GLOBAL NAVIGATION SATELLITE SYSTEM

IV Year B.Tech ECE II-Semester

UNIT 1

SATELLITE COMMUNICATION FUNDAMENTALS

SYLLABUS

Satellite Communication Fundamentals
Orbit and Description
Satellite Frequency Bands
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Coverage angle
Slant Range
Eclipse.

Satellite Subsystems
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Telemetry Command and Ranging Subsystem
Attitude Control Subsystem
Electrical Power Subsystem
Placement of a Satellite in a Geo-Stationary orbit.

INTRODUCTION TO SATELLITE COMMUNICATIONS

Satellite communications began in October 1957.

The first ever artificial satellite launched was Sputnik I by USSR.

Sputnik I carried only a beacon transmitter and did not have communications capability.

Sputnik I proved that satellites could be placed in orbit by powerful rockets.

US launched its first satellite called Explorer I from Cape Canaveral on Jan 31, 1958 on a Juno I rocket.

Communication over satellite is now well accepted as a key enabler across the telecommunications industry.

Satellite networks can supplement existing infrastructure by providing global reach where terrestrial networks are unavailable or not feasible.

Earth Station is a radio station located on the earth and used for relaying signals from satellites.

SATELLITE FREQUENCY BANDS

Satellite Frequency Band	Frequency Range (GHZ)
L	1 -2
S	2 - 4
C	4 - 8
X	8 - 12
Ku	12 - 18
K	18 - 27
Ka	27 - 40
O	40 - 50
V	50 - 75

The Global Positioning System (GPS) is a satellite-based navigation system made up of over 24 satellites.

GPS works in all weather conditions, anywhere in the world, 24 hours a day, with no subscription fees or setup charges.

The U.S. Department of Defense (DOD) originally put the satellites into orbit for military use, but they were made available for civilian use in the 1980s.

GPS Technology operates in the following frequency bands

GPS Band Designation	Center Frequency (MHz)	Bandwidth (MHz)
L1	1575.42	15.345
L2	1227.6	11
L5	1176.45	12.5

SATELLITE ORBITS AND DESCRIPTION

Types of Satellite Orbits

Low Earth Orbit (LEO)
Altitude 500 to 1,200km

LEO is densely populated with thousands of satellites in operation today.

Applications of LEO Satellites are in the areas of Science, Imaging and Low-bandwidth telecommunications.

The next generation of HTS (High Throughput Satellites) LEO satellites intends to serve communication markets such as mass-consumer and enterprise broadband internet.

Till mid 1963, 99% of all satellites had been launched in Low Earth Orbit (LEO) only.

LEO satellites have an orbital period of 1 hour to 3 hours.

Medium Earth Orbit (MEO)
Altitude 5,000 to 25,000km

MEO has historically been used for GPS and other navigation applications.

More recently, HTS MEO constellations have been deployed to deliver low-latency, high-bandwidth data connectivity to service providers, government agencies, and commercial enterprises.

MEO satellites bring fibre-like performance to remote areas where laying optical fibre (terrestrial communications) is not viable, such as cruise, commercial maritime, aero, offshore platforms, network backhaul in difficult terrain, and humanitarian relief operations.

The rotational period of MEO satellite is approximately 12 hours.

Satellite navigation systems, especially GPS (Global Positioning System) have revolutionized navigation and surveying.

In US, the aircraft navigation is entirely dependent on GPS and blind landing systems using GPS are also available.

Accurate navigation of ships, especially in coastal waters and bad weather is also heavily reliant on GPS.

Geosynchronous Earth Orbit (GEO)
Altitude 36,000km

GEO satellites match the rotation of the Earth as they travel.

GEO satellites have an orbital period of 24 hours.

Geostationary orbits are at an altitude 35,786 kilometers.

From the center of the Earth, this is approximately 42,164 kilometers.

At any inclination, a geosynchronous orbit synchronizes with the rotation of the Earth.

The time it takes for the Earth to rotate on its axis is 23 hours, 56 minutes, and 4.09 seconds, which is the same as a satellite in a geosynchronous orbit.

Geostationary orbits fall in the same category as geosynchronous orbits, but it's parked over the equator.

While the geostationary orbit lies on the same plane as the equator, the geosynchronous satellites have a different inclination.

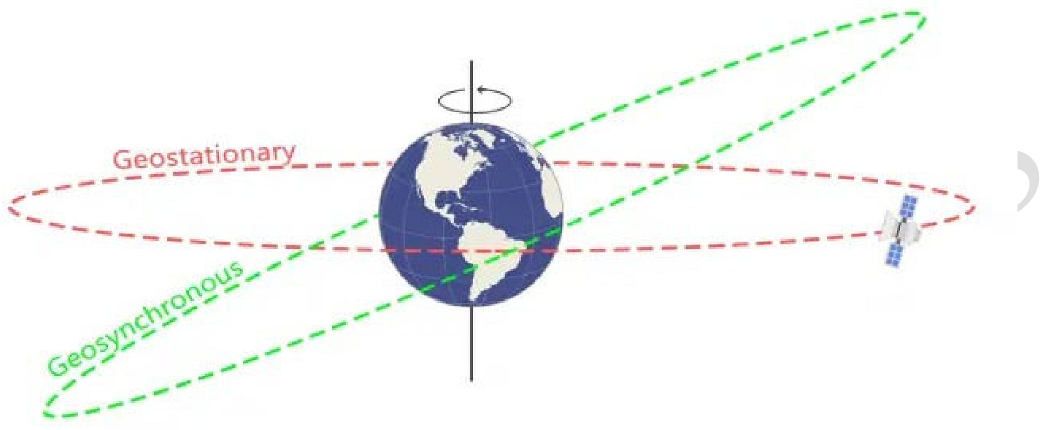

Fig. 1.1 Geosynchronous and Geostationary Orbits

Hundreds of GEO satellites are in orbit today, traditionally delivering services such as weather data, broadcast TV, and some low-speed data communication.

Over the past few years, GEO has been significantly enhanced by HTS, which are purpose-built for data.

GEO system architecture requires only one satellite to provide 24/7 operation over 1/3rd of the world.

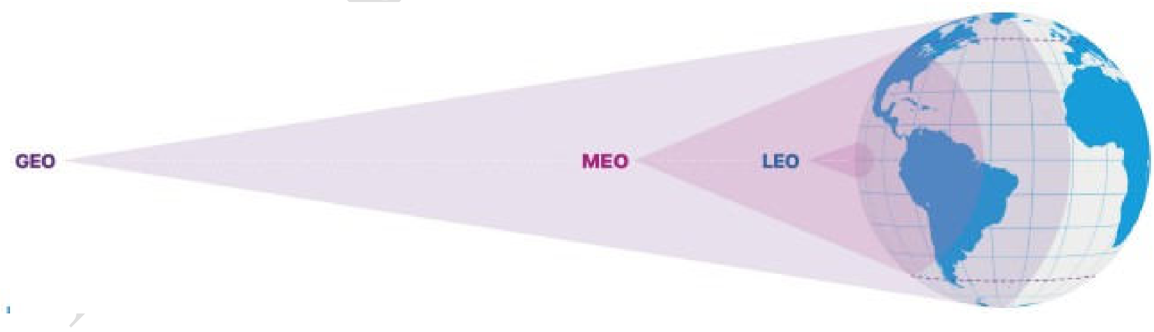

Fig. 1.2 Schematic of Orbital Altitudes and Coverage Areas

In 1970's and 1980's, there was a rapid development of GEO satellite systems for international, regional and domestic telephone traffic and video distribution.

This caused the available spectrum (bandwidth) in C-band (4-8 GHz) to be occupied completely, leading to expansion into Ku- band (12-18 GHz) followed by Ka-band (27-40 GHz).

Ka-band satellites would be needed to handle especially wideband delivery of high-speed Internet data.

APPLICATIONS OF SATELLITES

Weather Forecasting
Certain satellites are specifically designed to monitor the climatic conditions of earth.

They continuously monitor the assigned areas of earth and predict the weather conditions of that region.

This is done by taking images of earth from the satellite.

These satellites are exceptionally useful in predicting disasters like hurricanes, and monitor the changes in the Earth's vegetation, sea state, ocean color, and ice fields.

Radio and TV Broadcast
These dedicated satellites are responsible for making 100s of channels across the globe available for everyone.

They are also responsible for broadcasting live matches, news, world-wide radio services.

Military Satellites
These satellites are often used for gathering intelligence, as a communications satellite used for military purposes, or as a military weapon.

Navigation Satellites
The system allows for precise localization world-wide.

Ships and aircraft rely on GPS as an addition to traditional navigation systems.

Many vehicles come with installed GPS receivers.

Global Telephone
Instead of using cables it was sometimes faster to launch a new satellite.

Connecting Remote Areas
Due to their geographical location many places all over the world do not have direct wired connection to the telephone network or the internet (e.g., researchers on Antarctica) or because of the current state of the infrastructure of a country.

Here the satellite provides a communication.

Global Mobile Communication
The basic purpose of satellites for mobile communication is to extend the area of coverage.

Cellular phone systems do not cover all parts of a country.

Areas that are not covered usually have low population where it is too expensive to install a base station.

With the integration of satellite communication, however, the mobile phone can switch to satellites offering world-wide connectivity to a customer.

Satellites cover a certain area on the earth. This area is termed as a “footprint” of that satellite. Within the footprint, communication with that satellite is possible for mobile users.

KEPLER’S THREE LAWS OF PLANETARY MOTION

Johannes Kepler (1571–1630) was a German astronomer and scientist who developed the three laws of planetary motion

Kepler’s three laws are:

1. The orbit of any smaller body about a larger body is always an ellipse, with the center of mass of the larger body as one of the two foci.

2. The orbit of the smaller body sweeps out equal areas in equal time

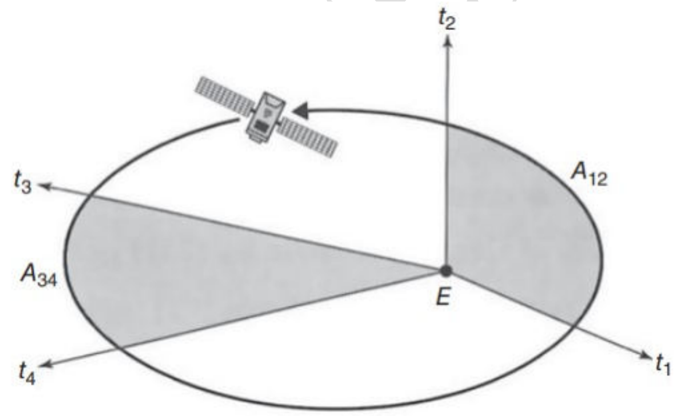

Fig. 1.3 Illustration of Kepler’s second law of planetary motion.

A satellite is in orbit around the planet earth, E.

The orbit is an ellipse with a relatively high eccentricity.

The figure shows two shaded portions of the elliptical plane in which the satellite moves, one is close to the earth and encloses the perigee while the other is far from the earth and encloses the apogee.

The perigee is the point in the orbit of a satellite at which it is closest to the earth.

The apogee is the point in the orbit that is furthest from the earth.

While close to perigee, the satellite moves in the orbit between t1 and t2 and sweeps out an area denoted by $\boldsymbol{A_{12}}$.

While close to apogee, the satellite moves in the orbit between times t3 and t4 and sweeps out an area denoted by $\boldsymbol{A_{34}}$.

If $\boldsymbol{t_1 - t_2 = t_3 - t_4}$ then according to Kepler's second law of planetary motion, $\boldsymbol{A_{12}} = \boldsymbol{A_{34}}$.

3. The square of the period of revolution of the smaller body about the larger body equals a constant multiplied by the third power of the semimajor axis of the orbital ellipse.

That is

$$\boldsymbol{T^2 = \frac{4\pi^2 a^3}{\mu}}$$

where **T** is the orbital period,
a is the semimajor axis of the orbital ellipse, and
μ is Kepler's constant.

If the orbit is circular, then a becomes distance r, defined as before, and we have

$$\boldsymbol{T = \frac{2\pi r^{3/2}}{\mu^{1/2}}}$$

SATELLITE ORBITAL ELEMENTS

Orbital elements are the parameters, which are helpful for describing the orbital motion of satellites. Following are the **orbital elements**.

- Semi major axis
- Eccentricity
- Mean anomaly
- Argument of perigee
- Inclination
- Right ascension of ascending node

The above six orbital elements define the orbit of earth satellites. Therefore, it is easy to discriminate one satellite from other satellites based on the values of orbital elements.

Semi major axis

The length of **Semi-major axis (a)** defines the size of satellite's orbit. It is half of the major axis. This runs from the center through a focus to the edge of the ellipse. So, it is the radius of an orbit at the orbit's two most distant points.

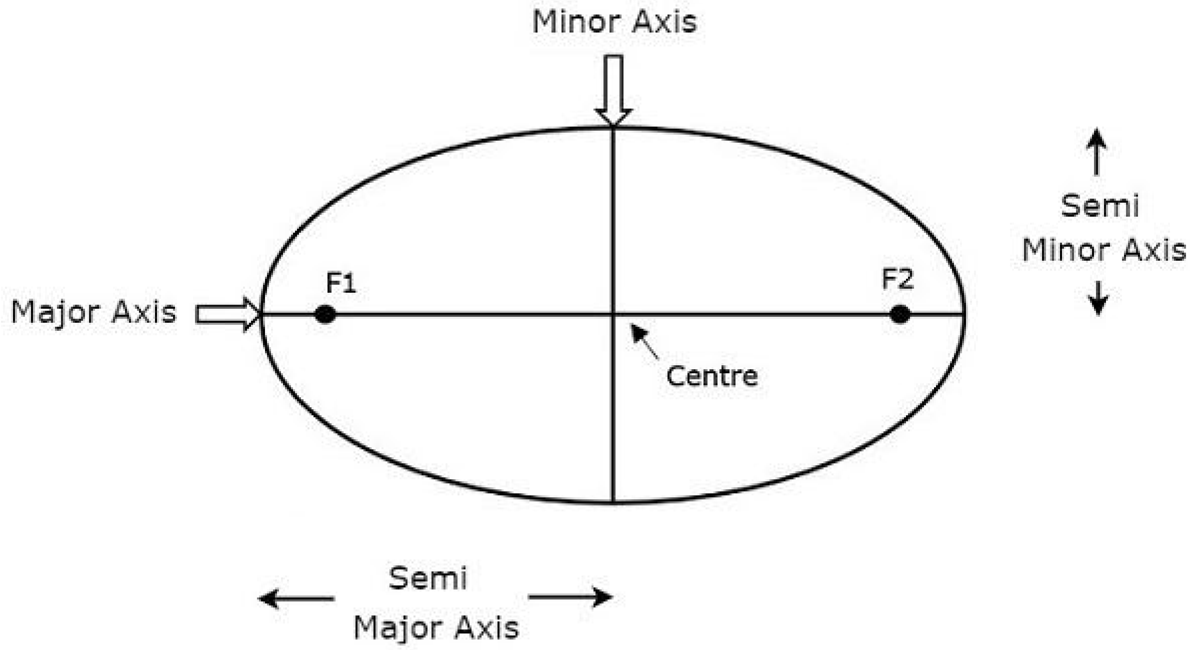

Fig. 1.4 Semi major axis and Semi minor axis of Satellite Elliptical Orbit

Both semi major axis and semi minor axis are represented in above figure. Length of semi **major axis (a)** not only determines the size of satellite's orbit, but also the time period of revolution.

If circular orbit is considered as a special case, then the length of semi-major axis will be equal to **radius** of that circular orbit.

<u>Eccentricity</u>

The value of **Eccentricity (e)** fixes the shape of satellite's orbit. This parameter indicates the deviation of the orbit's shape from a perfect circle.

If the lengths of semi major axis and semi minor axis of an elliptical orbit are a & b, then the mathematical expression for **eccentricity (e)** will be

e=a2−b2−−−−−−√ae=a2−b2a

The value of eccentricity of a circular orbit is **zero**, since both a & b are equal. Whereas, the value of eccentricity of an elliptical orbit lies between zero and one.

The following **figure** shows the various satellite orbits for different eccentricity (e) values

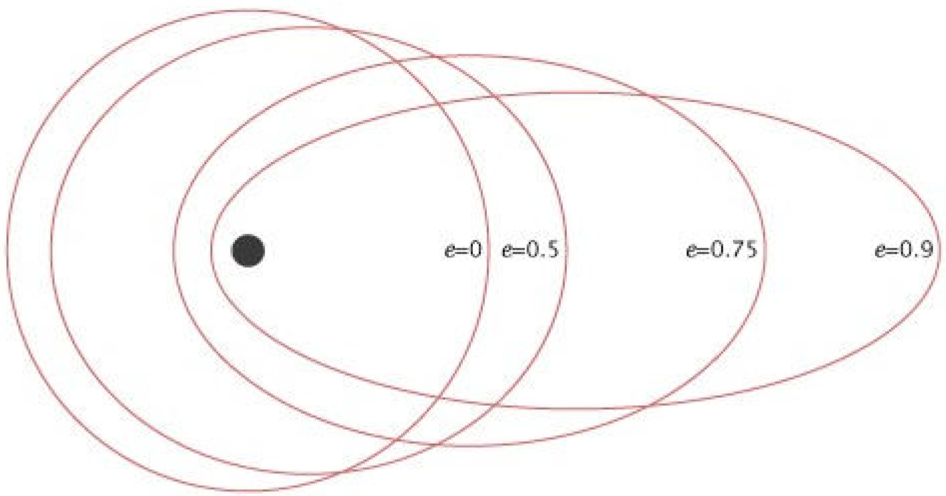

Fig 1.5 Orbits with Different Eccentricities

In above figure, the satellite orbit corresponding to eccentricity (e) value of zero is a circular orbit. And, the remaining three satellite orbits are of elliptical corresponding to the eccentricity (e) values 0.5, 0.75 and 0.9.

Mean Anomaly

For a satellite, the point which is closest from the Earth is known as Perigee. **Mean anomaly** (M) gives the average value of the angular position of the satellite with reference to perigee.

If the orbit is circular, then Mean anomaly gives the angular position of the satellite in the orbit. But, if the orbit is elliptical, then calculation of exact position is very difficult. At that time, Mean anomaly is used as an intermediate step.

Argument of Perigee

Satellite orbit cuts the equatorial plane at two points. First point is called as **descending node**, where the satellite passes from the northern hemisphere to the southern hemisphere. Second point is called as **ascending node**, where the satellite passes from the southern hemisphere to the northern hemisphere.

Argument of perigee (ω) is the angle between ascending node and perigee. If both perigee and ascending node are existing at same point, then the argument of perigee will be zero degrees

Argument of perigee is measured in the orbital plane at earth's center in the direction of satellite motion.

Inclination

The angle between orbital plane and earth's equatorial plane is known as **inclination (i)**. It is measured at the ascending node with direction being east to north. So, inclination defines the orientation of the orbit by considering the equator of earth as reference.

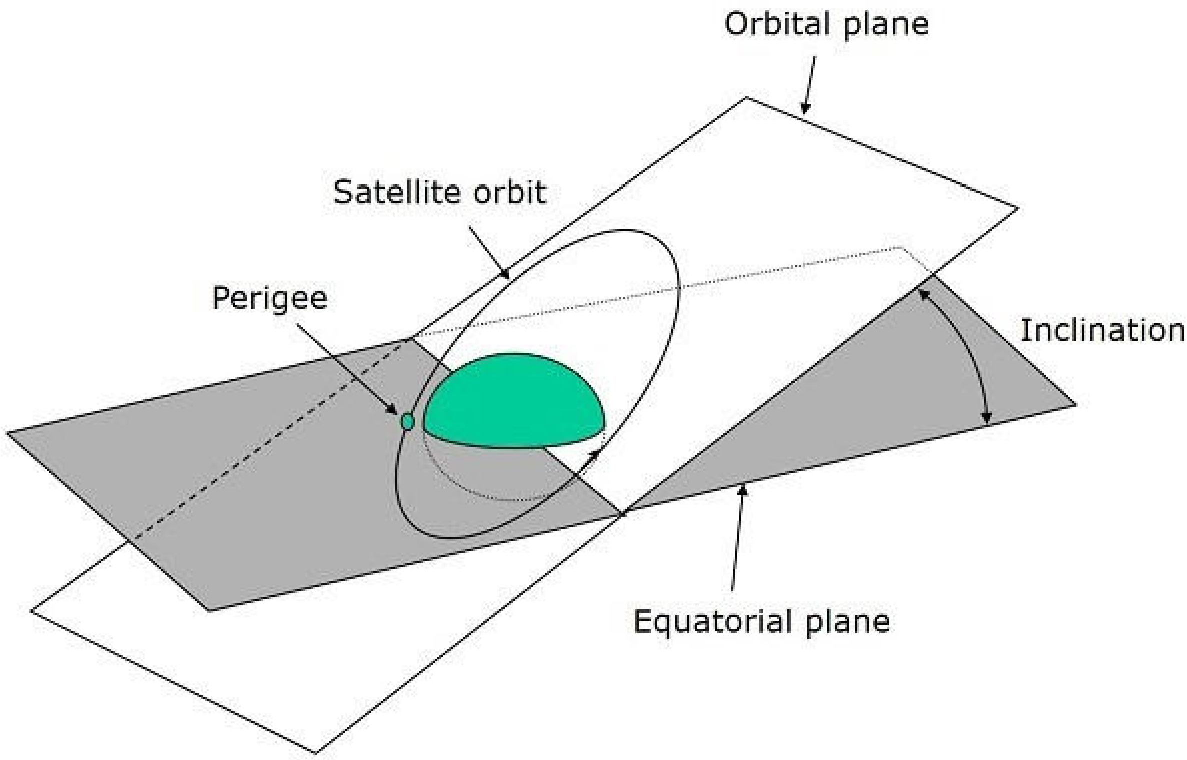

Fig. 1.6 Four Types of Orbits Based on the Angle of Inclination

There are four types of orbits based on the angle of inclination.

- **Equatorial orbit** − Angle of inclination is either zero degrees or 180 degrees.
- **Polar orbit** − Angle of inclination is 90 degrees.
- **Prograde orbit** − Angle of inclination lies between zero and 90 degrees.
- **Retrograde orbit** − Angle of inclination lies between 90 and 180 degrees.

Right Ascension of Ascending node

We know that **ascending node** is the point, where the satellite crosses the equatorial plane while going from the southern hemisphere to the northern hemisphere.

Right Ascension of ascending node **(Ω)** is the angle between line of Aries and ascending node towards east direction in equatorial plane. Aries is also called as vernal and equinox.

Satellite's **ground track** is the path on the surface of the Earth, which lies exactly below its orbit. The ground track of a satellite can take a number of different forms depending on the values of the orbital elements.

SATELLITE ORBITAL VELOCITY AND ORBITAL PERIOD

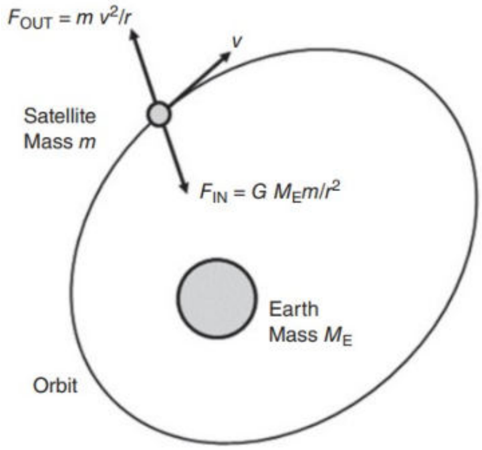

Fig. 1.7 Two opposing Forces acting on a satellite in a stable orbit around the earth

Gravitational force is inversely proportional to the square of the distance between the centers of gravity of the satellite and the planet the satellite is orbiting, in this case the earth.

When in a stable orbit, there are two main forces acting on a satellite:

1. A **centrifugal force** (F_{OUT}) due to the kinetic energy of the satellite, which attempts to fling the satellite into a higher orbit,
2. A **centripetal force** (F_{IN}) due to the gravitational attraction of the planet about which the satellite is orbiting, which attempts to pull the satellite down toward the planet.

Force = mass × acceleration

The standard acceleration due to gravity at the earth's surface is $9.806 \times 10^{-3}\ km/s^2$ or $981\ cm/s^2$

This value decreases with height above the earth's surface.

m = satellite mass
M_E = mass of earth
v = satellite velocity in orbit
a = acceleration due to gravity
r = distance from the center of the earth

$$a = \frac{GM_E}{r^2} = \frac{\mu}{r^2}\ km/s^2$$
$$\mu = GM_E = Kepler's\ constant$$

$$G = 6.672 \times 10^{-11} Nm^2/kg^2$$
$$\mu = 3.986004418 \times 10^5 km^3/s^2$$

The centripetal force acting on the satellite

$F_{IN} = m \times a = m \times \frac{\mu}{r^2} = m \times \frac{GM_E}{r^2}$

Similarly centrifugal acceleration is given by

$$a = \frac{v^2}{r}$$

v = final velocity of the satellite at the time 't'

Therefore, centrigugal force = $F_{OUT} = m \times \frac{v^2}{r}$

If the satellite is in stable orbit

$$F_{IN} = F_{OUT}$$

$m \times \frac{GM_E}{r^2} = m \times \frac{v^2}{r} = m \times \frac{\mu}{r^2}$

$$v = \left(\frac{\mu}{r}\right)^{1/2}$$

Kinetic energy is proportional to the square of the velocity v of the satellite.

If these two forces are equal, the satellite will remain in a stable orbit.

It will continually fall toward the planet's surface as it moves in its orbit but, due its orbital velocity, it will move away to compensate for the fall toward the planet and so it will remain at the same orbital height.

If the orbit is circular, the distance travelled by a satellite in its orbit around a planet is 2πr.

r = radius of the orbit from the center of the planet.

The satellite orbital period = T

$$T = \frac{2\pi r}{v} = \frac{2\pi r}{\left(\frac{\mu}{r}\right)^{1/2}} = \frac{2\pi r^{3/2}}{\mu^{1/2}}$$

The average radius of earth is taken as 6378.137 km.

ECLIPSE

For a Geostationary satellite powered by solar energy, the duration and periodicity of solar eclipses is very important because no solar energy is available during eclipses.

Angle of inclination of earth's equatorial plane w.r.t the direction of the sun = $i_e(t)$

$$i_e(t) = 23.4 \sin\left(\frac{2\pi t}{T}\right)$$

T = 365 days

$$i_{e,max}(t) = 23.4°$$

When $i_e(t) = 0$, equinoxes occur.

Time $t_A = autumn\ equinox\ on\ September\ 21$
Time $t_s = spring\ equinox\ on\ September\ 21$

When $i_e(t) = 23.4°$, solstices occur.

Time $t_w = winter\ solstice\ on\ December\ 21$
Time $t_{su} = summer\ solstice\ on\ June\ 21$

To find the eclipse duration, the sun is assumed to be at infinity w.r.t earth.

Therefore, earth's shadow is assumed to be a cylinder of constant diameter.

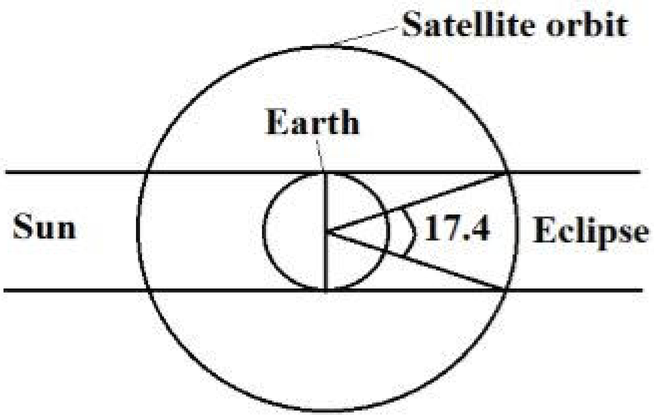

Fig.1.8. Satellite in Eclipse

$$\frac{2x6378.137}{42164.2} \times 360° = 17.4°$$

Eclipse Duration

$17.4°$ is covered in $\frac{17.4x24}{360} = 1.16$ hours

COVERAGE ANGLE

A satellite communicates with an earth station in its footprint using a global coverage antenna.

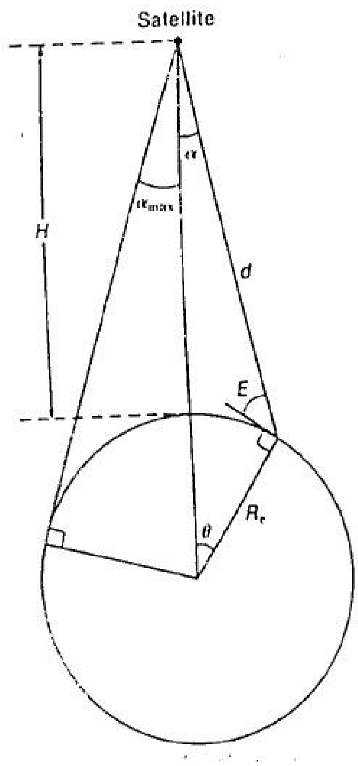

Fig. 1.9. Satellite Coverage Angle

Earth coverage angle = $2\alpha_{max}$
= total angle subtended by the earth as seen from the satellite.

For an elevation angle of the earth station antenna,
According to the law of sines,

$$\frac{Sin(\alpha)}{R_e} = \frac{Sin(90+E)}{H+R_e} = \frac{Cos(E)}{H+R_e}$$

H = altitude of the satellite orbit and is a constant for a Geostationary satellite.

H = 35,786 Km

$$\frac{Sin(\alpha)}{R_e} = \frac{Cos(E)}{H+R_e}$$

$$Sin(\alpha) = \frac{R_e Cos(E)}{H+R_e}$$

$$\alpha = \sin^{-1}\left(\frac{R_e Cos(E)}{H+R_e}\right)$$

$$2\alpha = 2\sin^{-1}\left(\frac{R_e Cos(E)}{H+R_e}\right)$$

$$R_e = 6378\ Km$$
$$H = 35{,}786\ Km$$

Earth coverage angle is found by setting E=0°

$$2\alpha_{max} = 2\sin^{-1}\left(\frac{R_e}{H + R_e}\right)$$

$$2\alpha_{max} = 2\sin^{-1}\left(\frac{6{,}378}{35{,}786 + 6{,}378}\right)$$

$$2\alpha_{max} = 2\sin^{-1}\left(\frac{6378}{42{,}164}\right)$$
$$2\alpha_{max} = 17.4°$$

$2\alpha_{max}$ = angle of satellite footprint
= earth coverage angle = 17.4°

$$\theta = 180° - (90° + E + \alpha)$$

When $E = 0°$, $\alpha = \alpha_{max}$ = 8.7°

$$\theta = 180° - (90° + 8.7°)$$
$$\theta = 81.3°$$

θ = Central angle corresponding to the Earth coverage angle, α_{max}

If $E = 5°$, $\theta = 76.3°$

Therefore, Polar Regions above *76.3°* N & S will not be covered by the footprint of the Geostationary satellite.

<u>SLANT RANGE (d)</u>

The Slant Range, d, determines the satellite round trip delay to the earth station.

From the law of cosines,

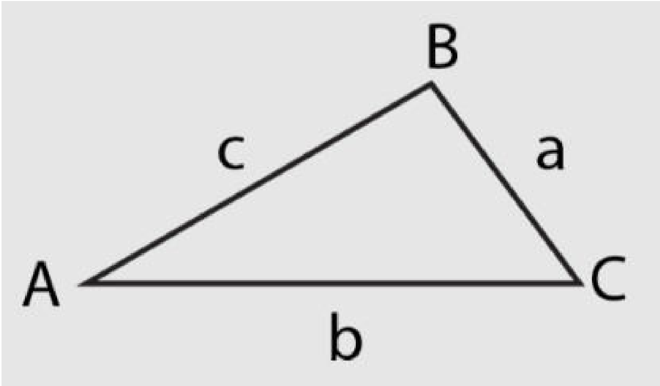

Fig. 1.10 Law of Cosines

$$c^2 = a^2 + b^2 - 2ab\,\mathrm{Cos}(C)$$

Applying the law of cosines to the triangle given below,

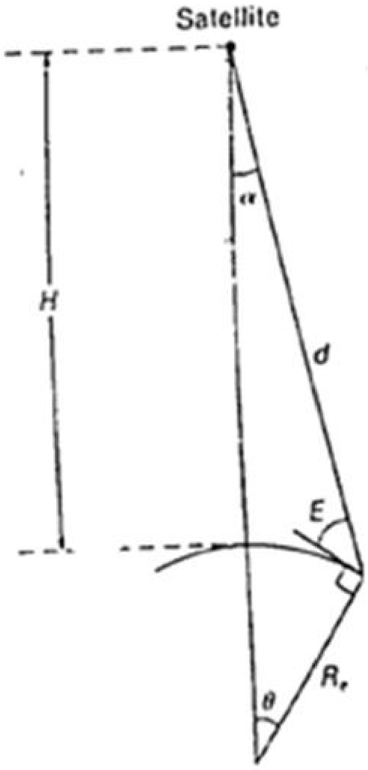

Fig. 1.11 Satellite Slant Range and Coverage Angle

$$d^2 = R_e{}^2 + (R_e + H)^2 - 2R_e(R_e + H)\,\mathrm{Cos}(\theta)$$

$$d^2 = R_e{}^2 + (R_e + H)^2 - 2R_e(R_e + H)\,\mathrm{Cos}(90^\circ - E - \alpha)$$

$$d^2 = R_e{}^2 + (R_e + H)^2 - 2R_e(R_e + H)\,\mathrm{Sin}(E + \alpha)$$

$$d^2 = R_e{}^2 + (R_e + H)^2 - 2R_e(R_e + H)\,\mathrm{Sin}(E + \sin^{-1}\left(\frac{R_e}{H + R_e} CosE\right))$$

$E_{min} = 5°$ for Gestationary orbit

$$R_e = 6378\ km$$
$$H = 35{,}786\ km$$

Substituting the values of E_{min}, R_e and H in the above equation, we get,

d = 41,127 Km

Slant Range = d = 41,127 Km

$c = 2.997925 \times 10^5$ Km/s

Satellite round trip delay = $\frac{2d}{c}$ = 0.274 sec

Summary of Coverage angle and Slant Range

Earth Coverage Angle = $17.4°$

Slant Range = 41,127 Km

Satellite round trip delay = 0.274 sec

SATELLITE SUBSYSTEMS

An operating communications satellite system consists of space segment and ground segment connected by network elements.

The information relayed may be voice, data, video, or a combination of the three.

The satellite is controlled from the ground through a satellite control facility, often called the master control center (MCC).

The ***space segment*** of the satellite system consists of the orbiting satellite (or satellites) and the ground control facilities necessary to keep the satellites operational.

The ***ground segment***, or earth segment, of the satellite system consists of the transmit and receive earth stations and the associated equipment to interface with the user network.

The major subsystems required on the satellite are:

1. Attitude and Orbit Control System (AOCS)
2. Telemetry Tracking and Command (TT&C)
3. Power System
4. Communication Subsystem

5. Satellite Antennas

Attitude and Orbit Control System (AOCS)
The attitude and orbit of a satellite must be controlled so that the satellite's antennas point toward the earth so that the user knows where in the sky to look for the satellite.

Attitude Control System

The ***attitude*** of a satellite refers to its orientation in space with respect to earth.

Attitude control is necessary so that the antennas, which usually have narrow directional beams, are always facing the earth.

The satellite will maintain its correct attitude without additional effort, unless disturbance torques are introduced.

External forces such as solar radiation, gravitational gradients, and meteorite impacts can generate undesired torques.

Internal effects such as motor bearing friction and antenna subsystem movement can also produce unwanted torque in the system.

There are two ways to make a satellite stable in orbit when it is weightless.
1. Spin satbilized satellite
2. 3-axis stabilized satellite

SPIN STABILIZED SATELLITE

For GSO satellites, the spin axis is maintained parallel to the spin axis of the earth, with spin rates in the range of 30 to 100 revolutions per minute.

Impulse type thrusters, or jets, are used to maintain spin rate and correct any wobbling (move unsteadily from side to side) or nutation (periodic variation in the inclination of the axis of a rotating object) to the satellite spin axis.

A spin stabilized satellite is usually cylindrical in shape, because the satellite is required to be mechanically balanced about an axis, so that it can be maintained in orbit by spinning on its axis.

Fig. 1.12 Spin Stabilized Satellite

The entire spacecraft rotates for spin-stabilized satellites that employ omnidirectional antennas.

When directional antennas are used, which is the prevalent case, the antenna subsystem must be ***despun***, so that the antenna is kept properly pointed towards earth.

The despun platform is driven by an electric motor in the opposite direction of the satellite spin, on the same spin axis and at the same spin rate as the satellite body, to maintain a fixed orientation for the antennas, relative to earth.

The antenna subsystem is mounted on a platform or shelf, which may also contain some of the transponder equipment.

The satellite is spun-up by small radial gas jets on the surface of the drum.

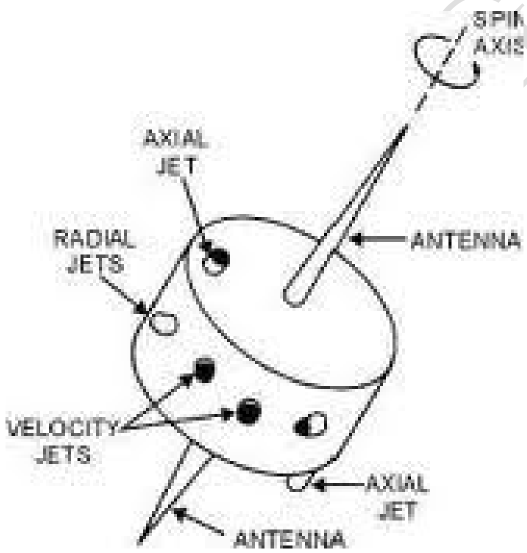

Fig. 1.13 Radial Gas Jets in Spin Stabilized Satellite

The rotation, ranging from 30 to 100 rpm, provides gyroscopic force stability for the satellite.

The propellants used include heated hydrazine or a bipropellant mix of hydrazine and nitrogen tetroxide.

<u>3-AXIS STABILIZED SATELLITE</u>

A three-axis stabilized satellite is maintained in space with stabilizing elements for each of the three axes, referred to as roll, pitch, and yaw.

The entire body of the spacecraft remains fixed in space, relative to the earth, which is why the three-axis stabilized satellite is also referred to as a bodystabilized satellite.

Active attitude control is required with three-axis stabilization.

Control jets or momentum wheels are used, either separately or in combination, to provide correction and control for each of the three axes.

A momentum wheel is basically a solid metallic disc driven by electric motor.

The wheel absorbs the undesired torques that would shift spacecraft orientation.

Fuel is expended for both the control jets and for the momentum wheels.
One momentum wheel is used for each of the 3-axes of the satellite or a single momentum wheel can be mounted and rotatied to provide a rotational force about any of the 3- axes.

Increasing the speed of the momentum wheel causes the satellite to rotate in the opposite direction according to the principle of conservation of angular momentum.

The three-axis stabilized satellite does not need to be symmetric or cylindrical, and most tend be box-like, with numerous appendages attached.

Fig. 1.14 3-Axis Stabilized Satellite

In 3-axis stabilized satellite, one pair of gas jets is needed for each axis to provide for rotation in pitch, roll and yaw directions.

X, Y and Z are Cartesian axes (mutually orthogonal) with the satellite at the origin.

X axis is tangent to the orbital plane and lies in the orbital plane.

Y axis is perpendicular to the orbital plane.

Z axis is directed towards the center of the earth and in the orbital plane.

Rotation about X axis is called “Roll”.

Rotation about Y axis is called “Pitch”.

Rotation about Z axis is called “Yaw”.

The satellite must be stabilized w.r.t. reference axes to maintain accurate pointing of its antenna beams.

For attitude control, a continual increase or decrease in momentum wheel speed is necessary.

When the upper or lower speed limit of the wheel is reached, it must be ‘unloaded’ by operating a pair of gas jets to reduce or increase the speed.

Orbit Control System

Orbital control, often called ***station keeping***, is the process required to maintain a satellite in its proper orbit location.

It is similar to, although not functionally the same as, attitude control.

GEO satellites will undergo forces that would cause the satellite to drift in the east-west (longitude) and north-south (latitude) directions, as well as in altitude, if not compensated for with active orbital control jets.

Orbital control is usually maintained with the same thruster system as is attitude control.

The non-spherical (oblate) properties of the earth, primarily exhibited as an equatorial bulge, cause the satellite to drift slowly in longitude along the equatorial plane.

Control jets are pulsed to impart an opposite velocity component to the satellite, which causes the satellite to drift back to its nominal position.

These corrections are referred to as ***east-west station keeping*** maneuvers, which are accomplished periodically every two to three weeks.

Typical C-band satellites must be maintained within 0.1◦, and Ku-band satellites within 0.05◦, of nominal longitude, to keep the satellites within the beamwidths of the ground terminal antennas.

For a nominal geostationary radius of 42 000 km, the total longitude variation would be about 150 km for C-band and about 75 km for Ku-band.

Latitude drift will be induced primarily by gravitational forces from the sun and the moon.

These forces cause the satellite inclination to change about 0.075◦ per month if left uncorrected.

Periodic pulsing to compensate for these forces, called ***north-south station keeping*** maneuvers, must also be accomplished periodically to maintain the nominal satellite orbit location.

North south station-keeping tolerance requirements are similar to those for east-west station keeping, 0.1◦ for C-band, and 0.05◦ for Ku-band.

Satellite altitude will vary about 0.1 %, which is about 72 km for a nominal 36 000-km geostationary altitude.
A C-band satellite, therefore, must be maintained in a 'box' with longitudinal and latitudinal sides of about 150 km and an altitude side of 72 km.

TheKu-band satellite requires a box with approximately equal sides of 75 km.

TELEMETRY, COMMAND AND RANGING SUBSYSTEM

The telemetry, command, and ranging subsystem provides essential spacecraft management and control functions to keep the satellite operating safely in orbit.

The telemetry, command, and ranging links between the spacecraft and the ground are usually separate from the communications system links.

Telemetry, command, and ranging is most often accomplished through a separate earth terminal facility specifically designed for the complex operations required to maintain one or more spacecrafts in orbit.

Figure below shows the typical telemetry, command, and ranging functional elements for the satellite and ground facility for a communications satellite application.

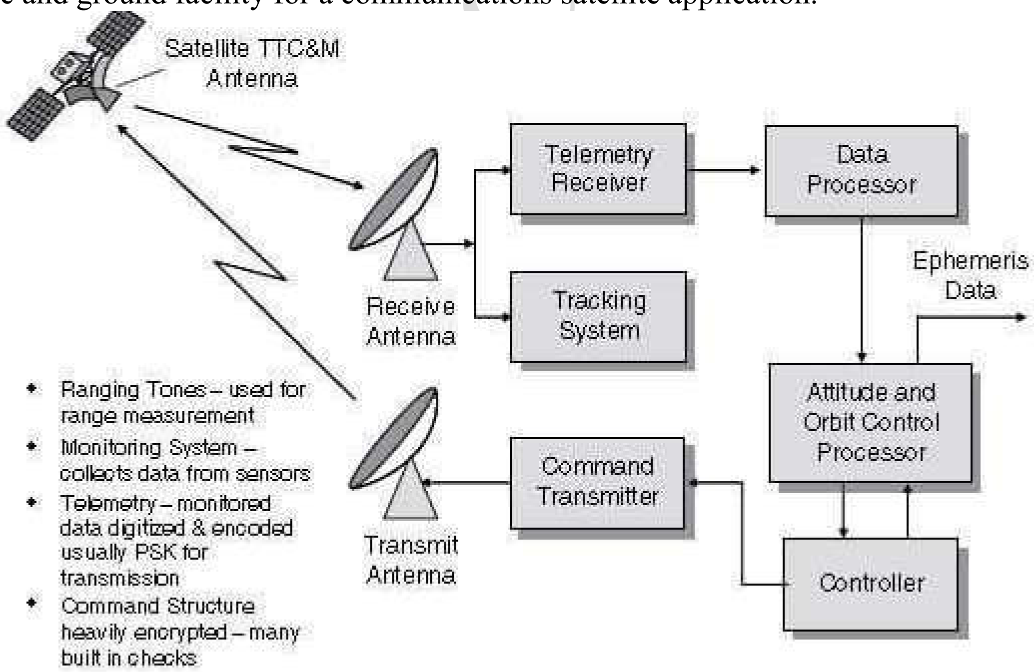

Fig. 1.15 Elements of Telemetry, Command and Ranging Subsystem

It comprises of the antenna, command receiver, tracking and telemetry transmitter, and possibly tracking sensors.

Satellite control and monitoring is accomplished through monitors and keyboard interface.

The TT&C earth station may be owned and operated by the satellite owner or it may be owned by third party and provide TT&C services.

Telemetry

The Telemetry system collects data from the hundreds of sensors within the satellite and sends these data to the controlling earth station.

The sensors are used to monitor pressure in the fuel tanks, voltage and current in the power conditioning unit, current drawn by each subsystem and critical voltages and currents in the communications electronics and the temperature of many subsystems.

The sensor data, the status of each subsystem and the positions of switches in the communications system are reported back to earth by the telemetry system.

If at all a unit is found faulty, command is given to disconnect it and a spare is brought in.

Telemetry data are digitized and transmitted as phase shift keying (PSK) of a low-power telemetry carrier using time division techniques.

The entire TDM frame may contain thousands of bits of data and take several seconds to transmit.

At the controlling earth station a computer can be used to monitor, store and decode the telemetry data.

Alarms can also be sounded if any vital parameter goes outside allowable limits.

Tracking

Tracking refers to the determination of the current orbit, position, and movement of the spacecraft.

The tracking function is accomplished by a number of techniques, usually involving satellite beacon signals, which are received at the satellite Telemetry, Command and Ranging earth station.

Velocity and acceleration sensors on the satellite can be used to establish the change in orbit from the last known position by integration of data.

The earth station controlling the satellite can observe the Doppler shift of the telemetry carrier to determine the rate at which range is changing.

Accurate angular measurements from the earth station antenna and range measurement is used to determine the orbital elements.

Range can be determined by transmitting a pulse or a sequence of pulses to the satellite and observing the time delay before the pulse is received again.

The propagation delay in the transponder must be accurately known.

Multiple earth stations with an adequate separation can observe the satellite and its position can be established by simultaneous range measurements.

With precision equipment at the earth stations, the position of the satellite, the position of the satellite can be determined within 10m.

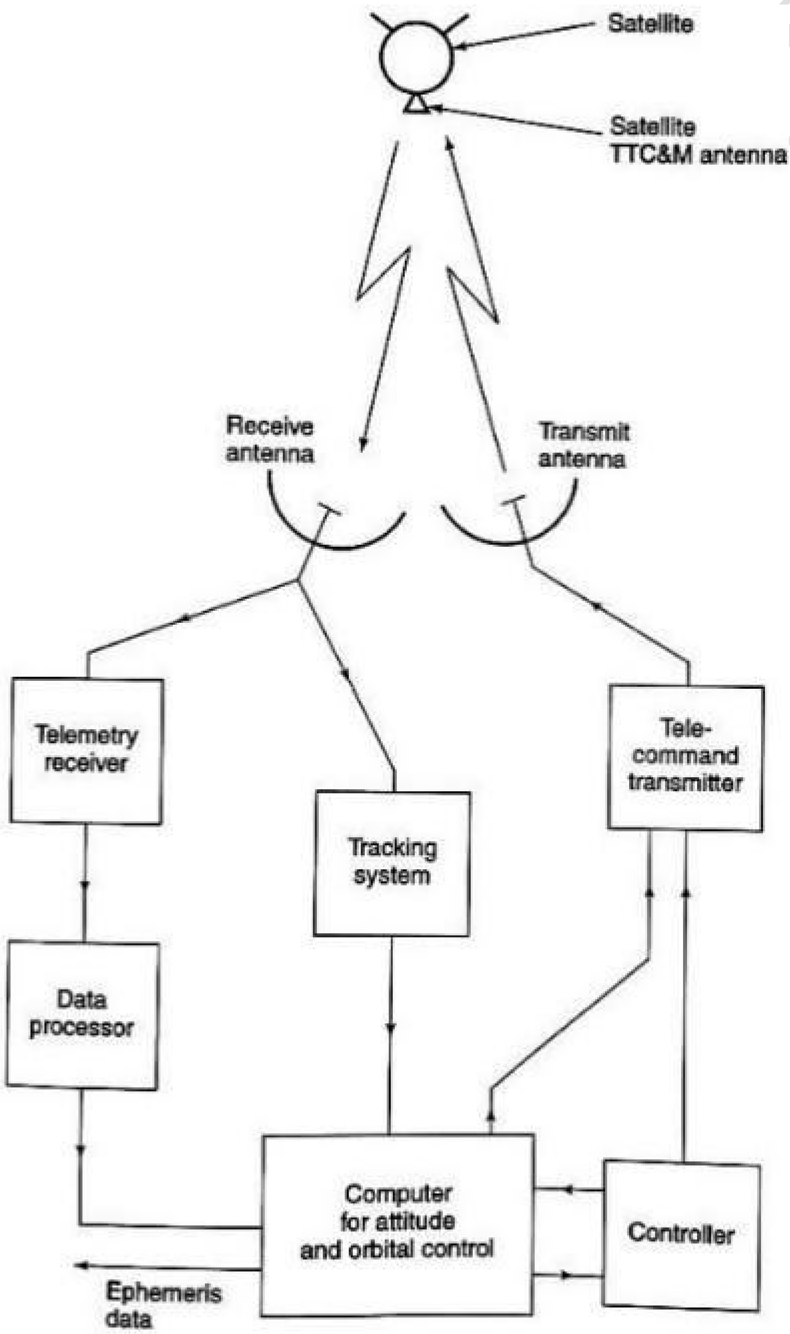

Fig. 1.16 Block Diagram of Telemetry, Command and Ranging Subsystem

COMMAND

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.
The command system is used to make changes in attitude and corrections to the orbit and to control the communication system.

During launch, it is used to control the firing of the apogee kick motor and to spin up a spinner or extend the solar sails and antennas of a 3-axis stabilized satellite.

The command structure must possess safeguards against unauthorized attempts to make changes to the satellite's operation and also against inadvertent operation of a control due to error in a received command.

Encryption of commands is used to provide security.

The commands originate at the control terminal of a computer.

The "control code" is converted into a "command word" which is sent in a TDM frame to the satellite.

After checking for validity in the satellite, the word is sent back to the control station via the telemetry link where it is checked again where it is checked again in the computer.

If it is found to have been received correctly, an execute instruction will be sent to the satellite so that the command is executed.

The entire process takes 5 to 10 seconds but minimized the risk of erroneous commands causing satellite malfunction.

During launch and injection of satellite into geostationary orbit, the main Telemetry, Command and Ranging system is inoperable.

A backup system with a great deal of redundancy is used to control the most important sections of the satellite during launch.

The backup system enables the satellite to be injected into orbit, turned to face the earth and switched to full electrical power so that handover to the main Telemetry, Command and Ranging system is possible.

If this system fails, the backup system can be used to keep the satellite on station.

The backup system also ejects the satellite from the geostationary orbit and to switch off all transmitters when the satellite life ends.

POWER SYSTEMS

All communications satellites obtain their electrical power from solar cells which convert incident sunlight into electrical energy.

Thermoneuclear generators can be used to supply electrical power but it poses a threat to the people if the launch fails.

The solar radiation incident on a geostationary satellite has an intensity of 1.39 kw/sq. m.

Solar cells typically have an efficiency of 20% o 25% at the Beginning of Life (BOL).

The efficiency decreases with ageing of cells and etching of the surface by micrometer impacts.

As sufficient power must be available at the End of Life (EOL) of the satellite to supply all the systems on board, about 15% extra of the solar cells is usually provided as an allowance for ageing.

A spin stabilized satellite has a cylindrical body covered in solar cells.

Due to the cylindrical body, only half of the cells are illuminated at any given time.

The unilluminated cells face cold space.

This increases their efficiency.

The output from the solar cells on spin stabilized satellite is slightly higher than would be obtained from a flat panel of the same area as the projected area of the cylinder.

A 3-axis stabilized satellite has solar cells arranged on flat panels that can be rotated to maintain normal incidence of the sunlight.

Only $1/3^{rd}$ of the total area of the solar cells is needed relative to a spinner.

Large communication satellites for direct broadcast operation generate of 6 to 10 kw from solar power.

Solar sails must be rotated by electric motor continuously to keep the cells in full sunlight.

A thick layer of glass is provided on top of the solar cells to protect them from micrometeorite bombardment.

Satellites carry batteries to power subsystems during launch and eclipses.

To avoid the need for large and heavy batteries, a part or all of the communications system load may be shut down during eclipse.

The batteries are usually of Nickel-Hydrogen type which are reliable and have long life.

A power conditioning unit controls the charging current and dumps the excess current from the solar cells into heaters or load resistors on the cold side of the satellite.

COMMUNICATIONS SUBSYSTEM

Description of the Communications System

A communications satellite provides a platform in geostationary orbit for the relaying of voice, video and data communications.

All other satellite subsystems exist solely to support the communications system.

The communications system is the only revenue generator for the system operator.

Therefore, communications satellites are designed to provide the largest traffic capacity possible.

The satellite transponders have limited output power and the earth stations are atleast 36,000km away from a GEO satellite, so the received power level is very small below 10^{-10}w.

The signal power must exceed the receiver noise by 5 to 25 dB.

The total channel capacity of a satellite can be increased by frequency reuse.

Frequency reuse employs several directional beams at the same frequency and orthogonal polarization.

Since the 500MHz bandwidth allocated for 6/4 and 14/11 GHz satellite communications became very congested, the band has been expanded to 1000 MHz.

Many systems use 14/11 GHz for TV broadcast.

30/20 GHz systems are providing internet services.

The standard spacing between GEO satellites was originally set at 3 degrees but the spacing was reduced to 2 degrees which opened up extra slots for new satellites.

Transponders

Carrier signals from an earth station are received at the satellite by either a zone beam or a spot beam antenna.

Zone beams can receive from transmitters anywhere within the coverage zone whereas spot beams have limited coverage.

The received signal is taken to 2 noise amplifiers and is recombined at the output to provide redundancy.

Redundancy is provided wherever failure of one component will cause loss a loss of a significant part of the satellite's communication capacity.

In a 6/4 GHz band, the 500MHz bandwidth is divided up into channels of 36 MHz each.

Each channel is handled by a separate transponder.

A transponder consists of

1. Band-pass filter to select a particular channel
2. Down converter to change the frequency from 6 GHz to 4 GHz.
3. Output amplifier.

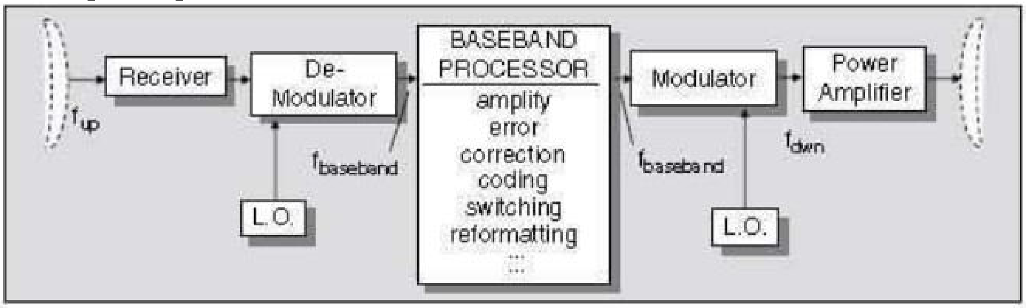

Fig. 1.17 On-Board Processing Transponder

The communication system has many transponders including some spares.

The transponders receive signals from one or more receive antennas and send their outputs to a switch matrix that directs each transponder band of frequencies to the appropriate antenna.

In a large satellite, there maybe 4 or 5 beams, to which any transponder can be connected.

The switching of the transponders between the downlink beams is controlled by the earth station as traffic patterns change.

Many domestic satellites operating in the 6/4 GHz band carry 24 active transponders each of 36 MHz with frequency reuse by orthogonal polarization.

The center frequencies of the transponders are spaced 40MHz apart to allow guard bands for the 36 MHz channels.

The output power amplifier is usually a solid state power amplifier unless a very high output power greater than 50w is required.

For higher power requirements, travelling wave tubes are used.

The local oscillator is at 225MHz to provide the frequency shift from 6GHz uplink to 4GHz downlink.

The band pass filter after the mixer removes unwanted frequencies resulting from the down-conversion.

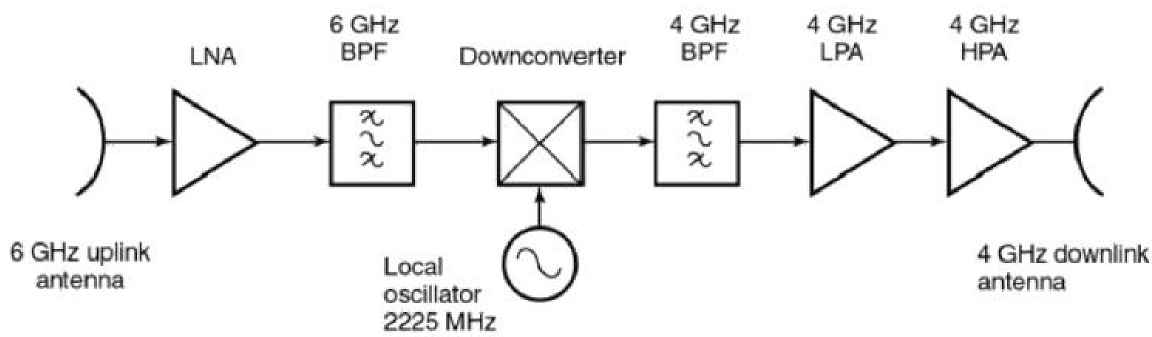

Fig. 1.18 Single Conversion Transponder for 6/4 GHz Band

Redundancy is provided for High power amplifiers in each transponder as they are the least reliable components.

Transponders in the 14/11 GHz band use double frequency conversion scheme.

It is easier to make filters and amplifiers in the intermediate frequency like 1100MHz than at 14 or 11 GHz.

Therefore, the incoming 14GHz carrier is translated to an IF of around 1GHz.

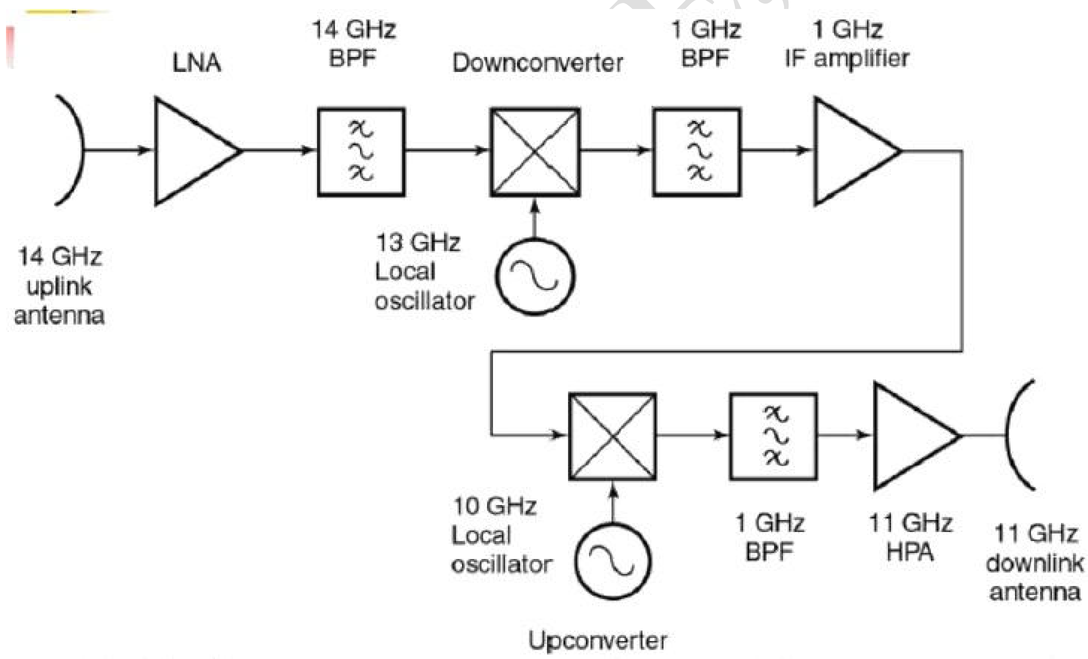

Fig. 1.19 Double Conversion Transponder for 14/11GHz Band

The amplification and filtering are performed at 1GHz for amplification by High power amplifier.

SATELLITE ANTENNAS

The antenna systems on the spacecraft are used for transmitting and receiving the RF signals that comprise the space links of the communications channels.

The antenna system is a critical part of the satellite communications system, because it is the essential element in increasing the strength of the transmitted or received signal to allow amplification, processing, and eventual retransmission.

4 main types of antennas are used on satellites.

1. Wire antennas
2. Horn antennas
3. Reflector antennas
4. Phased array antennas

Wire Antennas

Wire antennas are used primarily ate VHF and UHF to provide communications for the Telemetry, Command and Ranging subsystem.

They provide omnidirectional coverage.

They are used primarily at VHF and UHF for tracking, telemetry, and command links.

They are also important during launch operations, where the spacecraft attitude has not yet been established, and for satellites that operate without attitude control or body stabilization.

Horn Antennas

Horn antennas are used at frequencies from about 4 GHz and up, when relatively wide beams are required, such as global coverage from a GSO satellite.

A horn is a flared section of waveguide that provides gains of up to about 20 dBi, with beamwidths of 10◦ or higher.

If higher gains or narrower bandwidths are required, a reflector or array antenna must be used.

Reflector Antennas

The most often used antenna for satellite systems, particularly for those operating above 10 GHz, is the parabolic reflector antenna.

Parabolic reflector antennas are usually illuminated by one or more horn antenna feeds at the focus of the paroboloid.

Parabolic reflectors offer a much higher gain than that achievable by the horn antenna alone.

Gains of 25 dB and higher, with beamwidths of 1◦ or less, are achievable with parabolic reflector antennas operating in the C, Ku, or Ka bands.

Narrow beam antennas usually require physical pointing mechanisms on the spacecraft to point the beam in the desired direction.

Phased Array Antennas

There is increasing interest in the use of array antennas for satellite communications applications.

A steerable, focused beam can be formed by combining the radiation from several small elements made up of dipoles, helices, or horns.

Beam forming can be achieved by electronically phase shifting the signal at each element.

Proper selection of the phase characteristics between the elements allows the direction and beamwidth to be controlled, without physical movement of the antenna system.

The array antenna gain increases with the square of the number of elements.

Gains and beamwidths comparable to those available from parabolic reflector antennas can be achieved with array antennas.

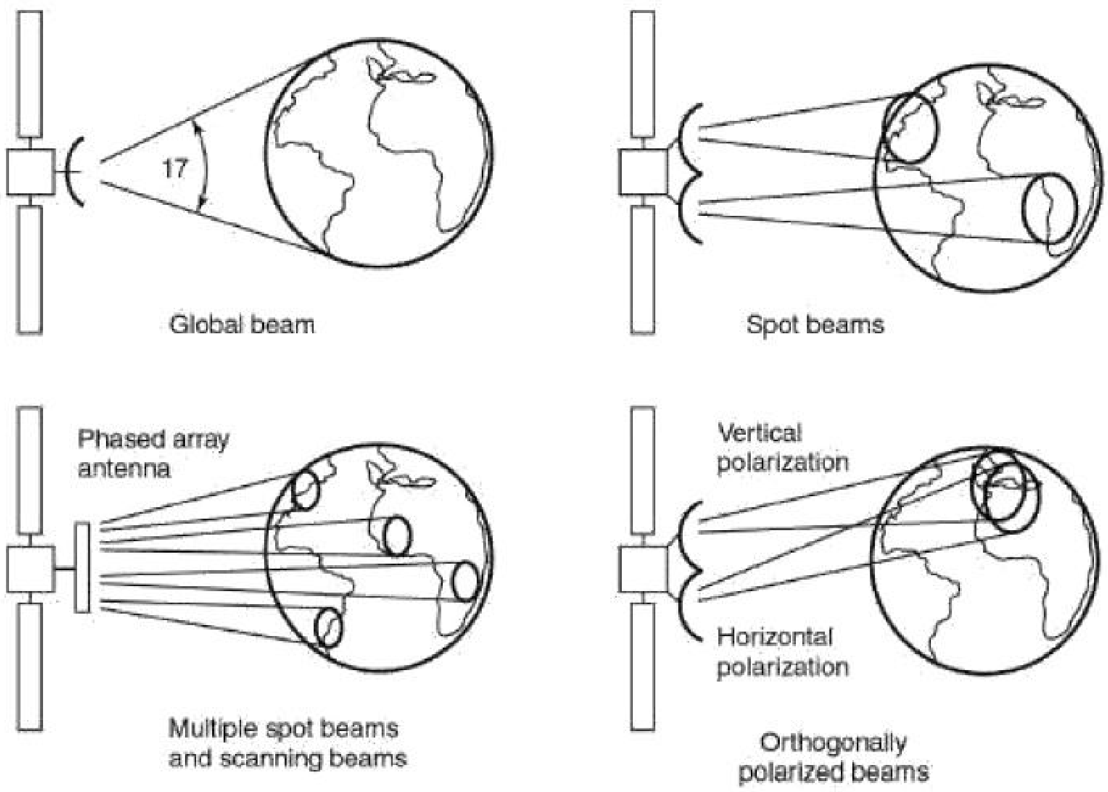

Fig. 1.20 Coverage Areas of Various Antennas

PLACEMENT OF A SATELLITE IN A GEO-STATIONARY ORBIT

The placement of a Satellite in a Geo-Stationary orbit involves the following steps:

1. The Launch vehicle which is a rocket or a space shuttle places the satellite in an elliptical transfer orbit whose apogee distance is equal to the radius of the geosynchronous orbit (42,164.2 km).

2. The perigee distance of the elliptical transfer orbit is in general about 6678.2 km from the center of the earth. It is about 300km above the earth's surface.

3. The satellite is stabilized in the transfer orbit so that the ground control can communicate with its telemetry system.

4. Once the orbit and attitude of the satellite have been determined exactly and when the satellite is at the apogee of the transfer orbit, the apogee kick motor (AKM) is fired to circularize the orbit.

5. The circular orbit, with a radius of 42,164.2km is a geostationary orbit if the launch is carried out at 0° latitude (equator).

6. If the satellite is launched from 28° N latitude, then the orbit will be geosynchronous with an inclination 'i' greater than or equal to the launch point.

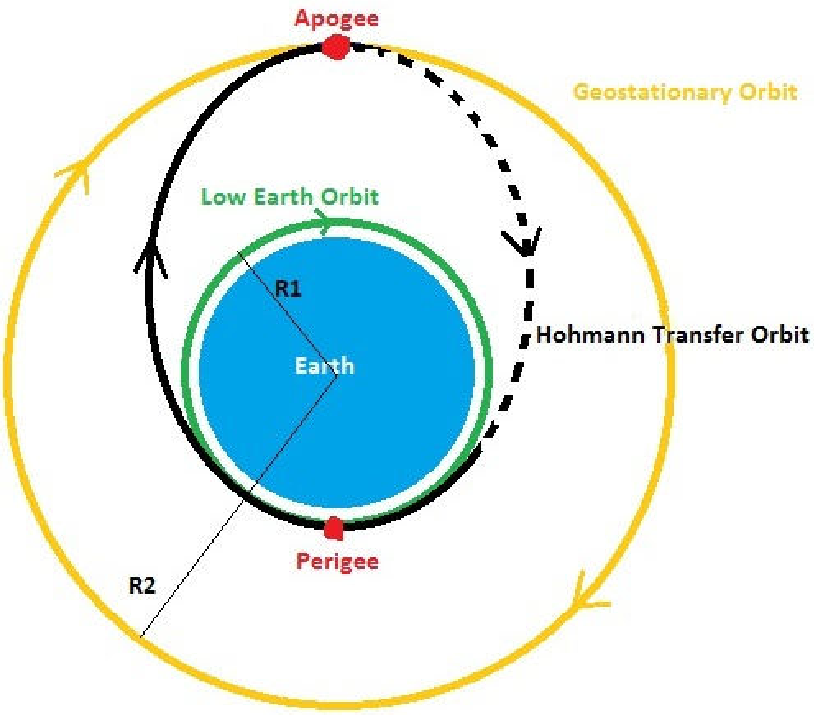

Fig. 1.21 Placement of a Satellite in its Orbit

Velocity of satellite at perigee = 10.15km/s

Velocity of satellite at apogee = 1.61km/s

Velocity in a synchronous orbit = 3.07km/s

Incremental velocity required to circularize the orbit at the apogee of the transfer orbit must be

$$\Delta V = 3.07 - 1.61 = 1.46km/s$$

LAUNCH VEHICLES

A satellite can be placed into a stable orbit only when the satellite velocity and altitude are simultaneously correct.

Higher is the orbit, greater is the energy required from the launch vehicle to reach that orbit.

In any satellite launch, maximum energy is expended by the rocket to accelerate the vehicle from rest until it is about 32km above the surface of the earth.

To efficiently use the fuel, it is common to shed excess mass from the launcher as it moves upwards. This is called staging.

Most launch vehicles have multiple stages and as each stage is completed , that portion of the launcher is expended until the final stage places the satellite into the desired orbit.

Hence the term, Expendable Launch Vehicle. Ex. Delta, Atlas, etc...

The space shuttle which is called the Space Transportation System (STS) by NASA is partially reusable.

The shuttle vehicle is flown back to earth for refurbishment and reuse.
Therefore, it is called Reusable Launch Vehicle (RLV).

If the launch is not to be into an equatorial orbit, the payload capabilities of any given rocket will reduce as the inclination increases.

End of UNIT 1