Advanced Electronic Communication Systems

Lecture 2

Launch Vehicles and Satellite Orbits

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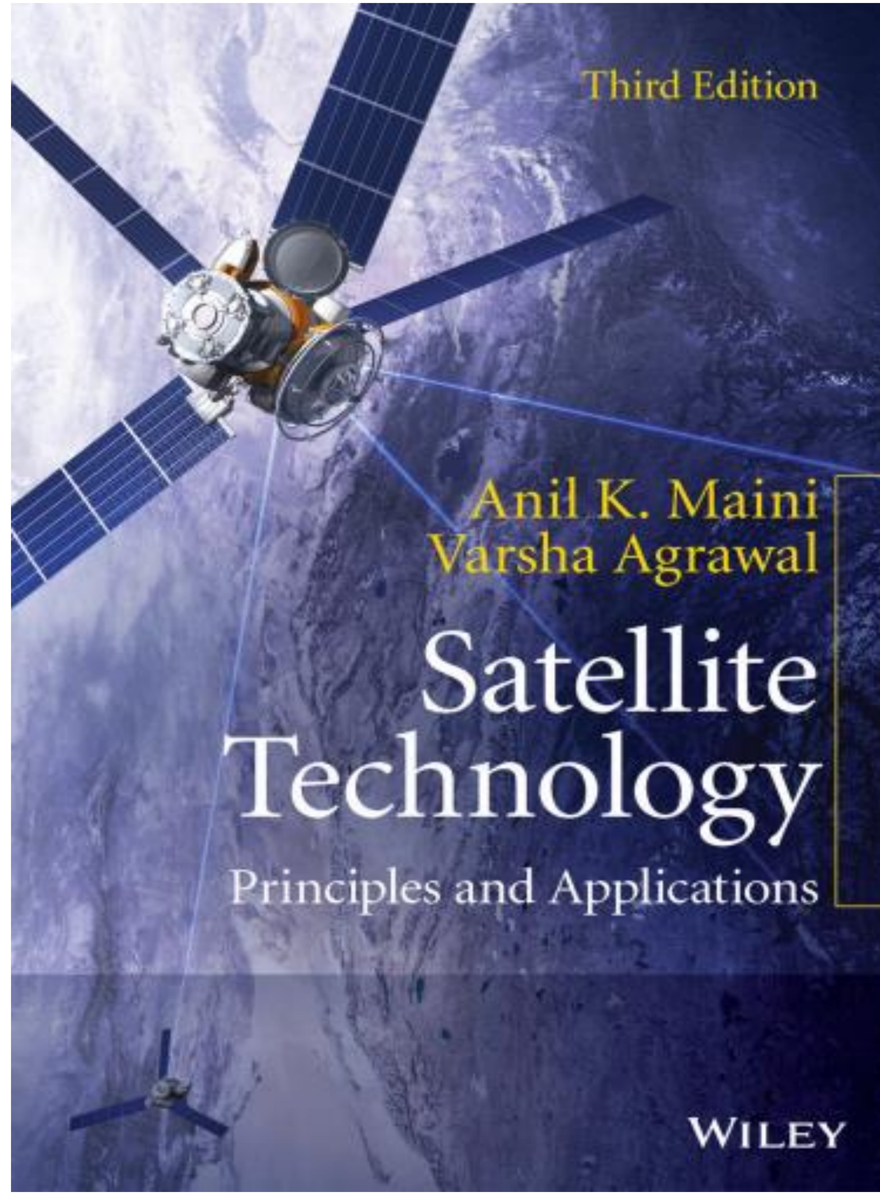
Still mostly with

Chapter (1)
Chapter (2)
Satellite Technology: Principles and Applications



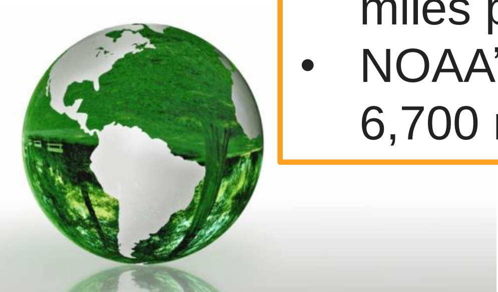
How Satellites Stay in Orbit Without Fuel?

- If you throw a ball into the air, the ball comes right back down. That's because of gravity
- To get into orbit, satellites first have to launch on a rocket.
- A rocket can go 25,000 miles per hour! That's fast enough to overcome the strong pull of gravity and leave Earth's atmosphere
- Once the rocket reaches the right location above Earth, it lets go of the satellite.
- The satellite uses the energy it picked up from the rocket to stay in motion. That motion is called momentum.

Wouldn't it just fly off in a straight line out into space?

How Satellites Stay in Orbit Without Fuel?

- Even when a satellite is thousands of miles away, Earth's gravity is still tugging on it.
- That tug toward Earth, combined with the momentum from the rocket cause the satellite to follow a path around Earth (an orbit).
- When a satellite is in orbit, it has a perfect balance between its momentum and Earth's gravity. But finding this balance is sort of tricky.
- Gravity is stronger the closer you are to Earth. And satellites that orbit close to Earth must travel at very high speeds to stay in orbit.



- NOAA-20 orbits just a few hundred miles above Earth with 17,000 miles per hour to stay in orbit.
- NOAA's GOES-East satellite orbits 22,000 miles above Earth with 6,700 miles per hour to stay in orbit.

Evolution of Launch Vehicles

- Satellite launch vehicles have also seen various stages of evolution in order to meet launch demands of different Sat. categories.
  - ✓ Smaller launch vehicles capable of launching satellites in low Earth orbits
  - ✓ Giant sized launch vehicles that can deploy multiple satellites in geostationary orbit
- Both have seen improvements in their designs over the last decades to innovate and improve the technology to become economically viable

- Ten countries have demonstrated independent orbital launch
- However, only Seven countries (i.e. the United States, the Russian Federation, China, Japan, India, Iran and Occupation Forces on Palestine land) and the European Space Agency (ESA) have operational launchers.

Major Space Centres

1. John F. Kennedy Space Centre at Cape Canaveral, United States
2. Baikonur Cosmodrome, Kazakhstan
3. Guiana Space Centre at Kourou, French Guiana
4. Yuri Gagarin Cosmonaut Training Centre (GCTC), Russia
5. Xichang Satellite Launch Centre, China
6. Jiuquan Satellite Launch Centre, China
7. Uchinoura Space Centre, Japan
8. Tanegashima Space Centre, Japan
9. German Aerospace Centre, Germany
10. Satish Dhawan Space Centre, Sriharikota (SHAR), India

Chapter (2)
Satellite Orbits

- An understanding of the orbital dynamics is needed to address issues like:
    - ✓ Types of orbit and
    - ✓ Their suitability for a given application,
    - ✓ Orbit stabilization,
    - ✓ Orbit correction and station keeping,
    - ✓ Launch requirements and typical launch trajectories
    - ✓ Earth coverage

- Artificial satellites that orbit the earth are governed by the same laws of motion that control the motion of the planets around the sun.

Satellite orbit determination is based on
the Laws of Motion
first developed by Johannes Keppler
and later refined by Newton

2.1 Definition of an Orbit and a Trajectory

- **A Trajectory** is a path traced by a moving body,
- **An orbit** is a trajectory that is periodically repeated.

The path followed by the motion of an artificial satellite around Earth or a planet around the sun is an orbit

The path followed by a launch vehicle is called the launch trajectory.

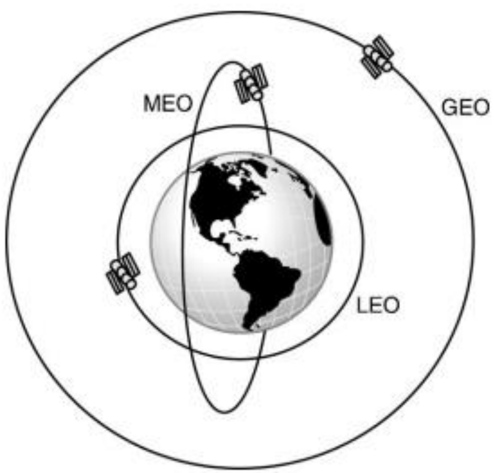


Figure 2.1 Example of orbital motion satellites revolving around Earth

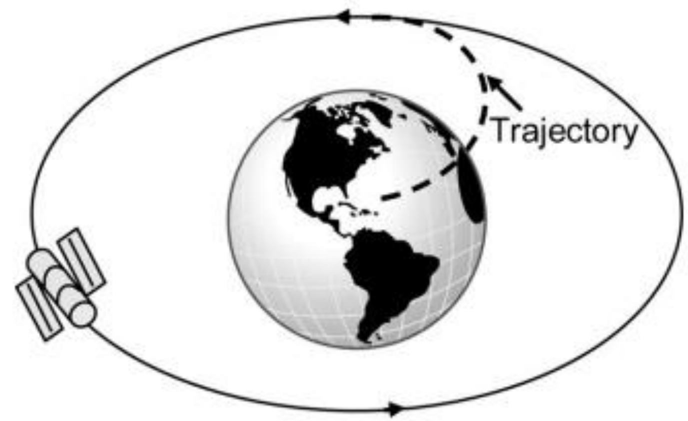


Figure 2.2 Example of trajectory path followed by a rocket on its way during satellite launch

2.1 Definition of an Orbit and a Trajectory

- **Usually, Satellites** do not assume final orbit at once but follow a trajectory of intermediate orbits first

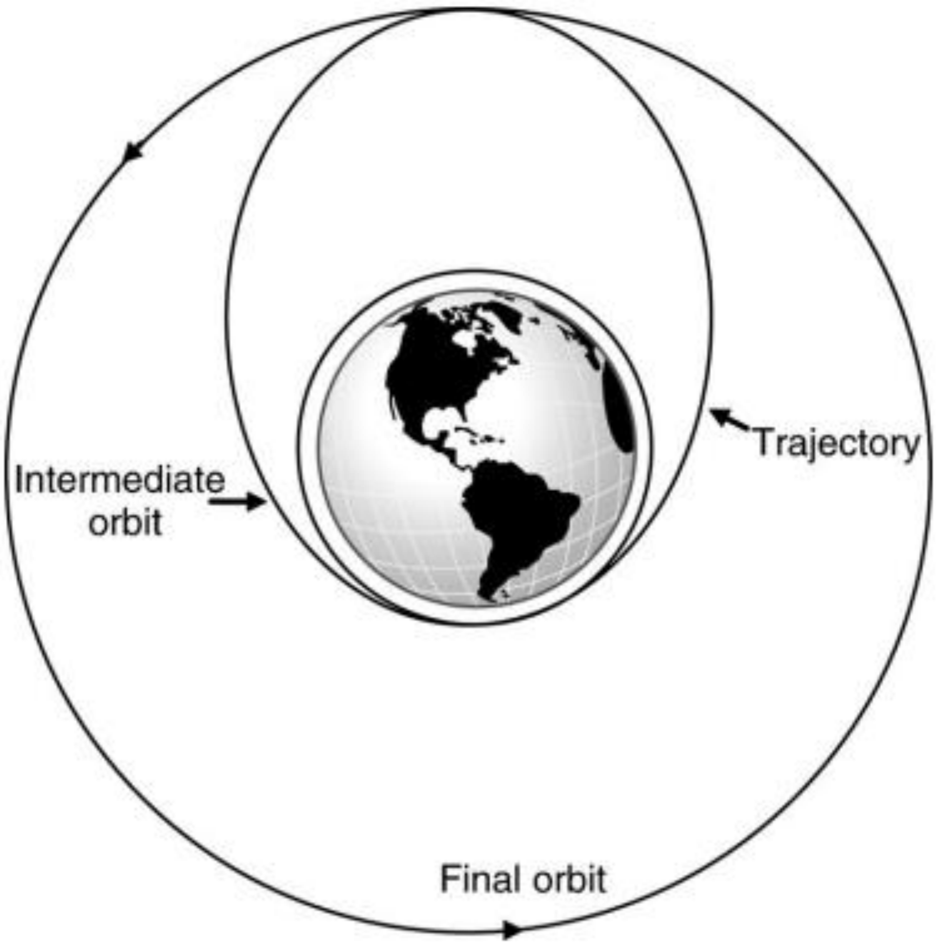
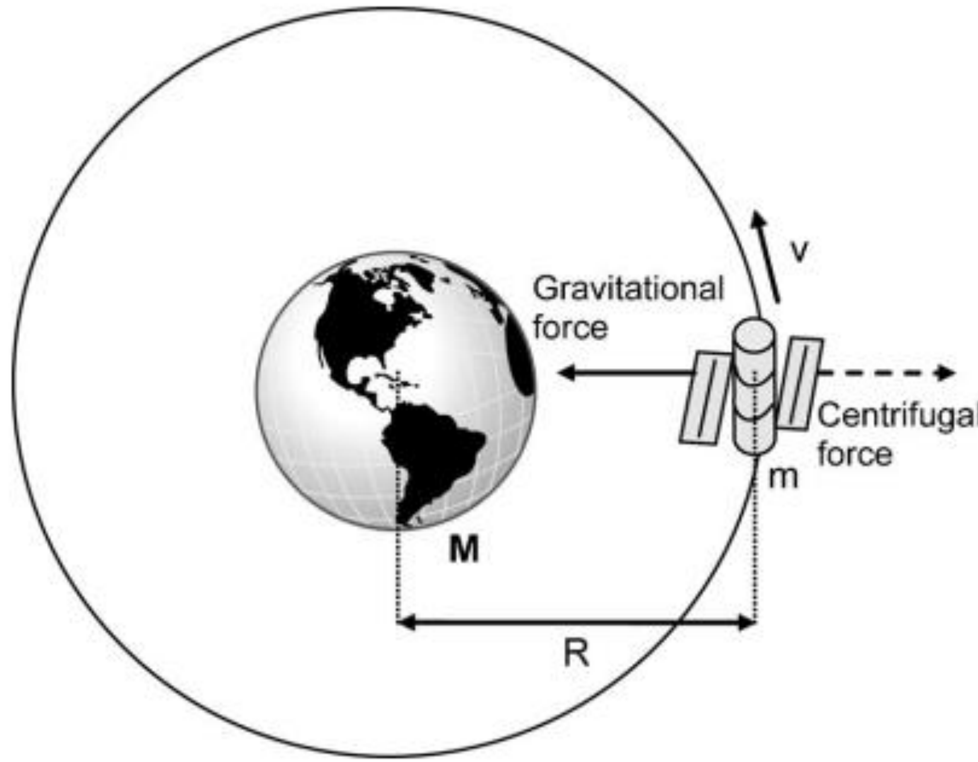


Figure 2.3 Example of trajectory -- motion of a satellite from the intermediate orbit to the final orbit

2.2 Orbiting Satellites -- Basic Principles

- **The main competing forces that act on the satellite motion:**

1. The centripetal force directed towards the centre of the Earth due to the gravitational force of attraction of Earth
2. The centrifugal force due to the orbital velocity that tends to pull the satellite away from the earth.



- **The two forces can be explained from:**

1. **Newton's law of gravitation and**
2. **Newton's second law of motion**

Newton's law of gravitation

Every particle irrespective of its mass attracts every other particle with a gravitational force whose magnitude is directly proportional to the product of the masses of the two particles and inversely proportional to the square of the distance between them

$$F = \frac{Gm_1 m_2}{r^2}$$

$m_1, m_2 =$ masses of the two particles
$r =$ distance between the two particles
$G =$ gravitational constant $= 6.67 \times 10^{-11}\ \mathrm{m^3/kg\,s^2}$

- ✓ The force with which the particle with mass $m1$ attracts the particle with mass $m2$ equals the force with which the particle with mass $m2$ attracts the particle with mass m 1
- ✓ The forces are equal in magnitude but opposite in direction

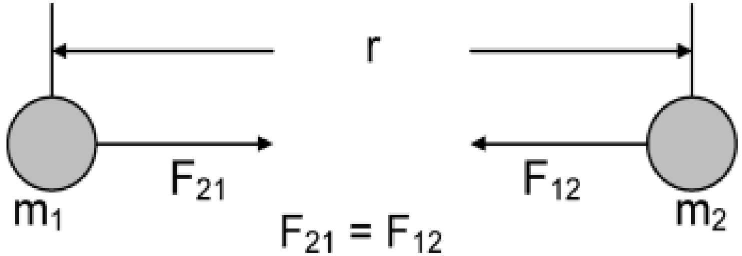


Figure 2.5 Newton's law of gravitation

Newton’s Second Law of Motion

The force equals the product of mass and acceleration.

- If the orbiting velocity is v , then the **centripetal acceleration** experienced by the satellite at a distance r from the centre of the Earth would be $\boldsymbol{v^2/r}$
- Then according to Newton’s law If the mass of satellite is m , it would experience a reaction force of $\boldsymbol{m\,v^2/r}$

Newton's Second Law of Motion

Circular Orbit

- The satellite orbits Earth with a uniform velocity v at constant orbit radius r, where the two forces must be equal

$$F_{in} = F_{out}$$

$$\frac{Gm_1 m_2}{r^2} = \frac{m_2 v^2}{r}$$

- The orbital velocity v can be expressed as

$$v = \sqrt{\left(\frac{Gm_1}{r}\right)} = \sqrt{\left(\frac{\mu}{r}\right)}$$

Elliptical Orbit

- The forces governing the motion of the satellite are the same.
- The velocity at any point on an elliptical orbit at a distance d from the centre of the Earth is given as

$$v = \sqrt{\left[\mu\left(\frac{2}{d} - \frac{1}{a}\right)\right]}$$

a = semi-major axis of the elliptical orbit

μ = Kepler's Constant (or Geocentric Gravitational Constant)

$$= Gm_1 = 3.986013 \times 10^5\ \mathrm{km^3/s^2} = 3.986013 \times 10^{14}\ \mathrm{N\,m^2/kg}$$

m_1 = mass of Earth

Newton’s Second Law of Motion

- The orbital period in both types of orbits are given as

Circular Orbit

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

Elliptical Orbit

$$T = \frac{2\pi a^{3/2}}{\sqrt{\mu}}$$

2.2.3 Kepler's Laws

- The laws that govern satellite motion are called "Kepler's Laws"
- These laws depends on laws of planetary motion that describe:
  - ✓ The shape of the orbit,
  - ✓ The velocities of the planet,
  - ✓ The distance a planet is with respect to the sun.

- Kepler's laws can be applied to any two bodies in space that interact through gravitation.
- The larger of the two bodies is called the primary, and the smaller is called the secondary.

Kepler’s laws of planetary motion

1. The orbit of a planet is an ellipse with the Sun at one of the two foci.

2. A line segment joining a planet and the Sun sweeps out equal areas during equal intervals of time.

3. The square of the orbital period of a planet is proportional to the cube of the semi-major axis of its orbit.

Kepler's First law

States that the path followed by a satellite around the earth will be an ellipse

- ✓ If no other forces are acting on the satellite, either intentionally by orbit control, or unintentionally, by gravity forces from other bodies, the satellite will eventually settle in an elliptical orbit, with the Earth as one of the foci of the ellipse.
- ✓ Because the mass of Earth (m1) is substantially greater than that of the satellite (m2), the center of mass of the two-body system will always coincide with the center of Earth (a.k.a. barycenter)

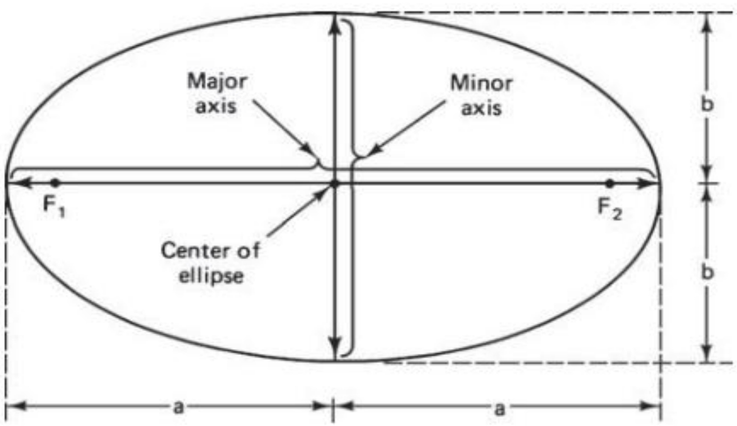
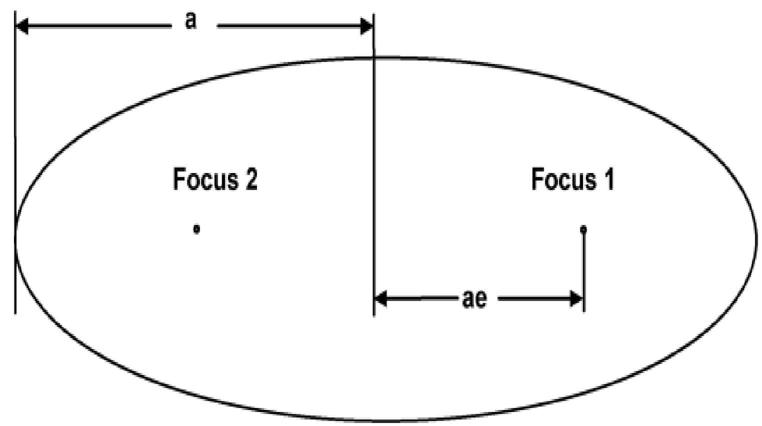


Figure 2.1 The foci F_1 and F_2, the semimajor axis a, and the semiminor axis b of an ellipse.



✓ **The elliptical orbit is characterized by:**

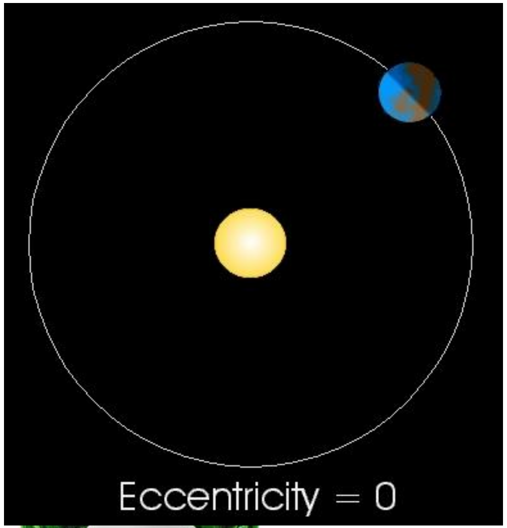
1. Its semi-major axis (a)
2. eccentricity e .

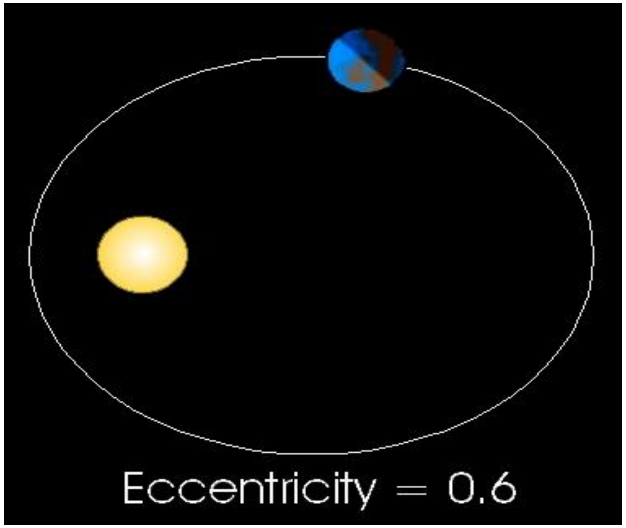
Eccentricity

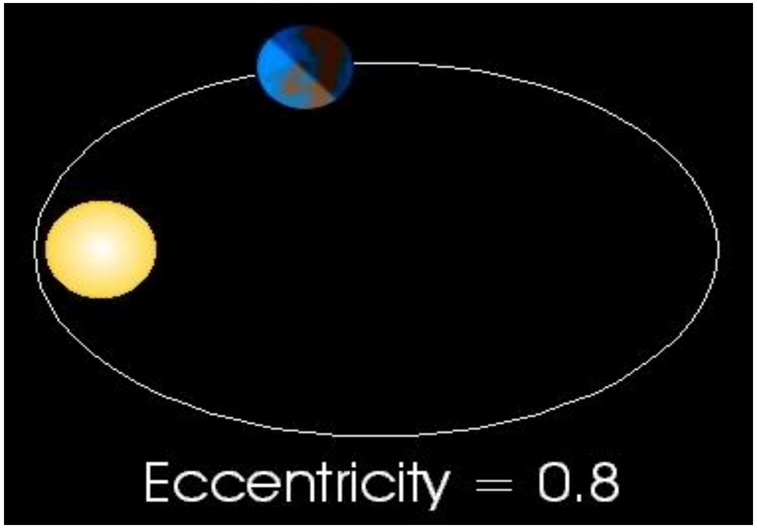
- The eccentricity determines the shape of the orbit.
- Eccentricity is the ratio of the distance between the centre of the ellipse and either of its foci (= ae) to the semi-major axis of the ellipse a .
- It tell us how round or flat the orbit is.
- b = semi-minor axis

$$e = \frac{\sqrt{a^2 - b^2}}{a}$$

- ✓ For a circle, e = 0
- ✓ The range of values of the eccentricity for ellipses is 0 < e < 1
- ✓ The higher the value of e, the longer, thinner, and flatter the ellipse

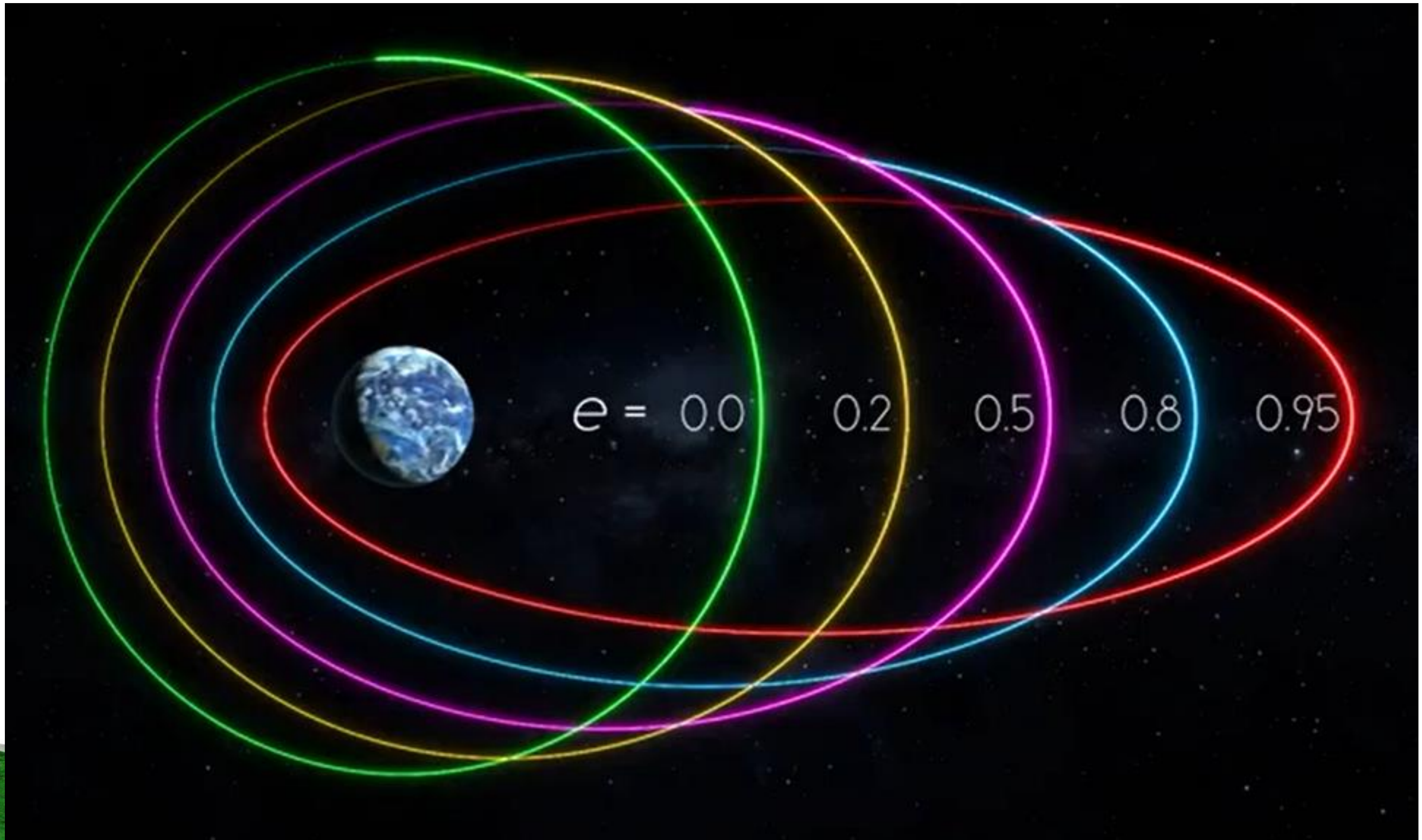






Eccentricity

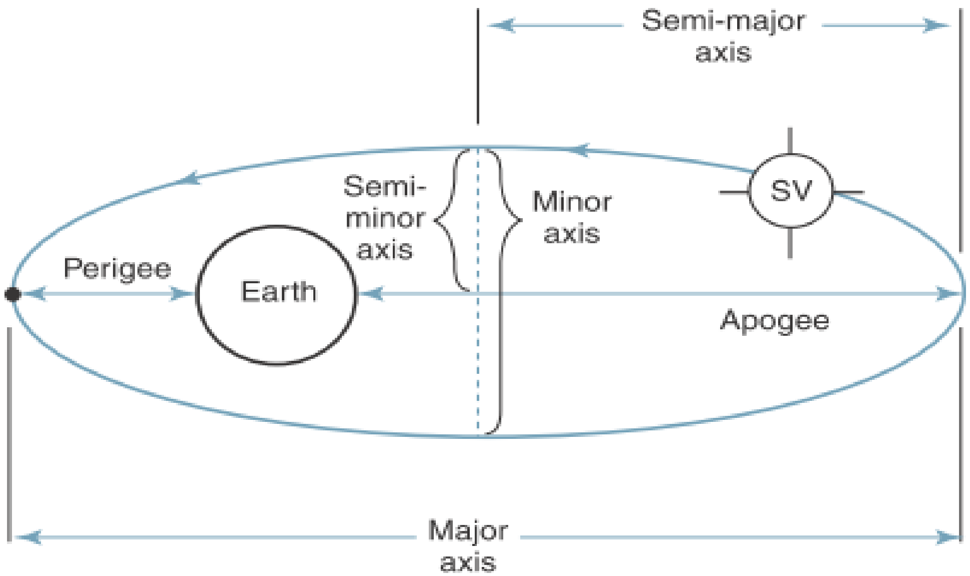
$$e = \frac{\sqrt{a^2 - b^2}}{a}$$



Apogee and Perigee (Orbital parameters)

Apogee. The point in an orbit that is located farthest from Earth

Perigee. The point in an orbit that is located closest to Earth



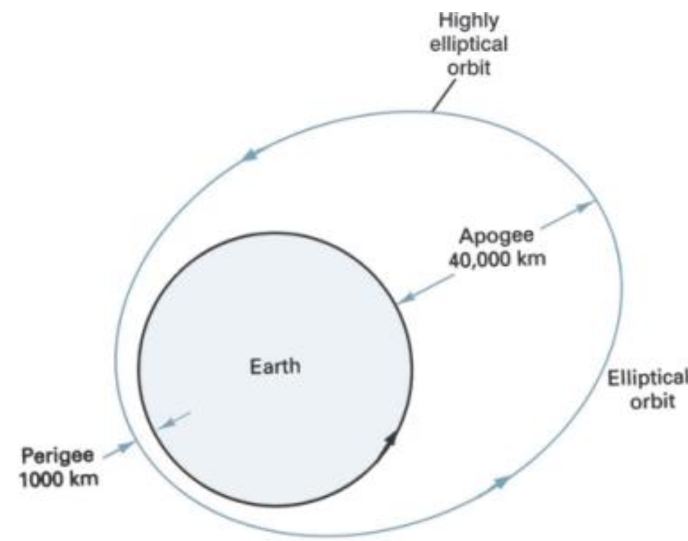


FIGURE 6 Soviet *Molniya* satellite orbit

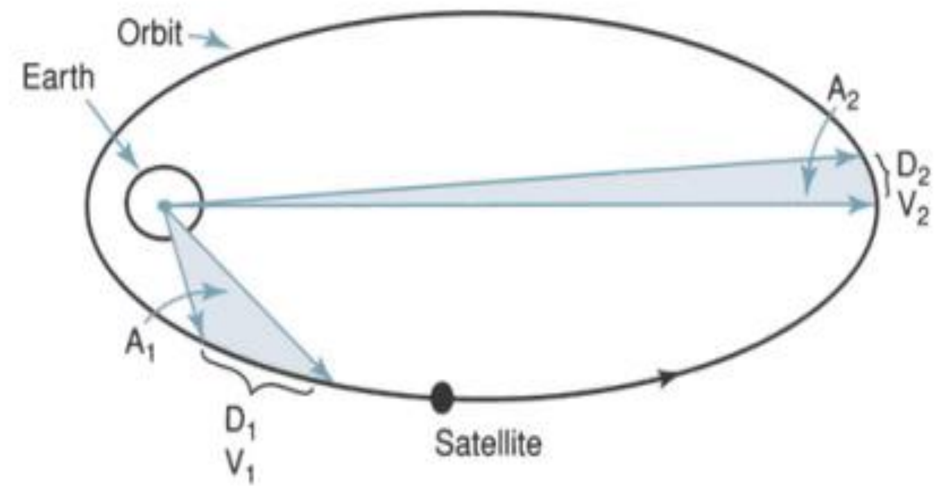
- Some references adds the radius of the earth to both perigee and apogee
- The satellite moves with minimum speed at apogee and with maximum speed at perigee

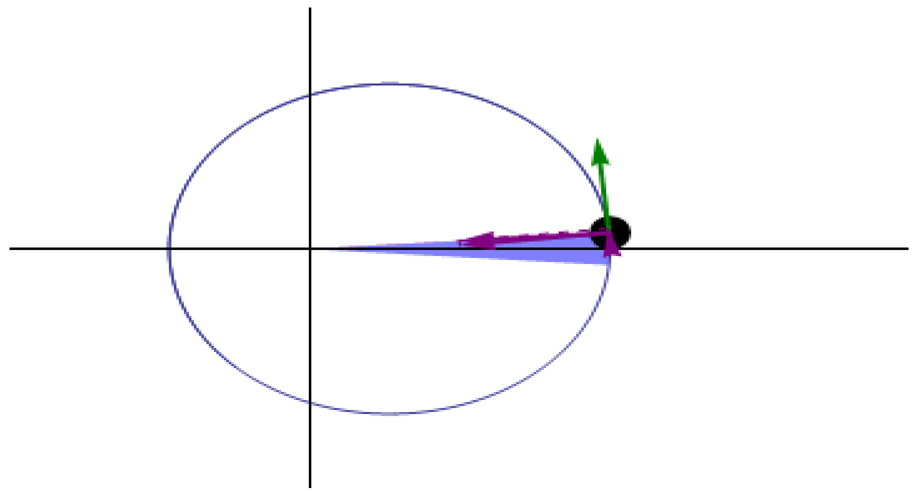
Apogee/Perigee versus Semi-Major Axis

- Notice that the semi-major axis is the average of both perigee and apogee
- The semi-major axis determines the size of the orbit. While eccentricity determines the shape

Kepler's Second law (the law of Areas)

Kepler's second law states that for equal intervals of time a satellite will sweep out equal areas in the orbital plane, focused at the barycenter.





- ✓ for a satellite traveling distances D1 and D 2 meters in 1 second,
- ✓ Areas A1 = A2
- ✓ Because of the equal area law, distance D1 > distance D2 , and, therefore, Velocity V1 must be greater than velocity V2 .

Kepler's Second law (the law of Areas)

- The rate of change of the swept-out area (A) is a constant given by

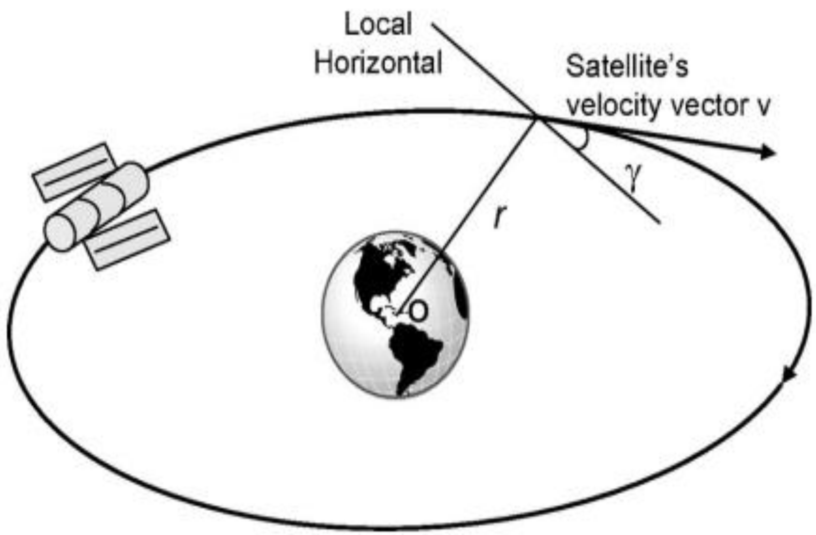
$$\frac{dA}{dt} = \frac{\text{angular momentum of the satellite}}{2m}$$

m: **mass of the satellite**

- Since this term is constant and m is constant, Kepler's second law is also equivalent to the law of **conservation of momentum,**

The angular momentum = const

$$= m\,r^2\,\omega = m\,(\omega\,r)\,(r) = m\,v'\,r$$



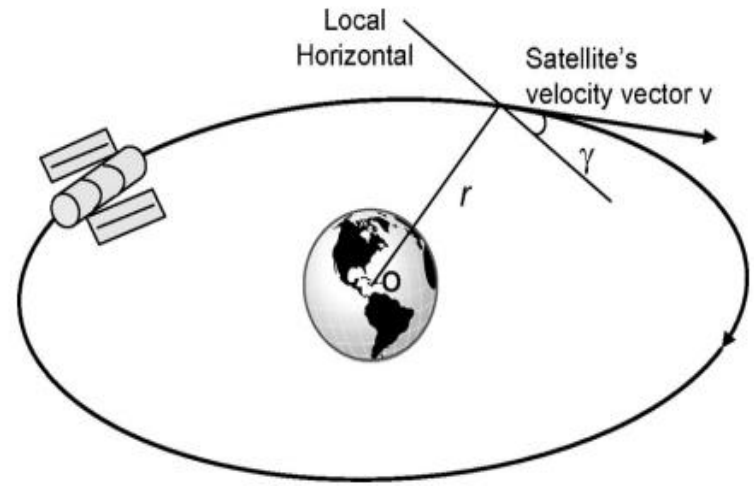
- ω **:** Angular velocity of the satellite
- v'**:** The component of the satellite's velocity v in the direction perpendicular to the radius vector

Kepler's Second law (the law of Areas)

- Hence $v' = v \cos\gamma$

γ: is the angle between the direction of motion and the **local horizontal**,

- The local horizontal, which is in the plane perpendicular to the radius vector r



- Since m is constant, this leads to the conclusion that:

$$r\,v' = r\,v\cos\gamma = \text{const}$$

$$v' = \text{const}/r$$

- Hence the satellite speed v' is inversely proportional to the distance from the earth, **which proves why satellite is at its lowest speed at the apogee point and the highest speed at the perigee point.**

> **This property can be used to design orbits to increase the length of time a satellite can be seen from particular geographic regions of the earth.**

Kepler's Second law (the law of Areas)

r v cos γ = const

This law means that, for any satellite in an elliptical orbit, the dot product of its velocity vector and the radius vector at all points is constant.

$$v_{\mathrm{p}} r_{\mathrm{p}} = v_{\mathrm{a}} r_{\mathrm{a}} = v r \cos \gamma$$

v_{p} = velocity at the perigee point
r_{p} = perigee distance
v_{a} = velocity at the apogee point
r_{a} = apogee distance
v = satellite velocity at any point in the orbit
r = distance of the point
γ = angle between the direction of motion of the satellite and the local horizontal

Thank you

Additional References

1. https://scijinks.gov/satellites-orbit/