linear Polarization is Vertical Polarization Uplink and Horizontal Downlink for the West Spot beam, and the reverse for the East Spot Beam.

Examples:

1. Channel number 43 is the 3rd transponder in the North West Zonal Beam B Polarization;
2. Channel number of 87 would be the 7th transponder in the B Polarization Global beam;
3. Channel 11/51 is West Hemispheric Beam (A Polarization) to North East Zone Beam (B Polarization) via 1-2 frequency slot. (WH/NEZ via 1-2);
4. Channel 43/73 is NWZ/ES via 5-6.

Flight Beacons

The Flight Beacons are the only signals, apart from the satellite telemetry channel, which are produced by the satellite. The majority of Earth stations use them for tracking and reference purposes. Each satellite transmits two Beacons in each of the frequency bands in the A Pol Global Beam. The C-band beacons are modulated with telemetry data, whereas the Ku-band beacons are always unmodulated. A list of the available beacon frequencies for the various bands is given in Table 2.5.

Table 2.5 INTELSAT Satellite Beacon Frequencies

BAND	BEACON FREQUENCY/ POL	INTELSAT SATELLITES						
		V & V-A	VI	VII	VII-A	VIII	IX	APR
C-band	3947.50/RHCP	X	X	X	X	X	X	
	3948.00/RHCP	X	X	X	X	X	X	
	3950.00/Lin Vertical			X	X	X	X	
	3952.00/RHCP	X	X	X	X	X	X	
	3952.50/RHCP	X	X	X	X	X	X	
	4190.976/LHCP							X
	4197.504/RHCP							X
Ku-band	11198.00/RHCP	X	X	X	X	X	X	
	11452.00/RHCP	X	X	X	X	X	X	
	11701.00/Lin			X		X		
	12501.00/Lin			X		X		

2.3 INTELSAT SATELLITE SERIES

INTELSAT VI

The INTELSAT VI satellites, shown in Figure 2.6, have 50 transponders operating in C- and Ku-band and a total bandwidth of 3,272 MHz. The C-band payload has two hemispheric coverage transponders, four zone beam transponders, and two global beam transponders. The Ku-band payload consists of two spot beam transponders. Figure 2.7 shows a transponder frequency plan and Figure 2.8 shows a typical beam coverage pattern.

The receiver sections contain a total of 20 receivers, arranged in five groups of four-for-two redundancy. These groups serve the spot, hemi, zone, and global repeaters.

All receivers are solid state units. The units use gallium arsenide field effect transistors to achieve noise figures of 3.2 dB at 6 GHz and 5 dB at 14 GHz.

The power amplifier sections contain driver amplifiers, upconverters, Traveling Wave Tube Amplifiers (TWTAs), and SSPAs in various combinations. In the 4 GHz channels, TWTAs with power levels from 5.5 to 16.0 Watts are used for the hemi, large zone, and global repeaters. The small zone repeaters use SSPAs.

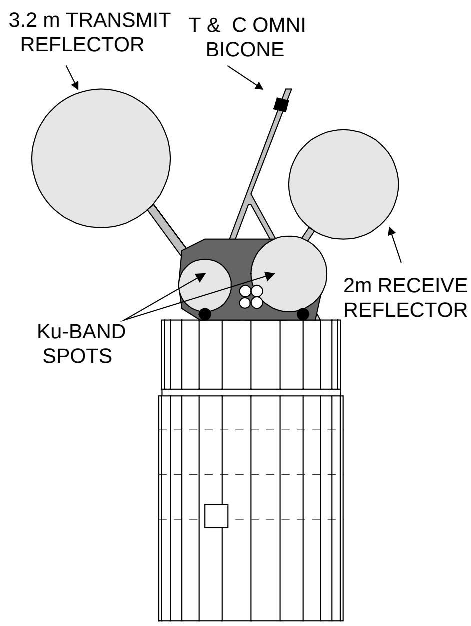


Figure 2.6 INTELSAT VI Satellite

Interconnection

The transponders are interconnectable, using either static switch matrices or a new dynamic switching network that provides Satellite-Switched Time Division Multiple Access (SS/TDMA) capability. Static interconnection matrices are provided for all channels except those in the global repeaters. Dynamic switches connect Channels 1-2 and 3-4 to provide SS/TDMA operation. Each of these switching units consists of a dynamic microwave switch matrix, with its associated digital control logic, and an input ring redundancy network with a bypass switch matrix. The dynamic switch is operated by redundant distribution and control units, each with three memories and a very stable timing source.

Position Keeping

The position keeping control subsystem for the INTELSAT VI makes it possible to maintain a pointing accuracy of ± 0.1 degree.

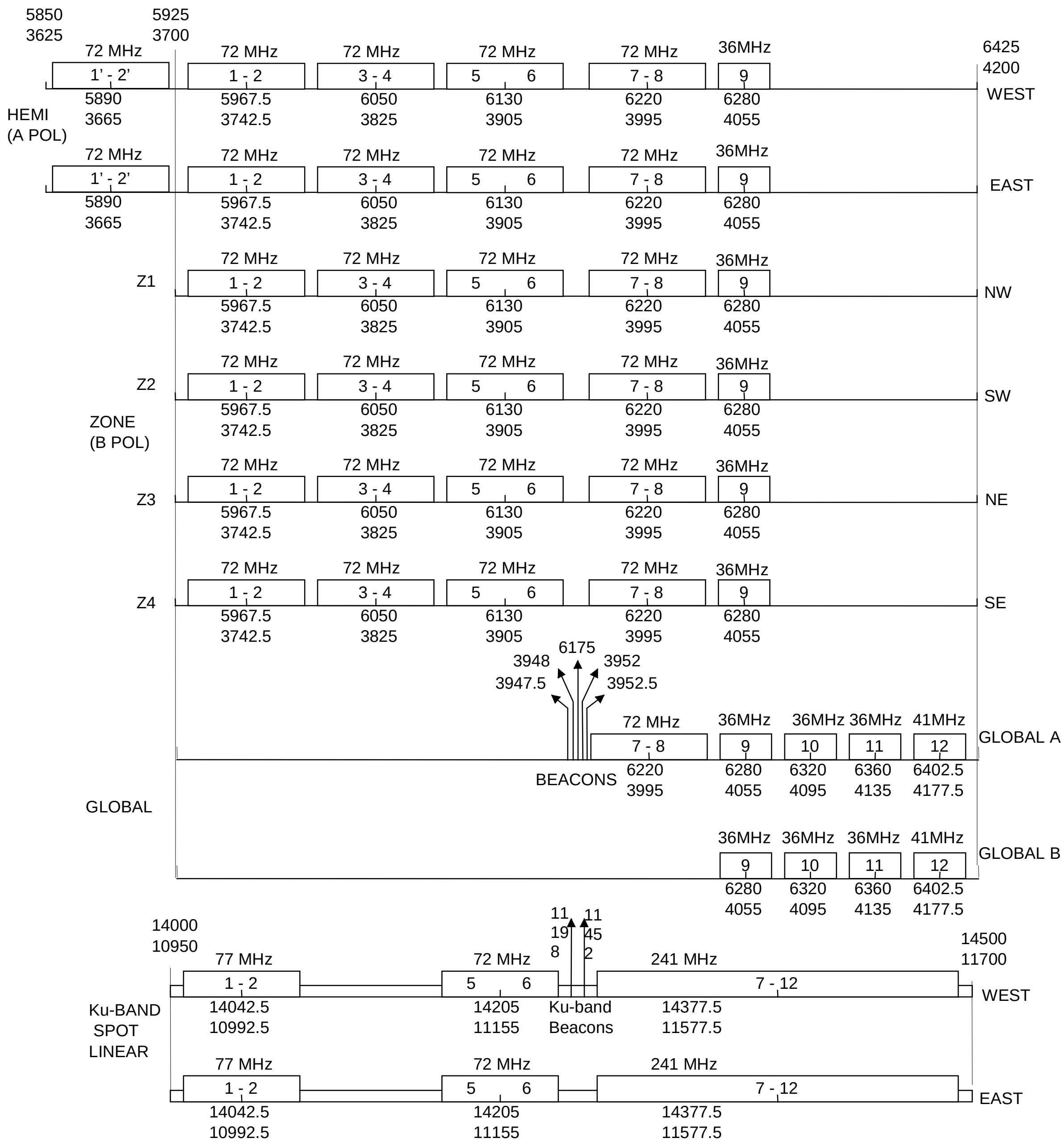


Figure 2.7 INTELSAT VI Transponder Frequency Plan

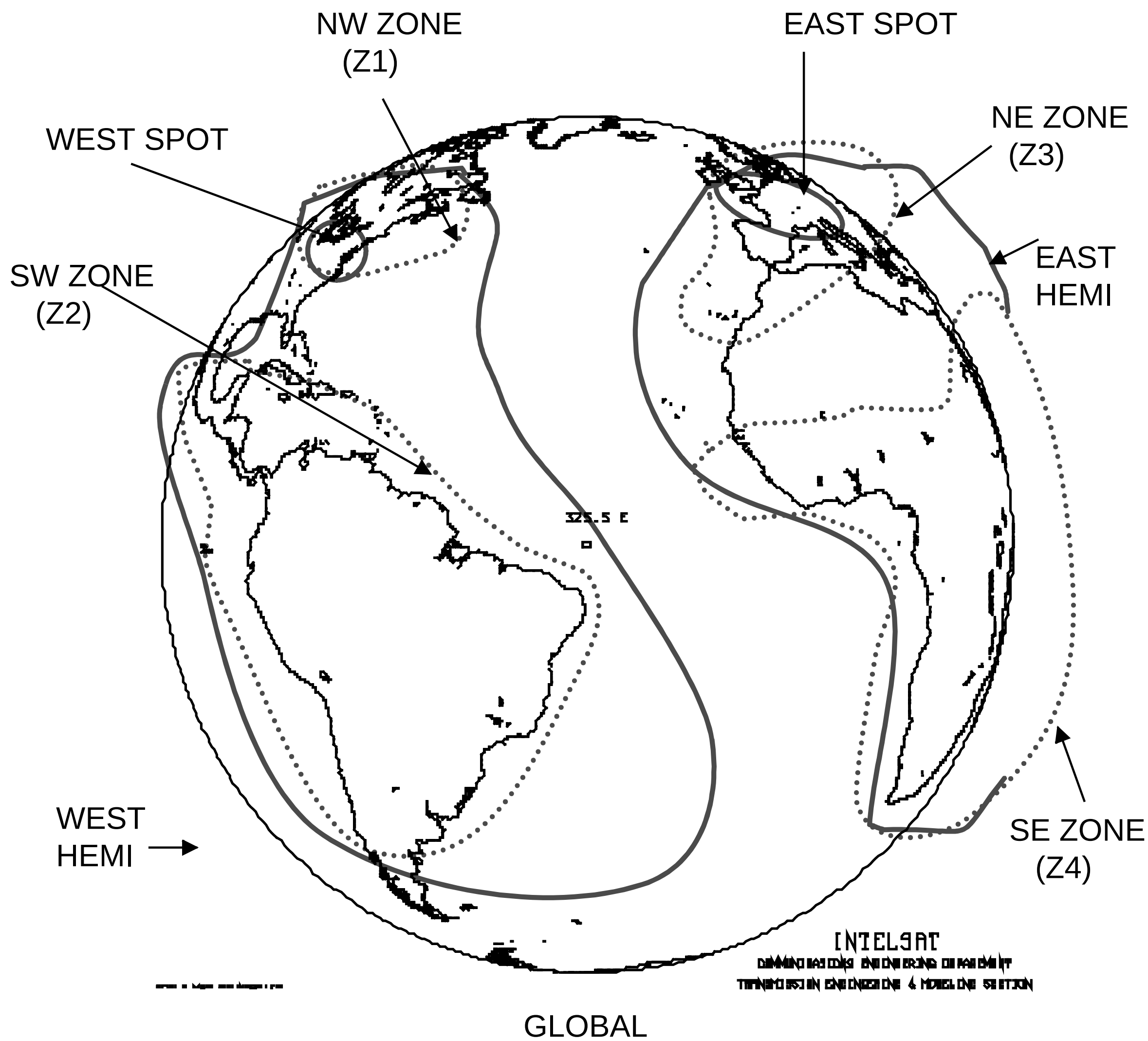


Figure 2.8 INTELSAT VI Typical Beam Coverage

INTELSAT VII

The INTELSAT VII series includes five satellites launched from October 22, 1993, to June 15, 1996. These satellites have a solar wing span of 21.8 meters that generates more than 4,000 Watts of power and a design life of 10.9 years.

This series carries a smaller payload than the INTELSAT VI in terms of number of channels, transponders, and total available bandwidth, but is optimized in EIRP, G/T, and flux density for operation with smaller Earth stations. INTELSAT VII satellites provide the choice of Ku-band, independently for each transponder, between 11 and 12 GHz as downlink frequency band, depending on the ITU regulations for each region.

Gain steps for INTELSAT VII and the following satellites are different from INTELSAT V and VI because they cover a large range (>14 dB) in small steps (<1.5 dB). The decision concerning the appropriate transponder gain step may depend on a number of factors, including the user's requirement, the services on the co-channel transponders, and the other services within the same transponder.

Transponder Configuration and Beam Connections

The INTELSAT VII has transponders of 34, 36, 41, 72, 77, and 112 MHz of bandwidth depending on the frequency band and the beam connection. It can be configured for cross-strapped operation. The C-band and Ku-band spot beams are fully steerable over the full Earth disc.

The INTELSAT VII can be operated in either normal or inverted attitude. (See Figure 2.9.) This allows the satellite to rotate 180° on the yaw axis to optimize the beam coverage at specific orbital locations (as shown in Figure 2.10). This avoids using more expensive and complex reconfigurable phase arrays for the antenna.

Normal coverage of the Pacific Ocean Region and the West Atlantic Ocean Region calls for a wide west hemispheric beam and narrow east hemispheric beam. Through attitude inversion, the satellite can also have a narrow west hemispheric beam and a wide east hemispheric beam for use in the East Atlantic and Indian Ocean Regions.

The INTELSAT VII has two sets of five C-band transponders available to four zone beams Z1 or I, Z2 or J, Z1A or L, and Z2A or K, grouped into two sets (Z1/Z1A and Z2/Z2A). In the uplink, a zone receiver can be connected to either one of the sets (Z1 or Z1A) or to the combination of the two (Z1/Z1A), called enhanced zone. This enhanced zone is connected to only one coverage in the downlink.

The C-band channels 9 to 12 can be allocated to the global coverage or to the C-spot coverage, independently for each channel and independently for each link (uplink and downlink). The C-spot beam is fully steerable.

All the power amplifiers for the C-band are SSPAs and the EIRP is 33 dBW for Hemi, Zone, and C-spot beams, 26 dBW for global. Channel 12 has 3 dB more EIRP when allocated to global or C-spot beams.

The Ku-band has two sets of transponders. Each set can be connected to one of the three spot beams' coverage, on a channel by channel basis, and the power amplifiers are LTWTA with an EIRP of 45 dBW.

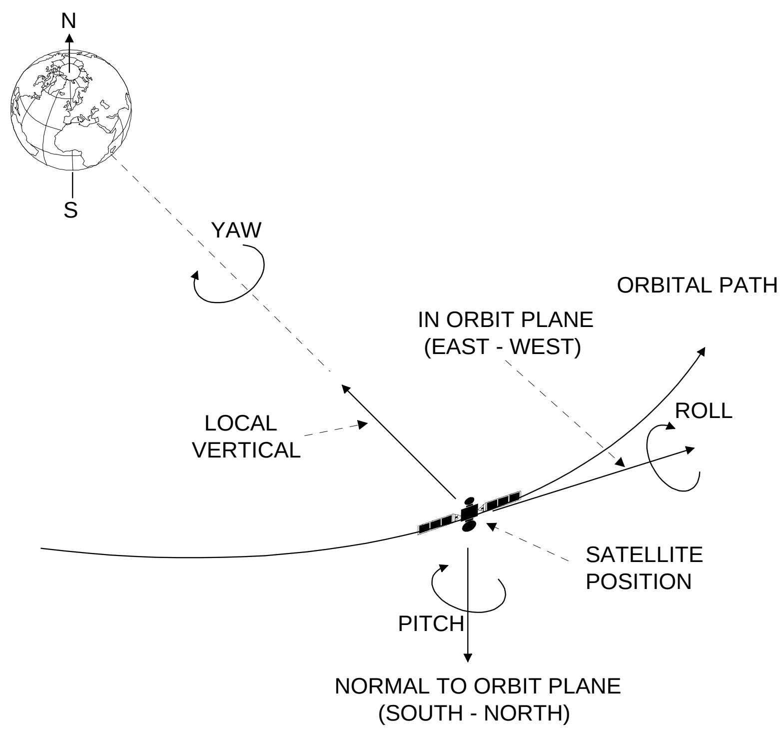


Figure 2.9 Attitude Inversion Concept

The naming convention for the beam coverage areas is consistent with the INTELSAT VI. In addition to the unique capability of the satellite to be deployed in normal and inverted attitude, the physical beam names [i. e., Hemi 1 (H1), Hemi 2 (H2), Zone Alpha (ZA or I), Zone Beta (ZB or J), Zone Gamma (ZC or K), and Zone Delta (ZD or L)], must also be indicated to ensure utilization of the specific parameters associated with each beam. References to the beam coverage include both the geographical and physical notation, e.g., the North-East Zone (ZB) corresponds to a satellite in normal attitude. (See Figure 2.10a.) Figure 2.11 summarizes the INTELSAT VII transponder layout.

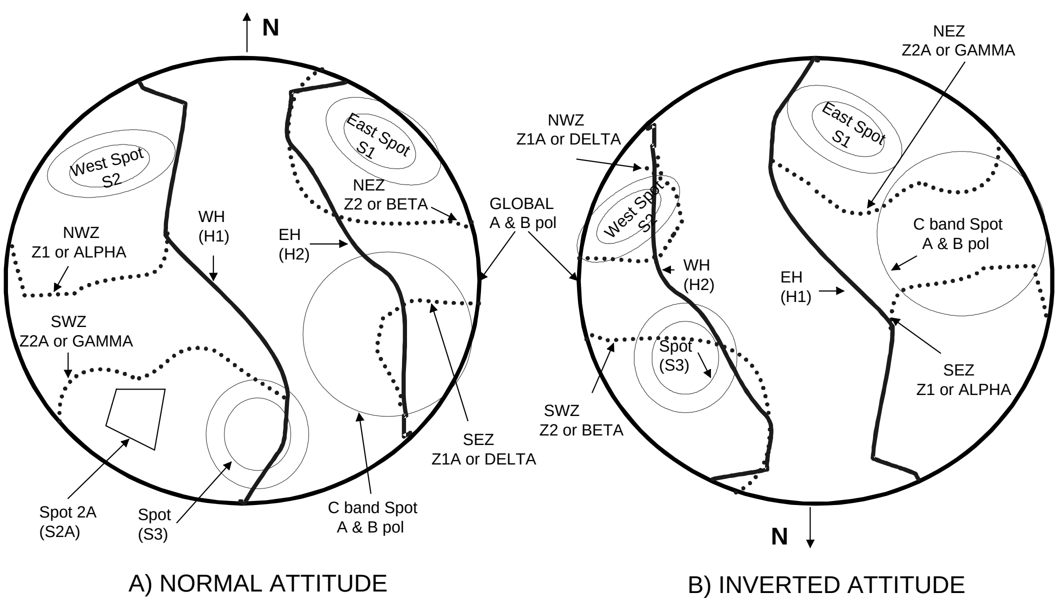


Figure 2.10 INTELSAT VII Typical Beam Coverage

Supplemental Beacons

Although C-band and Ku-band beacons are the same as their predecessors, an additional C-band unmodulated beacon transmitter is available for Earth station tracking purposes. It operates at 3950 MHz and is transmitted in global coverage vertical linear polarization. This enables small antennas operating in only one sense of polarization to receive the beacon signal. The INTELSAT VII operates at both 11 and 12 GHz in the Ku downlink, and is equipped with two extra-unmodulated Ku-band beacons operating at 11,701 MHz and 12,501 MHz with one of each connected to either Ku-spot beam.

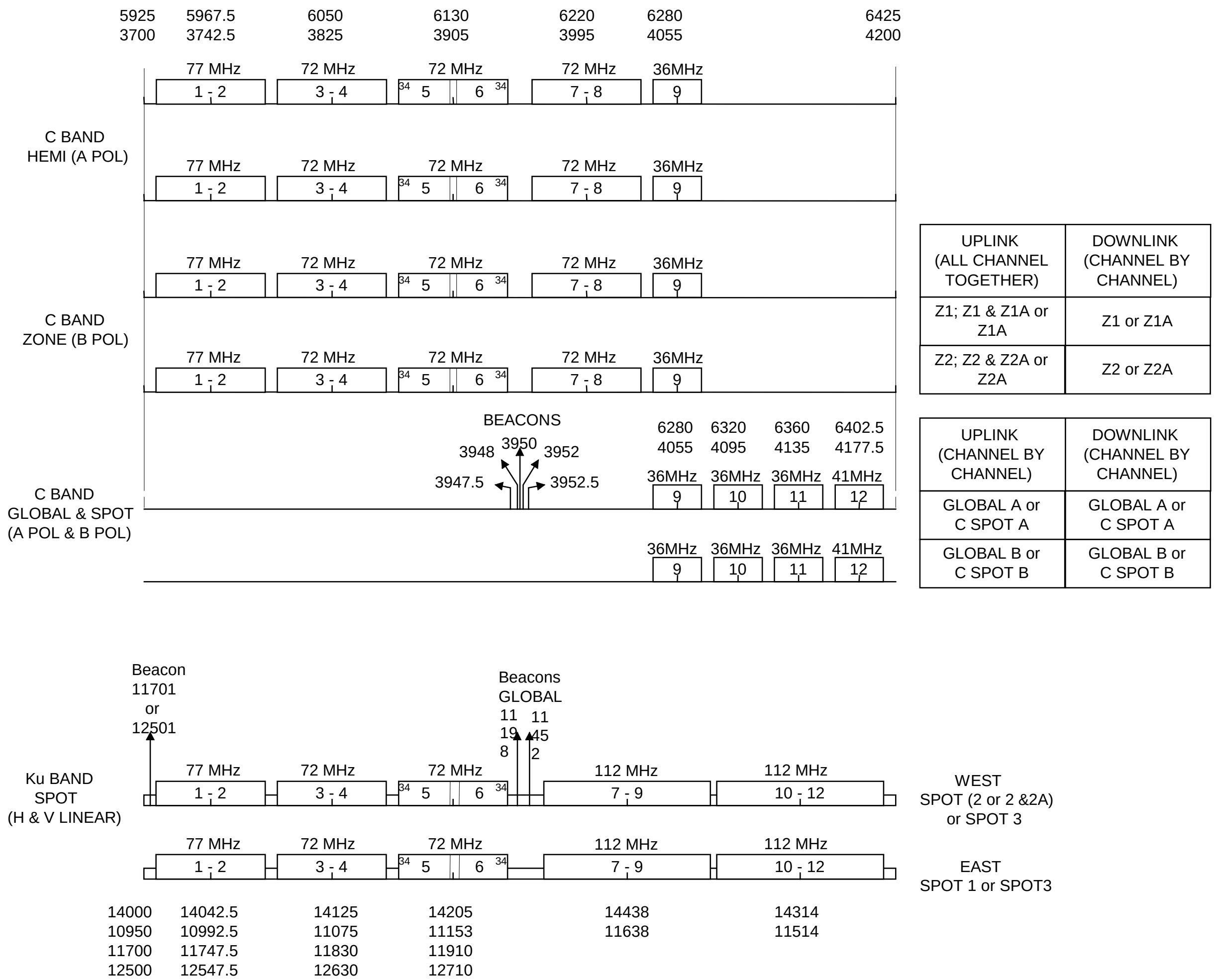


Figure 2.11 INTELSAT VII Transponder Frequency Plan

INTELSAT VII-A

INTELSAT ordered three additional and modified INTELSAT VII satellites, now called INTELSAT VII-A. INTELSAT VII-A satellites replaced the INTELSAT V-A satellites that reached the end of their operational lives in 1995 and 1996.

These satellites have the same attitude inversion feature and the same physical appearance as INTELSAT VII spacecraft, except for the taller body and the larger solar array wingspan (10.7 meters versus 8.6).

The INTELSAT VII-A differs from INTELSAT VII in the following areas.

Ku-band Enhancements

- Dual polarized spot beams with four additional wideband cross-polar transponders.
- Higher power LTWTAs.
- Paralleled LTWTA for "high power" mode (up to 47 dBW at beam edge) available for all the spot beams.
- Broadened circular Spot 3 beam (3.30 inner diameter, 4.40 outer diameter versus 20 and 2.750 respectively for INTELSAT VII), while maintaining the EIRP at between 43.2 to 44.9 dBW.
- Increased flexibility in the selection of the 11 or 12 GHz frequency band for Ku-band transponders in all three spot beams.
- Spot beams 1 and 2 can operate with cross-pol transponders. Spot beam 1 (S1) can have 5 transponders and 2 cross-pol transponders and are called S1X. The same description applies for spot beam 2.
- Up to five transponders from spots S1, S1X, S2, and S2X can be provided for spot 3.
- Transponder 12 in spot 3 uplink may be connected to either 1) Global A or C-band Spot A, or 2) Global B or C-band Spot B beams in the downlink.

C-band Enhancements

- Increased downlink EIRP of all Global and C-Spot transponders to 29 dBW and 36 dBW respectively.
- The EIRP of the 20 Hemi/Zone transponders has the same configuration and EIRP as the INTELSAT VII.

Figure 2.12 shows the transponder layout.

The payload enhancement of the INTELSAT VII-A is achieved by reusing four times the frequency in the C-band for Hemi and Zone Beams, two times in the Global/Spot beams, and four times in the Ku-band. More Ku-band capacity than the INTELSAT VII results from the eight additional wideband transponders.

For example, five transponders can be assigned to Spot 1 (East beam), two additional transponders can be assigned to Spot 1X (East beam cross-polar).

The same applies for Spot beam 2, the remaining four wideband transponders can be assigned to Spot beam 3. An additional coverage area is available for Spot 2 beam (spot 2A beam). In this enhanced spot 2, the Spot 2 and Spot 2A beams function as a single beam on both the up and downlinks. The enhanced spot 2 is intended to be used in the Pacific Ocean region only.
Finally, transponder 12 uplinking in the Spot 3 can be connected to either Global or C-band Spot in either polarization.

The typical beam coverage for this satellite is the same as for INTELSAT VII as shown in Figure 2.10 A and B.

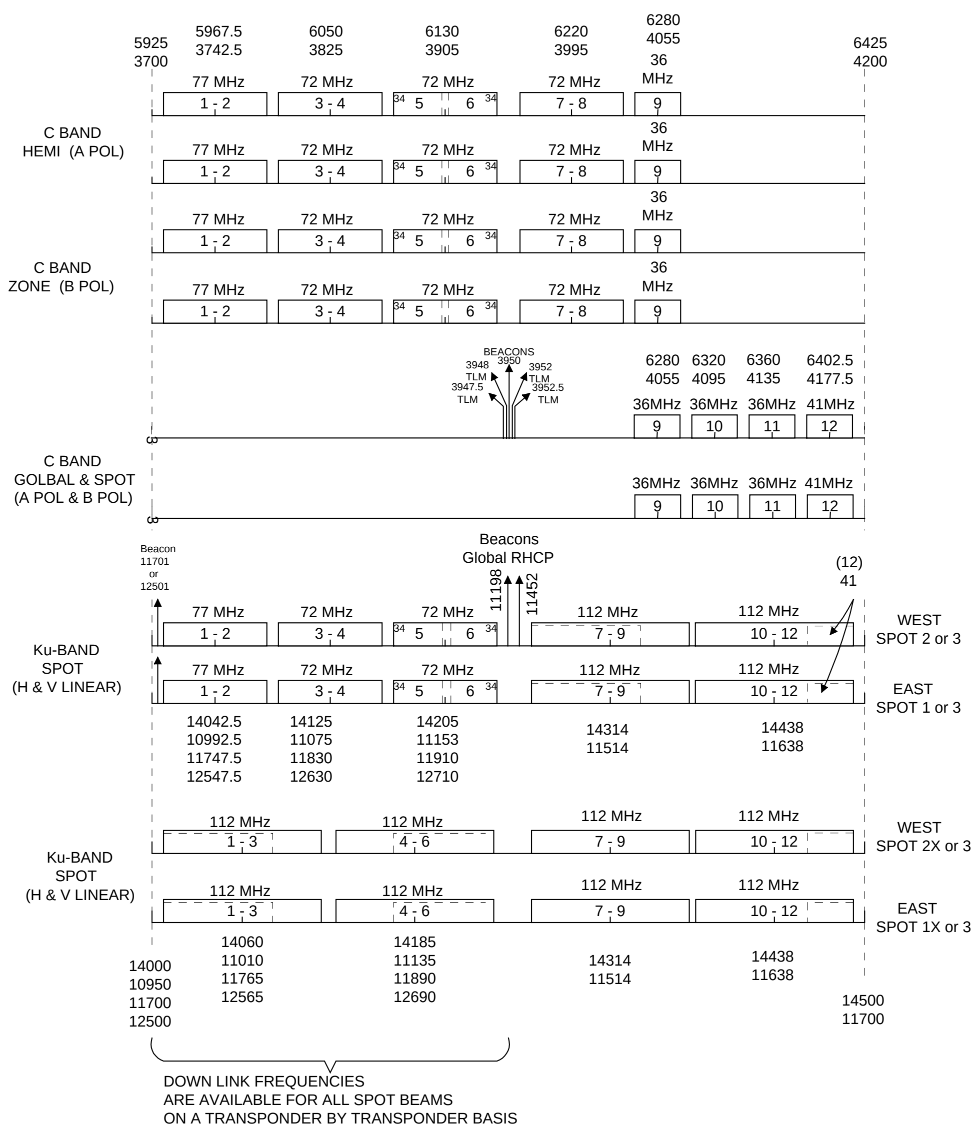


Figure 2.12 INTELSAT VII-A Transponder Layout

INTELSAT VIII

The INTELSAT VIII satellites have 38 C-band transponders and 6 Ku-band transponders with interconnection between these bands as shown in Figure 2.13. The Ku-band downlink frequency can be operated either at 14/11 or 14/12 GHz.

Like the INTELSAT VII series, the INTELSAT VIII is able to operate either in normal or inverted attitude by rotating the satellite YAW axis.

Designed as a predominantly C-band spacecraft, the INTELSAT VIII is used at those locations with minimal Ku-band capacity demand. These spacecraft provide more C-band capacity and improved EIRP to be used for INTELSAT Business Services (IBS), Intermediate Data Rate (IDR), and Very Small Aperture Terminal (VSAT) applications.

Interconnectivity Options

In Ku-band, these satellites are capable of inorbit reversal of the uplink and downlink polarization senses, and the flexible assignment of up to five (of the six available) transponders to either one of the two fully steerable spot beams. The spot beams can be pointed anywhere on the surface of the Earth that is visible from the satellite orbit.

Another new feature is the capability to connect the satellite receive channel 12 of either K-spot 1 or K-spot 2 beams to the satellite transmit channel 12 of either global A or global B beams. If one of these directions is established, the reverse path can also be established. This feature provides a backward communication link between small Ku-band transportable antennas and C-band antennas. This is ideal for satellite news gathering applications.

At C-band, a six-fold frequency reuse for channel bank (1-2), (3-4), (5-6), (7-8), and (9) is achieved by using two spatially isolated HEMI beams, and four spatially isolated ZONE beams (in the opposite polarization sense with the HEMI beams). This provides 10 additional C-band transponders compared to the INTELSAT VII. As in the IS-VI satellites, the extended C-band channel (1’-2’) is also available in the HEMI beam (not available in the VII series).

A new broadcast mode capability in the zone beams is offered by providing a transmission path in the uplink for the Zone 3 beam and simultaneous downlink to the three remaining zones (zone 1, zone 2, and zone 4 simultaneously). This broadcast mode is switchable by ground command on a channel-by-channel basis and is intended for one- way TV broadcast as Quasi B-pol hemi downlink. (See Figure 2.14.)

A special feature is the ability to separate the channel bank (5-6) into two separate uplinks (one for channel 5 and the other for 6) and connect them toward a common downlink.

The beam peak EIRP is 32.5 dBW for Global beams, 39 dBW for Hemispheric, 42.5 dBW for Zone beams (SSPA driven), and 52 dBW (using LTWTAs) for Ku-band spot beams. The transponder and channelization plan is the same as its predecessors.

The INTELSAT VIII is able to operate with 10 different coverages: 2 GLOBAL, 2 HEMI, 4 ZONE, and 2 Ku-band SPOT as shown in Figure 2.13.

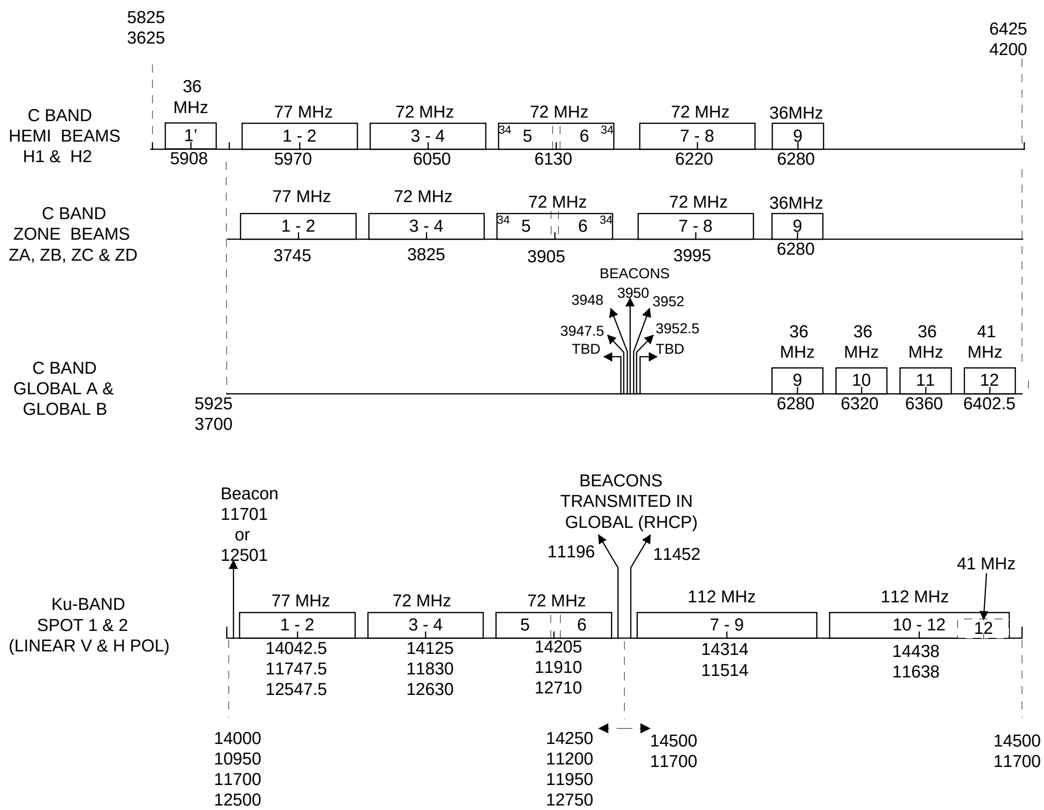


Figure 2.13 INTELSAT VIII Transponder Frequency Layout

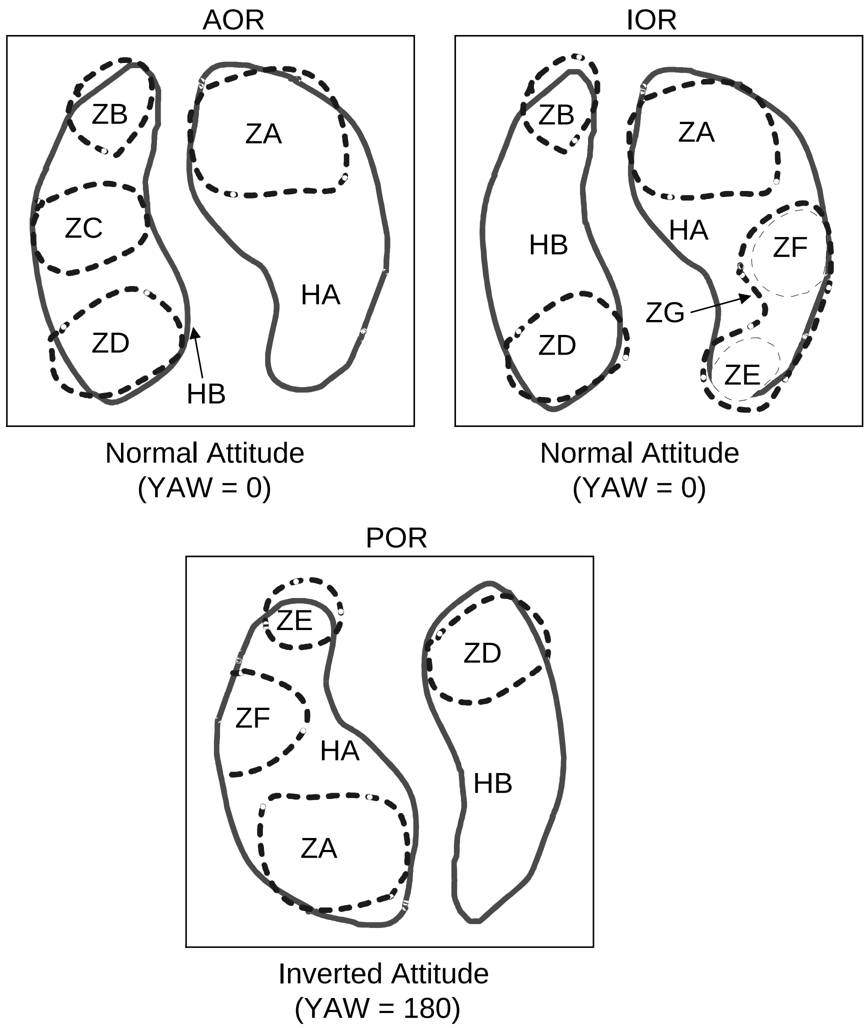


Figure 2.14 INTELSAT VIII Coverage Patterns

INTELSAT VIII-A

To respond to increased demand for landmass satellite coverage, a modification on the INTELSAT VIII series was ordered. Ideal for multimedia applications, it provides simultaneous connectivity over the Americas and Europe. INTELSAT 805 with high C-band EIRP levels, makes an ideal choice for multimedia applications such as Digital Video, VSAT, Internet, and Digital Networks.

The modified satellite is called INTELSAT VIII-A. INTELSAT 805 is located at 304.5°, and has the following main features.

	C-band	Ku-band
Total Transponders (in equivalent of 36MHz units)	36	6
Polarization	Linear	Linear
EIRP	Hemi Beam, 37.5 dBW up to 41.5 dBw (Beam Edge to Beam Peak)	Spot Beam Peak up to 53.5 dBW
Uplink Frequency	5850 to 6650 MHz	14.00 to 14.25 GHz
Downlink Frequency	3400 to 4200 MHz	12.50 to 12.75 GHz
Typical G/T Range	4.0 to -8.0 dB/°K (Beam Peak to Beam Edge)	Spot1 +6.2 to +2.7 dB/°K

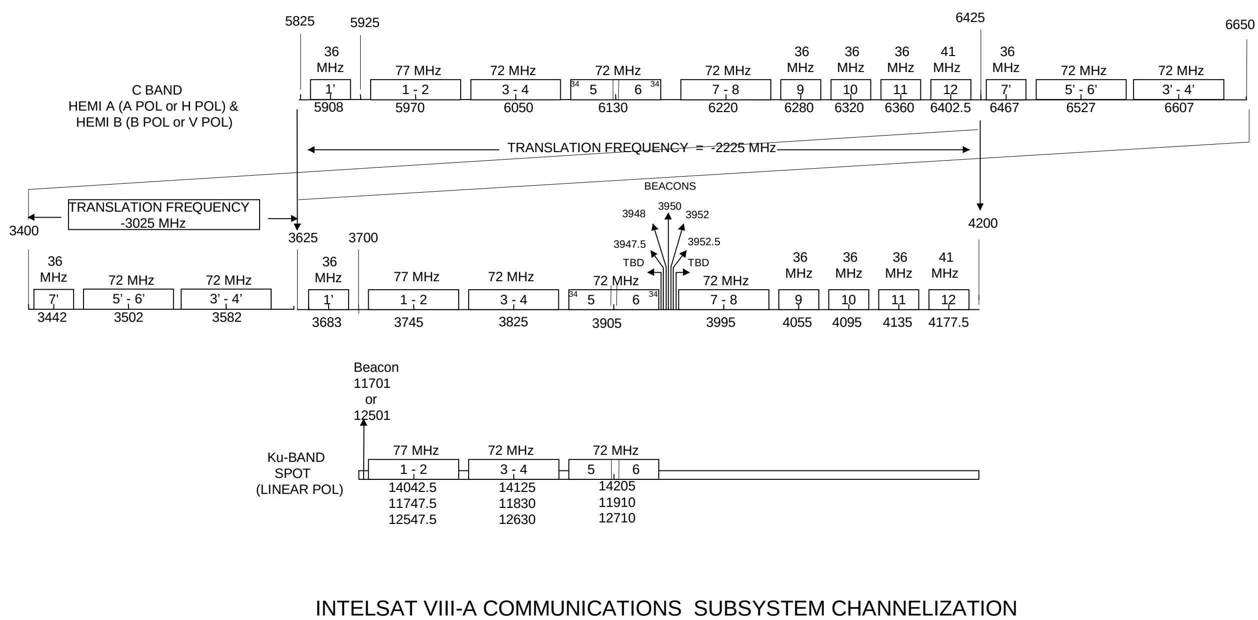


Figure 2.16 INTELSAT VIII-A Channelization Plan

APR - 1

The APR-1 satellite has a wide beam providing landmass coverage of Eastern Europe, Middle East, Asia, and the Pacific Rim. Additionally, it has a zone beam that provides service to the Indian subcontinent, China, and the Association of South East Asian Nations (ASEAN). The landmass coverage is ideal for users that require a wide service area with a high EIRP.

APR-1 has nine C-band transponders (11 x 36 MHz units), consisting of four wide beam transponders (2 x 36 and 2 x 72 MHz), and five zone transponders, all 36 MHz.

APR-1 transmits in the vertical linear polarization and receives in horizontal linear polarization. This is a significant difference from most of the other INTELSAT spacecraft that employ circular polarization in C-band.

A layout of the APR1 transponder frequency plan is shown in Figure 2.15. The APR1 satellite receive frequency range (uplink) is 5,850 to 6,650 MHz. The transmit frequency band (downlink) extends from 3,400 to 4,200 MHz. Transponders 6 through 17 have a translation frequency of 2,225 MHz. Transponders 1 through 5 operate in the extended C-band and have a translation frequency of 3,025 MHz.

Broad beam coverage and high EIRP levels make APR -1 ideal for video contribution/distribution services, Internet, VSAT networks, digital carrier services, and rural telephony.

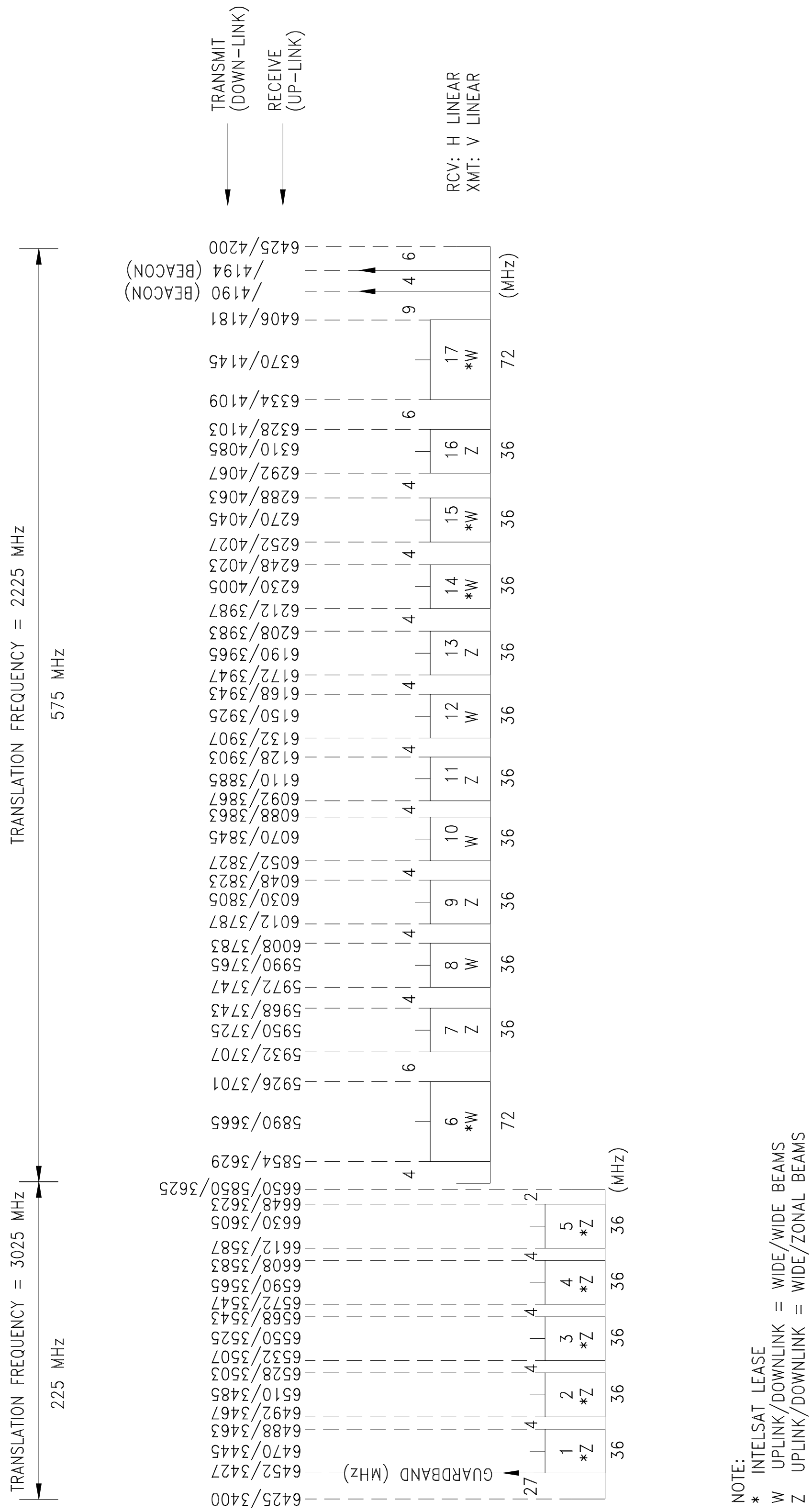


Figure 2.15 APR-1 Transponder Layout

INTELSAT IX

The INTELSAT IX series is INTELSAT's solution to providing customers the highest quality of advanced digital voice/data and video services. With their superior state-of-the-art technology, these satellites will replace the INTELSAT VI satellites and will deliver the services for:

- public and private voice/data networks;
- Internet and Intranet;
- Synchronous Digital Hierarchy (SDH) and Asynchronous Transfer Mode (ATM) traffic;
- broadcast and DTH Video;
- other broadband applications such as: high data rate trunking; telemedicine; and teleeducation; and,
- interactive video and multimedia.

INTELSAT IX satellites will provide high quality digital carriers at better than international standards. Because of their high power, INTELSAT IX satellites will also reduce Earth segment costs and facilitate services such as Satellite Newsgathering (SNG), Demand Assignment Multiple Access (DAMA), Internet, DTH, and VSAT networks.

The RF bandwidth of the INTELSAT IX satellite is divided into segments of 36, 41, 72, and 77 MHz, depending upon the frequency band and beam connections employed to meet traffic requirements. INTELSAT IX has the capability to operate in both the 6/4 GHz and 14/11 GHz frequency bands and to interconnect these bands. Therefore, communications between stations operating at 6/4 GHz and stations operating at 14/11 GHz can be established (cross-strapped operation).

In the 6/4 GHz band, up to seven times[1] frequency reuse is accomplished in the hemispheric and zone beams by spatial isolation of the East, West, North, and South beams together with circular polarization of opposite senses between the hemispheric and zone beams. The global beam operates in a dual circular polarization mode at 6/4 GHz to accomplish two times frequency reuse. Two times frequency reuse is accomplished in the 14/11 GHz band by spatial isolation of the Ku-band Spot beams, which can also have opposite linear polarization.

A transponder frequency plan illustrating beam configuration and polarization is provided in Figures 2.16 and 2.17.

[1] For the five Zone beams configuration, the Hemi/Zone coverages are used in seven times (2 Hemi's and 5 Zone's) frequency reuse. For the four Zone beams configuration, the Hemi/Zone coverages are used in six times (2 Hemi's and 4 Zone's) frequency reuse.

INTELSAT IX Zone and Hemispheric beams are not steerable, however, a platform bias is applied to achieve desired coverages at given satellite locations. The Global beams are not steerable. The Ku-band Spot 1 and Spot 2 beams are steerable independently of one another over the full Earth's disc.

INTELSAT IX has two sets of C-band Global beam transponders in channels 10, 11 and 12 and two sets of C-band Hemi beam transponders in channels 1'-2', 1-2, 3-4, 5-6, 7-8 and 9. It also has four or five sets of Zone beam transponders, operating at C-band, in channels 1-2, 3-4, 5-6, 7-8 and 9. As shown in the transponder plan in Figure 2.16, five Zone coverage areas Z1, Z2, Z3, Z4, and Z5 are available. When in five-Zone mode, only one transponder can be activated between Z2 and Z4 for each channel bank except in channels 1-2 and 3-4 (i.e., total of 44 C-band transponders are active.) When in four Zone mode, Z4 and Z5 can be combined into a single broader Zone coverage (Combined East) in IOR. Therefore, total of 42 C-band transponders are available in four Zone mode.

The uplink receive Hemi beam of channel 9 can be split into two segments each with an usable bandwidth of 16 MHz so that half of the transponder is connected in loopback mode and the other half is inter-connected between the Hemi beams. This capability allows the provision of a DAMA type of service in the Hemi transponders with quasi-global coverage and a 6 dB higher EIRP as compared to the global transponders. The downlink of channel 9A and 9B is combined into 36 MHz channel labeled as 9.

The uplink receive Global beam of channel 12 can be split into two segments each with an usable bandwidth of 18 MHz. This capability, which is included for SNG services will allow multiple carrier operation of the transponder with half of the transponder optimized for large transmit Earth station antennas and the other half optimized for small transmit Earth station antennas. The downlink of channel 12A and 12B is combined into 41 MHz channel labeled as 12.

INTELSAT IX has 2 sets of 8 Ku-band Spot beam transponders in channels 1-2, 3-4, 5-6, 7-8, 9, 10, 11, and 12. However, only 12 transponders out of these 16 available channels can be activated simultaneously. The selection of 12 transponders has been specified to be any 12 out of 16, with a maximum of 8 transponders per Spot beam. The uplink and downlink polarization senses of the Spot beams can be independently reversed in orbit by ground command.

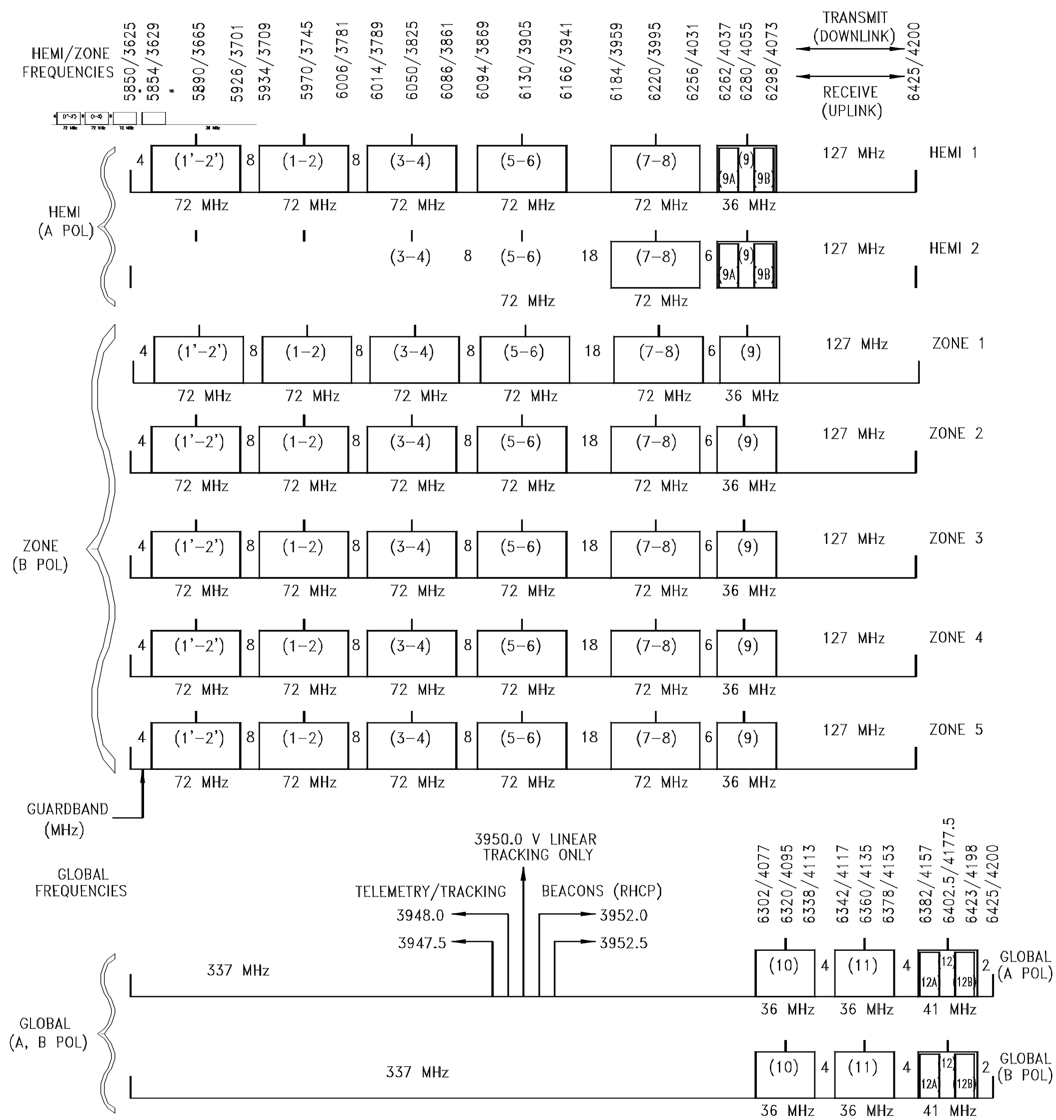


Figure 2.16 INTELSAT IX Transponder Layout (C-band)

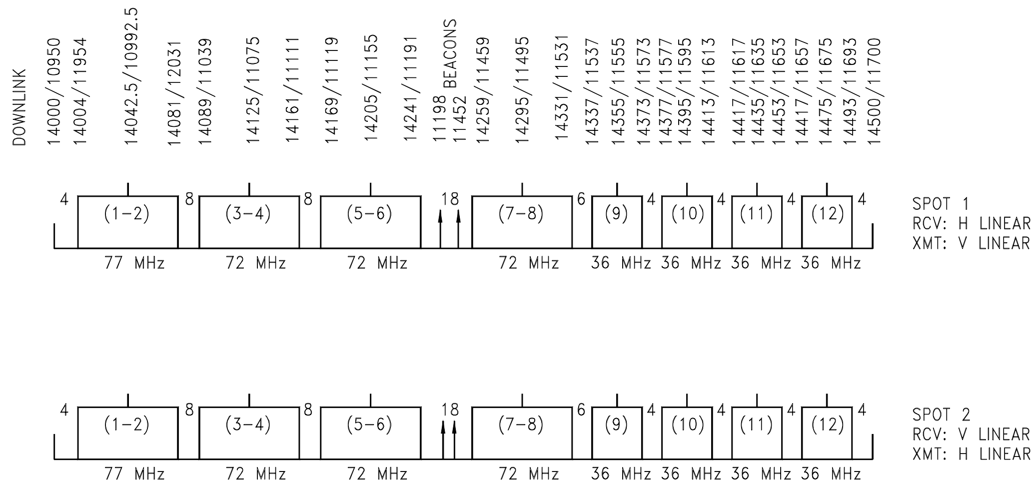


Figure 2.17 INTELSAT IX Transponder Layout (Ku-band)

2.4 Summary

INTELSAT is committed to offering its users a global network customized to meet every need while maintaining the connectivity, availability, and reliability that have characterized the INTELSAT system. Users can benefit not only from the most advanced technology, but also from customer assistance for their international, domestic, and regional services.

CHAPTER 3

EARTH STATION ANTENNAS

3.1 Introduction

This chapter discusses technical characteristics of antennas used in the INTELSAT system.

3.2 Antenna Configurations

An antenna with a feed in the center of the paraboloid (axisymmetric) represents the simplest antenna configuration that is potentially capable of meeting the RF specifications for Earth station applications. A major advantage of such a configuration is that mechanically, it is relatively simple, reasonably compact and, in general, fairly inexpensive. The circular symmetry of the main reflector leads to considerable cost savings in the manufacturing of the reflecting surface, backup structure, and antenna mount.

Center Feed Antennas

Simplest form of axisymmetrical configuration is a paraboloidal reflector with a primary feedhorn located at the focus (Figure 3.1). However, this leads to a long waveguide-run between the feed and the electronics box for antennas whose diameter is greater than about 3 meters. This is undesirable because it leads to reduction in signal power, and increase in noise. A more compact configuration, especially for larger antenna diameters, can be realized by the introduction of a subreflector. The feedhorn is located at the rear of the main reflector, eliminating the need for long, potentially lossy, waveguide runs. This is known as Cassegrain antenna and is shown in Figure 3.2. The subreflector is a section of hyperboloid situated within the focus of the main reflector.

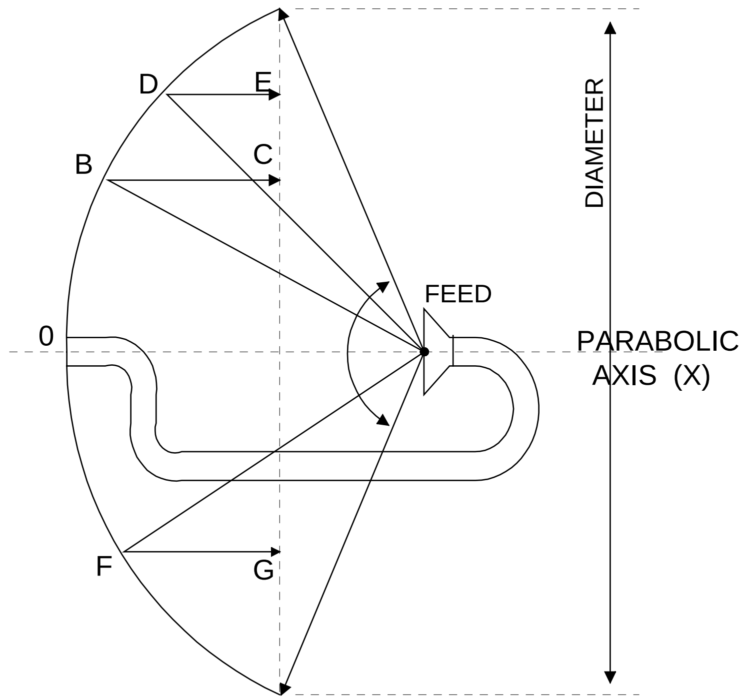


Figure 3.1 Center Feed Antenna

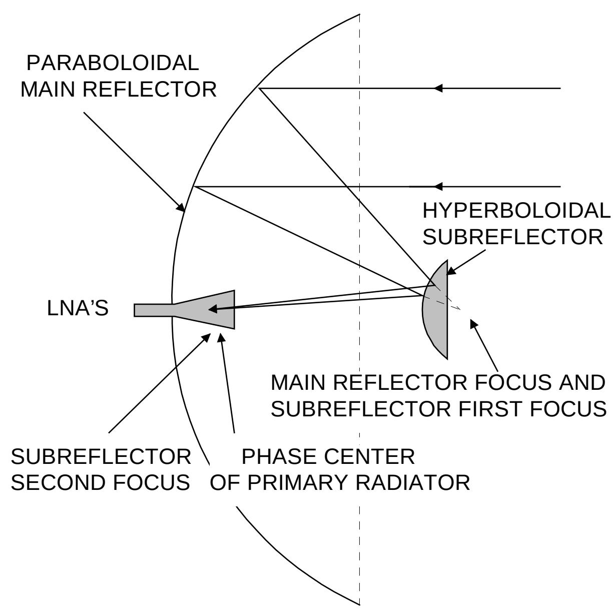


Figure 3.2 Basic Geometry of a Cassegrain Antenna

However, the subreflector and associated support legs cast an effective shadow that affects the antenna efficiency and its sidelobe envelope. Typically, for a Cassegrain configuration, a decrease in peak gain of 0.1 to 0.5 dB can be expected. Also, the subreflector may not intercept all that is radiated from the primary feed, and this could lead to degradation of the antenna sidelobe performance.

To increase the percentage of energy intercepted by the sub-reflector, the feed is configured to give a tapered illumination distribution at the subreflector. However, decreasing or tapering the subreflector edge illumination reduces the overall antenna efficiency. This would require some compromise between the sidelobe performance and the antenna efficiency.

It is feasible to achieve a reasonable wide-angle sidelobe performance and high-antenna efficiency. An improvement in antenna efficiency can be achieved by shaping the reflector profiles and controlling the aperture amplitude distribution while still maintaining a uniform phase distribution. The near-uniform aperture distribution achieved will, however, lead to higher sidelobes close to the boresight direction.

Offset Feed Antennas

The offset feed antennas, such as the offset Cassegrain and Gregorian, achieve a better radiation pattern because of lower aperture blockage. They are often known as nonsymmetrical antennas, and are generally used in small Earth stations because of construction problems and higher cost. The ITU-R handbook on satellite communications discusses offset feed antennas. Figures 3.3 and 3.4 show different antenna types.

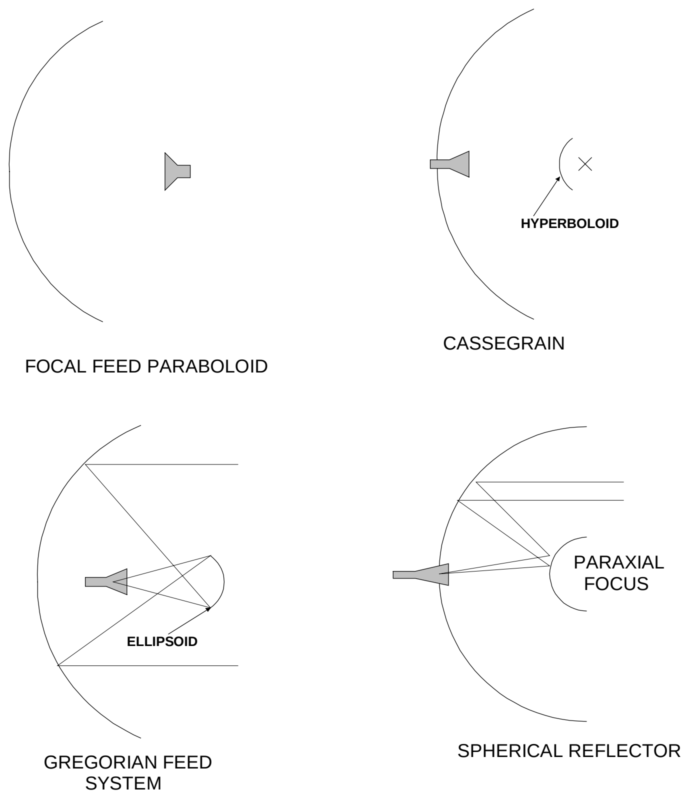


Figure 3.3 Common Antenna Feed Systems

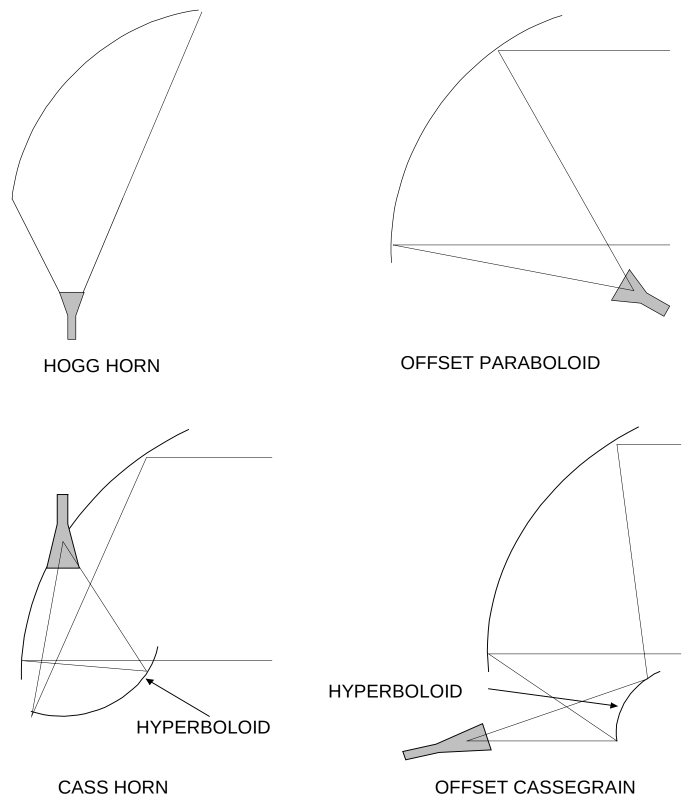


Figure 3.4 Other Feed Systems

3.3 Antenna Mounts

An Earth station antenna typically requires a rigid steel backup structure combined with an accurate dish surface. They are fitted with necessary bearings, gears, and drives to enable pointing accuracy within a few tenths of a degree. The structure must also be able to withstand extreme weather conditions, from excessive heat to cold, and hurricanes. Three common antenna mount types are X-Y mount, AZ/EL mount, and polar mount.

X-Y Mount

This mount is used for medium-sized antennas (10-13 meters). Figure 3.5 shows an X-Y mount. In this mount, the lower axis (X) is parallel to the ground. Rotation about this axis moves the antenna in elevation. The upper axis (Y) lies in a vertical plane, and is perpendicular to the X-axis. The position of the Y-axis in the vertical plane depends on the rotation of the X-axis, and can range from vertical to horizontal.

This is the simplest type of mount, but is a limited coverage mount. It provides coverage up to 90 degrees in the X-axis but, in some cases, only ± 5 degrees in the Y-axis.

AZ/EL Mount

The location of a point on Earth can be described by using the azimuth-over-elevation coordinate system. Azimuth is defined as an angle produced by rotation about an axis, which is perpendicular to the local horizontal plane. The elevation axis rotates in the local horizontal plane as the azimuth angle rotates. A change in the elevation angle will cause a rotation of the antenna in the vertical plane. Installation of an AZ/EL mount is relatively easy. The azimuth axis should be very nearly vertical to the local ground plane to minimize the change in elevation angle when azimuth is swept. Figure 3.6 shows a simplest form of AZ/EL mount. This type of mount has full elevation coverage and ± 180 degrees in azimuth.

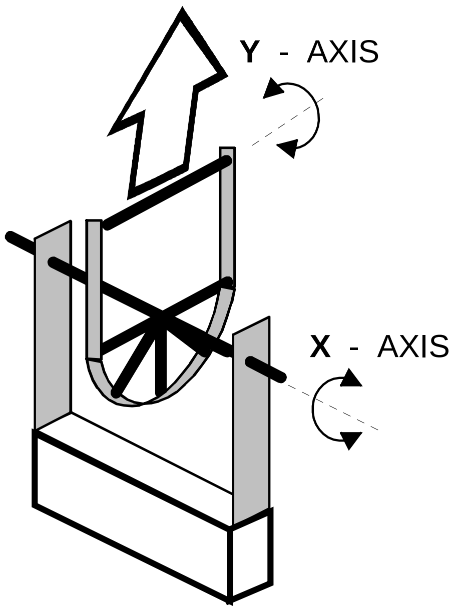


Figure 3.5 X - Y Mount

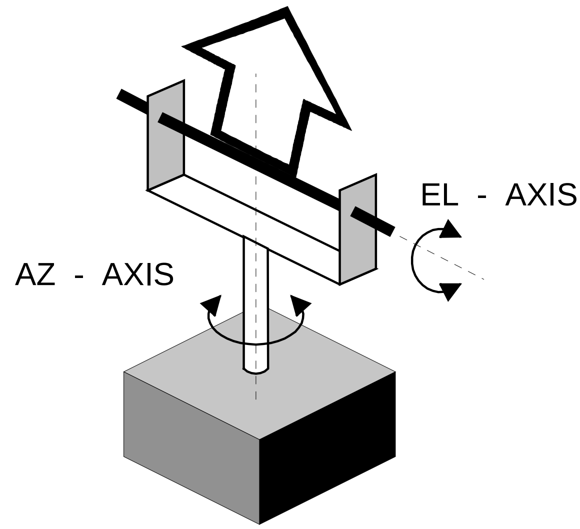


Figure 3.6 AZ/EL Mount

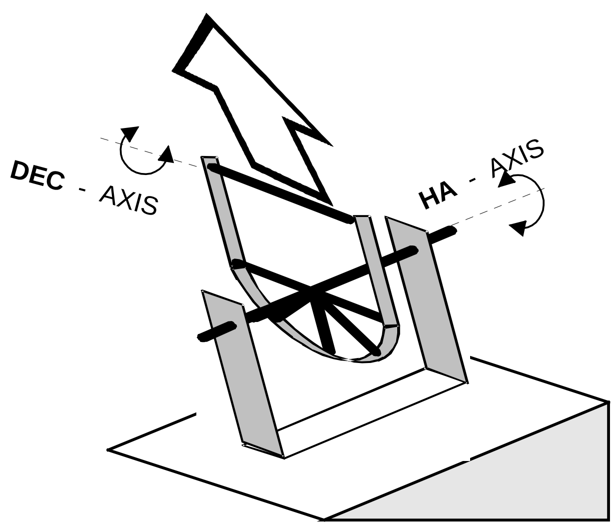


Figure 3.7 Polar Mount

Polar Mount

A polar mount has two axes of rotation as shown in Figure 3.7. The first one is the hour angle axis, which is parallel to the Earth's axis. It is inclined in the north-south direction from the local horizontal through an angle equal to the latitude of the site. Therefore, the hour angle axis is parallel to the ground at the equator and perpendicular to the ground at either the North or the South Pole. The second angle is the declination. Satellite longitude, Earth station longitude, and latitude determine the amount of declination required.

3.4 Dish Antennas Geometry

Satellite Earth stations use dish antennas of 0.5 - 30 meters in diameter. The dish surface contour is based on the equation for a parabola:

$$y^2 = 4fx$$

where f is the focal length, and x is the coordinate along the axis of the paraboloid.

A paraboloidal surface contour satisfies the requirement that all the energy radiated from a launcher at the focal point towards the surface will be reflected to form a phase coherent plane wavefront across the dish aperture. Expressed in another way, path lengths ABC, ADE, and AFG in Figure 3.8 are all equal.

3.5 Antenna Parameters

The important parameters of an antenna are gain, beamwidth, and sidelobes.

Antenna Gain

Antenna gain is defined as follows.

When a radio wave arriving from a distant source impinges on the antenna, the antenna "collects" the power contained in its "effective aperture" (Ae). If the antenna were perfect and lossless, the effective aperture area Ae would be equal to the actual projected area A. For a circular aperture, the projected aperture is:

$$A=\pi d^2/4$$

and the effective aperture area Ae = A (for an ideal antenna) (3.1)

where: d= antenna diameter

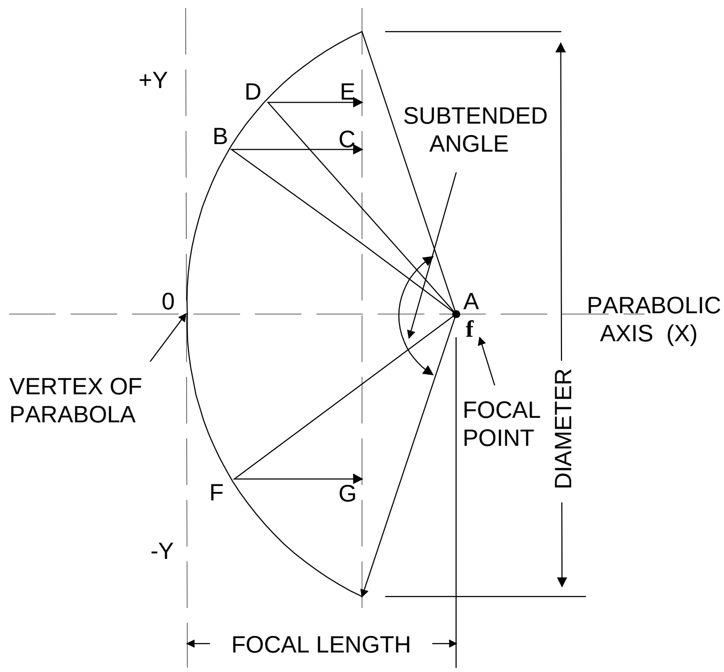


Figure 3.8 Geometry of a Paraboloid

Taking into account losses and the nonuniformity of the illumination law of the aperture, the effective area is in practice:

$$Ae = \eta A$$

$$Ae = \eta\pi(d/2)^2 \tag{3.2}$$

where η = antenna efficiency and $\eta < 1$.

Efficiency is an important factor in antenna design. Special techniques are used to optimize the efficiency of Earth station antennas.

Antenna efficiency is affected by:

a) The subreflector and supporting structure blockage.
b) The main reflector rms surface deviation.
c) Illumination efficiency, which accounts for the nonuniformity of the illumination, phase distribution across the antenna surface, and power radiated in the sidelobes.
d) The power that is radiated in the sidelobes.

Aperture efficiencies between 55 percent and 75 percent are typically attainable.

Then, the on-axis antenna power gain (relative to an isotropic radiator) is given by:

$$G = 4\pi Ae/\lambda^2 \qquad (3.3)$$

where: λ = is the free space wavelength
π = 3.14159....
Ae = effective aperture of the antenna

Substituting for Ae in (3.3) yields:

$$G = \eta\,(\pi d/\lambda)^2 \qquad (3.4)$$

or expressed in decibels:

$$G_{dBi} = 10 \log \eta + 20 \log \pi + 20 \log d - (20 \log \lambda) \qquad (3.5)$$

or

$$G_{dBi} = 10 \log \eta + 20 \log f + 20 \log d + 20.4 \text{ dB} \qquad (3.6)$$

Where:
η = antenna efficiency
d = antenna diameter in meters
f = operating frequency in GHz
20.4 dB = Constant value resulting from 10 log ($1*10^9*\pi/c$)

Beamwidth

Beamwidth is a measure of the angle over which most of the gain occurs. It is typically defined with respect to the Half-Power Beamwidth (HPBW) or –3 dB points of the main lobe in the antenna radiation pattern. (See Figure 3.9.) It is given by:

$$\text{HPBW} = \frac{\lambda}{d\sqrt{\eta}} \times 57.29$$

Where:
η= the antenna efficiency
d= the antenna diameter in meters
λ= the wavelength, c/f

A standard “A” Earth station with an antenna of 16 meters (52 feet), and an efficiency of 70 percent would thus have a beamwidth of 0.214 degree at 6 GHz.

Sidelobes

While most of the power radiated by an antenna is contained in the "main lobe", a certain amount of power can be transmitted, (or received), in off-axis directions. Sidelobes are an intrinsic property of antenna radiation and cannot be completely eliminated.

However, sidelobes are also due to antenna defects that can be minimized with proper design. ITU-R Record 580-1, Module 1, defines the desired sidelobe envelope for different types of antennas. They are:

A) Antennas installed after 1988 and with a ratio of $d/\lambda > 150$ must meet the following characteristics:

$$G = 29 - 25 \log \Theta \quad \text{dBi}$$

where Θ is degrees from boresight and $1° \leq \Theta \leq 20°$
d is the antenna diameter (meters)
λ is the wavelength for the operation frequency (meters)

B) For smaller antennas with d/λ between 35 to 100
(1.75m to 5m for C-band and 75cm to 2.1 m for Ku-band):

$$G = 52 - 10 \log d/\lambda - 25 \log \Theta \text{ dBi}$$
for $(100\lambda/d)° \leq \Theta \leq d/5\lambda\,°$

Example: Calculate the transmit sidelobe envelope for a 1.5m antenna operating at 14 GHz. ($\lambda = 0.021$m).

Ratio $D/\lambda = 70$;
$G = 52 - 10 \log (70) - 25 \log \Theta$
$G_{dBi} = 33.5 - 25 \log \Theta$
As $D/\lambda = 70$ then 1.4 degrees $\leq \Theta \leq$ 14 degrees

Figure 3.9 shows a radiation pattern for a paraboloidal antenna and the recommended sidelobe characteristics.

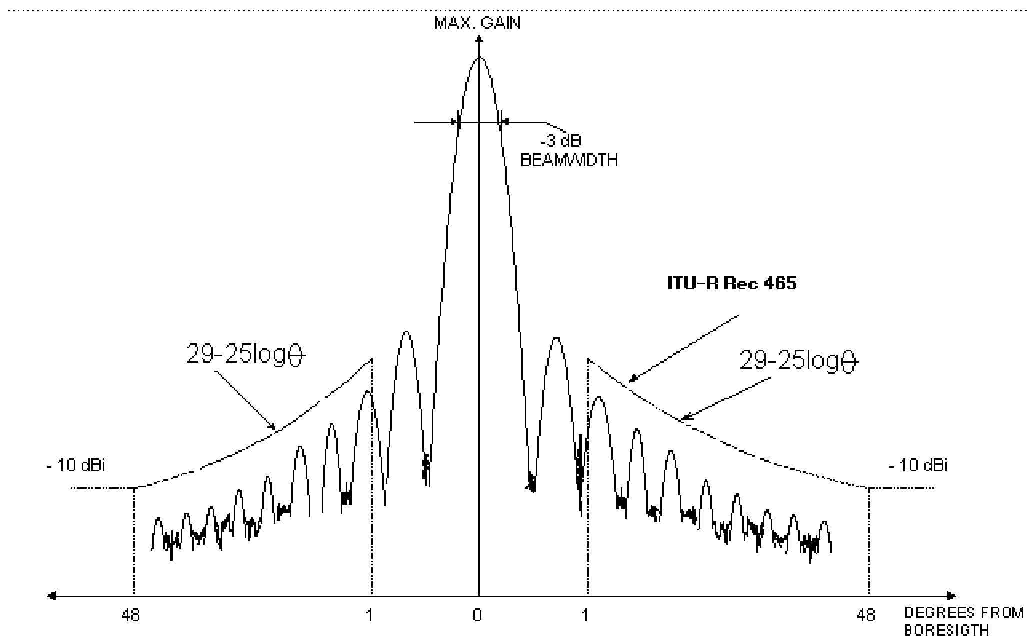


Figure 3.9 Antenna Radiation Diagram and Beamwidth

Diameter, operating frequency, and aperture efficiency affect antenna parameters; but sidelobe characteristic is one of the main factors in determining the minimum spacing between satellites and, therefore, the orbit/spectrum efficiency.

Figure 3.10 shows a plot of antenna gain as a function of antenna diameters while using frequency and efficiency parameters.

Bandwidth

Dish antennas are wideband devices. As seen from the gain equation, for a given diameter, the gain of a dish will increase as the frequency of operation increases. However, operation away from the design frequency will normally result in impaired performance due to the limitations of the feed/launch system.

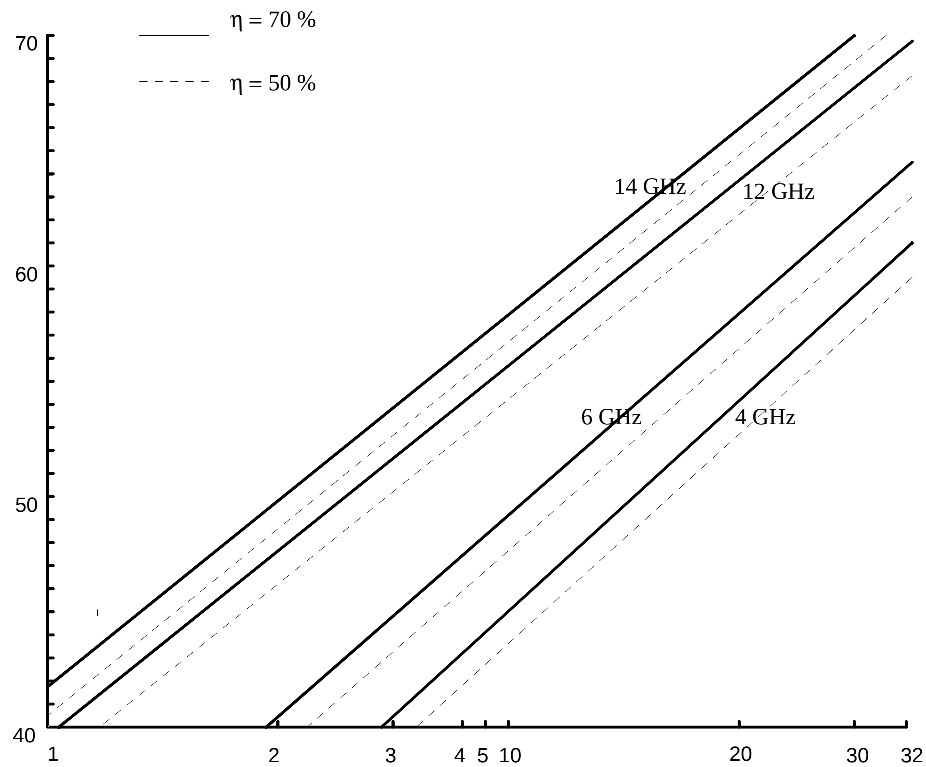


Figure 3.10 Antenna Gain vs. Diameter

3.6 Antenna Standards

Since 1965, various antenna standards have been approved for use within the INTELSAT system. These standards are classified by the following basic parameters.

1. Dish Diameter
2. Frequency of Operation in the RF Spectrum
3. Figure of Merit (Gain/System Noise Temperature)
4. Mode of Operation

Table 3.1 shows a summary of basic parameters for the different antenna standards.

Table 3.1. Summary of INTELSAT Standard Earth Stations

STANDARD TYPE	FREQUENCY BAND (GHz)	G/T (dB/°K)	DIAMETER (M)	SERVICES USED FOR	INTELSAT DOCUMENT
A	6/4	35.0	15 - 20	ALL	*IESS* 207
B	6/4	31.7	10 - 13	ALL	*IESS* 207
C	14/11; 14/12	37.0	11 - 15	IDR/IBS	*IESS* 208
E1	14/11; 14/12	25.0	2.4 - 3.5	IBS	*IESS* 208
E2	14/11; 14/12	29.0	3.7 - 4.5	IDR	
E3	14/11; 14/12	34.0	6.1	IBS, IDR	
F1	6/4	22.7	4.5 - 6.0	IBS	*IESS* 207
F2	6/4	27.0	7.0- 8.0	IBS, IDR	
F3	6/4	29.0	9.0 -10	IBS, IDR,	
H2	6/4	15.1	1.5 to 1.8	DAMA	*IESS* 207
H3	6/4	18.3	2.4 to 2.7	DAMA	
H4	6/4	22.1	3.5 to 4.2	DAMA	
K2	14/11; 14/12	19.8	1.2	VSAT IBS	*IESS* 208
K3	14/11; 14/12	23.3	1.8	VSAT IBS	
G	6/4C or 14/11; 14/12	-	All sizes	LEASED SERVICES*	*IESS* 601

* The leased services can be international and/or domestic services. There is no definition of G/T, diameter, and service for this application.

Standard A

This is commonly known as a "Large Dish" Earth station and has been in use since 1965 (INTELSAT I - "Early Bird"). In recent years a revised Standard A specification has been introduced to take advantage of the higher power available from the new generation satellites.

1. Dish diameter for the Standard A was about 30 meters; per the revised specification, it is about 13-20 meters.
2. It operates in the 6/4 GHz band, but it can be retrofitted, in some cases, to operate in the 11/14 GHz band.
3. For the old standard A, the Figure of Merit was 40.7 dB/°K. It is 35 dB/°K per the revised specification.

This standard can be used for all services.

Standard B

This type of Earth station was initially introduced as a more economical alternative to the standard A for use on "Thin Route" systems with low traffic capacity requirements.

This standard can be now used for all services.

Standard C

With the advent of the INTELSAT V satellites, which operate in Ku- as well as C-band, this standard was introduced. In recent years this specification has also been upgraded.

These stations can be equipped to operate any of the services available in the Ku-band. They can operate with any other station utilizing the Ku- band, and with C-band stations via cross-connected transponders.

Standard D

This standard has been discontinued.

Standard E

This standard was introduced initially for use on the INTELSAT Business Service (IBS) operating in Ku-band. The two larger dishes in this standard are authorized for use in the Intermediate Data Rate (IDR) services as well.

The choice of station depends on the user’s requirements.

Standard F

As with the Standard E, this standard was initially designed for use with IBS but has since been authorized for use with IDR (except for F1).

Standard G

This standard was introduced for those international carriers whose Earth stations do not conform to any of the above standards. They can operate in either C- or Ku-band.

There are no specific antenna sizes, figures of merit, or modulation methods, but they must conform to mandatory requirements, such as sidelobe gain, etc.

Standard H

This standard has been introduced to provide the INTELSAT DAMA service in the 6/4 GHz band.

Standard K

This standard is intended for the INTELSAT VSAT Business Service operating in the 14/11 GHz and/or 14/12 GHz bands.

3.7 Entry of Earth Stations into the INTELSAT System

Before approval can be given for an Earth station to operate in the INTELSAT system, the performance characteristic of an Earth station must be shown by verification testing, to meet the mandatory requirement for that Earth station standard set forth in the *IESS* documents. Table 3.2 sets out the sequence of steps (not necessarily chronologically) for a new station entering the INTELSAT system, and Figure 3.11 shows the Earth Station Registration and Approval Process.

Table 3.2 Planning Sequence for New Earth Stations

STEP	DESCRIPTION
1	Obtain INTELSAT documentation
2	Notify INTELSAT of intention to construct a new Earth station.
3	Coordinate the RF bands.
4	Estimate traffic.
5	Submit Earth station application.
6	Verify the Earth station performance.
7	Certify Earth station performance.
8	Obtain approval to operate.
9	Submit a transmission plan (as applicable).
10	Perform SSOG line-up.
11	Commence operation.

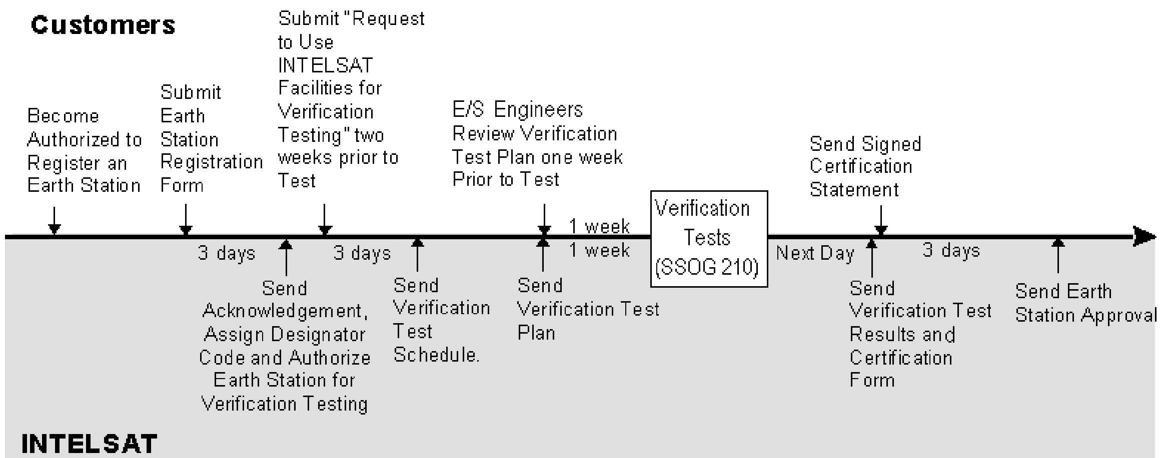


Figure 3.11 Standard Earth Station Registration and Approval Process

3.8 INTELSAT Documentation

The following documents, among others, are available from INTELSAT, and the authorized user should obtain those that are relevant.

INTELSAT EARTH STATION STANDARDS (IESS)

The *IESS* series sets out:

- Performance requirement of all INTELSAT standard Earth stations
- Specifications for INTELSAT services
- Description of INTELSAT satellites

SATELLITE SYSTEM OPERATIONS GUIDE (SSOG)

The SSOG series of documents describe the procedures involved in the operation of an Earth station. From the point of view of the procedures, an Earth station can be classified as follows.

i) INTELSAT standard or nonstandard
ii) Transportable
iii) Receive-only
iv) Type-approved

See *SSOG 200 for Earth Station Registration, SSOG 210 for Earth Station Verification*, and *SSOG 220 for Type-Approval of Antennas*.

INTELSAT Standards

The performance specifications of the antennas are defined in the *IESS* documents.

INTELSAT Nonstandard Stations

INTELSAT nonstandard stations are those that do not meet *IESS* performance requirements, but whose measured performance characteristics render them suitable for a particular requested use. These applications could be, for example, special events, emergencies, disasters, experiments, tests, and demonstrations.

Transportable Stations

Transportable stations are used in connection with fast-breaking events. The essential requirement of a transportable station is that the equipment should be easily transportable from one relocation to another. The performance characteristics should remain unaltered. Such stations would, therefore, be normally quite small, for example, from Standards D to G.

Receive-Only Stations

From INTELSAT's point of view, these stations need only comply with the G/T receive specification to enter the INTELSAT system. This requirement will ensure adequate receiver performance. The other receive characteristics (axial ratio, sidelobe patterns, etc.) may also be verified from the user perspective to ensure adequate interference rejection.

Type-Approved Stations

Developments in manufacturing technology now make it possible to manufacture antennas with good precision, within the bounds of statistical error, obviating the need for verification testing of each unit.

An INTELSAT type-approval means that a manufacturer's equipment meets INTELSAT's operating performance requirements, and that each unit of a particular model closely replicates the performance of every other unit of this model.

This consistency of performance is the result of advances in manufacturing, assembly technology, and quality control that make it possible to very accurately duplicate performance in certain types of antenna systems. Using type-approved equipment, therefore, significantly reduces or totally eliminates the need for verification testing on each individual Earth station unit.

Type-Approved Earth Stations

This is the most all-encompassing type of approval because it is for the entire Earth station. No further verification testing is necessary prior to being brought into service.

Type-Approved Antenna Systems

This is a type-approval for the antenna and the receiver. E.I.R.P. stability testing may be required after transmit equipment has been installed. In many cases, the manufacturer’s test data or “bench testing” satisfies this requirement without accessing a satellite.

Type-Approved Antenna Models

This approval is for the antenna and feed system only. G/T, EIRP, and frequency stability testing may be required after the antenna and feed have been integrated with the transmit and receive equipment. If this is necessary, INTELSAT will often accept the manufacturer's calculations or test data.

Verification Testing

A detailed step-by-step procedure for verification testing of all the mandatory requirements can be found in the *SSOG 210*. Antenna verification testing is carried out in cooperation with an INTELSAT Communication System Monitoring (CSM) station.

Typical tests that are performed using an INTELSAT satellite include:

- i) Transmit gain
- ii) Transmit sidelobe patterns
- iii) Transmit axial ratio
- iv) EIRP and frequency stability, tracking ability
- v) Receive G/T
- vi) Receive axial ratio
- vii) Receive sidelobe patterns

3.9 Earth Station Site Selection

The procedure to determine where each Earth station is to be located is generally known as the "site selection" process. Although a set of "rules" for site selection has not been adopted, there are certain guidelines that are generally adhered to in selecting the most appropriate site. These guidelines and other issues related to site selection, such as the field survey, RF interference (RFI) coordination, and site layout are discussed in this section.

Because the site selection guidelines are geared to include large Earth stations, some of these guidelines may not be applicable in instances where small and/or unattended Earth stations are involved. These may, therefore, be eliminated from consideration.

Site Selection Factors

Geographical

The geographical factors, which should be considered during the site selection process are as follows.

The site should be located so that sufficient clearance in elevation above the local horizon profile is obtained to maximize visibility of the geostationary arc. (See, for example, Figure 3.12.) This will ensure operability of the station with other geostationary satellites located within the visible geostationary arc over the design life of the station.

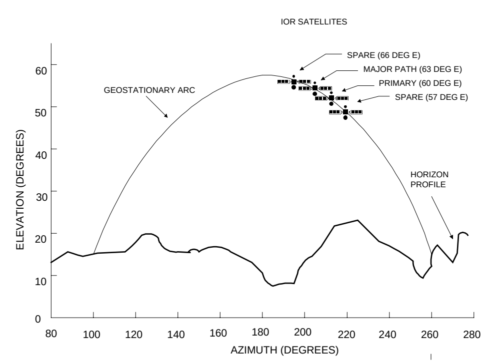


Figure 3.12 Locus of Satellite Look Angles at a Proposed Earth Station Site

If the presence of existing telecommunications or other installations (e.g., radar) interfere with the operation of the Earth station, the site should be located so that the interference is minimized.

As far as possible, the Earth station can also be collocated with an exchange or a switching center to minimize the number of terrestrial microwave repeaters and/or the length of coaxial cable that will be required for the backhaul. This will, in turn, ensure the reduction in the backhaul costs.

b. The site should be located reasonably close (e.g., less than 50 km) to the population center to be served. This will ensure staff availability, their living accommodations, and minimize transportation requirements and costs.

Geological

The geological factors to be considered are as follows.

The ground should be capable of bearing the load of the Earth station antenna and buildings. This is of particular concern for the larger and heavier antenna structures. Ideally, the site should consist of firm, and stable ground with bedrock located fairly close to the surface to obviate the need for expensive and extensive deep piling. A preliminary survey of the potential site would include site borings from various areas to enable analysis of the types of soil and underlying rock at various depths, as well as to determine the height of the water table.

An analysis of the sulfate content of the soil and groundwater should also be conducted to determine the risk of sulfate attack on any buried concrete foundations. Finally, soil resistivity could also be measured at the same time when the trial boreholes are being made.

The site should be evaluated for its susceptibility to flooding and subsidence. This applies also to the access road(s) for the site, especially if river or stream crossings are necessary.

Knowledge of Earthquake intensities and frequency of their occurrences in the area is very desirable to enable the provision of adequate mechanical safety margins for resisting and/or absorbing seismic forces. Except in the most Earthquake-prone regions, Earth station installation should be generally capable of surviving an Earthquake of intensity V on the modified Mercalli Scale without damage. (Mercalli measures intensity, Richter measures magnitude.)

Interference

There are basically two possibilities for RFI, namely:

i) interference from other telecommunication installations, radar, or corona discharge phenomena; and

ii) interference from the Earth station with some other telecommunication service, typically terrestrial microwave installations operating in the common transmit frequency band of 5925 to 6425 MHz.

To circumvent or minimize the possibility of RFI to or from the Earth station, the following guidelines should be observed.

a. The primary objective should be to minimize potential RFI through the selection of natural geographical bowls or depressions within which the Earth station may be located to take advantage of site shielding. If the topography of the area precludes the existence of such natural shielding, it may be necessary to resort to artificial shielding through the installation of man-made barriers or application of automatic interference cancellation techniques. Neither of these two techniques is desirable, however, due to their relative complexity and costs.

b. Interference from radar emissions is generally rare, especially if the guidelines described in "a" above have been adhered to. It might be prudent to consider possible artificial site shielding for an Earth station installation that may be located near a shoreline to preclude or minimize possible interference from shipboard radar stations.

c. Microwave noise interference from high-voltage power lines can usually be disregarded because of its very low level. However, in exceptional circumstances where a high-voltage power line operating at a few hundred kilovolts is close to an Earth station, it might be prudent to undertake field measurements during periods of high corona discharge to verify that the microwave noise interference is negligible. As a precaution, Earth station antennas should, if possible, be located a few hundred meters away from high-voltage power lines.

d. The presence of aircraft in the vicinity of an Earth station can result in interference through either partial blockage of the antenna beam or from radar emissions impinging on the aircraft being reflected into the Earth station antenna.

Partial Blockage

There is unlikely to be any significant effect unless the aircraft flies through the cylinder based on the antenna aperture. The probability of this occurring for an aircraft flying above 1500 meters is estimated to be negligibly small, even if the antenna beam should happen to intersect a busy airplane. However, care should be exercised in locating the antenna such that beam intersections with glide paths to airfields are avoided.

Radar Reflections from Aircraft

At most scatter angles, the aircraft must be in the Earth station antenna beam for interference to be significant. The effect may, therefore, be negligible for aircraft above 1500 meters; but antenna beams should not intersect glide paths. However, at scatter angles of less than 2 (i.e., when Earth station, aircraft, and radar are nearly in line) there is a possibility of interference via the antenna sidelobes. This is only significant for aircraft flying below 1500 meters (e.g., aircraft taking off or landing at an airfield). Therefore, it is recommended that Earth stations be situated so that terrain shielding of at least 1-degree elevation (from the Earth station) is provided in the direction of airfields or other areas where low-flying aircraft are expected.

Environmental

To ensure that proper allowances are made in the Earth station design for prevailing meteorological conditions, such as statistical data on wind velocity, prevailing direction, rain fall rate, ice and snow accumulation (if applicable), temperature and humidity ranges should be obtained from the meteorological office. These data should be obtained for as long a sampling period as possible. In addition to the above, the prevalence of sand or dust storms, and abnormal salinity (near-marine environment) should be taken into account, because an excess of either or both of these conditions will require extra surface protection, and treatment.

Logistics

a. The suitability of a station site will also generally depend on the availability of water. If there is no access to a nearby existing water supply, a well will be necessary. Generally, a well, together with suitable storage tanks, should be capable of providing a sufficient supply of water.

b. Land availability and right-of-way (i.e., permission to construct or use of roads to access the site) must be considered. Also, imposition of development restrictions to prevent future undesirable construction in the vicinity of the selected site that could result in the obstruction of the antenna beam (e.g., by tall structures) should be considered.

c. Availability of local public electricity supply should be assessed to determine whether or not a separate onsite standby power system (e.g., diesels and a no-break power system) is required. In any event, provision of a standby power system would be advisable to guard against failures of the public power supply.

d. Road/rail routes in the area should be adequate for the conveyance of large, heavy loads during the construction. In addition, any bridges that exist along the transportation route to the site should be examined with respect to maximum loading and height/width clearances.

Site Survey

A search for a suitable site for an Earth station commences with a map search for prospective sites that appear to meet the guidelines discussed above. Topographic maps with a scale of 1 in 50,000 and with contour intervals of 30 meters or less (preferably about 15 meters) are generally used.

Data on coordinates and directions of operation on existing and planned terrestrial microwave stations operating in the same frequency band as the communications satellite system as well as any radar installations are superimposed on the map. The search for prospective sites is usually confined to a zone, centered on the city or town to be served via satellite with a radius of approximately 100 to 150 km.

Following the selection of prospective sites, each must then be examined in more detail through field surveys which are conducted to verify the findings of the map survey, as well as to obtain supplementary information not available from the map survey. At each site, observations are made about access roads, road conditions, availability of electric power, and other factors discussed previously with a view to assessing its suitability.

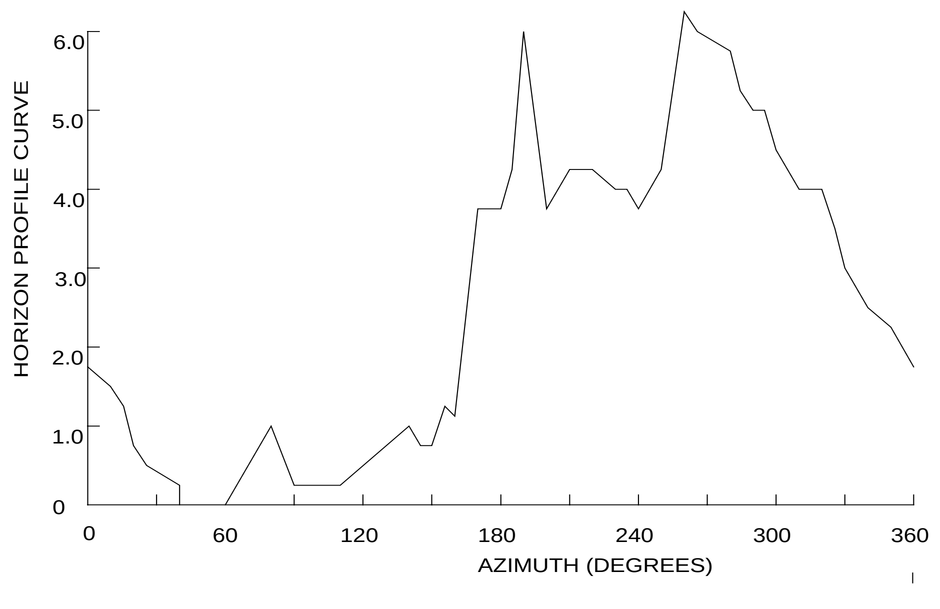


Figure 3.13 An Example of Horizon Profile

The horizon profile for each site (Figure 3.13) relative to the estimated vertex of the Earth station antenna is prepared either from the contour map of the area, or via direct measurements at 5° intervals in azimuth using a theodolite. In wooded areas, it may be necessary to conduct these measurements, (as well as any RFI measurements), from a temporarily erected tower.

A tower height of 25 to 30 meters should be sufficient to provide clearance of the surrounding trees and would approximate the vertex of the large antenna (16 meters for a Standard A). The horizon profile, which is an indication of the available site shielding, will be required in the next step of the site selection process, which is an evaluation of the susceptibility of the site to RFI. This evaluation is generally known as RFI coordination, and is discussed next.

The procedure for plotting these contours is detailed in Appendix 28 of the "Radio Regulations". In the event that the coordination contours extend into neighboring countries, it will be necessary to seek coordination with the respective administrations.

A majority, if not all, of terrestrial microwave repeaters that fall within the great circle coordination contours can usually be eliminated on the basis of free-space propagation loss on a line-of-sight path between Earth station and microwave. For cases in which predicted interference levels exceed the maximum acceptable interference for the frequency band of interest, it will be necessary to plot detailed terrain path profiles for the interfering links and estimate the over-the-horizon loss that would be achieved due to terrain blockage. If this still fails to eliminate the affected microwave repeaters, it may then be necessary to either resort to onsite measurements to verify the predicted cases of interference or to seek an alternative Earth station site.

Site Layout

Planning of the antenna layout and buildings on any new Earth-station site has to:

a) accommodate a growth in the number of antennas;

b) allow sufficient flexibility to cater to future changes in antenna sizes or types;

c) make provision for the future extension of buildings;

d) make the maximum use of the land available; and

e) minimize costs.

Location of microwave-radio antenna masts on the site will also require careful planning.

The power radiated by the main reflector of a paraboloidal antenna in the near-field close to the antenna is contained in a cylindrical beam with approximately the same diameter as the main reflector. The beam may be required to point to any part of the geostationary satellite orbit visible from the Earth station antenna, but not below 5° elevation.

All the antennas and other structures on an Earth station site must be arranged so that no antenna beam is obstructed. Allowances have to be made for the possible use of cranes and other elevated or wide support structures, such as scaffolding the temporary access towers during construction work, small variations from nominal antenna sizes or building dimensions and, where appropriate, the presence of staff and vehicles.

These unknowns are accounted for by setting a minimum clearance distance between each antenna beam and other structures. If this clearance distance is made too large, it will require wider spacing between antennas and buildings, thus resulting in a wasteful use of the land, and an increase in the length and cost of intersite roads, cables, and waveguides. If the clearance is too small, it could impose severe restrictions on future construction work, and flexibility in the future use of the site and the type and size of antennas.

Radiation patterns of antennas can be analyzed as a series of straight-line arrangements to determine the necessary distances to achieve specified clearances. Each site layout must include all the buildings that house equipment, offices, staff rooms, and other required structures. One of the most important factors is the need to connect each antenna to a main central building by a road and cable/waveguide trough. To minimize intersite cable and waveguide losses, it is necessary to use the shortest and most direct route between each antenna and main building. Consequently, some site layout patterns could require complicated arrangements to route the cables and waveguides from the antennas to their destinations in the main building.

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CHAPTER 4

ANTENNA TRACKING

4.1 Introduction

The vast segment of today's communications take part through satellites operated in geostationary orbit, that is, a circular orbit whose plane coincides with the equatorial plane of the Earth, and whose period of rotation matches that of the Earth. Thus, to an observer anywhere on the Earth within the line of sight of the satellite, the satellite would appear to be stationary with respect to the Earth. However, satellites are not precisely geostationary because the Earth is constantly subjected to forces such as the gravitational attraction of the Sun and the Moon, the radiation force of the Sun's light, and its own gravitational field. These influences drift the satellite from its nominal position in the North-South and East-West directions. Unless corrected, the orbital inclination plane (caused by the North-South drift) increases an average of 0.86 degree per year with respect to the equator. (See Figure 4.1.) Also, as the orbits do not remain perfectly circular, the East/West position is influenced.

4.2 Satellite Stationkeeping

To maintain the satellite at its assigned geostationary location, periodic adjustments are made by ground command from the Telemetry, Tracking, Control and Monitoring (TTC&M) station, by using propellant on board the satellites to enable repositioning of the satellite through the activation of propulsion jets. This procedure, known as satellite stationkeeping, keeps the satellite drifting within certain bounds (like drawing a box). For the INTELSAT satellites, stationkeeping is performed both in the east-west and north-south directions. The amount of propellant placed on board the satellite, therefore, determines the maneuver life of a satellite. If near-zero orbit inclination during the satellite launch phase (injection into geostationary orbit) is achieved, more fuel will be available for stationkeeping maneuvers.

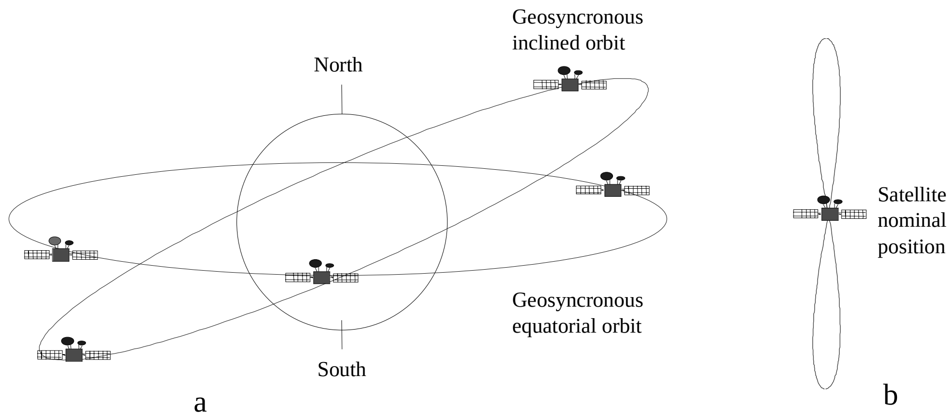

Figure 4.1 Geostationary and Inclined Orbits

For the INTELSAT V series satellites, the orbit inclination has nominally been kept within +0.1° while east-west longitudinal drift has been maintained within +0.1°. For INTELSAT VI satellites, much tighter limits are being achieved; north-south drift of +0.06° and east-west of +0.02°. The north-south limits for INTELSAT VII and subsequent satellite missions are +0.05°. The east-west drift is nonlinear and may vary between the values of +0.02 degree.

An Earth station antenna is required to track the satellite to minimize signal level degradation. The principal factors that determine the extent of the tracking requirement are the accuracy of the satellite stationkeeping, the size of the antenna, and the geographical location of the Earth station.

Because the electronics on the satellite continue to function satisfactorily well after the fuel is exhausted, some of the satellites are kept in inclined orbits by limiting the north-south stationkeeping and allowing the satellite to drift up to ±3 degrees in a highly inclined orbit.

An inclination of the satellite orbit causes the subsatellite point (point directly below the satellite) to move in an open ellipse, stronger than with nominal stationkeeping maneuvers. Refer to Figure 4.1a.

Inclined Orbit Impact

The propellant required to maintain the satellite within its stationkeeping tolerance in the north-south direction is consumed at a much faster rate than for east-west stationkeeping.

To extend the satellite's life, the north-south maneuvers are terminated a few months prior to the nominal end-of-maneuver of the satellite. The propellant saved by not performing 1 month of normal north-south stationkeeping can provide almost 1 year of additional east-west stationkeeping life.

The impact of inclined orbit satellites on Earth stations equipped with tracking systems should be minimal, but those stations with smaller antennas not equipped with tracking may experience service degradation due to the antenna gain reduction in the satellite direction caused by the satellite drift.

At small inclinations, the satellite motion has an apparent elliptical path; as the inclination increases, this ellipse becomes a figure "8" motion, as shown in Figure 4.1b. The size and orientation of this figure "8" depends on the geographical location of the Earth station relative to the satellite and the degree of satellite inclination.

Beam Coverage

With inclined orbit operation, the variation in the beam coverage that occurs as a result of the diurnal (24-hour) motion of the satellite causes a contraction of the beams' usable coverage area. This could be significant for the smaller Ku-band spot beams.

Horizon Blocking

Variations in the Earth station elevation angle that would occur with the motion of the satellite, may cause the elevation angle to drop below the 5° (C-band) or 10° (Ku-band) nominal operating limit, causing degradation to service due to excess of atmospheric absorption.

EIRP Stability

An Earth station's antenna pointing error is defined as the angle between the direction of the antenna main beam axis and the actual direction of the satellite. As this pointing error becomes larger, the effective antenna gain (i.e., the gain in the direction of the satellite) is reduced. Figures 4.5 to 4.8 show the gain reduction for various antenna types as a function of the pointing error.

Polarization Isolation

In addition to EIRP stability, it is also necessary to ensure that Earth stations will maintain the polarization purity within the mandatory limit specified in the *IESS* documents for the appropriate station type. Because voltage axial ratio performance is unique to each antenna, it will be necessary to refer the measured data from the antenna acceptance test, to determine the beam offset limit to maintain the mandatory polarization isolation. In some instances, the need to maintain the polarization isolation is, in fact, a more crucial factor in determining the need for tracking.

Doppler

The range between an Earth station and the satellite will change in a diurnal cycle with inclined orbit operation. (See Figure 4.2.) The transmission time will vary in a 24-hour cycle. The digital equipment must remove the cyclic time variation using the Doppler buffers.

The amount of delay shifts and hence the length of buffer required will depend on the station location and satellite orbit inclination; the worst station position is one that is close to the edge of visibility from the satellite.

The delay parameters for INTELSAT satellites are indicated in *IESS* 308.

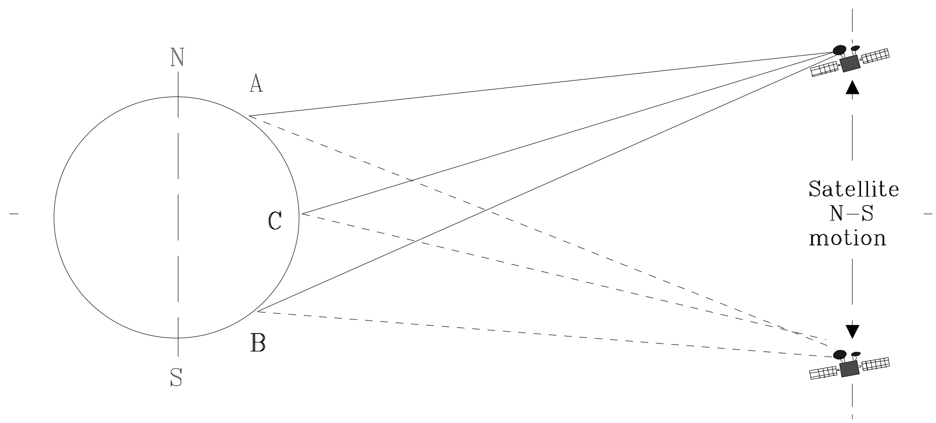

Figure 4.2 Impact of Orbital Inclination over Link Length

4.3 Look Angles to Geostationary Satellites

For an Earth station to track a satellite, it is necessary to have the means available to select the required elevation and azimuth angles from the ground antenna at the specific site. Figure 4.3 shows the geostationary satellite orbit geometry.

The satellite location is given as the longitude of the subsatellite point (U), the point of intersection between the surface of the Earth and the line from the center of the Earth and the satellite. The Greenwich meridian is used as reference for longitude.

Elevation angle (∠TES in Figure 4.3) is measured between the line connecting the satellite to the Earth station and the tangent plane at the Earth station point.

Azimuth angle (∠NET) is the angle between the north direction and the line connecting the satellite and the Earth station.

The great circle angle (∠SOE, noted α in equations) is the angle between radii from the center of the Earth to the subsatellite point (noted U on Figure 4.3) and to the Earth station location.

The elevation and the azimuth are a function of a satellite's orbital parameters and the ground site longitude and latitude.

The next formulas give us an approach to the elevation and azimuth angles for those who want to make a manual calculation.

Distance to the Satellite

The distance between an E/S and a geostationary satellite is:

$d^2 = R^2 + R_o^2 - 2RR_o\cos\alpha$

Where:

d = distance from Earth station to satellite
R = distance from satellite to center of Earth = 42,164 Km
R_o = radius of Earth (6,378 Km)
α = Great circle angle = arccos(cos Δωcos φ)
φ = Earth Station Latitude
Δω = Difference in Longitude between E/S and satellite

Elevation Angle

$$EL = \arctan\left(\frac{\cos\alpha - 0.15127}{\sin\alpha}\right)$$

Azimuth Angle

The azimuth angle depends on the relative location of the Earth station to the equator and satellite:

$$AZ = \arctan\left(-\frac{\tan\Delta\omega}{\sin\alpha}\right) + 180$$ for Northern Hemisphere

or

$$AZ = \arctan\left(-\frac{\tan\Delta\omega}{\sin\alpha}\right)$$ for Southern Hemisphere

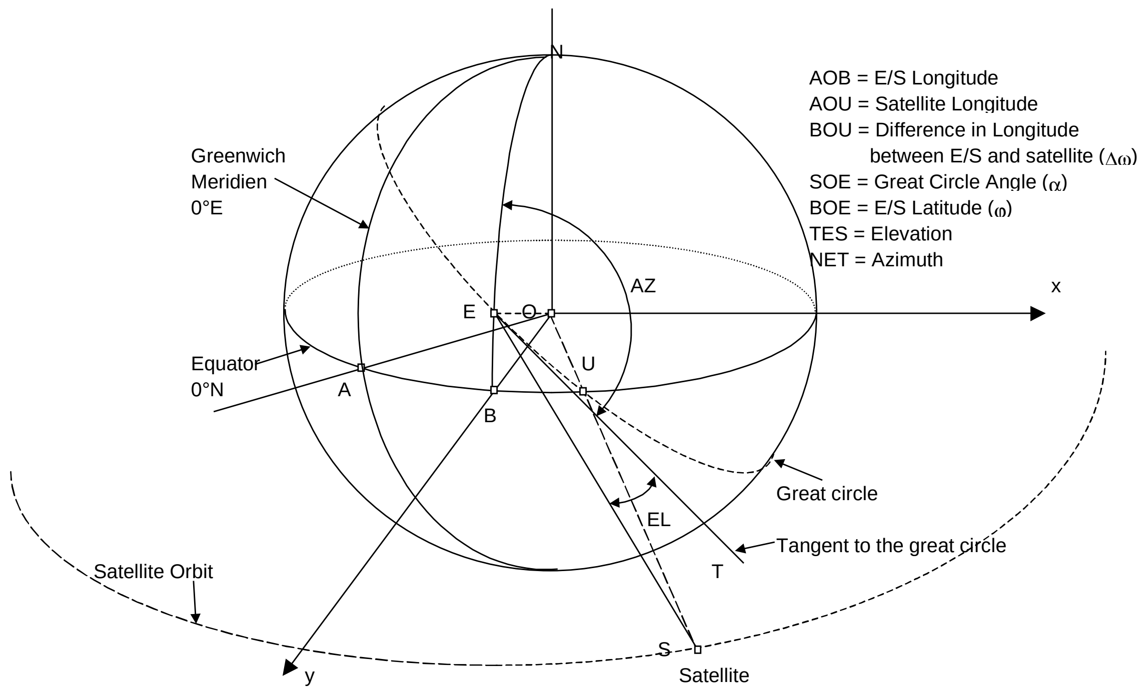

Figure 4.3 Geostationary Satellite Orbit Geometry

Earth Station Visible Arc

Geostationary satellites visible from an Earth station location can be determined using elevation angle as a function of the Earth station latitude and longitude difference between the Earth station and satellite. Figure 4.4 shows the visible arc for three Earth stations located at 25° N, 45° N, and 65° N.

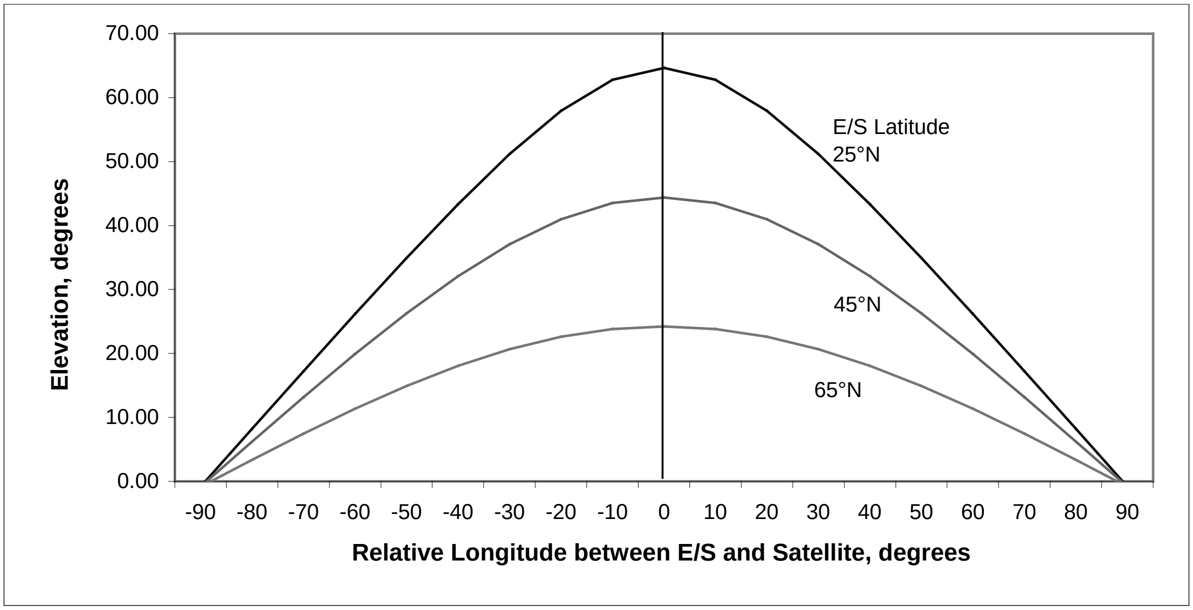

Figure 4. 4 Earth Station Visible Arc (Three E/S latitudes shown)

The center of the chart corresponds to the situation when the E/S and the satellite have the same longitude. For a given minimum elevation angle, the chart gives the relative longitudes of the visible satellites.

4.4 IESS 412

When it is believed that operating with a satellite having a high orbit inclination will result in excessive signal loss, the provision of some type of tracking must be considered.

To determine the actual satellite position or range of positions as a function of time, INTELSAT has a series of computer programs available upon request, using the 11 parameter ephemeris system described in the *IESS* 412. The INTELSAT IOC can provide ephemeris information on any operational INTELSAT satellite to users via the ESC telex system management network. The software and the ephemeris data are available for downloading from the INTELSAT Internet website.

Program Description

IESS-412 is not a pointing program, but rather a shell that helps the use of the BOX and POINT programs. It provides the users with a menu that allows editing of the data files for station information, satellite position, and 11 ephemeris parameters.

POINT Program

Calculates the Earth station pointing angles for a specified satellite by using the 11 ephemeris parameters.

BOX Program

Computes only the satellite position and prints a report whenever the satellite is within a specified box around its nominal position and the time when the satellite will be close to its center of stationkeeping position. This information is useful for nontracking antennas that need to know the optimum time to repoint their antenna to the satellite.

AZEL123

It is actually a spreadsheet template that can be used with the Lotus 1-2-3 program to implement the pointing algorithm.

TRANSFER

Finally a separate utility program is provided. This program provides a means for the pointing angles at one Earth station to be derived from those observed at another station. This can be used in the absence of ephemeris information.

4.5 Antenna Gain Rolloff

As shown in Figures 4.5 to 4.8, the antenna gain decreases as the offset angle, with respect to the on-axis (boresight) main lobe, is increased. The region of gain rolloff that is of immediate concern for satellite tracking is between the boresight, where the gain is maximum, and the half-power (or –3 dB) points.

The received signal degradation that would be experienced by a Standard B and a Standard A antenna, pointed at an INTELSAT satellite, if no antenna tracking were used, would be:

Standard B (11 m) antenna: -0.5 dB,
Standard A (15 m) antenna: -1.1 dB,
for an antenna mispointing angle of 0.1 degree in 4 GHz.

For other antenna types, Figures 4.5 to 4.8 show the pointing degradation for C- and Ku-band. This indicates the need for automatic tracking of the satellite for the large antenna. This requirement would become less stringent as the size of the antenna decreases.

For antennas of 8 meters or less, there might not be, in fact, any need to implement any form of automatic tracking although manual tracking with weekly or biweekly adjustments might be required (if the satellite is not in a highly inclined orbit).

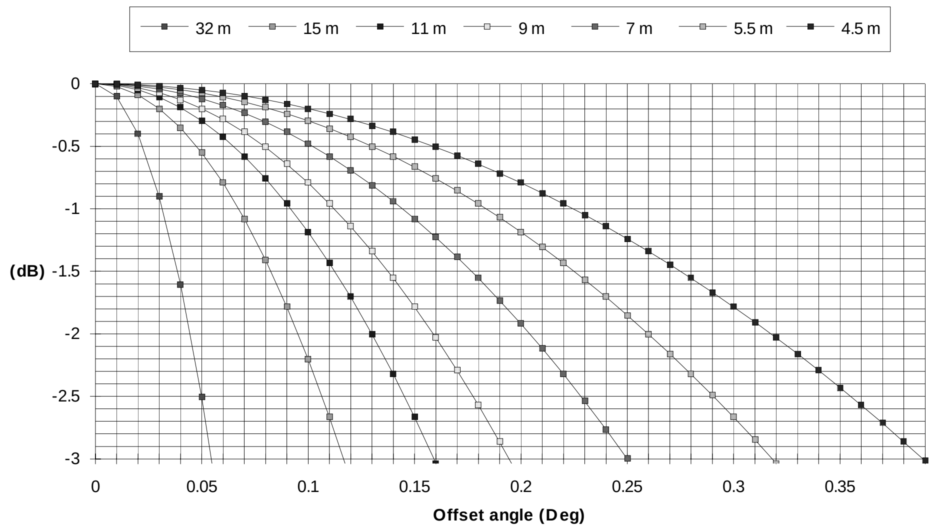

Figure 4.5 6 GHz Antenna Gain Roll-off vs. Pointing Offset

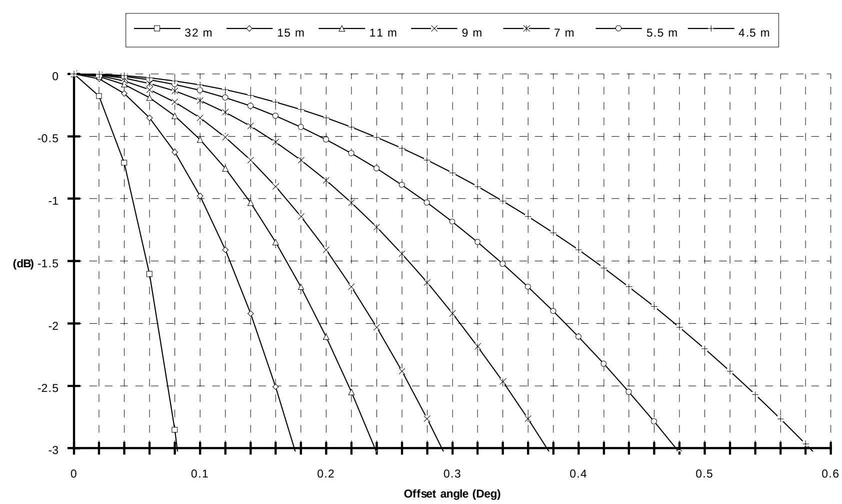

Figure 4.6 4 GHz Antenna Gain Roll-off vs. Pointing Offset

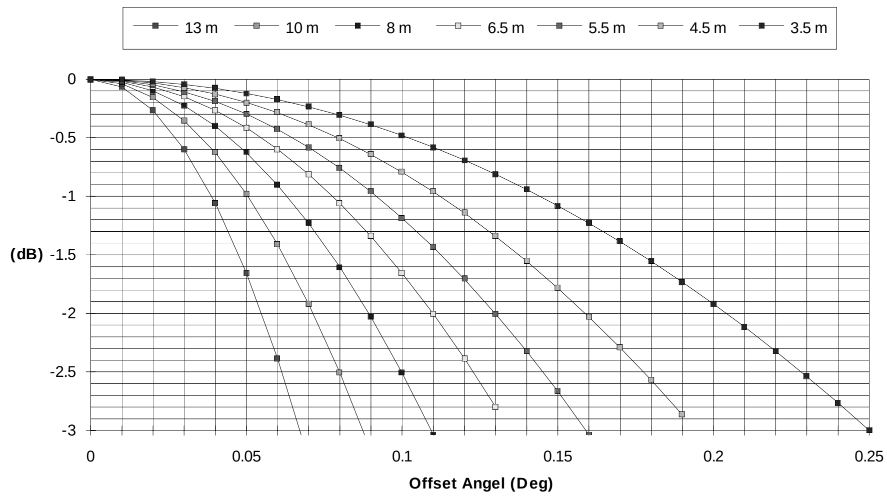

Figure 4.7 12 GHz Antenna Gain Roll-off vs. Pointing Offset

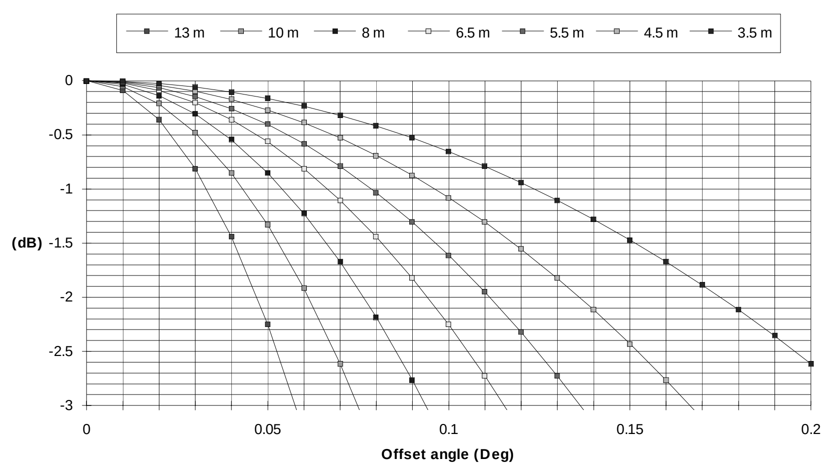

Figure 4.8 14 GHz Antenna Gain Roll-off vs. Pointing Offset

4.6 Tracking Systems

The approaches to antenna tracking used in Earth stations are:

a. Monopulse tracking
b. Steptrack tracking
c. Program/Memory tracking

During the early development of satellite communications, monopulse tracking of one form or another was used almost exclusively. Since the mid-1970's through the present, however, there has been a significant shift towards the use of steptrack autotracking systems. The following sections discuss the basic principles of these two tracking techniques.

Monopulse Tracking

The term 'monopulse' was derived from radar terminology to describe a case in which angular error could be obtained from a 'single pulse'.

The type of feed used is the higher mode detection feed.

Higher Mode Detection

Higher mode detection feeds use the fact that unless the boresight axis of the feed is perpendicular to the incident electromagnetic field, higher order modes as well as the dominant mode will be produced within the feed waveguide. (Refer to Figure 4.9.) By detecting the presence of these higher modes, tracking information relative to angular displacement can be derived.

In one particular square waveguide feed, the higher order mode detected in each axis is the TE20 mode. (See Annex1 for Higher Order Propagation Modes.) It is important to note that the phase of the TE20 mode changes depending on the angular direction of displacement relative to the antenna boresight. With this phase change, the tracking receiver is able to determine the antenna deviation, in terms of magnitude and direction.

The circular feed deployed by some manufacturers uses the same principles as described but, in this case, it is the TM01 mode which must be detected when the antenna is off-track. The fundamental mode for circular waveguide propagation is the TE11 mode. The TM01 mode is produced in circular waveguides as illustrated in Figure 4.10. Four couplers are concentrically mounted around the waveguide to intercept the TM01 wall currents that are then combined to produce a single error signal that will vary in phase and amplitude depending on the direction in which the antenna is off-axis.

All higher mode detection systems are similar because they all provide an error signal to the tracking receivers for processing. The final error voltages are sent to the servo system and are used to correct the off-track condition by moving the antenna to nullify the error voltages.

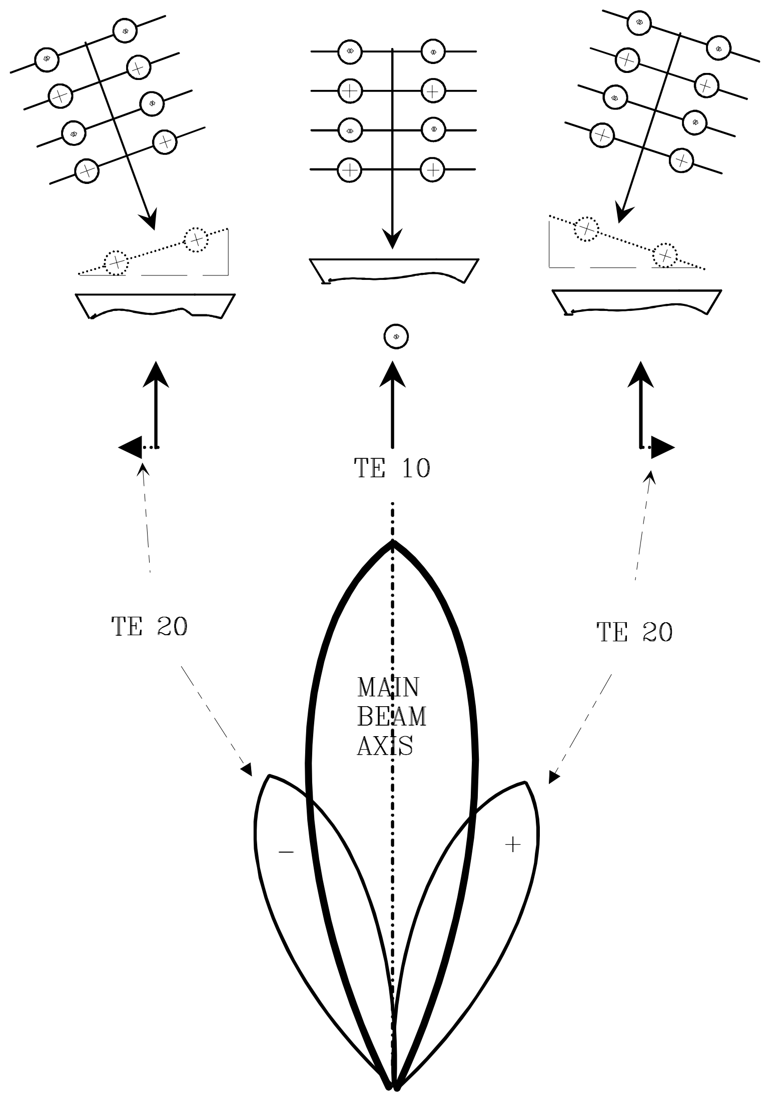

Figure 4.9 Higher Mode Generation for Tracking Purposes

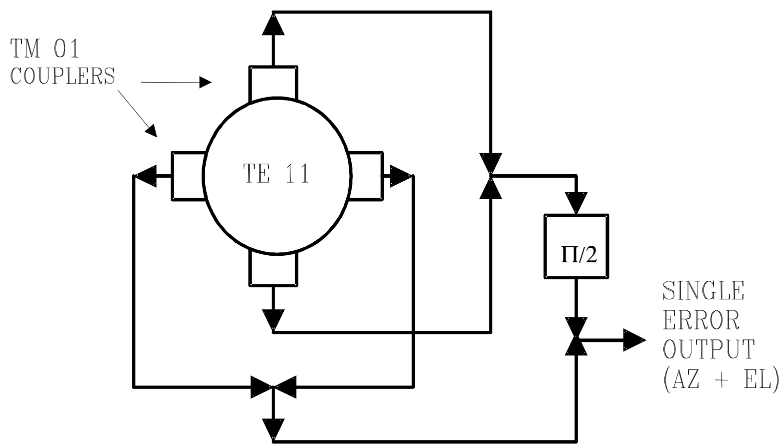

Figure 4.10 Circular Feed for TM01 Mode Detection

Steptrack Autotracking

With the continuing improvement in the stationkeeping accuracy of modern geostationary communications satellites, the opportunity arose to reduce significantly the complexity of the antenna autotracking system which, until fairly recently, was predominantly based on the monopulse tracking technique described in the previous section. While a monopulse autotracking system is inherently very accurate, it is a complex, expensive, and difficult system to maintain.

To take advantage of the greater stationkeeping accuracy of today's satellites, the monopulse tracking systems have been largely replaced in recent years by the steptrack system, principally because of the latter's great simplicity and consequently lower cost.

Steptrack Concept

The operational concept of the steptrack system is quite simple. After acquisition of the satellite beacon (or pilot) signal, the antenna is commanded to make an initial angular move. By comparing the received signal level before and after the move, the direction of the next move can be decided. That is, if the signal level has increased, the antenna continues to be moved in the same direction.

If the signal level has decreased, the direction of movement is reversed. This process is continuous and alternates between the two orthogonal antenna axes.

The main disadvantages of the steptrack system are:

1. Locating a beam maximum can never be as accurate as finding a sharp null.

2. Tracking can be degraded by amplitude fluctuations in the received signal levels due, for example, to atmospheric perturbations. This would also have a detrimental effect on the receive signal at the satellite where the levels are required to be kept within ±0.5 dB of nominal.

These limitations can be overcome, by choosing a step size that is sufficiently small, but not so small as to cause the antenna to continuously 'hunt' the satellite as, for example, during moderate wind loading conditions.

The biggest advantage of the steptrack system is its simplicity, which means significantly lower costs because a special tracking/communications feed to detect the higher modes is not required. The need for maintenance is also reduced.

Steptrack System Configuration

A typical block diagram for a steptrack system is illustrated in Figure 4.11. The satellite beacon signal is received along with all the other communications signals by the antenna and amplified in the low-noise amplifier (LNA). The broadband output of the LNA is then divided to provide four or more signal feeds for the receive ground communications equipment (GCE), expansion purposes, received spectrum monitoring, and the tracking system.

The satellite beacons are extracted from the receive spectrum by the beacon downconverter; in some cases the SCPC pilot is used instead of the beacon. The beacon signals, now at 70 MHz IF, are then passed to the beacon receiver which selects one of the available beacons (or pilots) and provides a DC voltage proportional to its signal strength as an input to the Antenna Control Unit (ACU).

The ACU is responsible for making the basic decisions regarding the optimization of the beacon signal level through the steptrack process by generating the necessary drive control signals to the azimuth and elevation motors for moving the antenna.

Synchros or variable potentiometers on each of the antenna axes provide feedback information on the position of the antenna to the ACU for display purposes.

Stow Position

A slewing capability is sometimes provided for quickly driving the antenna to a stow position during high wind conditions when the antenna could sustain damage. This feature is normally incorporated only in stations located in areas of the world that are subject to hurricane or typhoon weather.

A Practical Steptrack Tracking System

This is a description of a simplified steptrack tracking system used at some of the Standard B Earth stations.

General Description

The Antenna Tracking and Drive System as shown in Figure 4.11, consists of an ACU, an Antenna Position Indicator Unit (APIU), two sets of drive motors and two sets of angle detectors.

The ACU is used for steering the antenna either manually or automatically while the APIU displays the direction (azimuth and elevation) at which the antenna is pointed. The antenna may be driven by an AC three-phase induction motor or thyristor drive DC motor, coupled to a screw-jack mechanism on each axis.

The antenna angle indicator may use a solid-state digital panel meter and derives its angle readouts from potentiometers coupled to each antenna axis or Synchro transmitters. A functional block diagram of this steptrack and drive system (for one axis only) is shown in Figure 4.11.

The typical capabilities and limitations of this particular system are as follows:

1. Steering Mode
   a. Manual Tracking
   b. Step Autotracking

2. Step Autotracking Accuracy
   a. Wind Velocity 0-40mph Accurate to 0.04°
   b. Wind Velocity 40mph-60mph Accurate to 0.06°

3. Angle Indications
   a. Accuracy 0.2°
   b. Resolution 0.1°

4. Drive Motor Characteristics
   a. Rated Speed 1360 rpm at 50 Hz
   b. Rated Current 3.8A at 50 Hz
   c. Rated Output 1 H.P.

5. Drive Velocity
   a. AZ axis 0.03°/second
   b. EL axis 0.02°/second

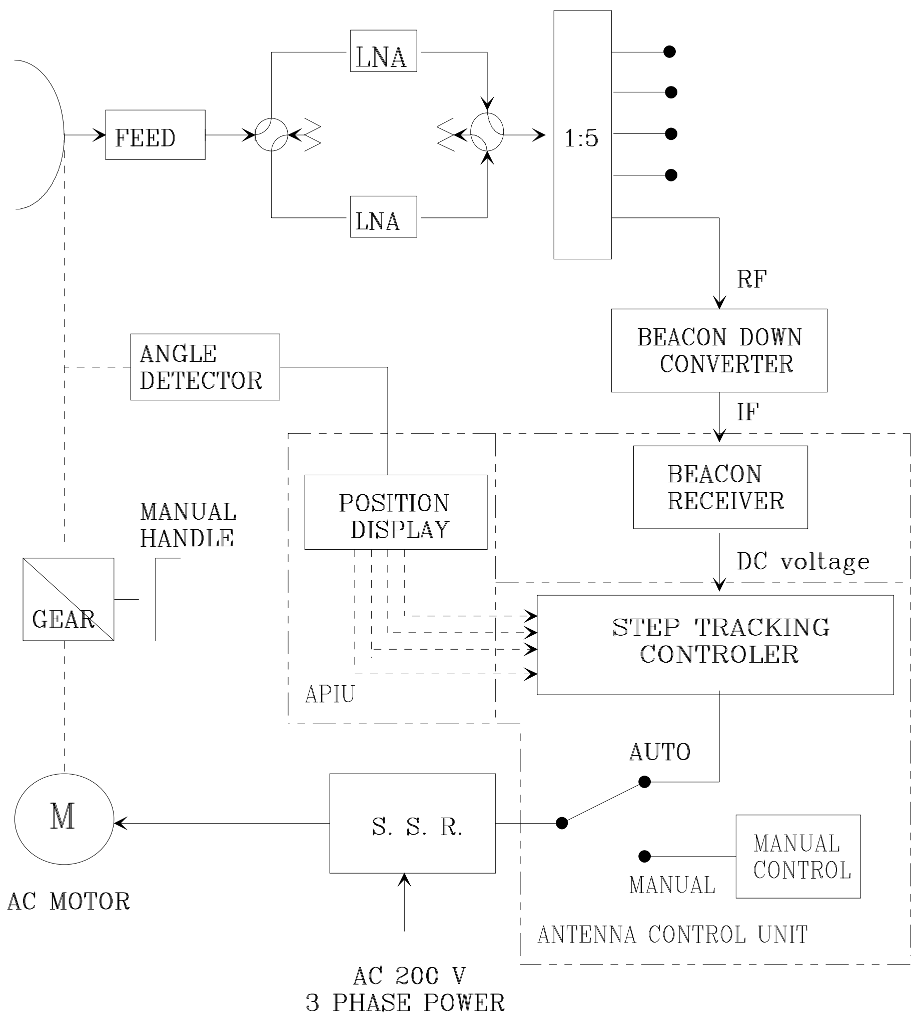

Figure 4.11 Typical Steptrack System

System Interfaces

Figure 4.12 illustrates the connection between the ACU, APIU, and the servo drive system. Note that, for Standard B Earth stations which use SCPC only, the signal often used by the autotracking system is the SCPC pilot which is located in the middle of the SCPC band.

On the downlink, this pilot is extracted by the SCPC terminal and passed on to the ACU.

INTELSAT spacecraft are equipped with different beacon frequencies. For a summary, see Table 2.5.

Steptrack Operation Cycle

The steptrack system is based on the optimization of the received beacon signal level and operates normally only at predetermined intervals of time (cycle time). After each optimization, the servo system goes into a standby mode until the cycle time has elapsed.

ACU Steptrack Circuit determines steptrack control as shown in Figure 4.12, and it can use a beacon (or a pilot in SCPC systems) level DC voltage to determine in which direction to move the antenna, and then produces a triggering signal to turn on the Solid State Relay (SSR).

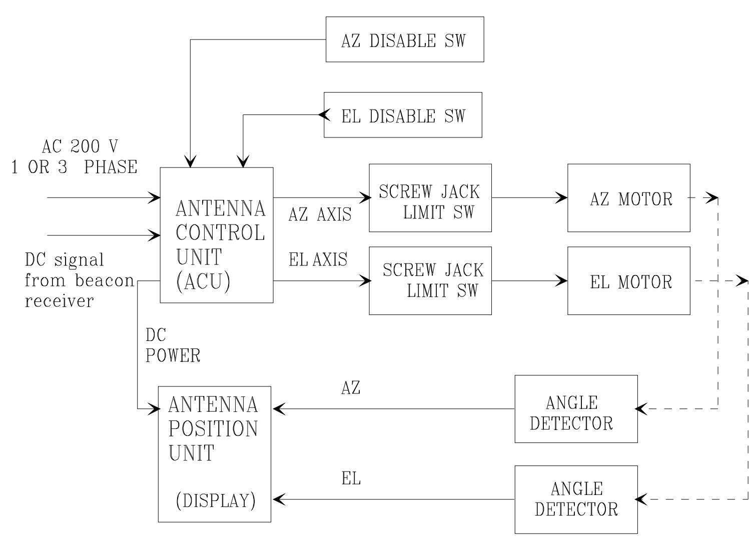

Figure 4.12 Antenna Control and Drive System Interfaces

A steptrack system cycles through a sequence, usually three times in each axis, i.e., ELEVATION/AZIMUTH/ELEVATION/AZIMUTH/ELEVATION/AZIMUTH (as shown in figure 4.13). Thus, at the end of the scan sequence, the antenna should be pointed correctly.

The system described above is simple in concept and is used for most Standard B Earth stations. For Standard A stations an additional feature is often incorporated which ensures added tracking capability if the beacon signal level changes (due, for example, to wind or satellite movement) by more than a certain presettable amount (typically, 0.2 dB) above or below a nominal ('on track') value. Between the scan intervals, however, the cycle timer will be overridden and scanning resumes immediately.

Program Tracking

With the advent of inclined orbit satellites a programmed tracking system becomes more attractive.

The antenna is under computer control and a permanent calculation of satellite orbital position is derived from pointing data (11 ephemeris parameters), thus eliminating the need for a satellite beacon.

Also available is the so called "Smooth Stepback" systems which are steptrack systems using computer memory which memorizes the satellite movement within the first 24 hours of acquisition, and then follows the memorized program. This feature is not recommended with inclined orbit.

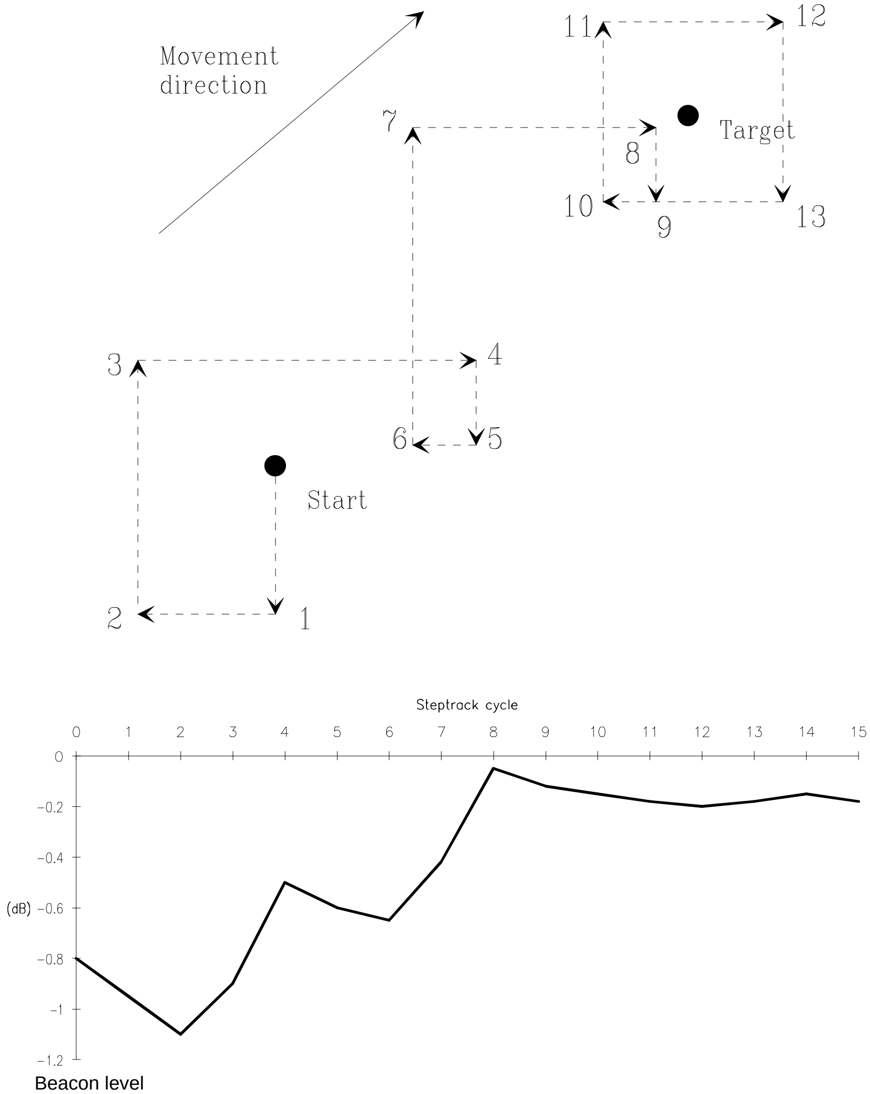

Figure 4.13 Steptrack Search Process

4.7 Student Question Paper

Question An Earth station with a latitude of 50.00° N and longitude 5.00° W is operating to the 335.50 E satellite (24.50W).

What are the Earth station elevation and azimuth angles?

(Solution: EL = 29.75; AZ = 204.81; Range = 38634.58)

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CHAPTER 5

POWER AMPLIFIERS

5.1 Introduction

The basic function of a power amplifier in an Earth station is to amplify the low-level RF carrier(s) provided by the transmit GCE to a higher power level to ensure that a correct EIRP per carrier is radiated to the satellite.

5.2 Power Rating

The rating or capacity of power amplifiers used in INTELSAT Earth stations for international traffic can range from a few Watts to several kiloWatts. For systems using the INTELSAT leased space segment, power amplifiers may have power ratings of 50 Watts or less for low-capacity traffic. In some instances, SSPAs with power ratings from 1 watt to about 10 Watts may be used for low bandwidth or VSAT applications.

5.3 Types of Power Amplifiers

Common types of power amplifiers found in Earth stations are the Klystron Power Amplifier (KPA), the Traveling Wave Tube Amplifier (TWTA), and the Solid State Power Amplifier (SSPA).

Users must be aware of the significant differences among the different types of power amplifiers, which may affect the proper selection of power amplifiers type and power capacity to satisfy the particular transmit carrier requirements. In recent times, SSPAs have gained place, especially where a medium or low power is required in applications, such as VSATs, low traffic stations, or old standard A antennas where the high-gain antenna (HGA) enables use of small amplifiers. With recent advances in solid state microwave power devices, phase combined SSPAs delivering up to 800W in C-band and 400 W in Ku-band, have become available.

Klystron Power Amplifier (KPA)

Figure 5.1 shows basic features of a typical multicavity Klystron (5 cavities typical for a modern 3kW KPA), and Figure 5.2 shows a typical block diagram of a KPA.

Electrons emitted by the electron gun pass through the cavity gaps in each of the resonators and through cylindrical metal tubes (called "drift tubes") located between the various gaps. In a Klystron amplifier, a low-level RF input signal is coupled into the first resonator, which is called the "buncher" cavity. The RF input signal excites oscillating currents in the cavity walls, which causes an electric field to appear across the buncher gap. This excited electric field velocity-modulates the electron beam creating bunches of electrons.

After leaving the buncher gap, the electrons proceed toward the collector in the drift tube region, passing through the intermediate resonators and the output ("catcher") cavity. If the "catcher" cavity is of the correct size (i.e., tuned to the proper frequency), large oscillating currents will be generated in its wall, thus resulting in a RF output from the tube.

To acquire the high-gain and the required saturated power levels, intermediate cavities such as the second and third cavities are used. The electron beam is focused from the gun through the cavity gaps and drift tubes to the collector by means of a focusing structure, that is either a permanent magnet for a short tube, or a solenoid for a long tube.

Beam Interception

The effectiveness of the electron beam focusing onto the collector will determine the amount of electron interception in the drift tubes, which will, in turn, determine the maximum power handling capability of the tube. The heat transfer capability of the tube structure will determine the amount of heat that can be tolerated before the structure melts or mechanical damage is done to the tube. (The intercepted electrons will produce heat that must be dissipated.)

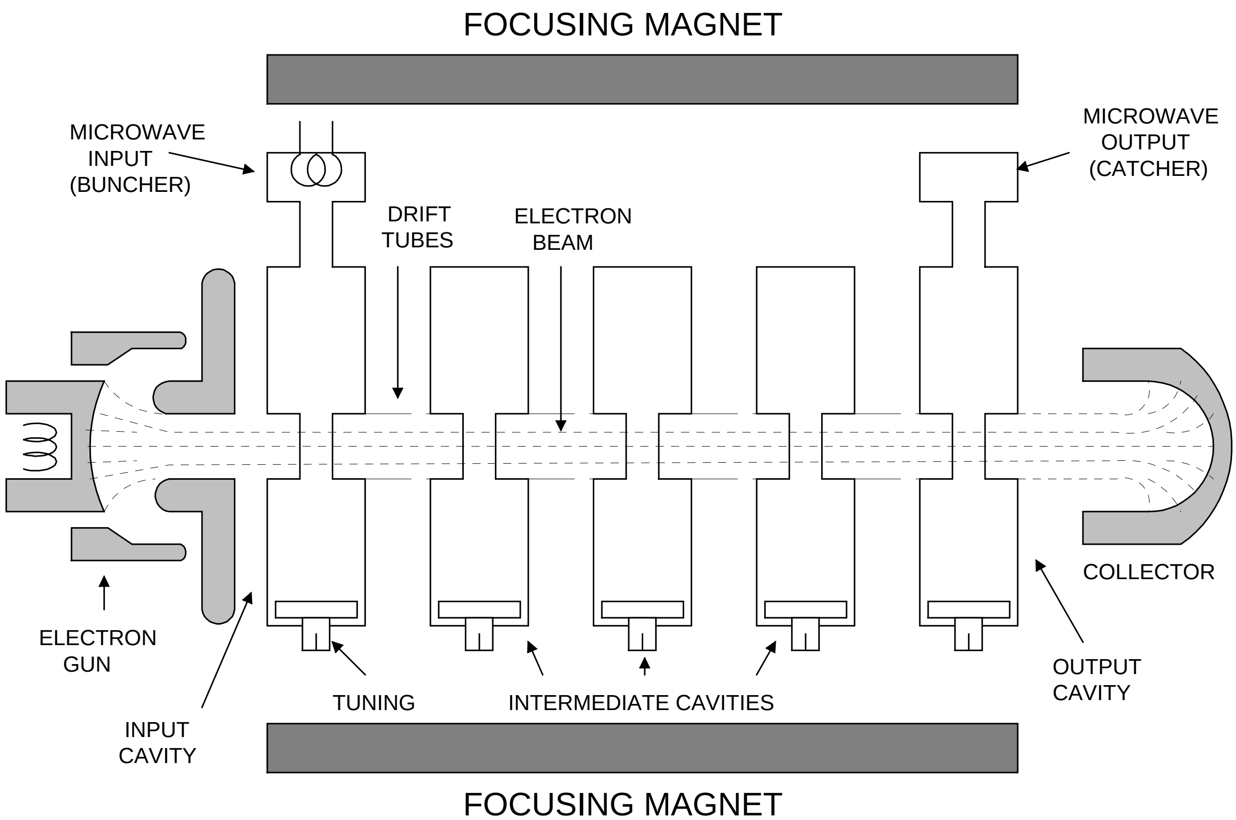

Figure 5.1 A Klystron

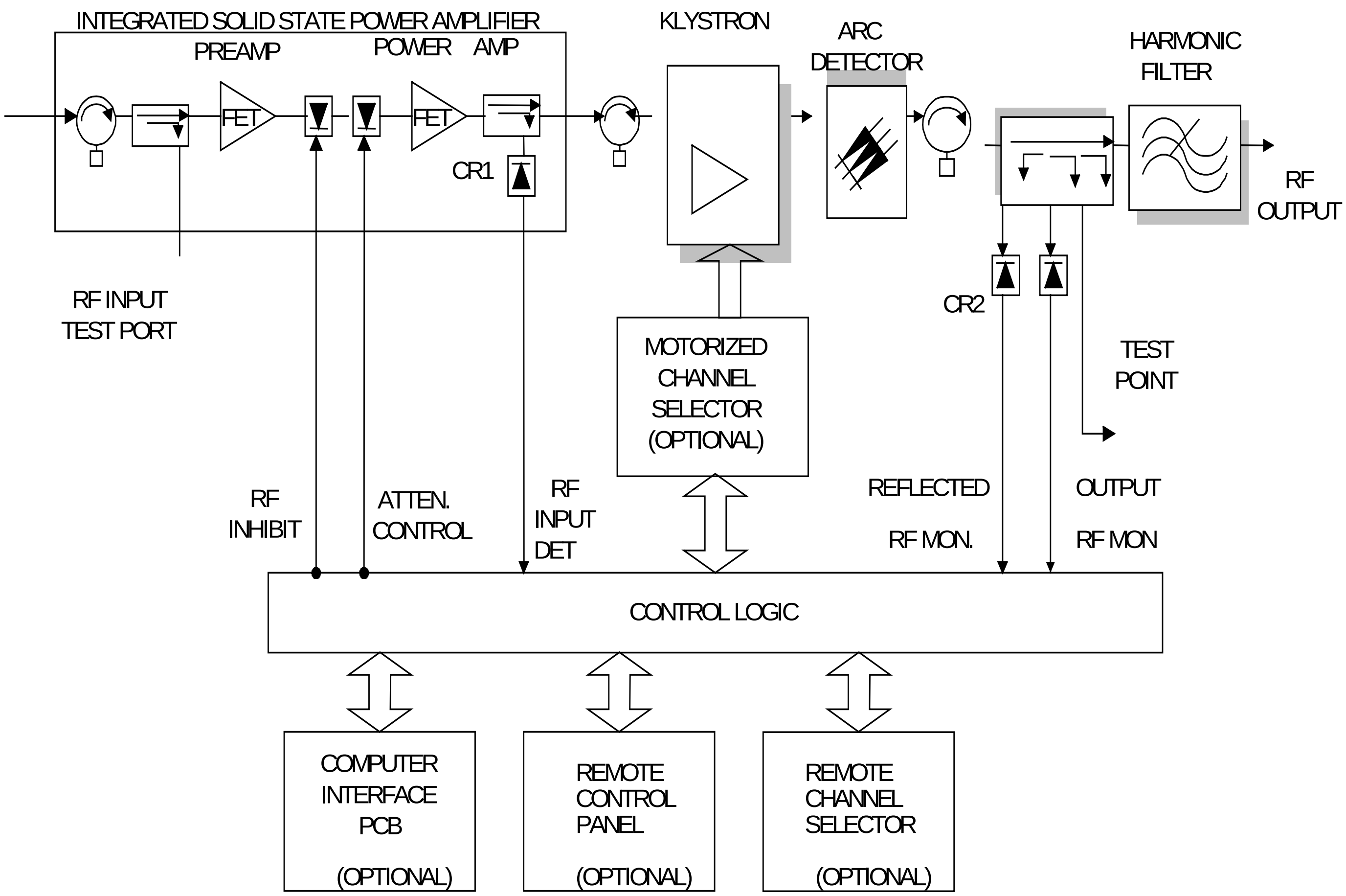

Figure 5.2 Klystron Power Amplifier Block Diagram

The Klystron Collector

The Klystron collector is a large and hollow structure as illustrated in Figure 5.1, thus providing a large surface area into which the heat resulting from the impingement of the electrons can be dissipated. The large collector surface furthermore facilitates the installation of either a water-cooling or an air-cooling circuit to promote efficient heat dissipation. In practice, most state-of-the-art Klystrons up to 3 kW in power rating are air cooled.

Tuning

Due to the mechanical characteristic of the resonator, Klystrons are tuned by changing the dimensions of the cavities thus causing them to resonate at different frequencies. The instantaneous frequency band of a Klystron is in the order of 40 to 80 MHz.

Noise and Distortion in KPAs

Because the electron bunches passing through the output cavity occur in quick "kicks", it is evident that the output current may not be purely sinusoidal and will, therefore, contain harmonic components.

In general, the harmonic components from the KPAs are largest with respect to the fundamental carrier power when the tube is operating at or near saturation or is being driven beyond saturation. Harmonic content decreases when the tube is operated below saturation. These harmonics are reduced in the output by using harmonic suppression filters.

A KPA will also generate a certain amount of "white noise", just like any other electron tube. White noise occurs primarily because an electron beam is never perfectly uniform.

KPA Power Supply

A typical KPA power supply block diagram is shown in Figure 5.3. It consists of high voltage beam power supplies, a low voltage heater, and control unit supplies.

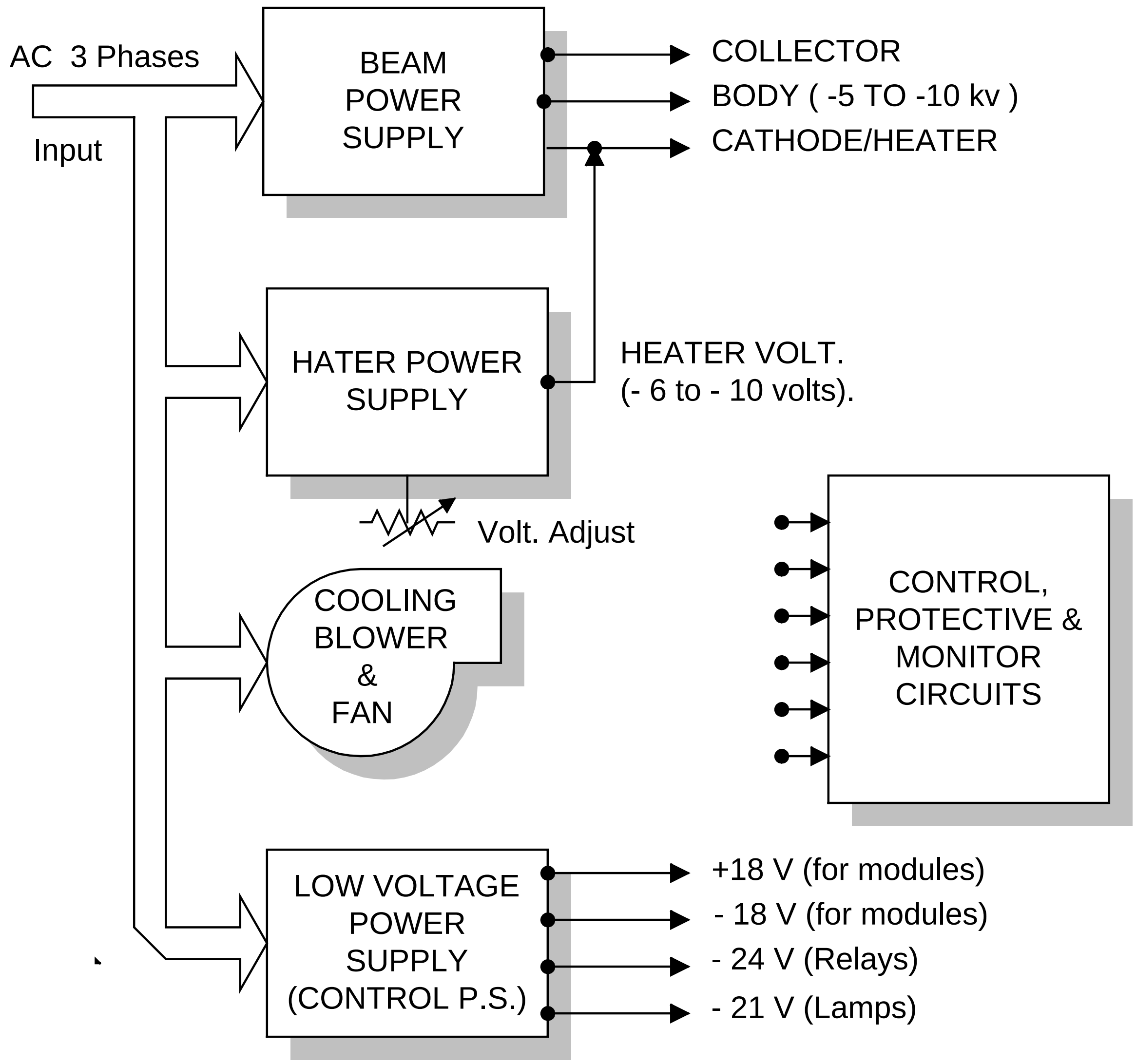

Figure 5.3 Typical Klystron Power Supply

Traveling Wave Tube Amplifier (TWTA)

A TWTA is an amplifier with a wide bandwidth and a power gain of typically 25 to 50 dB. The efficiency, in general, is a function of bandwidth and it ranges from 20 percent to 40 percent with 20 percent being a typical figure.

TWTA Operation

A TWTA uses a magnetically focused electron beam and a slow-wave structure such as a helix. The electron-beam velocity is adjusted to be approximately equal to the phase velocity of an electromagnetic wave propagating along the helix. Under these conditions, a strong interaction between the beam and the wave can take place.

A "slow wave" structure is located between the electron gun and the positive potential collector. It may take various forms, but the one shown in Figure 5.4 is a helix type. Other forms of slow-wave structures are iris-loaded circular guide, dielectric-loaded guide, interdigital line, ring and bar, and cloverleaf. The slow-wave structures must be protected against bombardment by the high intensity electron beam. Therefore, correct focusing is essential, and this is indicated by minimum helix current, typically 2mA for a 20 watt TWTA. The focus is accomplished with TWTA operating at a reduced output power level either by adjustment of the focusing coil, direct current (DC), repositioning the coil, or by repositioning the alternative periodic permanent magnets.

The following subsections describe the basic elements, construction, and function of traveling wave tubes (TWTs).

Electron Gun

The purpose of the electron gun is to generate an electron beam, which passes through the slow-wave structure. Energy coupled from the electron beam into the slow-wave structure provides the basic mechanism of RF amplification in a TWTA. As shown in Figure 5.4, the electron gun consists of a cathode, heater, focus electrode, and one or more anodes. The functions of each of these components are as follows.

Cathode

The cathode is the source of electrons for the electron beam. The area of the cathode is much greater than the required cross-sectional area of the electron beam. The compression of this area keeps the current density at the cathode surface at low values, thus preventing its destruction. Typical values for the compression ratio are 15:1 to 50:1.

Heater

The heater warms up the cathode to the temperature required for electron emission to occur. The heater is usually wound in a manner so that the current through it will not introduce an appreciable amount of magnetic field into the electron gun. This magnetic field would create a major perturbation in the trajectories of the electrons making the electron beam difficult to focus.

Focus Electrode

The focus electrode surrounds the cathode and controls the electric field near the surface of the cathode. The size and shape of this electrode is carefully chosen to cause the electrons to leave the cathode on the proper trajectories and to converge into a well-defined electron beam as they pass through the anode. Usually the focus electrode is electrically connected to the cathode within the electron gun.

Anode

Most TWTAs have a single anode, as shown in Figure 5.4. The anode controls the electric field in the region between the cathode and the anode. This electric field provides the accelerating force for the electrons. The voltage on the anode, therefore, provides control over the current in the electron beam, permitting the gain and RF power output of the TWT to be adjusted over a small range. Usually, the voltage on the anode is selected during TWTA testing and maintained at the same voltage thereafter.

Slow-Wave Structure

After leaving the electron gun, the electron beam passes through the slow-wave structure. The purpose of the slow-wave structure is to reduce the velocity of the RF wave that propagates along the TWTA.

Interaction Between the Slow-Wave Structure and the Electron Beam

The RF wave's electric field traveling in the slow-wave structure penetrates into the electron beam region, and causes some electrons to accelerate and some others to decelerate producing a periodic velocity modulation approximately in phase with the RF electric field.

The electron bunches thus formed tend to concentrate ahead of the accelerating field and behind the decelerating ones. Because the average velocity of the electron beam is slightly greater than that of the RF wave, the bunches will tend to move "back" into regions where the RF field will decelerate the electrons. As the electrons lose velocity, the energy lost by the electrons is transferred to the RF energy in the RF wave. This transfer of energy registers a constant gain in the amplitude of the RF wave per unit of length.

It is important to note that a slow-wave structure will support RF energy traveling from output to input as well as from input to output. The wave traveling from input to output will be amplified, and the wave traveling from output to input will not be amplified.

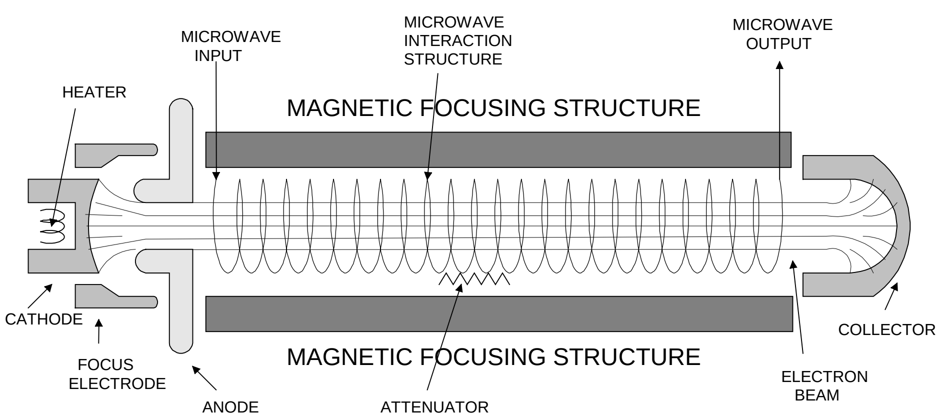

Figure 5.4 Traveling Wave Tube

However, in the presence of the inevitable reflections at the output and input couplers, some RF energy could be reflected back towards the input along the helix, and upon reflection from the input coupler, this signal will represent RF feedback. All practical TWTAs have sufficient gain for this feedback mechanism to result in self-oscillation. It is fairly simple to interrupt this feedback path by placing RF attenuation on one or more of the helix support rods. This attenuation is depicted in Figure 5.4 by a resistive section (sever). The attenuation is formed by placing a carefully controlled pattern of a resistive material on the rods prior to their installation into the helix structure.

Pyrolytic graphite (carbon) and titanium carbide are the most commonly used substances. The density of this attenuation pattern is selected to provide a very low reflection of RF energy so that any energy reflected from the output of the TWTA is absorbed in the attenuation. The region of the helix structure containing the attenuation is called a "sever" because the RF wave on the helix is terminated or "severed" at this point.

Coupled-Cavity

Various types of slow wave structure are used, and a coupled cavity slow-wave structure is shown in Figure 5.5.

The cavity sections are usually made of copper brazed together to form a structure consisting of many cavities in cascade. The dimensions of the cavities determine the frequency of operation for the TWTA. The coupling hole in the wall of each cavity serves to couple the RF energy from one cavity to the next.

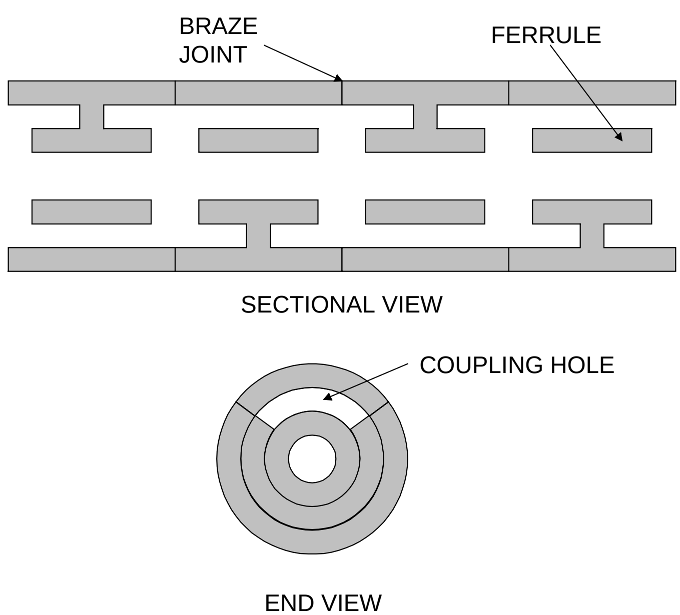

Figure 5.5 Coupled Cavity Slow Wave Structure

Collector

Having generated an electron beam in the electron gun and having used some of the kinetic energy in that electron beam to amplify the RF signal, it is now necessary to dispose of the electron beam. The collector does this job. In an elementary TWTA, the collector would consist of a metallic surface upon which the electron beam is caused to "impinge". This would be simple enough if the collector were to operate at ground potential (the same potential as the slow-wave structure), but this approach would be very wasteful. The RF amplification process only extracts a very small amount of the kinetic energy in the electron beam, typically 10 to 30 percent, causing the electron beam to develop kinetic energy which would be dissipated should the beam strike the grounded collector.

It is far more efficient to purposely decelerate the electron beam prior to allowing the beam to strike the collector surface, but this requires that the collector be operated at a potential (voltage) below ground potential. This is known as "depressed collector" operation. Ideally, the negative potential on the collector would be chosen so the electrons lose all of their remaining kinetic energy just as they reach the collector surface. The negative potential between the collector and ground is chosen in this example so that the electrons decelerate to zero kinetic energy just as they reach the surface of the collector.

On the power supply diagram in Figure 5.6, we see that the voltage on the collector is more positive, being just sufficient to compensate for the kinetic energy taken from the electron beam by the RF signal. Such a TWTA would have high efficiency.

The power supplies connected to the various electrodes of the TWTA would only need to provide the power, which is converted into the RF output.

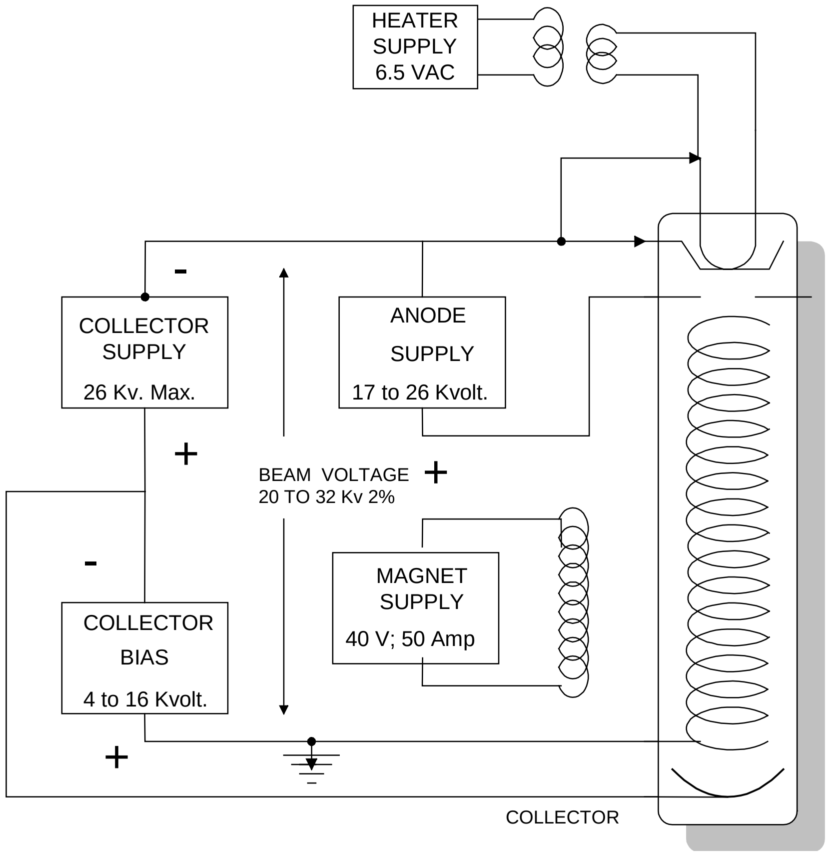

Figure 5.6 Depressed Collector Power Supply

Practical TWTAs usually operate with the collector voltage depressed to a value that is 30 to 60 percent of the original accelerating voltage. For most applications, TWTAs having two depressed collector stages provide the most logical compromise between TWTA efficiency and the complexity of the TWTA and power converter.

Beam Focusing

The electron beam must pass through a rather long slow-wave structure as it interacts with the RF fields in the slow-wave structure. Upon leaving the cathode surface, the electron beam is formed into a stream of electrons in which the current density is fairly high. The electrons within this beam possess negative charges and these negative charges cause the electrons to repel one another.

This space charge effect, if left to its own devices, would cause the beam to expand in diameter and intercept the slow-wave structure. It is necessary to provide a means of keeping the electron beam confined to a diameter, which is smaller than the inside diameter of the slow-wave structure. This is usually accomplished by providing a magnetic field parallel to the direction of electron flow. Historically, surrounding the TWTA with a large electromagnetic (solenoid) or a large permanent magnet produced this magnetic field. A scheme for beam focusing is one, where the magnetic field is concentrated along the TWTA axis by placing iron pole pieces along the outside of the slow-wave structure, and small cylindrical magnets between these pole pieces. These magnets are magnetized parallel to the axis of the magnet, and the polarity of adjacent magnets are reversed. This arrangement is called Periodic Permanent Magnet (PPM) focusing because of the periodic reversal of magnetic field direction. The PPM focusing system creates a series of convergent magnetic lines. The ferrules on the iron pole pieces help direct the magnetic field into the region occupied by the electron beam. The rms value of the magnetic field produced in the electron beam is roughly equivalent to a continuous magnetic field of the same value.

The PPM focusing scheme occupies much less space and weighs far less than an equivalent solenoid or permanent magnet focusing scheme. A further advantage is that the external stray magnetic field is very small for the PPM focusing scheme.

Heater Supply

The heater in a TWTA is sometimes called a "filament", and its supply voltage is identified as "EF". The current provided to the heater is identified as "IF". The heater can be provided with either AC or DC power. The use of DC power is sometimes dictated in systems (such as digital systems), where the small amount of spurious phase modulation induced by AC power on the heater could cause degradation of system performance. In most cases, this small amount of phase modulation is acceptable and the heater could just as well be provided with AC power.

Cathode Supply

The cathode supply connects between the TWTA cathode and the ground. The voltage of this supply is identified as EK. The current emitted from the TWTA cathode is called the cathode current, IK, but not all of this current must be provided by the cathode supply. In a well-focused TWTA, most of the current is collected by the depressed stages of the collector, and very little of this current is intercepted by the slow-wave structure. Note also that the first (undepressed) stage of the collector is connected to the ground. In helix TWTA, the current intercepted by the slow-wave structure (and any undepressed collector stage) is called the helix current (IW, where the "W" implies "wire"). In a coupled-cavity TWT, the same current is called the body current (also designated as IW). It should be pointed out that in a helix TWTA, the "cathode voltage" is sometimes called the "helix voltage".

Collector Supplies

As shown in Figure 5.6, the collector supplies are connected with their negative terminals to the TWT cathode and the positive terminals to the depressed collector stages. Most of the TWT cathode current is ultimately collected in the depressed stages of the collector. When the TWT is not amplifying any RF signal or is handling signals at very low output levels, most of the current will be collected on the most depressed collector stage, the stage nearest to the cathode voltage. As the RF signal being handled by the TWT is increased, the current collected by the less depressed stages of the collector will also increase. This causes the DC power consumed by the TWT to increase because more of the beam current is collected at high voltages. The end results are that, for a TWT with multiple stage collectors, the DC power consumed by the TWT tends to increase in proportion to the RF signal level being handled and the DC power dissipated tends to remain fairly constant.

A TWT with an undepressed collector or a collector with a single depressed stage tends to operate quite differently. The current to the single collector stage (and also the DC power consumed by the TWT) is nearly independent of the RF signal level being handled by the TWT. Therefore, as the output RF power decreases, the wasted power will increase.

Anode Supply

Most TWTs operate with the anode above ground potential, as shown in Figure 5.6. The negative terminal of the anode supply is usually connected to the ground. The anode intercepts very little electron beam current, causing the anode supply to deliver very little DC power to the TWT.

AC Components on Power Supply Voltages

Several interactions occur between the TWT and the power supplies, many of which are dependent upon the nature of the RF signal to be transmitted by the TWT.

As the amplification is achieved by modulating the electron beam velocity, any factor that affects the velocity of the electron beam will produce phase changes in the RF output signal. If the disturbing factor varies with time, as ripple and AC components do, the result will be phase modulation, for example:

1 percent of change in cathode voltage will produce
35° of variation in the output signal.

This value should not be considered in order of magnitude, but shows how ripple or AC components on TWT voltages can destroy a phase modulated signal; it also shows why the TWT power supply must be periodically checked.

To minimize the impact of ripple and at the same time reduce the size, most TWTs use DC-to-DC inverters in which the DC voltage obtained from the AC main input is chopped or modulated in a converter with a moderately high frequency (typically 5 kHz to 30 kHz). The output of this converter is stepped up in voltage by transformers, then rectified and filtered to provide the high DC voltage required by the TWT. This scheme results in high efficiency and produces ripple voltages, which are easily filtered.

Parameters that Affect the System Performance

The basic considerations in selecting a power amplifier for a specific application are center frequency, bandwidth, and power output. Several additional parameters must be considered however, in the specification process.

Harmonics

Due to the wide bandwidth and the TWT's high gain, and the fact that the tube acts as a nonlinear device in saturation, harmonics will be present in the RF output spectrum. Typically, at saturation for narrow band applications, the second harmonic will be 8 to 10 dB below the fundamental signal, but it is not important because it is out of band.

Intermodulation Distortion

All power amplifiers are nonlinear to some degree. If more than one carrier is transmitted by a single amplifier, mixing, or intermodulation (IM) processes will take place.

This results in intermodulation products, which are displaced from the carriers at multiples of the difference frequency. Even-order products, such as the second order product of (f1 + f2), cannot appear in narrow band systems, unless the ratio of the highest frequency (f2) to the lowest (f1) is at least 2 to 1.

Odd-order products, such as the third-order distortion products of 2f1-f2 or 2f2-f1, appear in the frequency band regardless of the frequency ratio. Third-order distortion may be defined as the ratio of the level of the undistorted two-tone output power of the primary fundamental signals, which are f1 and f2, to the output power of the first or closest pair of side band intermodulation products, which are 2f1-f2 and 2f2-f1.

The power level of these intermodulation products is dependent on the relative power level of the carrier and the amplifier linearity. If two balanced carriers are transmitted, Figure 5.7, shows the variation of carrier and IM products power level as drive power changes.

From Figure 5.7, we can also understand that:

A) In a multicarrier operation, the saturated power will not be the same as that we can achieve for a single carrier.

B) The IM distortion is significantly reduced in the small signal region of the RF drive range, because this region is more linear.

Communication power amplifiers are operated 2 to 10 dB below their saturation power level to minimize the IM effects.

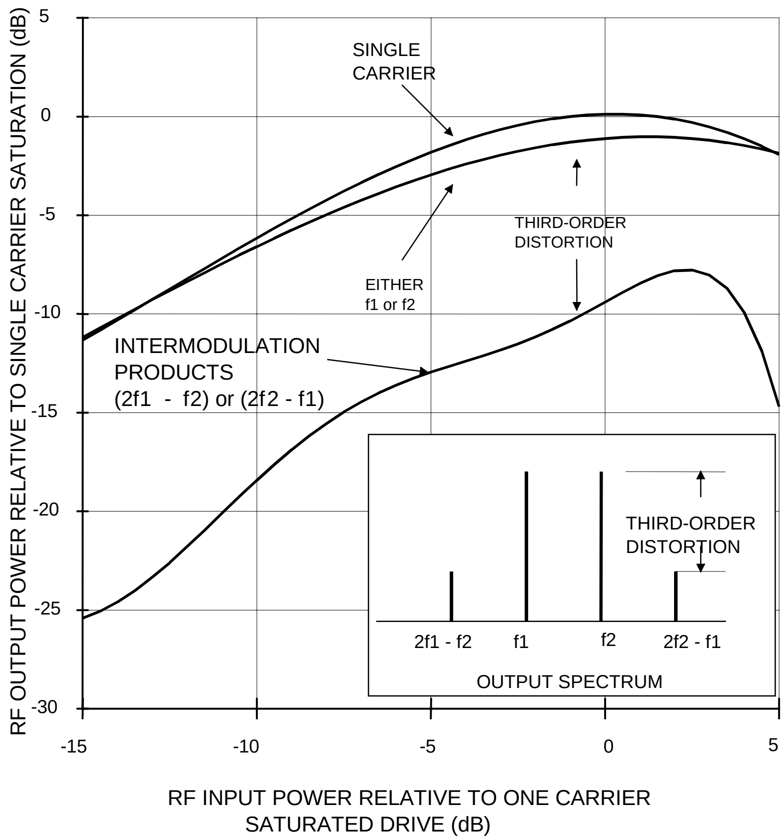

Figure 5.7 Typical Third-Order Intermodulation Data for TWTA

Transfer Curves

The drive characteristic of an ideal TWT is shown in Figure 5.8. The threshold of useful operation is determined by the Noise Figure of the tube.

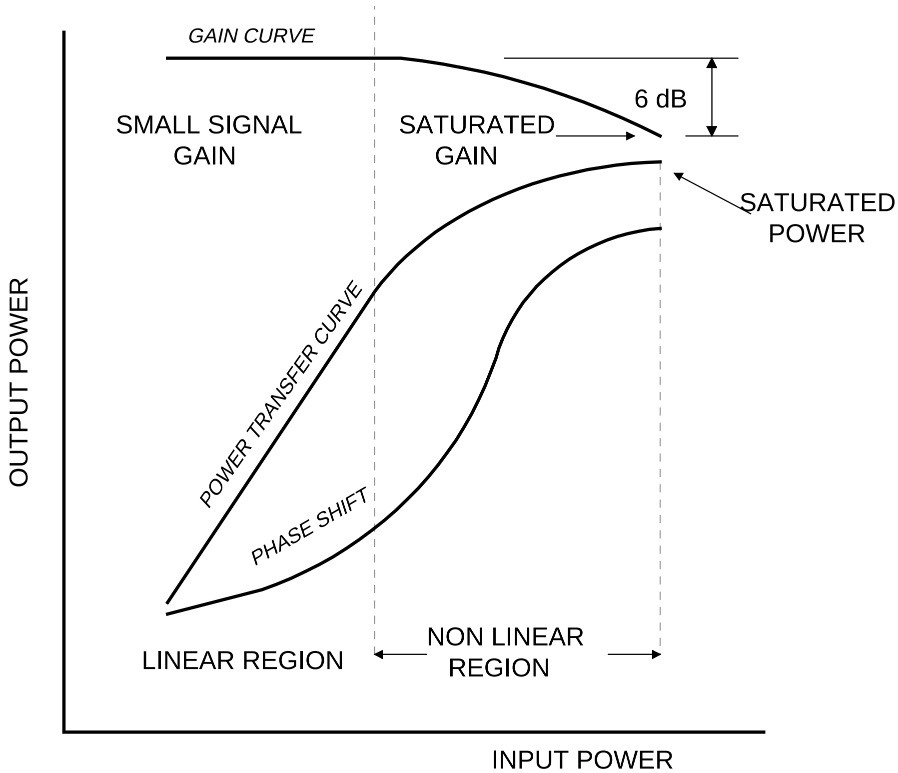

Figure 5.8 Dynamic Characteristic of a TWT

The dynamic range is that region between the threshold input level at which there is a departure from small signal or linear gain, until the point that the gain decreases by 6 dB or reaches the saturation power level. If the input power is increased beyond this point, the output power will decrease.

AM/PM Conversion

Amplitude modulation to phase modulation (AM/PM conversion) is the change in phase angle between the input and output signal as the input signal level varies. This factor is measured statistically, and is expressed in degrees per dB at a specified value of power output.

AM/PM conversion in a TWT is caused by the reduction in beam velocity that occurs as the input level signal is increased and greater amounts of energy are taken from the beam and transferred to the RF wave. At a level 20 dB below the input required for saturation, AM/PM conversion is negligible, beyond this point, AM/PM conversion increases sharply.

A typical power output and relative phase shift characteristic is shown in Figure 5.8. Here it is seen that phase shift is relatively insensitive to drive in the small signal (or the linear) portion of the transfer curve. The peak AM/PM conversion generally occurs at a drive level 3 to 10 dB below saturation drive and it is frequency dependent. The value of AM/PM conversion is less at the low frequency end of the tube's pass band than at the high frequency end. The curves show typical performance at the high end of the band, which of course is the worst case.

Backoff

If a number of carriers are present simultaneously in an amplifier, the operating point must be backed off to a linear portion of the transfer characteristic to reduce the effects of intermodulation distortion and AM-to-PM conversion. The backoff (BO) can refer to the input power (input backoff), which is the ratio in dB between the level required for a single carrier (SC) to reach the saturation level at the output, to any other input level. The output backoff is the ratio in dB between the saturation output power and any output power lower than saturation. The output backoff is determined from the IM3 requirement. If the maximum IM3 level permitted is –26 dBc, the resulting typical output backoff is 7 dB.

For example, if a 600-watt (+27.8 dBW) TWTA drives 3 carriers, it is required to have 7 dB of output backoff to avoid the intermodulation and AM-PM conversion effects. Then the maximum available multicarrier output power is:

Available Output Power = Saturated output power dBW - Output backoff
= + 27.8 dBW - 7 dB
= + 20.8 dBW or 119.7 Watts.

The remaining 480 Watts are not used due to the TWTA's nonlinear response.

As a rule of thumb frequently used, the output backoff for a TWT is 7 dB for multicarrier operation. This will keep the TWT working in the linear portion of its transfer curve.

Phase Nonlinearity and Group Delay for TWTA

Phase nonlinearity and associated group delay in the Earth station transmitter must be determined and specified so that the resulting error can be compensated. Two major factors within the power amplifier tubes contribute to this delay.

The first factor involves the finite time required for the RF energy to travel the distance from the input coupler to the output coupler. For a specific tube and operating voltage, this delay is fixed.

The second factor, and the major cause of phase nonlinearity through the tube, is cavity delay. The maximum rate of change in phase shift occurs at the resonant frequency of the cavity (fc). The group delay will decrease as the frequency is lowered or raised above the center frequency.

Spurious Signals

Spurious signals generated by the power amplifier tube fall into two major classes:

1. Broadband noise
2. Coherent spurious signals (TWTs have Noise Figures of about 40 dB; Klystrons will exhibit Noise Figures of approximately 35 dB.)

TWTA Linearizers

The use of TWTs in frequency modulated multiple-access systems with multicarrier operation results in intermodulation from the phase and nonlinear amplitude characteristics of the TWT. There are, at present, no known techniques of TWT design to reduce these effects, and the current practice is to back off the TWT some 7 dB, accepting the loss in power and efficiency.

A linearizer can be used to improve the intermodulation distortion of power amplifiers and, in turn, improve the output power. An example of a linearizer network is shown in Figure 5.9. It operates by producing an amplitude expansion and a phase lead when an increasing signal is fed into the input port, thus compensating for the gain reduction and the phase lag (AM-PM) of the TWTA when approaching saturation. The intermodulation ratio can be improved by about 10 dB (e.g., D3 increases from 26 dB to 36 dB for an 8 dB output backoff), and the phase variation can be minimized (e.g., 200 instead of 600). Typically, by using a linearizer, a 3 dB reduction in the output backoff may be obtained for a given intermodulation product level.

For a 3 kW power amplifier(TWTA) equipped with a linearizer, the following is typical.

Third-order distortion for two 500-watt carriers without a linearizer is less than 21 dB, and with a linearizer, it is less than 30 dB.

A substantial improvement can be obtained from the use of a linearizer, bearing in mind that deterioration of the TWT and other variables will require regular linearizer checking. Furthermore, linearizers have inherent losses, which tend to reduce the efficiency of the TWT amplifier, but preamplifiers within the linearizer can be used to ensure an overall gain of 0 dB.

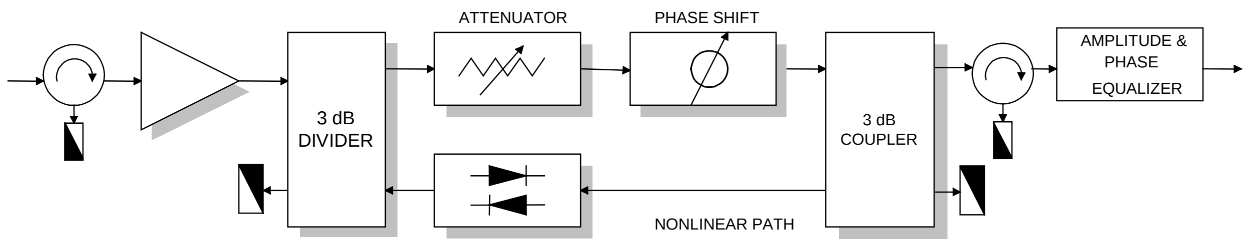

Figure 5.9 TWTA Linearizer

Solid State Power Amplifiers (SSPAs)

Advances in field effect transistor (FET) technology, particularly Gallium Arsenide FETs (GaAsFETs), have significantly impacted satellite communications, Earth station as well as spacecraft applications.

SSPAs are available today to replace TWTs in Earth stations and in the new generation satellites (all solid state). SSPAs offer the following advantages over TWTAs.

- Superior intermodulation distortion performance
- Higher reliability
- Lower maintenance costs
- Lower cost for spares
- Longer operating life compared to TWTA (one SSPA outlasts several tubes)
- Higher personnel safety - no dangerous high voltages
- Lower power consumption
- Lower total cost of ownership

GaAs is the substrate material for Metal Oxide Semiconductor FET (MOSFET) amplifiers due to the following factors.

a. In GaAs, the conducting electrons have six times larger mobility and twice the peak drift velocity than those in silicon. This results in a lower parasitic resistance, large transconductance, and shorter electron transit time.

b. The active layer is grown on semi-insulating GaAs substrate with resistivity larger than 107 ohm-cm, which leads to a lower gate-bonding pad parasitic capacitance.

These characteristics and adequate design yield amplifiers exhibit high frequency, relatively high power handling and low noise. The SSPAs have much better intermodulation performance than TWTs or Klystrons. The third-order intermodulation performance for a 20-watt SSPA is shown in Figure 5.10. The worst carrier-to-intermodulation ratio is 14 dB over the entire frequency band.

This carrier-to-intermodulation response for SSPAs is roughly 5 dB better than that of TWTAs.

For this reason, SSPAs can be operated typically with a 2 to 4 dB output backoff under multicarrier operation, instead of the > 7 dB required for TWTAs.

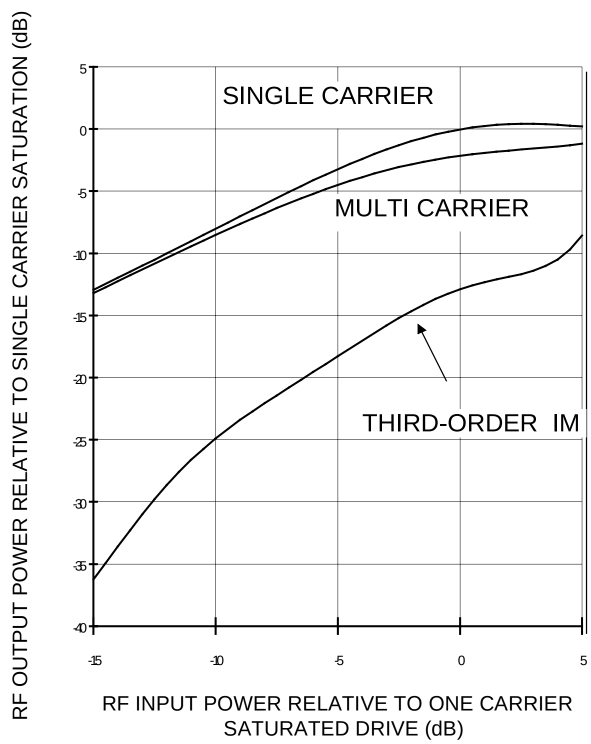

Figure 5.10 Typical Third-Order IM Performance of a SSPA

The maximum output power of a GaAsFET is inversely proportional to the square of the frequency. Therefore, a typical GaAsFET device that delivers 10 Watts at 6 GHz will deliver approximately 2 Watts at 14 GHz. It is possible to increase the output power capability by paralleling GaAsFET, as shown in Figure 5.11, or by incorporating additional amplifying stages in a single unit, but it is important to understand that there are tradeoffs between output power, efficiency and gain.

For example, Table 5.1 gives typical values of a single device optimized for each parameter.

Table 5.1 Tradeoffs Between GaAsFET Devices for Use in SSPAs

OUTPUT POWER (Watts)	GAIN	EFFICIENCY
1.26	6.5 dB	25%
0.75	5.5 dB	50%
0.7	9.0 dB	15%

Table 5.2 shows the typical power ratings of different SSPAs that are available.

Table 5.2 Typical SSPA Characteristics

Frequency Band	Nominal Saturated Output Power		Gain	AC Power Requirements
	dBm	Watts	dB	Watts
C-band	41	12	53	120
	44	25	53	200
	47	50	62	375
	50	100	62	700
	52	150	62	1100
	53	200	62	1300
	56	400	75	2700
Ku-band	40	10	50	175
	46	40	56	500
	49	80	56	950
	50	100	56	950

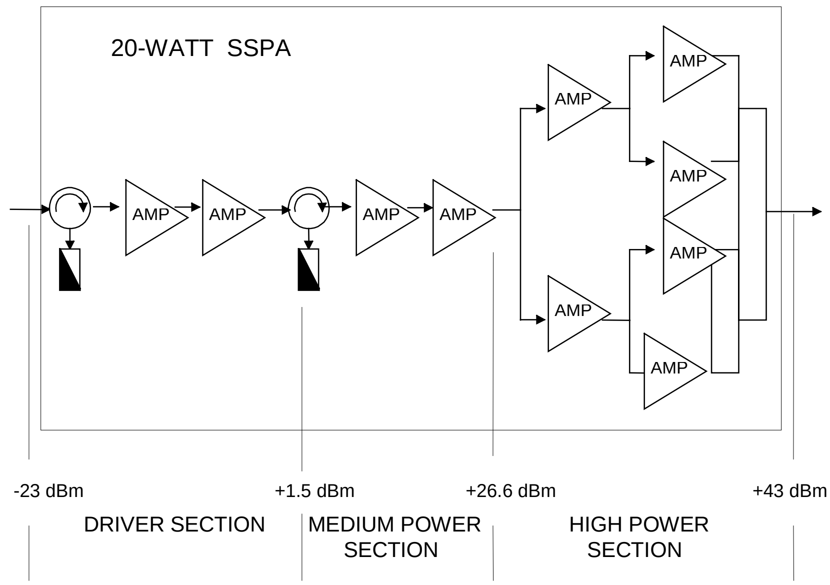

Figure 5.11 SSPA Amplification Stages

Note that high-power applications can be achieved by paralleling several low-power amplifiers. Some amplifiers are built in such a way that the power amplifier modules are mechanically separated and do not share the same power supply. As modules form the amplifier, possible module failure results in a limited output power drop. To fix the fault, the amplifier is not required to be off line and module exchange is possible while the amplifier is transmitting. This configuration, shown in Figure 5.12, allows the whole amplifier to operate as a self-redundant unit.

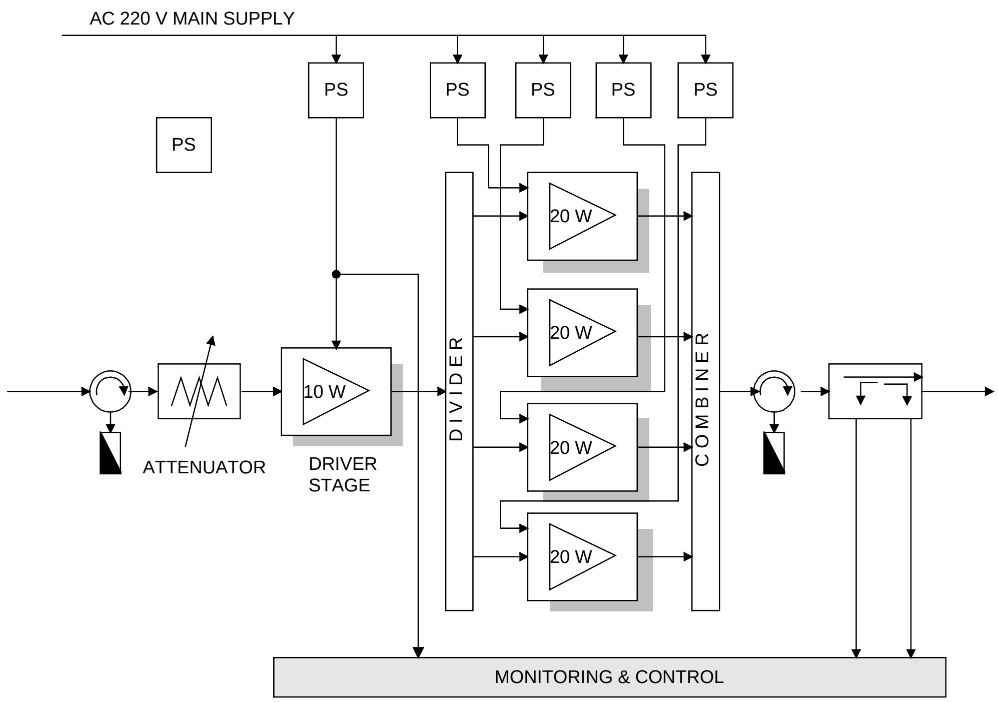

Figure 5.12 75-Watt SSPA Built from Four 20-Watt SSPA Modules

SSPA versus TWTA

This section explains the advantages of SSPAs for satellite Earth station applications. Solid state amplifiers have superior intermodulation characteristics, consume less power, cost less to operate, and last longer than tube amplifiers.

Intermodulation

Third-order intermodulation products (IM3) are generally located close in frequency to the desired signals, and cannot be easily filtered out. To minimize the generation of IM3 products, the amplifier is operated at less than its rated power.

The rated power for TWTA is the fully saturated power of the amplifier. TWTAs are advertised by the power output of the tube itself. This power is not available at the amplifier output and is usually 0.7 dB higher than the rated power.

For SSPAs, the rated power is 1 dB compression point, or P1 dB. SSPAs are advertised by their typical saturated power output, which is about 0.7 dB higher than P1 dB.

In conclusion, to obtain the rated power for TWTAs and SSPAs, it is necessary to subtract 0.7 dB from the advertised power. Therefore, the two types of amplifiers can be compared using the advertised or the rated powers, and the comparison remains valid.

Figure 5.13 shows the typical IM3 versus OBO (Output Backoff) relationship for TWTA and SSPA. To keep the IM3 level below –26 dBc, TWTA must be backed off approximately 7 dB, while the SSPA generates the same level of IM3 at 2.2 dB OBO. This gives the SSPA a performance advantage of 4.8 dB. In other words, an SSPA is equivalent to a TWTA with a 4.8 dB or higher rated power.

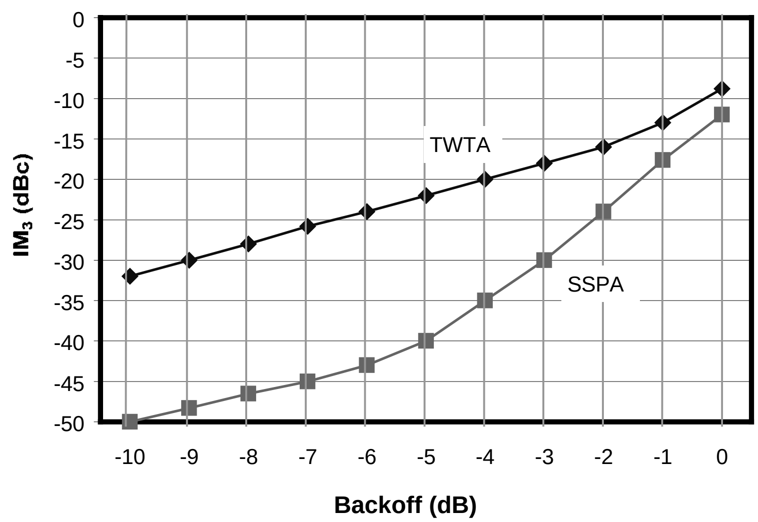

Figure 5.13 Two-Tone, Third-Order Intermodulation Distortion versus Output Power Backoff

Operating Costs

Because a lower power SSPA can replace a 4.8 dB higher power TWTA, there are potential savings in the cost of the electricity. Also, an SSPA can outlive several travelling wave tubes. A tube costs a significant fraction of the original cost of the amplifier. The cost of the spare parts for an SSPA is considerably lower than that for TWTA.

Maintenance

Solid state amplifiers are easier and safer to maintain due to the use of low voltage power supplies. Typical preventive maintenance of an SSPA consists of keeping the air filter free of dust and replacing the fans according to the manufacturer's instructions. Because there is no aging mechanism for SSPA, there are no adjustments required as is the case with the TWTA.

5.4 Power Combining (Multiplexing)

In a typical Earth station there could be more than one power amplifier connected to the feed port of the antenna serving a particular polarization. Under these circumstances, it is necessary to combine the output of the amplifiers into a single signal path to the antenna feed. The output from the amplifier is usually in waveguide and is connected via one or more RF combiners.

An RF combiner can be one of three types, namely hybrids, circulators, and diplexers.

Hybrid

The hybrid power combiner approach is the simplest and least expensive method for combining several signals. Hybrids used for this purpose are passive devices, and they are used to either split or combine the signal.

A 3 dB hybrid combiner splits each input signal so that 50 percent of the input power (of input 1 and 2) is combined, both signals suffer the same loss, and the lost power is dissipated in the matched load. Similarly, a combiner (as the one shown in Figure 5.14), which splits each input signal so that 67 percent of the input power in the cross arm and 33 percent in the through arm introduces a 1.8 dB loss to one signal, and 4.8 dB to the other.

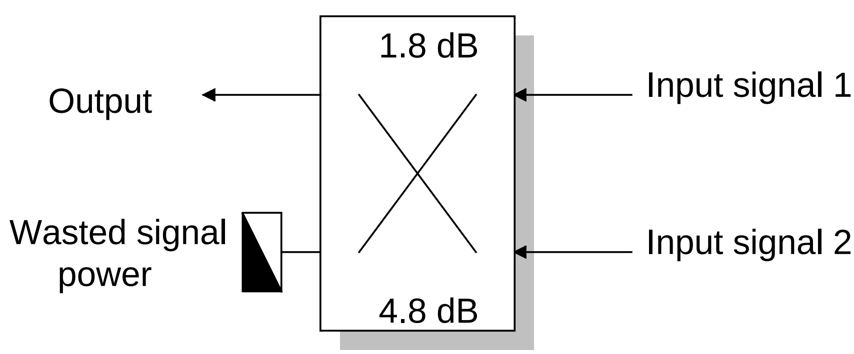

Figure 5.14 Hybrid RF Combiner

The signal wasted will be 33 percent of input 1 and 67 percent of input 2. This type of combiner is known as a Fixed Ratio. The power division in these types of combiners can vary from 0 percent to 100 percent.

A combiner that allows the ratio to vary at a given time, according to the needs of the stations, is known as a Variable Ratio. The main drawback is the large amount of wasted transmitted power.

The advantage is that the system is wideband. Figure 5.15 shows how three separate channels, plus a spare input, can be combined for transmission through one common antenna.

Diplexer

This approach is the most efficient for combining various signals. Each diplexer uses two hybrids and two band pass filters. Figure 5.15 shows a typical combiner/diplexer. It consists of two diplexers (and hence, four are hybrids and four are band pass filters). The ports in each hybrid are labeled A to D. Each hybrid is the same type as previously described: not only can it combine two signals into one, it can also split a single signal into two components.

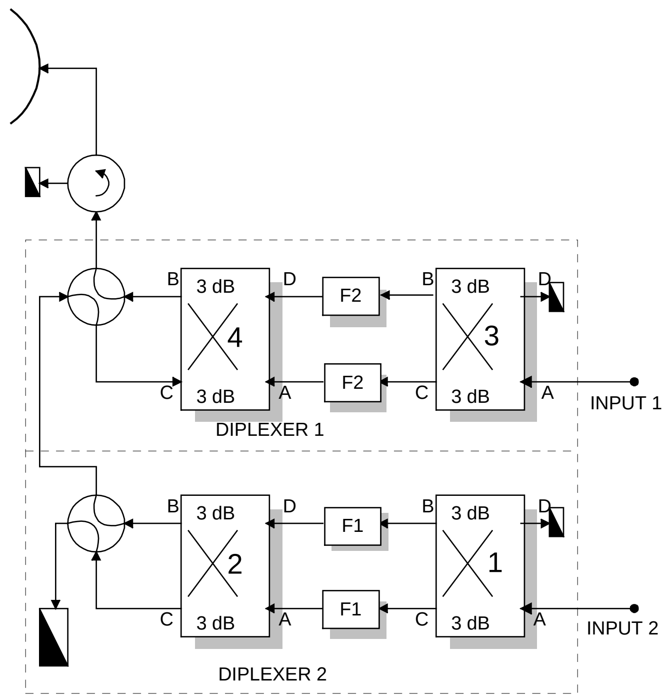

Figure 5.15 Typical Two-Port Diplexer/Combiner

The signal input 2 (or 1) is split by hybrid 1 (or 3) and will appear in ports 1-B (or 3-B) and the same signal shifted 90 degrees in port 1-C (or 3-C). Because the hybrid is a passive reciprocal device, it follows that if two versions of the same signal (one shifted 90 degrees with respect to the other) are connected to two input ports (as for hybrids 2), then the signal will combine to one of the output ports (port 2-B). But, they will be cancelled in the second port (port 2-C). The signal from diplexer 2 will enter hybrid 4 (diplexer 1), will split, and will be reflected by filters F2, and recombine to port 4-B reaching the combiner output.

Table 5.3 shows a typical insertion loss caused by the diplexer. The drawback with this approach is that every diplexer is designed for a specific frequency band, while it permits the use of smaller power amplifiers due to its low combining losses.

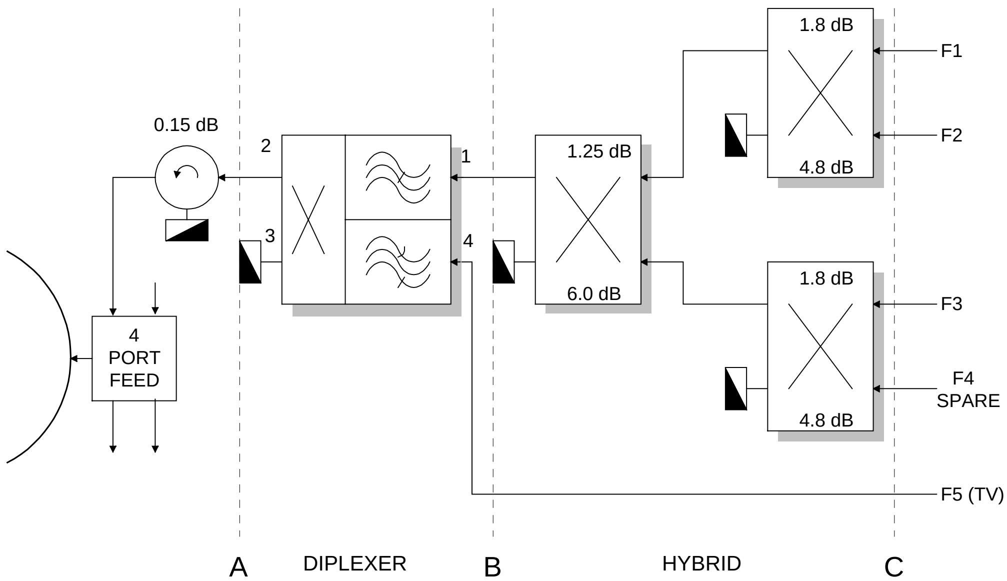

Figure 5.16 Typical Earth Station Combining System

Table 5.3 Combining Losses for Figure 5.15

INPUT	HYBRID LOSSES (To point B)	DIPLEXER LOSS (To point A)	TOTAL LOSSES
F1	3.0 dB	0.8 dB	3.8 dB
F2	6.0 dB	0.8 dB	6.8 dB
F3	7.8 dB	0.8 dB	8.6 dB
F4 (SPARE)	10.8 dB	0.8 dB	11.6 dB
F5 (TV)	---	1.8 dB	1.8 dB

Circulator

This method combines the output of the power amplifiers using band pass filters which allows only a given channel to pass the circulators. Refer to Figure 5.17. The drawback of this approach is its considerable narrow bandwidth.

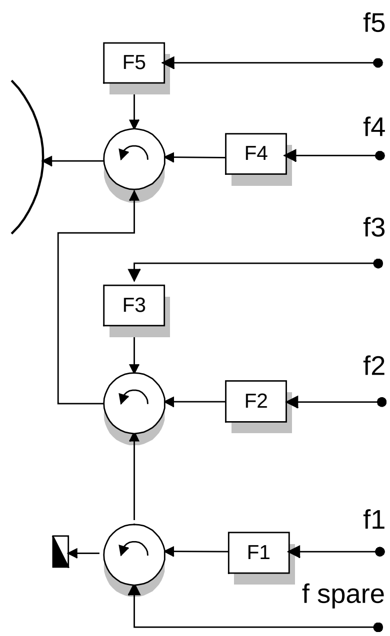

Figure 5.17 RF Circulator Combiner

5.5 Common Terminology Used with Power Amplifiers

Dynamic Range for Linear Operation

It is the level of the output signal at which the gain of the amplifier is reduced by one dB. (See Figure 5.18.)

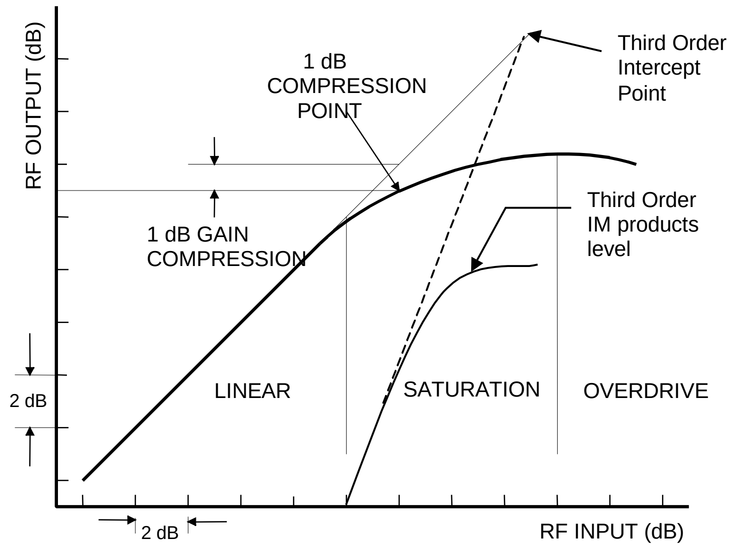

Figure 5.18 Amplifier Dynamic Range

Intercept point

On a plot of intermodulation distortion data as a function of RF input drive, the carrier data at small signal drive levels has a slope of 1:1, third order intermodulation products have a slope of 3:1 and fifth order intermodulation products have a slope of 5:1. Extrapolating the slopes for the carriers and the third order products produces an intercept point. The output power at this point is called the third order intercept point. Similarly, the fifth order intercept point is the point at which the carrier slope intercepts the fifth order products slope.

Equivalent Isotropic Radiated Power (EIRP)

The power, (PT) at the input of the transmitting antenna multiplied by the Gain (GT) of the same antenna is defined as the EIRP, and is usually expressed in dBW.

The latter also depends on the absolute power from the transmit amplifier and the loss in the combining and feed system.

Example: If an HPA transmits a carrier with 6 Watts of power, the feed loss is 0.2 dB and is connected to point f1 in Figure 5.16. The EIRP will be:

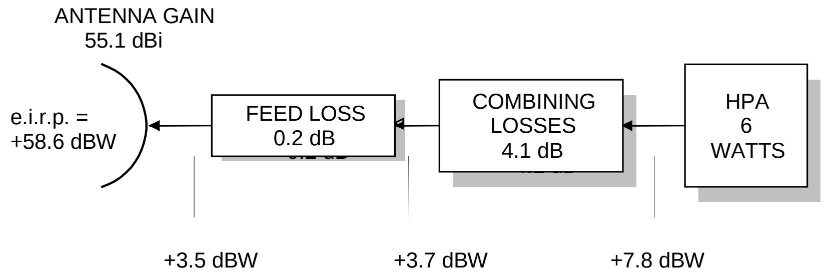

Figure 5.19 EIRP Calculation Example

EIRP = PA*$_{\text{(power)}}$ - (Feed loss) - (Combining losses) + Antenna Gain

Where:
PA*$_{\text{(power)}}$ = carrier power at power amplifier output flange.

5.6 Student Question Paper

An EIRP of 79.4 dBW is required for a 8.448 Mbit/s digital carrier. If the power amplifier is connected at input f2 in Figure 5.17 and 0.2 dB is the feed loss, what power output is required from the HPA to radiate this EIRP?

What is the amplifier rated power if the output backoff is 4 dB?

CHAPTER 6

LOW-NOISE AMPLIFIERS

6.1 Introduction

Low-noise amplifiers (LNAs), as the name suggests, are amplifiers that have a very good noise performance coupled with a wide bandwidth. This makes them essential for use as the first stage of a satellite ground station receiving chain.

Random movement of electrons causes thermal noise. Within semiconductors, thermal noise can be minimized by reducing the actual temperature of the LNA (by Peltier or cryogenic cooling) or the current method of using uncooled FET amplifiers employing High Electron Mobility Transistor (HEMT) technology.

The system Figure of Merit (G/T) for an Earth station is virtually determined by the Noise Figure (F) and gain of the LNA, along with the antenna gain. The LNA is generally mounted as close to the antenna feed as possible so that the transmission line losses to the LNA will be at an absolute minimum. An LNA must also provide sufficient gain to overcome losses in the transmission line between the receiver and the LNA.

6.2 Noise

The quadratic voltage that appears in the terminals of any resistor was discovered by Nyquist to be:

$V_n^2 = 4KTRB \ldots \quad V_{rms}^2$

where K = Boltzmann's constant (1.374×10^{-23} W/°K/Hz)

T = Device temperature in °Kelvin
R = Impedance in Ohm
B = Bandwidth in Hz

For convenience, this noisy resistor is represented as a noiseless resistor plus a noise generator. By applying the maximum power transfer theorem, the available noise power is

$N = KTB \ldots$ Watts

This noise power is available at the input of every device that the resistor matches. For a given bandwidth, if the equivalent temperature of the elements is known, the noise power generated is also known.

The Noise Temperature for any device is defined as the temperature (in °Kelvin) to which a resistor should be warmed to generate, in a noiseless device (theoretical), the same noise power generated by the actual device.

In any amplifier it is true that the matched impedance in the input will generate KTB Watts of noise (N_i), this noise at the output (N_o) will be multiplied by the gain plus its own internal noise. The relation N_o/N_i, gives a view of the device quality and is called Noise Figure (F).

The relation between Noise Temperature and Noise Figure is:

$F = 1 + T_e/T_o$ and $T_e = (F - 1)T_o$

where:
T_e is equivalent Noise Temperature (°K).
T_o is ambient temperature (290°K).

The equivalent Noise Temperature is referred to the input of the device.

Now consider a multistage device, (as shown in Figure 6.1), where N_0 is the input noise power for the first stage, N_1, N_2, and N_3 the noise powers at the output of the three devices, and T_{e1}, T_{e2}, and T_{e3} are their equivalent Noise Temperatures. The following equations apply:

$$N_1 = G_1N_0 + G_1kT_{e1}B$$

$$N_2 = G_2N_1 + G_2kT_{e2}B$$

$$N_3 = G_3N_2 + G_3kT_{e3}B$$

$$N_1 = G_1kT_0 + G_1kT_{e1}B$$

$$N_2 = G_2(G_1kT_0B + G_1kT_{e1}B) + G_2kT_{e2}B$$

$$N_3 = G_3[G_2(G_1kT_0B + G_1kT_e1B) + G_2kT_{e2}B] + G_3kT_{e3}B$$

Note that if $T = N_3/kB$, the Noise Temperature referred to the output of the system, then:

$$T = G_3G_2G_1T_0 + G_3G_2G_1T_{e1} + G_3G_2T_{e2} + G_3T_{e3}$$

or,

$$T = G_3G_2G_1(T_0 + T_{e1} + T_{e2}/G_1 + T_{e3}/G_2G_1) = G_3G_2G_1(T_0 + T_e)$$

Where T_e = Equivalent Noise Temperature of the System (referred to the input), then:

$T_e = T_{e1} + T_{e2}/G_1 + T_{e3}/G_2G_1$

Expressed as a general formula:

$T_e = T_1 + T_2/G_1 + T_3/G_1G_2 + ... + T_n/G_1G_2..G_{n-1}$
where $T_{1..n}$ is the equivalent Noise Temperature of every stage.
$G_{1..n}$ is the gain of every stage.

Therefore, the equivalent temperature of the first stage in our device has the same weighting in the total noise as the noise from the source.

Examples:

1) From Figure 6.1, calculate the total equivalent Noise Temperature.

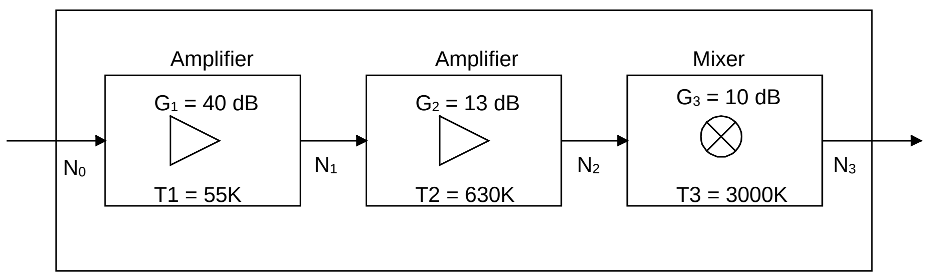

Figure 6.1 Block Diagram of a Multistage Device

Solution: T_{es} = 55K + (630/1x10^4) + {3000/(10^{4}x19.95)
T_{es} = 55.08 K

2) From the previous example let us calculate the Noise Figure and noise power at the output if the measurement bandwidth is 72 MHz.

F = 1 + (T_e/T_o)
= 1 + (55.08/290)
F = 1.19 or
F_{db} = 10logF = 0.5 dB

N_{dBm} = 10 log K + 10 log T_{es} + 10 log B + G
= -228.6 dBW/°K/Hz + 15.5 dB°K + 78.5 dBHz + 63 dB
N_{dBm} = -71.52 dBW or -41.52 dBm in a 72 MHz bandwidth

Therefore, an LNA with a Noise Factor of 1.19 has an equivalent Noise Temperature of 55°K.

6.3 FET Amplifiers

Due to the continuing development of the FETs, there are now commercially available transistor amplifiers capable of operating at 4 - 12 GHz with low noise and wide bandwidths. These amplifiers are known as low noise GaAsFET Amplifiers. The construction of the GaAsFET used in the LNA is surprisingly simple. Unlike microwave bipolar transistors, it requires no special diffusions to achieve “n” or “p” type layers of semiconductors. It consists of a layer of semi-insulating material on which a lightly doped n + type of GaAs is grown as an epitaxial layer. Then a layer of metal film such as gold is evaporated on the epitaxial layer to form a Shottky-barrier junction. After this, the source, gate, and drain contacts are etched using photolithographic techniques.

An FET is a three-port device in which the gate controls the flow of electron current from the source to the drain by varying the electric field, thus causing a depleted carrier region in the active layer beneath the gate. As the operation is similar to a junction mode FET, it is assumed that the student is familiar with the operation.

Typical FET

A typical FET LNA uses four stages of amplification with the first stage thermoelectrically cooled at -40° centigrade, thus producing a Noise Temperature of between 55°K and 80°K, with a total gain of 60 dB. A typical block diagram for such a configuration is shown in Figure 6.2.

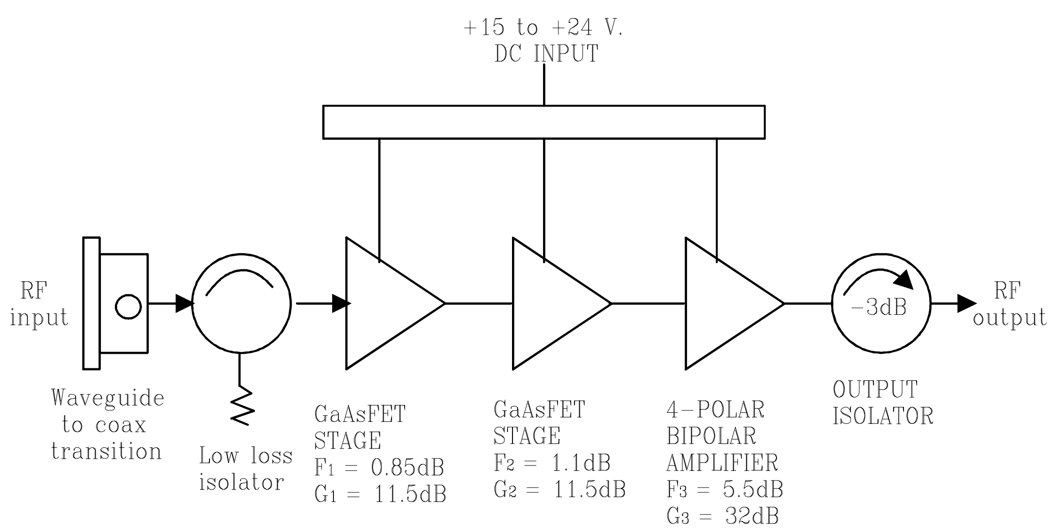

Figure 6.2 Typical GaAsFET Block Diagram

Maintenance

The maintenance requirements for a modern low noise amplifier system are minimal and consist of a regular Gain/Bandwidth check using a sweep oscillator. In the case of a parametric amplifier, occasional adjustment of the Varactor diode bias control and of the pump power level may be necessary. As for the GaAsFET, no adjustments are normally provided.

There has been a steady decrease in the Noise Temperature of commercially available GaAsFETs since their introduction into the market in 1972. This improvement has been achieved primarily with a reduction of the gate width. The earlier devices had 1 micron gate widths with typical Noise Temperatures of 290°K at 4 GHz. By reducing the gate width to half a micron, 120°K LNAs were manufactured. LNAs are now available with Noise Temperatures of less than 40°K.

A maintenance record of parameters for the LNA should be kept so that any degradation of the system, particularly when the bias or pump power has been adjusted, can be observed and corrective action taken. It is also useful when thermoelectric cooling is used to regularly monitor the cooling cycle time and to check the desiccant for moisture, and change it if necessary.

Low Noise Block Downconverters

Earth station receive electronics normally consist of an LNA at the antenna with a microwave cable connecting it to the indoor receivers. The receivers are equipped with downconverters to process either C-band or Ku-band.

Low noise block downconverters consist of a low noise amplifier and a downconverter combined into one package. Figure 6.3 shows an example of an LNB where the first frequency conversion of a double frequency conversion occurs. The output IF frequencies are in a lower frequency band and are fed to the receivers to final frequency tuning and further processing.

Even though there can be problems associated with operating an LNB outdoors, where it would be exposed to varying climatic conditions such as temperature and humidity, there are significant advantages to moving the first frequency conversion outdoors, as follows.

a) The loss in coaxial cables increases as a function of the frequency as well as their length; by decreasing the frequency, cheaper cable can be used and the loss is reduced.
b) One converter is shared by multiple receivers, making the receiver electronics cheaper.

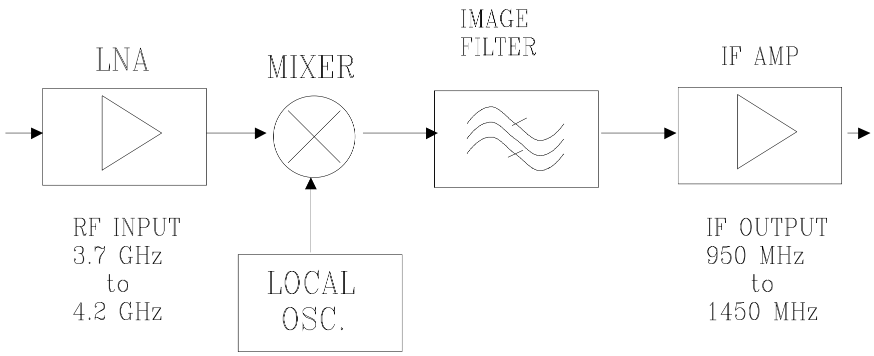

Figure 6.3 Block Diagram of an LNB

CHAPTER 7

FREQUENCY CONVERTERS

7.1 Introduction

Previous chapters discussed high-power amplifiers (HPAs), low-noise amplifiers, and the requirement to maintain a constant power (EIRP) to the satellite. The ability to maintain the correct frequency as allocated by INTELSAT must also be addressed. The frequency stability is a mandatory requirement and varies with the particular service. For example, IDR carriers are required to remain within ±3.5 kHz of the allocated frequency. To achieve these limits, the upconverter (U/C) on the transmit side and the downconverter (D/C) on the receive side are very important. This chapter discusses the principles of up-/down-conversion.

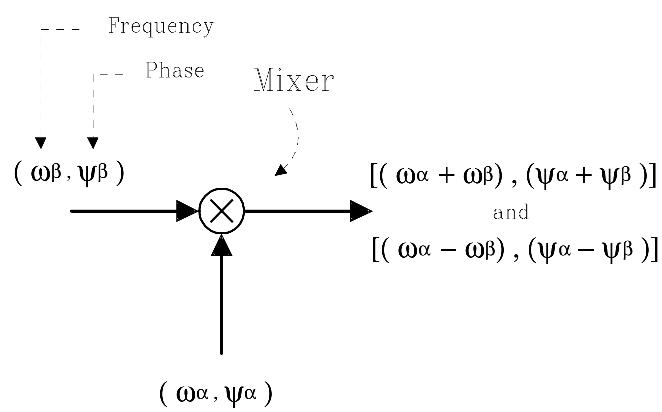

Figure 7.1 Mixer Principle

7.2 Frequency Conversion Principle

The key for the frequency conversion is the mixer that generates frequencies that are the sums and differences of two input frequencies. (See Figure 7.1.) In the mixer, the two mixed signals exist simultaneously in nonlinear devices (diodes). The nonlinearity produces signals with the desired sum or difference of frequencies, but it also produces many other signals, which can cause problems.

To understand which frequencies are produced, let us consider the following sine waves.

$$L(t) = A \cos \{a_I t + ‘_I\} \quad \text{and;} \quad S(t) = B \cos \{a_J t + ‘_J\}.$$

where: L(t) = Local oscillator signal,
S(t) = Signal to be frequency converted
‘ = represents the instantaneous phase

If both signals interact in a nonlinear device as the mixer is, the mixer output R(t) will be:

$$R(t) = K_m.L(t).S(t) \quad \text{or} \tag{7.1}$$

$$R(t) = K_m [A \cos \{a_I t + ‘_I\}][B \cos \{a_J t + ‘_J\}] \tag{7.2}$$

using the identity

$$\cos x \cos y = ½[\cos (x+y) + \cos (x-y)], \tag{7.3}$$

equation (7.2) can be expanded to:

$$R(t) = K_m[½A \cos \{(a_I t + a_J t) + `_I + `_J\}] + K_m[½BA \cos \{(a_I t - a_J t) - `_I - `_J\}] \tag{7.4}$$

where: K_m = Mixer gain

The waveform R(t) has its spectrum shifted to the two center frequencies, $\{a_I t + a_J t\}$ and $\{a_I t - a_J t\}$. A band pass filter following the mixer can be tuned to select either the sum or the difference of the mixer output. Hence the input spectrum can be up-converted to the sum frequency, or down-converted to the difference frequency.

It is important to recognize the importance of the master oscillator's stability, because offsets in the oscillator produce offsets in the output frequency. Phase variations on the local oscillator, such as phase noise variations, are transferred directly to the translated RF carrier. These effects become important because they can cause phase and frequency errors to permeate the entire system.

7.3
Frequency Converters

Single Conversion Upconverter

By using the principles described, the U/C translates the intermediate frequency (IF) signal into a RF signal (e.g., in the 6 GHz or 14 GHz band). Conversely, the D/C translates the RF signal (e.g., in the 4 GHz or 11-12 GHz band) into an IF signal (Figure 7.2).

Let us take an example of a "single" mixing technique for up-conversion:

f_1 = 70 MHz intermediate frequency
f_2 = 6250 MHz mixing frequency
f_3 = 6320 MHz wanted output frequency

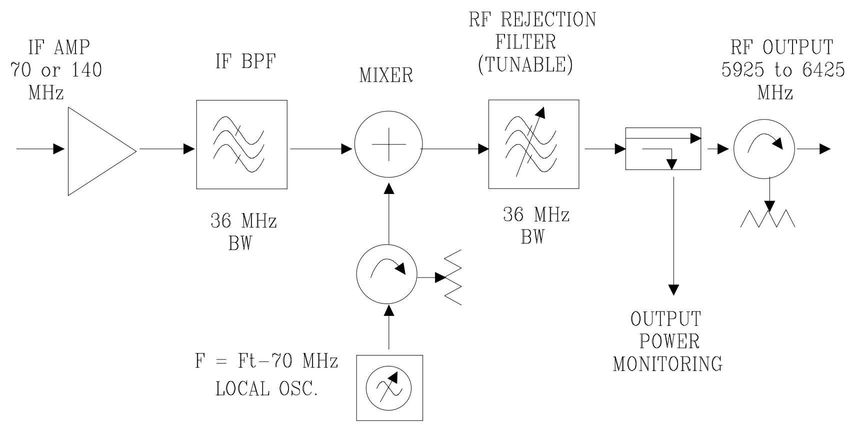

Figure 7.2 Single Conversion Upconverter

By mixing f_1 and f_2, the mixer will produce:
6250 MHz +70 MHz = 6320 MHz, but also
6250 MHz - 70 MHz = 6180 MHz

The desired frequency is 6320 MHz, but we also have 6180 MHz. These frequencies are called Upper Sideband and Lower Sideband respectively. A good band pass filter is needed to remove the unwanted sideband. The use of a narrow bandpass filter in the upconverter output is the main disadvantage of single mixing converters.

Single Conversion Downconverter

If the single mixing process is used in a downconverter as shown in Figure 7.3, the process would mix an unwanted in-band "image" frequency and produce two outputs.

f3 = 4150 MHz Wanted Frequency to down-convert
f2 = 4010 MHz Image Frequency
f1 = 4080 MHz Mixing Frequency

4150 MHz mixed with 4080 MHz = 70 MHz
Also, 4010 MHz mixed with 4080 MHz = 70 MHz

This shows that incoming 4150 MHz and 4010 MHz will give the same 70 MHz output.

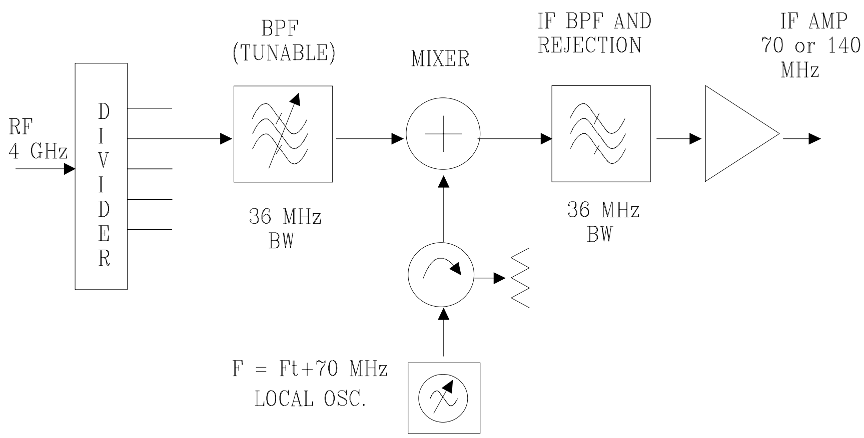

Figure 7.3 Single Conversion Downconverter

Therefore, a bandpass filter must be inserted at the input to reject the 4080 MHz signal. It can be seen from the examples that two bands of frequencies are produced:

a. the wanted band
b. the unwanted band

The tunable filters require a sharp bandpass characteristic and can take up to a few hours to retune, which means that a set of filters with tuning equipment has to be kept on site. To eliminate this problem, a broadband converter design using a double mixing technique to operate across the total 500 MHz band without the need for filter retuning is normally used in most Earth stations.

Requirements

Before describing the double mixing up/downconverter, we need to look at the total requirements.

If the RF signal bandwidth is relatively narrow, as is the case for 36 MHz bandwidth transponders, the IF can be the conventional 70 MHz frequency. However, if wideband RF signals are used, a higher IF must be chosen to improve the filtering of the unwanted signals in the "image" frequency band. A 140 MHz IF is usually selected. This is the case for transmission and reception of 120 Mbit/s TDMA-PSK signals. It is also the case, for example, for IDR.

Double Conversion Upconverters/ Downconverters

Upconverters and downconverters are usually composed of:

- an RF filter;
- two cascaded mixers.
- two local oscillators (LOs); one fixed frequency and the other variable frequency.
- IF amplifiers(s), possibly with automatic gain control;
- IF filters;
- group delay equalizer(s) (GDE(s)).

The main performance characteristics of the double upconverters, as shown in Figure 7.4, and downconverters, as shown in Figure 7.5, are listed below:

(i) Bandwidth
The RF bandwidth, which defines the capability of the converter to cover the operational RF band, i.e., to transmit (or receive), by adjusting the LO's frequency to cover the full RF bandwidth (about 575 MHz).

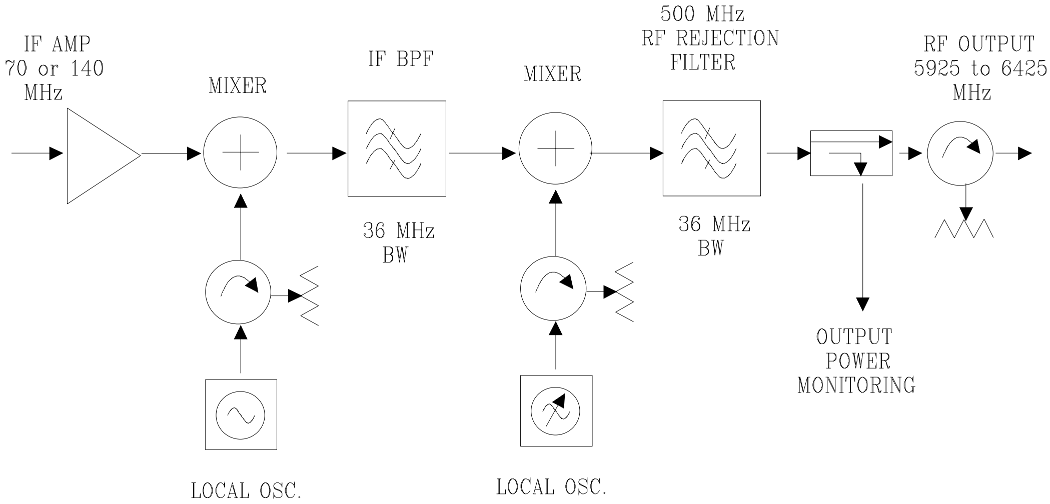

Figure 7.4 Double Conversion Upconverter

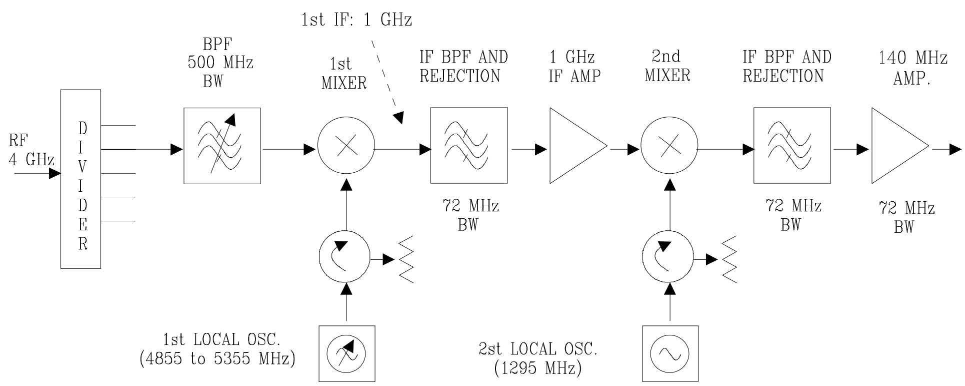

Figure 7.5 Double Conversion Downconverter

(ii) Frequency Agility

The frequency may vary due to changes in the frequency plan to accommodate traffic increments or when changing to a new satellite. Therefore, U/Cs and D/Cs that can be readily adjusted in frequency over the whole RF bandwidth are required to make these changes. Variable frequency synthesized local oscillators are used to meet the frequency change requirements. As explained below, frequency agility (i.e., the ability to change the RF carrier frequencies) is improved by the use of double conversion U/Cs and D/Cs, without the constraint of filter tuning.

(iii) Equalization

The amplitude-frequency response and group delay of the transmit and receive sections of Earth stations are equalized in their respective IF sections. (The group delay of satellite transponders are usually equalized in the IF section of the frequency upconverter.)

(iv) Linearity

In IDR, IBS, and INTELSAT DAMA systems , a number of carriers are frequency converted by one U/C or D/C, and intermodulation between carriers can occur. In the transmit section unit, it is necessary to keep these unwanted intermodulation products negligibly small compared to those in the HPA. Therefore, the upconverter is required to have good linearity. For a carrier with a large bandwidth, good linearity is also necessary to decrease distortion noise caused by the parabolic component of the delay equalizer IF section for the whole system as well as to prevent AM-PM conversion from occurring in the converter.

(v) Carrier Frequency Tolerance

The RF frequency tolerance (i.e., the maximum uncertainty of initial frequency adjustment plus long-term drift) for the transmission of IDR and IBS carriers in the INTELSAT system is specified as:

IDR: ±0.025R....Hz. (but always less than ± 3.5 kHz).
IBS: ±0.025R ...Hz. (but always less than ± 10 kHz).
DAMA: ±2.0 kHz; for information rates higher than 64 kHz the tolerance will be 0.025R....Hz. (but always less than ± 3.5 kHz).

Where R is the carrier transmission rate in bit per second.

Double Mixing Upconverters/ Downconverters

Figure 7.4 shows a double frequency conversion upconverter. This type of converter features high frequency agility because tuning of the first local oscillator (first LO or RF oscillator) is sufficient to change the RF frequency in the entire 500 MHz operational RF band. This type of converter is used most often in modern Earth stations. A typical block diagram of a corresponding downconverter is shown in Figure 7.5. In this downconverter, the 4 GHz receive input signal passes through a 500 MHz microwave filter, and then enters a mixer (LO1). It is then mixed with a variable oscillator frequency and converted into the first intermediate frequency (1st IF). The first IF signal passes through a band-pass filter with a 80MHz bandwidth and is converted into a 140 MHz signal at the output of the second mixer (LO2). In this configuration, by making the first IF higher than the RF bandwidth, the frequency in the operating band can be changed by only changing the frequency of (LO1), without the need for readjusting the filter. Consequently, combined with a frequency synthesizer, this type of converter is very attractive, satisfying requirements for quick frequency change and remote frequency control. It is also effective as a single standby unit for multiple converters.

Local Oscillators

The local oscillators used in frequency converters can be driven either by a crystal pilot or by a frequency synthesizer. In the first case, changing the frequency requires replacement of the crystal or switching between multiple crystals. In the second case, changing the frequency can be effected very simply by thumbwheels or by remote control. The required long-term frequency stability may range from ± 10-5 for TV, to 3 x 10-9 for SCPC, IDR, or TDMA.

Local oscillators must feature low-frequency noise at baseband signal frequencies to comply with the general requirements regarding Earth station equipment noise. It should be noted that both low- frequency noise requirements and frequency stability requirements are especially stringent in the case of digital transmission and reception. High performance crystal-controlled oscillators or frequency synthesizers must be used in this case.

Local oscillators are constructed by taking a pure oscillator carrier and multiplying and/or dividing its output frequency to all the desired frequencies needed. Oscillators are simple electronic devices coupled to tune mechanisms via some type of feedback. Resonance of the tuning circuit allows a sustained feedback oscillation to occur, producing an output tone at the resonant frequency. The oscillator tuning circuits commonly used are the resistance, inductance, capacitance (RLC), crystal quartz resonator, and the atomic resonators.

RLC Oscillators

RLC circuits are the simplest and easiest to construct and, therefore, are the more frequently used oscillators. However, component imperfections and aging often make it difficult to set and maintain precise tone frequency over long intervals.

Crystal Oscillators

Crystal oscillators use the crystal structure itself as a component of a resonant circuit to produce sharply tuned resonance and relatively stable output tones.

Atomic Oscillators

The common atomic resonator is the cesium beam that uses a stream of cesium atoms to interact with a magnetic field. The interaction produces an almost perfect oscillator at the specific frequency of 9.152 GHz. Rubidium resonators which use light beams interacting with rubidium vapor, produce a fixed oscillation at 6.8 GHz. Atomic oscillators are often inserted as frequency measurement standards and are used primarily as reference tones for systems requiring extreme frequency accuracy, such as the primary reference oscillator in a digital network.

An ideal oscillator produces a pure sinusoidal carrier with fixed amplitude, frequency, and phase. Practical oscillators, however, produce waveforms with parameters that may vary in time, owing to temperature changes, component aging, and inherent tuning circuit noise.

Amplitude variations are somewhat tolerable because they can be easily controlled with an electronic clipper circuit and limiting amplifiers.

More important to a communication system are the variations in frequency and phase that may appear on an oscillator output. Although preliminary system design may be based on the supposition of ideal carriers, the possibility of imperfect oscillators and the degradation they may produce must be considered eventually.

Frequency Offsets

Frequency offsets in oscillators are usually specified as a fraction of the oscillator design frequency. This fraction is generally normalized by a 10-6 factor and stated in units of parts per million (ppm). An offset of q¦ Hz in an oscillator designed for ¦o Hz output frequency will therefore be stated as having an offset of (q¦/¦o)106 ppm. Thus, for example, a 5-MHz oscillator, specified as having a stability of ±2 ppm, will be expected to produce an output frequency that is within ±2 x 10-6 x 5 x 106 = ±10 Hz of the desired 5 MHz output.

Oscillator frequency offsets are contributed primarily by frequency uncertainty (inability to set the desired frequency exactly), frequency drift (long-term variations due to components changes), and short-term random frequency variations.

Phase Noise

All electronic devices introduce random noise fluctuations due to thermal agitation of electrons. Oscillators are not immune to effects from random noise. The output signal is not pure, but contains phase/frequency and amplitude perturbations due to random noise. These noise perturbations appear as modulation sidebands around the oscillator carrier output.

This phase jitter effectively converts the fixed carrier phase of an ideal oscillator to a randomly varying phase noise process. This phase noise has a spectrum that is predominantly low frequency, extending out to several kilohertz. In general RLCs and VCOs tend to have higher phase-noise than crystal oscillators, whereas atomic resonators have the lowest phase noise. Phase-noise will always be of primary concern in angle-modulated systems, because oscillators' phase noise will add directly to any phase modulation placed in the carrier.

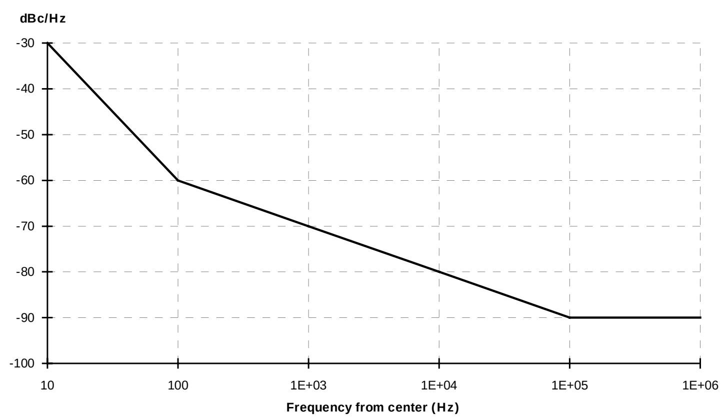

Figure 7.6 Continuous Single Sideband Phase Noise Requirement

The *IESS* specification requires that every Earth station satisfy the mask shown in Figure 7.6 for carriers of less than 2.048 Mbit/s, taking into account that the carrier phase noise to be measured is the cumulative total noise caused by the entire uplink path. That includes the modem's carrier oscillators, upconverters, and HPAs. In the downlink path, the only requirement is to check the downconverter oscillators' phase noise.

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Figure 7.7 shows a typical appearance of phase noise sideband spectrum. Not only phase noise, but also the discrete signals away from carrier frequency are important.

It is very important to distinguish phase noise from discrete signals. They have different sources but both can cause an unwanted phase change in the digital signal.

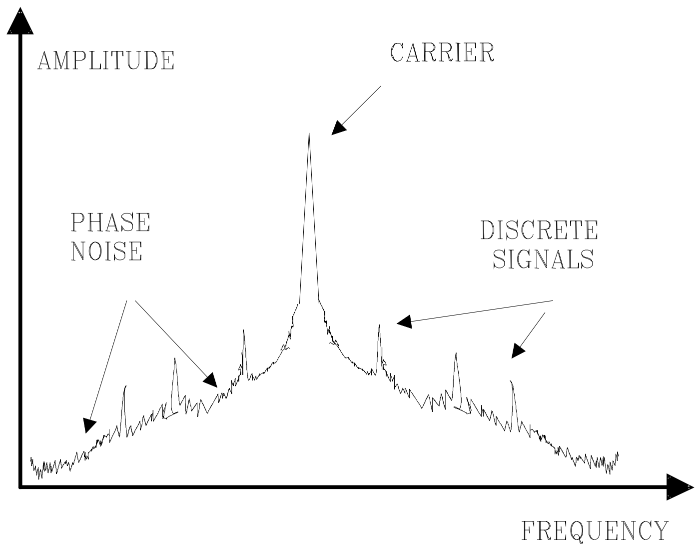

Figure 7.7 Noise Spectrum

Discrete signals are caused by lack of filtering of the main AC frequency in the power supply of equipment in the chain, and special attention should be paid to HPAs. For every discrete signal, it is true that:

Phase Deviation = {10 Exp (dBc/20)}*57.3 .. deg

where dBc is the distance in dB between the carrier and the measured noise spike.

Note that every noise spike will cause a carrier deviation. The discrete signals are stated separately and are quoted as the difference between the carrier level and the spike level. The *IESS* specifies that a spurious component in the fundamental AC line shall not exceed -30 dBc, and the sum (added on a power basis) of all others spurious components shall not exceed -36 dBc.

Phase Noise Effects

The largest problem experienced in satellite communications systems is local oscillator phase noise degrading the bit error rate (BER) performance of digital systems employing any type of phase modulation.

In such systems, the combined effects of phase noise on the local oscillators used in the transmission path cause phase errors in the received signal that, in turn, degrade the BER of the demodulated data. In severe cases, large bursts of errors may be generated which can cause synchronization loss in the digital equipment, making the service totally unusable.

This problem is more pronounced on low-bit rate systems where the phase noise occupies a large proportion of the wanted signal bandwidth, and consequently has a greater effect on the system degradation than in higher bit rate systems.

7.4
Student Question Paper

Question

a. When using a single mixing upconverter, if the required output frequency is 6320 MHz, and the IF is 70 MHz, what is the required oscillator frequency?

b. State how you would remove the unwanted frequency.

Question

In a double upconverter, the required output frequency is 6350 MHz. The IF is 140 MHz and the low frequency oscillator is 1000 MHz. What frequency is the high frequency oscillator?

Question

In a double downconverter, the required output frequency is 4095 MHz, the IF is 140 MHz, and the low frequency oscillator is 1225 MHz. What frequency is the high frequency oscillator?

Problem

Complete the following table with the required data and plot the phase noise characteristic of an Earth station if the results taken from measurements are:

Carrier Level	Frequency offset (from center freq.) Hz	Measured level (dBm)	Resolution Bandwidth filter (Hz)	Carrier-to-sideband noise ratio (dB)	dBc/Hz
+5 dBm	80	-52	100		
	190	-62.5	100		
	300	-65.3	100		
	500	-64.6	100		
	900	-66	100		
	3.00E+03	-54.7	1000		
	5.00E+03	-57	1000		
	1.00E+04	-58.6	1000		
	2.00E+04	-60.2	1000		
	5.00E+04	-66.2	1000		
	1.00E+05	-72.5	1000		

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CHAPTER 8

EARTH STATION TEST EQUIPMENT AND MEASUREMENT UNITS

8.1 Introduction

The basic requirements for the test equipment are given in SSOG documents. It should be noted that several items may be part of a single instrument. Basic descriptions of their operation principle are given below.

8.2 Power Meter

A common technique for measuring power at high frequencies is to employ a sensing element that converts the RF power to a measurable DC or low-frequency signal. The sensing element is often designed to form a termination that is matched to the characteristic impedance of the input transmission line. Various types of sensing elements are used.

Thermistor Sensors

Thermistor sensors provide a change of resistance. The typical power range is 1μW to 10mW; the maximum frequency is greater than 100GHz. Figure 8.1A shows a typical power sensor employing thermistors. The thermistors form the termination for the RF input. DC or audio power from the self-balancing bridge in Figure 8.1B raises the temperature of the thermistors until they each have a resistance of 2Z0. The RF impedance then becomes equal to Z0. Because the bridge keeps the thermistor resistance constant, any heat added by the RF power causes a corresponding reduction in bias power. The RF level is determined by measuring this change in bias power.

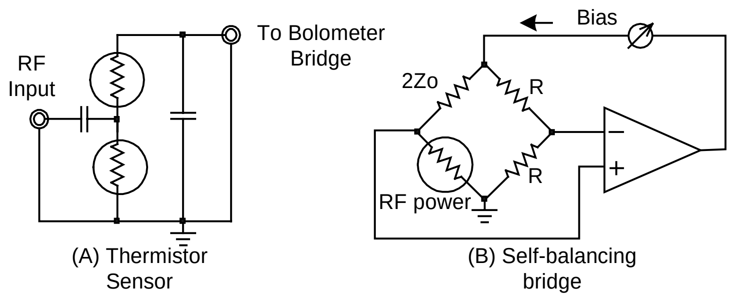

Figure 8.1 Power Measurement with Thermistor Sensor

Thermal Converter

Thermal converters provide a DC voltage (less than 10mv). The typical power range is 0.1 to 100 mW; the maximum frequency is less than 1GHz. Thermal converters employ a number of thermocouples (thermopile) mounted with good thermal contact to the RF termination (Figure 8.2). The RF power heats the termination, and the thermopile output voltage is proportional to the amount of power dissipated. The converter can be calibrated by applying a precisely known DC or RF power level at the input.

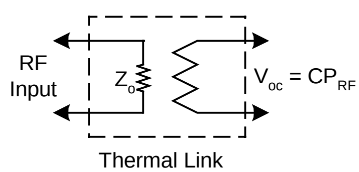

Figure 8.2
Thermal Converter

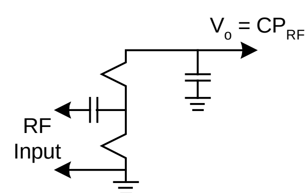

Figure 8.3
Thermocouple Sensor

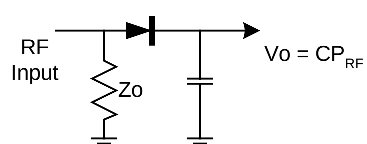

Figure 8.4 Diode Power Sensor

Thermocouple

Sensors

Thermocouple sensors provide a DC voltage (less than 10mV). The typical power range is 0.1µW to 100mW; the maximum frequency is greater than 100GHz. Thermoelectric sensors differ from thermal converters in that the thermocouples are used as the terminating resistors (Figure 8.3). This type of sensor must be calibrated with a precise RF power level.

Diode Sensors

Diode sensors provide a DC voltage (approximately 1V at 10mW). The typical power range is 0.1nW to 10mw; the maximum frequency is greater than 18GHz. Diode power sensors (Figure 8.4) use point contact or Shottky barrier diodes to detect the RF signal. If the RF voltage is less than 20mV, the diode output follows the square of the applied voltage, so the DC voltage is a function of the power. At higher levels, the rectified output gradually changes to the more familiar peak detection mode, and harmonics in the signal cause errors in the power reading. Diode sensors must be calibrated with precise RF signal.

8.3 Frequency Counter

The conventional counter measures the frequency of an input signal. It may also perform related basic measurements, like the period of the input signal.

The frequency of a repetitive signal is measured by counting the number of cycles within a time interval and dividing this number by the time interval. The block diagram of a frequency counter is shown in Figure 8.5.

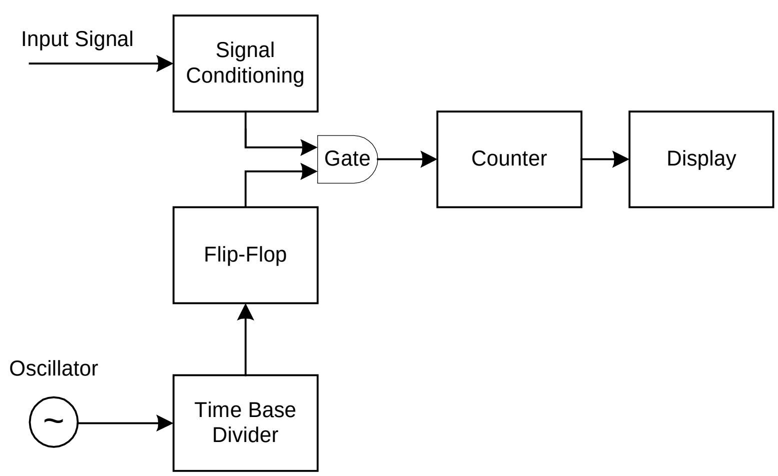

Figure 8.5 Block Diagram of a Frequency Counter

The counter totals the pulses passing through the gate when the flip-flop opens the gate. The time while the gate is open to count the pulses is adjusted with the time-base divider. For higher frequencies at the input, the time base is adjusted to open the gate for shorter periods of time, to avoid overflowing the counter.

The frequency displayed is calculated by dividing the number of counted pulses by the duration of the gating pulse at the output of the flip-flop. The accuracy of the frequency measurement depends on the accuracy of the oscillator. For this reason, all counters employ ovenized crystal oscillators with a very good long-term stability.

Microwave Frequency Counters

Because the digital circuits used limit the frequency range of a frequency counter, the signal must be downconverted. Four techniques are available: prescaling, heterodine downconversion, transfer oscillator downconversion, and downconversion.

Prescaling can be used in the lower microwave frequencies. A prescaler is a digital frequency divider that runs continuously ungated and provides a pulse for every n cycles of the input signal.

Heterodyne downconversion uses a high stability local oscillator and a mixer to beat the input microwave frequency. The resulting difference frequency signal can be measured with a conventional counter.

The transfer oscillator uses a phase lock loop circuit to lock a harmonic of a low frequency oscillator to the microwave input signal. The frequency of the oscillator can be measured with a conventional counter. To determine the harmonic relationship between that frequency and the input, a parallel channel with an offset oscillator is used.

8.4 Microwave Link Analyzer

Insertion Loss or Gain

Insertion loss or gain is defined as the loss or gain that appears upon inserting the network to be measured between a given source and receiver. In Figure 8.6A, Pt is the transmitted power of the source and Pr is the received power. In Figure 8.6A, Pt = Pr, but in Figure 8.6B, Pr is modified by the insertion of the network.

This change in power is the insertion loss or gain and is quoted in dB:

$$\text{Insertion Loss} = 10\log(Pr/Pt)$$

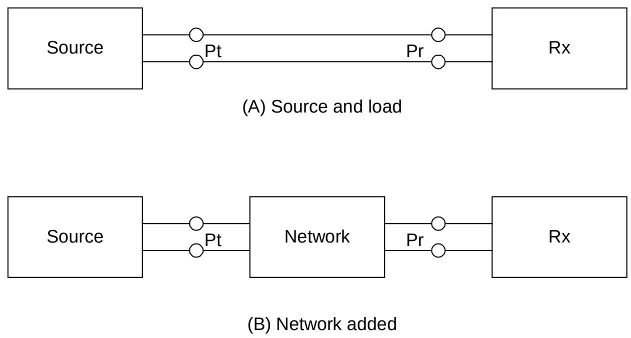

Figure 8.6 Insertion Loss or Gain

Amplitude Response

Amplitude response is also referred to as the flatness or frequency response, and is the variation in gain or loss with change in frequency over a defined frequency band. This parameter is important for wideband systems.

To measure amplitude response accurately, it is important that harmonics of the transmitted signal are not included in the measurement of the received power. Thus, the ideal measurement technique would be one using a tunable receiver. In practice the measurement of radio links using intermediate frequencies of 70 MHz or 140 MHz requires a swept frequency range that allows a simple low pass filter to remove harmonics. Additionally, errors due to the use of a wideband detector are generally low. This allows the use of a simple measurement principle shown in Figure 8.7.

Measurement receivers usually incorporate a frequency-tracking loop to give a recovered sweep signal that is used to drive the X deflection.

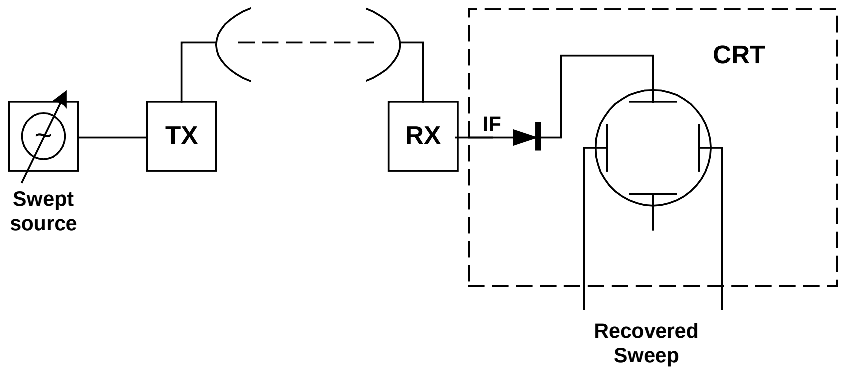

Figure 8.7 Amplitude - Response Measurement

Envelope-Delay Distortion

Envelope-delay distortion is also termed group-delay distortion and is effectively the variation in the derivative of the phase-versus-frequency response. If the phase-frequency characteristic is linear, then the group-delay distortion is zero. This means that all frequencies are transmitted through the system with equal time delay. The group delay is defined in units of time, but it is the variation that distorts broadband signals.

Group delay = $d\varphi/df$

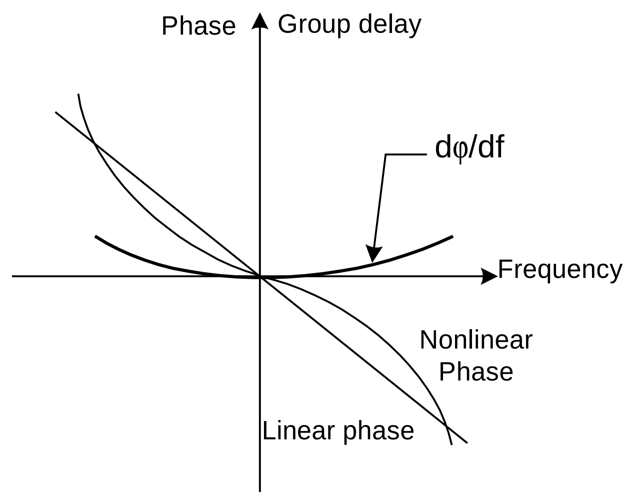

Figure 8.8 Phase and Group Delay versus Frequency

The nonlinear phase characteristic of Figure 8.8 will distort a broadband signal that will manifest itself in the form of noise and intermodulation.

Equalization is achieved by means of networks that give inverse group-delay variations. The most common types are those that compensate for linear or parabolic group-delay distortion. It is important that equalizers be connected as close as possible to the source of group-delay distortion, or before nonlinear stages. This is because nonlinearities that introduce amplitude to phase modulation conversion will produce effects that cannot be removed by group delay equalization.

Measurement of Group-Delay Distortion

There are several methods for the measurement of group-delay distortion, but the basis is that of comparing the phase of a modulated envelope with the phase of a reference signal. The usual method employs a frequency-modulated signal that is swept over the frequency band of interest.

Use of a phase-lock loop at the receiver makes possible the recovery of the frequency modulation, used then to give the variation in phase as the input signal is swept (Figure 8.9).

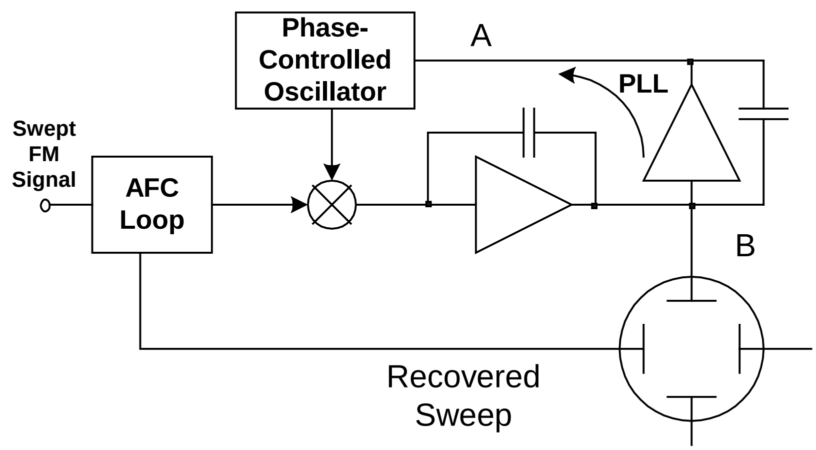

Figure 8.9 Measurement of Group-Delay Distortion

If point A represents the reference phase of the modulating signal, by going back around the integrating loop, the signal at point B is the derivative of this phase, or $d\varphi/dt$.

However, as the frequency is swept as time proceeds, the instantaneous voltage at point B represents the group delay ($d\varphi/df$) at the instantaneous value of the frequency.

The measurement of group-delay distortion involves the careful selection of several test parameters: sweep range, sweep rate, modulation frequency (test tone), modulation index, and post-detection bandwidth.

It is important to select a sweep range appropriate for the device or system under test. Some consideration should be given to the spectrum of the modulating signal, because the device under test will be subjected to the total spectrum. This is usually important for testing components such as narrow-band filters with lower test-tone frequencies.

The sweep rate employed is often in the range of 50 to 100 Hz. (This range may not be suitable for systems as satellite communication links where use of a lower sweep rate will allow a narrow bandwidth to be selected for the post-detection bandwidth.) This will enhance the measurement resolution by reducing the noise power.

The modulation frequency used is a compromise between two conflicting effects:

Use of too high a frequency will tend to conceal rapid fluctuations in group delay such as the ripple produced by imperfect impedance matching.

Use of too low a frequency will produce a low voltage at the output of the group delay detector, and the signal-to-noise ratio of the display will be too low.

It is, therefore, usual to select frequencies between 50 kHz and 500 kHz to give an appropriate compromise.

Return Loss

In the alignment of microwave radio links, it is important that the impedance of the various sections be well maintained. This is especially important where cabling is used between a source and a load, because any mismatch will produce time delayed reflections that may impair link performance. The normal way to describe the mismatch of a source and load is by using the term "return loss". Return loss is the measure of the ratio between the transmitted and reflected signals:

Return loss = 20log(Ei/Er)

Where:

Ei = incident signal

Er = Reflected signal

Return loss is a measure of magnitude of incident and reflected signals and does not take account of phase relationships.

Measurement of Return Loss

Long-Cable Method - In this method, a "long cable" is connected to the termination under test as shown in Figure 8.10. When the swept IF signal is applied to the long cable and its termination, a series of ripples will appear on the CRT display. If the test termination is removed, the open circuit produces a large amplitude of ripple that is then adjusted by the attenuator to equal the level when the termination is connected. The return loss is equal to two times the attenuation inserted.

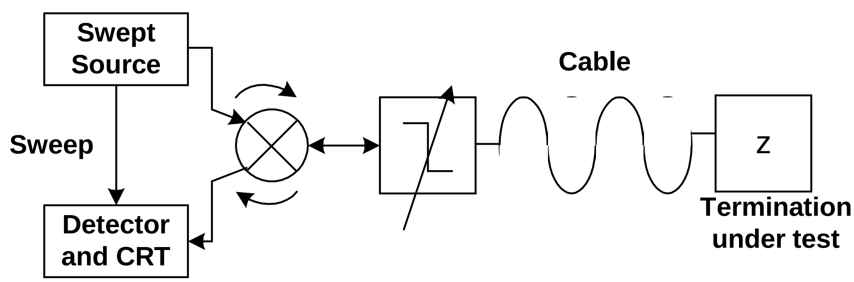

Figure 8.10 Return Loss Measurement by Long Cable Method

Note that the cable must be long enough to produce at least 1 ripple over the swept range, but more than 10 are required to observe variations across the band. Thus, for normal IF measurements, a length in excess of 20 m is required.

Standard-Mismatch Method - This method (Figure 8.11) relies on the measurement of power passed from a hybrid when it is terminated by a known mismatch and then by the test item. A typical mismatch of 17 dB is used to calibrate the power meter/detector, after which the actual return loss may be measured directly.

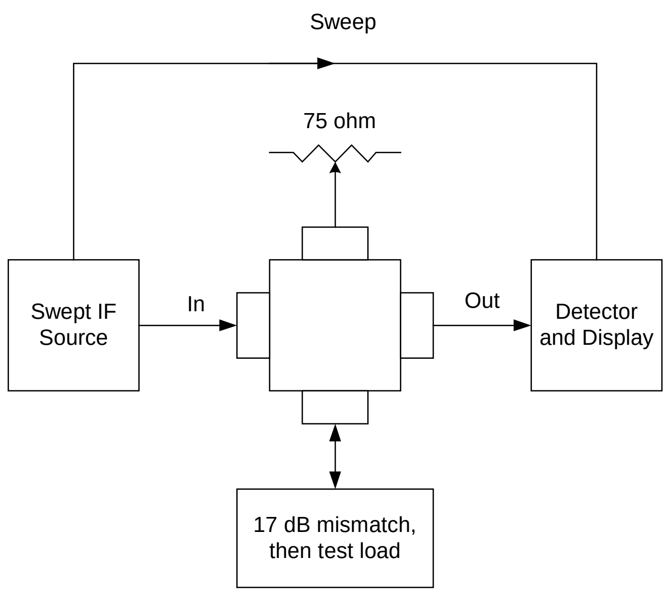

Figure 8.11 Measurement of Return Loss by Standard-Mismatch Method

8.5 BER Test Set

In digital communication, bit errors can be generated as a result of noise, jitter, or level variations. If such distortions occur, the transmitted information is received in a deformed condition, which means deterioration of the transmission quality.

Transmission quality is measured in terms of the degree of variation of bits (error rate). To measure the error rate accurately, a sequence of bits simulating the real data is transmitted at a rate equal to the transmission rate. This pattern, called Pseudo-Random Bit Sequence (PRBS), is then compared with the one generated at the receiver, and the ratio of detected mismatched bits to the total number of bits is calculated as the bit error rate.

The pseudo-random bit sequence must adhere to ITU-T Recommendations O.151 and O.152 to ensure compatibility between equipment. The length of test patterns is selected according to the transmission rate of the system being tested. Table 8.1 shows the recommended ITU-T test pattern for different transmission rates.

Table 8.1 Test Patterns According to Recommendations O.151 and O.152

Carrier Size (info. rate bit/s)	Pseudo-Random Pattern Length (bits)
64k	2047 (2^{11}-1)
192k	2047 (2^{11}-1)
384k	2047 (2^{11}-1)
512k	2047 (2^{11}-1)
1024k	2047 (2^{11}-1)
1544k	2^{15}-1
2048k	2^{15}-1
6312k	2^{15}-1
8448k	2^{15}-1
32064k	2^{15}-1
34368k	2^{23}-1
44736k	2^{15}-1

These test patterns are produced by means of a shift register incorporating appropriate feedback.

For example:

Test pattern 211-1

Number of shift registers 11

Pattern length 211-1 = 2047

Feedback Taken from the output of the 9th and 11th stage via an exclusive-OR-gate to the first stage.
10 (noninverted signal)

Longest sequence of zeros 10 (noninverted signal)

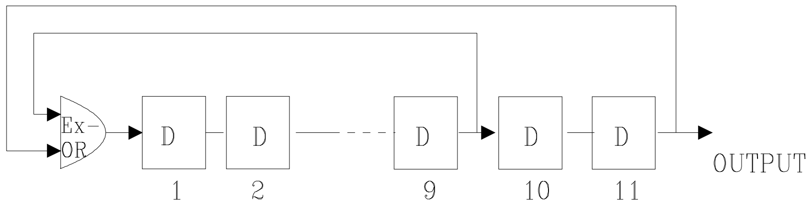

Figure 8.12 Circuit Example for a PRSB Generator

The true table for this circuit can be built starting with all "ones", however, this is too detailed to explain in this handbook due to the length of the sequence (2047 bits).

Problems Using the BER Test Set

A common cause of problems during tests is the option "FRAMED/UNFRAMED" that the test equipment gives. This option means that the PRBS will be transmitted with the frame structure for the transmission rate. For 2048 Kbit/s, this means that the pattern will give time for the Frame Alignment Word and other related information to be transmitted. Both stations should agree on the use of this option.

Another cause of problems is the option "ERROR INSERTION". This option automatically inserts a certain number of errors (specified by the user), in the sequence. This option may not be noticed in the link performance test if the Eb/No is low, because the number of errors generated by the noise is greater than that generated in the equipment. But once the errors generated by the noise are fewer than those generated by the equipment, the system will lock to account for a certain amount of errors even with a good Eb/No.

8.6 Spectrum Analyzer

The standard method for observing electric signals is to use an oscilloscope. The horizontal axis of a CRT oscilloscope increases by a unit of time; oscilloscopes are sometimes referred to as time-domain instruments. Observation in time domain is useful to obtain signal timings and phases.

But the performance of certain elements such as amplifiers, oscillators, mixers, modulators, filters, and others require the analysis of other characteristics (frequency response, harmonic distortion, intrinsic noise, etc.), and meaningful information is not attained until their frequency responses are obtained. Instruments that display levels of an electric signal as a function of the respective frequencies are called frequency-domain instruments. Typical instruments are the spectrum analyzer and the selective level meter.

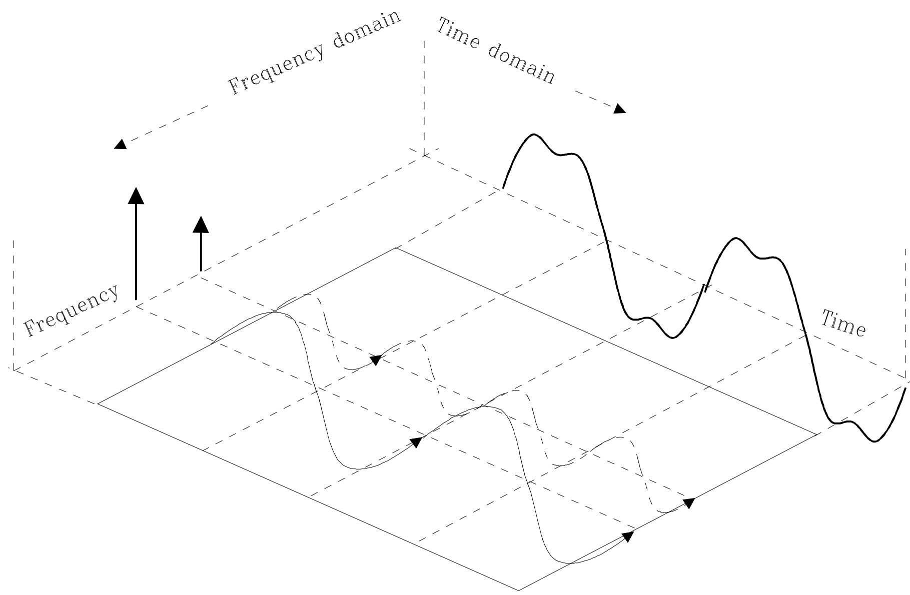

Figure 8.13 Frequency and Time Domains

Figure 8.13 shows the relation between the time domain and the frequency domain. In the time domain observation, the displayed waveform is a sum of frequency components. In addition, the components are separated and the level at each frequency is displayed in the frequency-domain observation.

Spectrum is a collection of sinewaves that, when combined properly, produce the time-domain signal under examination. Fourier transform says that any time-domain electrical phenomenon is composed of one or more sine waves (spectrum) of appropriate frequency, amplitude, and phase. The two descriptions of the same phenomenon are not independent. If one is known, the appropriate mathematical rules or equations lead to the other.

Spectrum analyzers are classified into scanning spectrum analyzers (superheterodyne spectrum analyzer) and nonscanning spectrum analyzers (multichannel filter and Fast Fourier Transform types).

The superheterodyne spectrum analyzer can be understood as a receiver with a sweeper (Figure 8.14). It consists of an input filter defined by its tuning range, a mixer, and the local oscillator to convert the input frequency band to an IF. The local oscillator is a VCO controlled by a ramp generator (sawtooth wave generator) which defines the scan time for the CRT and also the sweep time for the local oscillator.

The IF filters separate the frequency components of the signals; this capability is called resolution. Spectrum analyzer specifications indicate a 3-dB bandwidth for the available analyzer filters (known as resolution bandwidth). Resolution bandwidth indicates how close two equal amplitude sinusoids can be and still be resolved. (See Figure 8.15.) If two adjacent signals with a large signal level difference have to be resolved, the analyzer's bandwidth selectivity must be considered. The bandwidth selectivity is defined as the ratio of the 60-dB bandwidth to the 3-dB bandwidth. (See Figure 8.16.) It indicates how close two signals with large level differences can be and still be resolved. This ratio can be 25:1 for older spectrum analyzers, and 11:1 or better for newer ones. The extremely narrow resolution bandwidth using the new equipment is achieved by digitizing the IF and processing it with a Fast Fourier Transform algorithm.

The bandwidth selectivity obtained through this process is 5:1.

The spectrum signal at the output of the IF filter is detected for final conditioning in the post-detection gain and signal processing (known as video filters) which smoothes (or averages) the signal for final presentation.

One way to visualize the video filter is as a capacitor connected to the detector output. The larger the capacitor, the narrower the video filter. It takes time to pass a signal through this capacitor; hence the narrower video bandwidth which requires more sweep time. If the signal is swept too quickly, there will be a loss of displayed amplitude due to the time that the video filter takes to charge and discharge.

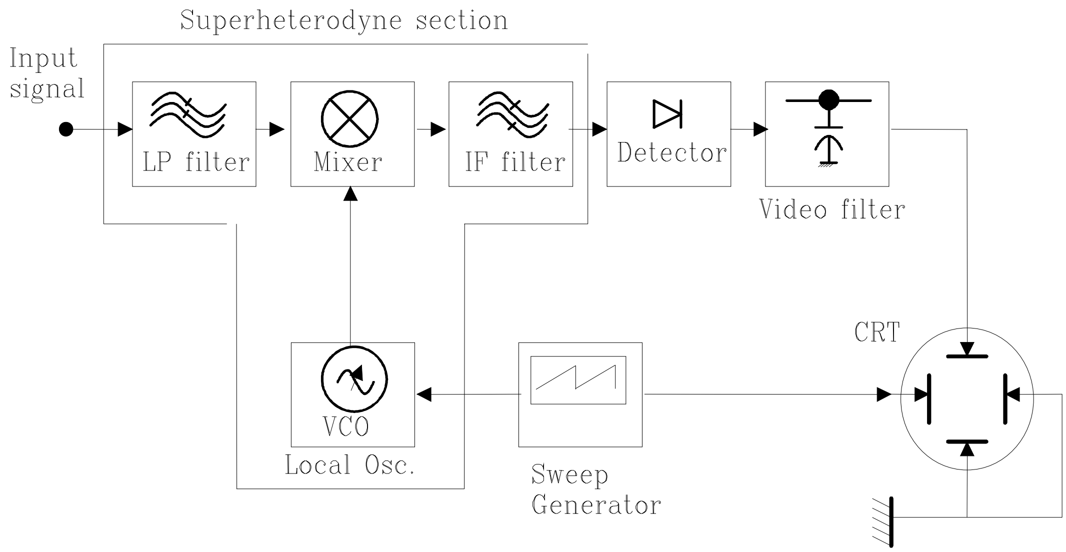

Figure 8.14 Spectrum Analyzer - Receiver with a Sweeper

Finally, as the spectrum analyzer is used for phase noise measurements, the intrinsic phase noise characteristic should be lower than the one in the equipment being tested to obtain reliable results.

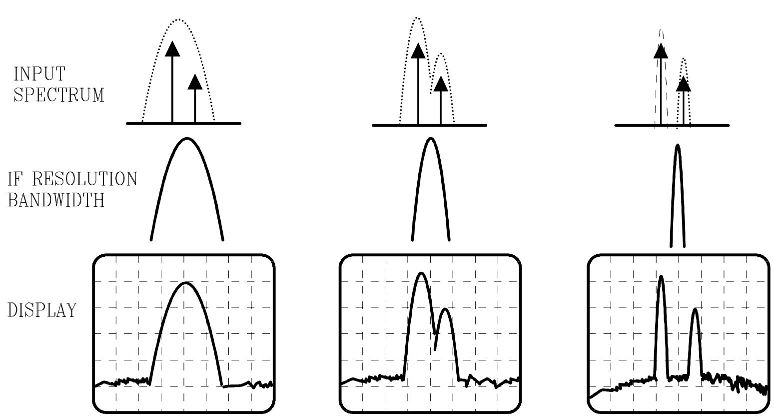

Figure 8.15 Resolution of Adjacent Sinusoids as a Function of IF Filters

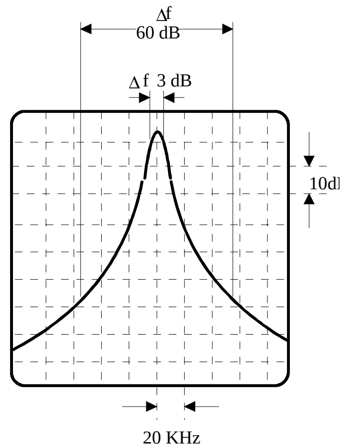

Figure 8.16 Bandwidth Selectivity

8.7 MEASUREMENT UNITS

Introduction

On its way from one station to another, the signal will pass through different elements such as amplifiers, attenuators, modems, antennas, and even free space.

Signal levels, EIRP, gain (amplification), and even system losses, can be mathematically unmanageable. A logarithmic-expressed quantity can reduce these numbers to a practical value; another advantage of logarithmic quantities is that many calculations will be reduced to addition and subtraction instead of multiplying or dividing.

The Decibel (dB)

The decibel (dB) is a subunit of the bel (B) and represents the ratio between two powers such as:

$$dB = 10 \log_{10} (P_o/P_i)$$

where: $\log_{10}$ is the logarithm in the base 10 (Brigg logarithm).
P_o is the output power in an amplifier.
P_i is the input power in the previous amplifier.

The result will be an amount representing the power gain of the amplifier. The dB cannot be used by itself to represent a magnitude unless a reference quantity is specified. The abbreviation for decibel is dB, and it is often modified to suggest the reference value.

Example: dBm is used to express power, relative to 1 milliwatt.
dBi is used to express the gain of an antenna, relative to isotropic antenna.

Occasionally, the gain has to be calculated from voltages instead of Watts, and the result has to be derived from the expression for power.

$$G_{dB} = 10 \log_{10}(P_o/P_i) = 10 \log_{10}\{(V_o^2/R_o)/(V_i^2/R_i)\}$$

where: R_i = system input impedance
R_o = system output impedance

Then: $G_{dB} = 10 \log_{10}\{(V_o^2/R_o)/(V_i^2/R_i)\}$

$$= 10 \log_{10}(V_o/V_i)^2 + 10 \log_{10}(R_o/R_i)$$

If the ratio (R_o/R_i) is the unity, the expression is reduced to:

$$G_{dB} = 20 \log_{10}(V_o/V_i).$$

If the ratio (R_o/R_i) is not the unity, the expression should be:

$$G_{dB} = 20 \log_{10}(V_o/V_i) + C$$

Where: $C = 10 \log_{10}(R_o/R_i)$ and is a correction factor due to the impedance mismatch

The dBm, dBW

An energy level can be expressed in decibel, only if a reference value is given, here a third letter is added to the abbreviation dB which describes the reference, the more popular designations are:

Designation	Reference	Conversion
dBm	1 milliwatt	dBm = dBW + 30
dBW	1 Watt	dBW = dBm - 30

The dBr, dBmO, and dBmOp

The “**dBr”** is the power ratio expressed in dB, between a given point and a reference point. Any power expressed in dBr does not specify the absolute level, it is a relative measurement only.

Example: The nominal level in a carrier supplier monitoring point is + 10 dBm; during a routine it is measured as + 8.7 dBm. In this case we can say that the level is -1.3 dBr (from nominal level).

The "**dBm0"** is the power in dBm referred to a zero transmission point, also called "point of zero transmission level" (0 dBr0).

Example: the signaling tone is -10 dBm0 in a channel. If the channel zero (or nominal) transmission level is -16 dBm, then the absolute level of signaling tone is -26 dBm.

The "dBm0p" is the noise power in dBm0, measured by a psophometer or noise measuring set having psophometric weighting. (Note: A psophometer emulates the frequency response of a human ear.)

Example: If a psophometer connected to a +8 dBm point shows a crosstalk level of -44 dBm, the expression in dBm0p will be:

-44 dBm - (+ 8 dBm) = - 52 dBm0p.

Special Units

The decibel concept is extended to allow the ratio of any two similar quantities to be expressed in decibel units. For example, two temperatures T_1 and T_2 may be expressed as $10 \log_{10}(T_1/T_2)$. If the temperature is referred to 1° Kelvin, (K), the temperature Kelvin expressed in decibels would be given as dBK.

As an example, 290°K (ambient temperature) in decibels is:

$10 \log_{10}(290/1) = 24.64$ dBK

Another example that occurs widely in practice is bandwidth referred to 1 Hz. Thus, a bandwidth of 36 MHz is equivalent to:

$$10 \log_{10} 36000000/1 = 75.56 \text{ dBHz}$$

Decibel units can be added directly, even if different reference units are used. If a power of 34 dBW is transmitted through a circuit that has a loss of 20 dB, the received power would be:

$$Pr = 34 \text{ dBW} - 20 \text{ dB} = 14 \text{ dBW}$$

Sometimes, different types of ratios are related. A good example is the ratio G/T in a receiving system. Expressed in decibel units, this is:

$$G/T_{dB/K} = G_{dBi} - T_{dBK}$$

The unit for G/T is dB/°K that is decibel relative to 1 Kelvin.

Another example is the ratio Eb/No, called "Energy per bit/Noise spectral density ratio", and is expressed in dB. This term is commonly used to evaluate the performance of digital modems, and is defined by:

$$Eb/No_{dB} = C/No_{dB\text{-}Hz} - 10 \log (\text{data rate})_{dB\text{-}Hz}$$

Where: $Eb_{dBW/Hz}$ = Energy per bit referred to the data rate
$No_{dBW/Hz}$ = Noise spectral density
C_{dBW} = Carrier power

This ratio relates symbol rate, hertz, and Watts, but can be easily handled by using decibels.

Working with Decibels

A very common error when working with decibels is made when one wants to add powers expressed in decibels. For example, 2 carriers are transmitted by an HPA, each with an output power of +11.5 dBW; the total power in this case will be +14.5 dBW (not +23 dBW). This is because powers are added as absolute values and to do so the carrier levels in decibels must be converted back to absolute values, the powers added, and then converted back to decibels.

If absolute quantities are needed, the conversion between decibels and absolute values is made with the formula:

$$A = 10^{R/10}$$

where: A = Absolute value
R = Ratio in decibels

8.8 Student Question Paper

1. What is the power in dBm and Watts of a carrier with an EIRP of 63 dBW if the antenna gain is 58.5 dBi?

2. An upconverter has a monitoring point that gives a sample of 15 dB down the output power (15 dB coupling factor). What is the output level if the power measured at the monitoring point is -12.7 dBm?

3. An HPA transmits two carriers. One is +7.2 dBW and the other +43.5 dBm. What is the total output power of the HPA (in dBW)? What is the output power value in Watts?

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CHAPTER 9

EARTH STATION DESIGN

9.1 Introduction

A satellite link is defined as an Earth station - satellite - Earth station connection. The Earth station - satellite segment is called the uplink and the satellite - Earth station segment is called the downlink.

The Earth station design consists of the Transmission Link Design, or Link Budget, and the Transmission System Design.

The Link Budget establishes the resources needed for a given service to achieve the performance objectives.

The Transmission System Design establishes the equipment characteristics necessary to meet the performance objectives for the services to be provided, such as the HPA rated power and the LNA noise temperature. During the analysis, tradeoffs can be made to achieve a balance between cost and performance.

9.2 Performance Objectives

Performance objectives for digital links consist of:

- BER for normal operating conditions
- Link Availability, or percentage of time that the link has a BER better than a specified threshold level

9.3 Link Budget

The satellite link illustrated in Figure 9.1 is composed primarily of three segments: (i) the transmitting Earth station and the uplink media; (ii) the satellite; and (iii) the downlink media and the receiving Earth station.

The carrier level received at the end of the link is a straightforward addition of the losses and gains in the path between transmitting and receiving Earth stations.

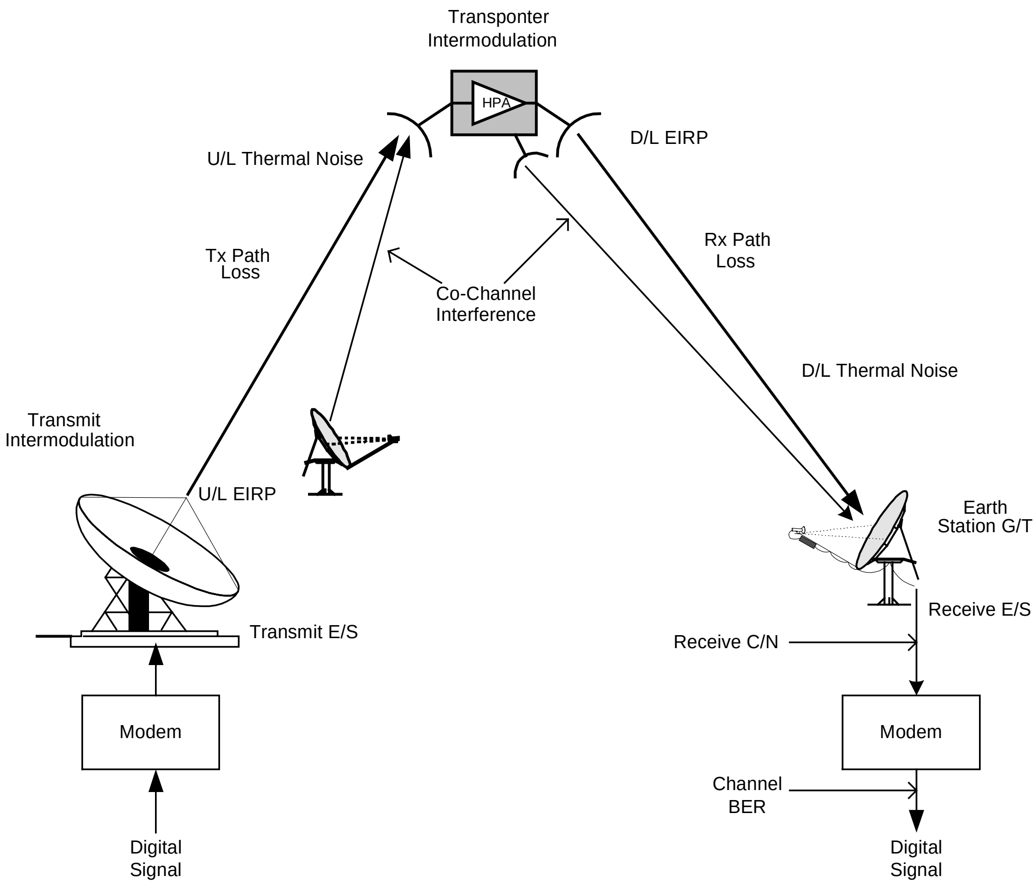

Figure 9.1 Typical Satellite Link

Carrier-to-Noise Relationship

The basic carrier-to-noise relationship in a system establishes the transmission performance of the RF portion of the system, and is defined by the receive carrier power level compared to the noise at the receiver input. Figure 9.2 illustrates how link components affect the receive C/N, and finally, the service quality.

For example, the downlink thermal carrier-to-noise ratio is:

$$C/N = C - 10\log(kTB) \qquad (9.1)$$

Where:

C = Received power in dBW

k = Boltzman constant, 1.38E-23 W/°K/Hz

B = Noise Bandwidth (or Occupied Bandwidth) in Hz

T = Absolute temperature of the receiving system in °K

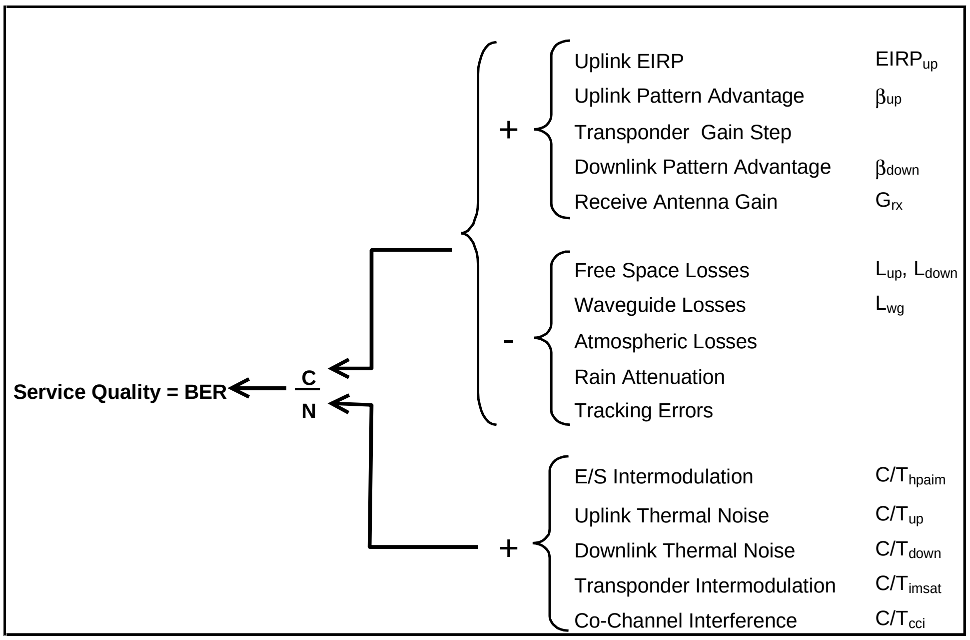

Figure 9.2 Link Parameters' Impact on Service Quality

Link Equation

The link equation in its general form is:

$$C/N = EIRP - L + G - 10\log kTB \qquad (9.2)$$

Where:

EIRP = Equivalent Isotropically Radiated Power (dBW)

L = Transmission Losses (dB)

G = Gain of the receive antenna (dB)

The first three terms give the received carrier power, and the final term is the noise power of the receiving system. The link equation applies for both uplink and downlink.

Transmission losses are defined as the free space transmission loss plus any additional path losses.

Equivalent Isotropically Radiated Power (EIRP)

The gain of a directive antenna results in a more economic use of the RF power supplied by the source. Thus, the EIRP is expressed as a function of the antenna transmit gain G_T and the transmitted power P_T fed to the antenna.

$$EIRP_{dBW} = 10 \log P_{T\ dBw} + G_{T\ dBi} \qquad (9.3)$$

Where:

$P_{T\ dBw}$ = antenna input power in dBW

$G_{T\ dBi}$ = transmit antenna gain in dBi

The EIRP must be accurately controlled, because an excessive EIRP will cause interference to adjacent and co-channel carriers, while a low EIRP will result in poor quality performance of the service.

Antenna Gain

In Chapter 3 the antenna gain, referred to an isotropic radiator, is defined by:

$$G_{dBi} = 10 \log \eta + 20 \log f + 20 \log d + 20.4\ \text{dB} \qquad (9.4)$$

Where:

η = antenna efficiency (Typical values are 0.55 - 0.75.)

d = antenna diameter in m

f = operating frequency in GHz

Transmission Losses

Transmission losses generally consist of four components:

$$L = L_o + L_{atm} + L_{rain} + L_{track} \quad (9.5)$$

Where:
L_o = free Space Loss
L_{atm} = atmospheric losses
L_{rain} = attenuation due to rain effects
L_{track} = losses due to antenna tracking errors

Free Space Loss

If an isotropic antenna radiates a power PT, the beam power will spread as a sphere in which the antenna is the center. The power at a distance "D" from the transmission point is given by the next equation.

$$W = P_T/4\pi D^2. \;.\;.\;.\;.\; (W/m^2) \quad (9.6)$$

As the transmit antenna focuses the energy (i.e., has a gain), the equation changes to:

$$W = G_T P_T/4\pi D^2. \;.\;.\;.\;.\; (W/m^2) \quad (9.7)$$

or

$$W_{dBW/m^2} = EIRP_{dBW} - 20 \log D - 71 \text{ dB} \quad (9.8)$$

Where:
$G_T P_T$ = EIRP
W = illumination level
D = distance in km
71 dB = $10 \log (4\pi * 10^6)$

As a receiver antenna 'collects' the signal, the amount of 'collected' signal will depend on the receiver antenna size. The received power P_R will be:

$$P_R = W * A_e \quad (9.9)$$

Where:

A_e = effective aperture of the receive antenna = $(\lambda^2/4\pi)/G_R$

Then,

$$P_R = [G_T P_T/4\pi D^2]*[(\lambda^2/4\pi)/G_R] \quad (9.10)$$

$$P_R = G_T P_T*(\lambda/4\pi D)^2*G_R \quad (9.11)$$

The expression $[4\pi D/\lambda]^2$ is known as the basic free space loss L_o. The basic free space loss is expressed in decibels as:

$$L_o = 20 \log D + 20 \log f + 92.5 \text{ dB} \qquad (9.12)$$

Where:

D = distance in km between transmitter and receiver, or slant range (See Chapter 3.)
f = frequency in GHz
$92.5 \text{ dB} = 20 \log \{(4\pi * 10^9 * 10^3)/c\}$

Expressing equation (9.11) in dB:

$$P_{R\ dBW} = EIRP - L_o + G_R \qquad (9.13)$$

In equation (9.13), if GR were the gain for a $1m^2$ antenna with 100 percent efficiency, P_R will become the illumination level per unit area in dBW/m^2; therefore, the illumination level in equation (9.8) can also be expressed as:

$$W_{dBW/m^2} = EIRP - L_o + G_{1m^2} \qquad (9.14)$$

Atmospheric Losses

Losses in the signal can also occur through absorption by atmospheric gases such as oxygen and water vapor. This characteristic depends on the frequency, elevation angle, altitude above sea level, and absolute humidity. At frequencies below 10 GHz, the effect of atmospheric absorption is negligible. Its importance increases with frequencies above 10 GHz, especially for low elevation angles. Table 9.1 shows an example of the mean value of atmospheric losses for a 10-degree elevation angle.

Table 9.1 Example of Atmospheric Attenuation

Atmospheric Loss	Frequency (f) in GHz
0.25	$2 < f < 5$
0.33	$5 < f < 10$
0.53	$10 < f < 13$
0.73	$13 < f$

A full explanation can be found in ITU report 564-2, 1990.

Rain Effects

An important climatic effect on a satellite link is the rainfall. Rain results in attenuation of radio waves by scattering and by absorption of energy from the wave.

Rain attenuation increases with the frequency, being worse for Ku-band than for C-band. Enough extra power must be transmitted to overcome the additional attenuation induced by rain to provide adequate link availability. The prediction of rain attenuation is a statistical process, and many models have been developed which yield results that confirm experimental observation. These models relate to operating frequency, rain rate statistics by geographic location, as well as the proposed link availability.

A full explanation of the matter can be found in ITU reports 564-2, 1990, and report 721-1, 1990. Typical values for rain margins can be found in IESS documents. Note that a reliable prediction of attenuation by rain is desirable to realistically determine the link availability and establish the appropriate link margin.

Tracking Losses

When a satellite link is established, the ideal situation is to have the Earth station antenna aligned for maximum gain, but normal operation shows that there is a small degree of misalignment which causes the gain to drop by a few tenths of a dB. The gain reduction can be estimated from the antenna size, the tracking type, and accuracy. (See Figures 5.3 to 5.6 in Chapter 5.) This loss must be considered for the uplink and downlink calculations. Typical values can be found in Tables 9.2 and 9.3 for C- and Ku-band antennas. Larger antenna diameters will always require tracking, and misalignment losses can be left as 0.5 dB for uplinks and downlinks.

Table 9.2 Earth Station Performance Characteristic (C-band, Antenna Efficiency 70%)

ANTENNA DIAMETER (m)	TX GAIN 6 GHz (dBi)	RX GAIN 4 GHz (dBi)	UPLINK LOSSES dB	DOWN-LINK LOSSES dB	TRACKING
1.2	35.6	32.1	0	0	FIXED
1.8	39.2	35.6	0	0	FIXED
2.4	41.7	38.1	0.4	0.2	FIXED
3.6	45.6	42.1	0.7	0.4	FIXED
7	51	47.4	0.9	0.9	MANUAL*
11	54.9	51.4	0.5	0.5	STEP TRACK

* Manual tracking requires weekly E-W angle adjustments.

Table 9.3 Earth Station Performance Characteristic (Ku-band, Antenna Efficiency 60%)

ANTENNA DIAMETER (m)	TX GAIN 14 GHz (dBi)	RX GAIN 11 GHz (dBi)	UPLINK LOSSES dB	DOWN-LINK LOSSES dB	TRACKING
1.2	42.6	40.5	0.4	0.2	FIXED
1.8	46.1	44	0.7	0.5	FIXED
2.4	48.7	46.6	1.1	0.8	FIXED
3.7	52.5	50.3	1.2	0.9	MANUAL*
5.6	56.1	53.9	0.8	0.7	MANUAL*
7	58	55.8	0.5	0.5	STEP TRACK
8	59.2	57	0.5	0.5	STEP TRACK

***Manual tracking requires weekly E-W angle adjustments.

Pattern Advantage

The satellite antenna pattern has a defined beam edge, (refer to Figure 9.2), to which the values of EIRP, G/T, and flux density are referenced. Adjustment factors to account for the location of an Earth station within the satellite beam may be applied to the link analysis. These factors, called beta-factors, aspect correction, or pattern advantage apply to all satellite beams, with the exception of the global beams.

The beta-factor is defined as the difference between the satellite beam edge gain and the gain in the direction of an Earth station. Each station location should consider the beta-factors for uplink (βup) and for the downlink (βdown), because for the same station (and also the same beam), the uplink beam coverage is not the same as for the downlink.

A rough calculation of these factors can be made through the satellite beam coverage as shown in the correspondent satellite *IESS* where the lines or contours in the "footprint" represent 1 dB incremental from beam edge. A more accurate value can be obtained by requesting it from INTELSAT, especially in those cases where fully steerable satellite beams are used.

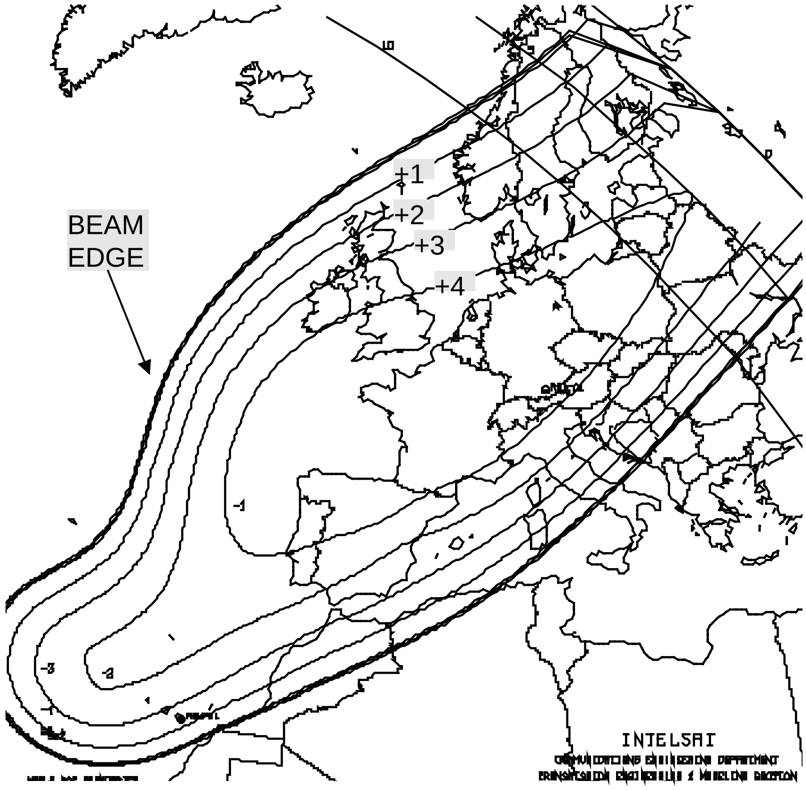

Figure 9.2 Example of Pattern Advantage

System Noise Temperature

The system noise temperature of an Earth station consists of the receiver noise temperature, the noise temperature of the antenna, including the feed and waveguides, and the sky noise picked up by the antenna.

$T_{system} = T_{ant}/L + (1 - 1/L)T_o + T_e$ (9.15)

Where:

L = feed loss in numerical value
T_e= receiver equivalent noise temperature
T_o= standard temperature of 290°K
T_{ant} = antenna equivalent noise temperature as provided by the manufacturer

Equation (9.15) shows that waveguide losses have a significant effect on system noise temperature.

For example, an attenuation of 0.3 dB (due to waveguide components between the antenna and the receiver pre-amplifier), contributes approximately 19°K to the system noise temperature. The feeder loss must be kept as small as possible, otherwise the benefits of a low noise antenna and LNA will be lost. This is why LNAs are mounted as close as possible to the antenna feed.

It should be noted that equation (9.15) is general and is also applicable to the spacecraft receiving system. The difference is that the spacecraft antenna "sees" the warm Earth instead of the "cold sky". Also, the spacecraft receiver has a much higher noise temperature than the Earth station receiver, so the typical noise temperature of the spacecraft receiving system is usually much higher than that of the Earth station.

Antenna Noise Temperature

The noise power into the receiver, (in this case the LNA), due to the antenna is equivalent to that produced by a matched resistor at the LNA input at a physical temperature of T_{ant}.

If a body is capable of absorbing radiation, then the body can generate noise. Thus the atmosphere generates some noise. This also applies to the Earth surrounding a receiving ground station antenna. If the main lobe of an antenna can be brought down to illuminate the ground, the system noise temperature would increase by approximately 290°K. Fortunately however, synchronous satellites require vertical angles of elevation of 5° or more. If the directivity of the antenna is such that the ground absorbs 5 percent of its radiated energy illuminates, then the same antenna used for reception would contribute 5/100 x 290°K, i.e., 14.5°K of noise.

Every antenna has sidelobes. These are augmented by "spillover" from the dish edge and scattering of energy by the launcher or by the subreflector and its supporting structure. All of these factors influence the noise temperature of the antenna.

The antenna noise temperature is a complex function of antenna gain pattern, background noise, temperature of the sky, equivalent atmospheric noise temperature, and noise temperature of the Sun. A typical curve variation of the antenna noise temperature with the antenna elevation angle is shown in Figure 9.3. It is usually a minimum at zenith, typically 15°K to 20°K for a low loss antenna with low sidelobes. It increases considerably as the elevation angle falls below 10°.

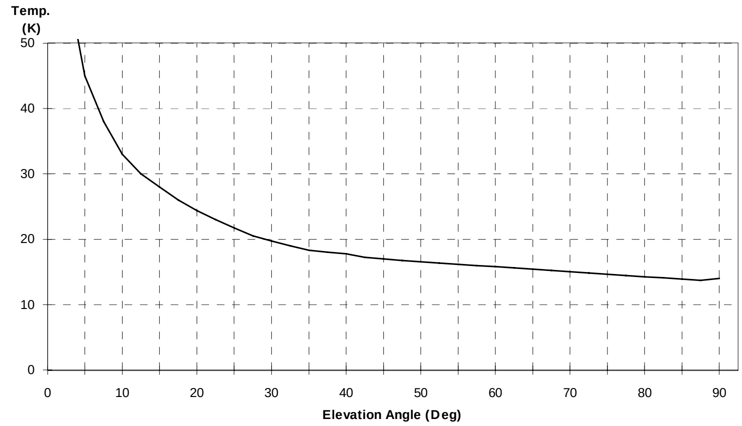

Figure 9.3 Noise Temperature of an Antenna as a Function of Elevation Angle

Figure of Merit (G/T)

In every transmission system, noise is a factor that greatly influences the whole link quality. The G/T_{dBK} is known as the "goodness" measurement of a receive system. INTELSAT requires a specific G/T for all of the standard Earth stations as presented in the *IESS* documents. This means that providing the Earth station meets the required G/T specification, INTELSAT will provide enough power from the satellite to meet the characteristic of every service.

G/T is expressed in dB relative to 1°K. The same system reference point, such as the receiver input, for both the gain and noise temperature must be used.

$$G/T = G_{rx} - 10\log T_{sys} \qquad (9.16)$$

Where:

G_{rx} = receive gain in dB
T_{sys} = system noise temperature in °K

As the antenna gain is frequency-dependent, the G/T must be normalized to a known frequency (normally either 4 or 11 GHz) by subtracting from equation (9.16) the factor 20 log f/f_o (f_o being 4 or 11) where “f” is the frequency in GHz.

Carrier-to-Noise Ratios

In the link equation, by unfolding the kTB product under the logarithm, the link equation becomes:

$$C/N = EIRP - L + G - 10\log k - 10\log T - 10\log B. \qquad (9.17)$$

The difference, G - 10logT, is the figure of merit:

$$C/N = EIRP - L + G/T - 10\log k - 10\log B \qquad (9.18)$$

Where:

L = transmission losses
G/T = figure of merit of the receiver
k = Boltzmann constant
B = carrier occupied bandwidth

Because the receiver bandwidth (B) is often dependent on the modulation format, isolate the link power parameters by normalizing out the bandwidth dependence. The new relation is known as Carrier-to-Noise Density ratio (C/N_o).

$$C/N_o = EIRP - L + G/T - 10\log k \qquad (9.19)$$

Note that:

$$C/N = C/T - 10\log kB \qquad (9.20)$$

Expressing C/T as a function of C/N, and replacing C/N with the right side of the link equation, results:

$$C/T = EIRP - L + G/T \qquad (9.21)$$

C/T is characteristic for each carrier size and type and indicates directly the level of carrier power required for a given G/T. For example, the C/T for an acceptable TV signal might be -140 dBW/°K as compared to perhaps -150 dBW/°K for a digital carrier, although the C/N for the two carriers at the input of the demodulator may be the same.

The ratio C/N_o allow us to compute directly the receiver Bit energy-to-noise density ratio as:

$$Eb/N_o = C/N_o - 10\log(\text{digital rate}) \qquad (9.22)$$

The term "digital rate" is used here because Eb/N_o can refer to different points with different rates in the same modem. Additional information on this is provided in *SSOG 308,* Annex 7.

Impact of G/T on Service Economics

The interpretation of equation (9.21) is that a given C/T required by a certain type of carrier and quality of service, can be obtained for different combinations of EIRP and G/T. EIRP represents the resource usage and finally is reflected in the operating costs because higher satellite EIRP means higher operating costs. On the other hand the G/T represents the capital expenditure, because higher G/T means larger antenna and/or better LNA, reflected in the cost of the equipment.

For a long term usage of an Earth station facility, it may be more economical to build a larger antenna that will require a lower downlink EIRP, compared to a smaller antenna that will require higher satellite EIRP for the same quality of service.

Note that in some cases the Earth station G/T could be improved by using a better LNA. For example, an Earth station with a receive gain of 53 dBi, antenna noise of 25°K at 25° in C-band, feeder noise temperature of 5°K and LNA noise temperature of 80°K would have:

$$G/T = G_{ant} - 10\log(T_{ant}+T_{feed}+T_{LNA}) \qquad (9.23)$$
$$G/T = 53-10\log(25 + 5 + 80) = 32.6 \text{ dB/°K}$$

This antenna would be classified as a standard B antenna.

Removing the LNA and replacing it with a 30°K LNA, the G/T is:

$$G/T = 53 - 10\log(25 + 5 + 30) = 35.2 \text{ dB/°K}$$

This reclassifies the antenna as a standard A. For elevation angles below 25°, the antenna noise would increase and the overall G/T would be too low for standard A.

The Satellite Transponder

Satellite transponders perform the same function as a radio relay repeater, i.e., receive transmission from the Earth and retransmit to the Earth after amplification and frequency translation. Satellite resources are shared among many Earth stations, with different categories of standard A, B, C, D, E, and F, and therefore, with different satellite requirements, from 51.2 kHz of bandwidth (for a 64 Kbit/s carrier with 3/4 FEC), to an entire transponder.

In addition to its bandwidth, the parameters for a given transponder are:
A) saturation flux density, (dBW/m^2)
B) receive G/T, (dB/°K)
C) saturation EIRP, (dBW)

(Also see *IESS 410.*)

Saturation flux density (SFD) is the total power flux density arriving at the satellite from the Earth segment that will produce the saturation EIRP from the satellite and can be found in *IESS* 410, Appendix A, Table 1.

Transponder Operating Point

As the transponder output power amplifier is not a linear device, it must be operated below the saturation point to avoid nonlinear distortions.

Therefore, an input and output backoff (IBO and OBO, respectively) will be required to achieve that point. (See Figure 9.6.) This is an unavoidable waste of available power in a typical TWTA.

The input backoff is defined as the ratio of saturation flux density to the operation flux density for a given carrier.

The output backoff is defined as the ratio of saturation EIRP to the operation EIRP for a given carrier.

The output backoff is also defined as

$$OBO = IBO - X \qquad (9.24)$$

"X" is the gain compression ratio between the IBO and OBO. This value is different for single carrier and multicarrier operation (as shown in Figure 9.6). The value can be obtained from *IESS* 410 Appendices B through E, Transponders Definition Tables, Note A3a.

Those tables have, for example:

X = 5.5 dB for a TWTA in INTELSAT VI HEMI/HEM.
X = 1.8 dB for a SSPA in INTELSAT VII HEMI/ZONE.
X = 1.7 dB for a LTWTA in INTELSAT VII-A Ku-spot.

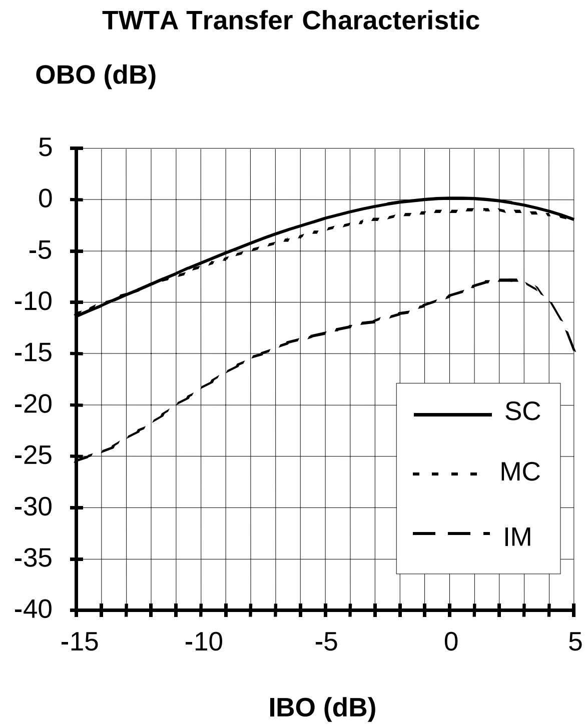

Figure 9.6 Transponder Transfer Characteristic and IM Products Generation

Transponder Operating EIRP

The operating satellite EIRP ($EIRP_{op}$) is calculated from equation (9.24) as:

$$EIRP_{op} = EIRP_{saturation} - OBO \quad (9.25)$$

Noise Components of the Link Budget

Uplink Thermal Noise

Uplink thermal noise is caused by the inherent noise in the satellite receiving system.

When calculating uplink C/T, a margin for the antenna pointing errors and rain attenuation should be taken into account. Typically, 0.5 to 1.0 dB is left for pointing errors. In the C-band it is normal to ignore rain attenuation except in areas with very high rainfall rates. In the Ku-band, margins of

2.0 to 4.0 dB are normal. INTELSAT can provide guidance in selecting appropriate margins for rain attenuation.

Uplink thermal noise is calculated using the following formula:

$$C/T_{up} = EIRP_{up} - L_{up} + G/T_{sat} + \beta_{up} - m_{up} \quad (9.26)$$

Where:
$EIRP_{up}$ = uplink EIRP
L_{up} = path loss for the uplink
β_{up} = uplink pattern advantage
m_{up} = margin for rain and tracking error, etc.

Earth Station HPA Intermodulation Products

Wideband HPAs operating under multicarrier conditions can generate intermodulation products over the entire satellite frequency band (500 MHz).

Thus, even if the user's plan involves only one carrier per HPA, there is still a potential for interference from intermodulation products generated from other stations operating under multicarrier conditions in the same uplink beam.

The C/T_{HPAIM} is derived from the HPA-IM limits provided in Tables 4 and 5 of *IESS*-601:

$$C/T_{HPAIM} = EIRP - A + X - 192.6 \text{ dBW/°K}$$

Where:

A = HPA IM limit at 10° elevation angle
X = correction factor for elevation angle and Earth station location:
$X = 0.02(\alpha_u - 10) + \beta_u + \gamma[0.02(\alpha_d - 10) + \beta_d]$
(For calculation, see *IESS-402*, Table 1.)

Where:

α_u = elevation angle of the transmit E/S
β_u = difference between the satellite receive beam edge of coverage gain and the gain in the direction of the transmit E/S (supplied by INTELSAT) in dB
γ = the fraction of the downlink factor to be used in total factor adjustment
α_d = worst located receiving E/S elevation angle
β_d = difference between the satellite transmit beam edge of coverage gain and the gain in the direction of the worst located receiving E/S (supplied by INTELSAT) in dB

Co-Channel Interference

This interference is caused by carriers on the same satellite, at the same frequency, but in different up and down beams (frequency reuse), which are separated either spatially or by using the opposite polarization.

Co-channel interference information is given in *IESS* 410 Table 1(a) for every satellite and beam. This value is given as a Carrier-to-Interference (C/I) ratio in dB. Therefore, to convert to C/T, use:

$$C/T_{cci} = C/I + 10 \log (OccBw) - 10\log k \qquad (9.31)$$

Where:

OccBW =carrier-occupied BW, and refers to the carrier for which the calculation is being performed.

Transponder Intermodulation

Transponder intermodulation is specified as a limit of EIRP density transmitted from the transponder in a 4 kHz bandwidth at the beam edge. The limits are given in *IESS* 410 Tables 2a and 2b, for every satellite beam.

$$C/T_{sat\ im} = EIRP_{down} - SAT_{im} + \beta_{down} - 192.6\ (dBW/°K) \qquad (9.32)$$

Where:
$EIRP_{down}$ = downlink EIRP
SAT_{im} = specified intermodulation limit in 4 kHz
β_{down} = D/L pattern advantage

Downlink Thermal Noise

The downlink thermal noise is the noise caused by the Earth station receiving system. As in the uplink thermal noise case, a margin should be considered to allow for rain attenuation and tracking errors.

$$C/T_{down} = EIRP_{down} - L_{down} + G/T_{E/S} - m_{up} \qquad (9.33)$$

Where:
C/T_{down} = downlink EIRP
L_{down} = downlink path loss
$G/T_{E/S}$ = Earth station figure of merit
m_{up} = downlink margin for tracking and rain.

Total Link Carrier-to-System Noise Temperature (C/T_T)

The value of the ratio C/T_T for the whole link, is obtained from the preceding ratios using the equation:

$$1/(C/T_T) = 1/(C/T_{up}) + 1/(C/T_{down}) + 1/(C/T_{im\ e/s}) + 1/(C/T_{sat\ im}) + 1/(C/T_{cci}). \quad (9.34)$$

Note that C/T ratios in the above formula are in numerical values and the C/T total has to be converted to a logarithmic relation. Furthermore, the total C/T ratio, as shown in Figure 9.5, will be lower than the lowest C/T ratio, as the noise is additive.

Therefore, in a satellite link, the uplink must be strictly kept at the nominal level; a low EIRP level means low C/N_o, but as shown in the figure below, a higher EIRP level does not necessarily mean better C/N_o.

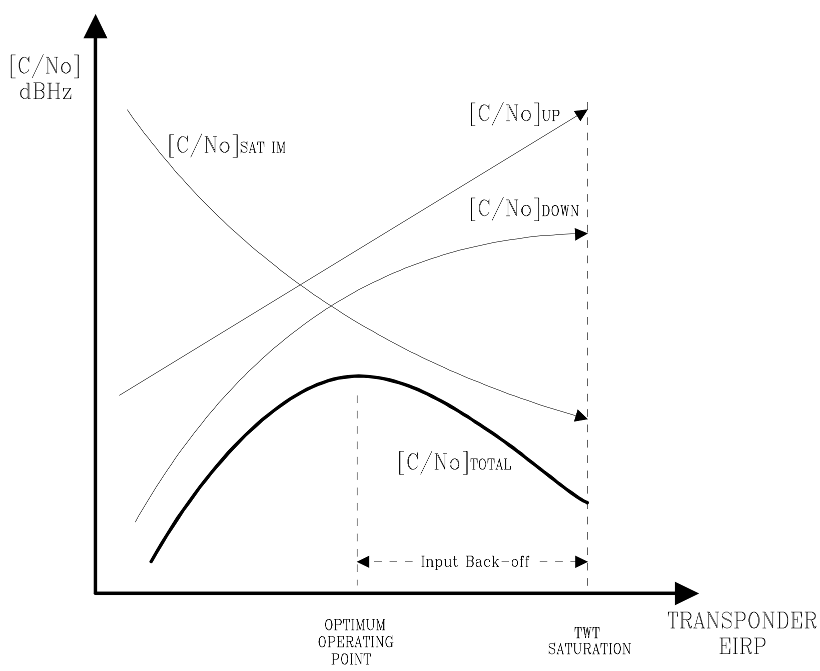

Figure 9.5 Variation of (C/N_o) as a Function of Carrier Power

HPA Sizing

The link budget calculations are made considering each carrier separately. However, when deciding the required HPA size, the total EIRP for all carriers must be taken into account, together with the required backoff.

For example, if the HPA transmits two carriers having $EIRP_1$ and $EIRP_2$ levels, then the total EIRP is calculated converting the two carrier powers to Watts.

After calculating the total power required at the antenna input, the feed losses and output backoff of the HPA must be taken into account as shown in the table below.

Table 9.5 HPA Sizing

Parameter	Formula	Value	Units
EIRP Carrier 1 ($EIRP_1$)		60.1	dBW
EIRP Carrier 2 ($EIRP_2$)		63.2	dBW
EIRP Total through HPA ($EIRP_t$)	=10*LOG(10^($EIRP_1$/10)+10^($EIRP_2$/10))	64.9	dBW
Antenna Gain (G_{ant})		52.9	dB
Feed Losses (L_f)		1.0	dB
Power required at HPA output (P_{req})	=$EIRP_t$-G_{ant}+L_f	13.0	dBW
HPA Back-off (PA_{OBO})		8.0	dB
Saturated HPA output power (P_s)	=P_{req}+PA_{OBO}	21.0	dBW
HPA Size	=10^(Ps/10)	126.8	W

9.4 Examples

Example 1. 1024 Kbit/s IDRcarrier
Country A wants to establish an IDR/LRE link with country B, to provide telephony services. Country A will transmit through INTELSAT 704 at 66 degrees E, using zone beams ZD/ZC.

Space segment parameters:

Transponder saturation EIRP:	32.7 dBW.	*
Bandwidth:	36 MHz.	*
Saturation Flux density (high gain)	-87.0 dBW/m^2	*
Receive system G/T	-4.8 dB/°K	*
C/I co-channel interference	19.0 dB	**
Transponder gain compression ratio	1.8 dB	***

* *From IESS 410*, Appendix A Table 1
** *From IESS 410*, Table 1(a)
*** *From IESS 410*, Appendix D, Table 3 Note 3A

Station parameters:

		Station A	Station B
Location	Latitude N	44.50°	28.15°
	Longitude E	20.63°	77.35°
Antenna Diameter		15.2 m	18.0 m.
Antenna gain (6 GHz)		55.16 dBi	57.32 dBi
Antenna efficiency		60%	65%
System G/T		35.6 dB/°K	36.4 dB/°K
Elevation angle		20.18°	55.90°
Beta factor		β_u = 0.6 dB	β_d = 1.7 dB*
Tracking		AUTO	AUTO

* From *IESS 409,* Rev. 2, Figure 11 (estimated value)

Carrier parameters:

(from *IESS 308,* Appendix D)

Carrier rate	1.024 Mbit/s
FEC rate	3/4
Occupied bandwidth	873.8 kHz
Typical BER at operational point	1×10^{-10}
C/T at operational point	-157.2 dBW/°K
C/No at operational point	71.4 dBHz
C/N at operational point	12.0 dB
Operational frequency	6280.00/4055.00 MHz

Preliminary calculations:

Slant Range:

Distance Station A to satellite:	39,536.363 Km
Distance satellite to Station B:	36,727.422 Km

Free space loss:

Using equation (9.12) where Lo = 20 log D + 20 log f + 92.5 dB
L_{ou} = 200.4 dB for uplink, at 6.280 GHz (Station A to satellite)
L_{od} =195.9 dB for downlink, at 4.055 GHz (Satellite to Station B)

Satellite EIRP

Equation (9.21) demonstrates that C/T = EIRP - L_o + G/T, therefore, the satellite EIRP can be calculated.

$EIRP_{SAT}$ = C/T - G/T + L_{od} - J_d + Margin

Where:
Margin = rain margin + tracking margin (3.5 dB for downlink.)
C/T is the expected C/T at the operational point.
G/T is the receive antenna G/T (Station B).

$EIRP_{SAT}$ = -157.2 dBW - 36.4 dB/°K+ 195.9 dB - 1.7 dB + 3.5 dB

$EIRP_{SAT}$ = 4.1 dBW

The backoff is calculated as:
OBO = $EIRP_{SATURATION}$ - $EIRP_{OPERATION}$
OBO = 32.7 dBW - 4.1 dBW
OBO = 28.6 dB

Input backoff (IBO):
IBO = OBO + X
IBO = 28.6 dB + 1.8 dB
IBO = 30.4 dB

Uplink operational flux density (OFD or illumination level W)

W = Saturation Flux density - IBO
W = -87.0 dBW/m^2 - 30.4 dB
W = -117.4 dBW/m^2

Transmit Station EIRP

From equation (9.14):
$EIRP_{dBW} = W + L_{ou} - G_{1m}{}^2 - J_u$ + Margin.

Where:
$G_{1m}{}^2$ = 37.3 dBm^2 for 6.280 GHz. from equation (9.4)
Margin = 2.5 dB, for rain and tracking (uplink margin)
$EIRP_{dBW}$ = -117.4 dBW/m^2 + 200.4 dB - 37.3 dBm^2 - 0.6 dB + 2.5 dB
EIRP = 47.6 dBW

The power required from the HPA will be:

P_{HPA} = EIRP - G + feeding losses
Where “G” is the transmit antenna gain.

Assuming 3.6 dB of feeding losses:

P_{HPA} = 47.6 dBW - 55.16 dBi + 3.6 dB
P_{HPA} = -3.96 dBW or 0.4 Watts

Link Quality

The overall link quality for clear sky conditions is computed by calculating the total C/T as explained previously, by using equations (9.26) to (9.34).

C/T_{up}

$C/T_{up} = EIRP_{dBW} - L_{ou\ dB} + G/T_{dB/°K} + J_u - Margin$

$C/T_{up} = 47.6 - 200.4 + (-4.8) + 0.6 - 2.5$

$C/T_{up} = -159.5$ dB/°K

C/T_{HPAIM}

$C/T_{HPAIM} = EIRP - A + X - 192.6$ dBW/°K

From *IESS-601*, the limit for intermodulation products at a 10° elevation angle at beam edge is –21 dBW/4kHz.

The correction factor "X" can be calculated from *IESS-402*.

$X = 0.02(20.18 - 10) + 0.6 + 0.4(0.02(10 - 10) + 1.7) = 1.5$ dB

Then:

$C/T_{HPAIM} = 47.6 - 21 + 1.5 -192.6 = -164.5$ dBW/°K

Satellite IM Products

As defined in *IESS* 410 Table 2(b) for INTELSAT VII, ZONE/ZONE beam, the maximum Transponder IM EIRP is -37.0 dBW/4 kHz, at beam edge. Using formula (9.32) from the above calculations, $EIRP_{SAT} = 4.1$ dBW.

$C/T_{SAT\ IM} = EIRP_{SAT} - SAT_{IM} + 10Log\ 4kHz - 228.6_{\ dBk}$

$C/_{TSAT\ IM} = 4.1$ dBW - (-37.0) dBW/4kHz - 192.5 dB

$C/_{TSAT\ IM} = -151.4$ dBW/°K

Satellite Co-Channel Interference

As defined in *IESS 410* Table 1(a) for INTELSAT VII, the maximum carrier-to-co-channel interference will be C/I = 19.0 dB. Converting this value to C/T by using the formula (9.31):

$C/T_{CO} = C/I + 10\log(\text{occupied BW}) - 228.6$

$C/T_{CO} = 19.0 + 59.41 - 228.6 = -150.18$ dBW/°K

Receive Station C/T

$C/T_{dn} = EIRP_{SAT} - L_{od\ dB} + G/T_{dB/°K} + J_d$ - Margin

C/T_{dn} = 4.1 dBW - 195.9 dB + 36.4 dB/°K + 1.7 dB -3.5 dB

C/T_{dn} = -157.2 dB/°K

C/T Total

The C/T total can be calculated using the formula (9.34) in numerical values.

$1/(C/T_T) = 1/(C/T_{UP}) + 1/(C/T_{DOWN}) + 1/(C/T_{HPAIM}) + 1/(C/T_{SAT\ TWT\ IM}) + 1/(C/T_{CO})$

$10 \log \{1/(C/T_T)\} = 1/(10^{-159.5/10}) + 1/(10^{-157.2/10}) + 1/(10^{-164.5/10}) + 1/(10^{-151.4/10}) + 1/(10^{-150.2/10})$

C/T_T = -166.0 dB/°K
C/N_o = C/TT + 228.6 dBK
C/N_o = 62.0 dBHz

C/N = C/N_o + 10 log (occupied BW)
C/N = 62.0 dBHz + 10 log (873.8kHz)
C/N = 3.0 dB

As is clearly seen at this point, the final C/N is 9.0 dB worse than the objective, but the actual process of calculating a link budget is iterative. Increasing the station EIRP and calculating the link quality again, the final transmit station EIRP will be 60.1 dBW.

Note that the values for C/I_{CO} and transponder IM assume the worst case values, therefore our carrier will have a better C/N.

Example 2 Level Plan

A Standard A Earth station with a G/T of 35.5 dB/°K will receive a 2048 Mbit/s IDR. A level plan must be prepared to align the receive path gain so as to have the demodulator input level as suggested in SSOG 308.

Carrier Characteristics

Information rate:2.048 Mbit/s
FEC 3/4
Overhead 96 Kbit/s
C/T = 155 dBW/°K for BER 10^{-10} (for INTELSAT VII)

The level plan in the receive station can be used to determine the proper gain in the down converter to drive the demodulator as the SSOG indicates "at least 10 dB above the minimum receive level". The power arriving at the receiver is calculated by using equation (9.21).

If $G/T_{dB/k}$ = C/T - EIRP + L_0 , then EIRP = (C/T - $G/T_{dB/°K}$) + L_0 the expression (C/T - $G/T_{dB/°K}$) represents the power arriving at the antenna.

Then,

Power arriving at the antenna = (C/T - G/T)
Power arriving at the antenna = -155 dBW/°K - 35.5 dB/°K
Power arriving at the antenna = -190.5 dBW (-160.5 dBm)

Equipment Characteristics

LNA gain	60 dB
Downconverter:	
Gain	25 to 45 dB variable
Gain adjustment	20 dB
Demodulator:	
Input level	-30 to -55 dBm
(A proper operational point would be	-40 dBm)

Figure 9.9 shows the proper setting in the receive path to provide the demodulator with an adequate input level.

Nr.	Equipment	Gain (dB)	Output Level (dBm)	Final Gain	Output Level Setting (dBm)
1	Received Level		-160.5		
2	Antenna Gain	55.8	-104.7		
3	Feed Losses	-0.2	-104.9		
4	Switching	-0.5	-105.4		
5	LNA	60	-45.4		
6	Switching	-0.5	-45.9		
7	RF Link	-1.3	-47.2		
8	Divider	-6.2	-53.4		
9	Divider	-6.2	-59.6		
10	Switching	-0.5	-60.1		
11	Downconverter	25 to 45	-35.1 to -15.1	38	-22.1
12	Switching	-0.5	-36.6 to -15.6	-0.5	-22.6
13	IF Link	-0.2	-35.8 to 15.8	-0.2	-22.8
14	Demodulator Protection Switch	-17.0	-52.8 to -32.8	-17.0	-39.8
15	Demodulator input level	-30 to -55			-39.8

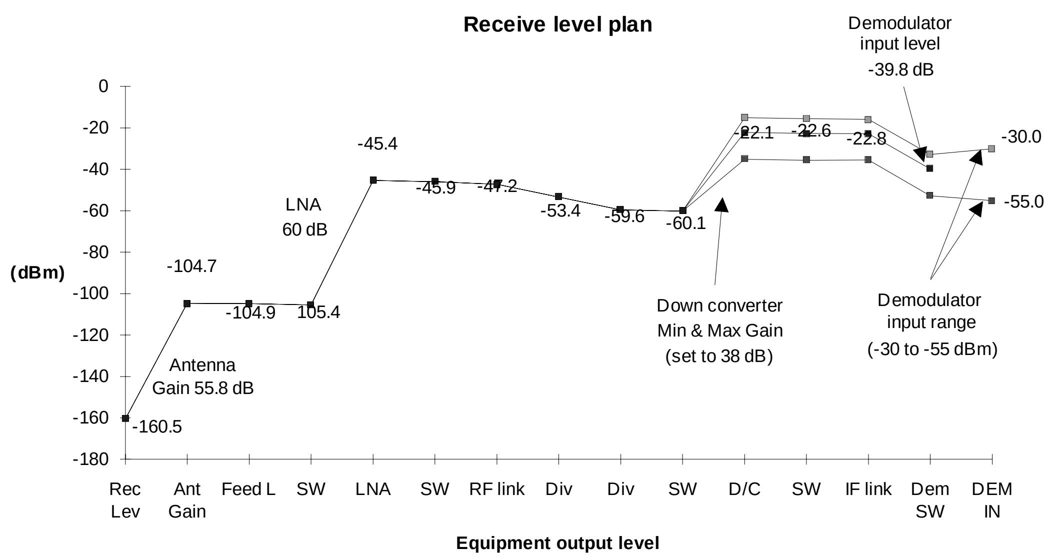

Figure 9.9 Receive Level Plan

Conclusions

Link analysis equations are essential to analyze the system performance. The same information can be used in antenna acceptance tests, equipment requirements, satellite resources requirement calculations, network design, and cost estimates.

9.5
Student Question Paper

Using the link analysis equations, determine the normalized receive station G/T for a F-2 Earth station (diameter 7.5 m), if the following information is provided:

Normalized frequency	4 GHz
Satellite EIRP	31.0 dBW
Downlink Aspect correction	1.85 dB
C/No measured at the receiver	88.4 dBHz
Downlink slant range	40,586.98 km
Atmospheric losses	0.15
Operating Frequency	4.037 GHz

SOLUTION : G/T = 27.3 dB/°K at 4 GHz

CHAPTER 10
ENGINEERING SERVICE CIRCUIT (ESC)
AND POWER PLANT

10.0 Introduction

The Engineering Service Circuits (ESCs) provide the communications facilities necessary for operational management of the INTELSAT system.

The conversion to a digital ESC network began in 1994 when the analog leased lines from INTELSAT to the ESC gateway sites were converted to 64 Kbit/s digital circuits. In 1996, the 64 Kbit/s digital circuits between the ESC gateways and INTELSAT were converted to frame relay. INTELSAT ESC will remain backward- compatible in support of keyboard-to-keyboard teletype until the end of 2001.

IESS 403 has been modified to define the physical interface and protocols used for the 64 Kbit/s ESC interface within the 96 Kbit/s overhead of IDR carriers 1.544 Mbit/s and above. IDR modem specifications have been modified to create a 64 Kbit/s digital channel for ESC. The 64 Kbit/s ESC channel combines the two 32 Kbit/s ADPCM channels, P1 and P2, currently used for analog ESC. By installing a Frame-Relay Access Device (FRAD) at the Earth stations, customers with IDR modems with the digital ESC interface can multiplex voice and data onto the 64 Kbit/s ESC channel and connect to the digital ESC network.

Digital ESC Features

INTELSAT's digital ESC Network provides a gateway to a variety of online operational, technical and financial services. The digital ESC creates an Extranet that is an extension of INTELSAT's corporate Intranet. With the exception of voice and facsimile, all applications available to participants of the digital ESC Network are based on Internet technology. Online documents and databases are viewed and searched by using a standard World Wide Web (WWW) browser on a workstation PC.

Capacity management tools and a TV booking application called TVMAX are also web-based applications that will be accessible on the digital ESC's Extranet. Electronic mail and a service called Internet Relay Chat (IRC) will replace the store-and-forward TTY and the conversational teletype of analog ESC. The IRC service allows users with the IRC client application to have a keyboard to keyboard real-time conversation with other users with the IRC client.

In addition to these Extranet applications, voice can operate simultaneously over the 64 Kbit/s ESC channel. In Frame Relay networks, voice and data packets coexist. Because PBXs have replaced the aging ESC switches at the Gateways, new features are available, such as station-to-station direct dialing to all ocean regions, and direct dial to INTELSAT internal extensions. The addition of the FRADs at the ESC gateways has made facsimile over ESC possible to stations with FRADs that support the facsimile feature.

Network Topology

The digital ESC network architecture is a star/mesh network topology. Frame-relay switches located at the gateway Earth stations provide the connectivity to the IOC via terrestrial digital networks. With the exception of Goonhilly, all gateway sites connect directly to the IOC via the Public Frame Relay Network. Goonhilly's frame-relay switch is connected via a drop-and-insert from a dedicated E1 circuit between Goonhilly and Madley. To provide additional redundancy for the AOR, a leased T1 circuit connects the Etam and Roaring Creek PBXs. In this configuration, many Earth stations will have redundant ESC paths to the IOC. Figure 10.1 shows the digital ESC network topology.

Any Earth station that has operational ESC to the IOC can be directly connected to any other station that is connected to the IOC, regardless of the ocean region. When two Earth stations wishing to establish a connection to each other work directly to the same ESC Gateway, the local Gateway switch will process the call. When two stations operating through different ocean regions establish a connection, the sites are connected through the IOC.

The primary route for calls between stations operating Etam and Roaring Creek is a dedicated T1 between the two sites; the secondary route is the frame-relay link to the IOC. Similarly, the primary route for calls between stations operating to Madley and Goonhilly is a dedicated E1 between the two stations, and the secondary route is the frame-relay link to the IOC. Figure 10.2 is an example of the global ESC network.

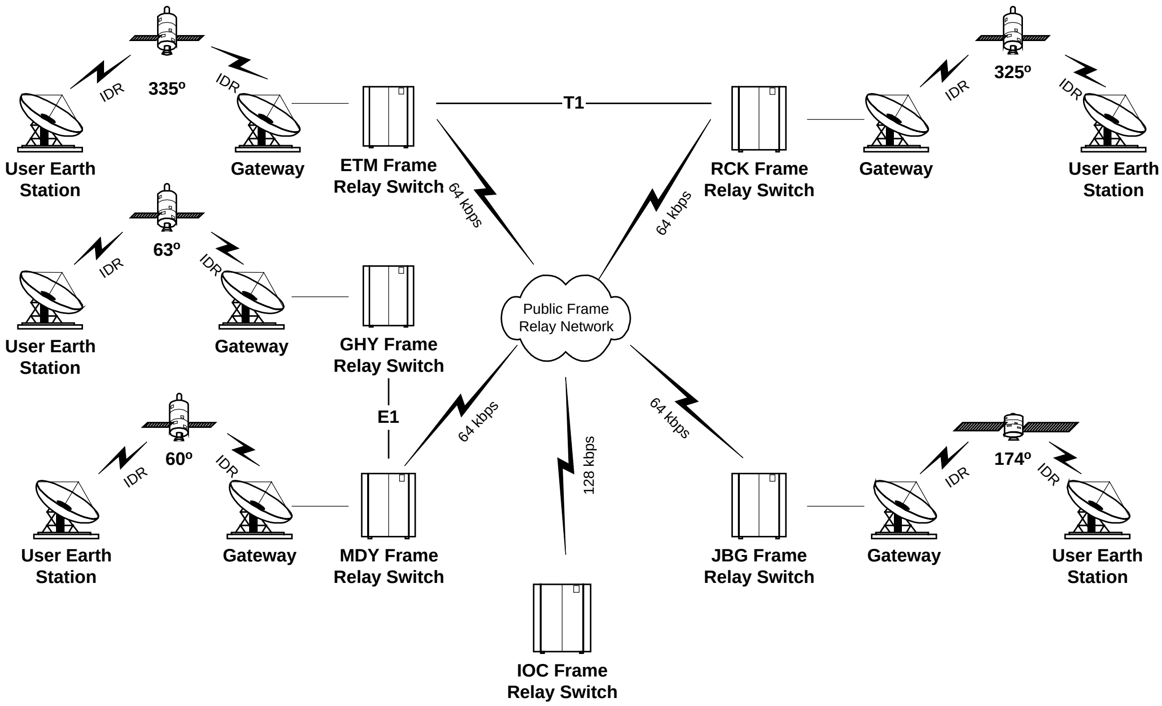

Figure 10.1 Global ESC Network

Each Earth station participating in the digital ESC network connects to the gateway frame-relay switch either through the 64 Kbit/s ESC interface of the digital IDR modem, or via P1 or P2 of the IDR modem.

For 64 Kbit/s digital ESC access, Earth stations will use the 64 Kbit/s ESC channel to connect to the INTELSAT Local Area Network (LAN). At the Earth station, a FRAD will be connected to the 64 Kbit/s ESC interface on the IDR modem. At the gateway site, the 64 Kbit/s ESC output of the IDR modem interfaces to a frame-relay switch, that routes the channel over the frame-relay network to INTELSAT, or to other Earth stations in the ESC network.

Backward Compatibility for Analog ESC

During the migration to a digital ESC network, the system will retain its backward compatibility for analog ESC users. Stations that cannot upgrade to a digital ESC will continue to access the ESC via P1 or P2.

Frame Relay Backbone

While Earth stations can have either analog or digital ESC access, the digital ESC network has an all-digital, terrestrial, frame-relay backbone. Frame-relay is a technology that is characterized by fast packet switching that can carry voice and data. Frame Relay allows assignment of a Committed Information Rate (CIR) to ensure a minimum service quality, making it ideally suited for traffic that is bursty in nature.

Frame Relay Equipment

Standard frame-relay equipment at the gateways and the IOC include frame-relay switches, FRADs, and frame-relay compliant routers. Frame-relay switches and routers reside in the IOC and at the gateway sites. FRADs are located at the gateway stations, in the IOC, and at the user Earth stations with 64 Kbit/s digital ESC access. Figure 10.3 shows the typical equipment configuration at the ESC gateways.

FRADs multiplex voice, facsimile, and data, where each service has assigned a specific priority to optimize the effects of delay and jitter. Because frame-relay makes use of silence in voice and data transmissions, compressions of 4-to-1 and even 8-to-1 can be achieved. Using CS-ACELP, the FRAD can maintain toll quality voice at bit rates between 4 and 8 Kbit/s.

Permanent Virtual Circuits (PVCs) are built from each ESC gateway's frame-relay switch to the IOC's frame-relay switch. PVCs are unidirectional logical connections to endpoints defined in the network. Frame-relay data are divided into variable-length frames, all of which include addressing information. The frames are delivered to the specified destination over an assigned PVC. Data Link Connection Identifiers (DLCIs) define the logical endpoints of a virtual circuit.

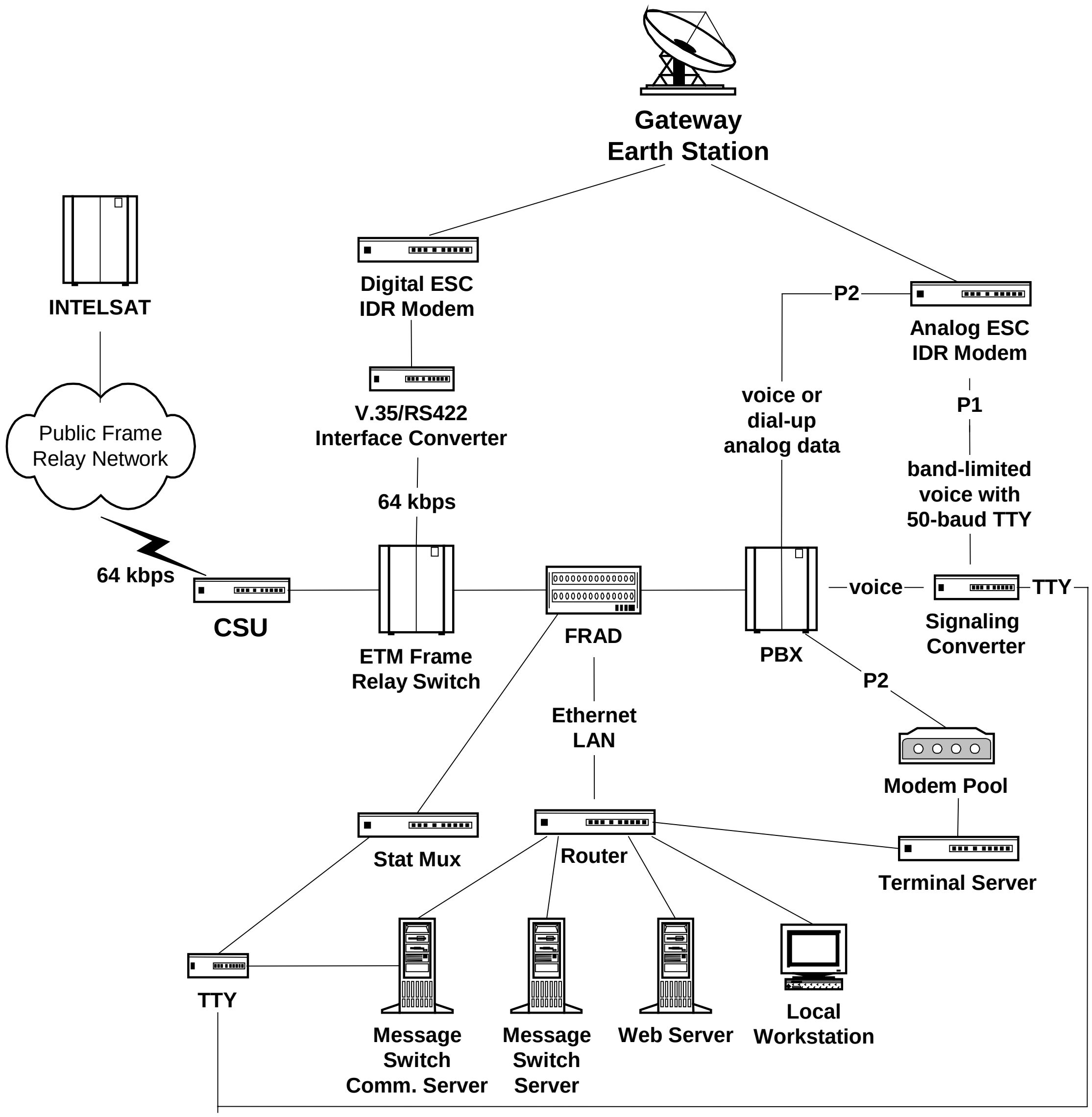

Figure 10.2 ESC Gateway Architecture

Implementation Options for 64 Kbit/s ESC Access via 2 Mbit/s IDR Carriers

The 64 Kbit/s ESC access requires that the station IDR modem support the 64 Kbit/s ESC channel and protocol. This access method provides the Earth station with 64 Kbit/s LAN access to the INTELSAT ESC Extranet, electronic mail, and station-to-station voice direct dialing.

Minimum Earth Station Equipment for 64 Kbit/s ESC

The minimum Earth station equipment required for the full 64 Kbit/s access includes an IDR modem that supports the 64 Kbit/s ESC, a FRAD that supports Ethernet LAN access, and at least one voice channel. Figure 10.4 shows the minimum Earth station equipment for 64 Kbit/s ESC.

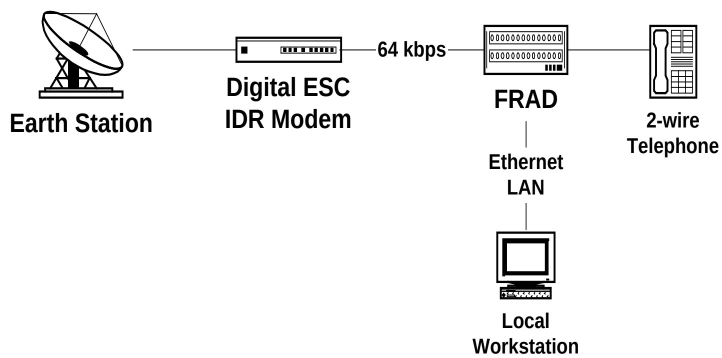

Figure 10.3 Digital ESC Earth Station Equipment

Analog Dial-Up ESC Extranet Options

Two possible configuration options are shown below for stations that have 2 Mbit/s IDR carriers working to one of the ESC gateways, but have IDR modems that cannot be upgraded to support the 64 Kbit/s ESC channel. Dial-up ESC Extranet access is available through the 32 Kbit/s ADPCM channel at a rate up to 9.6 Kbit/s. The signaling converter is required to translate the 2280 supervisory signaling to 2-wire dial-up modem.

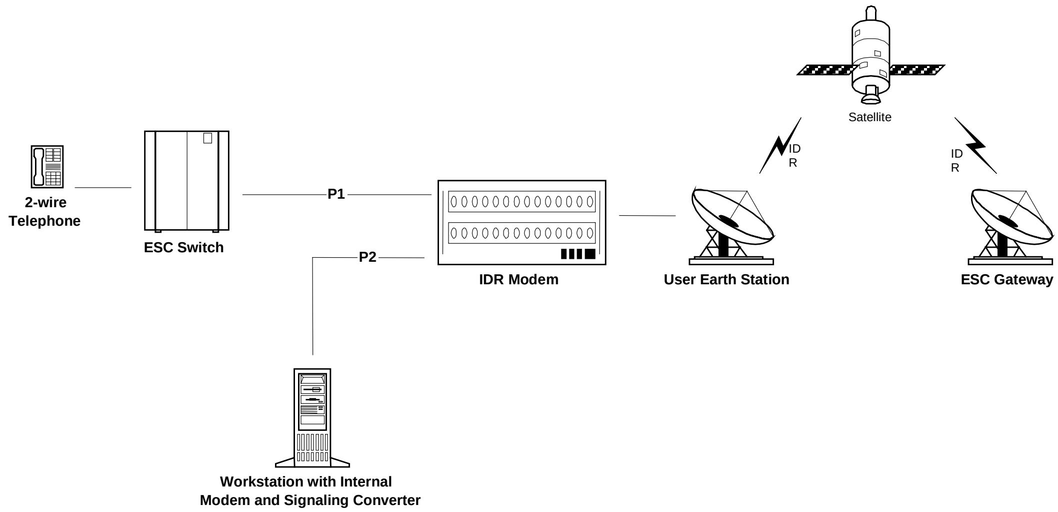

Figure 10.4 Analog Dial-Up for Station with ESC Switch

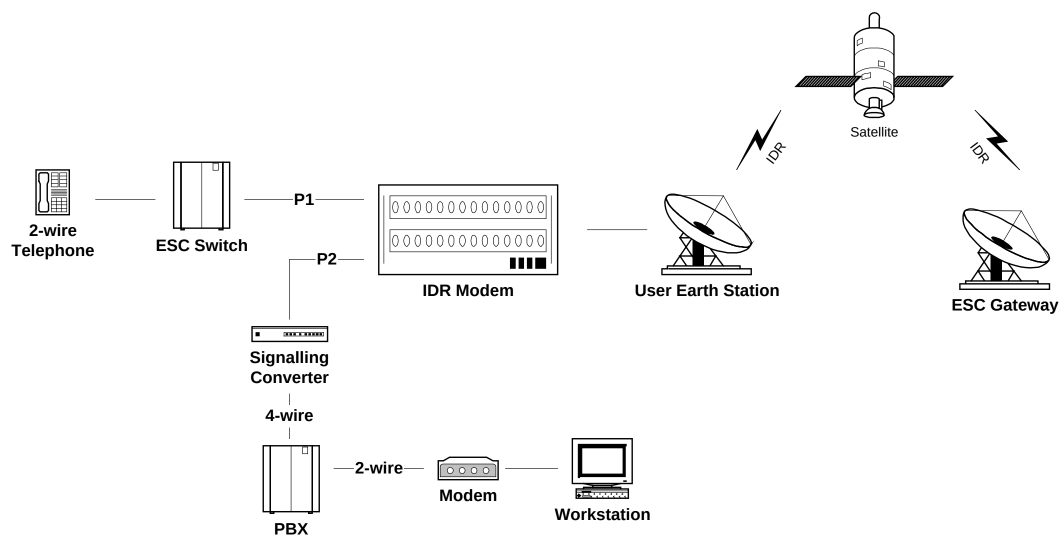

Figure 10.5 Analog Dial-Up for Station with PBX and ESC Switch

Priorities

Normally INTELSAT's communication will be via the telegraph ESCs of the system management network or IRC (Internet Relay Chat); however, occasions may arise that require INTELSAT to have priority access to the voice ESC's. For these occasions, there is a clearly defined order of priorities that is shown below.

PRIORITY 1: TOCC-to-Earth station calls in declared satellite emergencies.

PRIORITY 2: Service calls required for faults causing loss of traffic and calls required to implement rerouting or restoration procedures in the event of a major failure.

PRIORITY 3: Service calls required for faults affecting traffic or grade of service.

PRIORITY 4: Service calls required for line-up and introduction of new traffic.

PRIORITY 5: Service calls required for routine maintenance.

System Discipline

It must be emphasized that ESCs provide the primary communication required for the management, operation, and maintenance of the INTELSAT system. Therefore, the use of ESCs is only authorized for the system management network, control, and maintenance network, and backbone service network. Other communications should be via normal administration or commercial facilities.

POWER PLANT

Introduction

The power plant is most responsible for Earth station outages.

The continuation of reliable communications during power failures is of vital importance during emergency situations. Customers resent a telecommunications link failure. To the telecommunications operator, the loss of circuits due to power failures represents a loss of revenue. It is a fact that power faults, either directly or indirectly, account for 80 percent of all outages.

POWER DEFECTS ACCOUNT FOR 80 PERCENT OF ALL OUTAGES!

To protect circuits against outages due to power failures, telecommunications operators provide emergency power supplies. These range from the simple parallel operation of a rectifier and battery, through to uninterruptible power supplies (UPS) that provide power for the essential station load (HPAs, LNAs, etc).

Also, in the event of a main power supply failure, the most common cause of a standby generator failing to start is starter battery failure.

60 PERCENT OF ALL STANDBY POWER PLANT FAILURES ARE DUE TO STARTER BATTERY FAULTS!

Technicians must know the various systems used on their station and become familiar with the switching operations or procedures to be followed, either in the normal operation of the system or when unusual conditions prevail.

Supply Phases

The power supplied by the local authority may be taken as one or more voltages and may be single-phase or multiphase (usually three).

Isolator

The supply is generally taken at a high voltage from three phases. It normally passes through an isolator that is a switch whereby the main power supply can be isolated from the Earth station.

Transformer

From the high-voltage isolator the supply passes to a step down (reducing) transformer. This reduces the voltage to a value suitable for connection to three-phase equipment, and also extends the neutral connection so that a single phase supplied between each phase and neutral is available for lighting and other low-voltage single-phase loads.

Often the high-voltage isolator and transformer are installed in a separate brick enclosure.

Distribution

The output voltage then passes to the distribution switchboard. The output of the emergency generator(s) is at the same voltage, and arrangements are made to transfer the load to the generators either automatically or manually in the event of a power failure.

Figure 10.6 shows a typical distribution system. The distribution has been split into areas that have a noisy and quiet supply - sometimes referred to as dirty and clean supplies. Telecommunication equipment is connected to the quiet supply that is isolated from transients due to switching, and noncommunications equipment, such as lights and air conditioning, is connected to the noisy supply. Both supplies are rated as "essential".

Areas that are not essential to the maintenance of communications, i.e., administrative offices, etc., are often connected to the essential supply if generating capacity is available.

Uninterruptible Power Supplies (UPS)

The short delay between power failure and the automatic change over to generator supply after the engine has started up cannot be allowed to occur to essential equipment. This is especially so where the equipment carries a large number of circuits. In this case, arrangements must be made to supply the equipment with an UPS.

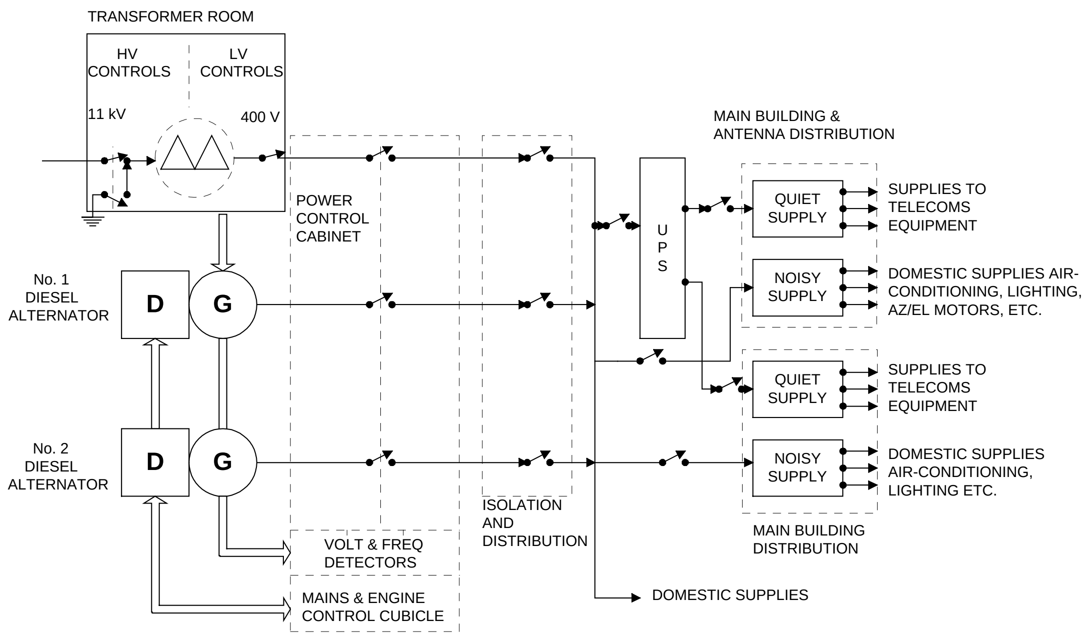

Figure 10.6 Typical Power System

Static Inverter

With the advent of high-power semiconductor devices, a type of equipment known as a "static inverter" to replace the motor alternator, and thus, eliminate the need for rotating machines, was developed. Figure 10.7 shows the static inverter arrangement.

The inverter accepts DC power at its input and delivers AC power at its output. It does this simply by acting as an electronic switch which connects the load alternatively to the positive/negative poles of a DC supply, and then to the negative/positive poles, at a rate appropriate to the frequency of the required AC output.

The switching elements used are semiconductor devices known as thyristors (silicon-controlled rectifiers).

The output is not sinusoidal but a square wave AC waveform of a frequency determined by the oscillator frequency. The square waveform is adequate for some purposes, e.g., lighting and motor drive applications. Most equipment requires a sinusoidal waveform making it necessary to pass the square wave through a filter to obtain the sinusoidal form.

Bypass Switch

All Earth stations equipped with no-break systems must have at least one standby generating system, which may be called on to supply the total load during routine maintenance of the no-break system or in the event that the no-break becomes faulty. A bypass switch must be provided to allow either automatic or manual transfer of the load (Figure 10.6).

The on-shift technician must be able to locate and operate the bypass switch in an emergency situation.

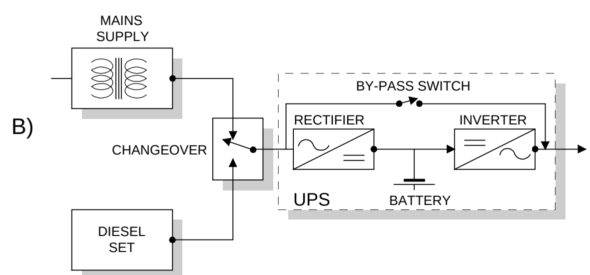

Figure 10.7 Power Plant Standby Diesel with No-Break

All power supplies, whether main, standby diesel sets, or no-break sets, should be grouped onto one or more adjacent switchboards. Switching arrangements should permit the transfer of loads between the various sources of supply. Loads need to be transferred back to the mains or between sets without a break, and these sets need to be synchronized during the switching operation. Facilities must be available to ensure correct synchronization and protection in the event of a malfunction. It must be emphasized that as a general rule, power supply companies do NOT allow parallel operation of private plant with their supplies and any local restrictions must be strictly followed. Parallel operation of your own plant requires experience and care and should not be attempted if there is any doubt.

Typical Earth Station Power System

The mains transformer and switching equipment in the transformer room is power rated for supply to the complete Earth station including the antenna.

The power plant schematic shows a standby-to-mains diesel-alternator set, power control cubicle, and power distribution.

The distribution is split into two systems.

a. The Quiet Supply for the telecommunication equipment that requires fairly close voltage limits and cannot tolerate switching transients.

b. The Noisy Supply for the equipment which can tolerate such switching transients.

The technician must take care when transferring the station load from the standby generator to the mains supply and vice versa.

The diesel-alternator can be selected to start automatically upon the failure of the mains supply.

Return to the mains power supply after operating the standby generator is achieved by manually synchronizing the mains supply to the running alternator, or by just switching back to the mains supply.

In the case of a station with two diesel alternator sets when one set is running on load, provision is made for manually synchronizing the second alternator set to it for peak power requirements, or when transferring loads from one set to the other if required.

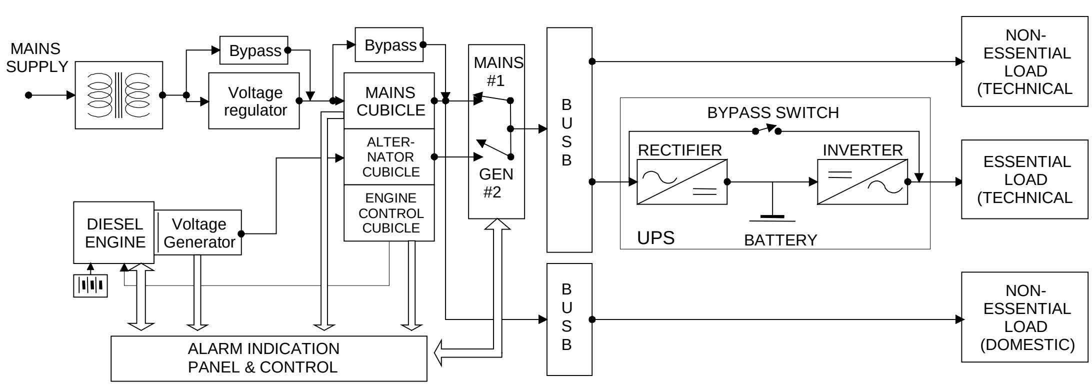

Figure 10.8 Typical Power Plant Schematic Diagram

The power control cubicle consists of three sections - Mains, Diesel-Alt, and Isolation and Distribution. Switches in the latter allow any of the sections to be completely isolated for maintenance purposes.

The following is a typical sequence of an automatic start standby diesel generating set shown in Figure 10.9.

The following conditions are monitored in the mains supply:

a. AC voltage - Must be within ± 10 percent of the nominal voltage.
b. AC frequency - Should be maintained within ± 1.5 Hz of the nominal frequency.

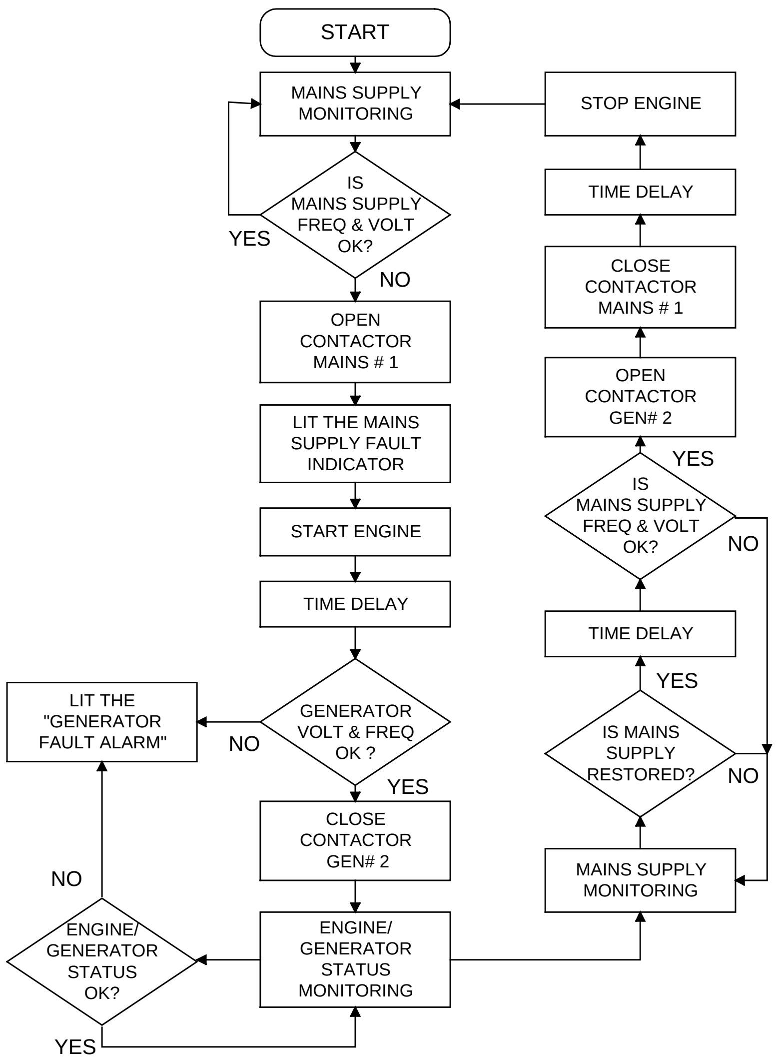

Figure 10.9 Typical Automatic Power Plant Flow Chart

The following Fault Conditions are typical of most diesel generating sets:

Engine monitoring:

a. Low Oil Pressure (LOP): should the engine oil pressure fall below a predetermined figure.
b. Engine Overspeed (OS): should the engine speed increase to 110 percent of nominal.
c. High Water Temperature (HWT): should the engine water temperature exceed 85 degrees C.

Generator:

a. AC voltage. Must be within ± 5 percent of the nominal voltage.
b. AC frequency. Must be within ± 5 Hz of nominal frequency.

If any of these conditions is out of specification, the engine will shut down.

BATTERIES

Introduction

The maintenance of batteries is very important and the on-shift technician often does the maintenance. The following text describes batteries and maintenance procedures.

Batteries (secondary cells) are used to store electrical energy for use when other supplies fail. Batteries may be required to spend a long period in the fully charged state, and then supply a large current for a short period, for example, the starter battery on an emergency diesel; or supply a lesser current for a longer period, for example, emergency lighting. To perform effectively and efficiently, careful and regular maintenance is essential.

Maintenance Equipment

Batteries may be of the lead/acid or the nickel/alkali type. The following list of equipment will usually cover the requirements of both types. Where both types of battery are in use, TWO SETS of equipment MUST be kept, and equipment from one type must NEVER be used on the other.

Electrolyte

Batteries that contain a liquid electrolyte require "topping up" from time to time. The level of electrolyte gradually becomes lower due to evaporation and/or electrolysis of the water content. Topping up entails the addition of sufficient water to restore the level. Water used for this purpose, or for mixing electrolyte, if necessary, MUST be distilled or deionized. Rainwater may be suitable, but it must be first analyzed to prove it is free of contamination. Tap water should NEVER be used.

A nonmetallic jug and funnel are useful for topping up, and a sealed container is useful for holding a stock of suitable water. Where batteries are installed in confined spaces, a rubber bulb syringe with a long nose is also very helpful.

Hydrometer

An hydrometer is essential to measure the specific gravity (sg) of electrolyte. The suction type in which the float is captive in a glass tube is most suitable for enclosed cells (e.g., engine starter batteries).

Thermometer

A thermometer that can be inserted into the cell to measure electrolyte temperature is needed. Specific gravity readings are modified by temperature and must be corrected to a standard, generally quoted by the manufacturers as 15° C. The correction to be applied is that, for each 3-degree change in Centigrade, the hydrometer reading changes by 0.002 point. When the change in temperature is positive, add the correction to the hydrometer reading.

Cell Voltage

The voltage of individual cells needs to be measured when being charged and discharged. Two different types of voltmeter are needed for these measurements. For voltage measurements while on charge, a central zero meter, scaled 3-0-3 volts, with scale divisions of 0.1 volt, is desirable; the same meter will serve to check the cell voltage while on normal discharge. However, it is necessary to simulate a high discharge current condition whenever a cell is suspected of increasing internal resistance. A special high-current discharge voltmeter, (sometimes called a flash-test meter), is used in these cases. It consists of a central zero voltmeter joined in parallel with a very low resistance load, and when applied across one cell this load, will draw upwards of 100 amperes. The voltmeter will read the cell terminal voltage under this loading; any abnormal internal resistance sulphation of the plates, or corrosion of the connections to individual plates, will cause an abnormal internal voltage drop which will lower the terminal voltage. This test should always be carried out when a cell is found to be slow in reaching the correct voltage/sg on charge when compared to other cells in the same battery.

Where a battery is made up of separate cells, the connections between them are clamped using nuts and bolts. A pair of wrenches, of the correct size, should be kept for this work and should be insulated except for the jaws. These may be purchased commercially or standard wrenches can be wrapped with tape. The main reason for insulating the wrenches is to prevent shorts across cells or between rows of cells.

Installation and Maintenance

The information given in this section is for guidance only, in the event that no manufacturers' instructions are available. When those instructions are at hand they MUST be followed.

Installation

The installation and first few charge/discharge cycles of a battery determine its subsequent length of life to a marked degree. The plates in cells, if they are supplied dry, are fragile and must be handled with care and if they are separate from the containers, extra care is needed when they are assembled into the containers. Cells supplied dry must be filled with electrolyte, and if this is made up locally, the information given previously should be understood and followed. Cells are often mounted on stands to raise them to a convenient height or to save floor space by mounting them in tiers. These stands must be strong enough to withstand the weight of the cells and rigid to prevent vibration. They must be treated with some form of anticorrosion finish and if the battery is to be insulated from Earth, then glass insulators will be needed between the stand and the cells. The charging arrangements must be able to supply the correct current for the length of time needed to complete the initial charge, and personnel must be available to record the progress of the charge during its entire length.

Connection

Connection surfaces between cells, and external wiring must be cleaned to bright metal, coated with a thin film of Vaseline (petroleum jelly), and tightened together using a nut and bolt, and the two spanners previously mentioned. Once it is tightened, the connection may be covered with a further coating of Vaseline. A fuse is sometimes fitted between two cells of a multicell battery, and it should normally be soldered between two terminal posts of adjacent cells. In general, this applies to low discharge current applications only.

Cleaning

An accumulation of dust and acid spray on stands, insulators and the tops of enclosed cells can lead to the slow discharge of cells, and regular cleaning should be part of any maintenance schedule. The frequency of the cleaning will depend on the environment of the battery room. Also, the tightness of connections can be verified, and a check made for any signs of corrosion. Loose or corroded connections can cause a drop in total terminal voltage, or where heavy discharge/charge currents are involved, local heating and loosening of the connections may take place leading in the extreme case to sparking and a risk of explosion. Corrosion must be dealt with by cleaning and remaking the connection.

Maintenance also includes the regular charging of batteries and the recording of voltage and sg readings.

Safety

Safety of personnel when working around batteries and handling electrolyte is of primary importance.

A safety checklist should include:

1. goggles for eye protection,
2. rubber apron for body protection,
3. rubber boots for protection of the legs and feet,
4. rubber gloves for protection of the hands.

All of the above are essential for adequate safety.

When using the safety equipment, the apron should hang down below the top of the boots so that any electrolyte running down the apron will not drop into the boots. Regular inspection to detect deterioration of these items is vital and it would be advisable to keep a complete set of spare items for immediate replacement in the case of accidental damage.

However much care is taken, electrolyte will be splashed or spilled, and a neutralizing agent should be kept available. For acid electrolyte, a solution of carbonate of soda crystals in water can be used. For alkaline electrolyte, a solution of vinegar and water is adequate. CAUTION: These solutions should NOT be used to clean the tops of cells; only distilled water is suitable for this job.

Contamination of the eyes requires very prompt action and, as a first line measure, washing with plain water is acceptable. Contamination of large areas of the skin can produce shock that would require consulting a physician for proper care.

The following list describes the important features of battery operation and maintenance.

ALWAYS carry out regular maintenance.

ALWAYS correct defects as soon as possible.

ALWAYS observe the safety precautions.

ALWAYS follow the manufacturers' instructions.

ALWAYS add acid to water if mixing electrolyte.

Heating and Cooling

Before discussing practical forms of heating and cooling we need to remember that the purpose of refrigeration is to remove unwanted heat.

Sources of unwanted heat are:

- heat leakage through structure (cold room walls, roof, sides, etc.)
- internal sources of heat (fan motors, lights, people inside buildings, etc.)
- warm air entering a cooled space from outside
- radiation onto cooled surfaces (usually solar)

The various configurations available on Earth stations vary from the individual "Household" window type air conditioners to complex central plants.

The air conditioning and heating system must maintain an adequate temperature within the buildings under the most severe environmental conditions. This is necessary for two reasons:

* to maintain a comfortable and healthy working environment for the staff. This usually requires a temperature of 20 degrees C.

* to provide suitable working temperatures for the Earth station equipment. The specification on operational temperature is usually about 10 to 35 degrees C. However, equipment is more reliable if it is operated in a stable temperature environment, and 15 to 20 degrees C is the common range used.

Fault-Finding and Correction

Good maintenance, knowledge of the plant and well-maintained records are the basis for avoiding the unexpected faults. However, an unexpected failure may cause circuit outages and emergency repairs may be necessary by the on-shift technician.

The station management must prepare an operating manual describing emergency procedures and should be available for use in the event of a fault.

The on-shift technician should be able to carry out emergency procedures as described in the operation manual as well as be familiar with the tools and safety aspects.

Grounding

Earth station communications equipment is subject to electrical noise and high-voltage surges. These transients occur predominantly in the common mode (line-to-ground), and are typically caused by lightning or power switching.

Lightning

When lightning-induced surges appear at the point of connection to a building (the service entrance), a high common-mode potential is generated between the current-carrying conductors and the ground. This potential produces a flow of current that seeks a path to Earth to complete the circuit.

Lightning can easily induce a 3000-ampere transient into a power line. When this transient reaches a building, the building ground at the service entrance can rise to 60,000 volts (assuming a building Earth resistance of 20A). The reference potential for ground in the rest of the building would rise proportionately.

To protect the building against these high-voltage surges, it is important to establish a low-resistance Earth ground at the service entrance. The *National Electrical Code* (Article 250, Part 4) specifies that the grounding at a building's service entrance should have a resistance to ground of 25A or less. The *IEEE Green Book* ("Recommended Practice for Grounding, ANSI/IEEE Std 142-1982") recommends that the ground resistance be less than 5A. If the building contains highly sensitive electronic communications equipment, a ground resistance of 5A or less is recommended if this value can be practically achieved with the given site conditions. Guidance on this issue can be also found in Reference [6] IEC publication 364 'Electrical installation of buildings' and the UK IEE Wiring regulations, 16th edition.

Types of Grounding

There are two major types of grounding: power distribution system grounding and telecommunications equipment grounding.

Power Distribution System Grounding

The power distribution system pertains to the incoming AC service, service entrance equipment, emergency plant, power panels, and electrical conductors providing the power to the electrical/mechanical equipment.

Grounding of the power distribution system is essential for:

* protecting occupants from exposure to dangerous shock voltage
* providing a path for ground fault current
* limiting excessive voltages due to lightning or utility switching

Typical grounding components for the power distribution system include the grounding electrode at the service entrance, a ground bus in the power panel, ground lugs in the other service entrance equipment such as the safety disconnect or transfer switch, a third wire grounding conductor for all the electrical equipment, and lightning and surge arresters.

Telecommunications Equipment Grounding

Electronic equipment such as radio systems, telephone switches, battery chargers and rectifiers, UPS equipment, and any other equipment that encloses or is adjacent to energized conductors require additional grounding. This sensitive electronic equipment must be protected from:

* excessive transients caused by lightning or utility switching
* degraded performance due to electromagnetic noise

Equipment grounding frequently uses a ground ring encircling the interior of the building (halo ground ring). Ground lugs attached to the various equipment housings and racks are connected to the ground ring. Ground bars at the waveguide entry and at each section of the cable ladder are also tied to the ground ring. Multiple external drops connect the internal ground ring to the exterior site ground ring.

Grounding Practices

The Grounding Conductor

To reduce inductance and surge voltages in a power distribution system, a ground path for protected devices should be provided. One method is to rely upon the conduit system to carry these transient currents. This is allowed by the National Electrical Code in Article 250-91 (b). The best method, however, is to include an extra conductor in the same conduit or raceway as the current carrying conductor.

The grounding conductor should extend to the ground connection in the service entrance equipment.

Equipment Ground Wires

When lightning strikes, it takes the path of least impedance (resistance and inductance). Cable bends increase inductance. Therefore, equipment ground wires should be large, and run straight for minimum inductance and voltage drop. The recommended bending radius is 6" when bends are unavoidable.

Equipment ground wires should be separated from all other conductors, and should not be run through metal conduit unless the conduit and ground wires are bonded at both ends.

Bonding

Even when the ground-to-Earth connection's impedance of the service entrance is minimized and grounding conductors are used in the feeder and branch circuits, high transient voltages can still occur in the power distribution system as a result of utility power switching. An effective method of limiting this noise (especially common-mode voltage differentials) is to bond all the equipment ground wires.

Bonding is the connection of all potential ground conductors (including racks, frames, cable ladder, conduits, metal enclosures, and exposed metallic members of the building structure) to each other.

Bonding does not eliminate voltage drops because transient currents will continue to take the path of least inductance. However, the current is sufficiently distributed throughout the bonded system to reduce the voltage gradients in any area to levels that prevent personal injury or equipment damage.

Proper bonding produces cross-connections of all equipment and structures. It provides many paths to ground from any one point. Since the bonded ground network is not part of the normal electrical power path, multiple inductive loops are not a concern. Only transient or fault currents can flow in and around network.

In addition to preventing the development of voltage gradients, cross-connection reduces the system's susceptibility to high-frequency noise. Since all conductors have some impedance, resonance will occur at some frequencies. At those frequencies, the impedance of the grounding conductor may be very high, and allow noise currents to develop increased voltage drops.

By bonding the ground network, however, there may be other conductors nearby that are not resonating, and a low impedance path for the noise signal can be maintained.

Faraday Cage

A Faraday cage provides an EMI shield to further reduce noise. The cage usually consists of multiple conductors in a box-like configuration. The steel reinforcement in the concrete shelter walls can form a highly effective Faraday cage if bonded to the grounding system. The amount of shielding depends on the size and spacing of the welded wire fabric.

Grounding System Performance Check

The original grounding installation must be periodically tested to determine whether resistance is remaining constant or increasing. An increase in resistance can be caused by several factors.

In lower conductive soils, high electric fields can develop at the ends of the ground rods, which can cause arcing in the soil. This arcing can cause glassification around the rods, beginning at the tip, and working its way upward. This glassification of the silica in the soil acts as an insulator, severely impairing the grounding characteristics of the rod. If resistance increases over time to an undesirable level, reduce the resistance by adding electrodes or chemically treating the soil to increase moisture content.

Typical Values of Resistivity

Conductivity and resistivity are inverse to one another. The resistivity of the ground varies according to rock type as shown below.

Rock type	Resistivity (ohm.m)
Top soil	5 - 50
Peat and clay	8 - 50
Clay, sand, and gravel mixtures	40 - 250
Saturated sand and gravel	40 - 100
Moist to dry sand and gravel	100 - 3000
Mudstones, marls and shales	8 - 100
Sandstones and limestones	100 - 1000
Crystalline rocks	200 - 10000

10.1
Student Question Paper

Question What do you understand by the terms "Noisy Supply" and "Quiet Supply"?

Question What type of UPS is used in your station?

Question What safety precautions must be taken when performing battery maintenance?

Question State the sequence of mixing the water and the acid when mixing electrolyte for topping up the batteries.

Question What type of air conditioning system is used in your station?

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APPENDIX A
WAVEGUIDES AND FEEDS

1.0 Introduction

In a closed system, electrical energy is normally made to flow down a wire or cable. However, at microwave frequencies, the attenuation of such a transmission line cannot be tolerated, hence an alternative means of transmission has to be used. Waveguide, as the name implies, is a device that guides a radio wave along its length, thereby providing a low-loss transmission path for microwave energy.

1.1 Electromagnetic Radiation

Electrical energy is normally thought of in terms of current and voltage, comprehensive electrical theory has been established on the simple relation V = IR. In radio engineering, it is more convenient and more easily understood to think in terms of the electrical field established by the voltage, and the magnetic field established by the current. Thus, the term electromagnetic radiation is extensively used.

In free space, an electromagnetic wave emanating from a point source will form an expanding spherical wavefront. However, to an observer situated at some distance from the source, it will appear as a plane wave. Such a plane wave is graphically shown in Figure A.1.

A plane wave is said to be transverse because both the E (electric) and H (magnetic) vector are transverse to the direction of propagation. Hence, it is referred to as a Transverse Electromagnetic (TEM) wave. The velocity of propagation is the speed of light (3 x 108 m/s) from which the following relation is derived:

$$f = \frac{c}{\lambda}$$

where:

f = frequency (Hz)
c = 3 x 108 m/s
λ = wavelength (m)

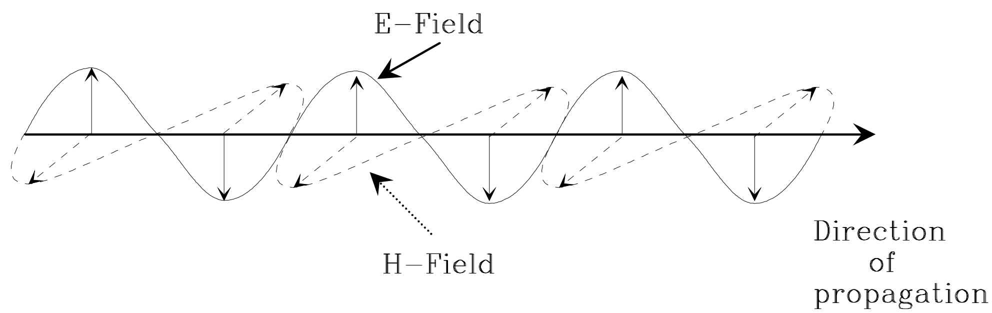

Figure A.1 Plane Wave

1.2 Two-Wire Open Line

A two-wire open line, or twin-wire feeder, propagates a TEM wave, as shown in Figure A.2. Rather than thinking of the transmission line providing a go and return path for the wave, it can be considered to guide the radio wave along its length.

A serious disadvantage of this type of transmission line is that above approximately 30 MHz, the loss due to radiation is considerable. Other sources of attenuation are conductor loss (skin effect) and dielectric loss.

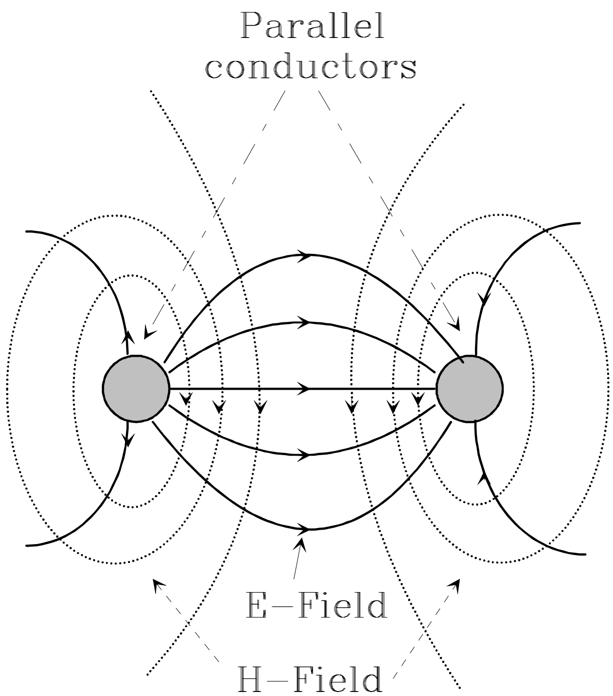

Figure A.2 TEM Wave on a Two-Wire Open Line

1.3 Coaxial Cable

A transmission line with two concentric conductors (coaxial cable) overcomes the problem of radiation as the E and H fields are confined within the outer conductor. (Refer to Figure A.3.) A coaxial cable normally propagates a TEM mode.

Attenuation due to conductor losses and dielectric losses increases with frequency. These losses can be reduced with the use of a larger diameter inner conductor and an air-spaced dielectric, respectively. Above 3 GHz, the attenuation of coaxial cable is approximately five times that of waveguide.

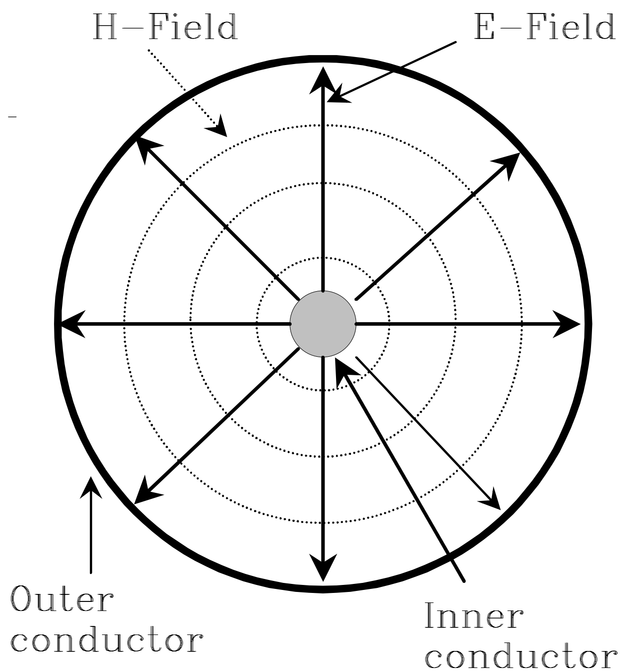

Figure A.3 TEM Wave in a Coaxial Cable

1.3 Waveguides

While a coaxial cable is a wideband transmission line, the waveguide can transmit only from a determined low frequency called "cutoff" frequency, which is the lowest frequency that can be transmitted, and depends on the waveguide sectional form and dimensions. At the higher frequency, other limits that have to be reached for the signal to be propagated along the waveguide.

For a wave to be propagated along a transmission line, Maxwell's Boundary Conditions, as shown in Table A.1, must be satisfied.

Table A.1 Maxwell's Laws - Boundary Conditions

1. INSIDE A PERFECT CONDUCTOR, AN ELECTRIC FIELD MUST VANISH. Since by definition there can be no potential gradient in a perfect conductor, then no electric field can exist.

2. AN ELECTRIC FIELD TANGENTIAL TO A PERFECTLY CONDUCTING BOUNDARY MUST VANISH AT THE BOUNDARY. Because the boundary is a perfect conductor, no electric field can exist inside it.

3. A MAGNETIC FIELD PERPENDICULAR TO A PERFECTLY CONDUCTING BOUNDARY MUST VANISH AT THE BOUNDARY. Because a magnetic field exists in conjunction with its perpendicular electric field, it must vanish if the electric field vanishes.

4. A MAGNETIC FIELD PARALLEL TO A PERFECTLY CONDUCTING BOUNDARY IS ASSOCIATED WITH A SURFACE CURRENT THAT IS AN INFINITELY THIN CURRENT SHEET FLOWING ON THE CONDUCTOR SURFACE.

An important property of the TE-mode wave is that it will not be transmitted unless the wavelength is sufficiently short. The critical wavelength at which transmission is no longer possible is called the "cutoff wavelength (Sc)".
The energy propagation along a hollow waveguide will exist in one of two types of waves.

1. **Wave TE_{mn}**
   The wave with transversal electric field TE, (also called H), is characterized by the fact that its electric field is transversal to the propagation direction.

2. **Wave TM_{mn}**
   The wave with transversal magnetic field TM (also called E), is characterized by the fact that its magnetic field is transversal to the propagation direction.

2. Propagation in Waveguides

The waveguide is a hollow conductor in which the electromagnetic wave is transmitted in its inner space. Along the inner walls there will be high frequency currents due to the electromagnetic waves. When the wave propagates, the wall currents will suffer losses due to the ohmic resistance of the wall. Therefore, the inner wall's surface should have as little resistance as possible, and must be free of cracks and bends.

2.1 The Rectangular Waveguide

As a normalized waveguide, it has a 1:2 relation for its lateral dimensions. The fundamental transmission mode for this waveguide is TE_{10}.

Figure A.5, shows a rectangular waveguide with a wave propagating in the Dominant Mode TE_{10}.

TE_{mn} has the two subscripts described as:

1st subscript (m) - the number of E field max along the b wall.

2nd subscript (n)- the number of E field max along the wall.

Note: In the USA, the order of subscript is as previously indicated, but in British notation, TE10 (US) = TE01 = H01.

2.2 Waveguide Bandwidth

Center of operating band:	S mean = 2Sc/3
Approximate Operating range:	2Sc/3±2

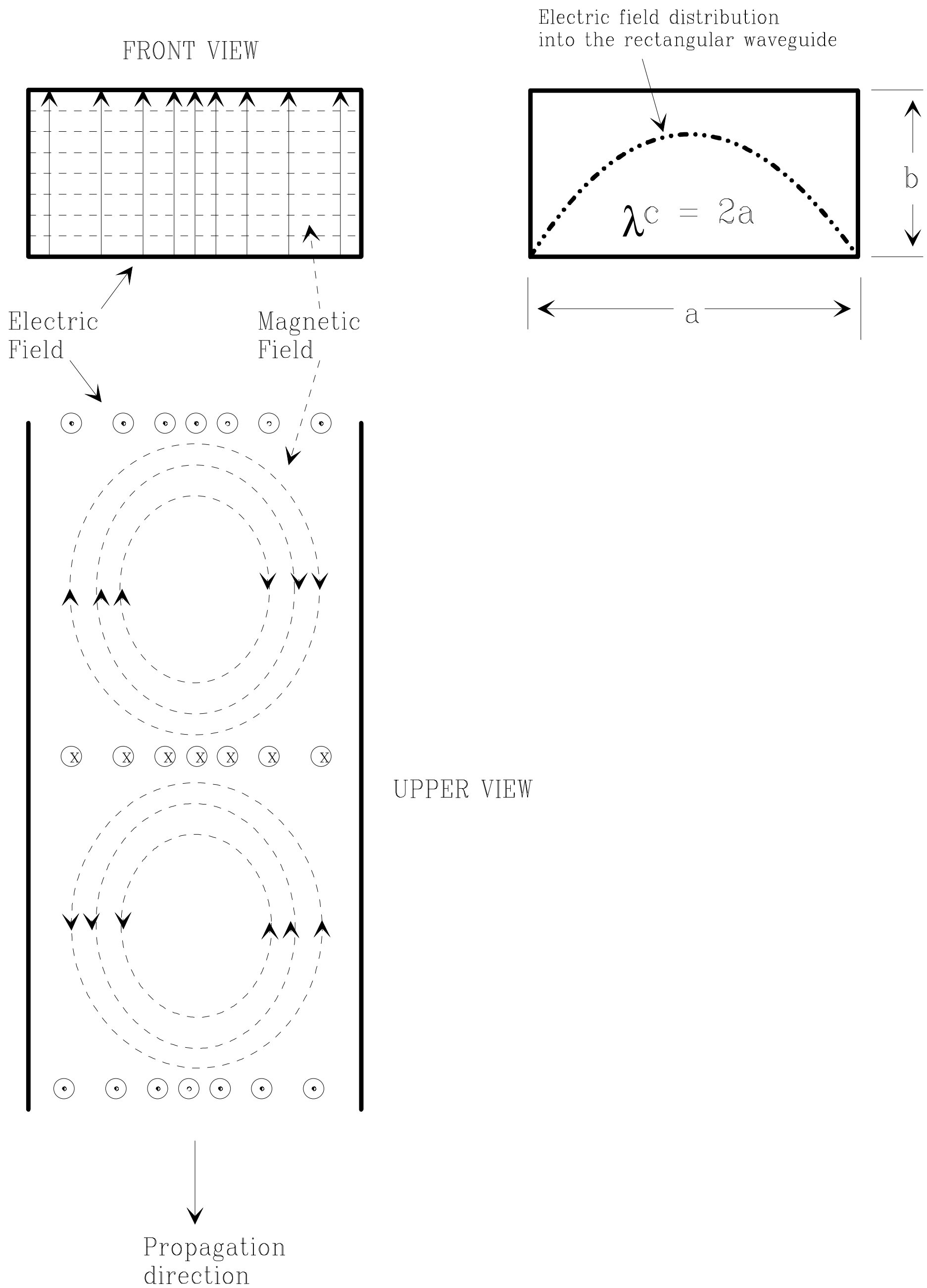

Figure A.5 Field Distribution into a Rectangular Waveguide

2.3 Waveguide Dimensions

a. Broad wall dimension 'a' (Refer to Figure 5.)

i. The lower frequency limit is given by Sc = 2a where Sc is the critical wavelength for the TE_{10} mode.

ii. The upper frequency limit is determined by the amount of multimoding that can be tolerated. The nearest higher order mode TE_{20} has a critical wavelength given by

$$Sc = a$$

The frequency range of a waveguide is usually given as mean ±20%.

Where mean = 2/3 Sc.

For wavelengths < S mean the TE_{20} mode is not propagated.

For wavelengths > S, mean attenuation increases rapidly as Sc is approached.

b. Narrow wall dimension 'b'

For the TE modes considered, this dimension is not critical, but the attenuation of rectangular waveguide also increases as the ratio of b to a decreases. If b is made too narrow, electrical breakdown is likely to occur (air has a breakdown voltage of 30kV/cm). If b = a higher modes like TE_{11} can appear. Therefore, as a compromise between low attenuation, high power handling capability, and preventing the higher modes to appear, the "b" dimension is usually made half the "a" dimension (a = 2b).

For manufacturers' equipment to be compatible, a standard range of rectangular waveguide is available for different frequency ranges. To reduce the weight, the large waveguides are normally constructed from aluminum, and the very small waveguides are normally constructed from silver to reduce the attenuation.

2.4 Higher Order Modes In Rectangular Waveguide

It is possible, as shown by Maxwell's equations, to propagate higher order modes of the form TE_{mn} where m and n are integers. Higher order modes are used in Earth station feed systems, and tend to be more highly attenuated than the dominant mode.

In contrast to the TE modes, there may be waves in which the magnetic component is transverse to the direction of propagation. These are known as Transverse Magnetic (TM) modes and are also of the form TM_{mn}. They are sometimes referred to as E_{mn} modes. Some examples of rectangular waveguide modes are shown in Figure A.6. Remember that these higher modes will appear only when the waveguide dimensions allow.

2.5 Flexible Twistable Waveguide

There are waveguide designs to overcome the passive intermodulation, gas, and RF leakage problems experienced with many of the conventional flexible twistable waveguides. It is a seamless flexible waveguide primarily for use where there is likely to be a stress buildup within a conventional waveguide system, and it is particularly useful in Earth station communications systems such as the Earth station coupling at the movable antenna to the feed. The waveguide comprises an inner layer of fine silver, with an outer structural layer of corrosion-resistant nickel.

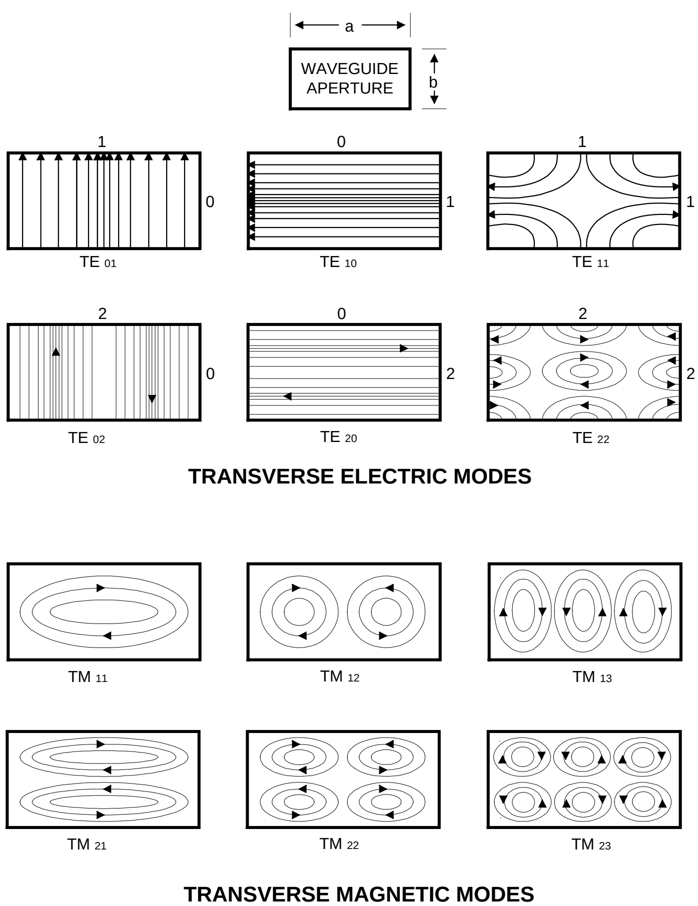

Figure A.6 Transverse Magnetic Fields

2.6 Heliax

Heliax is precision-formed and corrugated high-conductivity copper tubing with an elliptical cross section. The corrugated wall gives the waveguide excellent crush strength with light weight, good flexibility, and optimum stability. A rugged black polyethylene jacket provides protection during handling and installation. A full range of waveguide sizes covers the frequency range 1.9 - 19.7GHz. Heliax elliptical waveguides are optimized for lowest loss in specific user bands. Attenuation is significantly lower than comparable rectangular waveguides. A major advantage of Heliax is its availability in long continuous lengths that can be easily cut to length for any waveguide run, eliminating the need for multiple joints and elbows or flex sections.

Heliax minimizes detailed waveguide system planning and provides improved electrical performance, lower material cost, and lower installation cost compared with other types of waveguides. It is usually found in Earth station cross-site links.

The elliptical cross section propagates the TE_{11} dominant mode, which is similar to the TE_{10}. Operating in the dominant mode, it eliminates signal distortion due to mode conversion, and minimizes VSWR.

Heliax elliptical waveguide assemblies consist of a waveguide cut to a specific length and terminated at both ends. The termination includes a transition from the elliptical to the rectangular cross section to incorporate a rectangular waveguide flange, and then a transition from the rectangular waveguide to an N-type connector.

2.7 Pressurization

The waveguide should be maintained under dry air or dry nitrogen pressure to prevent moisture condensation. Pressure should be maintained at 30g/cm2. This is usually done at the Earth station by a recycling waveguide dryer, in some cases by regularly charging the system with a dry gas. Pressurization will avoid corrosion to create and, therefore, maintain the waveguide attenuation within its nominal values.

3.0 Circular Waveguide

Another common form of waveguide is circular or cylindrical. As for the rectangular waveguide, no TEM modes are possible, although TE and TM modes may exist. The dominant mode in circular waveguide is the TE_{11} mode.

As shown in Figure A.7, circular modes have different designations from their corresponding rectangular modes. This is because the subscripts represent values of certain parameters in the field equations that are quite different for circular and rectangular waveguide.

The subscripts describing the modes are:
1st subscript = number of full wave patterns of either field component around the circumference.
2nd subscript = number of half wave patterns of either field component along a diameter.

For a circular waveguide, TE_{11} is the dominant or the lowest order mode. Sometimes, combinations of TE and TM fields are used; fields consisting of a mixture of both modes are called hybrid modes and are given designations such as HE_{11}. Hybrid modes can be used to achieve a high degree of pattern symmetry in a conical horn by corrugating the walls of the horn. Examples of corrugated horns are described in later sections.

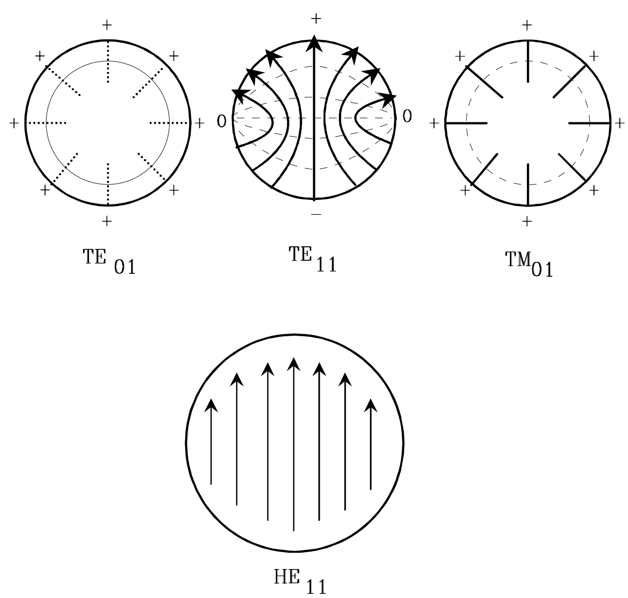

Figure A.7 Circular Waveguide Modes

4.0 Antenna Feeds

The antenna feeds of all Earth stations perform the same basic functions:

a. To shape the beam to provide the required uniform illumination of the main reflector.

b. To separate the transmit and receive signals with minimum loss and interference.

c. To convert from circular to linear polarization and vice versa for the downlink and uplink signals at C-band where circular polarization is employed.

d. To produce "error" signals that represent the degree and direction by which the main beam is 'off-track'. This is not required for antennas that use a steptrack system or are small enough not to need tracking.

4.1 Beam Shaping

The ideal beam for illuminating a dish is one that has a circular cross section of radiated E-field, i.e., the beamwidth in the E- and H-planes are identical.

The dominant TE_{10} rectangular waveguide mode has a distribution that is half-sinusoidal across the broad face (H-plane), and uniform across the narrow dimension (E-plane). As a result, the beamwidth in the H-plane is larger than in the E-plane that leads to increased sidelobe levels in the E-plane. With linear polarization, having a different aperture dimension in each axis can minimize this effect, but this would be unacceptable for circular polarization, as it would result in changing beamwidth depending on the vector position of the E-field.

A simple block diagram of a typical communications feed is shown in Figure A.8. With circular waveguide feeds, beam shaping is produced by corrugations along the length of a horn, or by corrugations along the flared section of the horn.

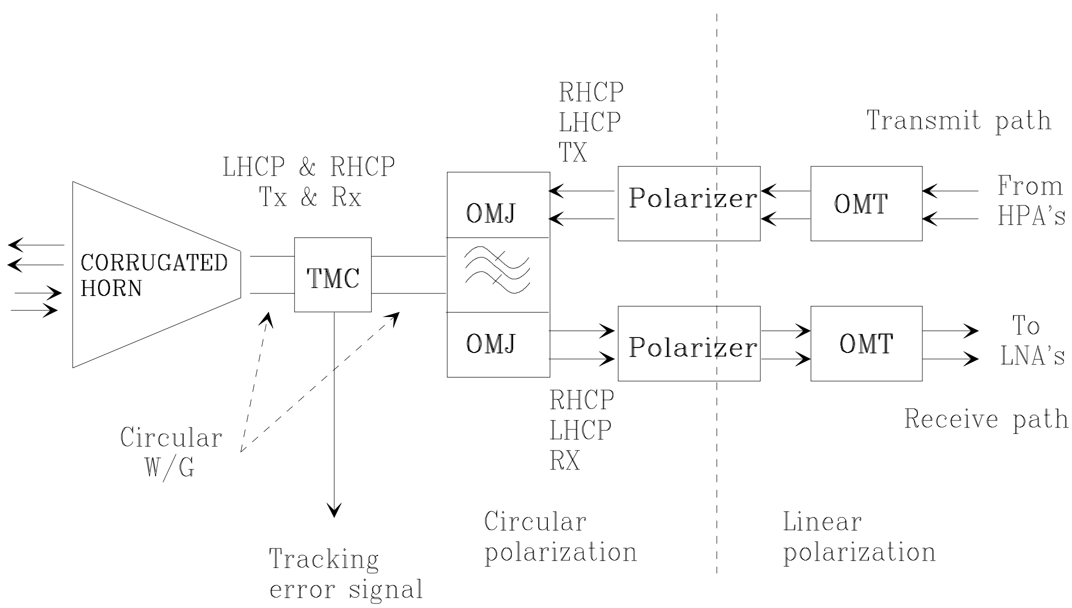

Figure A.8 Typical Four-Port Feed System Block Diagram

4.2 Feed Components

4.2.1 Corrugated Conical Horn

The corrugated conical horn, as shown in Figure A.8, is the most popular feed for the Cassegrain antenna system. It radiates a beam with negligibly low sidelobes, resulting in a high efficiency antenna system.

Practically all Standard A and B feed horns are flare angle-limited. This means that the flare angle controls the beamwidth rather than the aperture dimensions. Many of these feed horns use the technique of corrugating the horn wall with radial grooves nominally 1/4S deep to optimize the radiation pattern symmetry about the axis, and thus improve the off-axis polarization characteristics of the horn. This type of horn is designed by making the aperture size sufficiently large so that the maximum phase deviation across the aperture does not exceed 0.5 wavelength.

TMC	Tracking Mode Coupler
OMJ	Orthomode junction
OMT	Orthomode transducer

This type of horn has the crucial advantage of having a beamwidth that is relatively independent of frequency. Its primary disadvantage is that it requires an aperture size approximately 1.5 times larger than would be expected for an aperture-limited horn.

Typical feed dimensions for an 11-meter antenna are 0.45 meter for the aperture and 26° for the total flare angle of the conical section.

4.3 Diplexer (Orthomode Coupler)

The diplexer, shown in Figure A.9, can transmit and receive signals to co-exist in a common waveguide unit with minimum interaction between the two. This enables the removal of energy at the receive frequency with no resultant effect on the transmit frequency.

Coupling to the orthogonal receive signal is achieved by positioning a metal plate (septum) in the linearly polarized E-plane of the signal that effectively short-circuits the waveguide section behind the coupling slot. The design of the slot, and matching of the receive arm of the coupler with an optimized septum position, directs the received signal into the orthogonal arm.

The transmit signal arrives via a stepped taper for matching from the rectangular-to-square waveguide whose E-plane is at right angles to the received signal. It is thus unaffected by either the septum or the coupling slot, and passes through to the circular polarizer.

To ensure that the transmit signals from the high power amplifier do not interfere with the receive signals, a low-pass (transmit reject) filter is typically connected to the receive port of the diplexer. This filter provides isolation of better than 50 dB over the transmit bandwidth.

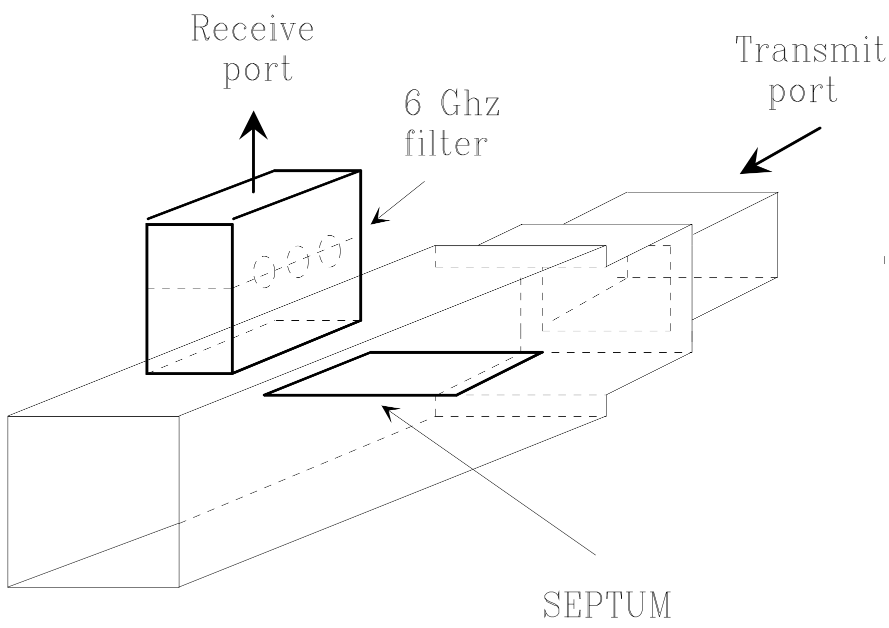

Figure A.9 Diplexer

4.4 Sense of Polarization

All electromagnetic waves are polarized. Polarization refers to the orientation of the electric field vector and is most commonly defined with respect to the position of the electric field (E-field) as a function of time, and as measured at a fixed position in space. This is known as the fixed plane definition. It can also refer to the position of the E-field as a function of spatial position at a fixed instant of time. This is known as the fixed time definition. The fixed plane definition is the one that is most commonly used.

To clarify the fixed plane definition, consider a wave traveling away from an observer as shown in Figure A.10. Its sense of polarization is observed to pierce a fixed plane:

> RIGHT-HAND if the vector tip rotates clockwise with time.
> LEFT-HAND if the vector tip rotates counterclockwise with time.

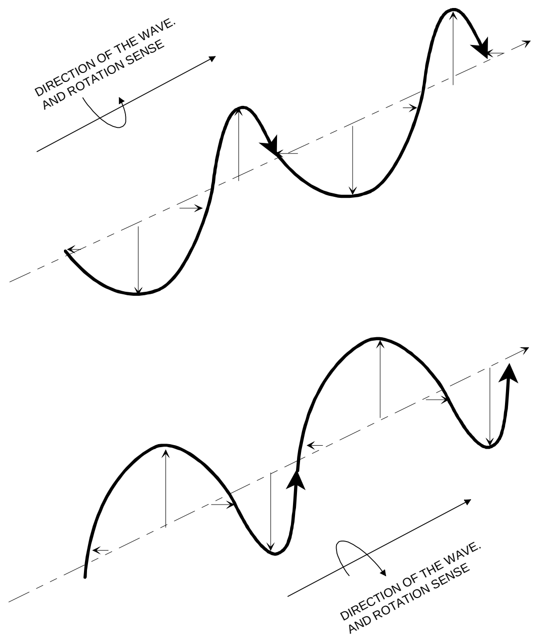

Figure A.10 Circular Polarization

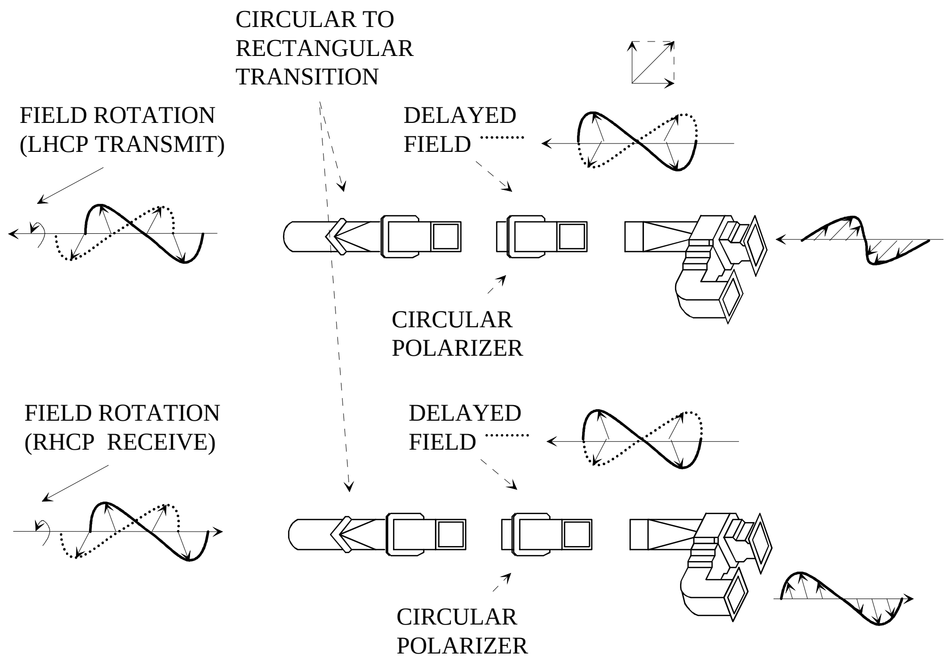

Figure A.11 Circular Polarizer

The polarizer converts the linear polarization of the transmit signal (from the diplexer) to circular polarization, and converts the receive circular polarization signal from the satellite to linear polarization which will be orthogonal to that of the transmit signal.

Circular polarization is achieved in the waveguide by splitting the linear polarized signal into two orthogonal vectors, and then delaying one with respect to the other by a quarter of a wavelength (90°) through the polarizer. Figure A.11 shows the input waveform, and the input and output vector position where the resulting output is circular polarization. Conversely, linear polarization is derived from circular polarization through the reverse process.

4.5 Polarization Orthogonality

Frequency reuse is a technique whereby a given frequency band is used more than once for the satellite to effectively increase the available spectrum capacity.

Because different transmission signals will be required to co-exist at the same carrier frequencies, it is necessary that they be isolated from each other by employing orthogonal polarizations on each link.

In Figure A.12, traffic "A" is carried on polarization "A" (shown as "vertical" in the illustration), and traffic "B" is carried on the orthogonal polarization. A clear sky polarization isolation of typically 27-30 dB must be maintained to ensure negligible mutual interference.

To further clarify this concept, let us examine elliptic polarization in more detail. The magnitude of the vector will generally be changing size as it rotates. Its tip will always trace an ellipse on the plane and the wave is elliptically polarized (See Figure A.13.) The ellipse has a major axis (magnitude E_{max}) and a minor axis (magnitude E_{min}). The axial ratio, r, is the (voltage) ratio of the major axis to that of the minor axis.

$$r = E_{max}/E_{min}$$

and the axial ratio in dB is:

$$R = 10\log_{10} r$$

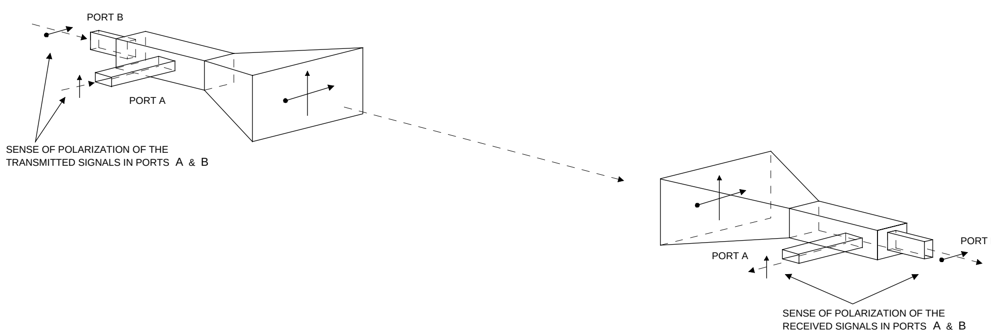

Figure A.12 Polarization Orthogonality

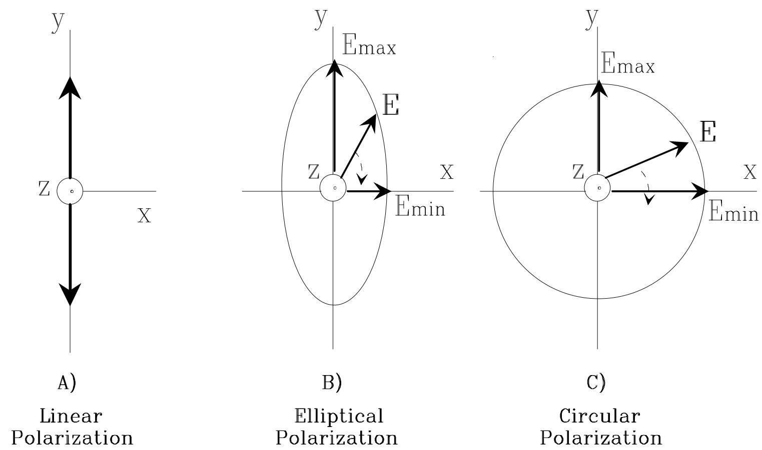

Figure A.13 Linear, Elliptical, and Circular Polarization

If the axial ratio is unity, the wave is said to be circularly polarized. If the axial ratio is nearly infinity, the wave is said to be linearly polarized. For in-between values, the wave is said to be elliptically polarized.

In practice, when the axial ratio (R) is less than about 3 dB, the wave is considered to be circularly polarized; when the axial ratio (R) is greater than about 20 dB, the wave is considered to be linearly polarized.

The cross polarization discrimination between orthogonal polarizations provides the isolation necessary for frequency reuse and can be calculated by:

$$xp = \frac{(r_1 + r_2)^2 + (1 - r_1^2)(1 - r_2^2)\cos^2(\theta_1 - \theta_2)}{(r_1 - r_2)^2 + (1 - r_1^2)(1 - r_2^2)\cos^2(\theta_1 - \theta_2)}$$

Where:

r_1, r_2 = axial ratios for the two polarizations
θ_1, θ_2 = tilt angles of the major axis of the ellipses relative to the horizontal

Figure A.14 is a plot of the cross polarization isolation against the antenna axial ratio (R) during clear sky conditions.

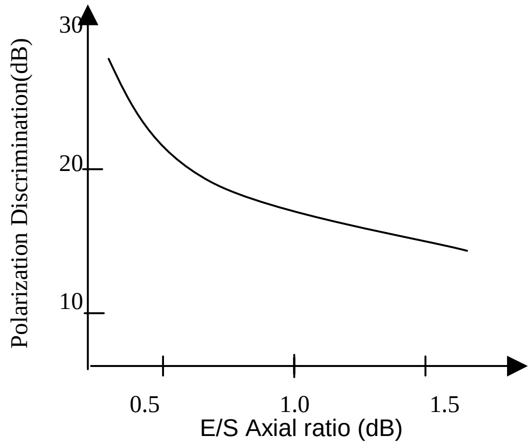

Figure A.14 Circular Polarization Degradation

4.6 Frequency Reuse Feeds

INTELSAT Earth station antennas are equipped with dual-polarized feeds that can receive (and/or transmit) signals of the same frequency but with orthogonal senses of polarization:

- right-hand circular polarization (RHCP) or
- left-hand circular polarization (LHCP) in the 6/4 GHz band vertical and horizontal linear polarization is employed at Ku band.

Table A.2 shows the axial ratio and polarization discrimination requirements for the different Earth station standards. A block diagram of a frequency reuse feed is shown in Figure A.15.

Table A.2 Performance Standards

Frequency Band	Polarization Type	Antenna Standard	Frequency Reuse	Axial ratio (r in dB)	Polarization Discrimination (dB)
C	Circular	A, B	Yes	1.06	30.7
		F1, F2, F3	Yes	1.09	27.3
		Rx Only	No	1.40	15.5
		Other <4.5m	Yes	1.30	17.7
	Linear	A, B, F3	Yes	31.60	30.0
		F1, F2, H	Yes	22.40	27.0
Ku	Linear	C, E	Yes	31.60	30.0

NOTE:
The axial ratio should be achieved over the 1-dB beamwidth of the antenna to account for pointing and tracking errors. All other performance requirements remain unchanged.

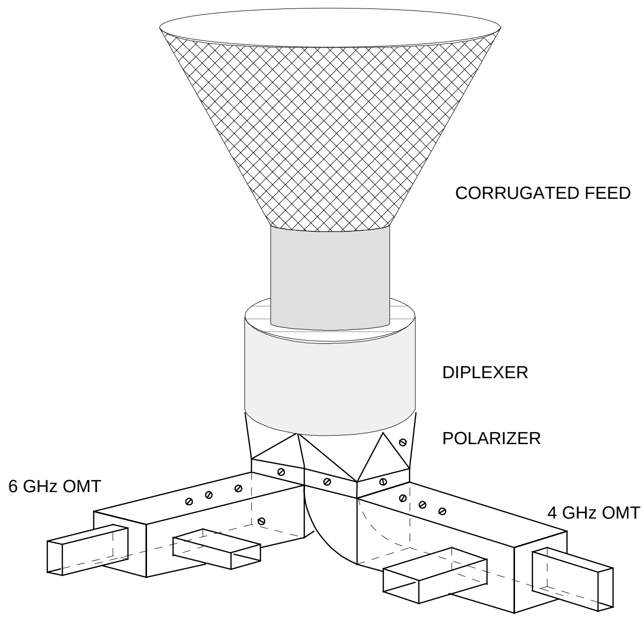

Figure A.15 A Frequency Re-Use Feed Block Diagram

4.7 Beam Waveguide Feeds

The beam waveguide feed system is widely used for Standard A antenna feeds. The reason for its popularity stems from the fact that it allows all RF equipment to be removed from the antenna structure, thus eliminating cable wraps, waveguide rotary joints, and the shelter required to house the low noise amplifiers on the antenna structure. The beam waveguide as shown in Figure A.16, consists of a corrugated feed horn and a set of four reflectors to image the horn fields onto the subreflector. Usually, two of the reflectors are flat and two others provide the focusing action required. The beam waveguide reflectors are usually enclosed in a metal shroud for protection, and rotation is possible using the slip rings in the shroud. In the case of the paraboloidal beam waveguide, one is required to adjust the azimuth rotation below the lowest reflector and the elevation rotation between the upper two reflectors.

To reduce beam waveguide loss to less than one percent per reflector, the feed horn must provide a very low illumination (typically less than –20 dB) on each reflector. Also, the reflectors must be large relative to their spacing to prevent losses resulting from diffraction effects.

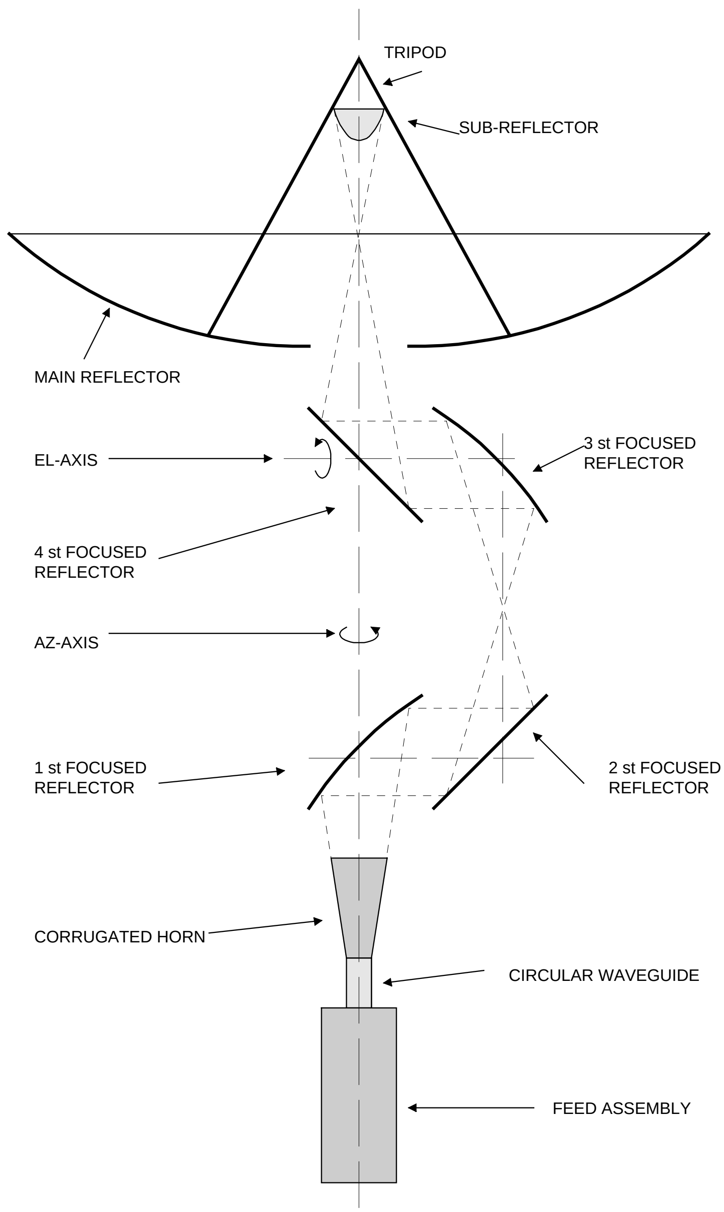

Figure A.16 Beam Waveguide System Figure

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Acronyms and Abbreviations Used in this Handbook

Amplitude Modulation (AM)
Antenna Control Unit (ACU)
Antenna Position Indicator Unit (APIU)
Asia Pacific Region (APR)
Association of South East Asian Nations (ASEAN)
Asynchronous Transfer Mode (ATM)
Atlantic Ocean Region (AOR)
backoff (BO)
bel (B)
bit error rate (BER)
Carrier-to-Interference (C/I)
Committed Information Rate (CIR)
Communication System Monitoring (CSM)
Data Link Connection Identifiers (DLCIs)
decibel (dB)
Demand Assigned Multiple Access (DAMA)
direct current (DC)
Engine Overspeed (EOS)
Engineering Service Circuits (ESCs)
Equivalent Isotropically Radiated Power (EIRP, EIRP)
field effect transistor (FET)
Frame Relay Access Device (FRAD)
Gain-to-Noise Temperature ratio (G/T)
Gallium Arsenide FETs (GaAsFETs)
ground communications equipment (GCE)
group delay equalizer(s) (GDE(s))
High Electron Mobility Transistor (HEMT)
High Water Temperature (HWT)
high-gain antenna (HGA)
High-Power Amplifiers (HPAs)
Indian Ocean Region (IOR)
INTELSAT Business Service (IBS)
INTELSAT EARTH STATION STANDARDS (IESS)
Intermediate Data Rate (IDR)
intermediate frequency (IF)
intermodulation (IM)
Internet Relay Chat (IRC)
Klystron Power Amplifier (KPA)
left-hand circular polarization (LHCP)
Linearized Traveling Wave Tube Amplifiers (LTWTAs)
Local Area Network (LAN)
local oscillators (LOs)
Low Oil Pressure (LOP)
Low-Noise Amplifier (LNA)
Metal Oxide Semiconductor FET (MOSFET)
Noise Figure (F)
OBO (Output Backoff)

Acronyms and Abbreviations Used in this Handbook (continued)

operational flux density (OFD)
Pacific Ocean Region (POR)
Periodic Permanent Magnet (PPM)
Permanent Virtual Circuits (PVCs)
Phase Modulation (PM)
Pseudo-Random Bit Sequence (PRBS)
Radiofrequency (RF)
resistance, inductance, capacitance (RLC)
RF interference (RFI)
right-hand circular polarization (RHCP)
Satellite Newsgathering (SNG)
SATELLITE SYSTEM OPERATIONS GUIDE (SSOG)
Satellite-Switched Time Division Multiple Access (SS/TDMA)
single carrier (SC)
Solid State Power Amplifiers (SSPAs)
Solid State Relay (SSR)
specific gravity (sg)
Synchronous Digital Hierarchy (SDH)
Telemetry, Tracking, Control and Monitoring (TTC&M)
Transverse Electromagnetic (TEM)
Transverse Magnetic (TM)
Traveling Wave Tube Amplifier (TWTA)
uninterruptible power supplies (UPS)
Very Small Aperture Terminal (VSAT)
World Wide Web (WWW)