SATELLITE COMMUNICATIONS

UNIT I

Elements of orbital mechanics. Equations of motion. Tracking and orbit determination. Orbital correction/control. Satellite launch systems. Multistage rocket launchers and their performance

UNIT II

Elements of communication satellite design. Spacecraft subsystems. Reliability considerations. Spacecraft integration.

UNIT III

Multiple access techniques. FDMA,TDMA,CDMA. Random access techniques. Satellite onboard processing.

UNIT IV

Satellite link design: Performance requirements and standards. Design of satellite links – DOMSAT, INSAT, INTELSAT and INMARSAT. Satellite - based personal communication. links.

UNIT V

Earth station design. Configurations. Antenna and tracking systems. Satellite broadcasting.

Textbooks:

- **D. Roddy, Satellite Communication (4/e), McGraw- Hill, 2009.**
- **T. Pratt & C.W. Bostain, Satellite Communication, Wiley 2000.**

References:

- **B.N. Agrawal, Design of Geosynchronous Spacecraft, Prentice- Hall,1986**

UNIT – I

Satellite communications is possible as earth is a sphere.

Radio waves travel in straight lines at microwave frequencies (wide band communication)

Hence repeater is required

As satellites cover larger area , a good place to locate repeater.

Repeater: a receiver linked to earth station amplify it, and retransmit it to another earth station.

Satellites are at an altitude of 35,786Km.

Path length from an earth station to a satellite is 38,500Km

Signals reaching a satellite are weak

Signals received from satellite are also weak because of the limits on weight of satellite, and the electrical power they can generate.

- **Satellite communication systems are dominated to receive very weak signals.**
- **Satellite systems operate in the microwave and millimeter wave frequency bands between 1 to 50 GHz.**
- **Above 20 GHz rain can cause sufficient attenuation that can fail the link.**
- **Initially analog communication was widely used employing FM.**
- **Then digital communication**
- **Satellites form an essential part of telecommunications systems worldwide, carrying large amounts of data and telephone traffic in addition to television signals.**

Satellites offer a number of features:

- **Because very large areas of the earth are visible from a satellite**
- **Simultaneously linking many users who may be widely separated geographically.**
- **Provides communications links to remote communities in sparsely populated areas that are difficult to access by other means.**
- **Satellite signals ignore political boundaries as well as geographic ones.**
- **The cost is distance insensitive, meaning that it costs about the same to provide a satellite communications link over a short distance as it does over a large distance.**

- Satellites are also used for remote sensing- Detection of water pollution and the monitoring and reporting of weather conditions.
- Remote sensing satellites also form a vital link in search and rescue operations.

Different types of applications:

- The largest international system, Intelsat.
- The domestic satellite system in the United States, Domsat
- U.S. National Oceanographic and Atmospheric Administration (NOAA) series of polar orbiting satellites used for environmental monitoring and search and rescue.

Frequency Allocations for Satellite Services:

- To facilitate frequency planning, the world is divided into three regions:
- **Region 1:** Europe, Africa, what was formerly the Soviet Union, and Mongolia.
- **Region 2:** North and South America and Greenland
- **Region 3:** Asia (excluding region 1 areas), Australia, and the southwest Pacific

Some of the services provided by satellites are:

- **Fixed satellite service (FSS):** Provides links for existing telephone networks as well as for transmitting television signals to cable companies for distribution over cable systems.
- **Broadcasting satellite service (BSS):** For direct broadcast to the home (direct broadcast satellite (DBS) service) [in Europe it may be known as direct-to-home (DTH) service].
- **Mobile satellite services:** Include land mobile, maritime mobile, and aeronautical mobile.
- **Navigational satellite services:** Include global positioning systems (GPS)
- **Meteorological satellite services:** Provide a search and rescue service.

Frequency band designations:

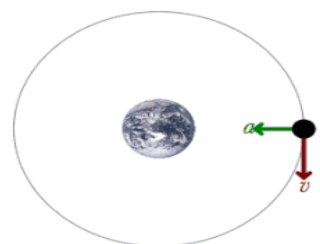
- Ku - Band under the K band – DBS & FSS
- Ka - Band above the K band.
- C band – FSS (4 to 6 GHz), and no DBS.
- VHF band - Certain mobile and navigational services and for data transfer from weather satellites.
- L band - Mobile satellite services and navigation systems.

Frequency range, (GHz)	Band designation
0.1–0.3	VHF
0.3–1.0	UHF
1.0–2.0	L
2.0–4.0	S
4.0–8.0	C
8.0–12.0	X
12.0–18.0	Ku
18.0–27.0	K
27.0–40.0	Ka
40.0–75	V
75–110	W
110–300	mm
300–3000	µm

- For the FSS in the C band, the most widely used subrange is approximately 4 to 6 GHz
- The higher frequency is nearly always used for the uplink to the satellite.
- Denote the C band by 6/4 GHz, giving the uplink frequency first).
- For the direct broadcast service in the Ku band, the most widely used range is approximately 12 to 14 GHz, which is denoted by 14/12 GHz.

Orbital Mechanics:

- Study of the motions of artificial satellites and space vehicles moving under the influence of forces such as gravity, atmosphere drag, thrust etc..
- The motion of these objects is usually calculated from Newton's laws of motion and the law of universal gravitation.



- How earth orbit is achieved, the laws that describe the motion of an object orbiting another body, how satellites move in space, and the determination of the look angle to a satellite from the earth.

To achieve a stable orbit around the earth a spacecraft must first be beyond the bulk of the earth's atmosphere (space).

Newton's laws of motion:

s = Distance travelled from time t=0

u = Initial velocity of the object at t=0

P= Force acting on the object

m = Mass of the object

a = Acceleration of the object

$$s = ut + (1/2)at^2$$
$$v^2 = u^2 + 2at$$
$$v = u + at$$
$$P = ma$$

The force acting on a body is equal to the mass of the body multiplied by the resulting acceleration of the body.

$$a = F/m$$

In a stable orbit, there are two forces acting on a satellite.

Centripetal force: Due to the gravitational attraction of the planet which pulls the satellite down to the planet

Centrifugal force: Due to the Kinetic energy of the satellite which attempts to fling the satellite into a higher orbit.

- **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 forward in the orbit, but by virtue of its orbital velocity it could have moved forward, hence maintains same orbital height.**

F = ma Newtons

A newton is the force required to accelerate a mass of 1Kg with an acceleration of 1m/S^2.

Newton units are Kg x 1m/S^2

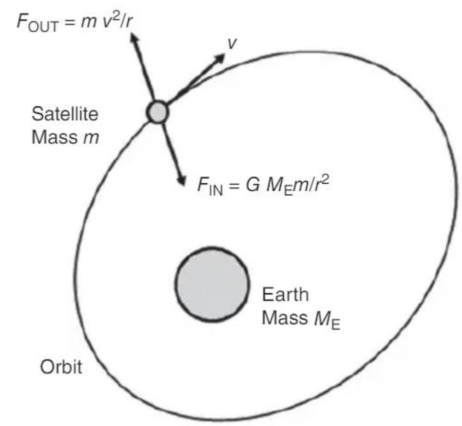
The standard acceleration due to gravity at the earth's surface is 9.80665 x 10^{-3} Km / S^2 or 981 cm/ S^2

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

The acceleration a due to gravity at a distance r from the center of the earth is

$$a = \mu / r^2 \ Km / S^2$$

μ = Product of universal gravitational constant G and mass of the earth M_E



GM_E = Kepler's constant = $3.986004418 \times 10^5\ Km^3/S^2$

G =universal gravitational constant = $6.672 \times 10^{-11} Nm^2 / Kg^2$

$= 6.672 \times 10^{-20}\ Km^3 / Kg\ S^2$

F = ma

The centripetal force acting on the satellite F_{IN}

$F_{IN} = m \times (\mu / r^2)$

$= m \times (GM_E / r^2)$

The centrifugal acceleration is

$a = v^2 / r$

The centrifugal force $F_{OUT} = m \times (v^2 / r)$

If the forces on the satellite are balanced $F_{IN} = F_{OUT}$

$m \times (\mu / r^2) = m \times (v^2 / r)$

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

If the orbit is circular, the distance travelled by a satellite in one orbit around a planet is $2\pi r$

r = radius of the orbit from the satellite to the center of the earth

Time = distance / Velocity

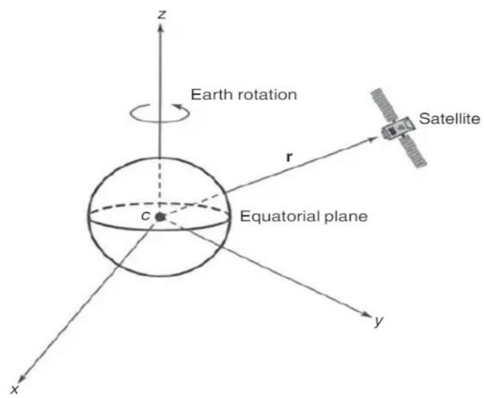
T = 2πr / v

= 2πr / (μ / r)^{½}

$$\boxed{T = (2\pi r^{3/2}) / (\mu\ )}$$

Radius of the earth = 6378.137 Km

Geocentric coordinate system: **To describe the orbit a cartesian coordinate system is used with earth at the center and the reference planes coinciding with the equator and the polar axis**



With the satellite mass m located at a vector distance r from the center of the earth, the gravitational force F on the satellite is given by

$$\overline{F} = -\frac{GM_E m\overline{r}}{r^3}$$

Force = mass × acceleration

$$\overline{F} = m\frac{d^2\overline{r}}{dt^2}$$

Equating the above two equations,

$$-\frac{\overline{r}}{r^3}\mu = \frac{d^2\overline{r}}{dt^2}$$

Results in

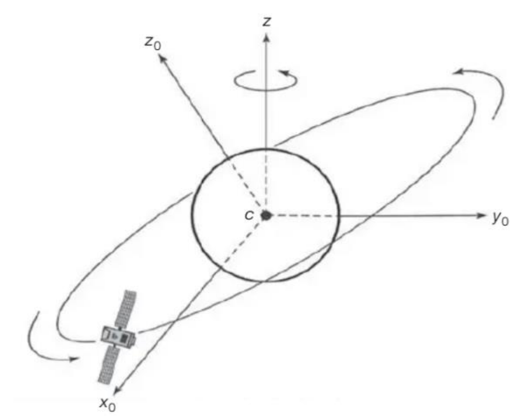
$$\frac{d^2\bar{r}}{dt^2} + \frac{\bar{r}}{r^3}\mu = 0$$

- **A second order linear differential equation and its solution will involve six undetermined constants called the orbital elements.**
- **The orbit described by these orbital elements can be shown to lie in a plane and to have a constant angular momentum.**
- **The solution to the above equation is difficult since the second derivative of r involves the second derivative of the unit vector r**

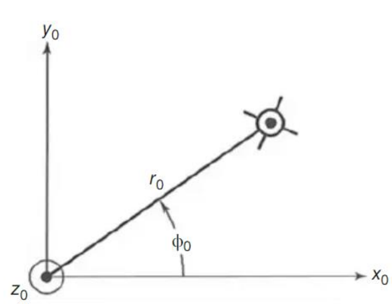
To remove this dependence, a different set of coordinates can be chosen to describe the location of the satellite such that the unit vectors in the three axes are constant.

- **This coordinate system uses the plane of the satellite's orbit as the reference plane.**

The orbital plane coordinate system:
In this coordinate system the orbital plane is used as the reference plane. The orthogonal axes x0 and y0 lie in the orbital plane. The third axis, z0 is orthogonal to the x0 and y0 axes to form a right hand coordinate set. The z0 axis is not coincident with the earth's z axis through the earth's north pole unless the orbital plane lies exactly in the earth's equatorial plane



- **Expressing in terms of the new coordinate axes x0 expressed in a polar coordinate system rather than a Cartesian coordinate system.**
- **The polar coordinate system is shown**
- **With the polar coordinate system shown in and using the transformations and equating the vector components of *r*0 and ϕ0 in turn, y0, and z0 gives**



$$\hat{x}_0\left(\frac{d^2x_0}{dt^2}\right) + \hat{y}_0\left(\frac{d^2y_0}{dt^2}\right) + \frac{\mu\left(x_0\hat{x}_0 + y_0\hat{y}_0\right)}{\left(x_0^2+y_0^2\right)^{3/2}} = 0$$

$$x_0 = r_0\cos\phi_0$$
$$y_0 = r_0\sin\phi_0$$
$$\hat{x}_0 = \hat{r}_0\cos\phi_0 - \hat{\phi}_0\sin\phi_0$$
$$\hat{y}_0 = \hat{\phi}_0\cos\phi_0 + \hat{r}_0\sin\phi_0$$

$$\frac{d^2r_0}{dt^2} - r_0\left(\frac{d\phi_0}{dt}\right) = -\frac{\mu}{r_0^2}$$

$$r_0\left(\frac{d^2\phi_0}{dt^2}\right) + 2\left(\frac{dr_0}{dt}\right)\left(\frac{d\phi_0}{dt}\right) = 0$$

Equation of the radius of the satellite orbit

Where, e = eccentricity

θ_o = constant

p = semilatus rectum of ellipse

h = magnitude of the orbital angular momentum

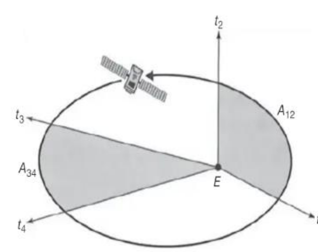
Kepler's Three Laws of Planetary Motion:

Johannes Kepler (1571–1630) was a German astronomer and scientist who developed his three laws of planetary motion by careful observations of the behavior of the planets in the solar system over many years, with help from some detailed planetary observations by the Hungarian astronomer Tycho Brahe.

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.**

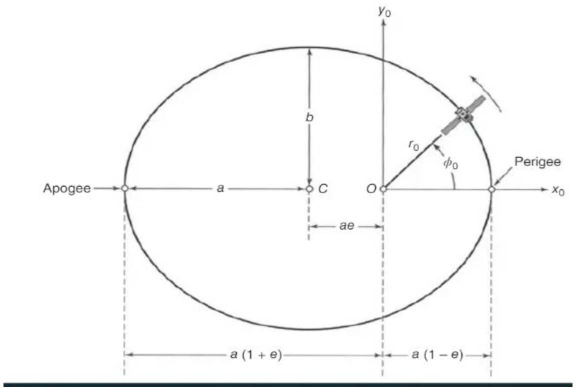
2. **The orbit of the smaller body sweeps out equal areas in equal time.**



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.**
   Where,
   ***T* is the orbital period,**
   ***a* = is the semi major axis of the orbital ellipse**
   μ = Kepler's constant.
   If the orbit is circular, then *a* becomes distance *r*

The path of the satellite in the orbital plane:

O = Center of the earth
C = Center of the ellipse
The two centers do not coincide unless the eccentricity, e, of the ellipse is zero (i.e., the ellipse becomes a circle and a = b.
a = semimajor axis
b = semiminor axis of the orbital ellipse



Perigee: The point in the orbit where the satellite is closest to the earth.

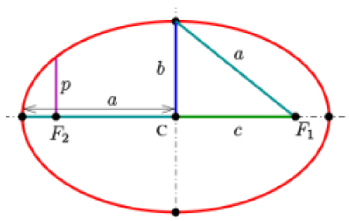
Apogee: The point where the satellite is farthest from the earth.

- The perigee and apogee are always exactly opposite each other.
- To make θ0 equal to zero, x0 axis so that both the apogee and the perigee lie along it and the x0 axis is therefore the major axis of the ellipse.

Eccentricity:

$$e = \frac{c}{a} = \sqrt{1 - \left(\frac{b}{a}\right)^2}$$

Latus rectum: The length of the chord through one focus, perpendicular to the major axis



- The differential area swept out by the vector r0 from the origin to the satellite in time dt is given by

$$dA = 0.5r_0^2\left(\frac{d\phi_0}{dt}\right)dt = 0.5hdt$$

h = Magnitude of the orbital angular momentum of the satellite.
This equation determines the period of the orbit of any satellite, and it is used in every GPS receiver in the calculation of the positions of GPS satellites.

- **To find the orbital radius of a GEO satellite, for which the period T must be made exactly equal to the period of one revolution of the earth for the satellite to remain stationary over a point on the equator**
- **An important point to remember is that the period of revolution, T, is referenced to inertial space, that is, to the galactic background.**

Orbital period: The time taken by the orbiting body to return to the same reference point in space with respect to the galactic background.

- **The primary body will also be rotating and so the period of revolution of the satellite may be different from that perceived by an observer who is standing still on the surface of the primary body.**
- **The orbital period of a GEO satellite is exactly equal to the period of rotation of the earth, 23 hours 56 minutes 4.1seconds, but, to an observer on the ground, the satellite appears to have an infinite orbital period: it always stays in the same place in the sky.**

To be perfectly geostationary, the orbit of a satellite needs to have three features:

(i) **It must be exactly circular (i.e., have an eccentricity of zero);**
(ii) **It must be at the correct altitude (i.e., have the correct orbital period);**
(iii) **It must be in the plane of the equator (i.e.,have a zero inclination with respect to the equator).**

- **If the inclination of the satellite is not zero and/ or if the eccentricity is not zero, but the orbital period is correct, then the satellite will be in a geosynchronous orbit.**
- **The position of a geo synchronous satellite will appear to oscillate about a mean look angle in the sky with respect to a stationary observer on the earth's surface.**
- **The orbital period of a GEO satellite, 23 hours 56 minutes 4.1 seconds, is one sidereal day.**
- **A sidereal day is the time between consecutive crossings of any particular longitude on the earth by any star, other than the sun(Gordon and Morgan 1993).**
- **The mean solar day of 24 hours is the time between any consecutive crossings of any particular longitude by the sun, and is the time between successive sunrises (or sunsets) observed at one location on earth, averaged over an entire year.**
- **Because the earth moves round the sun once per 365 ¼ days, the solar day is 1440 / 365.25 = 3.94 minutes longer than a sidereal day.**

Locating the Satellite in the Orbit:

- **The angle ϕ0 is measured from the x0 axis and is called the true anomaly.**

Anomaly: A measure used by astronomers to mean a planet's angular distance from its Perihelion, (the shortest distance between Earth and the sun), measured as if viewed from the sun.

$$r_0 = \frac{a(1-e^2)}{1+e\cos\phi_0}$$

- x_0 axis so that it passes through the perigee, ϕ_0 measures the angle from the perigee to the instantaneous position of the satellite.
- The rectangular coordinates of the satellite are given by

$$x_0 = r_0 \cos \phi_0$$
$$y_0 = r_0 \sin \phi_0$$

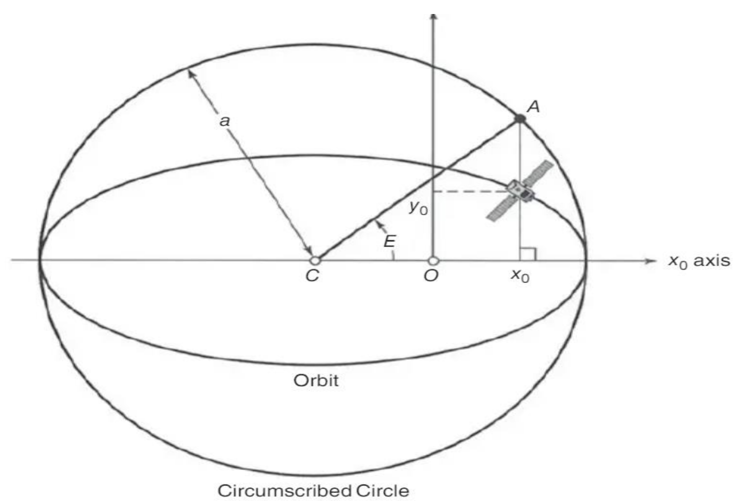
- The orbital period T is the time for the satellite to complete a revolution in inertial space, traveling a total of 2π radians.
- The average angular velocity η is thus

$$\eta = (2\pi)/T = (\mu^{1/2})/(a^{3/2})$$

- The orbit is an ellipse, the instantaneous angular velocity will vary with the position of the satellite around the orbit.
- Enclose the elliptical orbit with a circumscribed circle of radius a, then an object going around the circumscribed circle with a constant angular velocity η would complete one revolution in exactly the same period T as the satellite requires to complete one (elliptical) orbital revolution.

- Locate the point (indicated as A) where a vertical line drawn through the position of the satellite intersects the circumscribed circle.
- A line from the center of the ellipse (C) to this point (A) makes an angle E with the x0 axis.
- E is called the eccentric anomaly of the satellite.
- It is related to the radius r0 by

$$r_0 = a(1 - e \cos E)$$



$$a - r_0 = ae \cos E$$

- An expression that relates eccentric anomaly E to the average angular velocity η

$$\eta dt = (1 - e \cos E)dE$$

tp = Time of perigee.

- **This is simultaneously the time of closest approach to the earth; the time when the satellite is crossing the x0 axis; and the time when E is zero.**
- **If we integrate both sides of**

$$\eta(t - t_p) = E - e \sin E$$

- **The mean anomaly, M**

$$M = \eta(t - t_p) = E - e \sin E$$

- **The mean anomaly M is the arc length (in radians) that the satellite wouldhavetraversed since the perigee passage if it were moving on the circumscribe d circle at the mean angular velocity η.**

- **If we know the time of perigee, tp, the eccentricity, e , and the length of the semimajor axis, a, we now have the necessary equations to determine the coordinates (r0, ϕ0) and(x0, y0) of the satellite in the orbital plane.**

  The process is as follows:

- **Calculate η using** $\eta = (2\pi)/T = (\mu^{1/2})/(a^{3/2})$
- **Calculate M using** $M = \eta(t - t_p) = E - e \sin E$
- **Solve** $M = \eta(t - t_p) = E - e \sin E$ **for E.**
- **Find r0 from E using** $a - r_0 = ae \cos E$
- **Solve Eq.** $r_0 = \dfrac{a(1 - e^2)}{1 + e \cos \phi_0}$ **or ϕ0.**

- **Use Eqs.** $x_0 = r_0 \cos \phi_0$ **to calculate x0 and y0**
  $y_0 = r_0 \sin \phi_0$

Orbital Elements:

Apogee: **A point for a satellite farthest from the Earth.**

Perigee: **A point for a satellite closest from the Earth.**

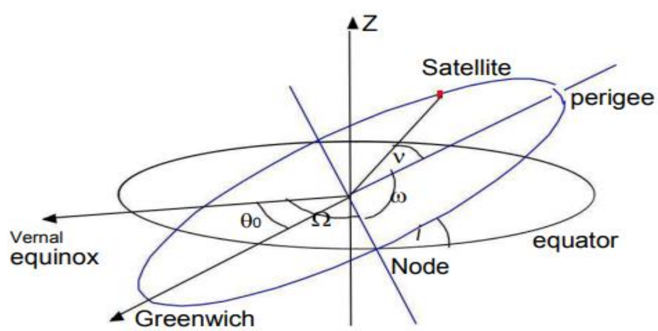
Line of Apsides: **Line joining perigee and apogee through centre of the Earth. It is the major axis of the orbit. One-half of this line's length is the semi-major axis equivalents to satellite's mean distance from the Earth.**

Ascending Node: **The point where the orbit crosses the equatorial plane going from north to south.**

Descending Node: **The point where the orbit crosses the equatorial plane going from south to north.**

Inclination: **The angle between the orbital plane and the Earth's equatorial plane.**

- **Its measured at the ascending node from the equator to the orbit, going from East to North.**
- **Also, this angle is commonly denoted as i.**



Line of Nodes: **The line joining the ascending and descending nodes through the centre of Earth.**

Argument of Perigee: **An angle from the point of perigee measure in the orbital plane at the Earth's centre, in the direction of the satellite motion.**

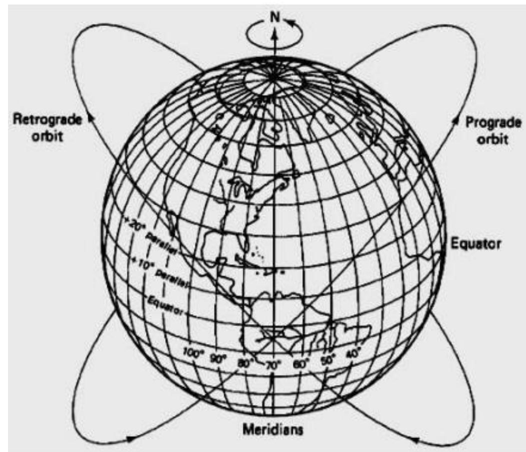
Right ascension of ascending node: **The definition of an orbit in space, the position of ascending node is specified.**

- **But as the Earth spins, the longitude of ascending node changes and cannot be used for reference. Thus for practical determination of an orbit, the longitude and time of crossing the ascending node is used.**
- **For absolute measurement, a fixed reference point in space is required. It could also be defined as "right ascension of the ascending node; right ascension is the angular**

position measured eastward along the celestial equator from the vernal equinox vector to the hour circle of the object".

Prograde Orbit: An orbit in which satellite moves in the same direction as the Earth's rotation.

- Its inclination is always between 0^0 to 90^0.
- Many satellites follow this path as Earth's velocity makes it easier to launch these satellites.
- **Retrograde Orbit:** An orbit in which satellite moves in the same direction counter to the Earth's rotation.

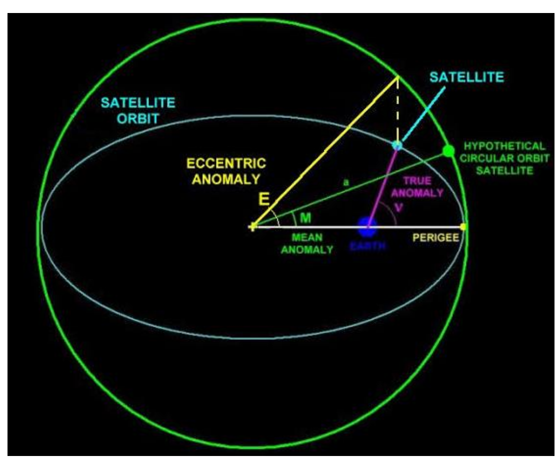


Prograde and Retrograde orbits

Mean anamoly: It gives the average value to the angular position of the satellite with reference to the perigee.

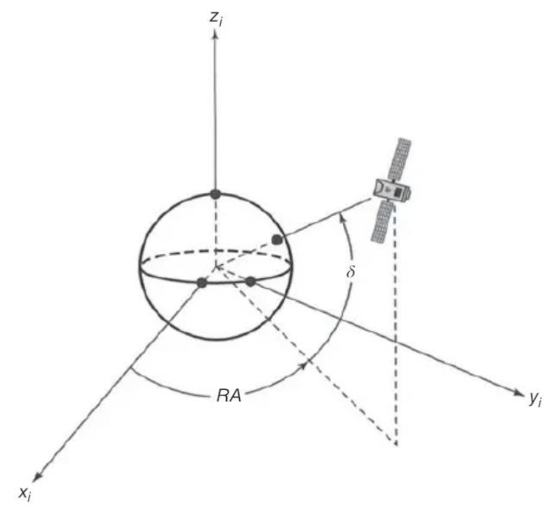
True anamoly: It is the angle from point of perigee to the satellite's position, measure at the Earth's centre.

Mean anomaly M: The arc length (in radians) that the satellite would havetraversed since the perigee passage if it were moving on the circumscribed circle.



Locating the Satellite With Respect to the Earth:

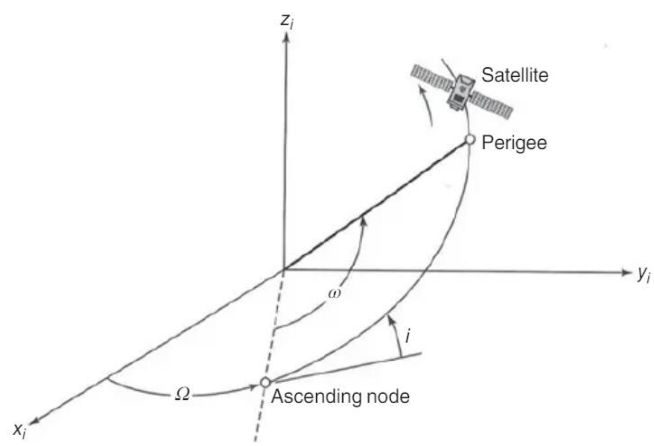
- To locate the satellite from an observation point that is not at the center of the earth.
- The satellite to be located from a point on the rotating surface of the earth.
- Lets consider a geocentric equatorial coordinate system.
- The xi axis points to the first point of Aries.
- **First point of Aries:** The direction of a line from the center of the earth through the center of the sun at the vernal equinox (20 or 21 March in the Northern Hemisphere), the instant when the subsolar point crosses the equator from south to north.
- In the above system, an object may be located by its right ascension RA and declination δ



Right ascension(RA): Angular distance measured eastward in the equatorial plane from the xi axis.

Nodes: The two points at which the orbit penetrates the equatorial plane.

Ascending node: The satellite moves upward through the equatorial plane at the ascending node and downward through the equatorial plane at the descending node.



- The *right ascension of the ascending node* is called Ω.
- **Inclination i:** The angle that the orbital plane makes with the equatorial plane

  or

- The planes intersect at the line joining the nodes.
- The variables Ω and *i* together locate the orbital plane with respect to the equatorial plane

The argument of perigee west (ω): The angle measured along the orbit from the ascending node to the perigee.

To locate the orbital coordinate system with respect to the equatorial coordinate system we need

- **Standard time for space operations and most other scientific and engineering purposes is universal time (UT), also known as zulu time (z).**
- **The mean solar time at the Greenwich Observatory near London, England.**
- **UT is measured in hours, minutes, and seconds or in fractions of a day. It is 5 hours later than Eastern Standard Time, so that 07:00 EST is 12:00:00 hours UT.**

Orbital Elements:

To specify the absolute (i.e., the inertial) coordinates of a satellite at time *t* , we need to know six quantities: Orbital elements.

- **Eccentricity (*e*),**
- **Semimajor axis (*a*)**
- **Time of perigee (*tp*)**
- **Right ascension of ascending node (Ω)**
- **Inclination (*i*)**
- **Argument of perigee (ω)**

The mean anomaly (*M*) at a given time is substituted for *tp*.

Look angle determination:

- **Navigation around the earth's oceans became more precise when the surface of the globe was divided up into a grid like structure of orthogonal lines: latitude and longitude.**

  Latitude: **The angular distance, measured in degrees, north or south of the equator**

  Longitude: **The angular distance, measured in degrees, from a given reference longitudinal line.**

- **There are 360° of longitude (measured from 0° at the Greenwich Meridian, the line drawn from the North Pole to the South Pole through Greenwich, England) and ±90° of latitude, plus being measured north of the equator and minus south of the equator.**
- **Latitude 90°N (or +90°)is the North Pole and Latitude 90°S (or −90°) is the South Pole.**

- Earth stations that communicate with satellites are described in terms of their geographic latitude and longitude when developing the pointing coordinates that earth station must use to track the apparent motion of the satellite.

Look angle: The coordinates to which an earth station antenna must be pointed to communicate with a satellite.

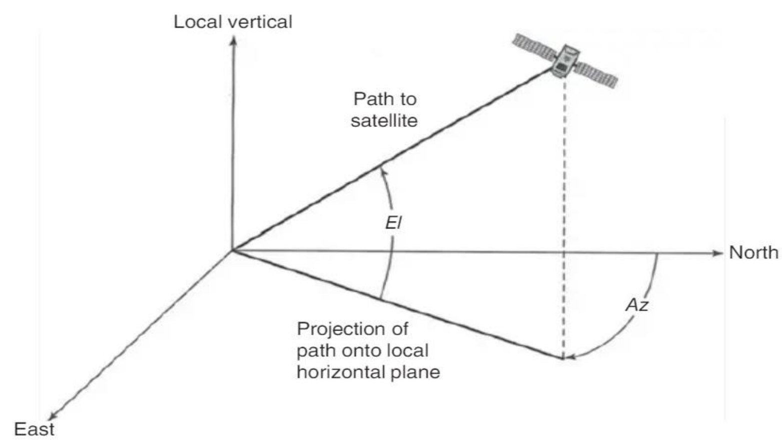
- *Azimuth* (Az)
- *Elevation* (El)

In all look angle determinations, the precise location of the satellite is critical. A key location in many instances is the *subsatellite point.*

Look angles:

Azimuth: Measured eastward (clockwise) from geographic north to the projection of the satellite path on a (locally) horizontal plane at the earth station.

Elevation: The angle measured upward from the local horizontal plane at the earth station to the satellite path.



The Subsatellite Point: The location on the surface of the earth that lies directly between the satellite and the center of the earth.

N*adir*: Pointing direction from the satellite

For a satellite in an equatorial orbit, it will always be located on the equator.

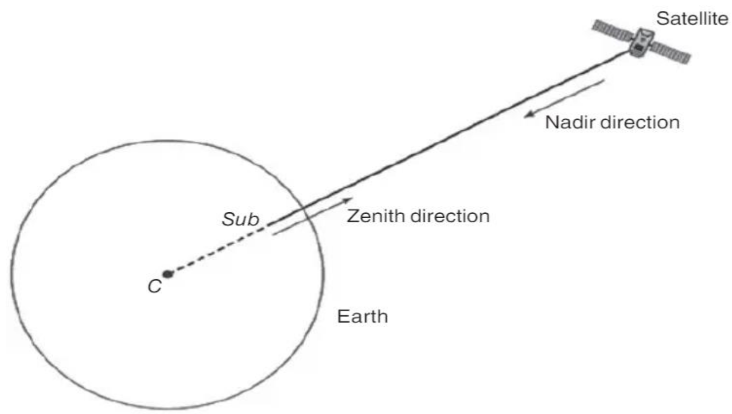
- Since geostationary satellites are in equatorial orbits and are designed to stay stationary over the earth, it is usual to give their orbital location interms of their subsatellite point.
- As noted in the example given earlier, the Intelsat primary satellite in the Atlantic Ocean Region (AOR) is at 335.5°E longitude.

Zenith and Nadir pointing directions:

- The line joining the satellite and the center of the earth, C , passes through the surface of the earth at point Sub, the subsatellite point.

N*adir:* Pointing direction from the satellite.

Zenith: Pointing direction from earth station.



- The satellite is directly overhead at this point and so an observer at the subsatellite point would see the satellite at zenith (i.e., at an elevation angle of 90°.)
- The pointing direction from the satellite to the subsatellite point is the nadir direction from the satellite.
- If the beam from the satellite antenna is to be pointed at a location on the earth that is not at the subsatellite point, the pointing direction is defined by the angle away from nadir.
- In general, two off-nadir angles are given: the number of degrees north (or south) from nadir; and the number of degrees east (or west) from nadir. East, west, north, and south directions are those defined by the geography of the earth.
- The zenith and nadir paths are therefore in opposite directions along the same path.

Elevation Angle Calculation:

r_s = The vector from the center of the earth to the satellite

r_e = The vector from the center of the earth to the earth station

d = The vector from the earth station to the satellite. These three vectors lie in the same plane and form a triangle.

Central angle γ: Angle measured between re and rs

The angle between the earth station and the satellite

ψ = The angle (within the triangle) measured from re to d (non-negative)

γ is related to the earth station north latitude Le (i.e., Le is the number of degrees in latitude that the earth station is north from the equator) and west longitude le (i.e., le is the number of degrees in longitude that the earth station is west.

Orbit Determination:

- **Orbit determination requires that sufficient measurements be made to determine uniquely the six orbital elements needed to calculate the future orbit of the satellite, and hence calculate the required changes that need to be made to the orbit to keep it within the nominal orbital location.**
- **Three angular position measurements are needed because there are six unknowns and each measurement will provide two equations.**
- **Conceptually, these can be thought of as one equation giving the azimuth and the other the elevation as a function of the six (as yet unknown) orbital elements.**

  The control earth stations used to measure the angular position of the satellites also carry out range measurements using unique time stamps in the telemetry stream or communications carrier.

  These earth stations are generally referred to as the TTC&M (Telemetry Tracking Command and Monitoring) stations of the satellite network.

  Major satellite networks maintain their own TTC&M stations around the world. Smaller satellite systems generally contract for such TTC&M functions from the spacecraft manufacturer or from the larger satellite system operators, as it is generally uneconomic to build advanced TTC&M stations with fewer than three satellites to control.

Orbital Perturbations:

- **Model the earth and the satellite as point masses influenced only by gravitational attraction.**
- **Under these ideal conditions, a Keplerian orbit results, which is an ellipse whose properties are constant with time.**

  In practice, the satellite and the earth respond to many other influences
- **Asymmetry of the earth's gravitational field**
- **Gravitational fields of the sun and the moon**

- Solar radiation pressure.

  For LEO satellites, atmospheric drag also influences.

  All of these interfering forces cause the true orbit to be different from a simple Keplerian ellipse.

  If unchecked, they would cause the subsatellite point of a nominally geosynchronous satellite to move with time.

- Incorporating additional perturbing forces into orbit descriptions.
- The approach normally adopted for communications satellites is first to derive an osculating orbit for some instant in time with orbital elements (a, e, t_p, Ω, i, ω).
- The perturbations are assumed to cause the orbital elements to vary with time and the orbit and satellite location at any instant are taken from the osculating orbit calculated with orbital elements corresponding to that time.
- Assume that the osculating orbital elements at time t_0 are (a_0, e_0, t_p, Ω_0, i_0, ω_0).
- Then assume that the orbital elements vary linearly with time at constant rates given by (da/dt , de/dt , etc.).
- The satellite's position at any time $t_1$is then calculated from a Keplerian orbit with elements
- As the perturbed orbit is not an ellipse - Defining the orbital period.
- Since the satellite does not return to the same point in space once per revolution, the quantity most frequently specified is the so-called anomalistic period - the elapsed time between successive perigee passages.
- Orbit not being a perfect Keplerian ellipse, there will be other influences that will cause the apparent position of a geostationary satellite to change with time.
- Mainly longitudinal changes and those that principally affect the orbital inclination

Longitudinal Changes:

Effects of the Earth's Oblateness:

- The earth is neither a perfect sphere nor a perfect ellipse - Triaxial ellipsoid.
- The earth is flattened at the poles.
- The equatorial diameter is about 20 km more than the average polar diameter.

- **The equatorial radius is not constant, although the non circularity is small.**
- **There are regions where the average density of the earth appears to be higher.**
- **Regions of mass concentration or Mascons.**
- **The non sphericity of the earth, the non circularity of the equatorial radius, and the Mascons lead to a non-uniform gravitational field around the earth.**
- **The force on an orbiting satellite will therefore vary with position.**
- **A geostationary satellite is weightless when in orbit.**
- **The smallest force on the satellite will cause it to accelerate and then drift away from its nominal location.**
- **The satellite is required to maintain a constant longitudinal position over the equator, but there will generally be an additional force toward the nearest equatorial bulge in either an eastward or a westward direction along the orbit plane.**
- **Since this will rarely be inline with the main gravitational force toward the earth's center, there will be a resultant component of force acting in the same direction as the satellite's velocity vector or against it, depending on the precise position of the satellite in the GEO orbit.**
- **This will lead to a resultant acceleration or deceleration component that varies with longitude in allocation of the satellite.**
- **Due to the position of the Mascons and equatorial bulges, there are four equilibrium points in the geostationary orbit: two of them stable and two unstable.**
- **The stable points are analogous to the bottom of a valley, and the unstable points to the top of a hill.**
- **If a ball is perched on top of a hill, a small push will cause it to roll down the slope into a valley, where it will roll backward and forward until it gradually comes to a final stop at the lowest point.**
- **The satellite at an unstable orbital location is at the top of a gravity hill.**
- **Given a small force, it will drift down the gravity slope into the gravity well (valley)and finally stay there, at the stable position.**
- **If a satellite is perturbed slightly from one of the stable points, it will tend to drift back to the stable point without any thruster rings required.**
- **A satellite that is perturbed slightly from one of the unstable points will immediately begin to accelerate its drift toward the nearer stable point and, once it reaches this**

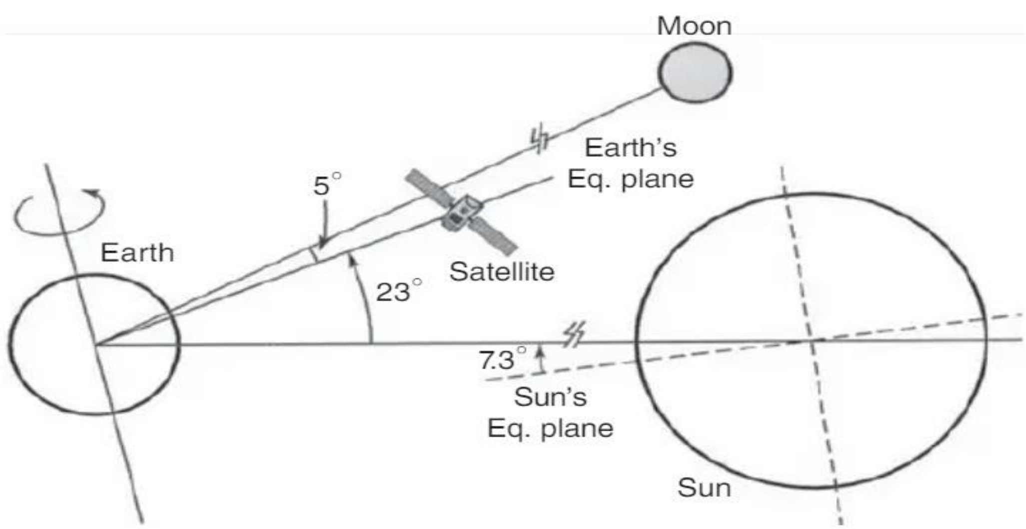
point, it will oscillate in longitudinal position about this point until (centuries later) it stabilizes at that point.

- These stable points are sometimes called the *graveyard* geosynchronous orbit locations (not to be confused with the grave yard orbit for a geo synchronous satellite – the orbit to which the satellite is raised once the satellite ceases to be useful). Note that, due to the non sphericity of the earth, etc., the stable points are neither exactly 180° apart no rare the stable and unstable points precisely 90° apart.

Inclination Changes:

Effects of the Sun and the Moon:

- The plane of the earth's orbit around the sun – the ecliptic – is at an inclination of 7.3° to the equatorial plane of the sun.
- The earth is titled about 23° away from the normal to the ecliptic. The moon circles the earth with an inclination of around 5° to the equatorial plane of the earth.
- Due to the fact that the various planes–the sun's equator, the ecliptic, the earth's geo-graphic equator (a plane normal to the earth's rotational axis), and the moon's orbital plane around the earth – are all different, a satellite in orbit around the earth will be subjected to a variety of out-of-plane forces.
- There will generally be a net acceleration force that is not in the plane of the satellite's orbit, and this will tend to try to change the inclination of the satellite's orbit from its initial inclination. Under these conditions, the orbit will precess and its inclination will change.



- The mass of the sun is significantly larger than that of the moon but the moon is considerably closer to the earth than the sun.

- **The acceleration force induced by the moon on a geostationary satellite is about twice as large as that of the sun.**
- **The net effect of the acceleration forces induced by the moon and the sun on a geostationary satellite is to change the plane of the orbit at an initial average rate of change of 0.85°/year from the equatorial plane are acting on the same side of the satellite's orbit, the rate of change of the plane of the geostationary satellite's orbit will be higher than average.**
- **When they are on opposite sides of the orbit, the rate of change of the plane of the satellite's orbit will be less than average.**
- **These rates of change are neither constant with time nor with inclination.**
- **They are at a maximum when the inclination is zero and they are zero when the inclination is 14.67°.**
- **From an initial zero inclination, the plane of the geo-stationary orbit will change to a maximum inclination of 14.67° over 26.6years. The acceleration forces will then change direction at this maximum inclination and the orbit inclination will move back to zero in an other 26.6 years and out to−14.67° ,over a further 26.6years, and so on.**
- **In some cases, to increase the orbital maneuver lifetime of a satellite for a given fuel load, mission planners deliberately place a satellite planned for geostationary orbit into an initial orbit with an inclination that is substantially larger than the nominal 0.05° for a geostationary satellite. The launch is specifically timed, however, so as to set up the necessary precessional forces that will automatically reduce the inclination error to close to zero over the required period with out the use of any thruster firings on the spacecraft. This will increase the maneuvering lifetime of the satellite at the expense of requiring greater tracking by the larger earth terminals accessing the satellite for the first year or so of the satellite's operational life**
- **Ground controllers command space craft maneuvers to correct for both the in plane changes (longitudinal drifts) and out-of-plane changes (inclination changes) of a satellite so that it remains in the correct orbit.**
- **For a geostationary satellite, this means that the inclination, ellipticity, and longitudinal position are controlled so that the satellite appears to stay within a box in the sky that is bounded by ±0.05° in latitude and longitude over the subsatellite point.**
- **Some maneuvers are designed to correct for both inclination and longitude drifts simultaneously in the one burn of the maneuvering rockets on the satellite.**
- **In others, the two maneuvers are kept separate: one burn will correct for ellipticity and longitude drift; another will correct for inclination changes.**

- **The latter situation of separated maneuvers is becoming more common for two reasons.**
- **The first is due to the much larger velocity increment needed to change the plane of an orbit (the so-called north–south maneuver) as compared with the longitude/ellipticity of an orbit (the so-called east–west maneuver).**
- **The difference in energy requirement is about 10:1. By alternately correcting for inclination changes and in-plane changes, the attitude of the satellite can be held constant and different sets of thrusters exercised for the required maneuver.**
- **The second reason is the increasing use of two completely different types of thrusters to control N–S maneuvers on the one hand and E–W maneuvers on the other.**
- **In the mid-1990s, one of the heaviest items that was carried into orbit on a large satellite was the fuel to raise and control the orbit. About 90% of this fuel load, once on orbit, was to control the inclination of the satellite.**
- **Newer rocket motors, particularly arc jets and ion thrusters, offer increased efficiency with lighter mass.**
- **Initially, the low thrust, high efficiency electric thrusters were mainly used for N–S maneuvers leaving the liquid propellant thrusters, with their inherently higher thrust (but lower efficiency) for orbit raising and in-plane changes.**
- **For Small Sats and Cube Sats, where there is little available on-orbit mass, electric propulsion has been universally adopted.**
- **Increasingly, the higher available on-orbit power available from solar arrays has made the use of electric propulsion more attractive for all satellites.**

Space Launch Vehicles and Rockets:

The evolution of launch vehicles: To place a satellite in to orbit as reliably as possible - Major elements of the launch vehicles be recovered and used again.

- **Note that making parts of a launcher re-usable lowers the available payload as a significant additional mass needs to be added to the rocket to bring atleast the booster stage(s) back to a designated recovery area.**
- **Reduced payload mass is more than compensated for by the reduced expense of refurbishing a booster as opposed to having to build a brand new one.**
- **The first one that was successful was Pegasus - First privately developed launch vehicle (Northrop grumman.**

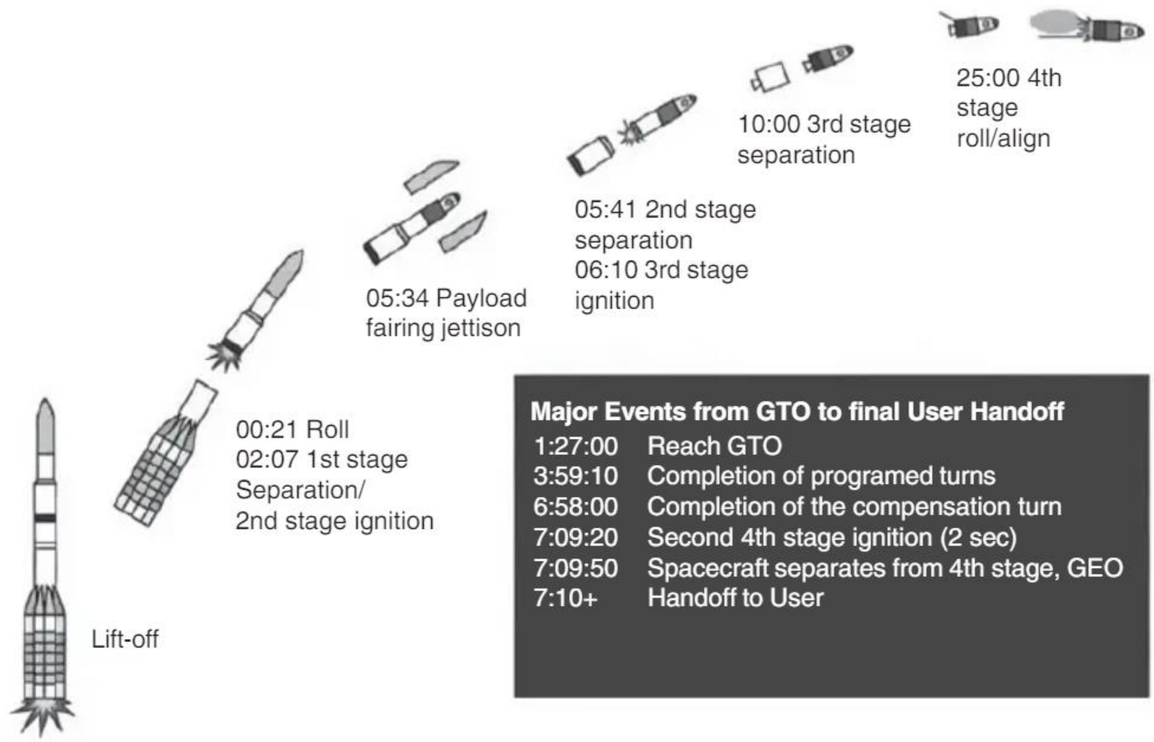
- **Velocity vector and the orbital height – two parameters to place satellite into a stable orbit.**
- **A geostationary satellite, for example, must be in an orbit at a height of 35786.03km above the surface of the earth (42164.17km radius from the center of the earth) with an inclination of zero degrees, an ellipticity of zero, and a velocity of 3074.7m/s tangential to the earth in the plane of the orbit, which is the earth's equatorial plane.**
- **Greater energy - for further out to reach that orbit.**
- **The largest fraction of the energy expended by the rocket is used to accelerate the vehicle from rest until it is about twenty miles (32km) above the earth.**
- **Staging: Shedding excess mass from the launcher as it moves up through the atmosphere - efficient use of fuel.**

Advantages of Air-launching:

- **A significant portion of the atmosphere is below the rocket, and the airplane has imparted a horizontal velocity vector to augment that of the rocket stage(s).**

  Expendable Launch Vehicle – ELV :

- **Multiple stages**
- **Each stage completes its burn that portion of the launcher is expended until the final stage places the satellite in to the desired trajectory.**
- **Of equal importance to the orbital height the satellite is intended for is the inclination of the orbit that the spacecraft needs to be launched into**



- **The earth spins toward the east.**

  At the equator, the rotational velocity of a sea level site in the plane of the equator is (2π × radius of earth) / (one sidereal day)

  = 0.4651km/s.

  This velocity increment is approximately 1000mph (~1610km/h).

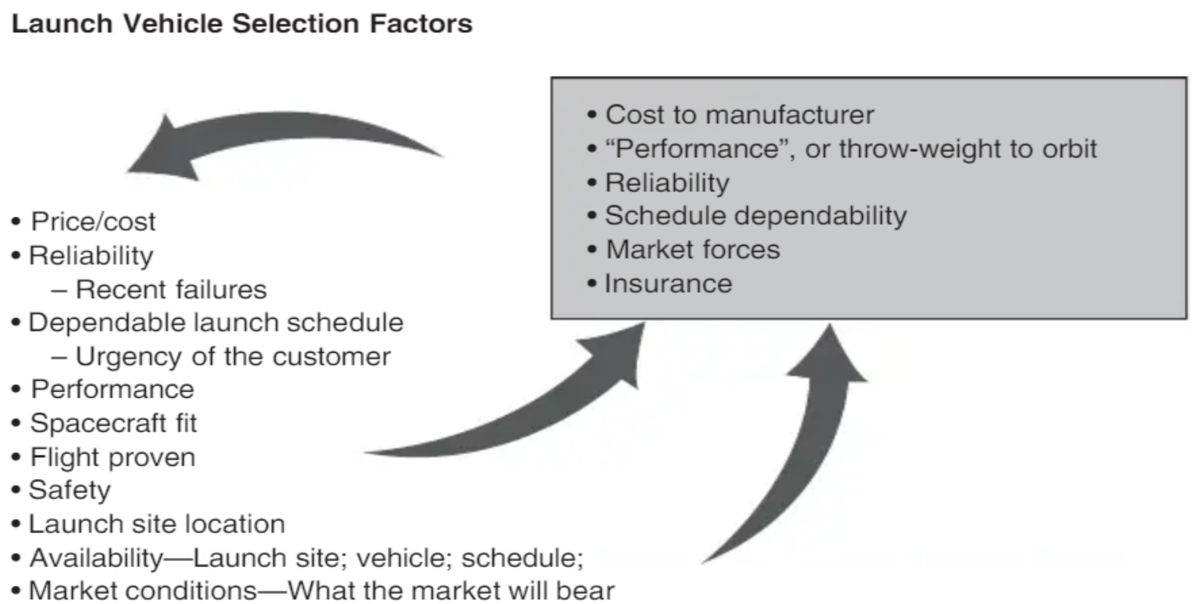
  An easterly launch from the equator has a velocity increment of 0.465 km/s imparted by the rotation of the earth.

  A satellite in a circular, equatorial orbit at an altitude of 900km requires an orbital velocity of about 7.4km/s tangential to the surface of the earth.

- **A rocket launched from the equator needs to impart an additional velocity of (7.4–0.47) km/s = 6.93km/s**
- **The equatorial launch has reduced the energy required by about 6%.**
- **If a rocket launch is not to place a satellite in to an equatorial orbit, the payload capabilities of any given rocket will reduce as the required orbital inclination increases.**
- **A satellite launched into a prograde orbit from a latitude of Φ degrees will enter an orbit with an inclination of Φ degrees to the equator.**

- If the satellite is intended for geostationary orbit, the satellite must be given a significant velocity increment to reorient the orbit into the earth's equatorial plane.
- The lower latitude of the launch sites results in savings in the fuel required by the AKM.
- Of probably more significance than the additional velocity increment provided by the spin of the earth, a launch close to the equator of a satellite intended for a geostationary orbit is the much lower energy needed to change the plane of the orbit from an inclination to zero inclination.
- For a given spacecraft, a change in plane uses approximately 10 times more fuel than a change in velocity in the same plane for a given angular change.

Launch vehicle selection factors:



Reliability: State of having low risk of technical failure based on a history of prior mission success— Increase the chances that payloads will reach orbit.

Launchers performance and suitability:

Performance of a vehicle: Capability of lifting a certain payload mass to a desired orbit and its ability to insert its payload(s) into the proper orbit.

Suitability: Vehicle's compatibility with various types of payloads and its payload margins

Price: 25 percent or more of a satellite project's total cost, launch price, including insurance.

Availability and Schedule:

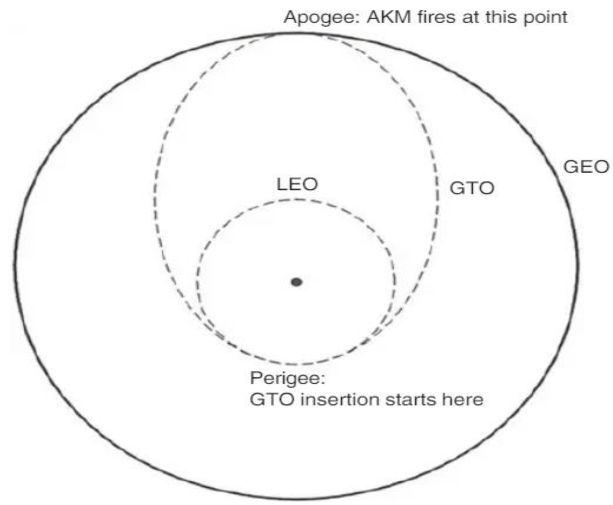
Whose availability is compatible with their desired launch schedules.

- **Return on investment**
- **Life cycle cost and availability**
- **Mission availability**

Placing Satellites In to Geostationary Orbit:

Geostationary Transfer Orbit and AKM:

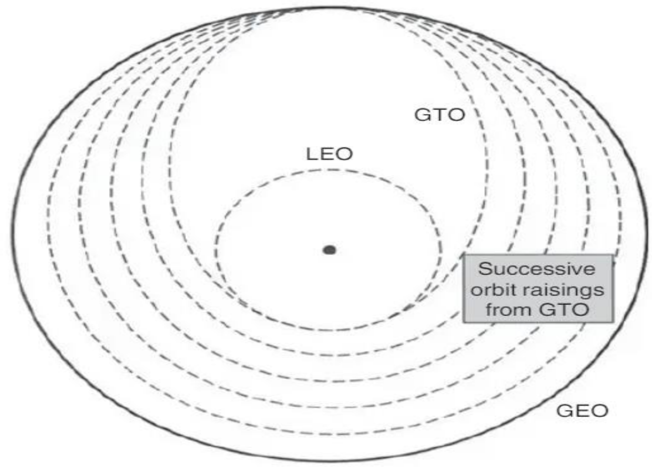
- **The initial approach to launching geostationary satellites was to place the spacecraft, with the final rocket stage still attached, in to LEO.**
- **After a couple of orbits, during which the orbital elements are measured, the final stage is reignited and the spacecraft is launched into a GTO.**
- **The GTO has a perigee that is the original LEO orbit altitude and an apogee that is the GEO altitude.**



- **The position of the apogee point is close to the orbital longitude that would be the in-orbit test location of the satellite prior to it being moved to its operational position.**
- **After a few orbits in the GTO while the orbital elements are measured, a rocket motor (usually contained with in the satellite itself) is ignited at apogee and the GTO is raised until it is a circular, geostationary orbit.**
- **Since the rocket motor fires at apogee, it is commonly referred to s the AKM.**
- **The AKM - To circularize the orbit at GEO and to remove any inclination error so that the final orbit of the satellite is very close to geostationary.**

Geostationary Transfer Orbit With Slow Orbit Raising:

- The space craft thrusters are used to raise the orbit from GTO to GEO over a number of burns instead of AKM.
- Since the space craft cannot be spin stabilized during the GTO many of the satellite elements are deployed while in GTO, including the solar panels.
- The satellite normally has two power levels of thrusters: one for more powerful orbit raising maneuvers and one for on-orbit (low thrust) maneuvers.



- Since the thrusters take many hours of operation to achieve the geostationary orbit, the perigee of the orbit is gradually raised over successive thruster firings.
- The thruster firings occur symmetrically about the apogee although they could occur at the perigee as well.
- The burns are typically 60–80 minutes long on successive orbits and up to six orbits can be used.
- In AKM and Slow Orbit Raising, the GTO may be a modified orbit with the apogee well above the required altitude for GEO.
- The excess energy of the orbit due to the higher-than-necessary altitude at apogee can be traded for energy required to raise the perigee.
- The net energy to circularize the orbit at GEO is therefore less and the satellite can retain more fuel for on-orbit operations.
- The use of an initial orbit insertion well above that needed for GEO occurs when the launch vehicle has the ability to add additional fuel at launch (due to a lighter satellite or the rocket has increased efficiency due to developments since the original launch agreement was signed).

Direct Insertion to GEO:

- The launch service provider contracts to place the satellite directly into GEO.
- The final stages of the rocket are used to place the satellite directly into GEO rather than the satellite use its own propulsion system to go from GTO to GEO