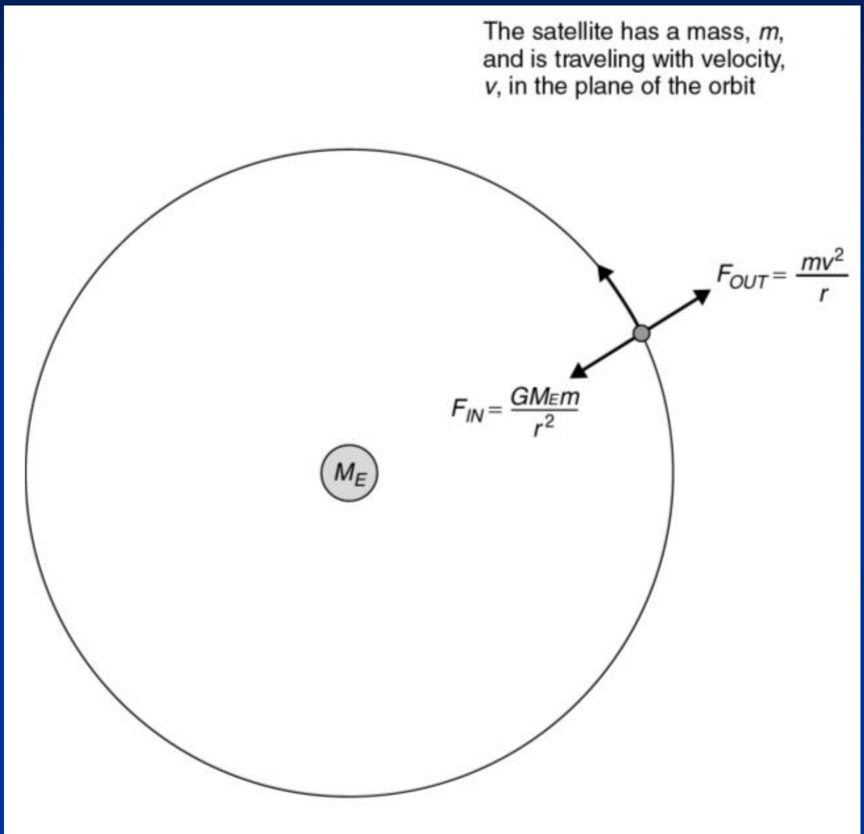
Orbital Mechanics

Part 2

Orbital Forces

Why a Sat. remains in orbit ?

Bcs the centrifugal force caused by the Sat. rotation around earth is counter-balanced by the Earth's Pull.



A body in circular motion will have a constant velocity vcirc determined by the force it must "balance" to stay in orbit

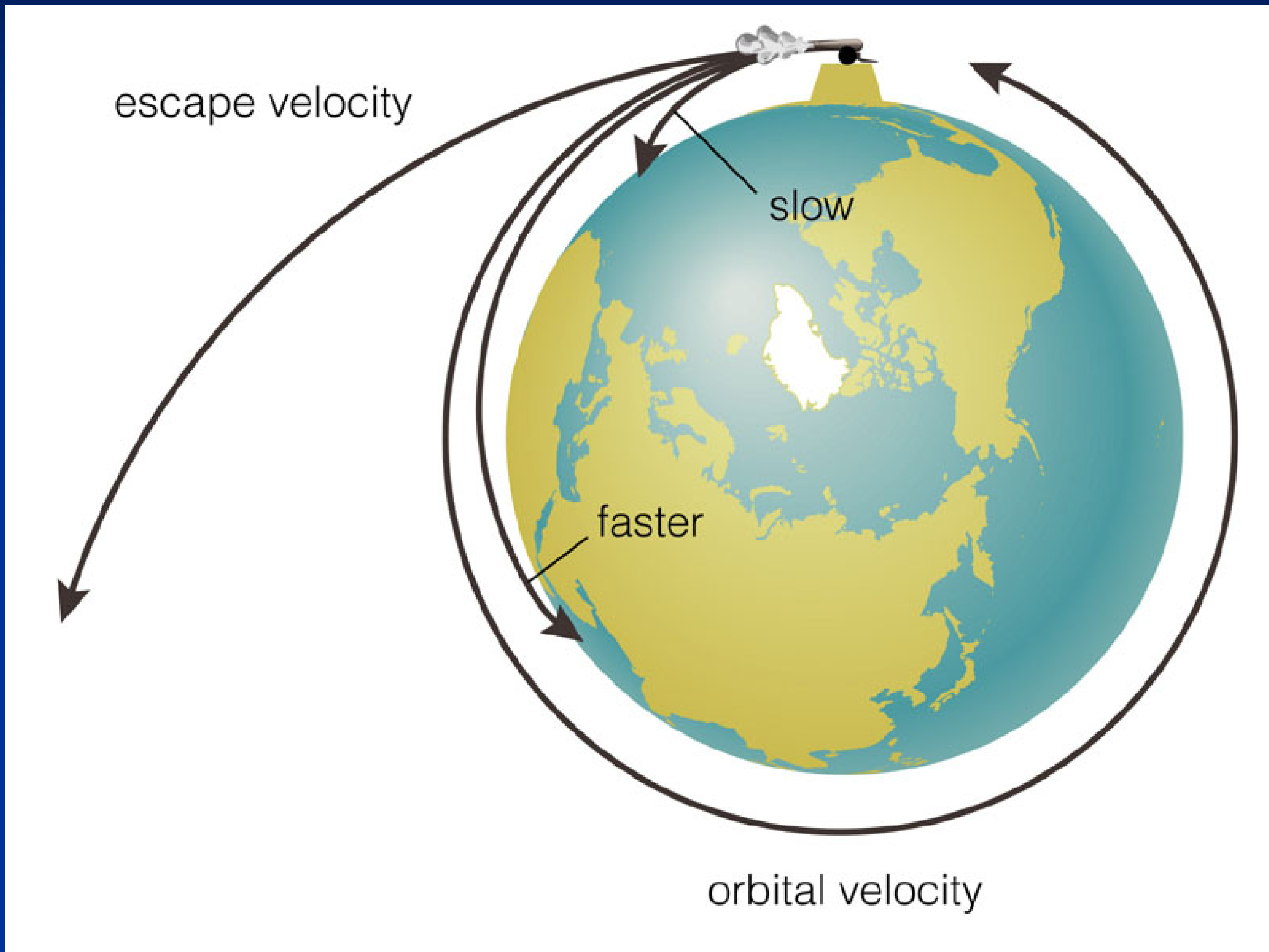
$$v_{circ} = \sqrt{\frac{GM}{r}}$$

Escape velocity

- **Escape velocity is the velocity a mass must have to escape the gravitational pull of the mass to which it is "attracted".**
- **We define a mass as being able to *escape* if it can move to an infinite distance just when its velocity reaches zero. At this point its *net* energy is zero and so we have:**

$$\frac{GMm}{r} = \frac{1}{2} m v_{esc}^{2} \quad \Rightarrow \quad v_{esc} = \sqrt{\frac{2GM}{r}}$$

Escape velocity

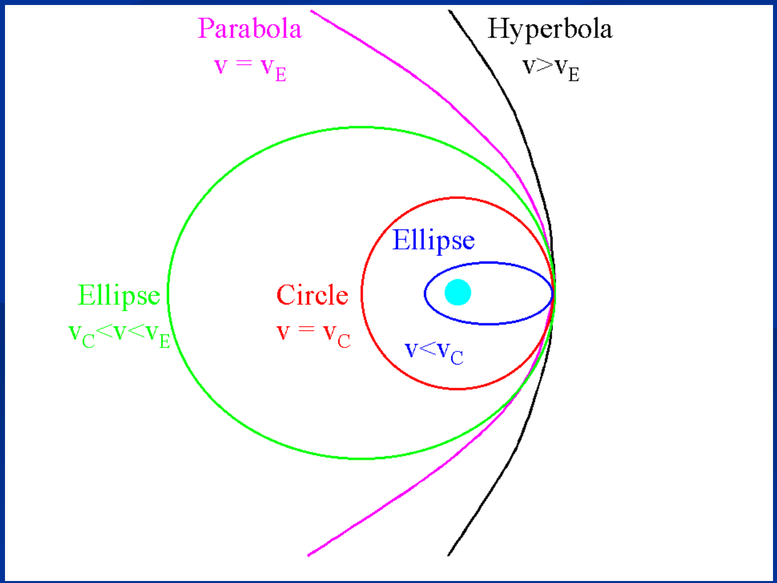


Orbital Energy

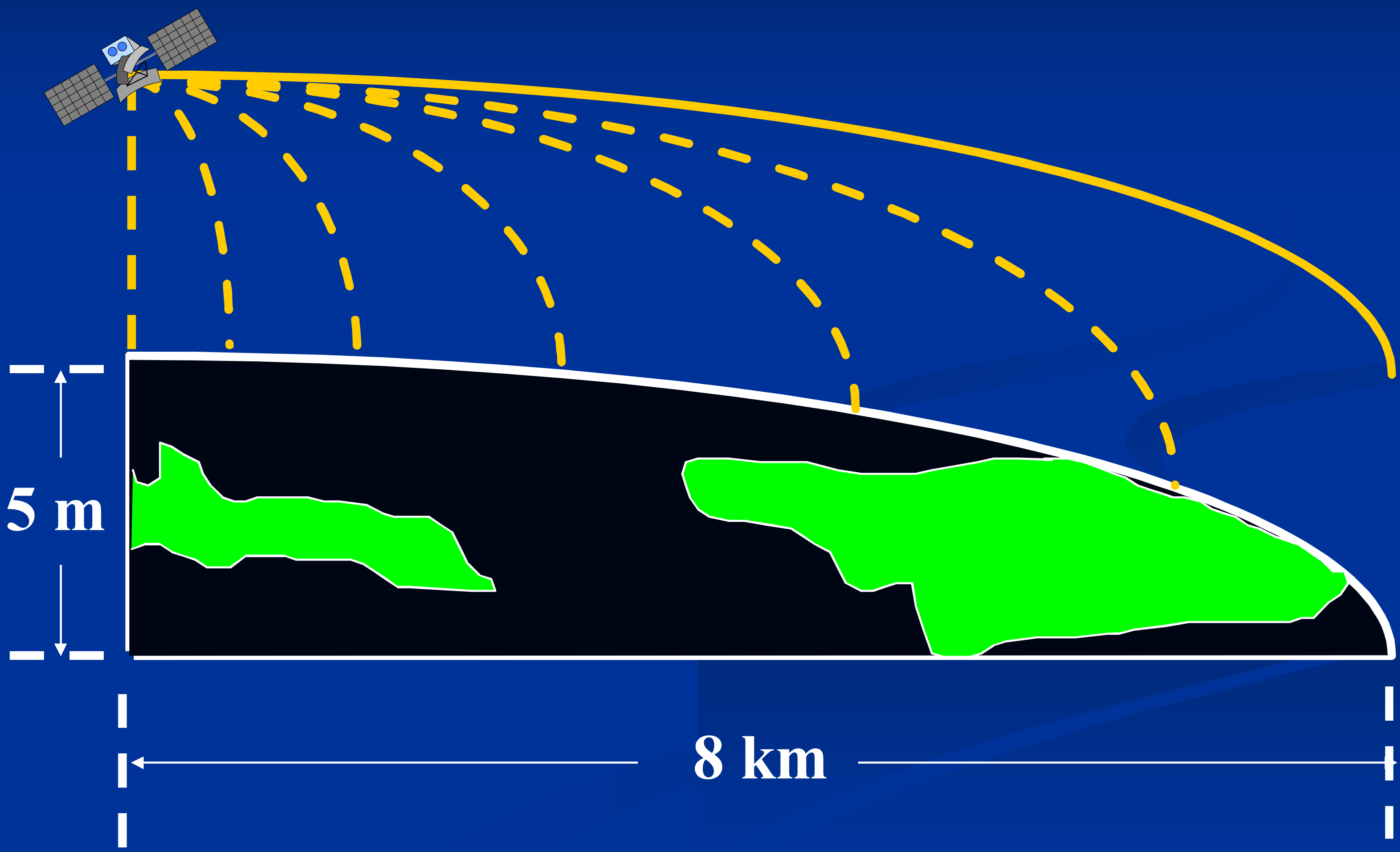
$$E = -\frac{GMm}{2a} = \frac{m}{2}v^2 - \frac{GMm}{r}$$

- **In the solar system, bodies observed:**
  - **planets etc. = elliptical, some nearly circular;**
  - **comets = elliptical, parabolic, hyperbolic;**
  - **some like comets or miscellaneous debris have low energy orbits and we see them plunging into the Sun or other bodies**

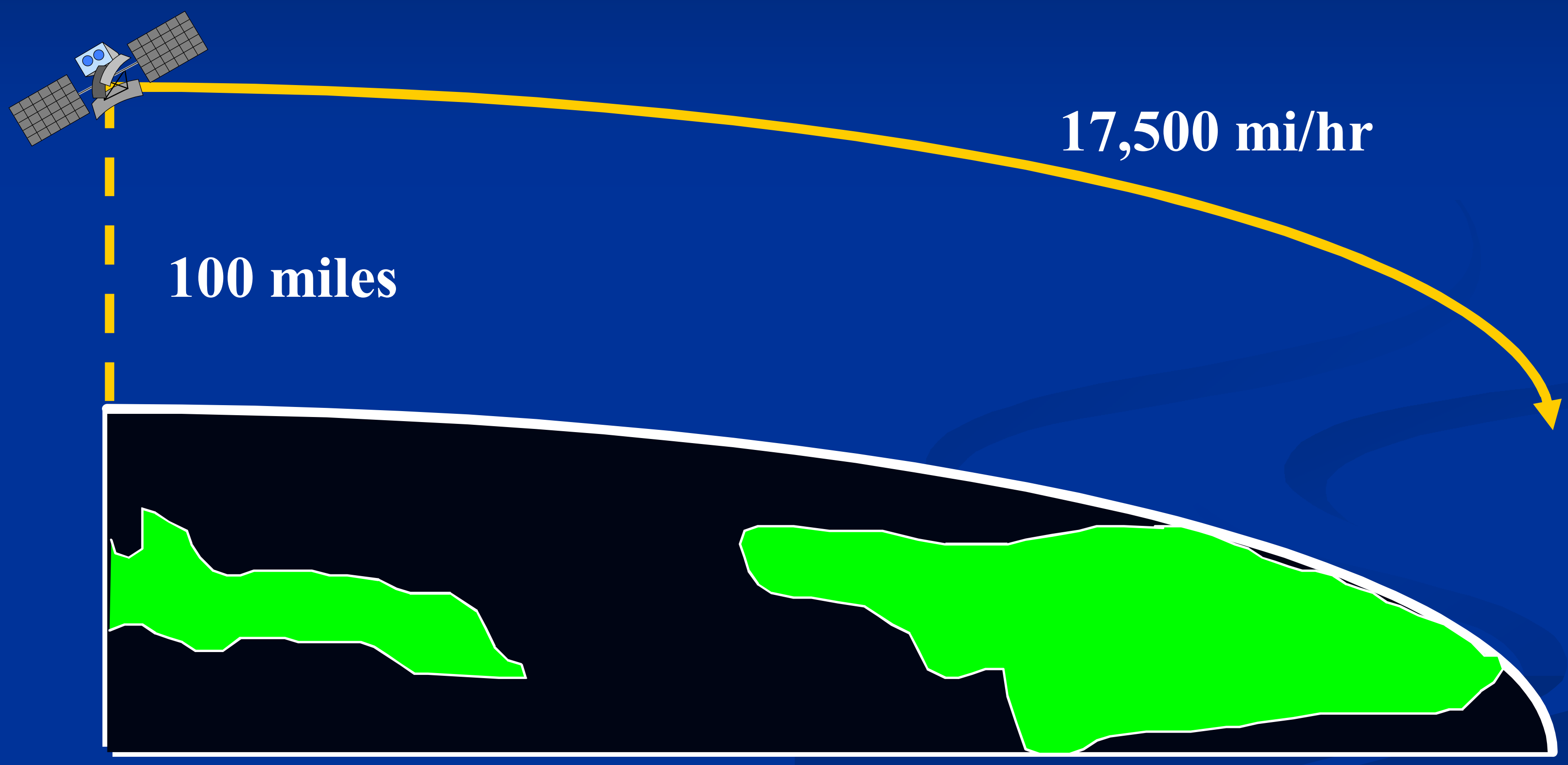
orbit type	v	E_{tot}	e
circular	$v=v_{circ}$	E<0	e=0
elliptical	$v_{circ}<v<v_{esc}$	E<0	0<e<1
parabolic	$v=v_{esc}$	E=0	e=1
hyperbolic	$v>v_{esc}$	E>0	e>1



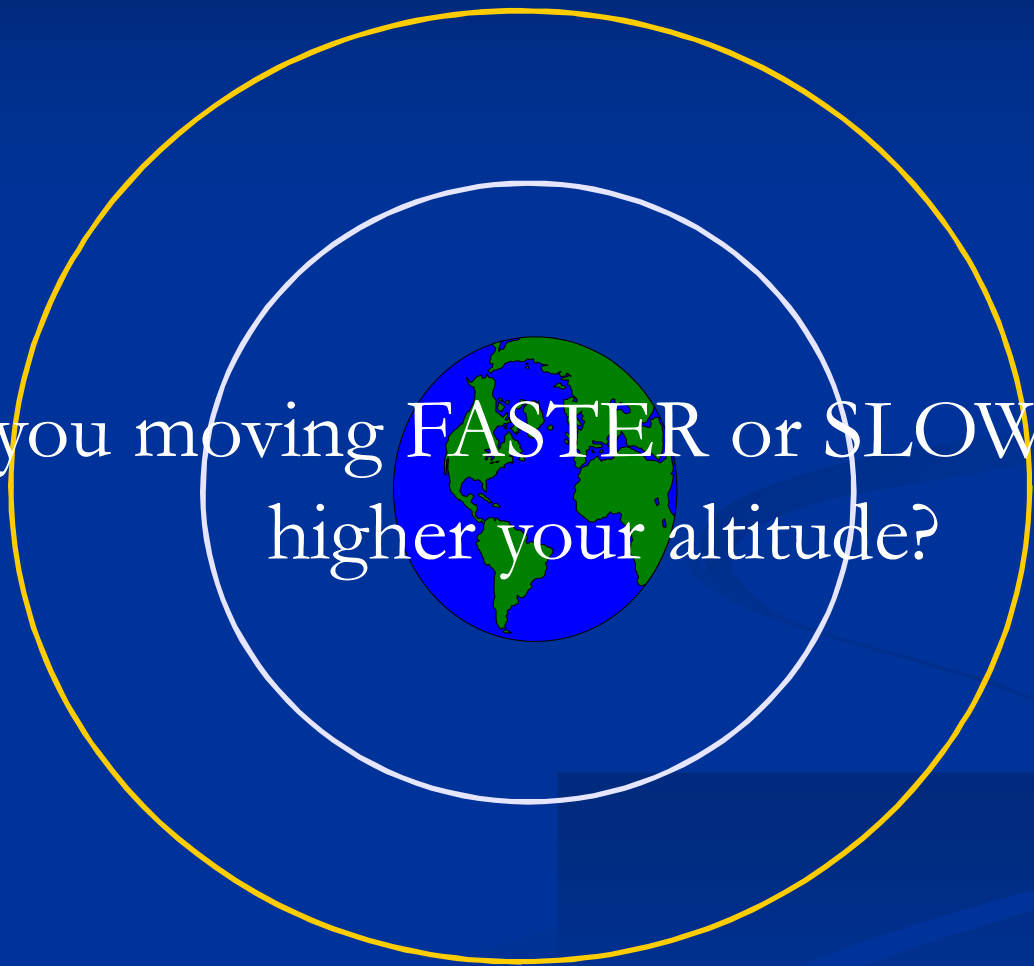
Injection Requirements: Speed



Injection Requirements: Speed



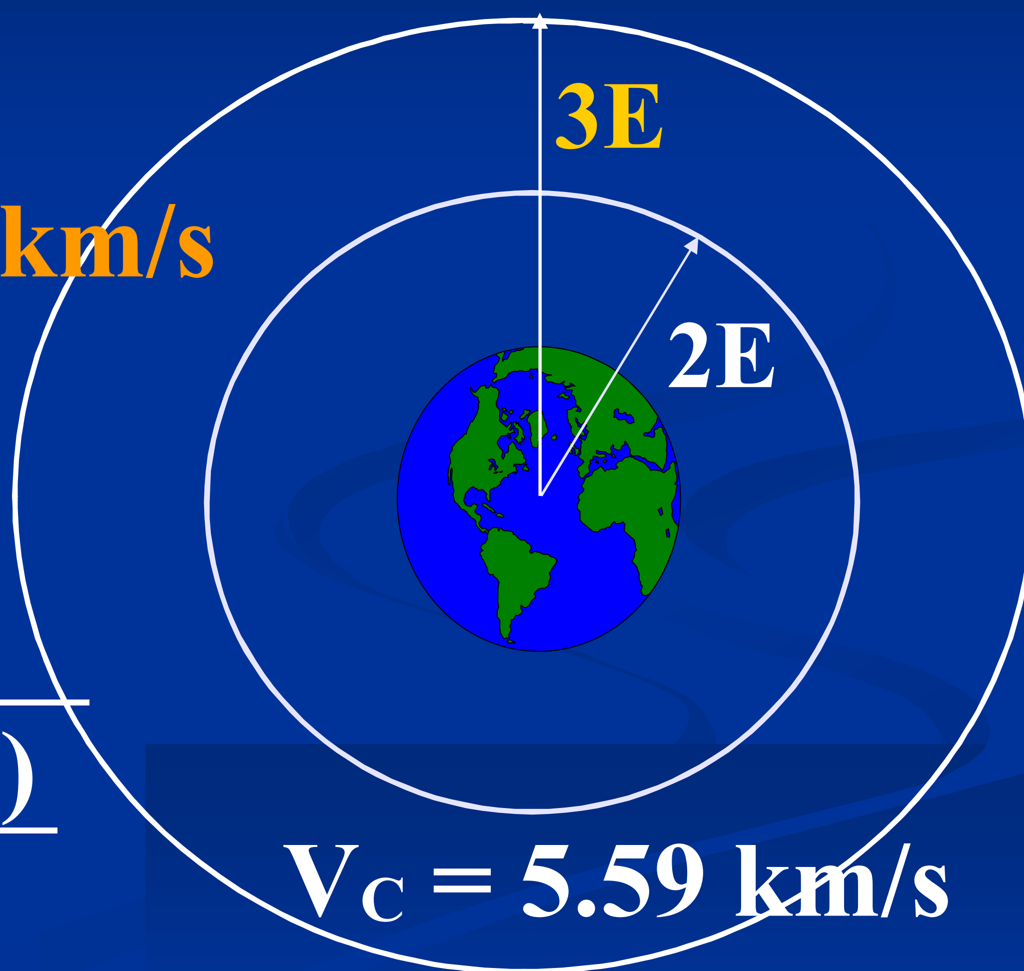
Injection Requirements: Altitude



Are you moving FASTER or SLOWER the higher your altitude?

Injection Requirements: Altitude

V_C = 4.56 km/s



V_C = 5.59 km/s

$$V_C = \sqrt{\frac{G(m_1+m_2)}{a}}$$

Injection Requirements: Altitude

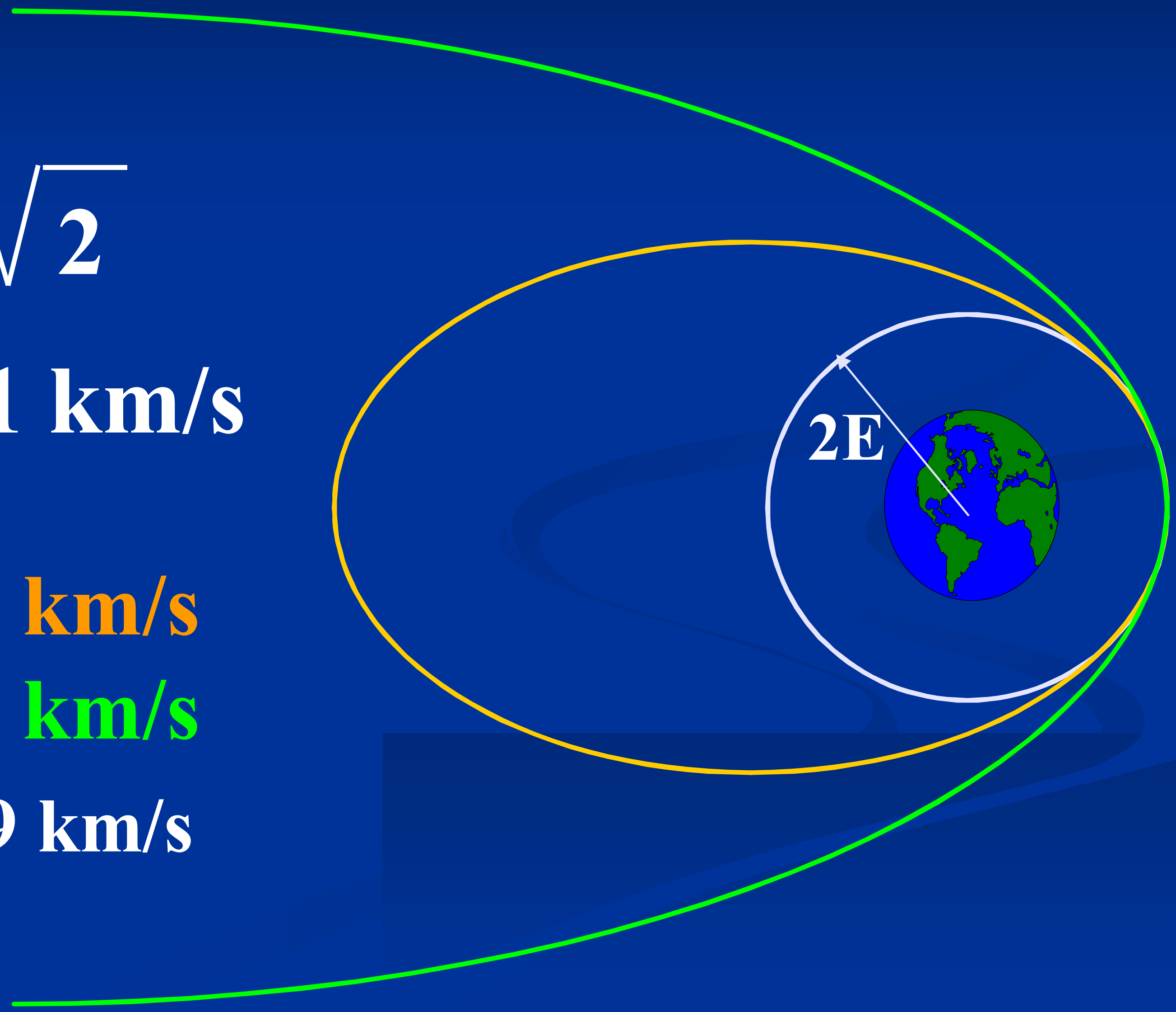
$$V_E = V_C\sqrt{2}$$

$$= 7.91 \text{ km/s}$$

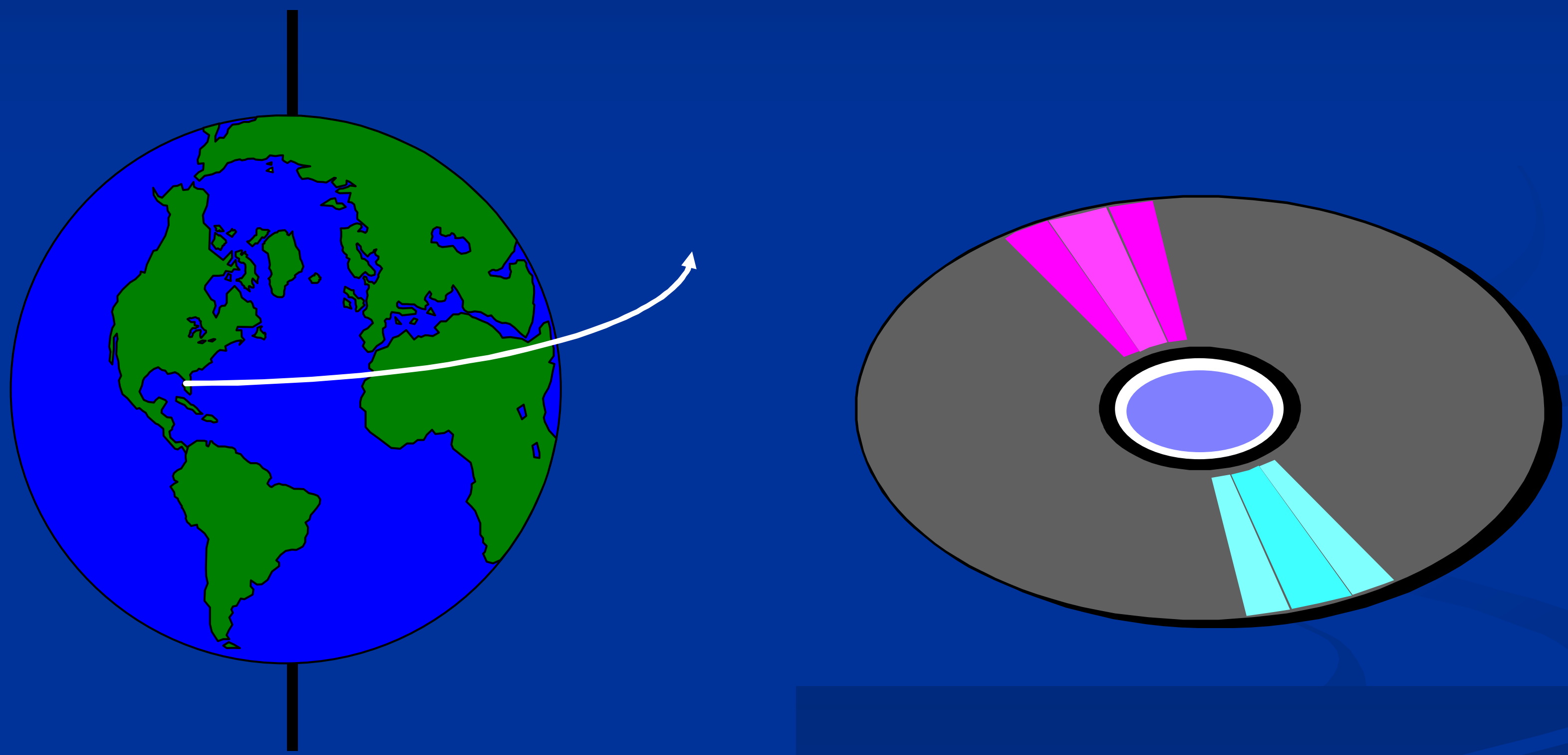
V < 7.91 km/s

V > 7.91 km/s

$V_C = 5.59$ km/s



Injection Requirements: Direction



Vis-Viva Equation

- Knowing the relation between orbital energy, distance, and velocity we can find a general formula → the *Vis Viva* equation

$$-\frac{GMm}{2a} = \frac{m}{2}v^2 - \frac{GMm}{r} \quad \Rightarrow \quad v^2(r) = 2GM\left(\frac{1}{r} - \frac{1}{2a}\right)$$

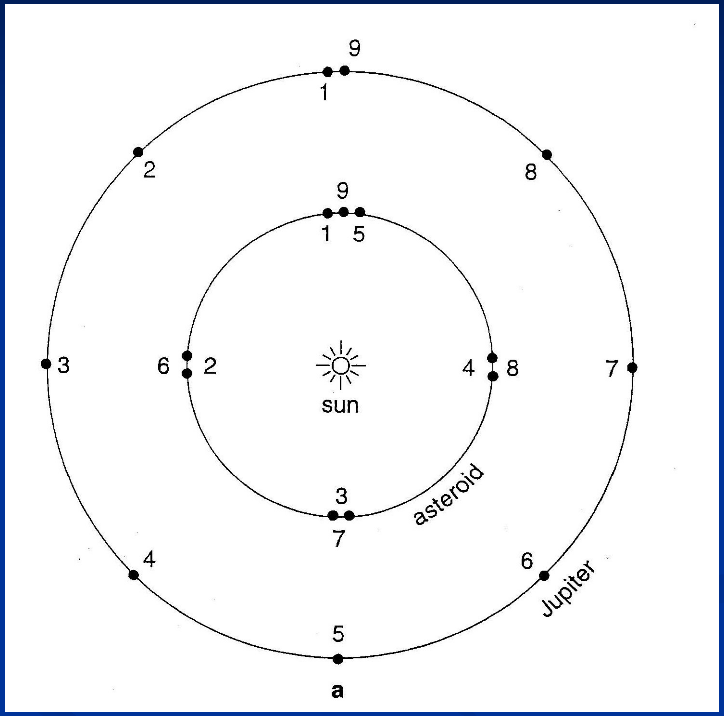
- Does not depend on orbital eccentricity.
- If a new object is observed in space, knowing its current velocity and distance, we can determine its orbital semimajor axis, and, thus have some idea where it came from.

Vis-viva equation

- A meteor is observed to be traveling at a velocity of 42 km/s as it hits the Earth's atmosphere. Where did it come from?

Resonances

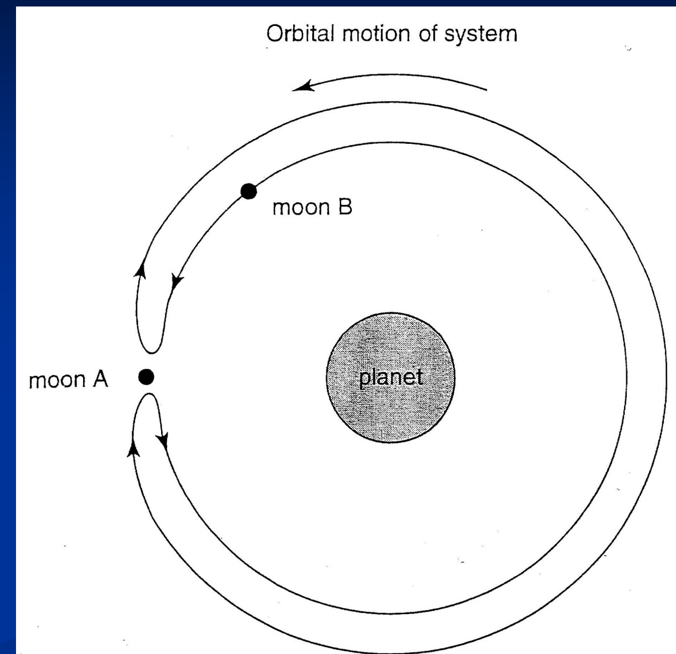
- If the orbit of a small body around a larger one is a small-integer fraction of the larger body's period, the two bodies are *commensurable*.
- Some resonances (3:2 resonance of Jupiter) actually have a stabilising effect.



Example: An asteroid in a 1:2 resonance with Jupiter completes two revolutions, while Jupiter completes one

Horseshoe orbits

- Two small moons of Saturn, Janus and Epimetheus, only separated by about 50 km.
- As inner (faster moving) moon catches up with slower moon, it is given a gravitational kick into a higher orbit.
- It then moves more slowly and lags behind the other moon.



Coordinate Systems

- Defines positions and directions in a consistent manner -- allows communication
- Facilitates the description of a satellite's position and subsequent motion
- Proper choice of reference determines the utility of a coordinate system

Coordinate Systems

Classifications

- Inertial
  - Non-rotating
  - Time Independent
- Non-inertial
  - Rotating
  - Time Dependent

Coordinate Systems

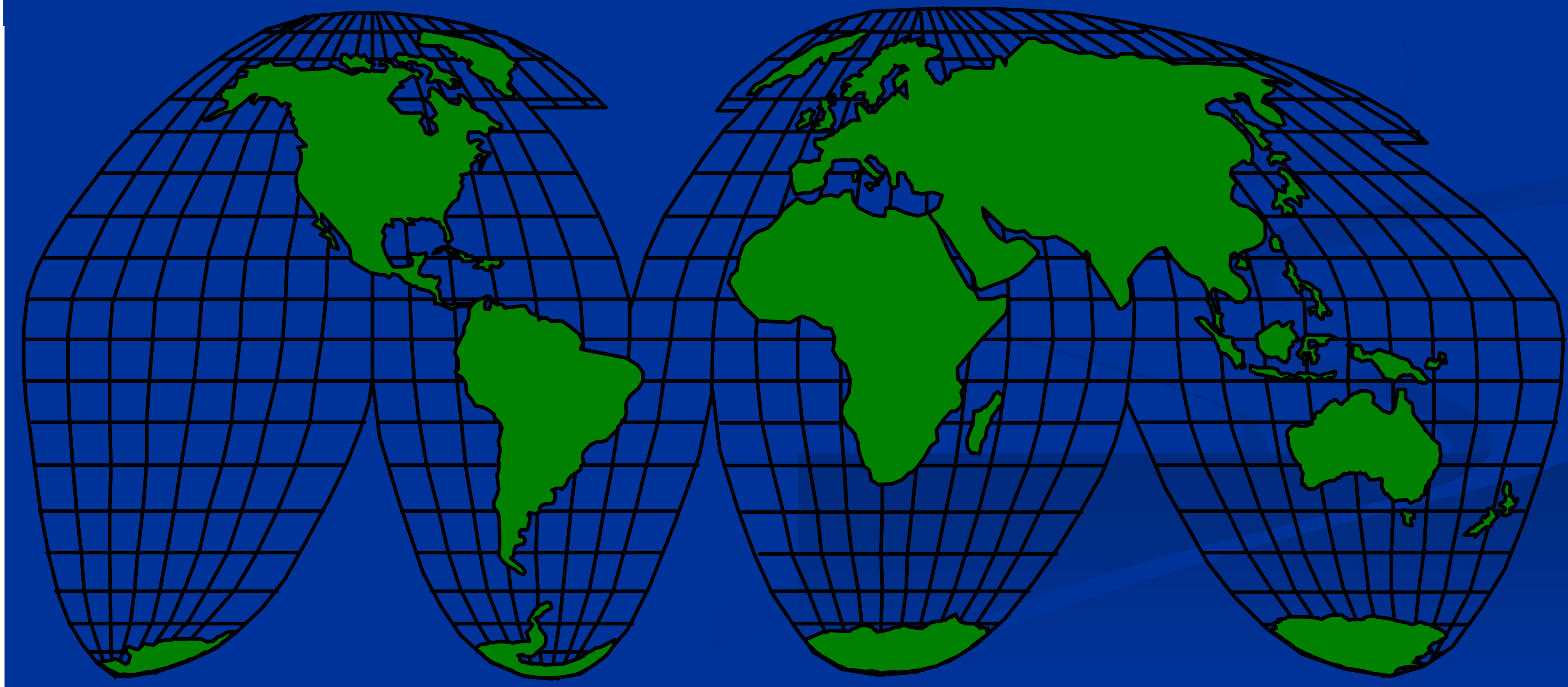
Examples

- Geographic
- Geocentric Inertial
- Topocentric
- Orbit Inertial

Coordinate Systems

Geographic

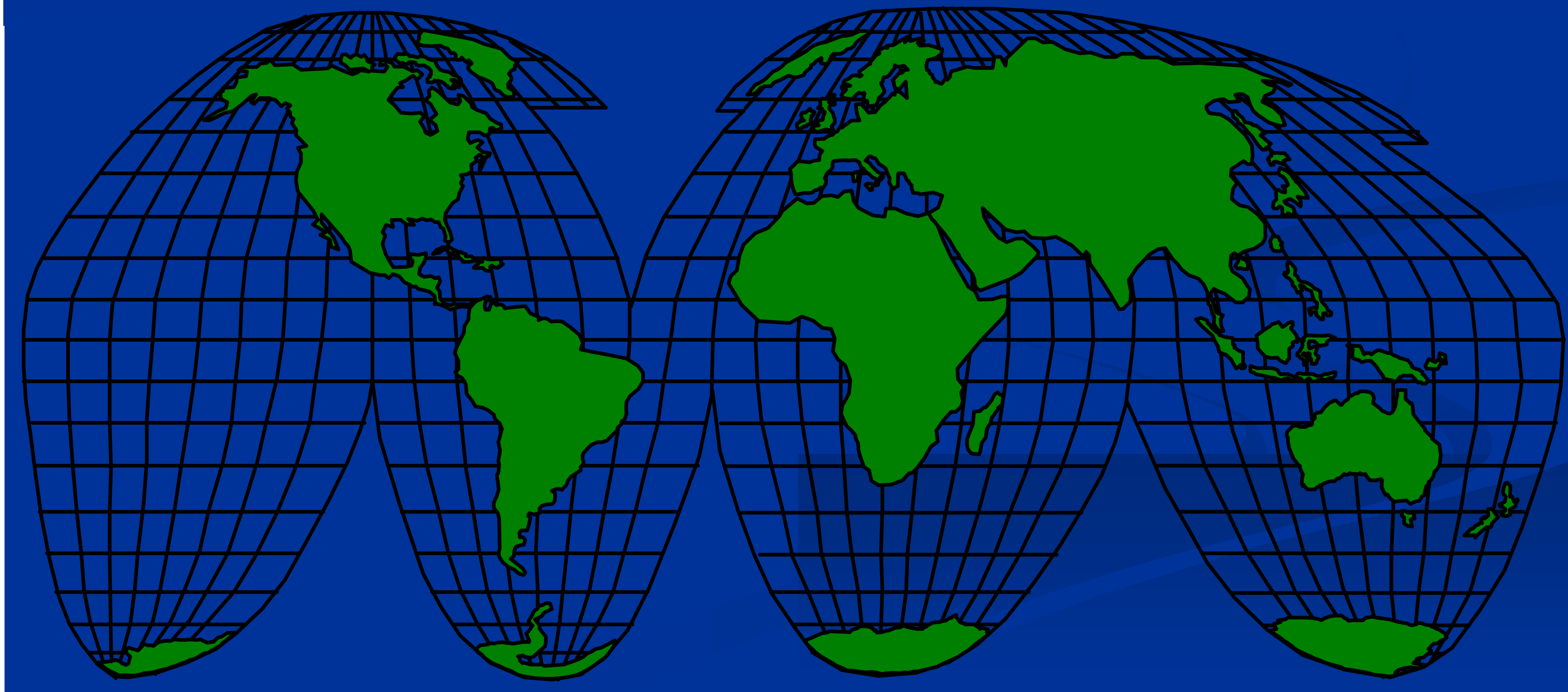
- Purpose: To locate points on the Earth's surface



Coordinate Systems

Geographic

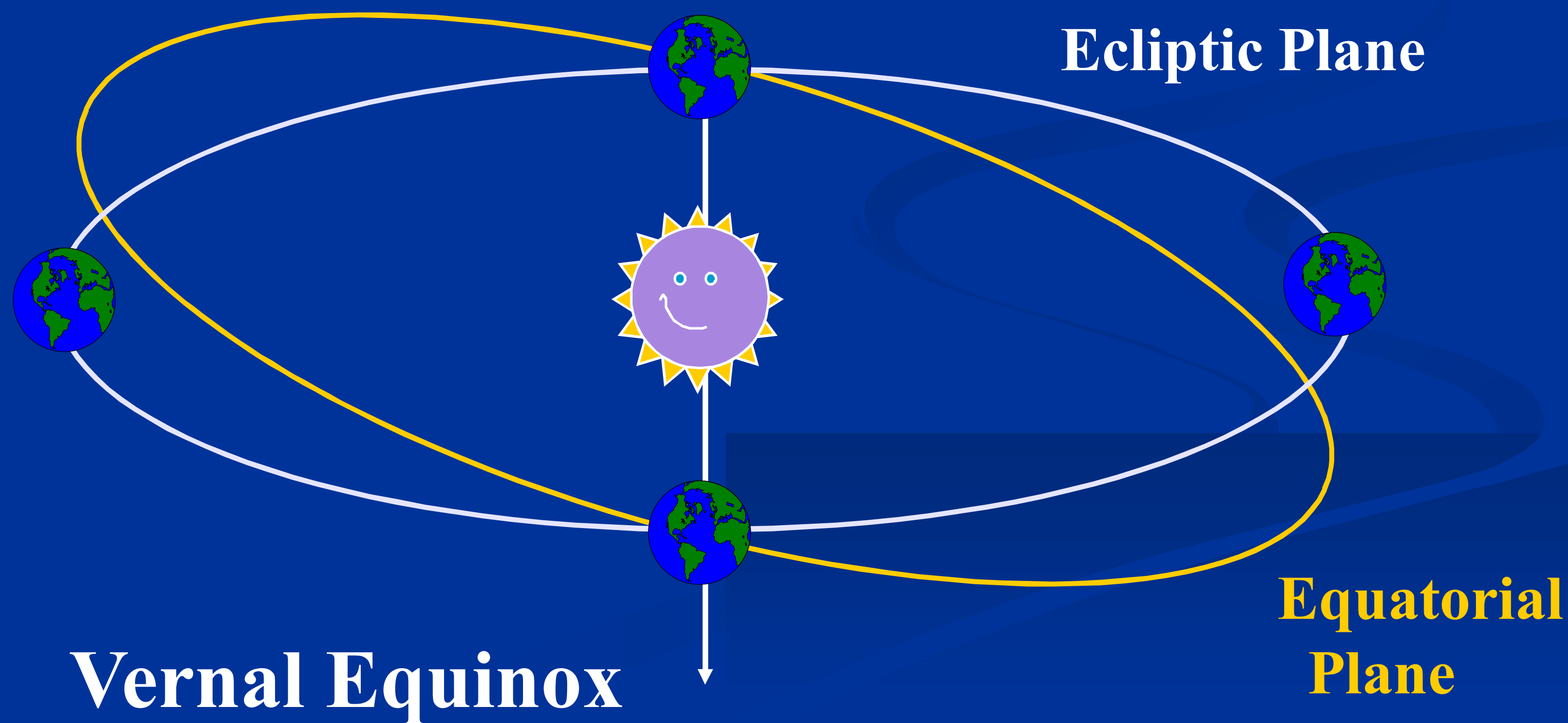
- Purpose: To locate points on the Earth's surface



Coordinate Systems

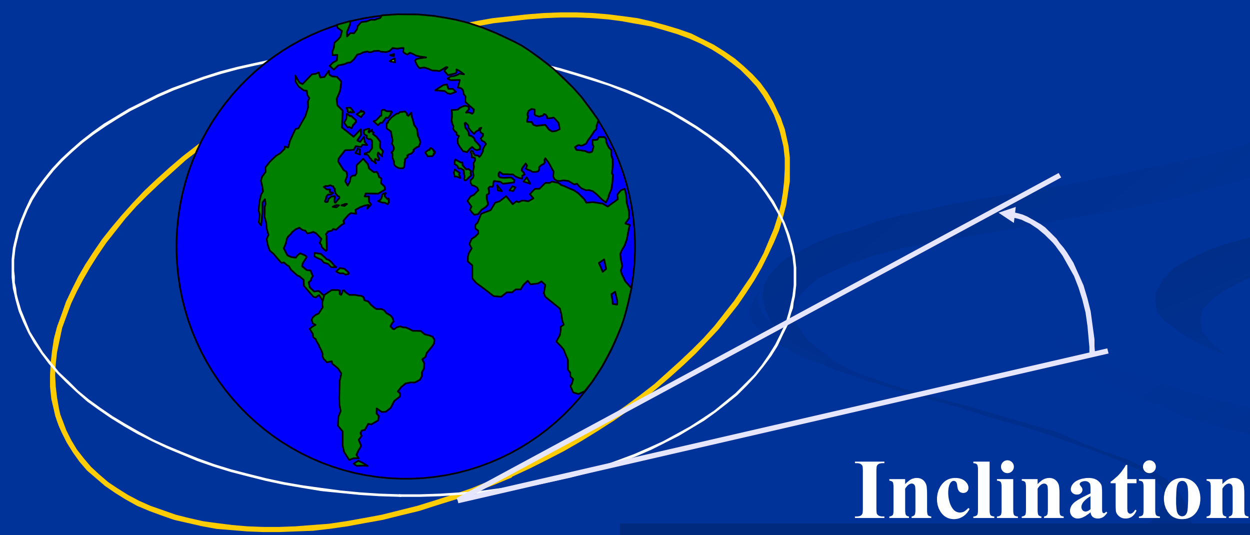
Geocentric Inertial

- Purpose: To determine the exact orientation of an orbital plane and to locate points in space with respect to the Earth



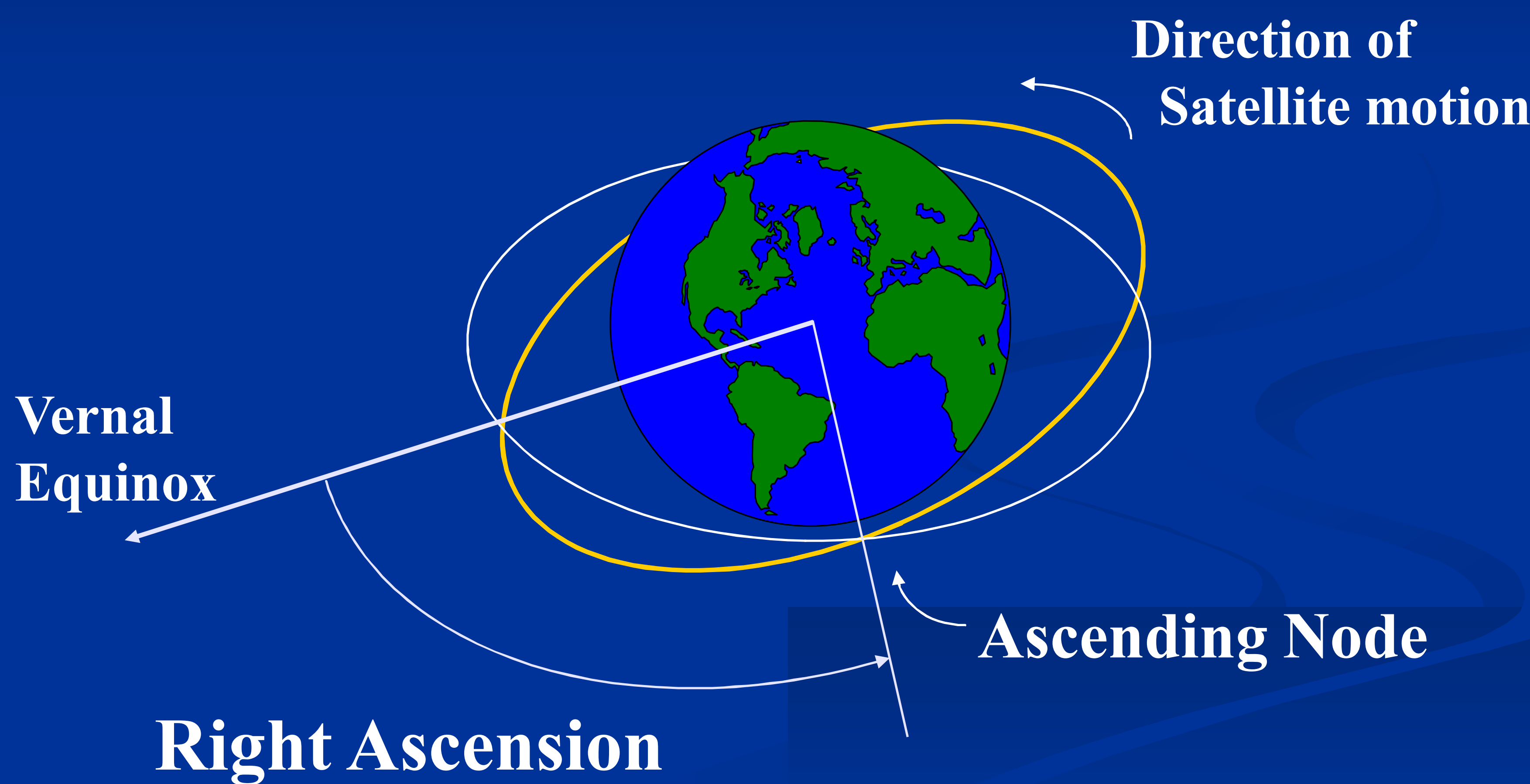
Coordinate Systems

Geocentric Inertial



Coordinate Systems

Geocentric Inertial



The Orbital Plane

- In the orbital plane, the position vector **r** and velocity vector **v** specify the motion of the satellite.

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

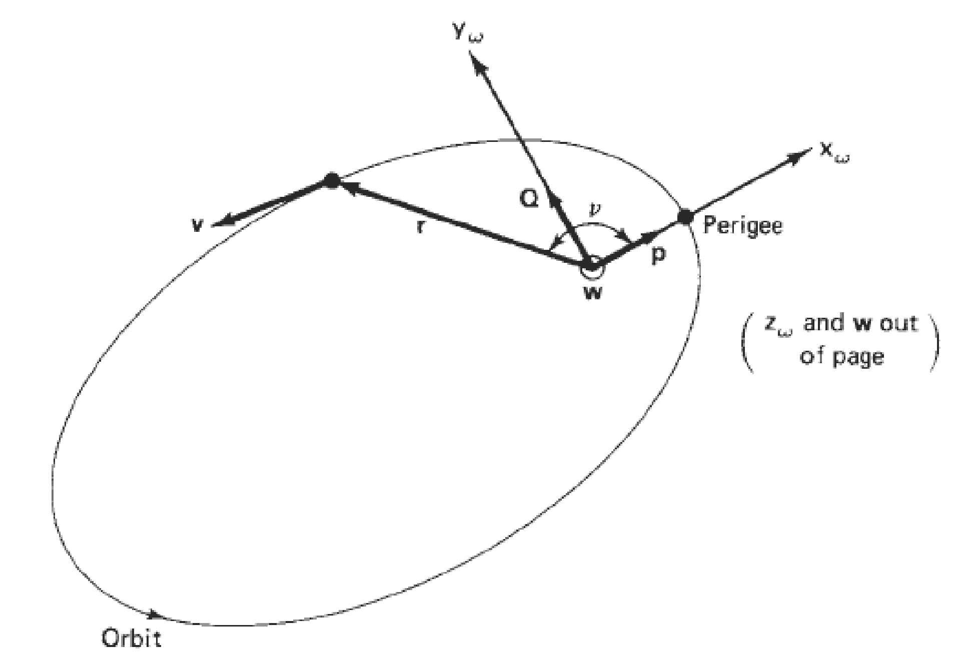


Figure 2.8 Perifocal coordinate system (PQW frame).

- Knowing the mean anaomaly, the eccentric anamaly E :

$$M = \left(E - e\sin E\right) \Rightarrow M - \left(E - e\sin E\right) = 0$$ (Iterative Sol.)

- Knowing E:

$$\tan\left(\frac{v}{2}\right) = \sqrt{\frac{1+e}{1-e}}\tan\left(\frac{E}{2}\right) \Rightarrow r = a(1-2\cos E)$$

- For near Circular Orbits (e→0):

$$v \cong M + 2e\sin M + \frac{5}{4}e^2\sin 2M$$

Example

Example 2.13 Given that the mean anomaly is 205 degrees and the eccentricity 0.0025, calculate the eccentric anomaly.

solution

$M := 205 \cdot deg \qquad e := 0.0025$

$E := \pi$ ...This is the initial guess value for E.

$E := root\,(M - E + e \cdot \sin(E), E)$ ...This is the root equation which Mathcad solves for E.

$E = 204.938 \cdot deg$

Example

Example 2.14 For satellite no. 14452 the eccentricity is given in the NASA prediction bulletin as 9.5981×10^{-3} and the mean anomaly at epoch as 204.9779°. The mean motion is 14.2171404 rev/day. Calculate the true anomaly and the magnitude of the radius vector 5 s after epoch. The semi-major axis is known to be 7194.9 km.

solution

$$n = \frac{14.2171404 \times 2\pi}{86400} \cong 0.001 \text{ rad/s}$$

$$M = 204.9779 + 0.001 \times \frac{180}{\pi} \times 5$$

$$= 205.27° \quad \text{or} \quad 3.583 \text{ rad}$$

Example

Since the orbit is near-circular (small eccentricity), Eq. (2.26) may be used to calculate the true anomaly ν as

$$\nu \cong 3.583 + 2 \times 9.5981 \times 10^{-3} \times \sin 205.27 + {}^{5}/_{4} \times 9.5981^{2} \times 10^{-6} \sin(2 \times 205.27)$$

$$= 3.575 \text{ rad}$$

$$= 204.81^{\circ}$$

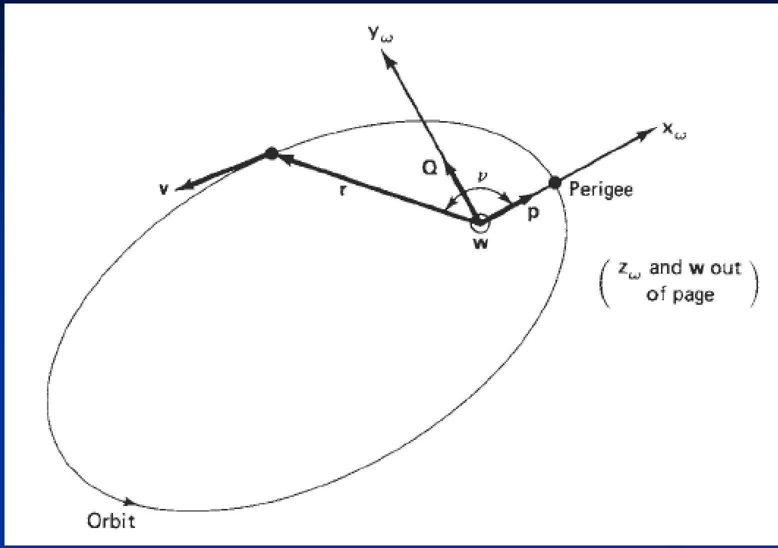
$$r = \frac{a(1-e^{2})}{1+2\cos\nu}$$

$$r = \frac{7194.9 \times (1 - 9.5981^{2} \times 10^{-6})}{1 + (9.5981 \times 10^{-3}) \times \cos 204.81} \cong \underline{\underline{7257 \text{ km}}}$$

The Perifocal (PQW) System

- The position vector in the Perifocal coordinate system (PQW):

$$\mathbf{r} = (r\cos v)\mathbf{P} + (r\sin v)\mathbf{Q}$$



Example 2.15 Using the values $r = 7257$ km and $\nu = 204.81°$ obtained in the previous example, express r in vector form in the perifocal coordinate system.

solution

$$r_P = 7257 \times \cos 204.81 = -6587.6 \text{ km}$$

$$r_Q = 7257 \times \sin 204.81 = -3045.3 \text{ km}$$

Hence

$$\boldsymbol{r} = -6587.6\mathbf{P} - 3045.3\mathbf{Q} \text{ km}$$

The Geocentric-equatorial (IJK) Frame

- PQW is conveniet for motion descrption
- Equatorial Bulge causes rotationsof PQW system
- Geocentric is suitable: refernced to fixed stars

- The transformation in vector notation btewwn PQW and IJK frames:

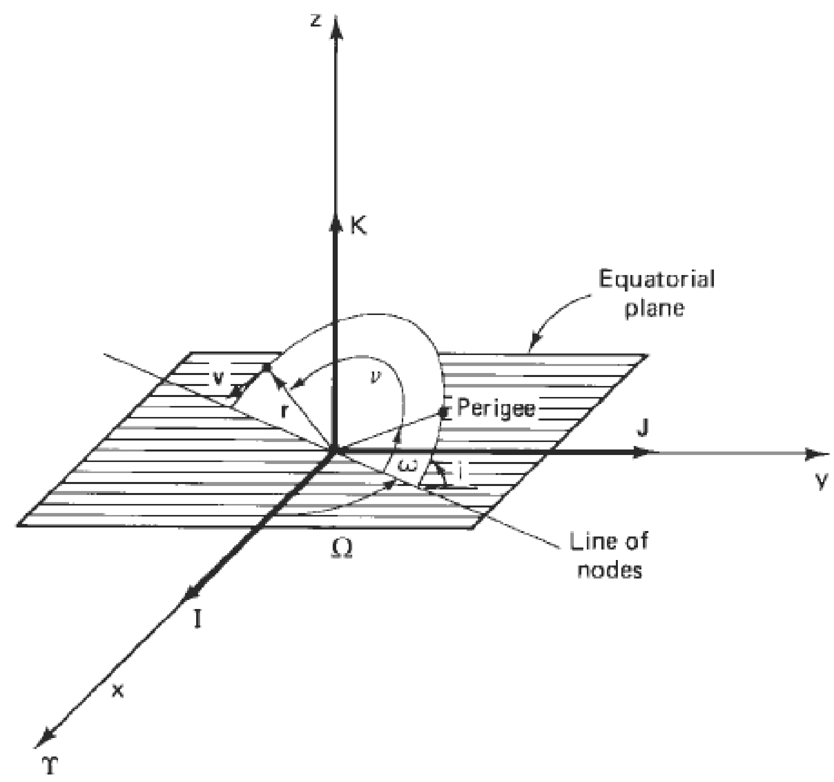


Figure 2.9 Geocentric-equatorial coordinate system (IJK frame).

$$\begin{bmatrix} r_I \\ r_J \\ r_K \end{bmatrix} = \tilde{\mathrm{R}} \begin{bmatrix} \mathrm{r}_P \\ \mathrm{r}_Q \end{bmatrix}$$

$$\tilde{\mathrm{R}} = \begin{bmatrix} (\cos\Omega\cos\omega - \sin\Omega\sin\omega\cos i) & (-\cos\Omega\sin\omega - \sin\Omega\cos\omega\cos i) \\ (\sin\Omega\cos\omega + \cos\Omega\sin\omega\cos i) & (-\sin\Omega\sin\omega + \cos\Omega\cos\omega\cos i) \\ (\sin\omega\sin i) & (\cos\omega\sin i) \end{bmatrix}$$

Example

Example 2.16 Calculate the magnitude of the position vector in the **PQW** frame for the orbit specified below. Calculate also the position vector in the **IJK** frame and its magnitude. Confirm that this remains unchanged from the value obtained in the **PQW** frame.

solution The given orbital elements are

$$\Omega := 300 \cdot \text{deg} \quad \omega := 60 \cdot \text{deg} \quad i := 65 \cdot \text{deg} \quad r_P := -6500 \cdot \text{km}$$
$$r_Q := 4000 \cdot \text{km}$$

$r := \sqrt{r_P{}^2 + r_Q{}^2}$ ...from Eq. (2.32)

$$r = 7632.2 \cdot \text{km}$$
$$= = = = = = = =$$

Equation (2.33) is

$$\begin{bmatrix} r_I \\ r_J \\ r_K \end{bmatrix} := \begin{pmatrix} \cos(\Omega)\cdot\cos(\omega) - \sin(\Omega)\cdot\sin(\omega)\cdot\cos(i) & -\cos(\Omega)\cdot\sin(\omega) - \sin(\Omega)\cdot\cos(\omega)\cdot\cos(i) \\ \sin(\Omega)\cdot\cos(\omega + \cos(\Omega)\cdot\sin(\omega)\cdot\cos(i) & -\sin(\Omega)\cdot\sin(\omega) + \cos(\Omega)\cdot\cos(\omega)\cdot\cos(i) \\ \sin(\omega)\cdot\sin(i) & \cos(\omega)\cdot\sin(i) \end{pmatrix} \begin{pmatrix} r_P \\ r_Q \end{pmatrix}$$

$$r_i = -4685.3 \cdot \text{km}$$

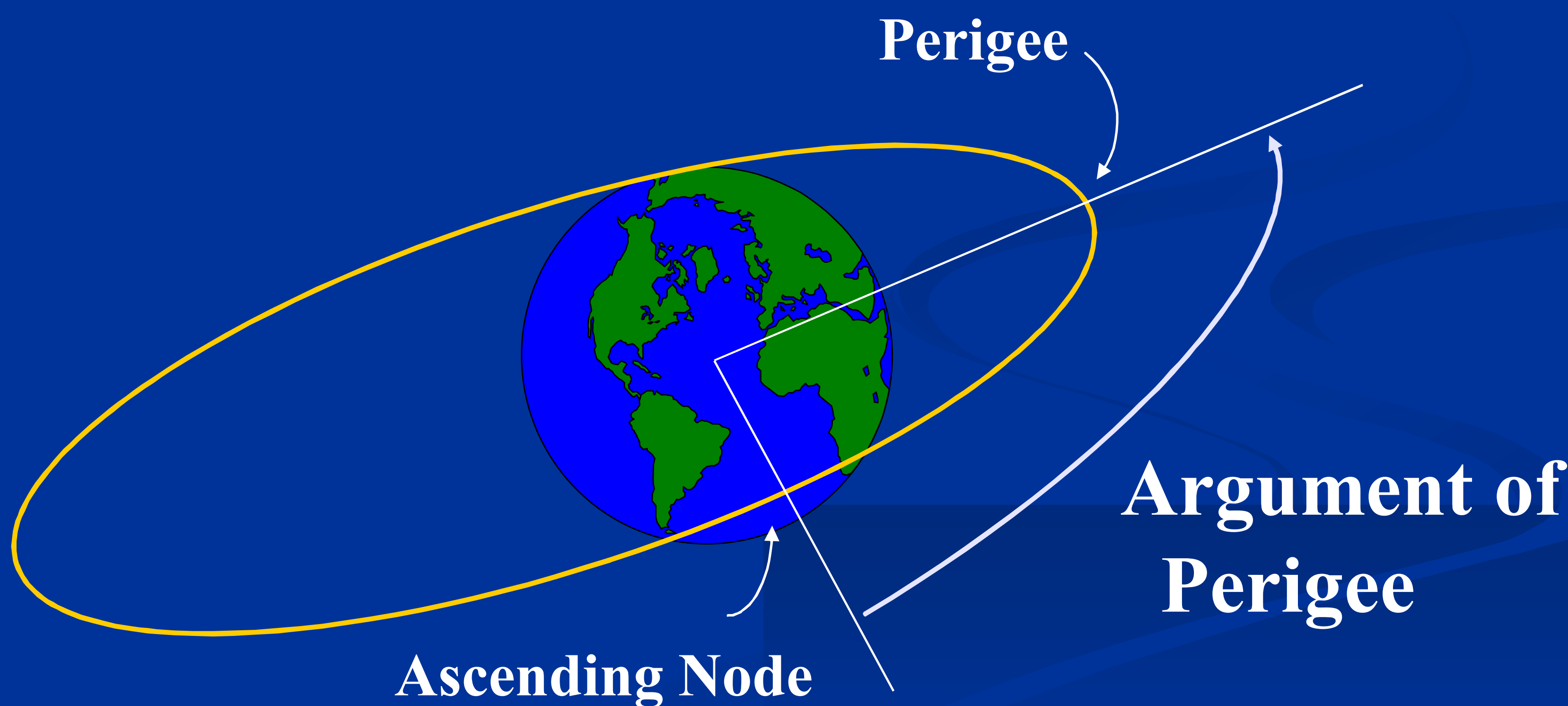
$$r_J = 5047.7 \cdot \text{km}$$

$$r_K = -3289.1 \cdot \text{km}$$

$$|\ r\ | = 7632.2 \cdot \text{km}$$

Coordinate Systems
Orbit Inertial

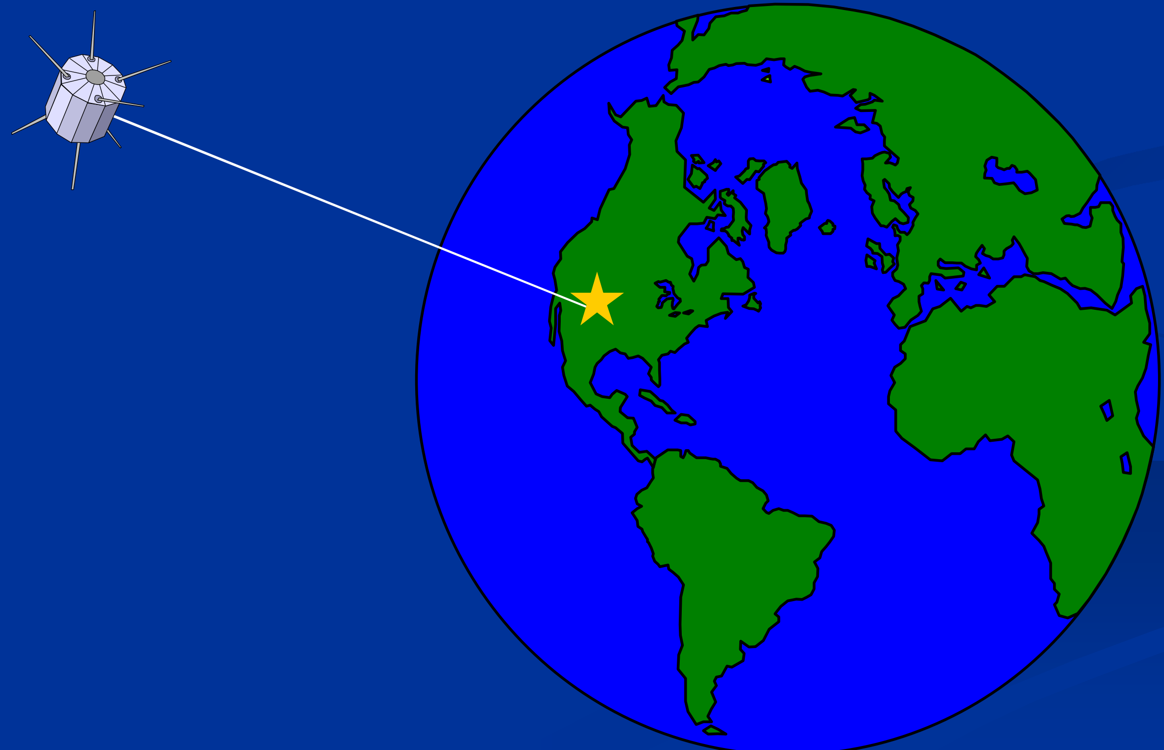
- Purpose: To fix the satellite orbit in the orbital plane



Coordinate Systems

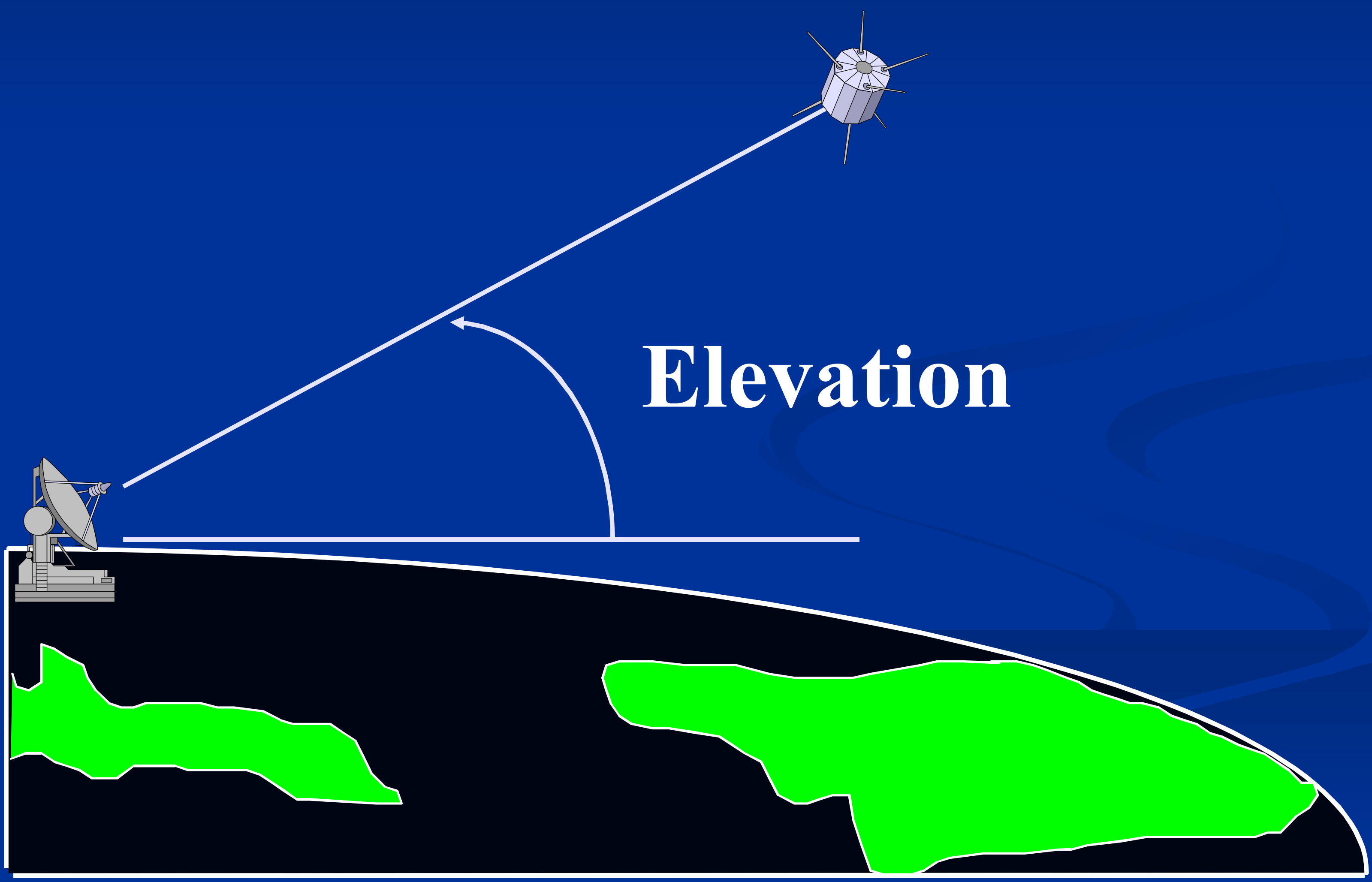
Topocentric

- Purpose: To locate a satellite with respect to a specific point on the Earth



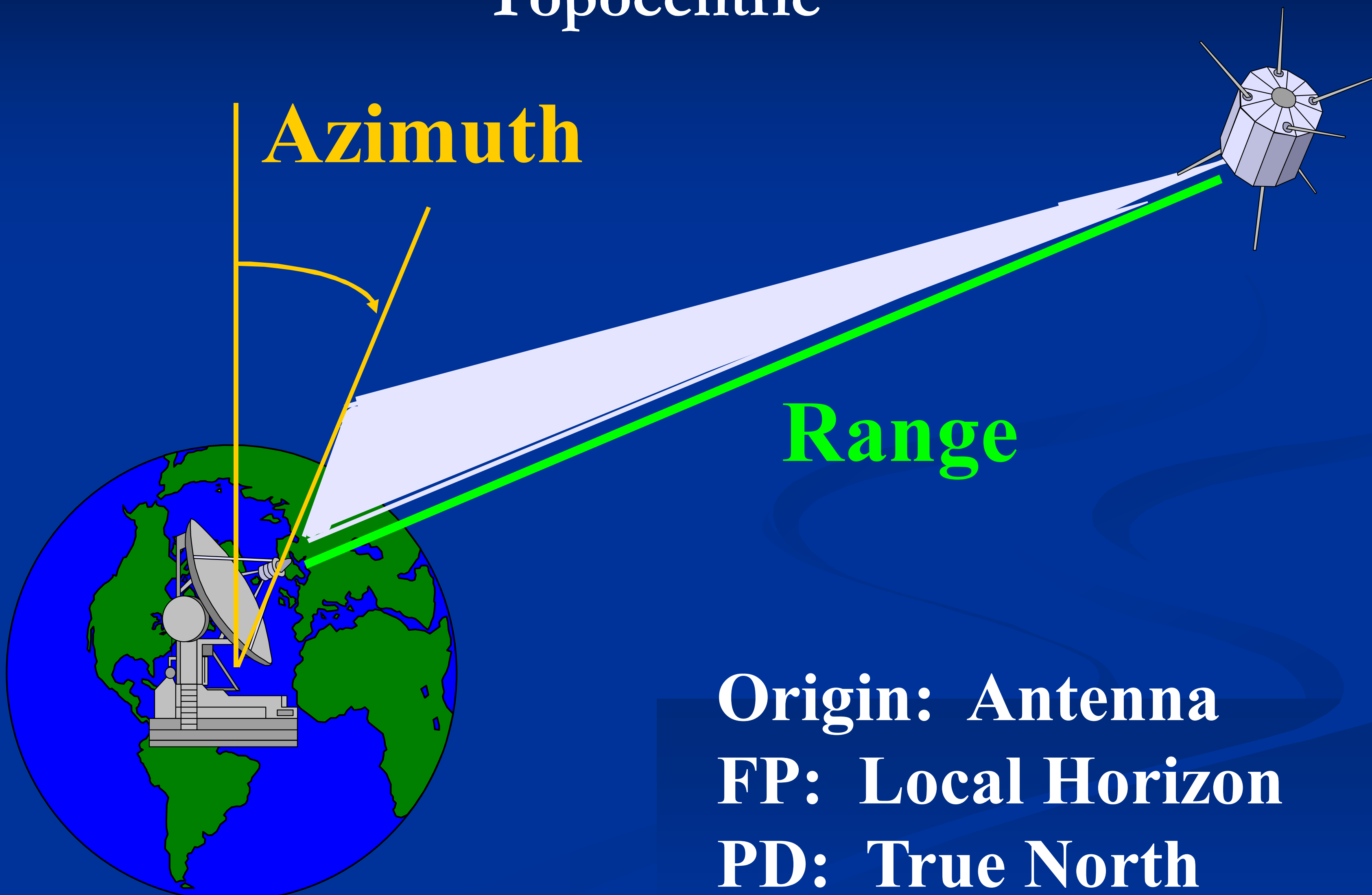
Coordinate Systems

Topocentric



Coordinate Systems

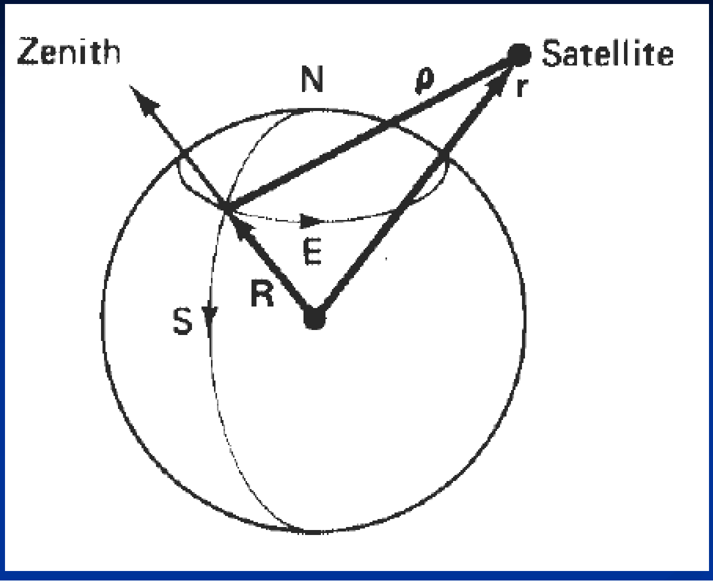
Topocentric



Origin: Antenna
FP: Local Horizon
PD: True North

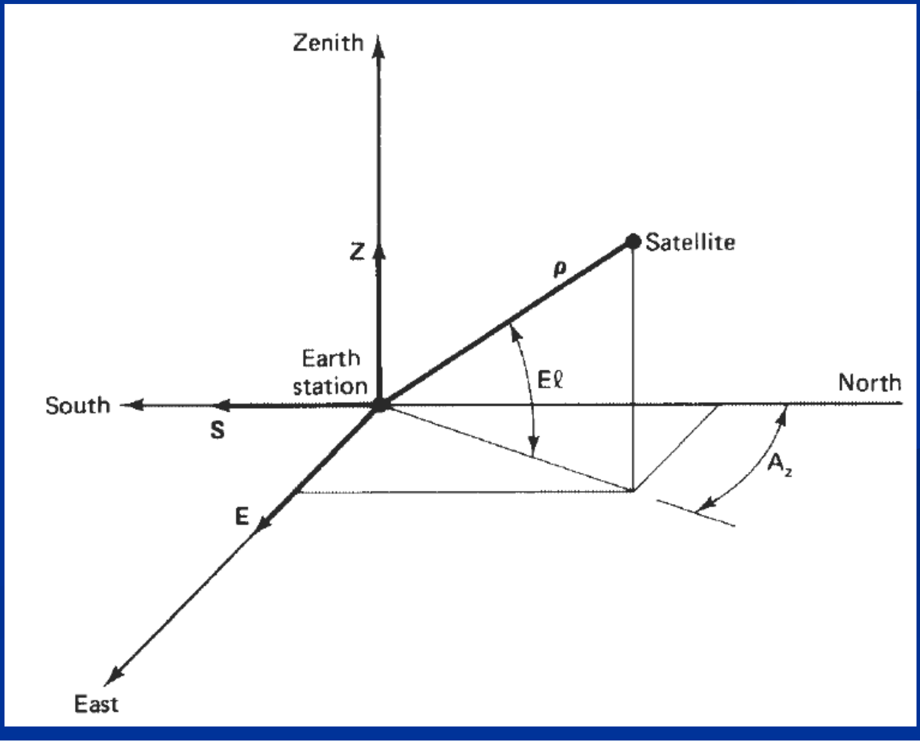
The Topocentric-horizon System

- The position of the sat. measured from the erath stattion in terms of the azimuth, elevation and range



- The fundamental plane is the observer
- +x→ south (S)
- +y → east (E)
- +z up→ zenith (Z)

(SEZ frame)



The Topocentric-horizon System

- The position of the sat. measured from the erath stattion in terms of the azimuth, elevation and range

$$\rho = \sqrt{\rho_S{}^2 + \rho_E{}^2 + \rho_Z{}^2}$$

$$El = \arcsin\left(\frac{\rho_Z}{\rho}\right)$$

$$\alpha = \arctan\frac{|\rho_E|}{|\rho_S|}$$

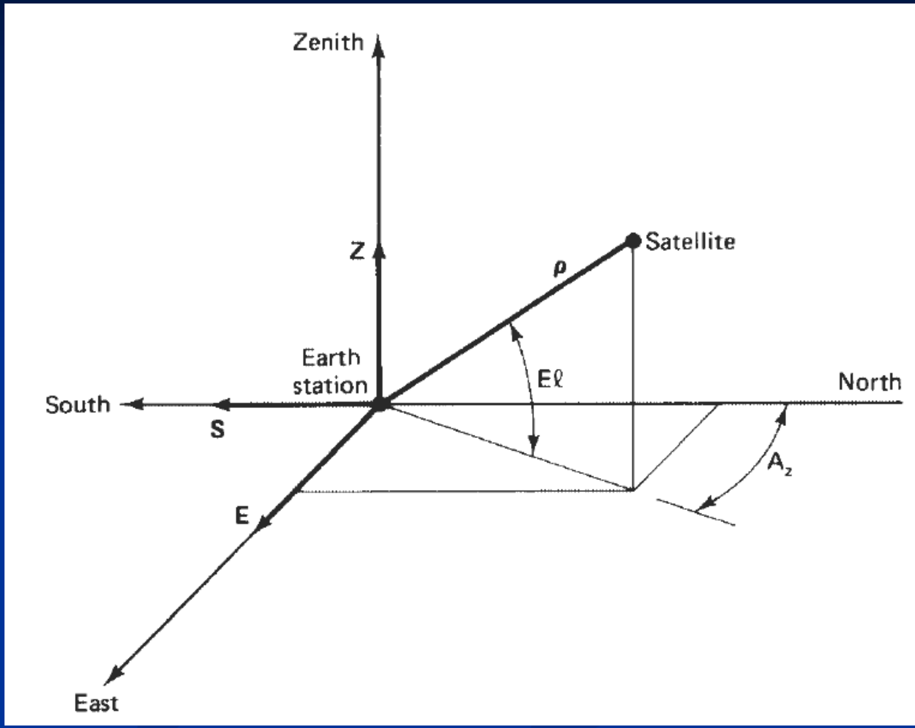


TABLE 2.2 Azimuth angles

ρ_S	ρ_E	Azimuth degrees
−	+	α
+	+	$180 - \alpha$
+	−	$180 + \alpha$
−	−	$360 - \alpha$

Example

- Given

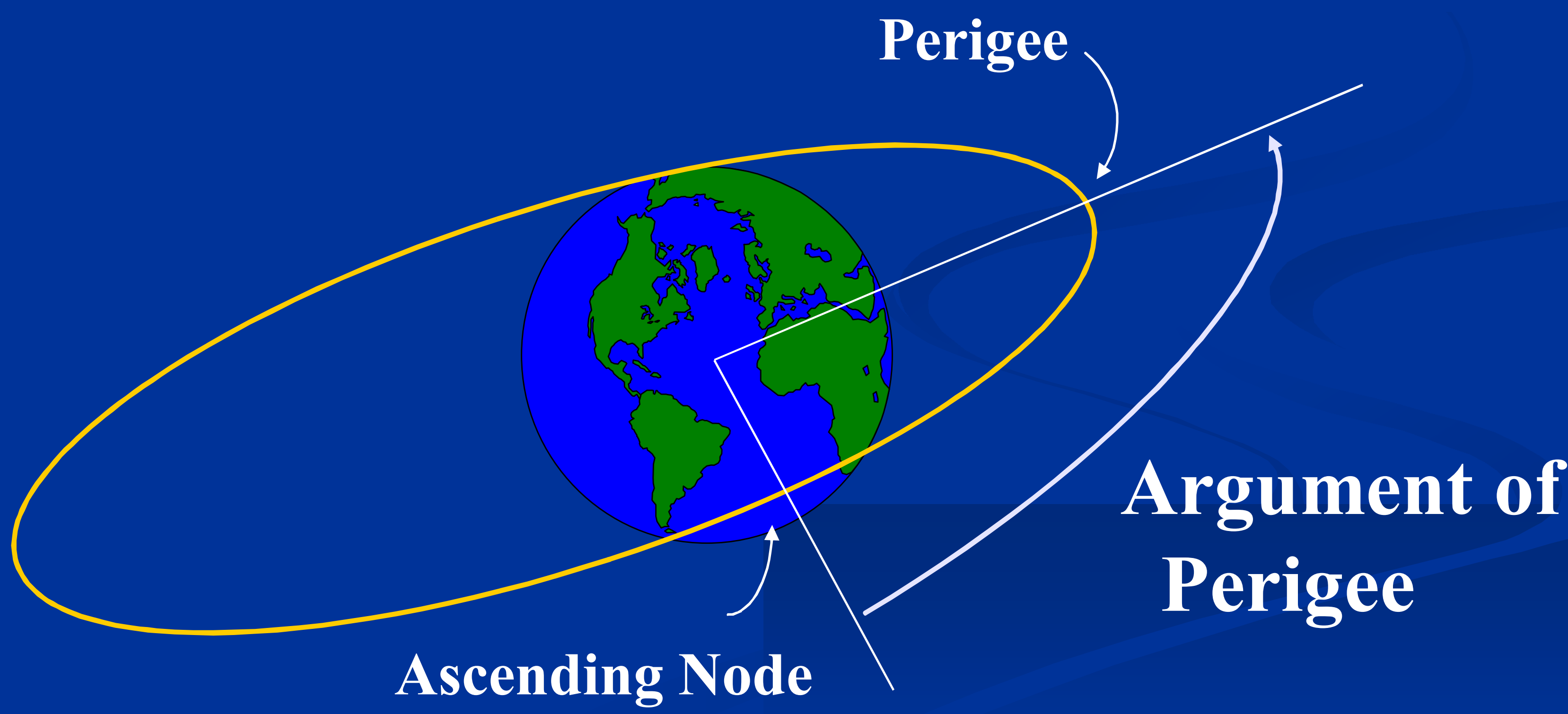
$$\begin{bmatrix} \rho_S \\ \rho_E \\ \rho_Z \end{bmatrix} := \begin{pmatrix} 323 \\ 1740.6 \\ 377 \end{pmatrix} \cdot km \quad \Rightarrow \quad \sqrt{{\rho_I}^2 + {\rho_J}^2 + {\rho_K}^2} = 1810 \cdot km$$

$$El := asin\left(\frac{\rho_Z}{\rho}\right) \quad \Rightarrow \quad \underline{\underline{El = 12 \cdot deg}}$$

$$\alpha := atan\left(\left|\frac{\rho_E}{\rho_S}\right|\right) \quad \Rightarrow \quad \underline{\underline{Az = 100.5 \cdot deg}}$$

Coordinate Systems
Orbit Inertial

- Purpose: To fix the satellite orbit in the orbital plane



Orbit Classification

- Size/Period
- Location
- Shape

Orbit Classification

Size/Period

- Defined by semi-major axis (a)
- Low Earth Orbit (LEO)
- High Earth Orbit (HEO)
- Semi-synchronous Orbit
- Geo-synchronous Orbit

Orbit Classification

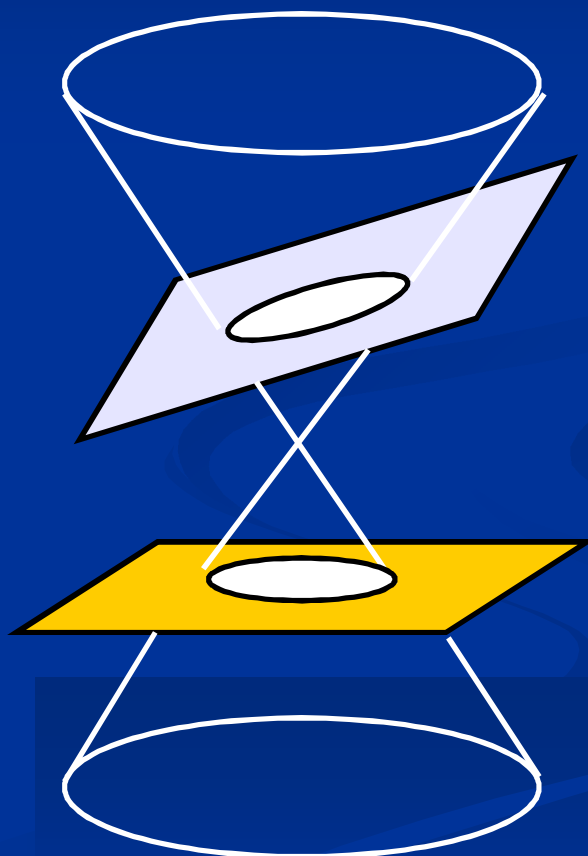
Location

- Equatorial
- Polar

Orbit Classification

Shape (Conic Sections)

Circle
Ellipse

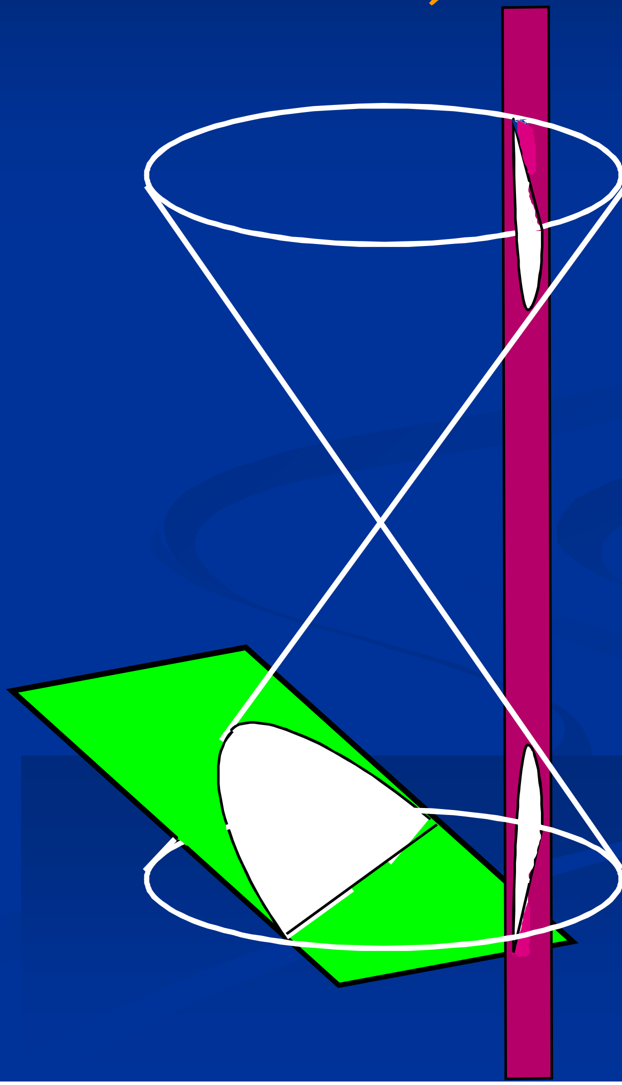


Orbit Classification

Shape (Conic Sections)

Trajectories:

- Parabola
- Hyperbola



ORBIT CLASSIFICATIONS

Circular Orbits

- Characteristics
  - Constant speed
  - Nearly constant altitude
- Typical Missions
  - Reconnaissance/Weather (DMSP)
  - Manned
  - Navigational (GPS)
  - Geo-synchronous (Comm sats)

ORBIT CLASSIFICATIONS

Elliptical Orbits

- Characteristics
  - Varying speed
  - Varying altitude
  - Asymmetric Ground Track
- Typical Missions
  - Deep space surveillance (Pioneer)
  - Communications (Polar comm.)
  - Ballistic Missiles

ORBIT CLASSIFICATIONS

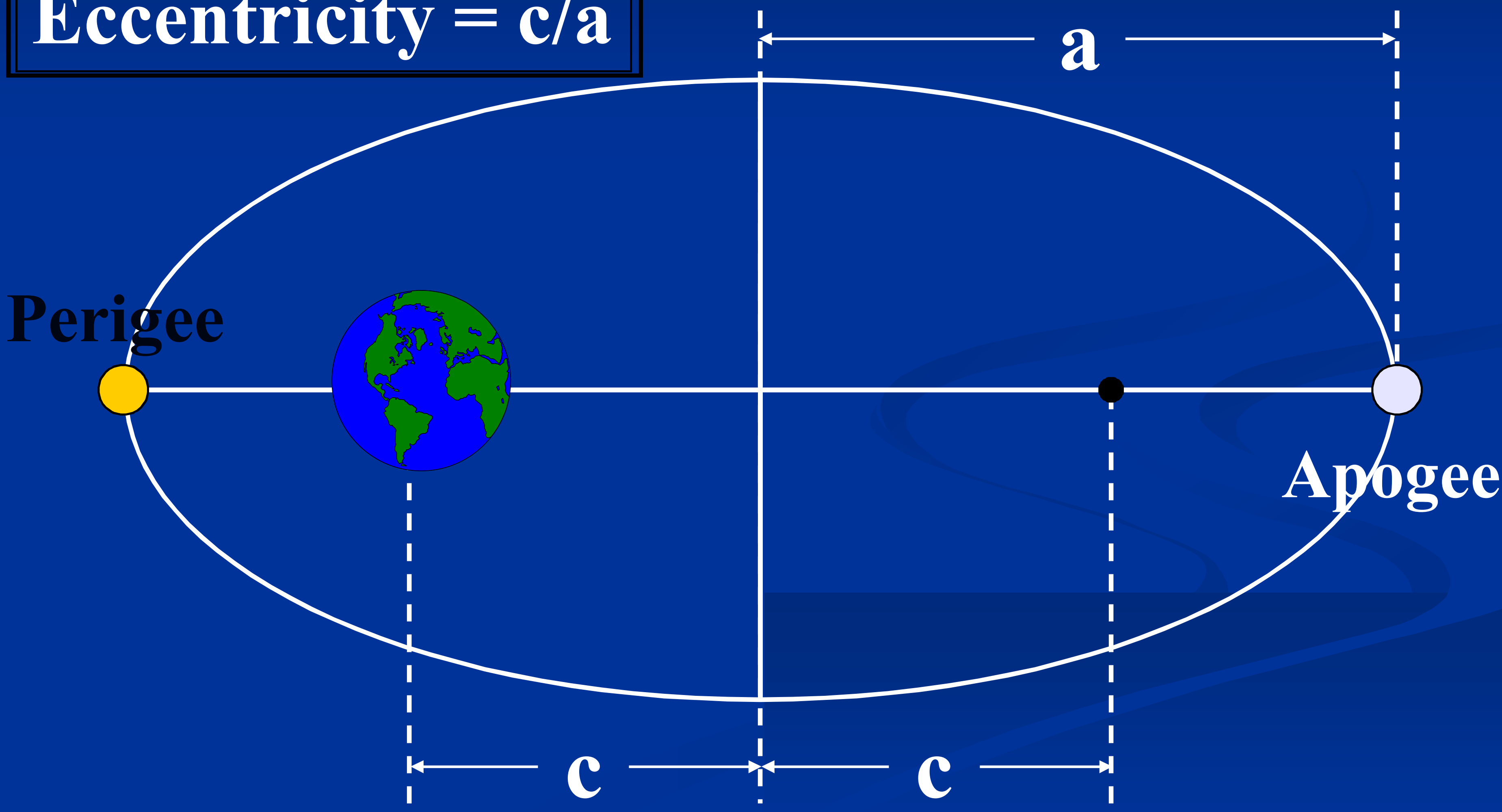
Parabolic/Hyperbolic Trajectories

- Characteristics
  - Escaped Earth's gravitational influence
  - Heliocentric
- Typical Missions
  - Interplanetary exploration (Galileo, Phobos, Magellan)

ORBIT CLASSIFICATIONS

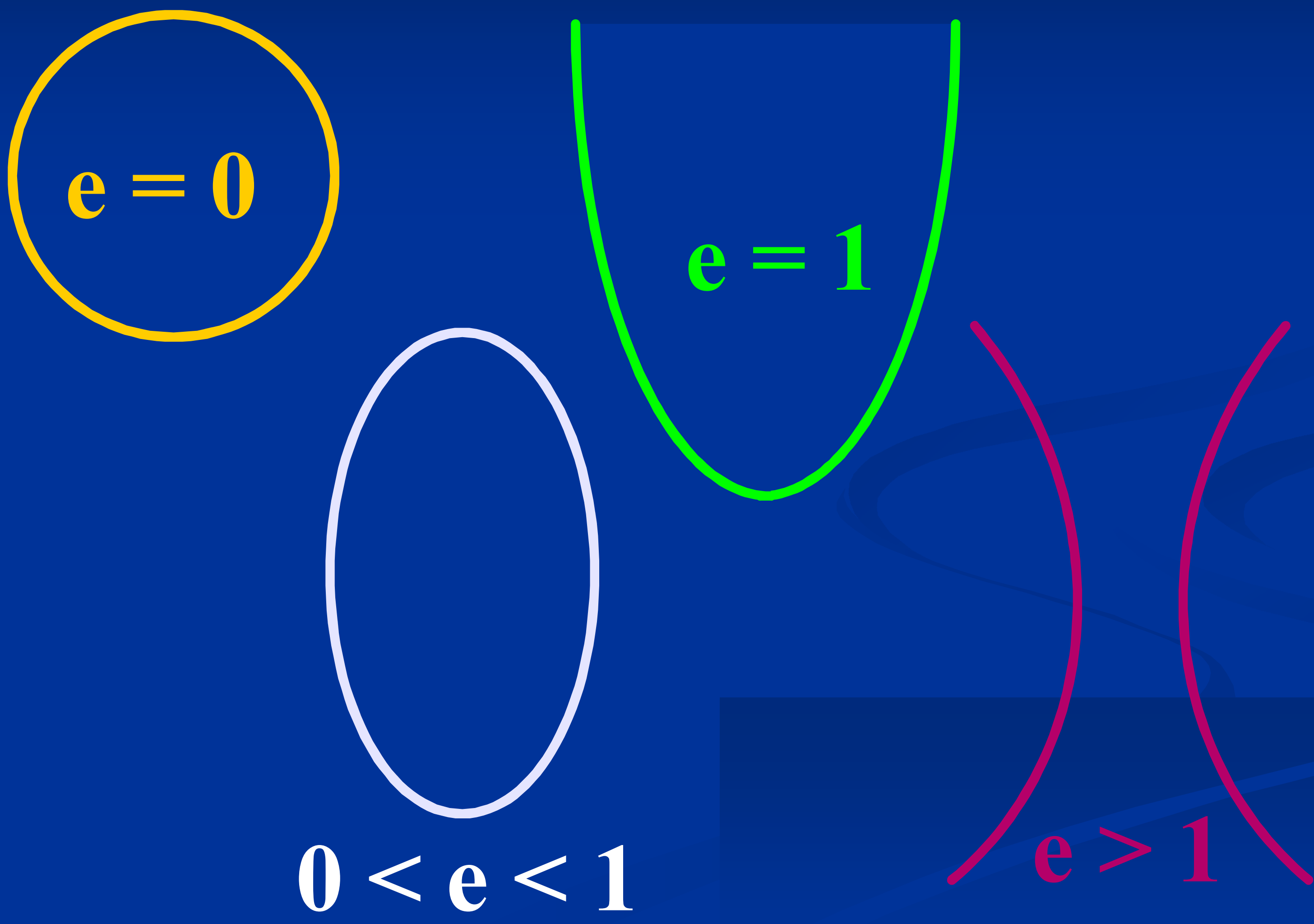
Orbit Geometry

Eccentricity = c/a



ORBIT CLASSIFICATIONS

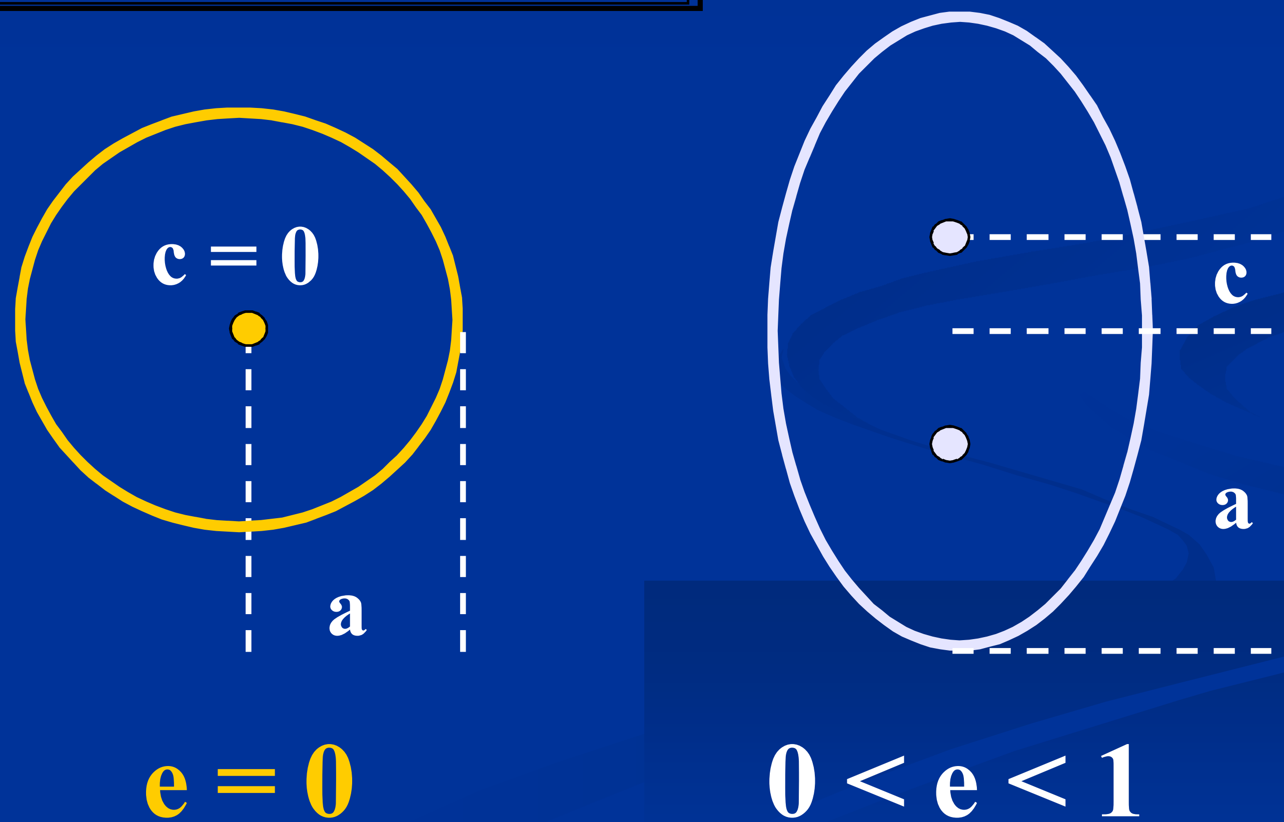
Eccentricity



ORBIT CLASSIFICATIONS

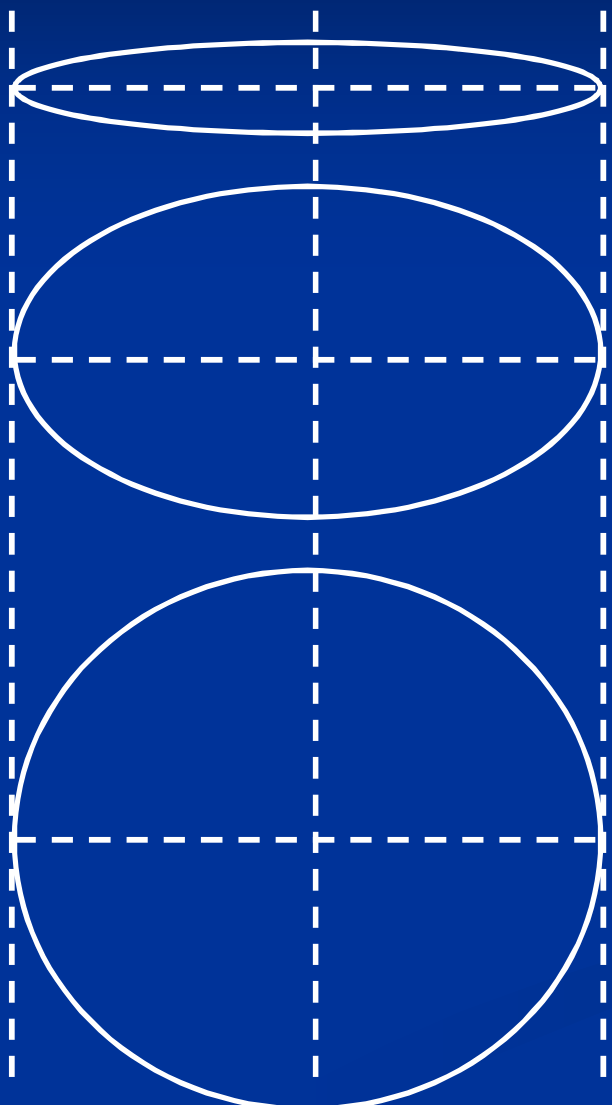
Eccentricity

Eccentricity = c/a



ORBIT CLASSIFICATIONS

Eccentricity



e = 0.75

e = .45

e = 0

Eccentricity = c/a

ORBITAL MECHANICS

- Origins
- Physical Laws
- Requirements for Injection
- Classifications of Orbits
- Coordinate Reference Systems
- Orbital Elements

Satellites

- Several types
- LEOs - Low earth orbit
- MEOs - Medium earth orbit
- GEOs - Geostationary earth orbit

GEOs

- Originally proposed by Arthur C. Clarke
- Circular orbits above the equator
- Angular separation about 2 degrees - allows 180 satellites
- Orbital height above the earth about 23000 miles/35000km
- Round trip time to satellite about 0.24 seconds

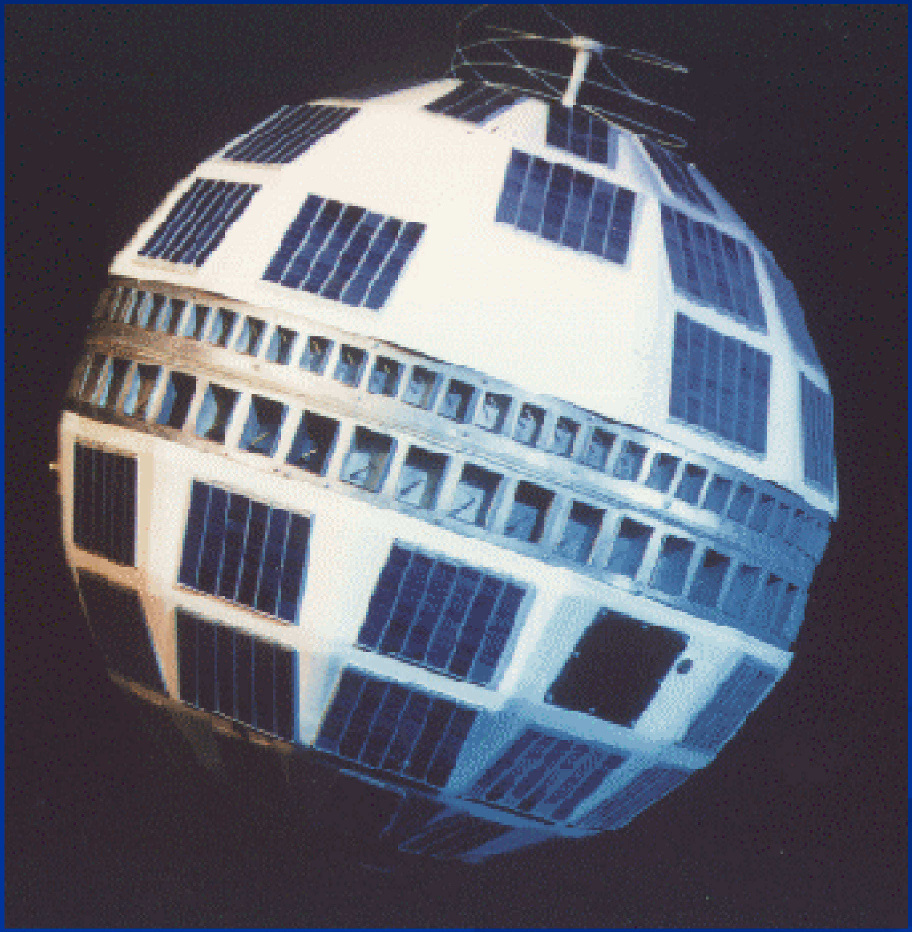
GEOs (2)

- GEO satellites require more power for communications
- The signal to noise ratio for GEOs is worse because of the distances involved
- A few GEOs can cover most of the surface of the earth
- Note that polar regions cannot be “seen” by GEOs

GEOs (3)

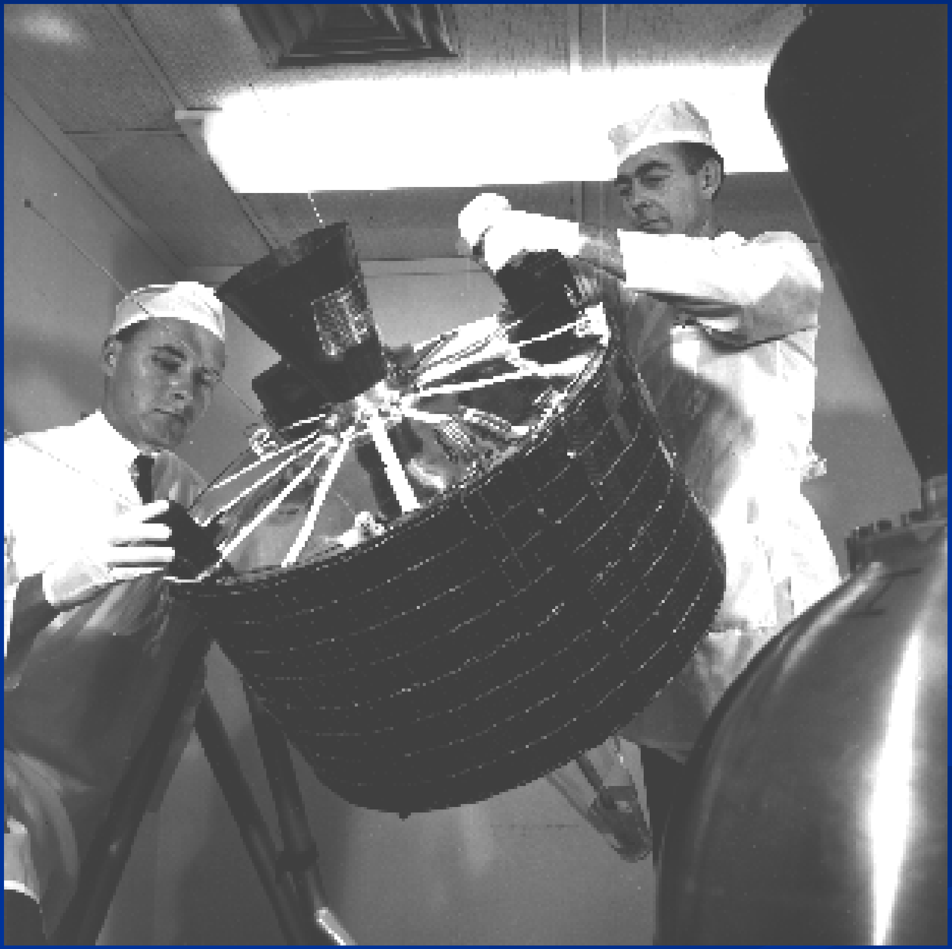
- Since they appear stationary, GEOs do not require tracking
- GEOs are good for broadcasting to wide areas

TELSTAR



- Picture from NASA

SYNCOM 2



- Picture from NASA

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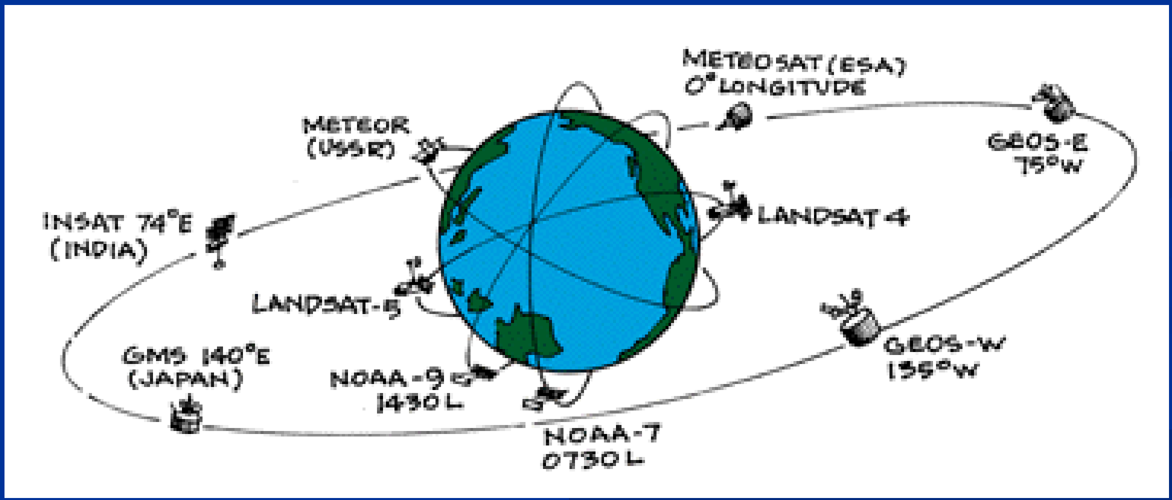
Satellite Orbits
인공위성 궤도



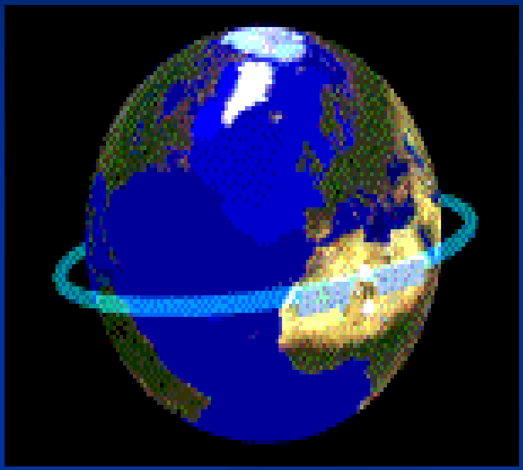
Launch Animation

NASA server

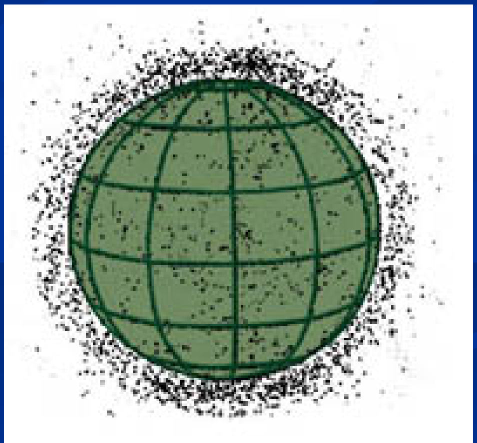
KNU Server:
no sound but storable

Low Earth Orbits
저궤도

- Close to Earth (320~800km)
- ~27,000 km/h
- 90min period

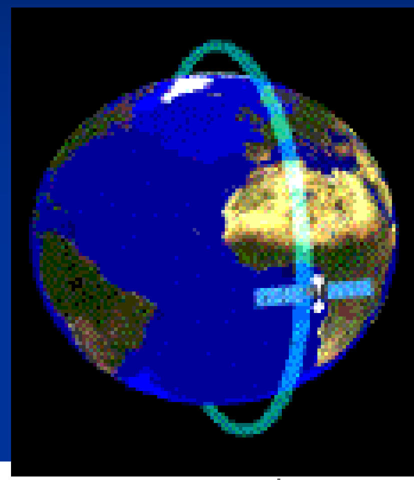


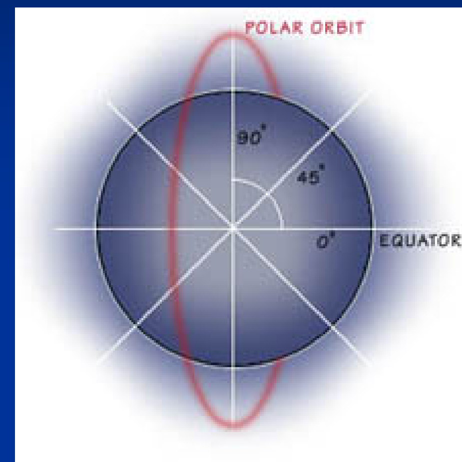
- Space Shuttle
- Some Remote Sensing Satellites and weather satellites
- ~8,000 Space Junks – satellites, old rockets, metals, etc.

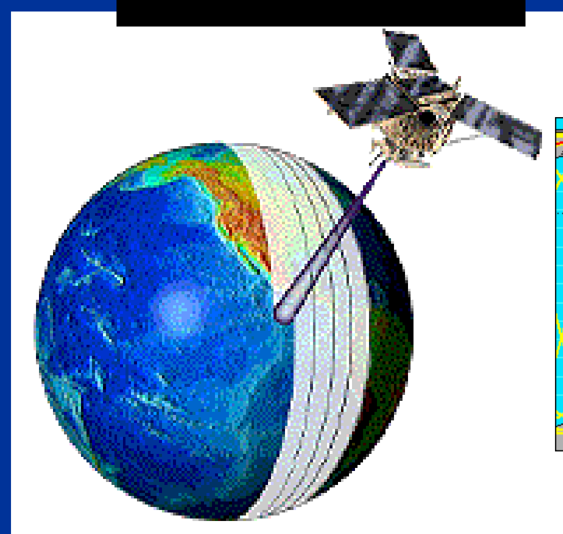


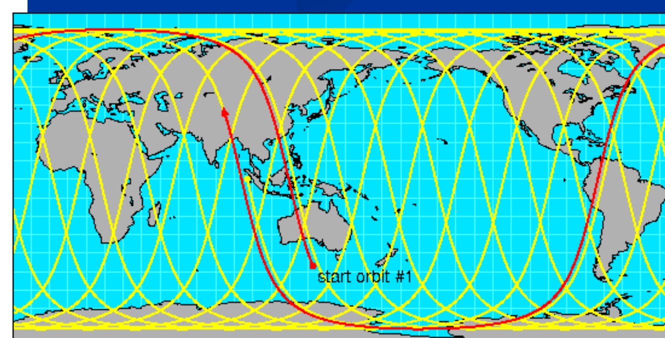
Polar Orbit
극궤도

- One type of LEO
- High inclination
- Can scan the entire surface due to earth rotation (east-west) and satellite orbit (north-south)
- Most remote sensing satellites and some weather satellites



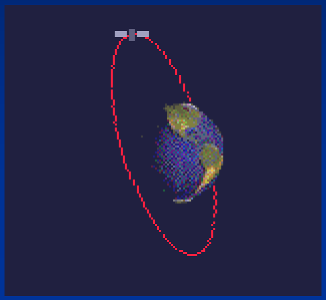


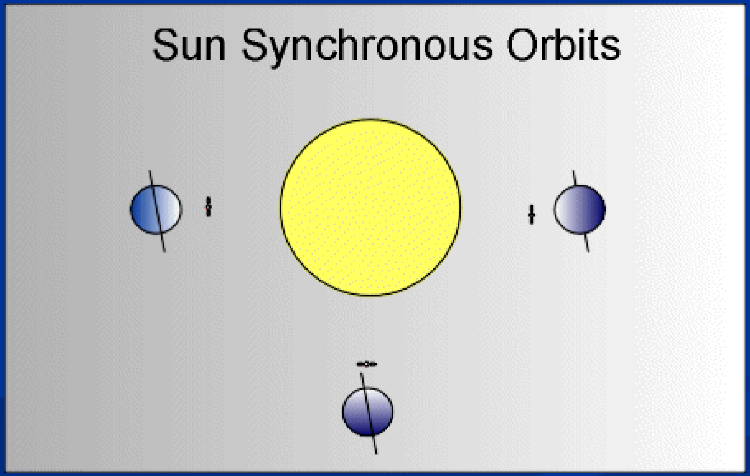




Sun-synchronous Orbit

- These orbits allows a satellite to pass over a section of the Earth at the same time of day.
- Since there are 365 days in a year and 360 degrees in a circle, it means that the satellite has to shift its orbit by approximately one degree per day.
- These satellites orbit at an altitude between 700 to 800 km.
- These satellites use the fact since the Earth is not perfectly round (the Earth bulges in the center, the bulge near the equator will cause additional gravitational forces to act on the satellite.
- This causes the satellite's orbit to either proceed or recede.
- These orbits are used for satellites that need a constant amount of sunlight.
- Satellites that take pictures of the Earth would work best with bright sunlight, while satellites that measure longwave radiation would work best in complete darkness.

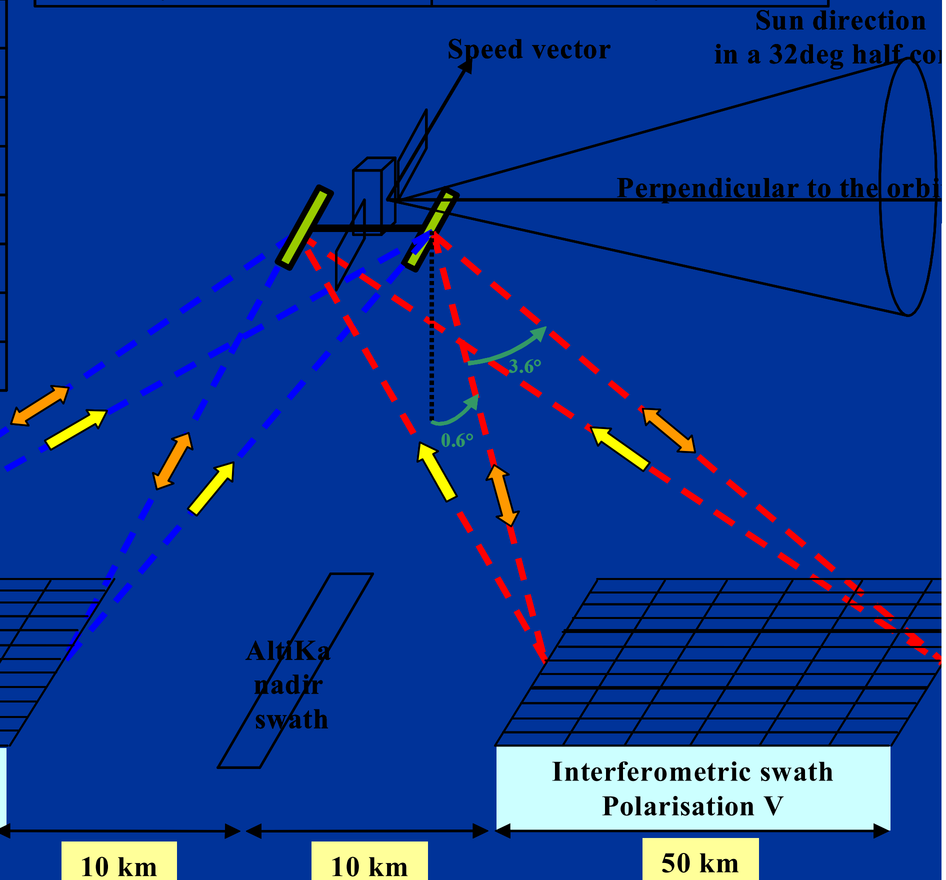




Reminder : WATER MISSION on a Sun-Sync. o

Frequency	Ka (36.5 GHz)
Bandwidth	200 MHz
Pulse duration	6,3 µs
PRF (2 antennas)	9000 Hz
Peak emission power	1500 W
Mean instrument power	800 W
Antenna length	3.80 m
Antenna width	0.28 m
Mast length	10 m
Near range view angle	0.6 deg
Far range view angle	4.3 deg

Altitude	824.03 km
Inclination	98.705 °
Cycle duration	16 days



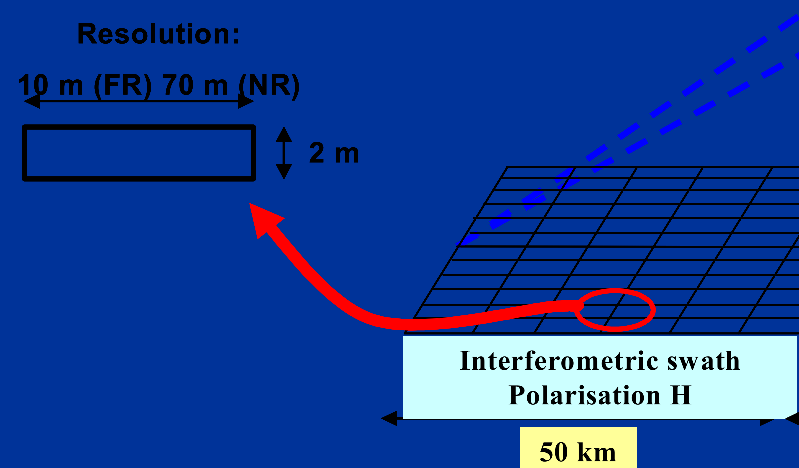
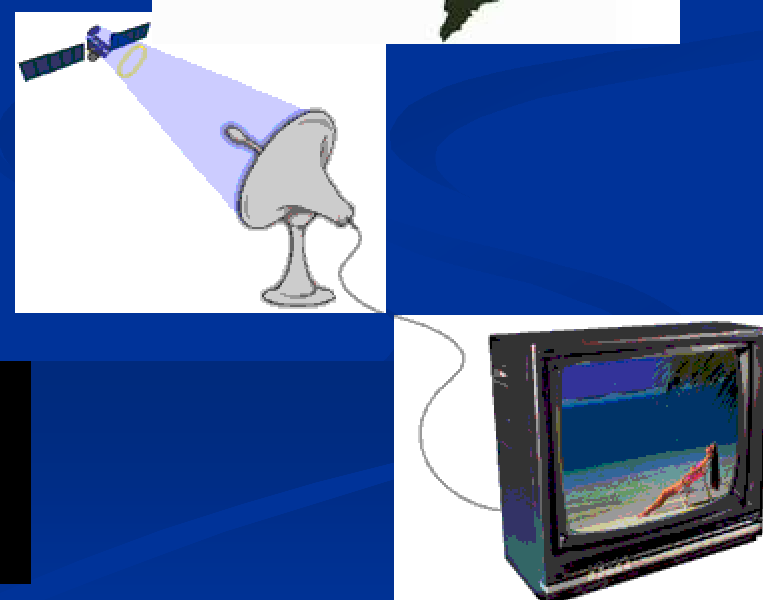
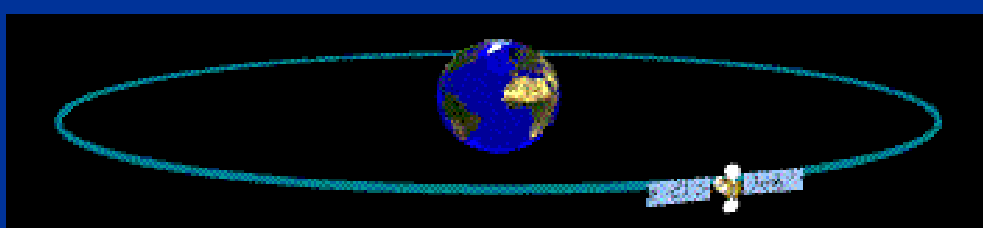


Fig. 4: Conceptual illustration of the WatER mission

Geosynchronous Orbit
지구정지궤도

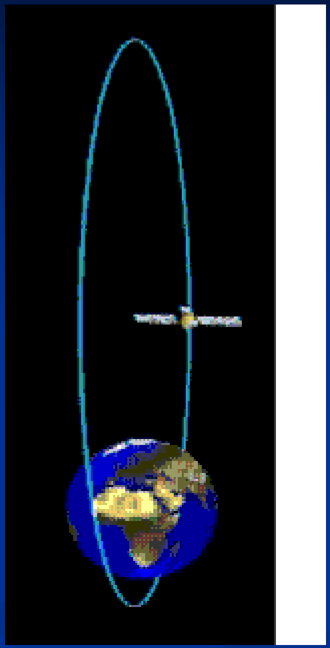
- Satellite is always at the same position w.r.t the rotating earth
- Altitude: 35790km exactly
- T=23hrs 56min 4.09sec
- 'Big-picture view'
- Broadcast or Communication satellites
- Orbit plane = Earth rotation plane





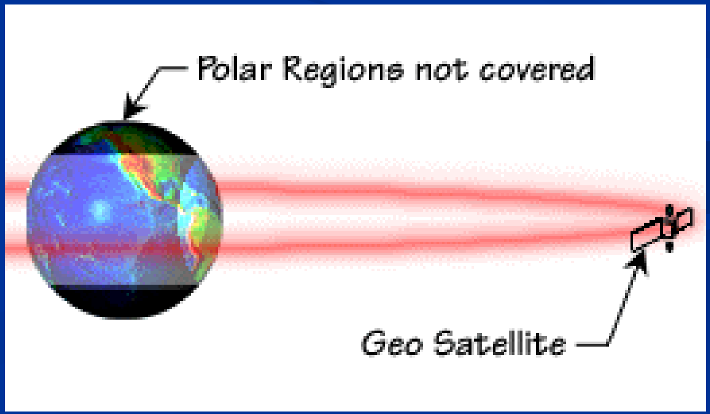
Elliptical Orbit
타원궤도

Apogee



Perigee

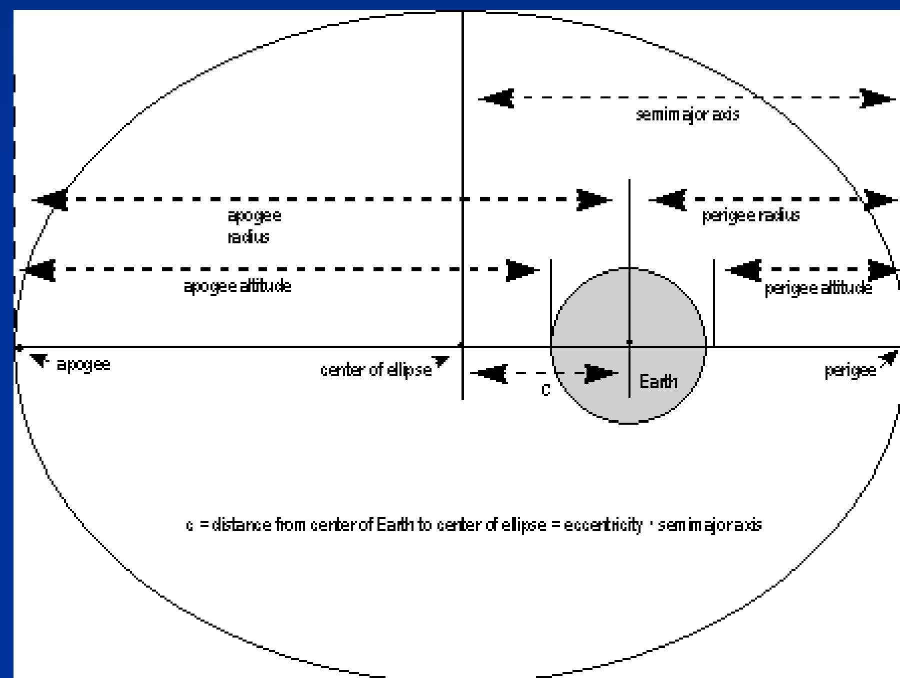
- Perigee(closest), Apogee(farthest)
- Period: ~12hrs
- Polar coverage
- Ccommunication satellites for north and south region



Orbit Size and Shape

Parameter Definition

- **Semimajor Axis:** Half the distance between the two points in the orbit that are farthest apart
- **Apogee/Perigee Radius:** Measured from the center of the Earth to the points of maximum and minimum radius in the orbit
- **Apogee/Perigee Altitude:** Measured from the "surface" of the Earth (a theoretical sphere with a radius equal to the equatorial radius of the Earth) to the points of maximum and minimum radius in the orbit
- **Period:** The duration of one orbit, based on assumed two-body motion
- **Mean Motion:** The number of orbits per solar day (86,400 sec/24 hour), based on assumed two-body motion
- **Eccentricity:** The shape of the ellipse comprising the orbit, ranging between a perfect circle (eccentricity = 0) and a parabola (eccentricity = 1)



Orbit Period

- Universal Law of Gravitation = Centripetal Force

$$\frac{GMm}{r^2} = mr\omega^2$$

$$\omega = \frac{2\pi}{T}$$

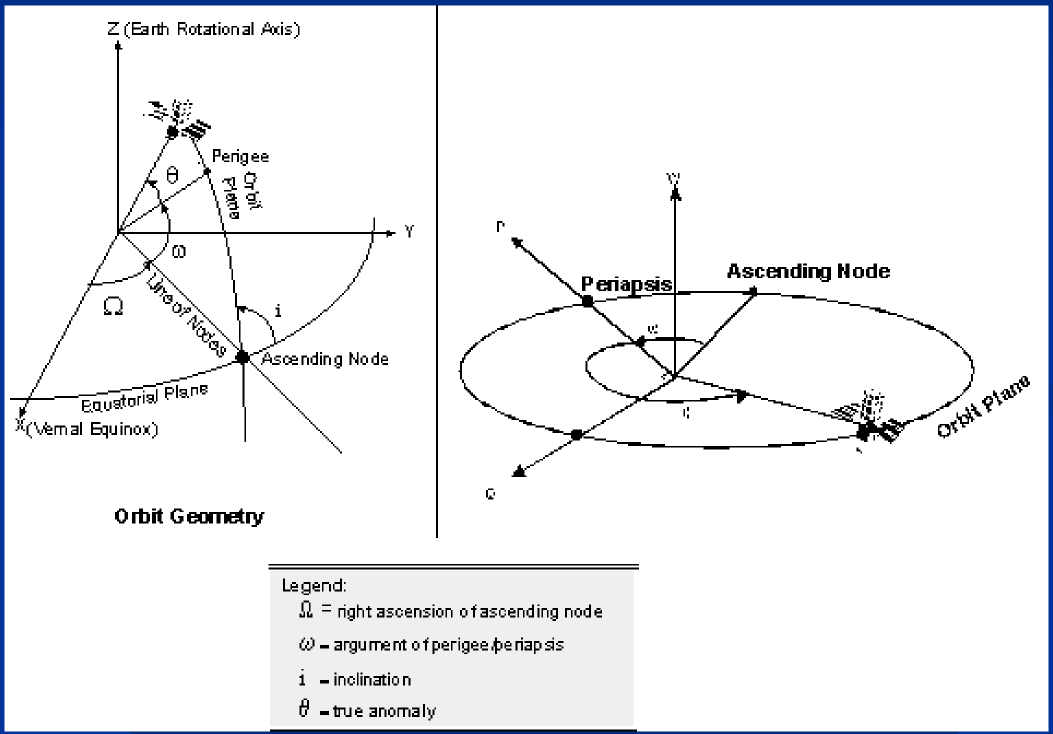
$$T^2 = \left(\frac{4\pi^2}{GM}\right) r^3$$

- T is proportional to r
- T only depending on the mass of the central body
- It holds for elliptical orbit when r is a, the semi-major axis of the ellipse.
- T^2 / a^3 is constant for every satellites

Orbit Orientation

Parameter Definition

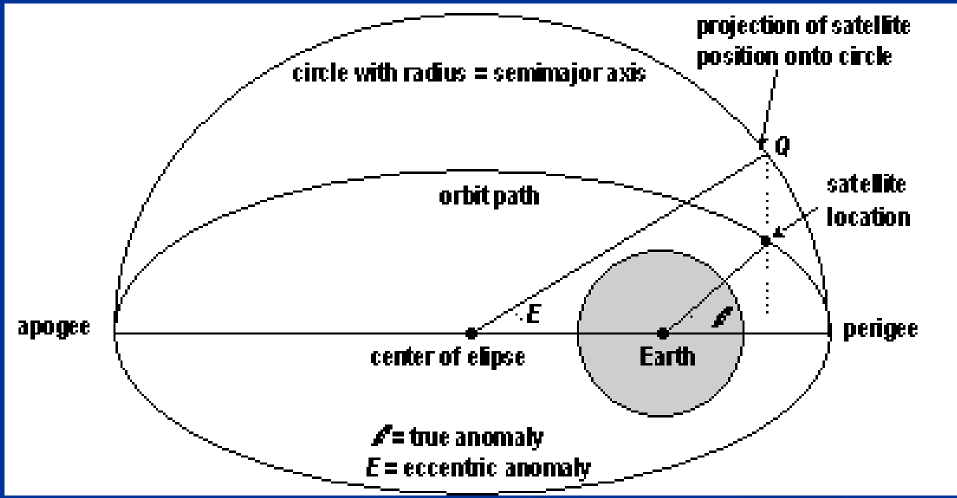
- **Inclination:** The angle between the orbital plane and the Earth's equatorial plane (commonly used as a reference plane for Earth satellites)
- **Right Ascension of the Ascending Node:** The angle in the Earth's equatorial plane measured eastward from the vernal equinox to the ascending node of the orbit
- **Argument of Perigee:** The angle, in the plane of the satellite's orbit, between the ascending node and the perigee of the orbit, measured in the direction of the satellite's motion
- **Longitude of the Ascending Node:** The Earth-fixed longitude of the ascending node



Satellite Location

Parameter Definition

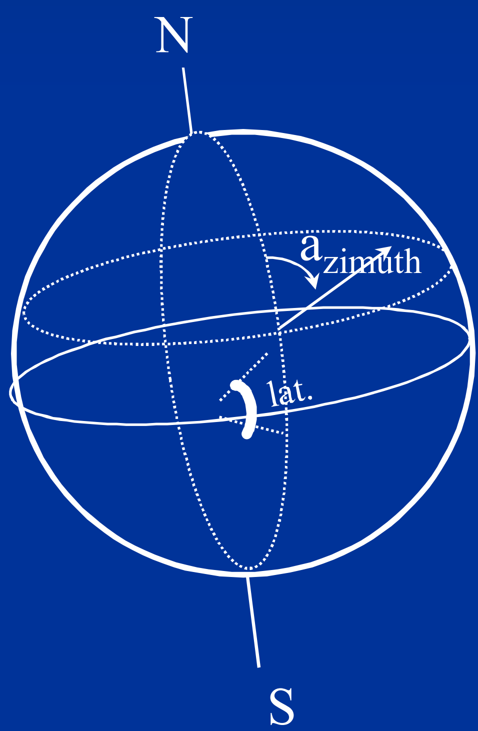
- **True Anomaly:** The angle from the eccentricity vector (points toward perigee) to the satellite position vector, measured in the direction of satellite motion and in the orbit plane.
- **Mean Anomaly:** The angle from the eccentricity vector to a position vector where the satellite would be if it were always moving at its angular rate.
- **Eccentric Anomaly:** An angle measured with an origin at the center of an ellipse from the direction of perigee to a point on a circumscribing circle from which a line perpendicular to the semimajor axis intersects the position of the satellite on the ellipse.
- **Argument of Latitude:** The sum of the True Anomaly and the Argument of Perigee.
- **Time Past Ascending Node:** The elapsed time since the last ascending node crossing.
- **Time Past Perigee:** The elapsed time since last perigee passage.

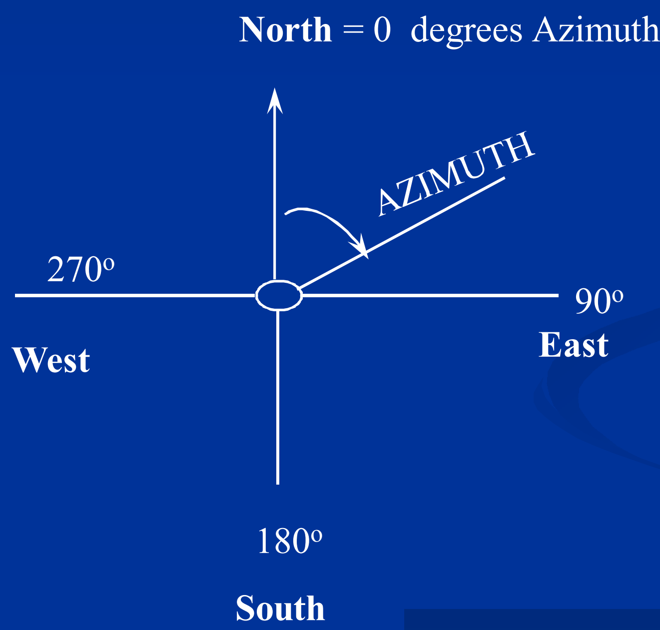


INCLINATION

FUNCTION OF LAUNCH AZIMUTH AND LAUNCH SITE LATITUDE

cos *i* (inclination) = cos (latitude) sin (azimuth)





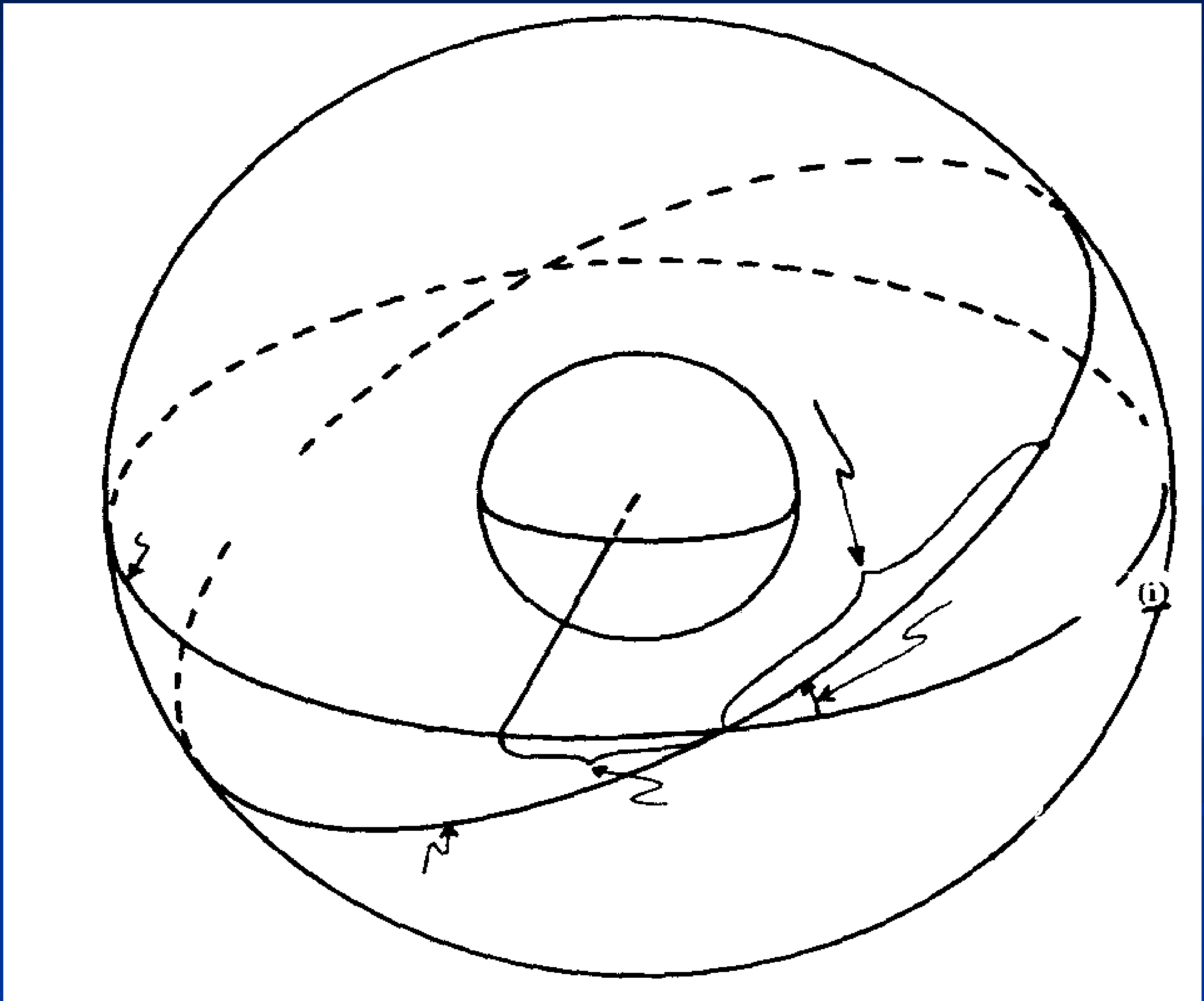
cos i + cos (lat) sin (az)

sin 90° = 1
sin 0° = 0
sin 180° = 0
sin 270° = -1

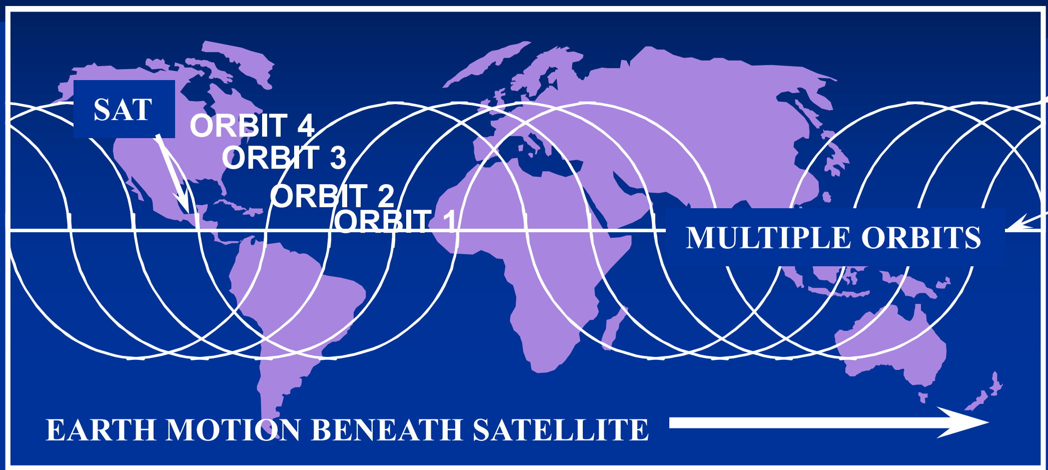
launch azimuth from 180° to360° = retrograde orbit

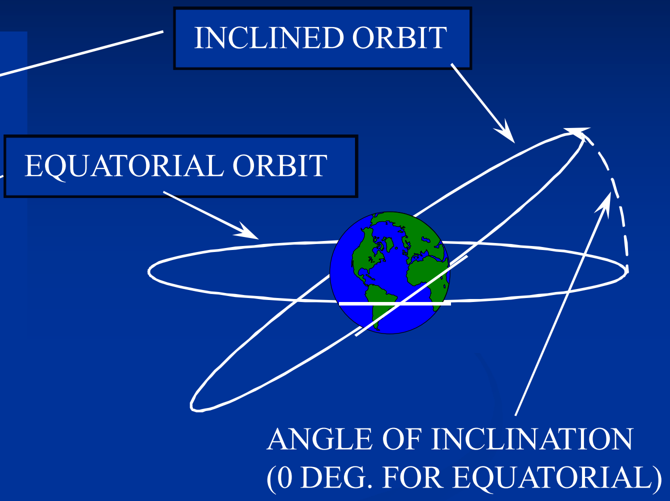
launch azimuth from 0° to 180° = posigrade orbit

Celestial Sphere



ORBITAL MECHANICS: GROUND TRACES





GROUND TRACES

THE POINTS ON THE EARTH'S SURFACE OVER WHICH A SATELLITE PASSES AS IT TRAVELS ALONG ITS ORBIT

PRINCIPLE : GROUND TRACE IS THE RESULT OF THE ORBITAL PLANE BEING FIXED AND THE EARTH ROTATING UNDERNEATH IT

AMPLITUDE OF GROUND TRACE (LATITUDE RANGE) IS EQUAL TO THE ORBITAL INCLINATION

MOVEMENT OF GROUND TRACE IS DICTATED BY THE SATELLITE ALTITUDE AND THE CORRESPONDING TIME FOR IT TO COMPLETE ONE ORBIT

ORBITAL MECHANICS: SPECIFIC ORBITS AND APPLICATIONS

- **POLAR (100- 700 NM AT 80 - 100 DEG. INCLINATION)**
  - SATELLITE PASSES THROUGH THE EARTH'S SHADOW AND PERMITS VIEWING OF THE ENTIRE EARTH'S SURFACE EACH DAY WITH A SINGLE SATELLITE
- **SUN SYNCHRONOUS (80 - 800 NM AT 95 - 105 DEG INCLINATION)**
  - PROCESSION OF ORBITAL PLANE SYNCHRONIZED WITH THE EARTH'S ROTATION SO SATELLITE IS ALWAYS IN VIEW OF THE SUN
  - PERMITS OBSERVATION OF POINTS ON THE EARTH AT THE SAME TIME EACH DAY
- **SEMISYNCHRONOUS (10,898 NM AT 55 DEG INCLINATION)**
  - 12 HR PERIODS PERMITTING IDENTICAL GROUNDTRACES EACH DAY
- **HIGHLY INCLINED ELLIPTICAL (FIXED PERIGEE POSITION)**
  - SATELLITE SPENDS A GREAT DEAL OF TIME NEAR THE APOGEE COVERING ONE HEMISPHERE
  - CLASSICALLY CALLED "MOLNIYA ORBIT" BECAUSE OF ITS HEAVY USE BY THE RUSSIANS FOR NORTHERN HEMISPHERE COVERAGE
- **GEOSYNCHRONOUS (GEO) (CIRCULAR, 19,300 NM AT 0 DEG INCLINATION)**
  - 24 HR PERIOD PERMITS SATELLITE POSITIONING OVER ONE POINT ON EARTH.
  - ORBITAL PERIOD SYNCHRONIZED WITH THE EARTH'S ROTATION (NO OTHER ORBIT HAS THIS FEATURE)

Linear and Angular Motion

	ANGULAR MOTION	LINEAR MOTION
Distance	$\theta = S/r$ radians	$S = r\,\theta$ ft
Velocity	$\omega_{avg} = \dfrac{\theta_f - \theta_f}{t_f - t_o}$ radians/sec	$V_{tangential} = r\,\omega$ ft/sec
Acceleration	$\alpha_{avg} = \dfrac{\omega_f - \omega_o}{t_f - t_o}$ radians/sec^2	$a_{tangential} = r\,\alpha$ ft/sec^2

$$\omega_f = \omega_o + \alpha\, t$$

$$\theta = \omega_o t + \frac{\alpha t^2}{2}$$

(1 radian = 57.3 degrees)

Major problems for satellites

- Positioning in orbit
- Stability
- Power
- Communications
- Harsh environment

Positioning

- This can be achieved by several methods
- One method is to use small rocket motors
- These use fuel - over half of the weight of most satellites is made up of fuel
- Often it is the fuel availability which determines the lifetime of a satellite
- Commercial life of a satellite typically 10-15 years

Stability

- It is vital that satellites are stabilised
  - to ensure that solar panels are aligned properly
  - to ensure that communications antennae are aligned properly
- Early satellites used spin stabilisation
  - Either this required an inefficient omni-directional aerial
  - Or antennae were precisely counter-rotated in order to provide stable communications

Stability (2)

- Modern satellites use reaction wheel stabilisation - a form of gyroscopic stabilisation Other methods of stabilisation are also possible
- including:
  - eddy currrent stabilisation
  - (forces act on the satellite as it moves through the earth's magnetic field)

Reaction wheel stabilisation

- Heavy wheels which rotate at high speed - often in groups of 4.
- 3 are orthogonal, and the 4th (spare) is a backup at an angle to the others
- Driven by electric motors - as they speed up or slow down the satellite rotates
- If the speed of the wheels is inappropriate, rocket motors must be used to stabilise the satellite - which uses fuel

Power

- Modern satellites use a variety of power means
- Solar panels are now quite efficient, so solar power is used to generate electricity
- Batteries are needed as sometimes the satellites are behind the earth - this happens about half the time for a LEO satellite
- Nuclear power has been used - but not recommended

Harsh Environment

- Satellite components need to be specially "hardened"
- Circuits which work on the ground will fail very rapidly in space
- Temperature is also a problem - so satellites use electric heaters to keep circuits and other vital parts warmed up - they also need to control the temperature carefully

Alignment

- There are a number of components which need alignment
  - Solar panels
  - Antennae
- These have to point at different parts of the sky at different times, so the problem is not trivial

Antennae alignment

- A parabolic dish can be used which is pointing in the correct general direction
- Different feeder "horns" can be used to direct outgoing beams more precisely
- Similarly for incoming beams
- A modern satellite should be capable of at least 50 differently directed beams

Satellite - satellite communication

- It is also possible for satellites to communicate with other satellites
- Communication can be by microwave or by optical laser

LEOs

- Low earth orbit satellites - say between 100 - 1500 miles
- Signal to noise should be better with LEOs
- Shorter delays - between 1 - 10 ms typical
- Because LEOs move relative to the earth, they require tracking

Orbits

- Circular orbits are simplest
- Inclined orbits are useful for coverage of equatorial regions
- Elliptical orbits can be used to give quasi stationary behaviour viewed from earth
  - using 3 or 4 satellites
- Orbit changes can be used to extend the life of satellites

Communication frequencies

- Microwave band terminology
  - L band 800 MHz - 2 GHz
  - S band 2-3 GHz
  - C band 3-6 GHz
  - X band 7-9 GHz
  - Ku band 10-17 GHz
  - Ka band 18-22 GHz

Early satellite communications

- Used C band in the range 3.7-4.2 GHz
- Could interfere with terrestrial communications
- Beamwidth is narrower with higher frequencies

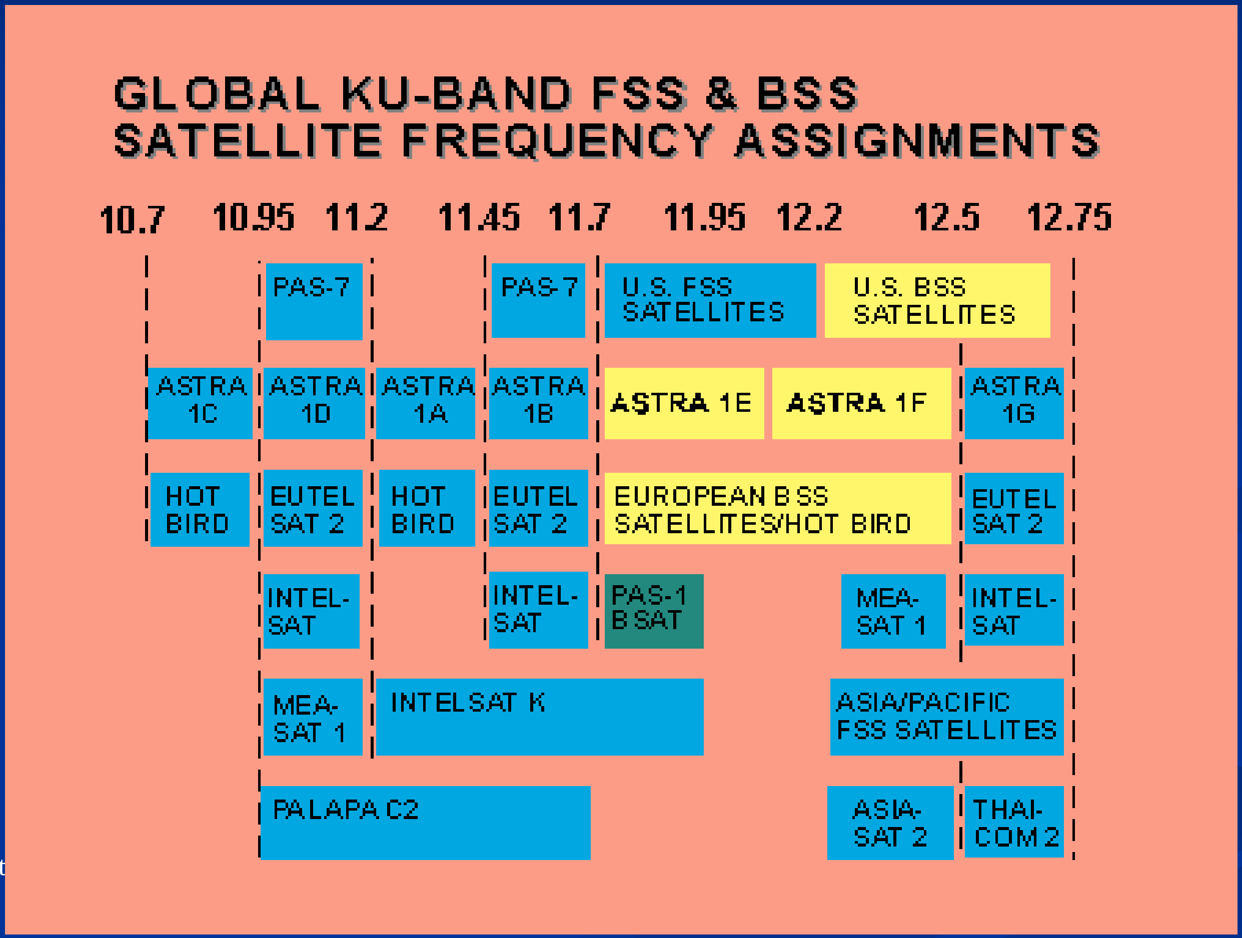
More recent communications

- Greater use made of Ku band
- Use is now being made of Ka band

Rain fade

- Above 10 GHz rain and other disturbances can have a severe effect on reception
- This can be countered by using larger receiver dishes so moderate rain will have less effect
- In severe rainstorms reception can be lost
- In some countries sandstorms can also be a problem

Ku band assignments

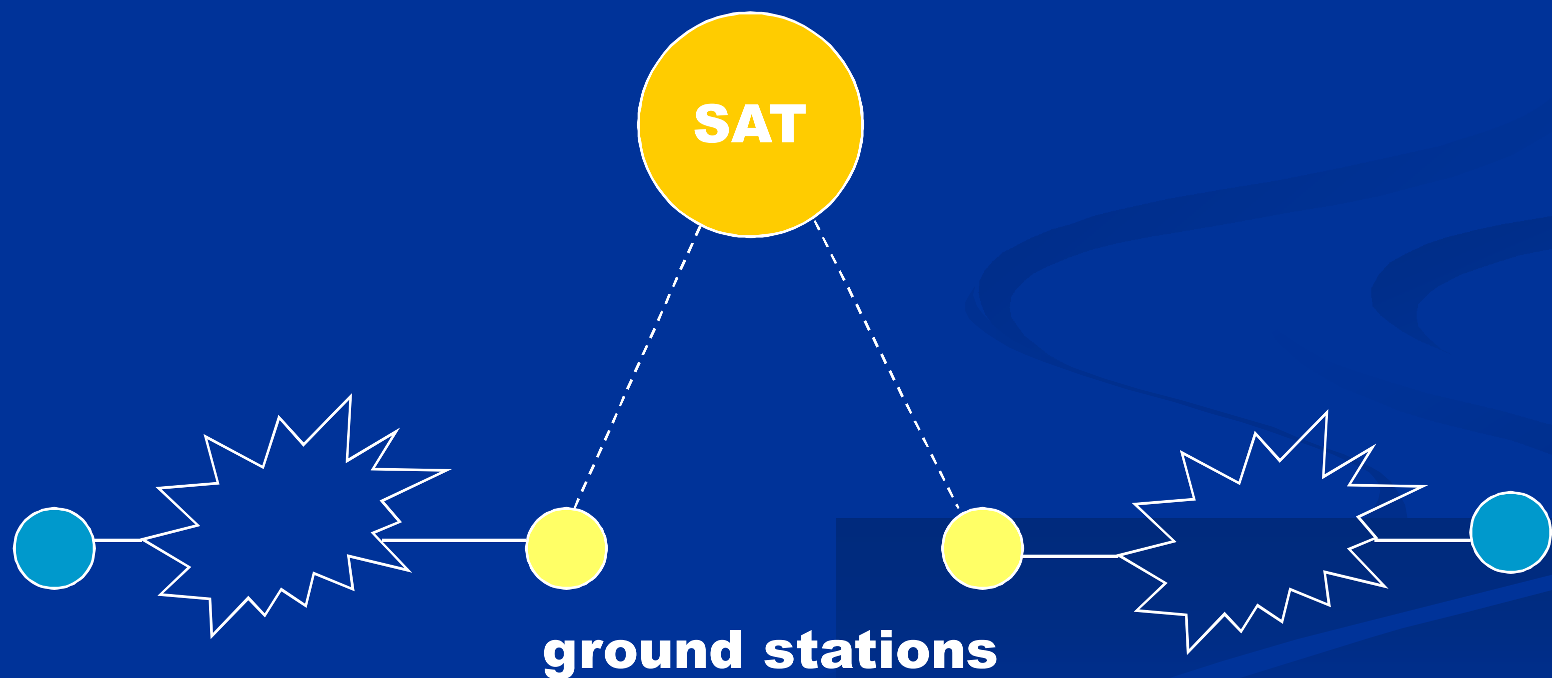


Satellite management

- Satellites do not just "stay" in their orbits
- They are pushed around by various forces
- They require active management

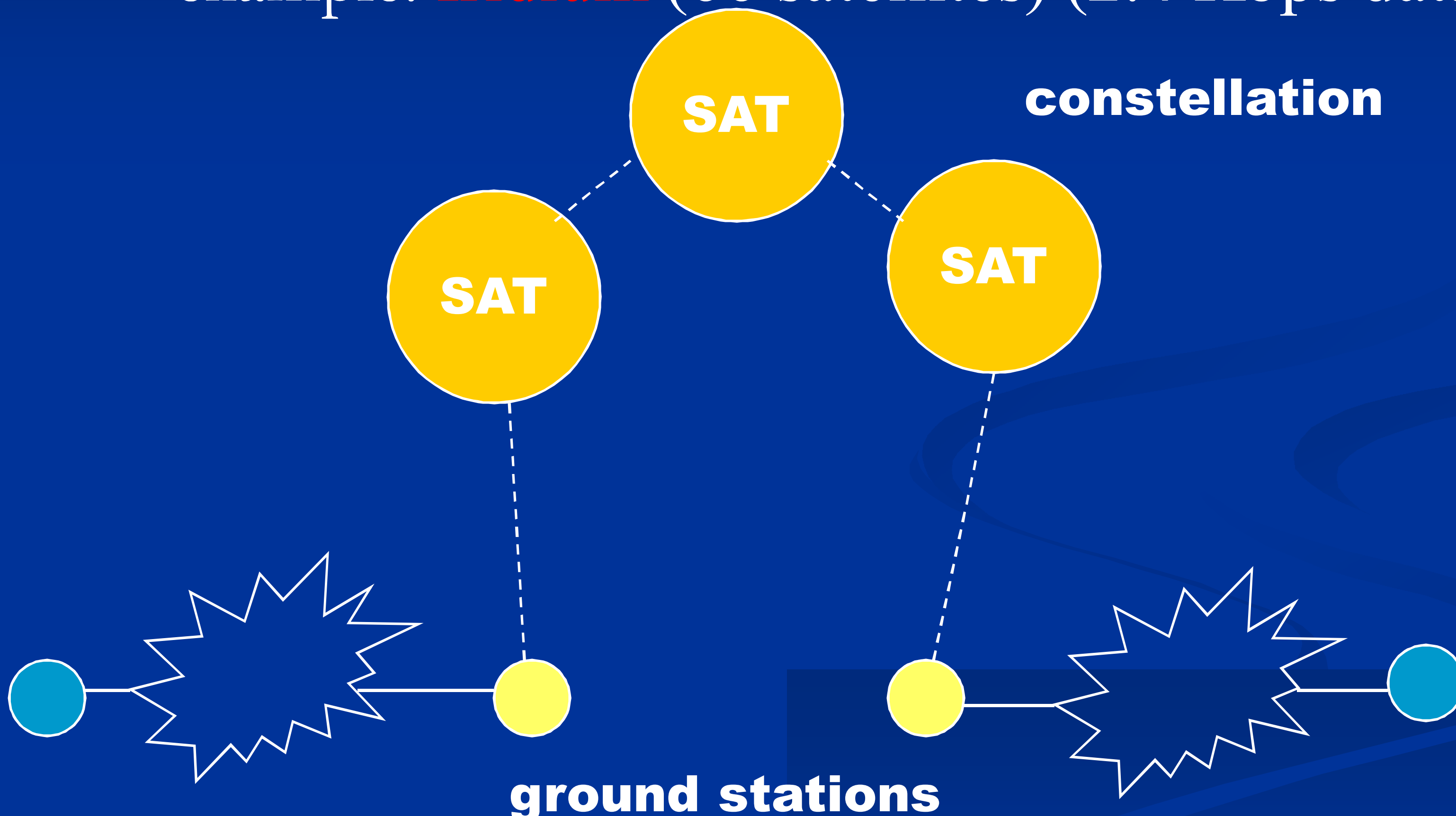
Satellites

- Geostationary Earth Orbit (GEO) Satellites
  - example: Inmarsat



Satellites

- Low-Earth Orbit (LEO) Satellites
  - example: Iridium (66 satellites) (2.4 Kbps data)



Satellites

- GEO
  - long delay - 250-300 ms propagation delay
- LEO
  - relatively low delay - 40 - 200 ms
  - large variations in delay - multiple hops/route changes, relative motion of satellites, queueing