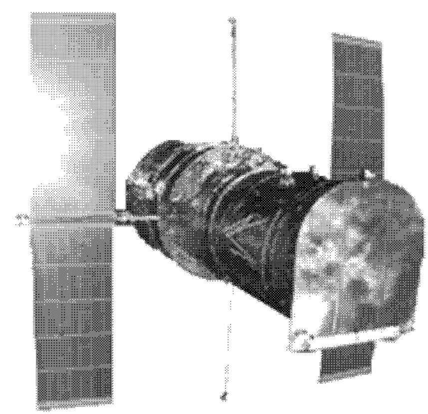
Orbital Mechanics

Version 14.1

ACE-170

Learning Objectives

- At the end of this lesson you should be able to:
  - Recognize the fundamental laws to get to and stay in orbit
  - Correctly apply basic terminology
  - Describe the different types of orbits



Orbits: Gravity & Motion

- An orbit is the constrained motion of a body (think satellite) about a common center of mass (think the earth)
- There are two forces acting on a body in space
  - Gravity provides an attractive force between two bodies
  - Motion (velocity) provides a force that tends to separate two bodies
- Put two bodies in space with no motion and they will pull toward one another

Balancing Forces

- Newton's Law of Universal Gravitation:

$$F = Gm_1m_2 / r^2$$

Where:

G = gravitational constant
(6.674 x 10^{-11} N*m^2/kg^2

m_1 = mass of object 1

m_2 = mass of object 2

r = distance between them

- Newton's 2^{nd} Law:

$$F = ma$$

Where:

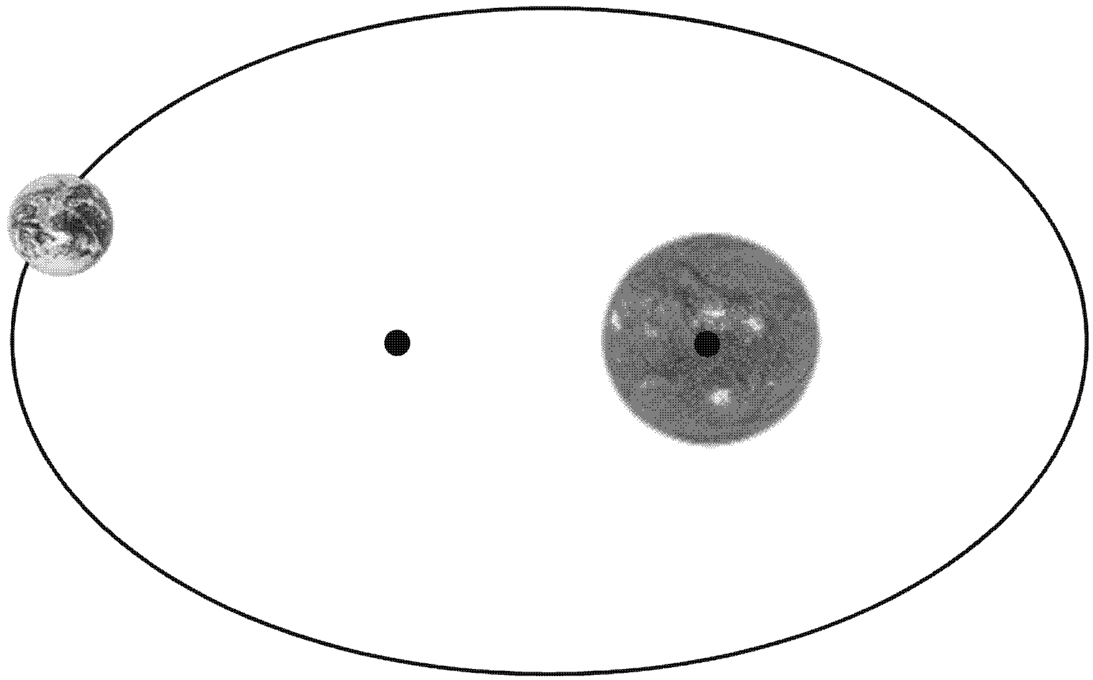
F = Force acting on the body

m = mass

a = acceleration (change in velocity)

Kepler's 1st Law

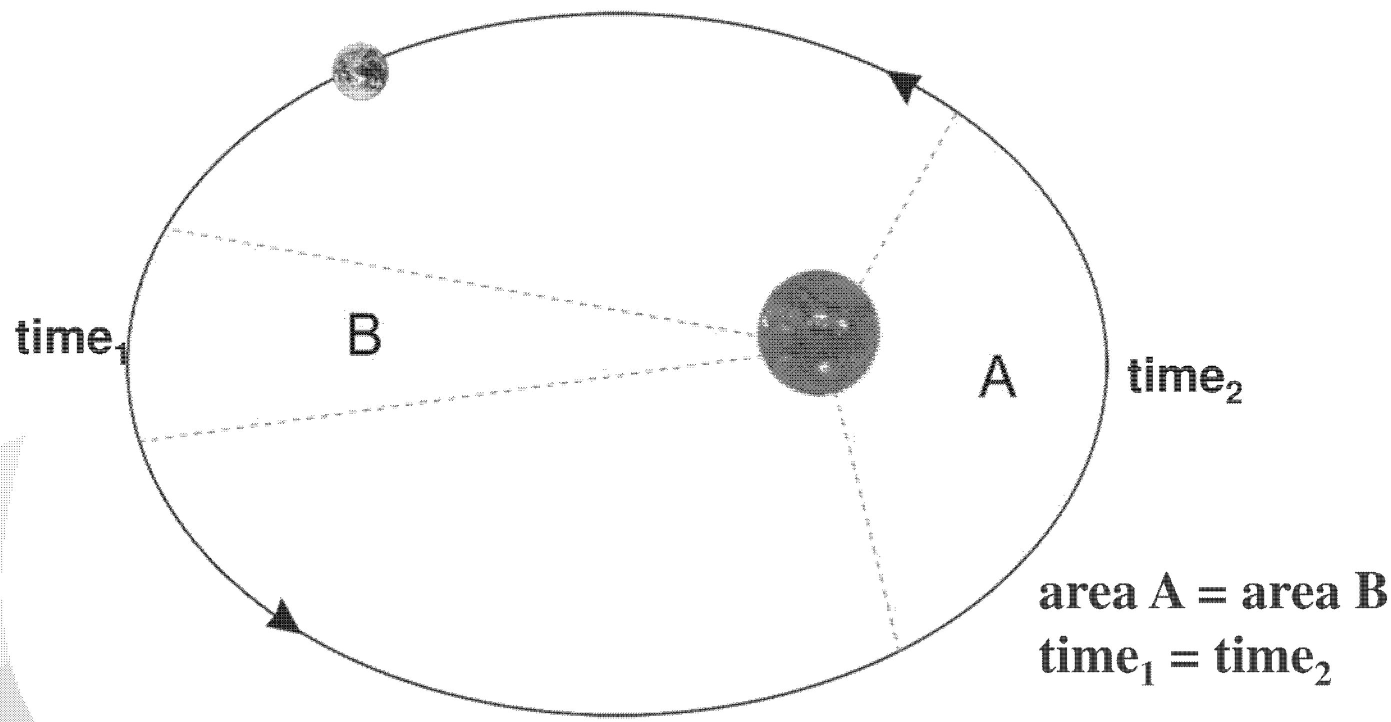
- The orbits of the planets are ellipses with the sun at one focus



- The law also applies to satellites orbiting the earth

Kepler's 2^{nd} Law

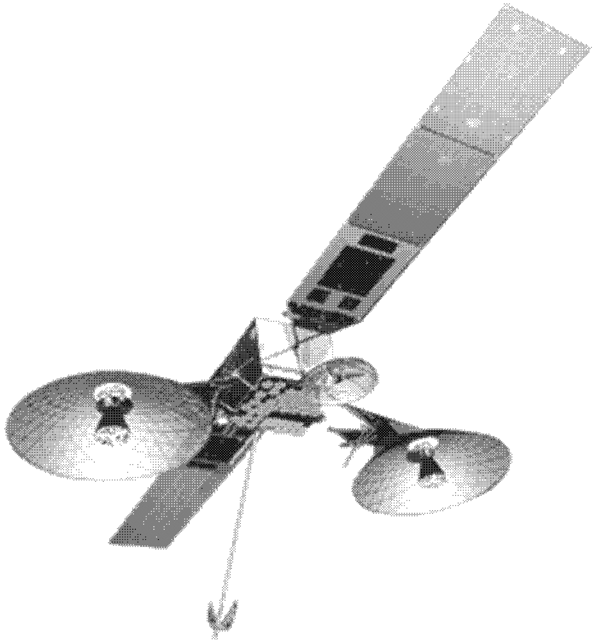
- The line joining the planet to the sun sweeps out equal area in equal times



- This allows us to determine the speed of a orbiting body at various points in the orbit

Defining an Orbit

- To specify a satellite's orbit in space, we need to know four things about it:
  - Size – Semi-Major Axis
  - Shape – Eccentricity
  - Orientation – Inclination
  - Location – Ground Track

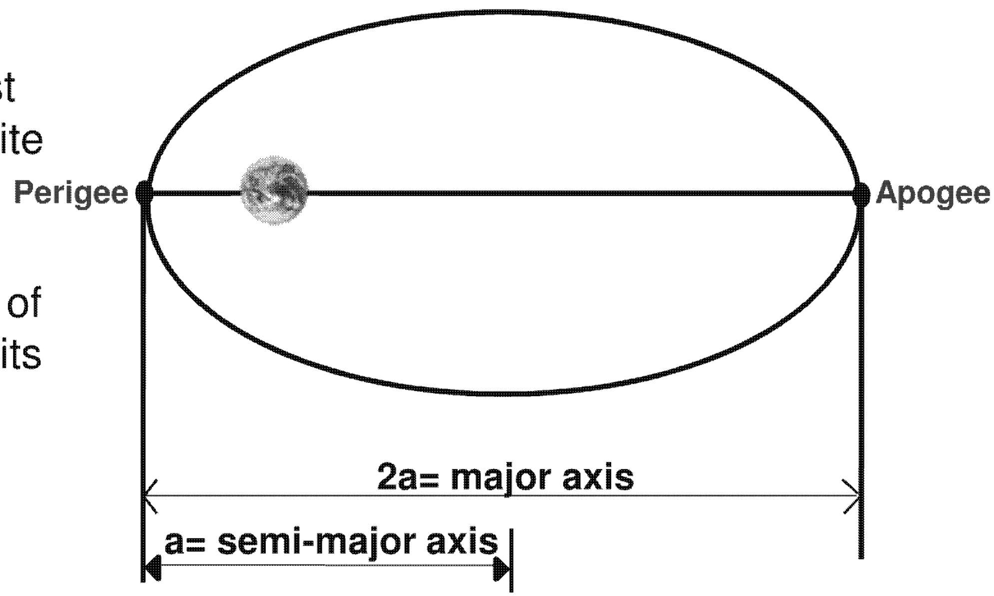


Semi-Major Axis = a

- Describes the size of an orbit: half the distance of the major axis
- The larger the "a," the larger the orbit, the greater the energy

Perigee - Closest distance the satellite passes from the primary body

- Forward velocity of the satellite is at its greatest
- Gravitational pull from the Earth is strongest point



Apogee – Furthest distance the satellite reaches from the primary body

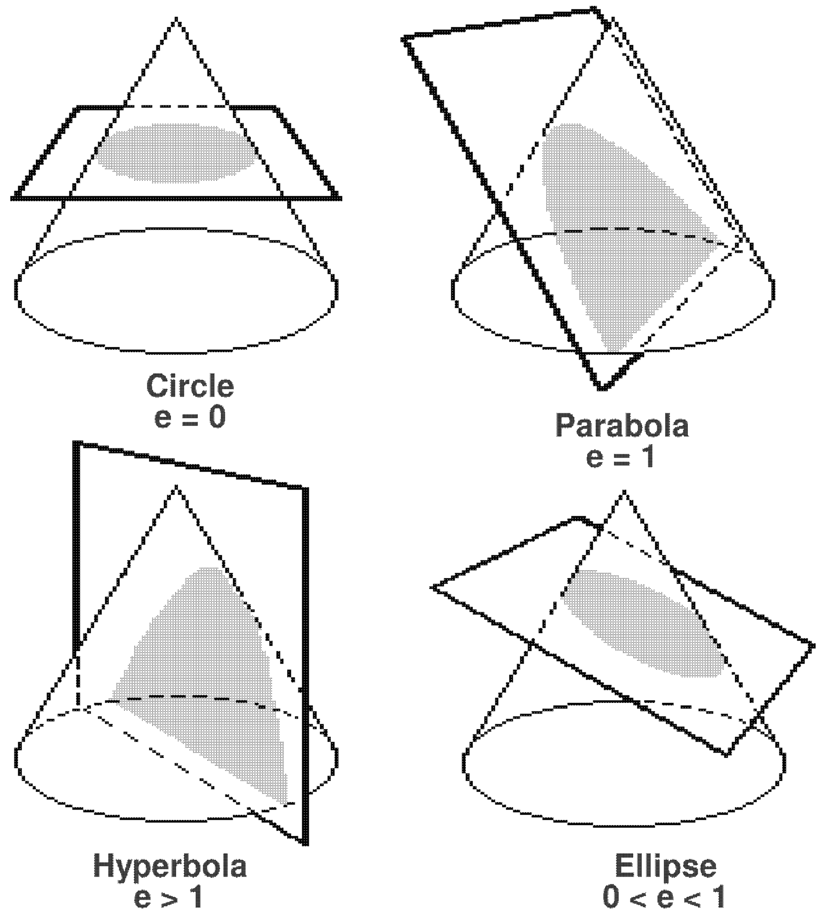
- Forward velocity of the satellite is at its minimum point
- Gravitational pull from the Earth is weakest point

Eccentricity - e

- **Eccentricity (e)** defines the elongation of an ellipse and measures the shape of an orbit
- The value of eccentricity in any closed orbit lies between zero and one
- The larger the value, the more elliptical the orbit

Eccentricity – e (con't)

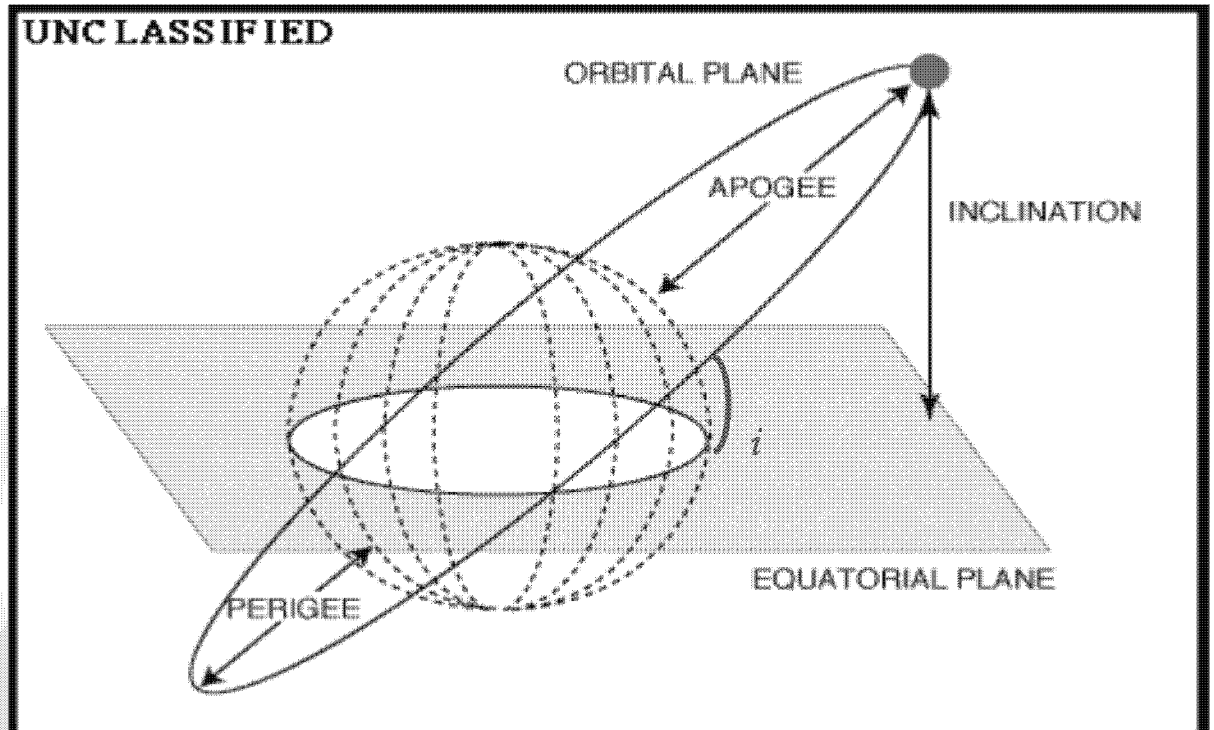
- Shape of the orbit, described as the type of conic section
  - Circle e = 0
  - Ellipse 0 < e < 1
  - Parabola e = 1
  - Hyperbola e > 1



Conic Sections

Inclination - i

- Describe the tilt of the orbit plane with respect to the equatorial plane



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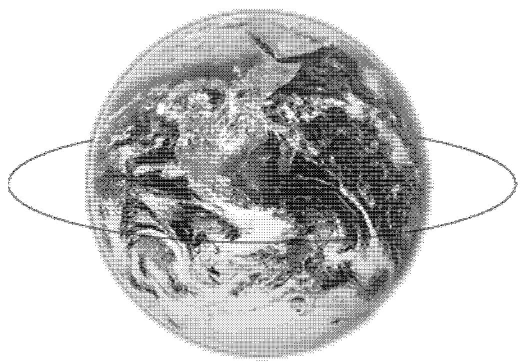
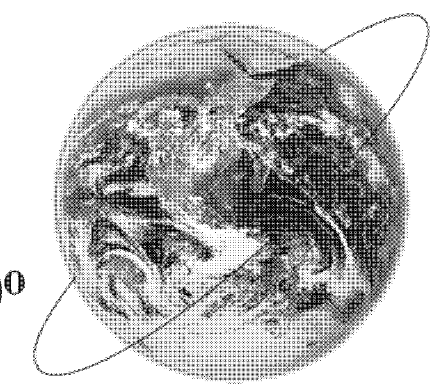
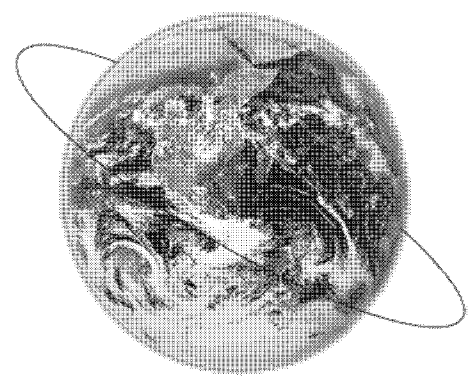
Inclination – i (con't)



$i = 0^{o}$
Equatorial

$i = 90^{o}$
Polar





$0^{o} < i < 90^{o}$
Prograde

$90^{o} < i < 180^{o}$
Retrograde

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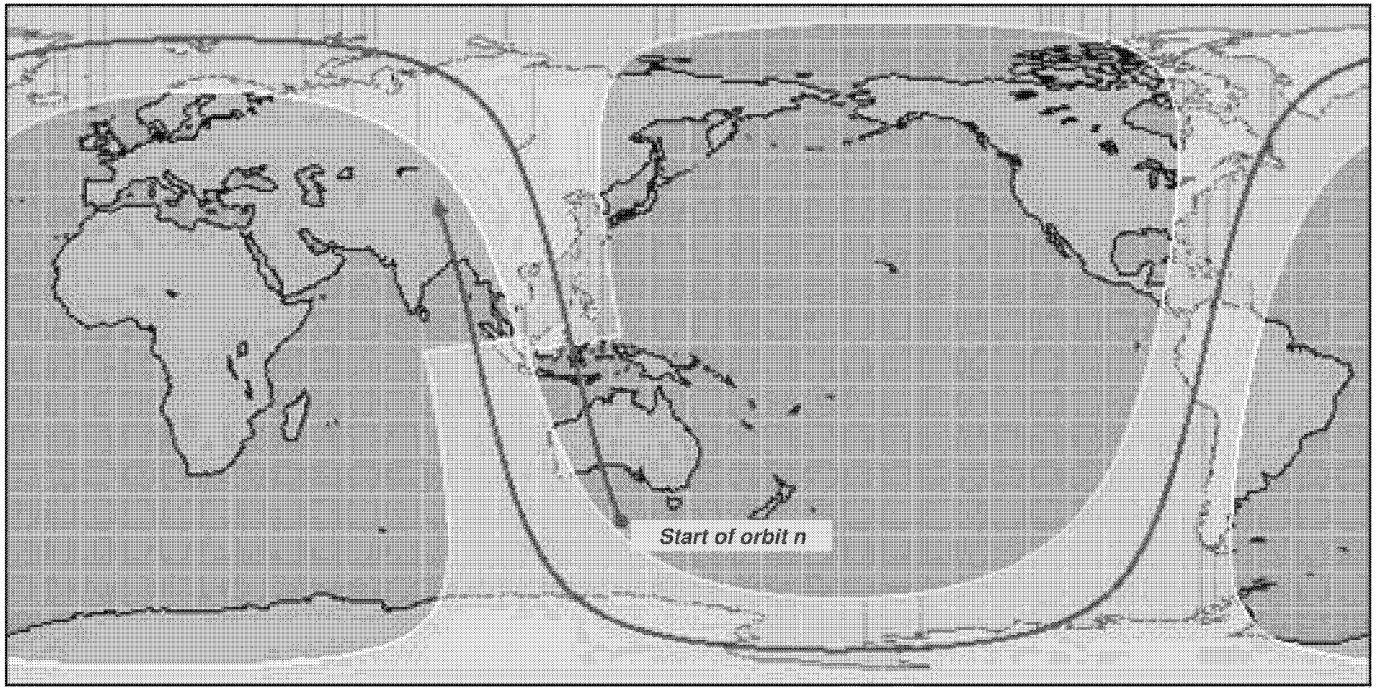
Satellite Ground Tracks

- Ground tracks are the intersection of the orbit plane with the **rotating** earth
- Due to the earth's rotation, the ground track shifts as the satellite revolves around the earth
- The amount of shift depends upon the altitude, eccentricity, and inclination

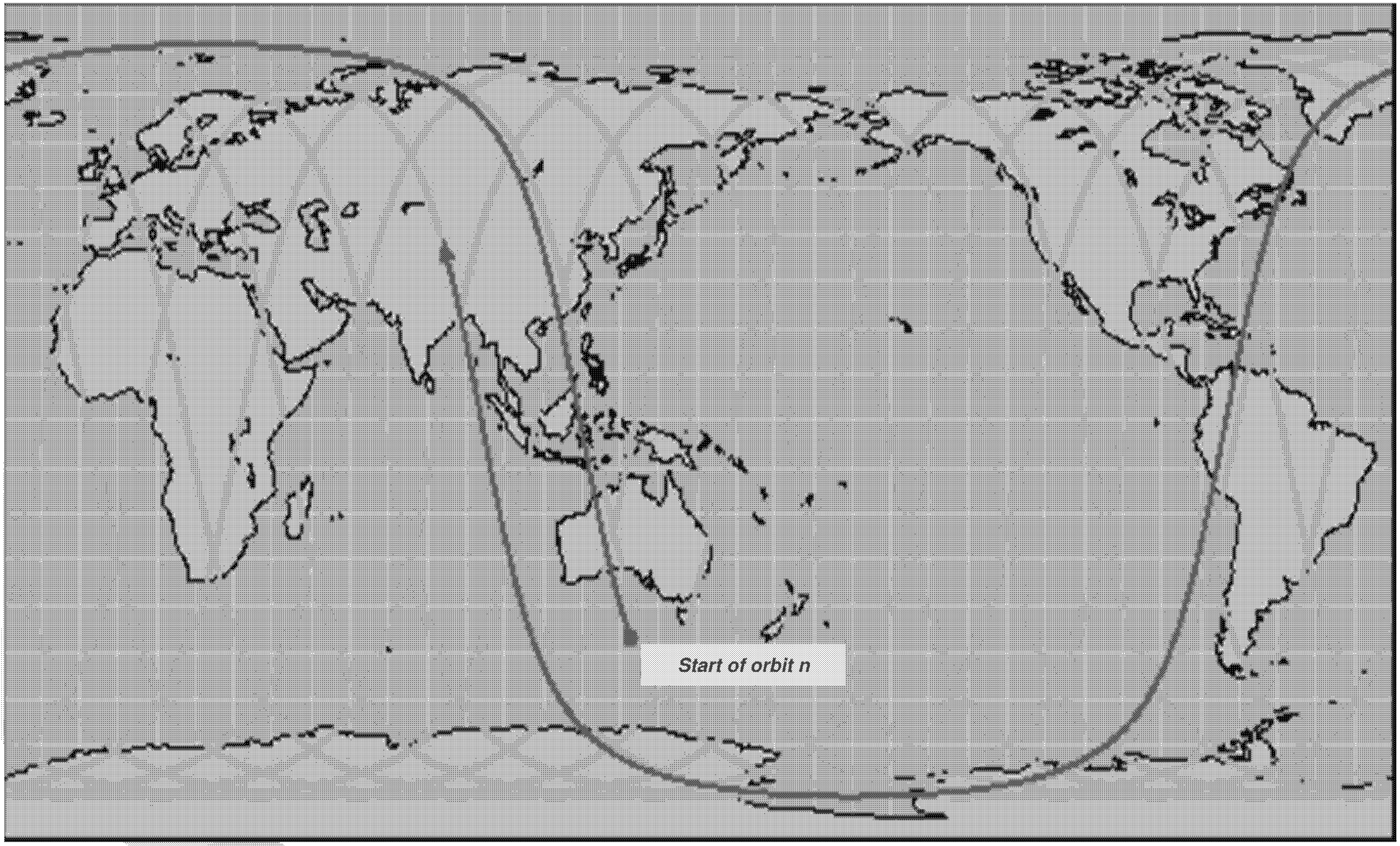
Orbit to Ground Track Video

Ground Tracks

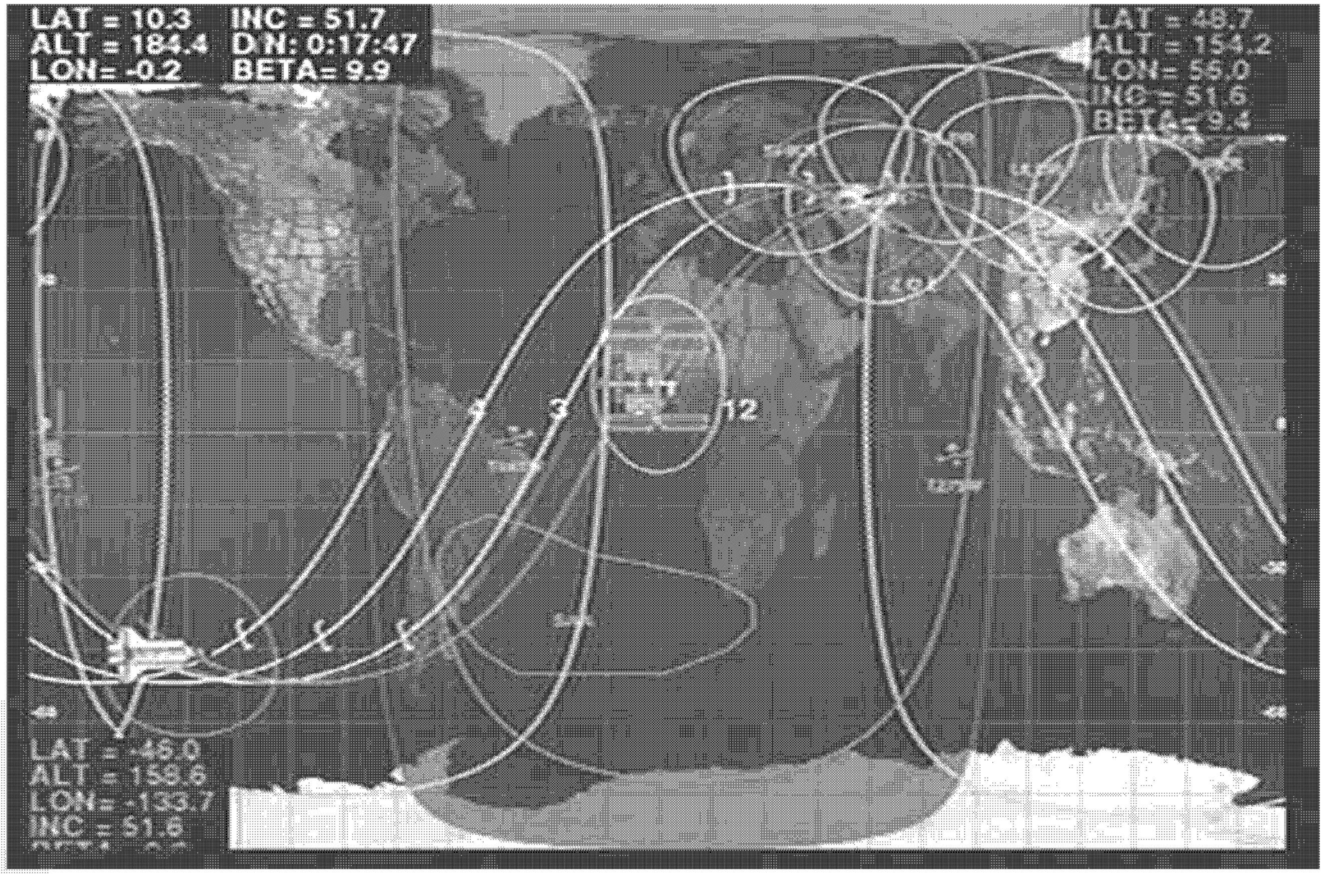


- The satellite is "fixed" in inertial space – the orbit plane doesn't move unless acted on by some external force
- But the earth rotates under the satellite
  - This makes the satellites ground path move west or east over the surface of the earth

Ground Tracks of Near-Polar Sat

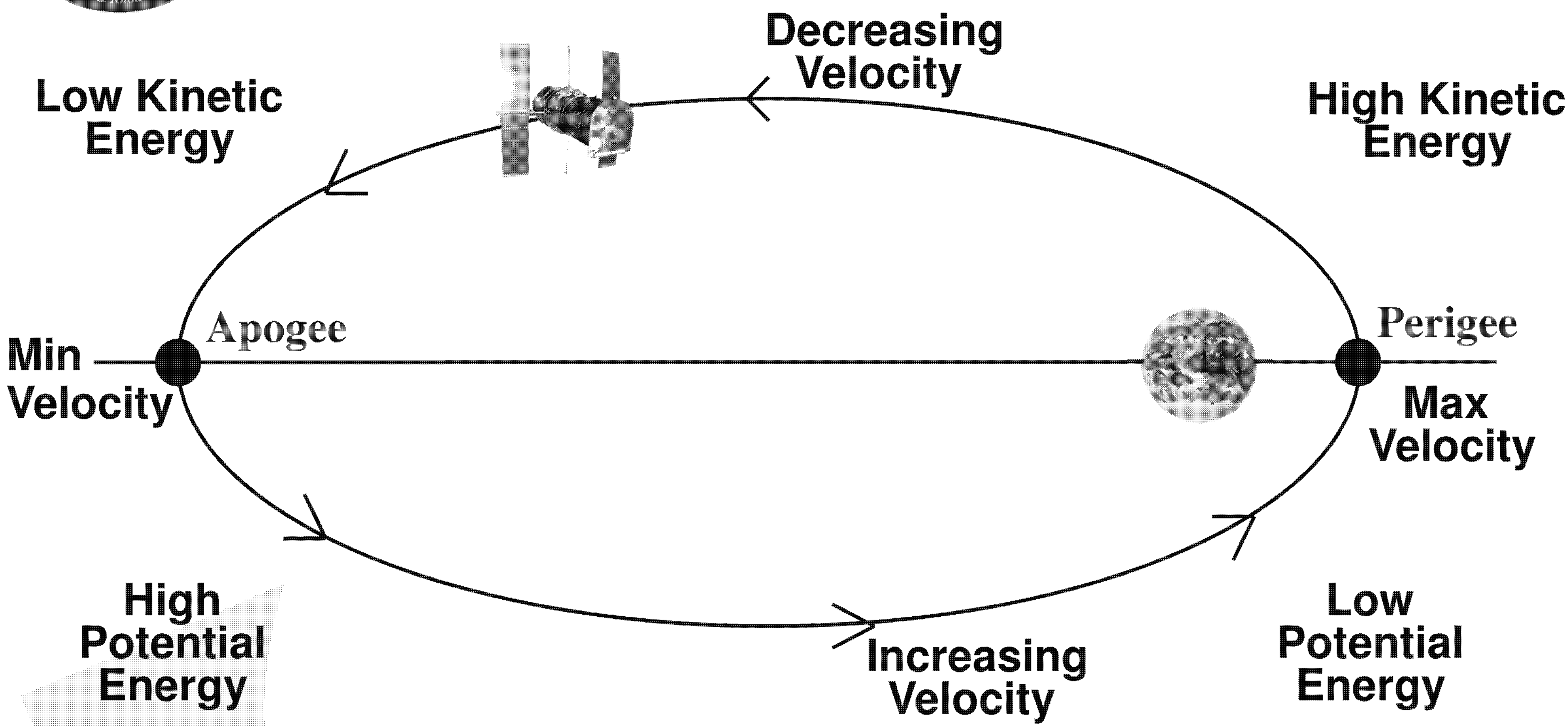


Shuttle Ground Track Example



51.6 Degrees Prograde Inclination

Total Energy in an Orbit



Total Energy = Kinetic Energy + Potential Energy

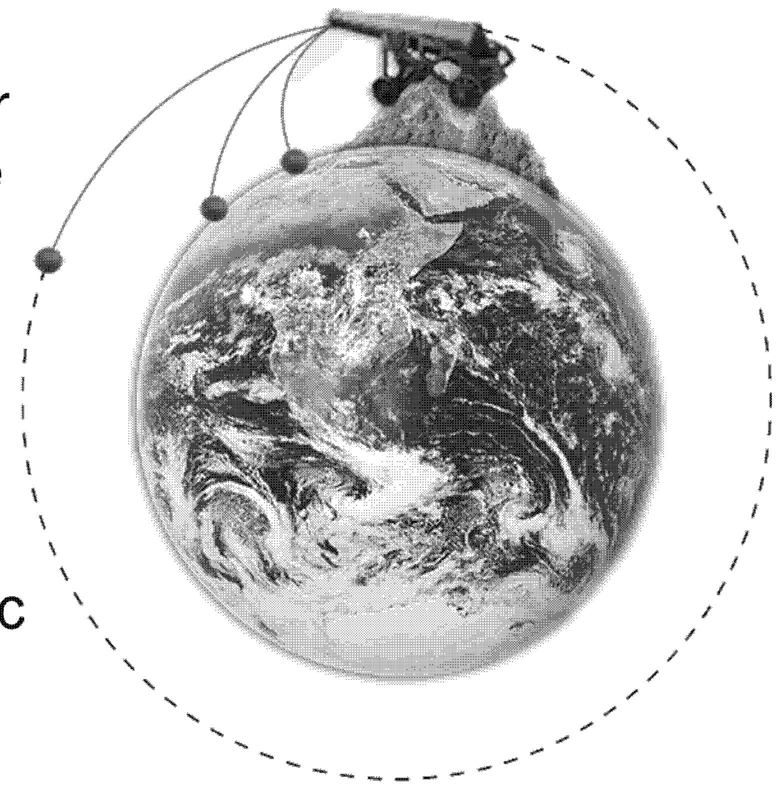
How Satellites Get to Orbit

- A satellite sitting on a booster is only affected by one of the forces (gravity) since it has no velocity
- To achieve orbit a satellite must accelerate to a velocity sufficient to have gravity balanced by motion

$$Gm_1m_2 / r^2 = F = F = m_2a$$

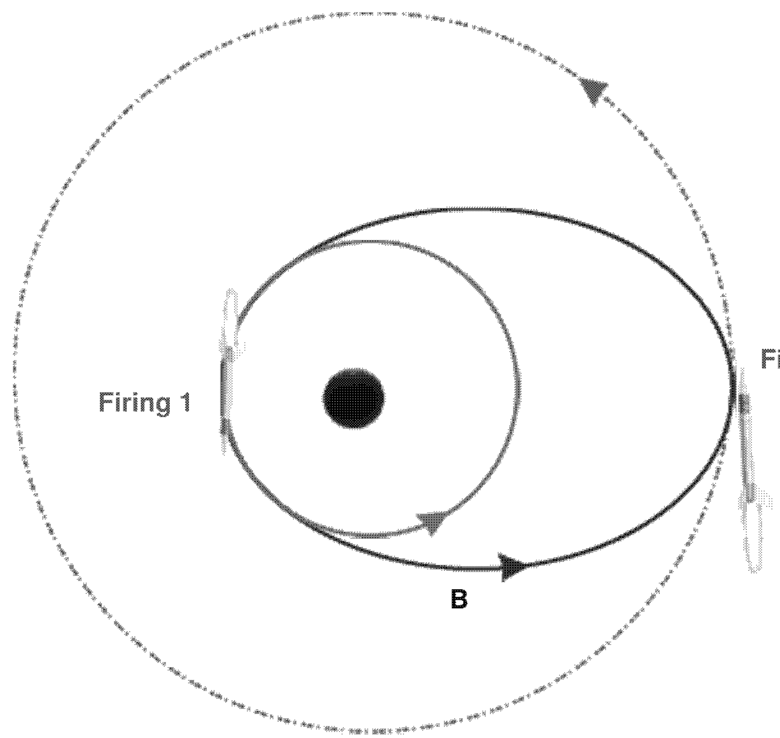
How Satellites Get to Orbit (con't)

- Gravity will cause a projectile to fall 5 meters in one second
- The earth's curvature is 5 meters for each 8000 meters along the surface (assuming a spherical earth)
- To avoid impacting the surface, the projectile must travel at least 8000 meters before is falls 5 meters, i.e., within one second
- Minimum velocity is 8000 meters/sec (17,600 mph) with smooth spherical earth and no atmosphere



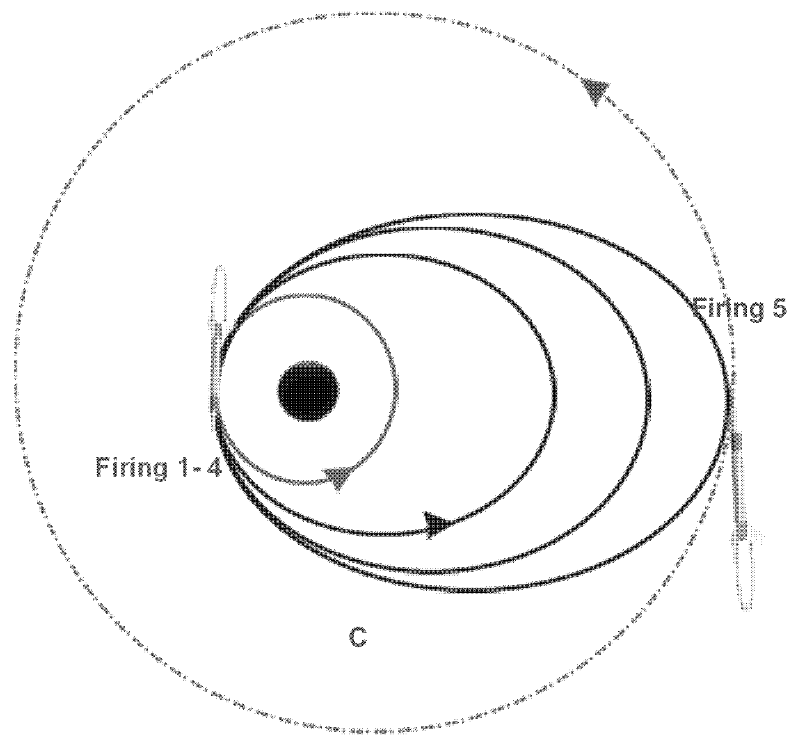
Getting to Orbit

- Launch vehicle accelerates satellite to orbital velocity for minimum-energy sustainable orbit; a low earth orbit (blue)
- To achieve final orbit, satellite fires thrusters to increase velocity (adding energy), which makes it climb and causes orbit to become elliptical (black)
- Thrusters are fired at desired perigee
- Satellite fires thruster again to adding energy and circularizing orbit (dashed)

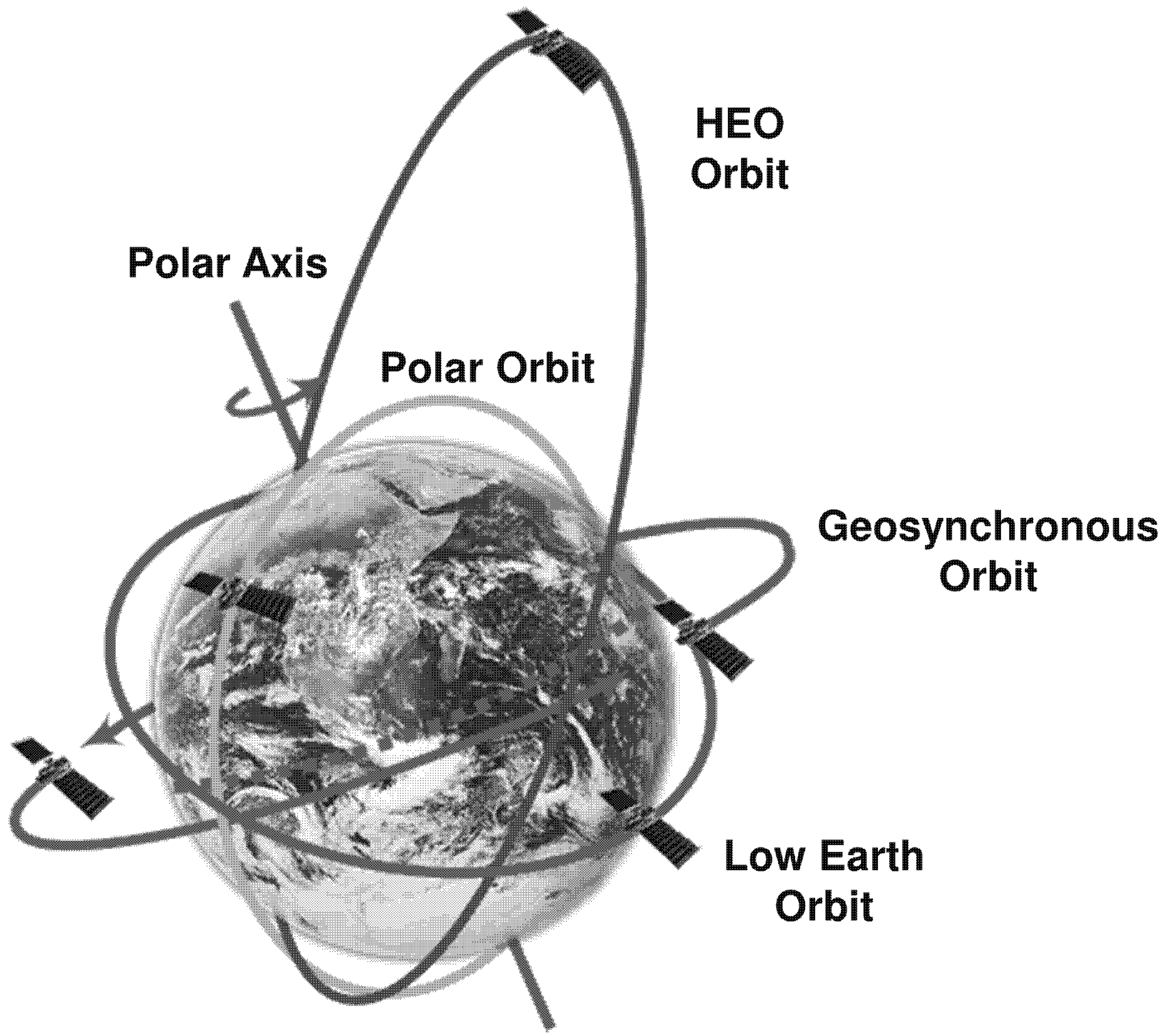


Getting to Orbit (con't)

- Multi-burn transfer:
  - Initial process same as single burn transfer
  - As necessary, satellite fires thruster again, adding more energy and increasing ellipticity
  - As before, thruster fires at desired perigee
  - When desired apogee altitude is reached, thrusters fire to circularize orbit (or reduce ellipticity and raise perigee)

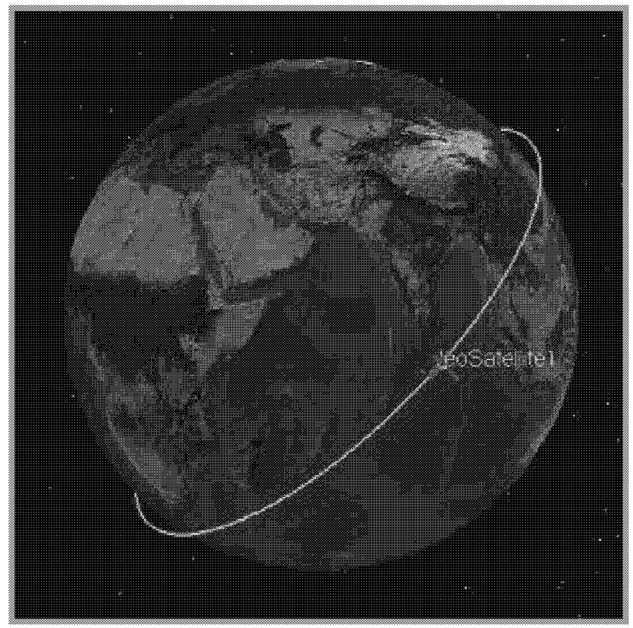


Common Types of Orbits



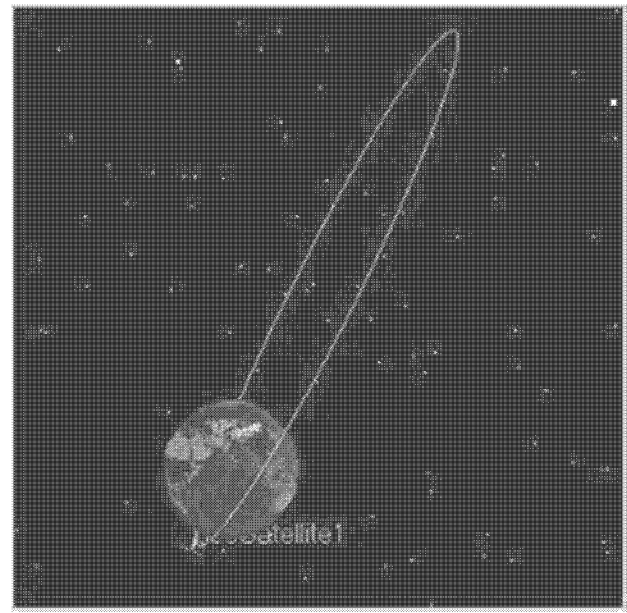
Low Earth Orbit (LEO)

- Satellite deployment
- Surveillance
- Usually circular w/ constant height
- Most periods ~ 90 minutes w/ constant velocity
- Full range of inclinations
- Examples
  - Space Shuttle
  - International Space Station (ISS)

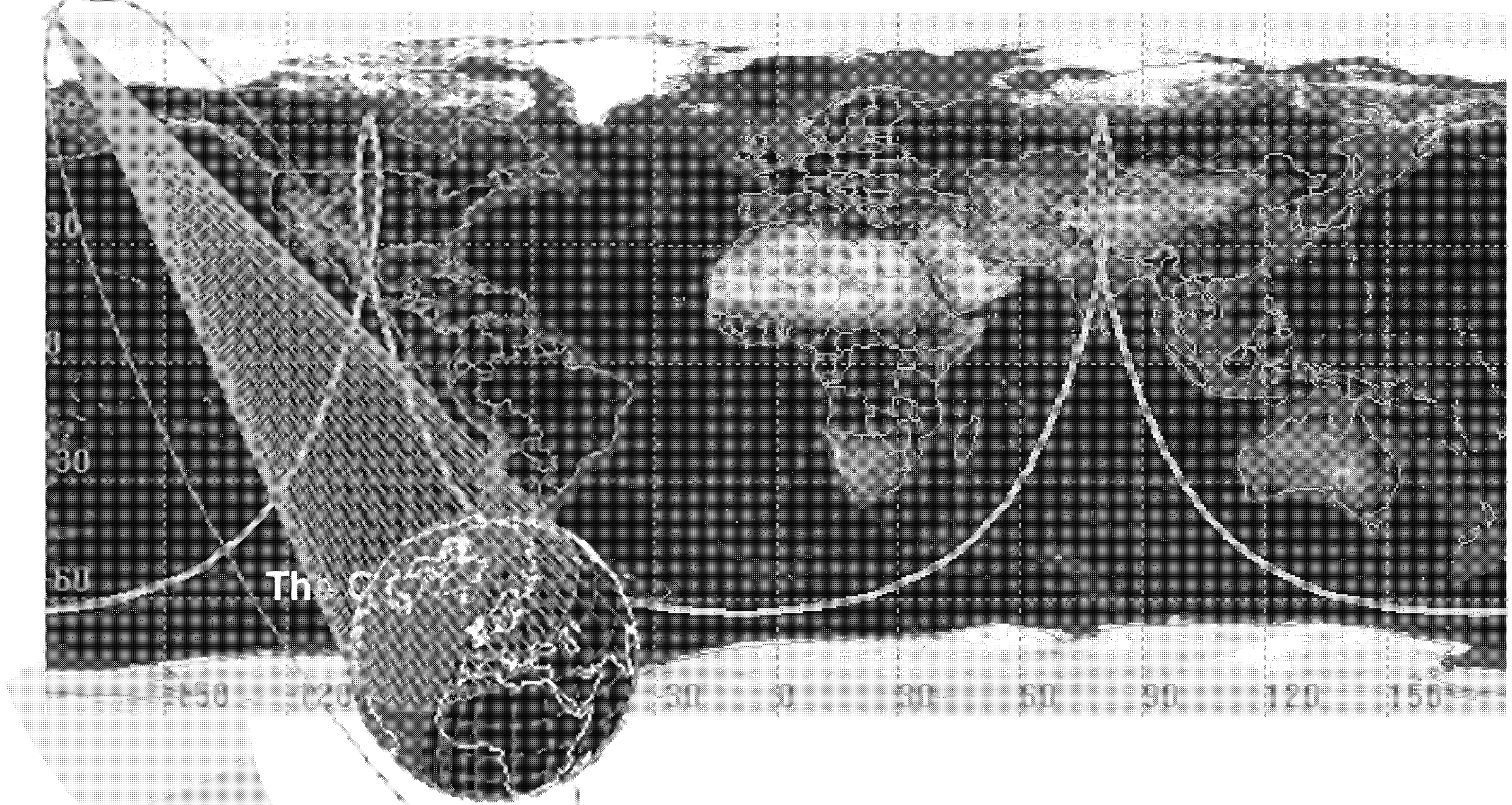


Highly Elliptical Orbit (HEO)

- Navigation (Nav) and Communications (Comms)
- Highly elliptic
- Period is 12 hours (Semi-Synchronous)
- Inclinations between 50 to 70 degrees
- Examples:
  - Molniya



Molniya Orbit (HEO)

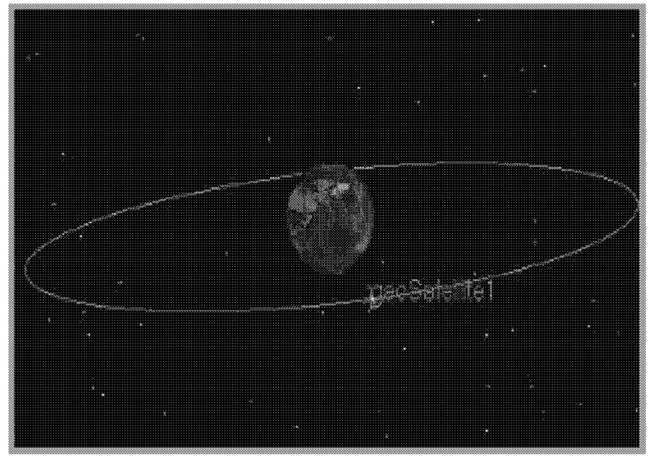


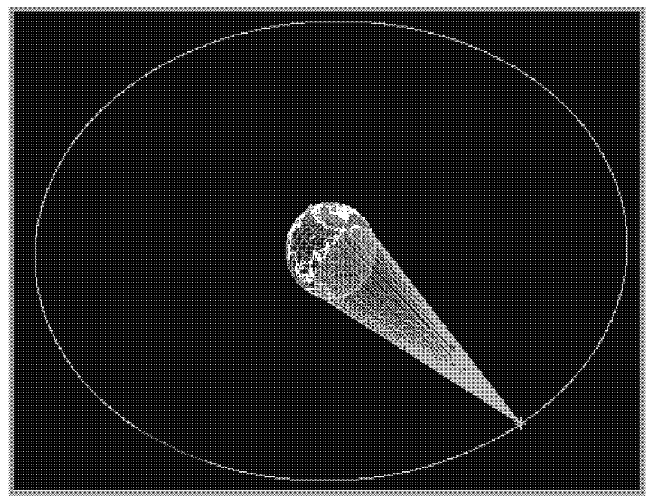
The Instantaneous Field of View (FOV)

Molniya Orbit to Ground Track Video

Geostationary (GEO)

- Comms & Surveillance
- Most circular orbits
- Periods near 24 hrs
  - a = 23,000 miles
  - i = 0 to 15 degrees
- Geostationary
  - Circular, 24 hr period
  - i = 0
- Examples:
  - MILSTAR
  - Satellite TV





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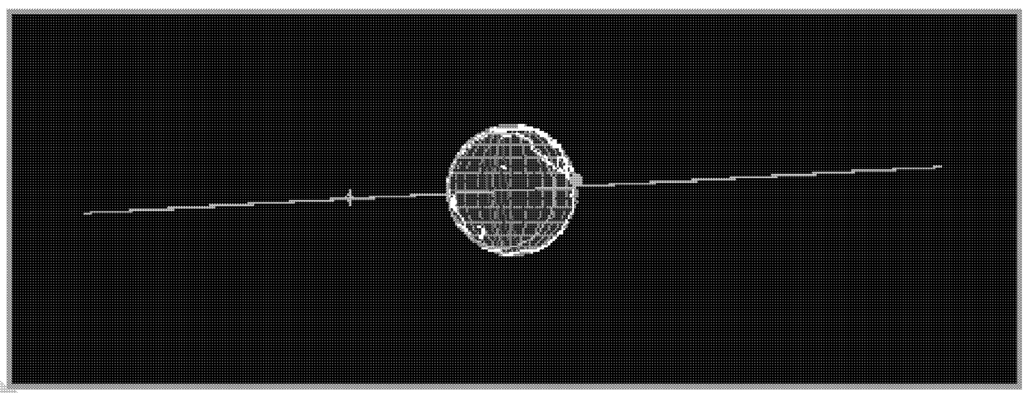
Geostationary vs. Geosynchronous

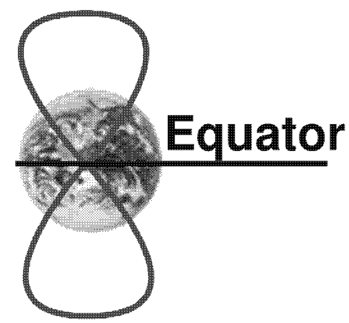
Geostationary	Geosynchronous
e = 0	Period = 24 hrs
i = 0	
Period = 24 hrs	

- The Geostationary orbit has a more stringent criteria than a Geosynchronous orbit

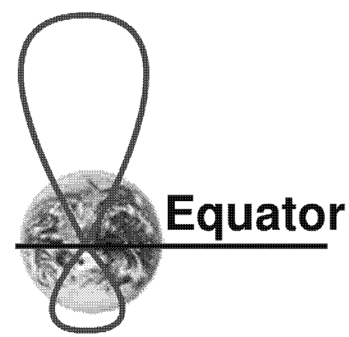


Geosynchronous Orbits

- A geostationary orbit that isn't over the equator
- If the orbit is circular, but inclined, the ground track is a symmetric figure 8

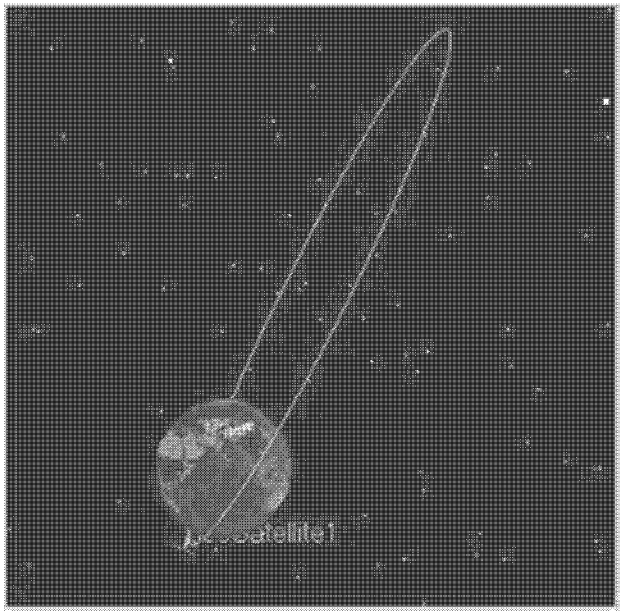


- If the orbit is a 24 hour orbit, but elliptical, the figure 8 is asymmetric



Other Orbits of Interest

- MEO
  - Between ~2000 – 35786km, usually ~20000km
  - Circular
  - GPS, GLONASS, Galileo
- Non-synchronous elliptic orbits
  - Inclinations between 50 to 70 degrees



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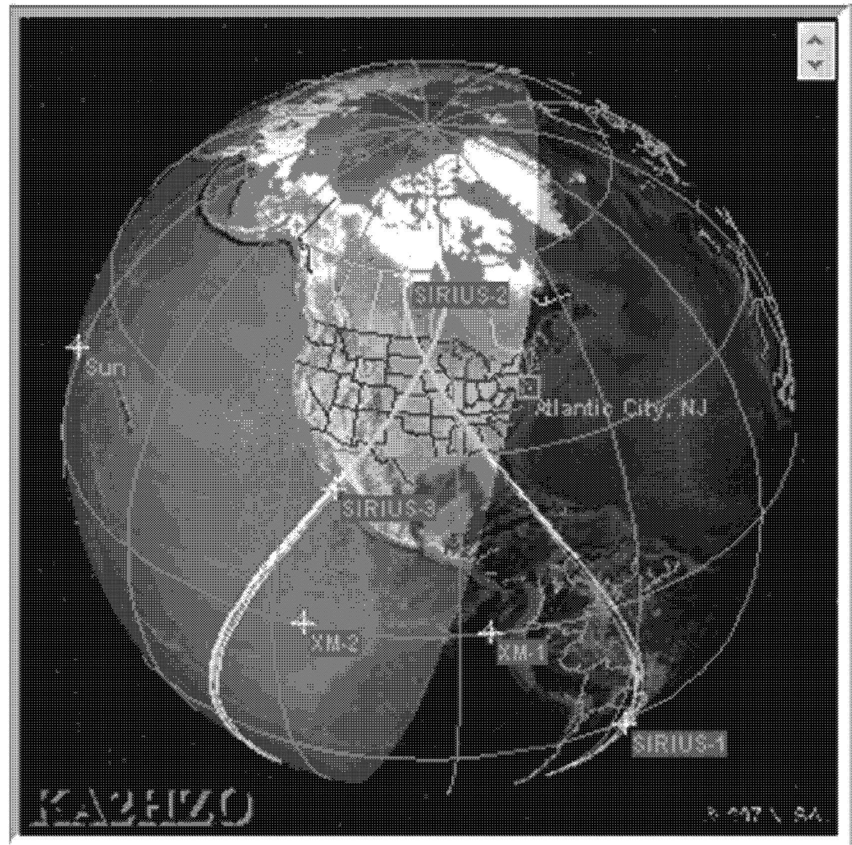
Repeating Ground Track Example

- Sirius Satellite Radio wanted the minimum number of satellites possible to give 24/7 coverage over the US, Canada, and Central/ South America
- Considerations
  - Polar orbits would require dozens of satellites
  - Geos can't see into Canada



Perturbations

- **Perturbations** – External forces affect satellite orbits and vary depending on the altitude and inclination
- Types:
  - **Earth's Oblateness** – Gravitational forces not uniform
  - **3rd Bodies** - Moon, Sun, Planets
  - **Solar Wind** - Increasing effects further out in space
  - **Earth's Electromagnetic Field** – Charged particles affects metal components on the spacecraft
  - **Atmospheric Drag** - Slows satellites down and bleeds off satellite energy

Dominant Perturbations (con't)

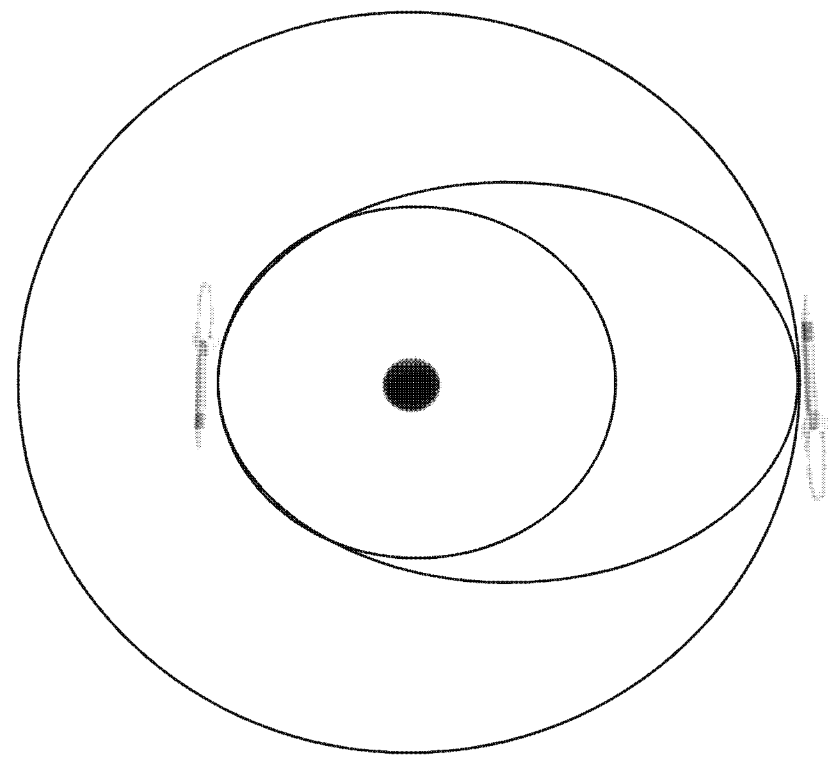
Type of Orbit	Oblateness	3^{rd} Body Effects	Atmosphere
LEO	Large	Small	Moderate
HEO	Moderate	Moderate	Moderate
GEO	Small	Large	None

Making Orbit Adjustments

- Orbit adjustments are made to:
  - Correct for perturbation effects
  - Nodal changes to collect new targets
  - Optimize collection in case of launch / spacecraft failure
- Orbit Adjustments take significant fuel and can reduce operating life
  - Changes are carefully planned
  - Executed to minimize fuel consumption

Making Orbit Adjustments (con't)

- Orbit adjustment to change nodal position
  - Westward move
    - + ΔV to move to higher altitude
    - Higher altitude, less V, longer period
  - At correct node
    - - ΔV to drop back to geosynchronous orbit
  - Eastward move, reverse process



Orbital Selection Summary

- Orbits are selected to balance:

Item	Impact
Resolution / Sensitivity	Altitude (lower is better)
Coverage	Trade between number of satellites and altitude
Access	Trade between number of satellites and altitude
Cost	Number of satellites and capability

Summary

- You should now be able to:
  - Recognize the fundamental laws to get to and stay in orbit
  - Correctly apply basic terminology
  - Describe the different types of orbits