UNIT - II

2 Space Segment

Syllabus

Spacecraft Technology - Structure, Primary power, Attitude and Orbit control, Thermal control and Propulsion, communication Payload and supporting subsystems, Telemetry, Tracking and command - Transponders - The Antenna Subsystem.

Contents

2.1 Spacecraft Technology

- An operating communications satellite system consists of several elements or segments, ranging from an orbital configuration of space components to ground based components and network elements.
- Important space craft subsystem includes,
  1. Attitude and Orbital Control System (AOCS)
  2. Telemetry Tracking and Command (TT and C)
  3. Power System
  4. Communications System
  5. Antennas
- The space segment equipment carried aboard the satellite can be classified under two functional areas : the ***bus*** and the ***payload***.

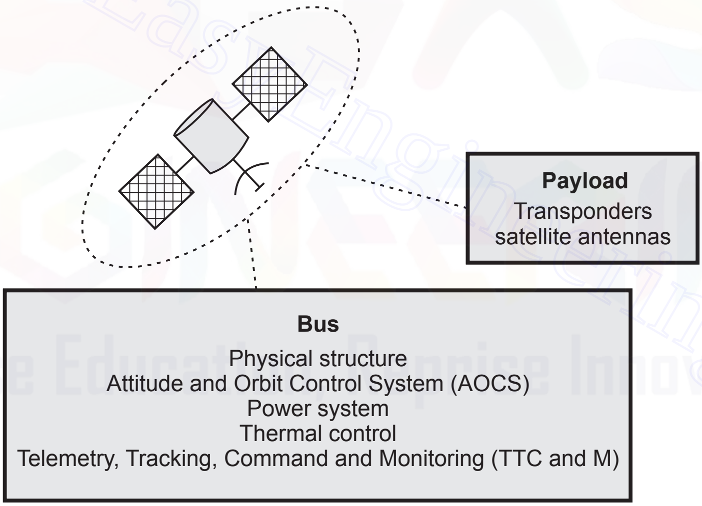


Fig. 2.1.1 Satellite subsystem

Bus

- The bus refers to the basic satellite structure itself and the subsystems that support the satellite.
- The bus subsystems are : the physical structure, power subsystem, attitude and orbital control subsystem, thermal control subsystem and command and telemetry subsystem.

Payload

- The payload on a satellite is the equipment that provides the service or services intended for the satellite.

- A communications satellite payload consists of the communications equipment that provides the relay link between the up and downlinks from the ground.
- The communications payload can be further divided into the transponder and the antenna subsystems.

2.2 Satellite Subsystem

Spacecraft Subsystem : A communication satellite incorporates various subsystems whose functions are distinct. The three common essential characteristics of subsystems are -

a) Minimum mass

b) Minimum power consumption

c) High reliability.

- For any particular mission to be fulfilled each subsystem is specified and designed by considering above three criteria. A list of platform subsystems with its principal functions and their important characteristics are expressed in Table 2.2.1.

Sr. No.	Subsystem	Functions	Characteristics
1.	Telemetry, tracking and command (TTC)	Exchange of house keeping information	Security of communications, number of channels
2.	Attitude and orbit control (AOC)	Attitude stabilization and orbit determination	Accuracy
3.	Propulsion	Velocity increments	Specific functions
4.	Thermal control structure	Temperature maintenance	Dissipation capacity
5.	Electric power supply	To supply electric energy	Voltage stability, power

Table 2.2.1 Various subsystems

- The performance and specification of a particular subsystem is decided by the presence of other interconnected subsystem. The interconnection of subsystems may affect various parameters such as vibration, temperature, coupling etc. These are shown in Fig. 2.2.1.

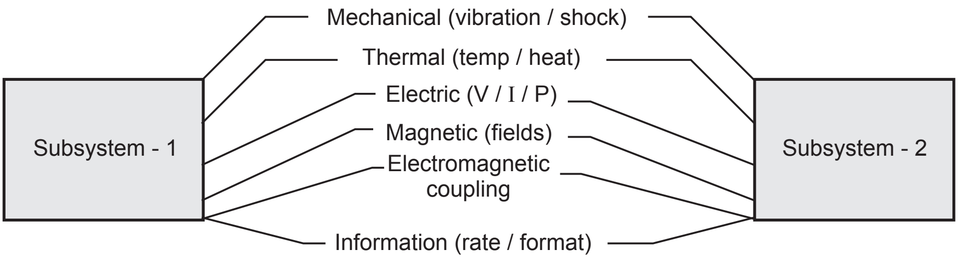


Fig. 2.2.1 Interfacing two subsystems

2.2.1 Electric Propulsion

- The role of the propulsion subsystem is mainly to generate forces which act on the centre of mass of the satellite. These forces modify the satellite orbits.
- The electric propulsion involves the use of an electrostatic or electromagnetic field to accelerate and eject ionized material. It requires large amount of electrical power. It is characterized by low thrust with a high impulses. The thrust is typically 0.1 N of impulses ranging from 1000 to 10,000 sec. The specific power of the propulsion is defined as the ratio of electric power to the thrust. Typically its value is 25 to 50 W/mN depending on the type of thruster.

Electric Propulsion Techniques

- Various electric propulsion techniques are -
  a) Electrothermal propulsion
  b) Plasma propulsion
  c) Ionic propulsion

Review Question

1. *List out the major subsystems required on satellite.*

2.3 Power System

- The power system is meant to provide DC power to all subsystems throughout the life of a spacecraft. Thus system should generate power, regulate power and also provide alternate energy source for periods when power cannot be generated.
- Sun is a powerful source of energy. Solar cells are used because solar power is available for over 99 % of satellite lifetime. Average power above earth's atmosphere is 137 mW/cm^2 (approximately).

- Amount of power generated by a cell depends on the conversion efficiency and the intensity of incident solar radiation. Solar radiation intensity reduction is caused by either a small eccentricity (0.0167 approx.) in earth's orbit around sun and variation in tracking sun position by solar arrays.
- Silicon solar cells are widely used. The efficiency of solar cells varies between 20 % - 25 % at the Beginning of Life (BOL) and 7 % - 10 % towards End of Life (EOL).
- Solar cell output falls when temperature rises. An increase in 10 °C to 70 °C can reduce power output by 25 % approximately.
- The satellites are equipped with batteries to power subsystems during launch and during eclipses. A geostationary satellite undergoes 88 eclipses an year and rechargeable batteries provide power during this period.
- Nickel - cadmium (Ni - Cd) batteries are commonly used because of their high reliability and long lifetime.
- Nickel - Hydrogen (Ni - H) cells have higher capacity per unit mass and tolerance to higher depths of discharge and are preferred nowadays.
- Batteries are conditioned before each eclipse i.e. batteries are discharged to a limit and then recharged.

Review Question

1. *What are the different components of satellite's power supply subsystem ? Briefly describe the role of each component.*

2.4 Attitude and Orbit Control

- Spacecraft control is usually synonymous with "Attitude Control," the engineering discipline of keeping a satellite or spacecraft pointed in the right direction.
- The attitude and orbital control subsystem checks that a spacecraft is placed in its precise orbital position, and maintains, thereafter, the required attitude throughout its mission.
- Control is achieved by employing momentum wheels, which produce gyroscopic torques, combined with an auxiliary reaction control gas thruster system. Many various sensors are employed to detect attitude errors, including Sun's initial orientation purposes.
- The AOCS performs satellite orientation and accurate orbital positioninghroughout its lifetime, because loss of attitude renders a spacecraft useless.

- AOCS is needed to get the satellite into the correct orbit and keep it there. AOCS performs following major functions -
  1. Orbit insertion
  2. Orbit maintenance
  3. Fine pointing
- The objective of attitude control is to keep the antenna RF beam pointing at the intended areas on the Earth, which procedure involves as follows :
  1. Measuring the attitude of the satellite by sensors;
  2. Comparing the results of measurements with the required values;
  3. Calculating the corrections to reduce eventual errors and
  4. Introducing these corrections by operating the appropriate torque units.
- The major parts of AOCS are -
  1. Attitude control system
  2. Orbit control system

2.4.1 Forces acting on a Synchronous Satellite

- At GEO orbit altitude the moon's gravitational force is about twice as strong as the sun's.
- Moon orbit is inclined to the equatorial plane by approximately 5 degrees.
- The plane of the earth's rotation around the sun is inclined to 23 degrees to the equatorial plane.
- The plane of the earth's rotation around the sun is inclined to 23 degrees to the equatorial plane.
- Net gravitational force on the satellite tends to change the inclination of the satellite.
- Approximately 0.86 degrees per year from the equatorial plane.
- LEO satellites are less affected by this gravitational pull from the sun and moon
- At the equator there are bulges of about 65 m at longitudes 162 degrees East and 348 degrees East.
- Satellite is accelerated towards one of two stable points on GEO orbit at the longitude of 75 degree East and 252 degrees East.

2.4.2 Attitude Control System

2.4.2.1 Attitude Control Functions

- The role of attitude control usually consists of maintaining the mechanical axes in alignment with the local co-ordinate system to an accuracy defined by the amplitude of rotation about each of the axes.

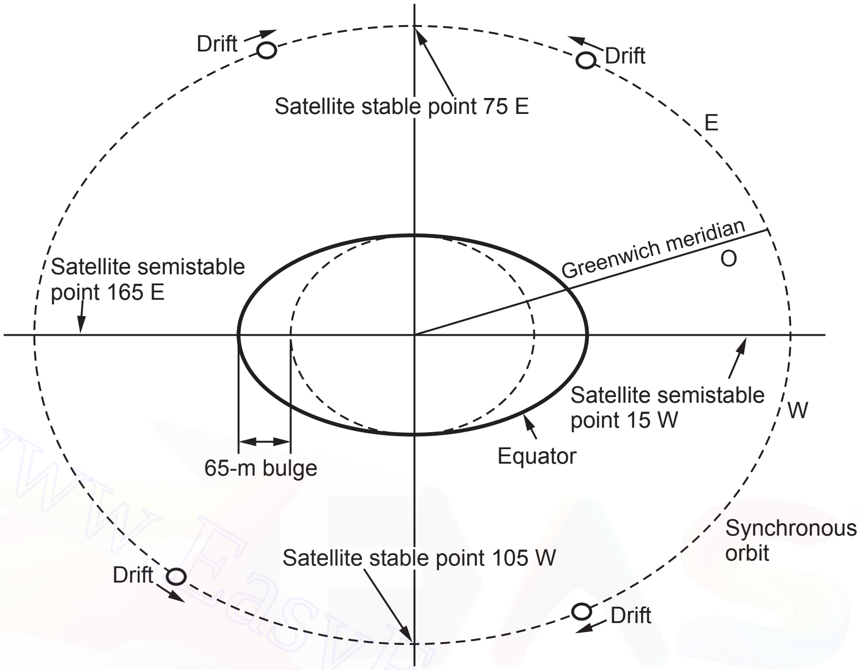


Fig. 2.4.1 Forces on a synchronous satellite

- The typical ranges are ± 0.05° for roll axis ± 0.2° for yaw axis and ± 0.05° for pitch axis for a geostationary satellite.
- For maintaining attitude control two functions are required.
  1. **Steering function :** It consists of causing the part of the satellite which must be oriented towards the earth to turn about the pitch axis in order to compensate for the apparent movement of earth with respect to the satellite.
  2. **Stabilization function :** Stabilization function involves compensating for the effects of attitude disturbing torques due to gravitational forces, solar radiation pressure etc.

2.4.2.2 Fine Positioning

- Satellite must be stabilized to prevent nutation (wobble) move unsteadily.
- There are two principle forms of attitude stabilization.
  1. Body stabilized (spinners, such as INTELSAT VI)
  2. Three-axis stabilized (such as the ACTS, GPS, etc.)
- Two ways to make the satellite stable in orbit when it is weightless.
  1. Satellite can be rotated at a rate between 30 and 100 rpm to create gyroscopic force that provides stability (spinner satellites).
  2. Satellites can be stabilized by one or more momentum wheels, called three-axis stabilized satellites.

2.4.2.3 Orbit Insertion and Maintenance - GEO

- Must control location in geo and position within constellation.
- Satellites need in-plane (E-W) and out-of-plane (N-S) maneuvers to maintain the correct orbit.
- LEO systems less affected by sun and moon but may need more orbit-phasing control.
- Two types of motors used on satellites.
  1. Traditional bipropellant thruster
     a. Bipropellants used are Mono-methyl hydrazine and Nitrogen tetra-oxide
     b. They are hypogolic, i.e., they ignite simultaneously on contact without any catalyst or heater.
  2. Arc jets or ion thrusters
     a. High voltage is used to accelerate ions.
- Fuel stored in GEO satellite is used for two purposes -
  1. Apogee Kick Motor (AKM) that injects the satellite into its final orbit.
  2. Maintain the satellite in that orbit over its lifetime.

2.4.2.4 Definition of Axes

- Attitude of a satellite is represented with respect to three axes - Roll axis, Pitch axis and Yaw axis.

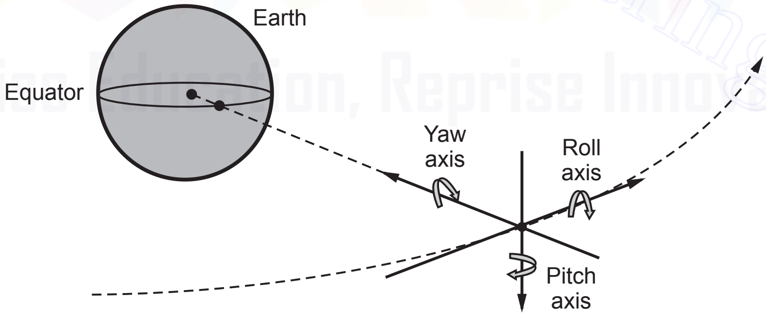


Fig. 2.4.2 Roll, Pitch and Yaw axes

1. Roll axis

- The Roll axis is the plane of orbit, perpendicular to the Yaw axis and in the direction of the velocity.
- Roll axis rotates around the axis tangent to the orbital plane (N/S on the earth)

2. Pitch axis

- The pitch axis is perpendicular to both other axes and originated such that the co-ordinated system is regular.

- Attitude Pitch axis moves around the axis perpendicular to the orbital plane (E/W on the earth).

3. Yaw axis

- The Yaw axis points in the direction of center of the earth.
- Yaw axis moves around the axis of the sub-satellite point.

2.4.2.5 Active and Passive Attitude Control

- The attitude control may be either **active or passive.**
  1. A **passive** attitude-control system maintains the attitude by obtaining equilibrium at the desired orientation without the use of active attitude devices.
  2. An **active** control system maintains the attitude by the use of active devices in the control loop.

Review Questions

1. *Write a short note on attitude control system.*
2. *List various types of control required to maintain the satellite in space and explain attitude and orbital control system in detail.*
3. *Explain the following with respect to satellite.*
   i) Attitude control system
   ii) Orbit control system
4. *Explain :*
   i) Attitude control system
   ii) Orbital control system

2.5 Communication Payload and Supporting Subsystem

- The heart of a communication satellite is the communication subsystem. The communication subsystem is a set of transponders that receive the uplink signals and retransmit them to earth.
- The main objective of communication system is to provide a reliable communication between the satellite and the ground station.
- A communications satellite exists to provide a platform in the orbit for relaying of voice, video, and data. Communication satellites are designed to provide the largest traffic capacity possible. (e.g. the INTELSAT system).
- The INTELSAT example shows that successive satellites become larger, heavier, more expensive, and handles more traffic. Result : Lower cost per telephone circuit.

2.5.1 Functions of Communication Subsystem

- The main functions of the communication subsystem (payload) :
  1. To capture the carriers transmitted by the earth station. Also capture as little interference as possible.
  2. To amplify the received carriers.
  3. To change the frequency of the carriers from the uplink to the down-link (e.g. 14 to 11 GHz).
  4. To provide the power required for down-link transmission.
  5. To radiate the carriers in the given frequency band and with the required polarization.

2.5.2 Characteristics of the Communication Subsystem

- The characteristics of the communication subsystem :
  1. Transmitting and receiving frequency bands.
  2. The transmit and receive coverage.
  3. The Effective Isotropic Radiated Power in a given direction (EIRP).
  4. The EIRP required at the satellite in order to produce the required performance.
  5. The figure of merit of the receiving system (G/T) ratio.
  6. The non-linear characteristics.
  7. The reliability after N years.

2.5.3 Elements of the Communication Subsystem

- The elements of the communication subsystem :
  1. Transmitting and receiving antennas.
  2. Amplifiers, Low Noise (LNA) and High Power (HPA).
  3. Filters, RF and IF band-pass.
  4. Oscillators.
  5. Up and down converters.
  6. Multiplexers and de-multiplexers.
  7. Electronic switches.

2.6 Telemetry, Tracking, Command and Monitoring (TTC and M)

- The tracking, telemetry, command and monitoring (TTC and M) subsystem provides essential spacecraft management and control functions to keep the satellite operating safely in orbit.
- The TTC and M links between the spacecraft and the ground are usually separate from the communications system links.
- **Tracking** refers to the determination of the current orbit, position and movement of the spacecraft.
- The **telemetry** function involves the collection of data from sensors on-board the spacecraft and the relay of this information to the ground. The telemetered data include such parameters as voltage and current conditions in the power subsystem, temperature of critical subsystems, status of switches and relays in the communications and antenna subsystems, fuel tank pressures, and attitude control sensor status.
- **Command** is the complementary function to telemetry. The command system relays specific control and operations information from the ground to the spacecraft, often in response to telemetry information received from the spacecraft.

2.6.1 Telemetry

2.6.1.1 Telemetry Functions

- The important functions that Telemetry, Tracking and Command (TT and C) subsystem performs are mentioned -

1. To receive the control signals from the earth station to initiate manoeuvres and also to control or change the state of operation of equipment.
2. To transmit results of measurements, information regarding satellite operations.
3. To facilitate the measurements of ground satellite distance, radial velocity etc.
4. On Board Data Handling (OBDH), it includes all house-keeping data processing and formatting with data traffic.
5. Reporting spacecraft health
6. Monitoring command actions
7. Determining orbital elements
8. Launch sequence deployment
9. Control of thrusters
10. Control of payload (communications, etc.)

2.6.1.2 TTC Subsystem

Fig. 2.6.1 shows block diagram of TTC subsystem.

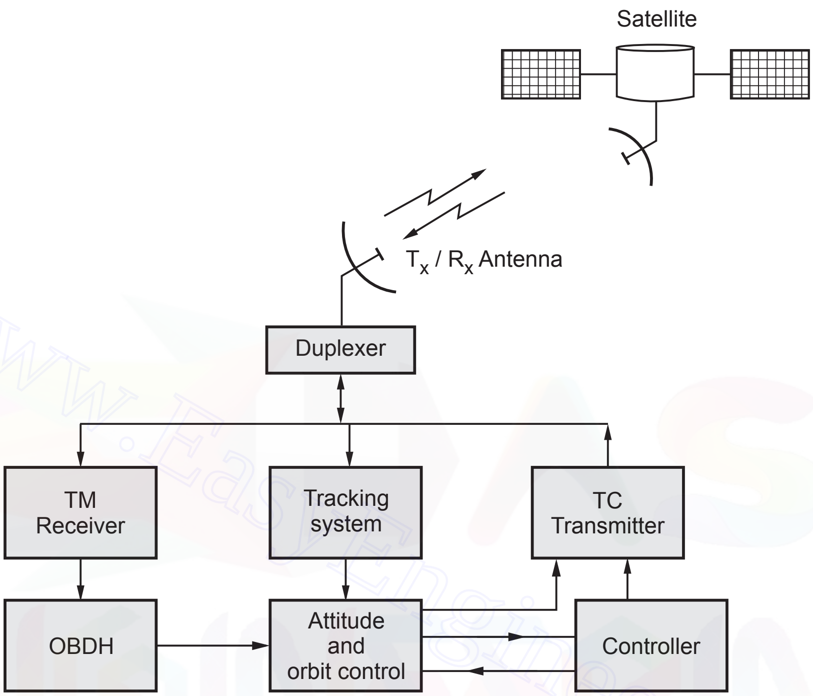


Fig. 2.6.1 TTC subsystem

- Telemetry links (TM links) and command links (TC links) are low bit rate links typically few kbps. Nominal frequency band of communication payload can be used to handle TTC data.

TM receiver (Telemetry Receiver)

- The data from various sensors of different subsystems are collected by TM receiver by TM links. The TM links are carriers which are phase or frequency modulated by a sub-carrier at a 40.96 kHz. The data rate is ranging between few tens of bits/sec to a few kilo bits/sec. Such a low data rate allow the receiver at the earth station to have a narrow bandwidth and thus maintain a high carrier-to-noise (C/N) ratio.
- The data can be obtained either -
  - i. Directly from satellite equipment.
  - ii. Conditioned (ADC, formatting) in telemetry.
  - iii. At the output of On Board Data Handling (OBDH) unit.

Tracking system

- Tracking involves distance (range) measurement and radial velocity measurement.
- Doppler shift of telemetry carrier gives the round trip delay and hence the distance of the satellite. Also the radial velocity can be obtained by doppler effect. Here it is necessary to ensure frequency and phase coherence between the uplink and downlink carriers. The radial velocity as a function of frequency difference Δf between the received frequency and nominal frequency can be obtained.

TC transmitter (Telecommand transmitter)

- The command links are provided by a carrier whose frequency depends on the band used and is phase or frequency modulated by a subcarrier at 8 kHz.
- The data commands to be transmitted are either regulating commands to adjust a parameter on board the satellite to a particular value e.g. current of travelling wave tube or opening and closing of relay.
- Commands can be executed immidiately or stored in memory and executed on reception of a specific command.
- The command links must possess safeguards against unathorized attempts to make changes to satellite position for this precautions are taken such as error correcting, coding of data words, deferred execution of commands etc. In deferred execution of commands, the command is detected by satellite, stored in memory and retransmitted to the ground by telemetry for verification of authenticity and then after proper authentication it is executed. Also the precautions are to be taken from signals transmitted by intruders, these include narrow band reception, input limiters insensitive to non-standard signals and data encryption.

On Board Data Handling (OBDH)

- OBDH unit performs following functions -
  1. Command processing : It covers decoding validation, acknowledgement and execution of command signals.
  2. Data storage and processing.
  3. Data traffic management.
  4. Data timing and synchronization.

2.6.2 Tracking

- Regular estimation of orbital parameters are necessary to maintain a satellite in its assigned orbit and to provide look angle information to the earth station.
- The function of tracking is to provide necessary sources to Earth stations for the tracking and determination of orbital parameters. In such a way, to maintain a satellite in its assigned orbital slot and provide look angle information to Earth

Station (ES) in the network, it is necessary to estimate the orbital parameters regularly. These parameters can be obtained by tracking the communications satellite from the ground and measuring its angular position and range.

- Tracking involves following :
  1. Measuring range repeatedly
  2. Compute orbital elements
  3. Plan station-keeping maneuvers
  4. Communication with main control station and users

2.6.3 Command

- The command sub-system receives commands transmitted from the ground control centre, verifies reception and executes commands to perform various functions of the satellite during its operational mission, such as :
  1. Satellite transponder and beacon switching,
  2. Antenna pointing control,
  3. Switch matrix reconfiguration,
  4. Controlling direction and speed of solar arrays drive,
  5. Battery reconditioning,
  6. Thruster firing and switching heaters of the various systems.
- The command system is used during launch to control the firing of the boost motor, deploy appendages such as solar panels and antenna reflectors, and 'spin-up' a spin-stabilized spacecraft body.
- The command procedure also involves multiple transmissions to the spacecraft, to assure the validity and correct reception of the command, before the execute instruction is transmitted.

Review Questions

1. *Explain with help of block diagram typical tracking, telemetry command and monitoring system.*
2. *Explain : Tracking, telemetry and command system.*
3. *With the help of block diagram, explain typical tracking, telemetry, command and monitoring system.*
4. *What is TTC ? Explain in brief.*

2.7 Transponders

- Transponder is a term derived from transmitter and responder.
- The component in the satellite that receives the uplink signal, amplifies and possibly processes the signal, and then reformats and transmits the signal back to the ground, is called the **transponder**, designated by the triangular amplifier symbol in the Fig. 2.7.1 (the point of the triangle indicates the direction of signal transmission).
- Two transponders are required in the satellite for each link.
- To utilize the full 500 MHz bandwidth for a 6/4 GHz link a satellite might use 12 transponders at 40 MHz steps. Most systems include redundant items in case of failure of particular channels.
- Transponders can channel the satellite capacity both in frequency and in power. A transponder may be accessed by one or several carriers. Transponders exhibit strong nonlinear characteristics and multicarrier operations, unless properly balanced, which may result in unacceptable interference.

Types of transponders

- Two major types of transponders are :
  1. Frequency translation transponder
  2. On-board processing transponder

1. Frequency translation transponder

- The majority of satellite transponders are **frequency translation** that is, they amplify the uplink signal, shift it in frequency and transmit it as the downlink.
- The frequency translation transponder, also referred to as a **non-regenerative repeater, transparent** or **bent pipe,** receives the uplink signal and, after amplification, retransmits it with only a translation in carrier frequency.
- Fig. 2.7.1 shows the typical implementation of a dual conversion frequency translation transponder.

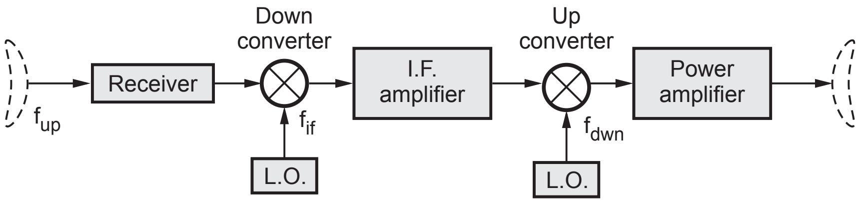


Fig. 2.7.1 Frequency translation transponder

- The non-regenerative repeater offers signal amplification / Gain ≈ 110 dB.
- The uplink radio frequency (f_{up}) is converted to an intermediate lower frequency (f_{if}) amplified, and then converted back up to the downlink RF frequency (f_{dwn}) for transmission to earth.
- The uplinks and downlinks are codependent, meaning that any degradation introduced on the uplink will be transferred to the downlink, affecting the total communications link. This has significant impact on the performance of the end-to-end link.
- Transparent transponder is a repeater in the sky it performs amplification and frequency translation and No processing. Fig. 2.7.2 illustrates its function in satellite communications.

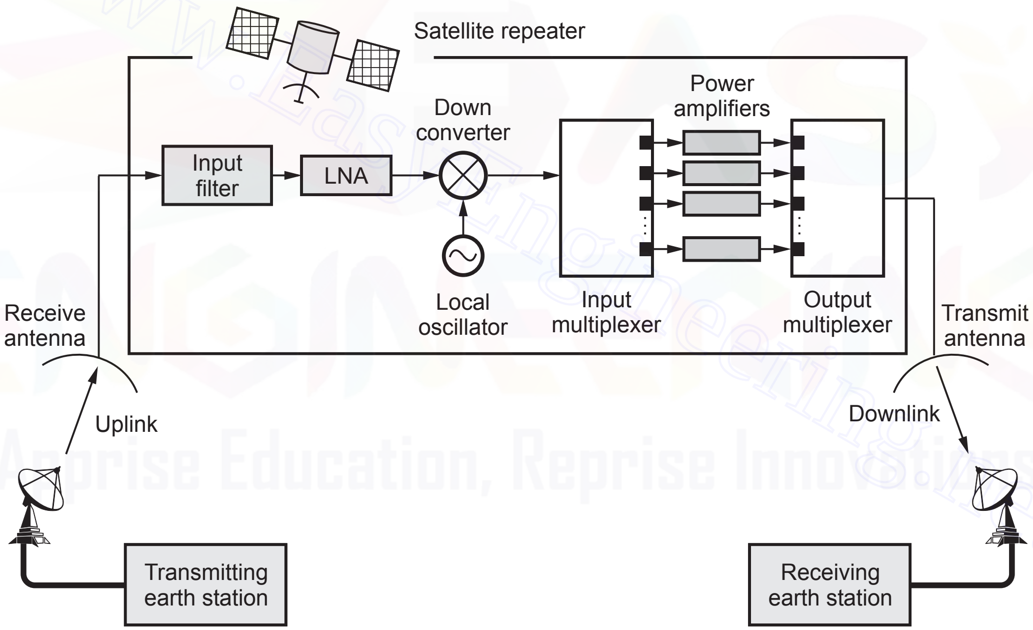


Fig. 2.7.2 Transperent transponders

2. On-board processing transponder

- Fig. 2.7.3 shows the **on-board processing** transponder, also called a **regenerative repeater demod/remod transponder** or **smart satellite.**
- The regenerative transponder performs amplification and frequency translation along with signal processing.

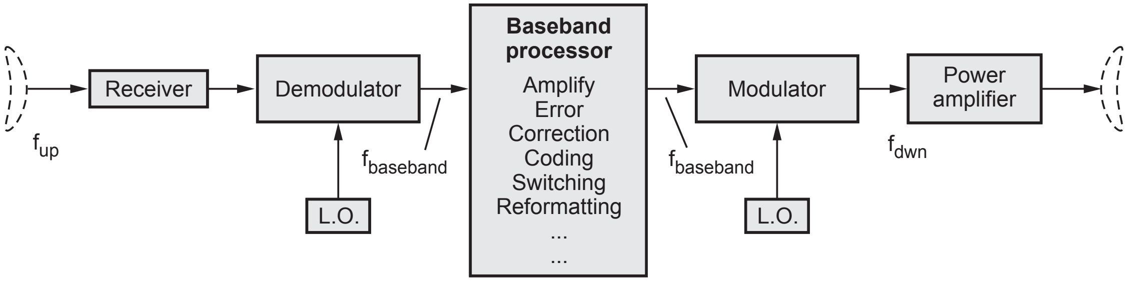


Fig. 2.7.3 On-board processing transponder

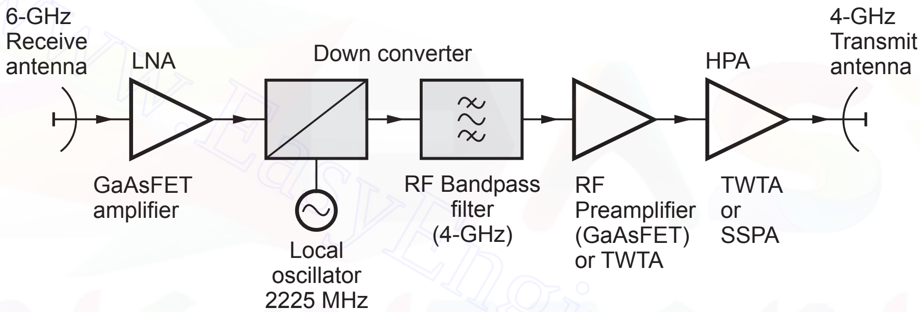


Fig. 2.7.4 Single conversion transponder for 6 / 4 GHz

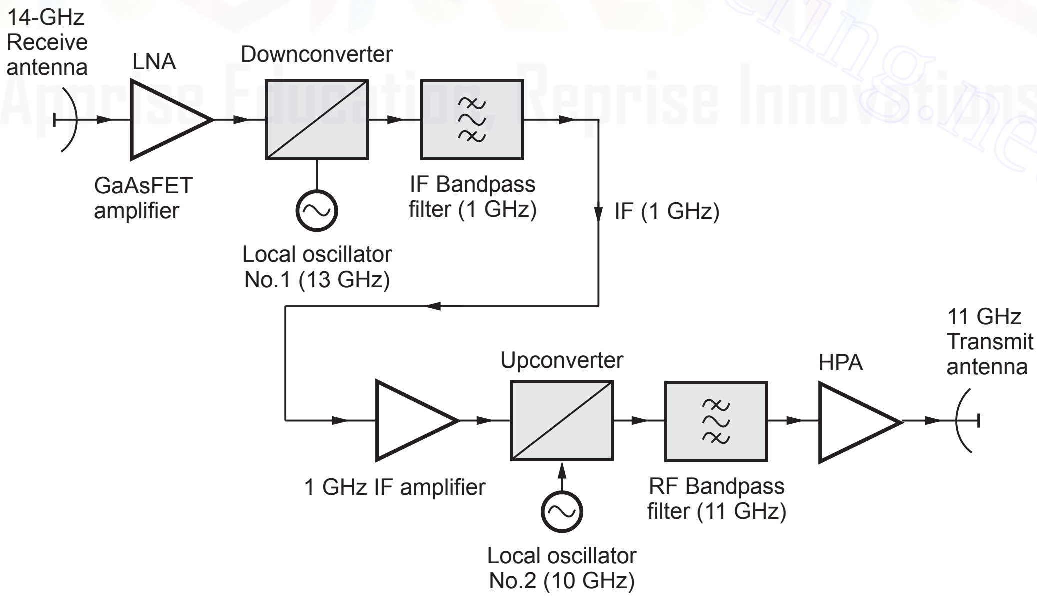


Fig. 2.7.5 Double conversion transponder

Up - Conversion : The IF frequency (70 MHz/140 MHz) translated to higher frequency using single or double stage conversion process.

Down - Conversion : The RF Frequency is translated to IF frequency (70 MHz/140 MHz) using single or double stage conversion process.

- The uplink signal at f_{up} is demodulated to baseband, $f_{baseband}$. The baseband signal is available for processing on-board, including reformatting and error-correction.
- The baseband information is then re-modulated to the downlink carrier at f_{dwn}, possibly in a different modulation format to the uplink and, after final amplification, transmitted to the ground.
- The demodulation/re-modulation process removes uplink noise and interference from the downlink, while allowing additional on-board processing to be accomplished.
- Thus the uplinks and downlinks are independent with respect to evaluation of overall link performance, unlike the frequency translation transponder where uplink degradations are codependent.

Classification of transponder based on frequency conversion

1. Single conversion transponder
2. Double conversion transponder

2.7.1 Single Conversion Transponder for 6 / 4 GHz

- The single conversion transponder is simple, low cost and features a reduced part count compared to double - conversion type. Today, this repeater type is mostly used in commercial satellites - for example carrying several ten transponders operating in Ku or Ka band - to keep costs down.
- This transponder type implies the availability of signal amplifiers - after the down - conversion - operating at relatively high frequencies, which were not cheaply available till a few years ago.

2.7.2 Double Conversion Transponder for 14 / 11 GHz

- The double conversion transponder implies that the bulk of the repeater gain is achieved by the Intermediate Frequency Amplifiers (IFA), whose operating frequency can be suitably lowered (thus enhancing the gain performance of the IFAs) by a suitable choice of the conversion frequencies generated by the Local Oscillator (LO). This approach is older than single conversion type and substantially more conservative, at the expense of a higher part count , mass and DC power consumption.

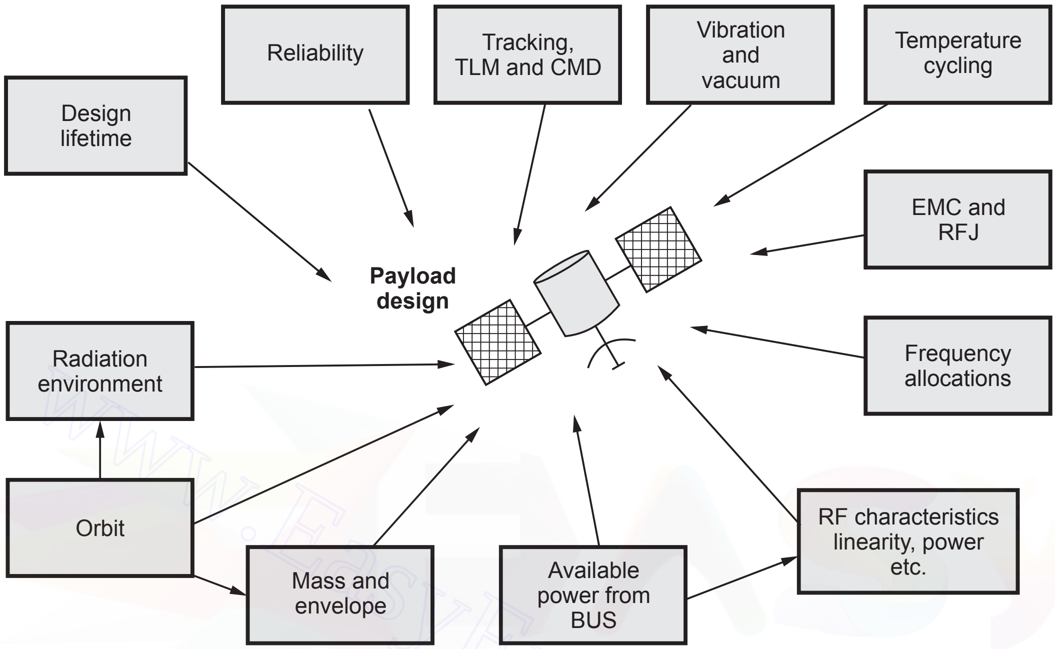


Fig. 2.7.6 Factors affecting transponder/payload design

2.7.3 Factors affecting Transponder / Payload Design

- Various factors affecting transponder design are -

1. Reliability
2. Tracking
3. Vibration and vacuum
4. Temperature cycling
5. EMC and RFI
6. Frequency allocation
7. RF characteristics - Linearity, power etc.
8. Available power from bus
9. Mass of satellite
10. Orbit
11. Radiation environment
12. Design lifetime

Review Questions

1. *Explain double conversion transponder for 14/11 GHz band. Support your answer with suitable diagram and specify frequencies of local oscillators and IF amplifiers.*
2. *Explain the transponder arrangement and frequency plan (uplink and downlink) for any satellite. Also draw block diagram of single conversion transponder for 6/4 GHz band.*

2.8 Antenna Subsystem

- The process, in which energy in some other form is converted into Electromagnetic (EM) waves, is known as *radiation*. When radiation is desired, the electromagnetic waves must be excited from the given source in the required direction as efficiently as possible.
- The system that acts as the matching unit between the source and the waves in free space is known as the *radiator* or *antenna.* Theoretically, any structure can radiate EM waves but not all structures can serve as efficient radiation mechanism.
- An **antenna** can be defined as an elevated metallic conductor which means for radiating or receiving radio waves into and from the free space. Actually, the antenna is the transitional structure between free-space and a guiding device.
- The guiding device can be transmission line, co-axial line or wave guide and it is used to transport EM energy from the transmitting source to the antenna or from antenna to the receiver. The antenna is meant for two main reasons -
  i. Efficient radiation
  ii. Matching wave impedances to minimize reflection.
- The antenna uses voltage and current from the transmission line to radiate an EM wave into the medium. The EM waves can be radiated by a time varying currents. Also in order to have efficient radiation the size of the antenna must be comparable to the wavelength.

2.8.1 Antenna Basics

- For analyzing and defining the performance of any antenna various parameters are defined. Some important parameters are radiation pattern, directive gain, power gain, efficiency, effective aperture, radiation resistance, beam width, bandwidth etc.

2.8.1.1 Radiation Pattern

- Radiation pattern of an antenna is a graphical representation or a mathematical function of radiation properties of an antenna as a function of space co-ordinates. Three dimensional spherical co-ordinate system is shown in Fig. 2.8.1.
  (See Fig. 2.8.1 on next page.)

Radiation pattern lobes

- The maximum radiation of pattern is called as **major lobe**. The main lobe is represented in the z-direction. The most of the radiation is in major lobe. Lobes (side and back) are called **minor lobes**. The minor lobes are in the directions different than major lobes.

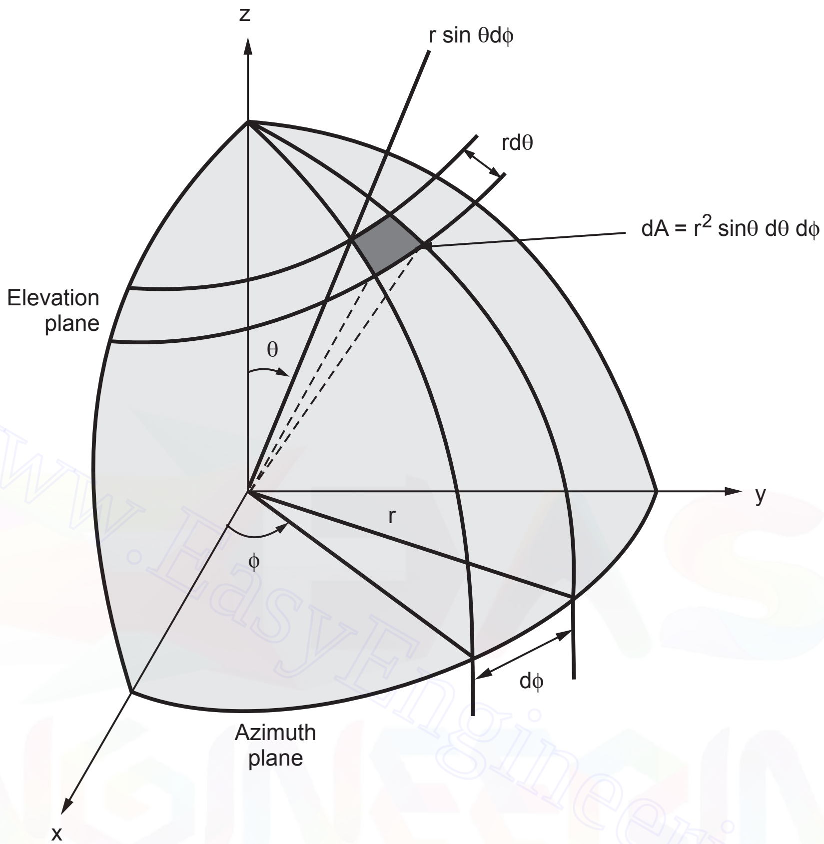


Fig. 2.8.1 Dimensional spherical co-ordinate system

- Minor lobes usually represent radiation undesired direction, hence they should be minimized. A minor radiation lobe whose axis makes an angle of approximately 180° with respect to the major lobe axis is called as **back lobe**. Between the lobes when field becomes zero are called as **nulls**. Fig. 2.8.2 shows three dimensional field pattern of a directional antenna. (See Fig. 2.8.2 on next page.)
- **Radiation pattern** of an antenna is a three dimensional representation of field or power as a function of spherical co-ordinates (θ and ϕ) at far field.
- When the component of E-field is plotted, it is called the **field pattern (voltage pattern)**. When the square of amplitude of E-field is plotted it is called the **power pattern**.
- Fig. 2.8.3 shows field patterns and power pattern. (See Fig. 2.8.3 on next page.)

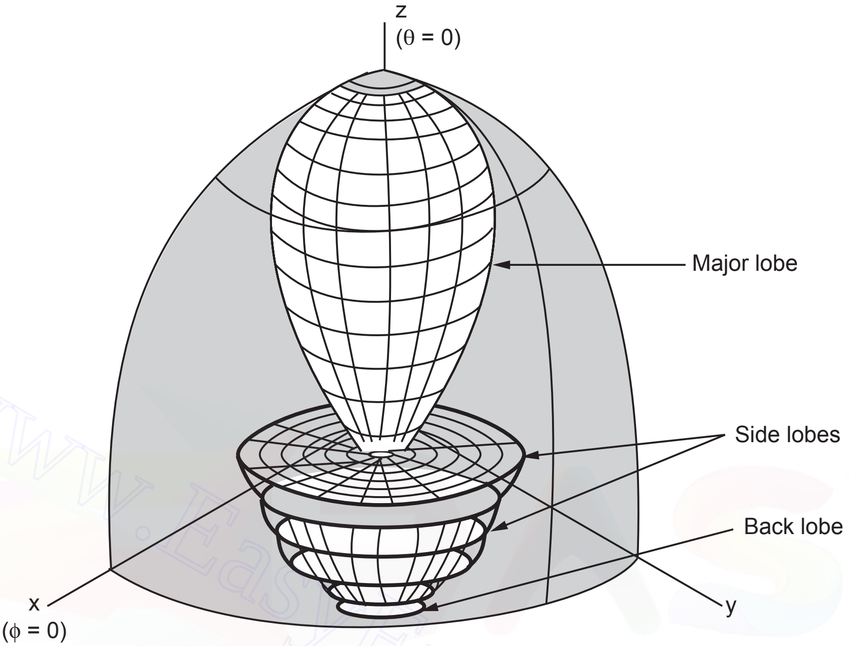


Fig. 2.8.2 Three dimensional field pattern

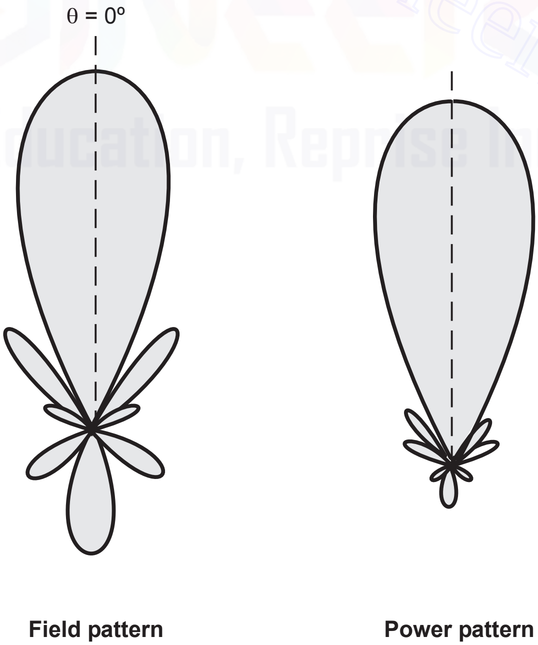


Fig. 2.8.3

Principal pattern

- Performance of linearly polarized antenna is described in terms of its principal patterns. Also instead of showing three-dimensional view of radiation pattern, planner section of radiation pattern are convenient to represent. The planner radiation pattern can be plotted in two different views.
  1. **E-plane pattern -** (Plane containing electric field vector and direction of maximum direction)
- The E-plane pattern is a view of the radiation pattern obtained from a section containing the maximum value of the radiated field and electric field lies in the plane of the section i.e. E-field versus θ is plotted for a constant ϕ (= zero). It is also called as **vertical pattern**.
  2. **H-plane pattern -** (Plane containing magnetic field vector and direction of maximum radiation)

     The **H-plane pattern** is a sectional view in which the H-field lies in the plane of section i.e. plot of E-field versus ϕ for $\theta = \frac{\pi}{2}$. It is also called as **horizontal pattern**.

Two dimensional pattern

- Two dimensional pattern in rectangular co-ordinates on linear or logarithmic (dB) scale is shown in Fig. 2.8.4.

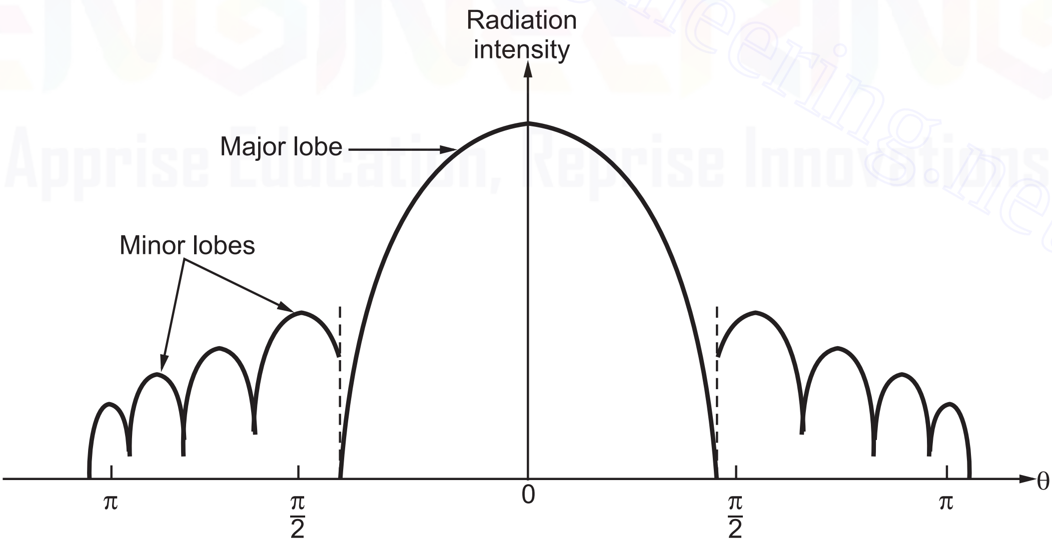


Fig. 2.8.4 Two dimensional plot of radiation pattern and its associated lobes

Normalized field pattern :

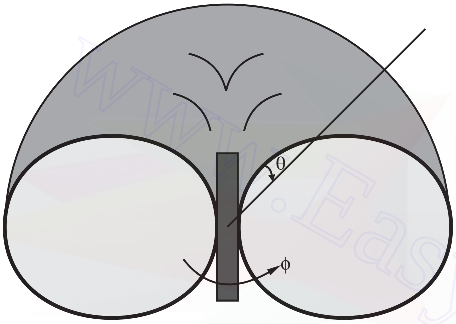
- Normalized field pattern is obtained by dividing field component by its maximum value. It is a dimensionless quality. Its maximum value can be unity.

- Normalized field pattern $E(\theta, \phi)_n = \frac{E_\theta(\theta,\phi)}{E_\theta(\theta,\phi)_{max}}$

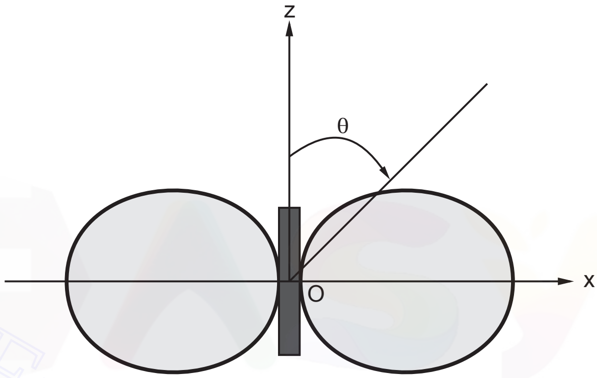
Similarly

Normalized power pattern $P_n(\theta, \phi)_n = \frac{S(\theta,\phi)}{S(\theta,\phi)_{max}}$

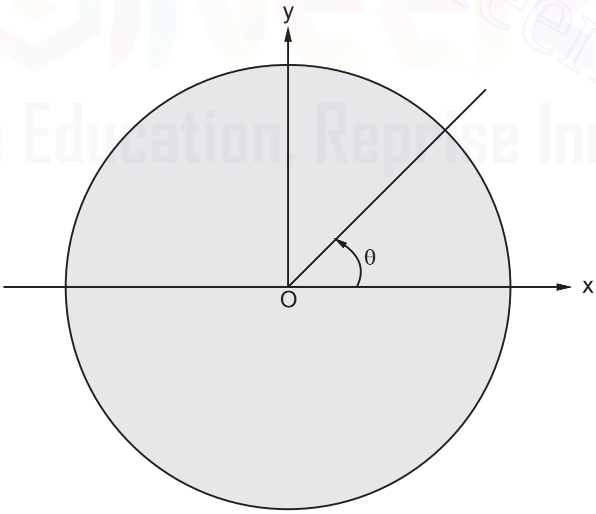
The field patterns for Hertzian dipole are shown in Fig. 2.8.5.



(a) Three dimensional pattern



(b) E-plane pattern



(c) H-plane pattern ($\theta = \frac{\pi}{2}$)

Fig. 2.8.5 Power radiation patterns of Hertzian dipole

- The distance from center O represents the strength of radiation field. The scale chosen is usually in dB with reference to an isotropic source or with reference to a half-wave dipole. When the reference is isotropic source it is denoted as dBi and when reference is half-wave dipole it is denoted as dBd.

$$0 \text{ dB} = 2.14 \text{ dBi}$$

$$G(\text{dBd}) = G(\text{dBi}) - 2.14 \text{ dB}$$

2.8.1.2 Antenna Gain

- **Antenna gain** is a gain relative to a reference antenna (isotropic radiator).
- Antenna gain is a measure of directional capabilities and efficiency of antenna.
- Antenna gain is defined as the ratio of the radiation intensity in a given direction to the radiation intensity by a reference (isotropic) antenna for similar power input to both antenna. The reference antenna can be short dipole or horn antenna whose gain can be calculated. Usually reference antenna is lossless isotropic source.

$$\text{Antenna gain } G(\theta, \phi) = \frac{P(\theta, \phi)}{P_{acc} / 4\pi r^2}$$

Where P_{acc} is the total power accepted by the antenna from the transmitter (watts) and $\mathbf{P_{acc}}$ is radiated power density if all the $4\pi r^2$ power is radiated isotropically (watts/metre^2).

- The power accepted by the antenna is greater than the actual radiated power because of reflection (mismatch) efficiency and polarization loss factor.
- Fig. 2.8.6 shows gain of half-wave dipole antenna with respect to isotropic radiator.
- The Fig. 2.8.6 indicates that half-wave dipole has a gain of 2.15 dB compared to isotropic radiator.
- **Effective radiated power :** When the gain of an antenna is multiplied by its power input, the result is termed as Effective Radiated Power (ERP).

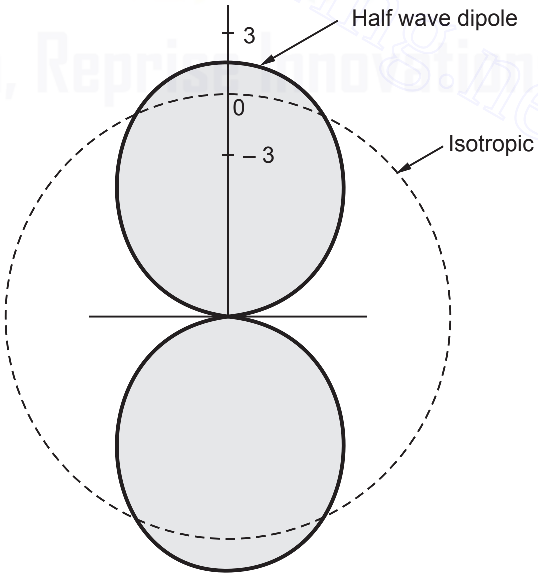


Fig. 2.8.6 Half-wave dipole and isotropic field pattern

2.8.1.3 Antenna Efficiency

- The **efficiency of an antenna** is defined as the ratio of power radiated to the total input power applied to the antenna and is denoted by η.

Antenna efficiency $\eta = \frac{P_r}{P_{in}}$

where P_r represents radiated power.

P_{in} represents total input power.

2.8.1.4 Directive Gain

- The electromagnetic energy radiated from antenna is concentrated in certain direction. The specified pattern frequently incorporate the intention to enhance the radiation in certain directions and suppress in others.
- The directive gain in a direction is defined as the ratio of the radiation intensity in that direction to the average radiated power.

$$\text{Directive gain } (G_d) = \frac{\text{Radiation intensity in particular direction}}{\text{Average radiated power}}$$

2.8.1.5 Directivity

- The maximum directive gain is called as directivity at an antenna and is denoted by 'D'. **Directivity D** of an antenna is defined as the ratio of maximum radiation intensity of the subject antenna to the radiation intensity of an isotropic (reference) antenna radiating the same total power.

$$\text{Directivity (D)} = \frac{\text{Maximum radiation intensity of subject antenna}}{\text{Radiation intensity of an isotropic antenna}}$$

$$D = \frac{P(\theta,\phi)_{max}}{P(\theta,\phi)_{av}}$$

The average radiation intensity is equal of the total power radiated by the antenna divided by 4π.

$$D(\theta,\phi) = \frac{P(\theta,\phi)_{max}}{\frac{1}{4\pi}\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi} P(\theta,\phi)\sin\theta\, d\theta\, d\phi}$$

$$D(\theta,\phi) = \frac{4\pi P(\theta,\phi)_{max}}{\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi} P(\theta,\phi)\sin\theta\, d\theta\, d\phi}$$

$$D(\theta,\phi) = \frac{4\pi}{\int_0^{2\pi}\int_0^{\pi} \frac{P(\theta,\phi)\sin\theta\, d\theta\, d\phi}{P(\theta,\phi)_{max}}}$$

$$D(\theta,\phi) = \frac{4\pi}{\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi} P_n(\theta,\phi)\sin\theta\, d\theta\, d\phi}$$

where $P_n(\theta,\phi) = \frac{P(\theta,\phi)\sin\theta\, d\theta\, d\phi}{P(\theta,\phi)_{max}}$

$P_n(\theta,\phi)$ is called as normalized power.

$$\boxed{D(\theta,\phi) = \frac{4\pi}{\Omega_A}}$$

where Ω_A is beam solid angle.

$$\Omega_A = \int_0^{2\pi}\int_0^{\pi} P_n(\theta,\phi)\sin\theta\, d\theta\, d\phi$$

- **Beam solid angle :** It is defined as the solid angle through which all the power of the antenna would flow if its radiation intensity is constant for all angles.
- Beam solid angle is given by integral of normalized power pattern over a sphere.
- The value $D(\theta,\phi)$ is a numeric, dimensionless ratio. It will have a value less than unity in directions in which radiation is suppressed and a value exceeding unity where the radiation has been enhanced.
- In characterizing an antenna, one must be careful to distinguish between directivity and gain. Directivity is used to compare the radiation intensity in a given direction to the average radiation intensity and thus pays no careful attention to the power losses in antenna system. While, gain includes losses by the definition of gain.

$$G(\theta,\phi) = \frac{P(\theta,\phi)}{P_{acc} / 4\pi r^2}$$

where P_{acc} is total power accepted by the antenna from the transmitter, measured in watts.

- The denominator is the value, in watts per square metre, that the radiated power density would have if all the power accepted by the antenna were radiated isotropically. Since the power accepted is greater than the actual power radiated, the denominator of gain expression is larger than that of directivity expression.

Hence $G(\theta,\phi) < D(\theta,\phi)$

- In other words, directivity is the gain calculated assuming a lossless antenna. But practically every antenna have some losses. The gain and directivity are related by

$$G_d = D\eta$$

where, G_d represents directive gain.

D represents directivity.

η represents antenna efficiency.

2.8.1.6 Effective Length

- The **effective length** of an antenna represents the effectiveness of an antenna as radiator or collector of electromagnetic energy.
- Effective length indicates how far an antenna is effective in transmitting or receiving the electromagnetic wave energy.
- Effective length is given as the ratio of induced voltage at the terminal of the receiving antenna under open circuited condition to the incident electric field intensity.

$$\text{Effective length} = \frac{\text{Open circuited voltage}}{\text{Incident field strength}}$$

$$l_e = \frac{V}{E}$$

2.8.1.7 Effective Area / Effective Aperture

- **Effective aperture** of an antenna is defined as the ratio of power received by the antenna to the power density of the incident wave.

$$\text{Effective aperture } (A_e) = \frac{\text{Power received}}{\text{Incident power}}$$

2.8.1.8 Radiation Resistance

- **Radiation resistance** is a resistance which when substituted in series with the antenna will consume the same amount of power as it actually radiates. Radiation resistance is denoted by R_r or R_{rad}.

$$R_r = \frac{\text{Power}}{(\text{Current})^2}$$

$$R_r = \frac{P}{I^2}$$

where, P represents total radiated power from the antenna.

I represents effective r.m.s. value of antenna current at feed point (ampere).

- The radiation resistance can also be defined as the portion of an antenna input resistance that is the result of power radiated into the space.

2.8.1.9 Front to Back Ratio

- **Front to back ratio** of the power radiated is defined as the ratio of power radiated in desired direction to the power radiated in the opposite direction.

$$\text{FBR} = \frac{\text{Power radiated in desired direction}}{\text{Power radiated in opposite direction}}$$

Higher FBR is desirable than the maximum gain. It is generally expressed in dBs.

2.8.1.10 Antenna Bandwidth

- The **bandwidth** of an antenna is defined as the range of frequencies over which the antenna maintains the given set of specifications.

The specifications can be gain, FBR, resistance pattern.

$$\text{Bandwidth } \Delta f = \frac{\text{Centre frequency } (f_r)}{Q}$$

2.8.1.11 Beamwidth

- Usually a directional antenna emits a beam of radiation in one or more directions.

Various parts of radiation patterns are referred as **Lobes**.

Major lobe :

- It is the radiation lobe in the direction of maximum radiation.

Minor lobe :

- These are the lobes other than major lobe. A minor lobe is radiation in undesired direction hence it should be minimized.

Side lobe :

- It is the lobe in any direction other than the major or intended lobe.

Back lobe :

- It is a radiation whose axis makes an angle of approximately 180° with respect to beam of antenna.
- The **beam width of an antenna** is defined as the angle between its half power points in major lobes. These are also the points where power density is 3 dB less than it is at its maximum point.

2.8.1.12 Beam Efficiency (BE)

- For an antenna with its major lobe directed along the z-axis ($\theta = 0$), the beam efficiency is defined as :

$$\text{Beam efficiency} = \frac{\text{Power transmitted with in cone angle } \theta_1}{\text{Power transmitted by the antenna}}$$

$$\text{Beam efficiency} = \frac{\int_0^{2\pi}\int_0^{\theta_1} P(\theta,\phi)\sin\theta\, d\theta\, d\phi}{\int_0^{2\pi}\int_0^{\pi} P(\theta,\phi)\sin\theta\, d\theta\, d\phi}$$

- In other words, beam efficiency is the ratio of the main beam area to the total beam area (including minor lobe).
- Beam efficiency is denoted by ε_M.

$$\varepsilon_M = \frac{\Omega_M}{\Omega_A}$$

where Ω_M = Main beam area

Ω_A = Total beam area or beam solid angle.

A very high beam efficiency is necessary for antennas used in radiometry, astronomy, radar and other applications where received signal through side lobes must be minimized.

2.8.1.13 Polarization

- **Polarization** of antenna refers to the direction in the free space of the electric vector of the electromagnetic wave radiated from it.
- The direction of antenna and polarization is same i.e. if an antenna is vertical it will radiate vertically **polarized waves**.
- Usually polarization is elliptical. If the tip of electric field traces a circle the wave is said to be circularly polarized.

Linear polarization

- When the electric field vector in space is always directed along a line as a function of time, the field is said to be **linearly polarized**.
- Let a plane wave travelling in positive z direction. In linear polarization the electric field vector varies at all times in y direction. The electric field component E_1 is zero. Then the electric field as a function of time is expressed by,

$$E_y = E_z (\sin \omega t - \beta z)$$

- The linear polarization exists when electric field vector posses :
  1. Only one component.
  2. Two orthogonal linear components that are in time phase or $n\pi$.

2.8.1.14 Effective Isotropic Radiated Power (EIRP)

- **EIRP** is defined as the product of actual power going into the antenna multiplied by its gain with respect to an isotropic radiator.

$$\text{EIRP} = P_t G_t$$

$$\text{EIRP} = \text{ERP} + 2.14 \text{ dB}$$

Solved Examples for Illustration

Example 2.8.1 *An antenna has a directivity of 20 and a radiation efficiency of 90 %. Compute the gain in dBs.*

Solution : $D = 20,$

$$\eta = 90\ \% = 0.9$$

The gain and directivity are related by the expression -

$$G = \eta D$$

$$G = 0.9 \times 20$$

$$G = 18$$

$$\text{Gain in dBs} = 10 \log_{10} G$$

$$= 10 \log_{10} 18$$

$$= \mathbf{12.55\ dB}$$

... **Ans.**

Example 2.8.2 *What is the maximum power received at a distance of 0.5 km over a free space for 1 GHz frequency system consisting of a transmitting antenna with a 2.5 dB gain and a receiving antenna with a 20 dB gain ? The transmitting antenna is fed with 150 watt power.*

Solution : $P_t = 150$ watts

$$G_t = 25 \text{ dB} = 1.77$$

$$f = 1 \text{ GHz} \quad \therefore \lambda = \frac{c}{f} = \frac{3\times10^8}{1\times10^9} = 0.3 \text{ m}$$

$$d = 0.5 \text{ km} = 500 \text{ meters}$$

$$G_r = 20 \text{ dB} = 100$$

Received power is given by -

$$P_r = \frac{P_t \cdot G_t \cdot G_r \lambda^2}{16\pi^2 d^2}$$

$$P_r = \frac{150 \times 1.77 \times 100 \times 0.3^2}{16 \times \pi^2 \times 500^2}$$

$$P_r = \mathbf{60.52\ \mu watt} \quad \text{... Ans.}$$

2.8.2 Spacecraft Antennas

- The size of satellite antennas are related to the transmission frequency.
- There is a inverse relationship between frequency and wavelength.
- As wavelength increases (and frequency decreases), larger antennas (satellite dishes) are necessary to gather the signal.
- Four main types of antennas are used on spacecraft.
  1. Wire antennas (monopoles and dipoles).
  2. Horn antennas.
  3. Reflector antennas.
  4. Array antennas.

1. Wire antennas

- Wire antennas are used primarily at VHF and UHF to provide communication for thr TTC and M.

2. Horn antennas

- Horn antennas are used at microwave frequencies when relatively wide beams are required as for global coverage.

3. Reflector antennas

- Reflector antennas are usually illuminated by one or more horns and provide a large aperture than can be achieved by one horn alone.

4. Array antennas

- Array antennas are also used on satellites to create multiple beams from a single aperture.
- Typical satellite antenna patterns and coverage zones are shown in Fig. 2.8.7.
  (See Fig. 2.8.7 on next page.)
- The antenna for the global beam is usually a waveguide horn. Scanning beams and shaped beams require phased array antennas or reflector antennas with phased array feeds.

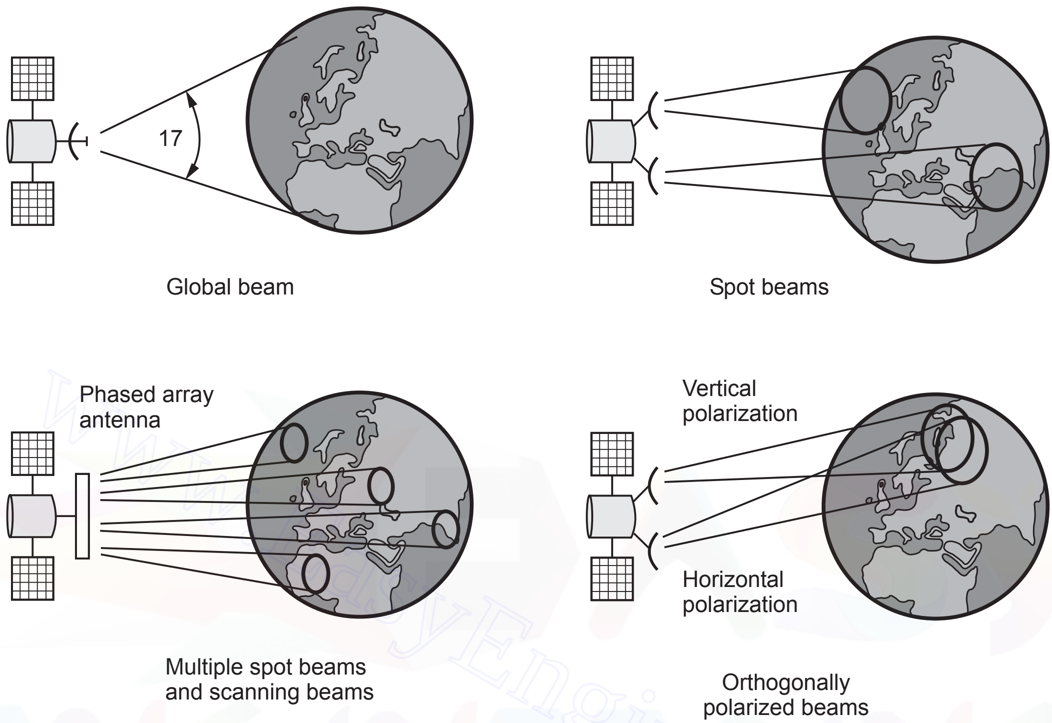


Fig. 2.8.7 Satellite antenna patterns and coverage zones

2.8.3 Selection of Antennas for Communications Satellite

- Following approximate relations can be used for selecting antenna for satellite.

1. An aperture antenna has a gain G :

$$G = \eta_A \, 4\pi \, A/\lambda^2$$

where A is area of antenna aperture in meters,

λ is operating wavelength in meters,

η_A is aperture efficiency of antenna.

2. For circular aperture antenna gain G :

$$G = \eta_A \left[\pi D/\lambda^2\right]$$

where D is diameter of circular aperture in meters,

3. 3 dB beamwidth for an antenna θ_{3dB} :

$$\theta_{3dB} = 75\lambda/D \quad \text{degrees}$$

where $\theta_{3\,dB}$ is beamwidth between half power points of antenna patterns,

D is antenna aperture dimension of antenna,

Solved Examples for Illustration

Example 2.8.3 *Earth subtends an angle of 17 degrees when viewed from geostationary orbit.*

a) What should be the dimensions of a reflector antenna to provide global coverage at 4 GHz ?

b) What will be the antenna gain if efficiency = 0.55 ?

Solution : a. θ_{3dB} = 17 degrees

$$\theta_{3dB} = \frac{75\,\lambda}{D}$$

$$D \cong \frac{75\,\lambda}{\theta_{3dB}} = \frac{75 \times 0.075}{17} = 0.33\,\text{m}$$

b. $\eta = 0.55$

$$\text{Gain} \cong \eta\left(\frac{75\pi}{\theta_{3dB}}\right)^2 = 0.55\frac{(75\,\pi)^2}{17^2} = 105.65 = 20.23 \text{ dB}$$

Example 2.8.4 *Continental US subtends a "rectangle" of 6 × 3 degrees.*

Find gain and dimensions of a reflector antenna to provide global coverage at 11 GHz

a. Using 2 antennas (3 × 3 degrees)

b. Using only 1 antenna (3 × 6 degrees)

Solution : a. 3 dB = 3 degrees

$$\theta_{3dB} = \frac{75\,\lambda}{D}$$

$$D \cong \frac{75\,\lambda}{\theta_{3\,dB}} = \frac{75 \times 0.075}{17} = 0.33\,\text{m}$$

$$D \cong \frac{75\,\lambda}{\theta_{3\,dB}} = \frac{75 \times 0.0273}{3} = 0.68 \text{ m}$$

$$\text{Gain} \cong \eta\left(\frac{75\pi}{\theta_{3dB}}\right)^2 = 0.55\left(\frac{75\pi}{3}\right)^2 = 3392.7 = 35.2 \text{ dB}$$

b. 3_{dBA} = 6 degrees 3_{dBE} = 3 degrees

$$D_E = 0.68 \text{ m}$$

$$D_A = \frac{75\,\lambda}{\theta_{3\,dB}} = \frac{75 \times 0.0273}{6} = 0.34 \text{ m}$$

$$\text{Gain} \cong \eta \frac{(75\pi)^2}{\theta_{3dB}\,\theta_{3dBE}} = 0.55 \frac{75\pi}{6 \times 3}^2 = 1696.3 = 32.3 \text{ dB}$$ ... **Ans.**

Example 2.8.5 *A satellite at a distance of 40,000 km from a point on the earth's surface radiates a power of 10 W from an antenna with a gain of 17 dB in the direction of the observer. Find the flux density at the receiving point, and the power received by an antenna at this point with an effective area of 10 m^2.*

Solution : $R = 40{,}000 \text{ km}, \; P_t = 10 \text{ W}$

$$G_t = 17 \text{ dB} = 50, \; A_e = 10\,m^2$$

Flux density :
$$F = \frac{EIRP}{4\pi R^2} = \frac{P_t G_t}{4\pi R^2}$$
$$= 10 \times 50 / [4 \times \pi \times (4 \times 10^7)^2]$$
$$= 2.48 \times 10^{-14}\, W/m^2$$

Received power :
$$P_r = F \times A = 2.48 \times 10^{-14}\, W/m^2 \times 10$$
$$= 2.48 \times 10^{-13}\, W$$ ...**Ans.**

Review Questions

1. *Write a short note on satellite antennas.*
2. *Explain in the following for orbital satellite : Antenna subsystem*
3. *What are different types of antennas used in satellite systems ? Explain importance of each.*
4. *Explain the following : Antenna subsystem*
5. *Write short note : Satellite antennas.*

2.9 Part A : Short Answered Questions [2 Marks Each]

Q.1 What is meant by station keeping ?

Ans. : Station Keeping -

- Station keeping is the process of maintenance of satellite's attitude against different factors that can cause drift with time.
- Satellites need to have their orbits adjusted from time to time because the satellite initially placed in the correct orbit; natural forces induce a progressive drift.

Q.2 What is Sun transit outage ?

Ans. : Sun Transit Outage

- An event which must be allowed for during the equinoxes is the transit of the satellite between earth and sun, such that the sun comes within the beamwidth of the earth-station antenna.
- When this happens, the sun appears as an extremely noisy source which completely blanks out the signal from the satellite.
- This effect is termed sun transit outage and it lasts for short periods. Each day for about 6 days around the equinoxes.
- The occurrence and duration of the sun transit outage depends on the latitude of the earth station, a maximum outage time of 10 min being typical.

Q.3 Enlist various satellite subsystems.

Ans. : Satellite subsystems

- Satellite subsystems include -
  1. Power supply
  2. Attitude and orbit control
  3. Thermal control
  4. Propulsion subsystem
  5. Communication payload
  6. Antenna
  7. TT & C

Q.4 Which basic mode of communication is used in satellite communication ? Which type of wave propagation is used in this mode ? Write the expression for the maximum line of sight distance d between two antennas having heights h_1 and h_2.

Ans. : Line of sight mode is used in the satellite communication.

Space wave propagation is used in line of sight mode.

$d = \sqrt{2Rh_1} + \sqrt{2Rh_2}$ where R = radius of the earth

Q.5 Why uplink frequencies are higher than downlink frequencies in case of satellite communication ?

Ans. : The satellite gets power from solar cell. So, the transmitter is not being of higher power. On the other hand, the ground station can have much higher power. As less attenuation is required and better signal-to-noise ratio, lower frequency is more suitable for downlink and higher frequency is commonly used for uplink.

2.10 Multiple Choice Questions

Q.1 Satellite signal transmitted from a satellite transponder to earth's station is called _______.

a uplink
b downlink
c terrestrial
d earthbound

Q.2 Helical antenna is used for satellite tracking because of ______.

a circular polarization
b maneuverability
c beamwidth
d gain

Q.3 Transponder function is to ______.

a receives a signal from Earth station and amplifies
b changes the frequency of the received signal
c retransmits the received signal
d does all of the above-mentioned functions

Q.4 Orbital disturbances of a geosynchronous satellite are due to _____.

a Moon
b Sun
c Earth
d All of the above

Answer Keys for Multiple Choice Questions

Q.1	b	Q.2	a	Q.3	d
Q.4	d				

Notes