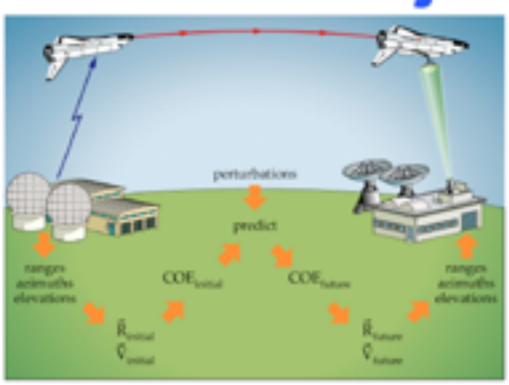
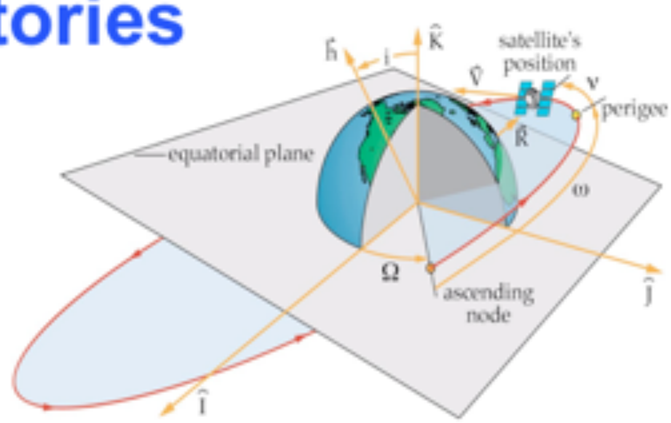
An Introduction to Astronautics
and
Space Systems

Block 2 Study Guide

Orbits & Trajectories





Lesson 1 - The Space Environment

Review

‣ For our purposes, space begins at an altitude where a satellite can briefly maintain an orbit. Thus, space is close. It's only about 130 km (81 mi) straight up.
‣ Six major environmental factors affect spacecraft in Earth orbit.

- Gravity - Earth exerts a gravitational pull which keeps spacecraft in orbit. We best describe the condition of spacecraft and astronauts in orbit as free fall, because they're falling around Earth.
- Atmosphere - Earth's atmosphere isn't completely absent in low-Earth orbit. It can cause drag exposure to atomic oxygen
- Vacuum - In the vacuum of space, spacecraft can experience: Outgassing, Cold Welding and Heat Transfer issues
- Micrometeoroids and space junk - can damage spacecraft during a high speed impact
- Radiation - from the Sun, can cause: Heating on exposed surfaces, Damage to electronic components and disruption in communication, and Solar Pressure, which can change a spacecraft's orientation
- Charged particles
  - Three sources: Solar wind and flares, Galactic cosmic rays (GCRs), and Van Allen radiation belts
  - Earth's magnetic field (magnetosphere) protects it from charged particles. The Van Allen radiation belts contain charged particles, trapped and concentrated by this magnetosphere.
  - Charged particles from all sources cause: Charging, Sputtering, Single event phenomena (SEP) and Total dose effects

Key Terms

- Atmosphere
- Atomic Oxygen
- Charged Particles
- Cold-welding
- Conduction
- Convection
- Drag
- Free-fall
- Gravity

Micrometeoroids
Out-gassing
Radiation
Solar Pressure
Space Junk
Vacuum

Lesson 1 - Mission Problems

1. Where does space begin?

2. List and briefly describe the six major hazards of the space environment and their effect on spacecraft.

3. Match the following terms with the appropriate statement below: outputs from the Sun, outgassing, single-event phenomenon, free-fall

a. falling under the influence of gravity, free from any other forces
b. a single charged particle can penetrate deep into the spacecraft to disrupt electronics
c. release of trapped gases and evaporated material from spacecraft in orbit
d. electromagnetic radiation that we see as light and feel as heat and charged particles

4. Define the following terms:

Van Allen Radiation Belts

South Atlantic Anomaly

Lesson 2 - Understanding Orbits Part 1

Review

‣ Orbits are like giant racetracks on which spacecraft "drive" around Earth.
‣ From a conceptual standpoint, orbital motion involves giving an object enough horizontal velocity so that, as gravity pulls it down, it is traveling fast enough to have Earth's surface curve away from it so that it never hits Earth.

- As a result, it stays above the surface.
- An object in orbit is essentially falling around the Earth but going so fast it never hits it.

‣ Near the Earth's surface, circular orbital velocity is about 8 km/s

- This velocity varies with altitude. The higher the altitude, the lower the circular orbital velocity.

Key Terms

- Acceleration due to gravity
- Aristotle
- Circular orbit
- Elliptical orbit
- Galileo
- Hyperbolic trajectory
- Velocity

Lesson 2 - Mission Problems

1. Explain how an object's horizontal velocity allows it to achieve orbit.

2. An object in a circular orbit is given a bit of extra velocity. What type of orbit will it now be in?

3. Match the following terms or values to the appropriate descriptions below: 8 km/sec, orbits, horizontal velocity, 3.1 km/sec

a. if an orbiting object has enough of this, as gravity pulls it down, it is traveling fast enough to have Earth's surface curve away from it so it never hits the Earth.
b. circular orbital velocity 35,000 km above the Earth's surface
c. circular orbital velocity near the Earth's surface
d. giant racetracks on which spacecraft "drive" around the Earth

4. Briefly describe the following:

Aristotle's view of falling objects -

Galileo's view of falling objects -

Lesson 3 - Understanding Orbits Part 2

Review

‣ Combining Newton's Second Law and his Law of Universal Gravitation, we form the restricted two-body equation of motion

- The coordinate system used to derive the two-body equation of motion is the geocentric-equatorial system
    - Origin—Earth's center
    - Fundamental plane—equatorial plane
    - Direction perpendicular to the plane in the North Pole direction
    - Principal direction—vernal equinox direction
- In deriving this equation, we assume
    - Drag force is negligible
    - Spacecraft is not thrusting
    - Gravitational pull of third bodies and all other forces are negligible
    - $m_{Earth} >> m_{spacecraft}$
    - Earth is spherically symmetrical and of uniform density and we can treat it mathematically as a point mass
    - Spacecraft mass is constant, so $\Delta m = 0$
    - The geocentric-equatorial coordinate system is sufficiently inertial for Newton's laws to apply

‣ Solving the restricted two-body equation of motion results in the polar equation for a conic section

Key Terms

- Drag
- Fundamental plane
- Geocentric-equatorial
- Inertial
- Law of Universal Gravitation
- Newton's 2nd Law
- Origin
- Principle direction
- Symmetrical
- Two-body equation of motion
- Third body

Lesson 3 - Mission Problems

1. List the simplifying assumptions that we use to “restrict” the two-body equation of motion.

2. Describe the potential, kinetic and total energy of a baseball that is thrown into the air, reaches its highest point and then hits the ground.

3. Match the following names with the correct statement below: Newton’s First Law, Newton’s Second Law, Newton’s Third Law, Newton’s Law of Universal Gravitation

a. a net force causes an acceleration
b. action/reaction
c. a body at rest, stays at rest
d. force is inversely proportional to the square of the distance

4. In solving the restricted two-body equation of motion, we obtain the polar equation of a conic section. Why is this significant?

Lesson 4 - Describing and Using Orbits Part 1

Review

- To specify a spacecraft's orbit in space, you need to know six things about it
  - Orbit's size
  - Orbit's shape
  - Orbit's orientation (three angles)
  - Spacecraft's location
- The six classic orbital elements (COEs) specify these six pieces of information
  - Semimajor axis, a—one-half the distance across the long axis of an ellipse. It specifies the orbit's size and relates to an orbit's energy.
  - Eccentricity, e—specifies the shape of an orbit and tells what type of conic section it is
  - Inclination, i—specifies the orientation or tilt of an orbital plane with respect to a fundamental plane: the equator
  - Right ascension of the ascending node, Ω—specifies the orientation or swivel of an orbital plane with respect to the principal direction
  - Argument of perigee, ω—specifies the orientation of an orbit within the plane
  - True anomaly, ν—specifies a spacecraft's location along its orbital path

Key Terms

- Argument of perigee, ω
- Ascending node
- Classical Orbital Elements (COEs)
- Eccentricity, e
- Inclination, i
- Right ascension of the ascending node, Ω
- Semimajor axis, a
- True anomaly, ν

Lesson 4 - Mission Problems

1. How many initial conditions (ICs) do we need for solving the two-body equation of motion? Give an example of one set of ICs.

2. What four things do classic orbital elements (COEs) tell us about a spacecraft's orbit and the spacecraft's position in the orbit?

3. Match the following with the appropriate descriptions below: semimajor axis, eccentricity, inclination, argument of perigee, right ascension of the ascending node and true anomaly.

a. orbital out of roundness

b. measured in the direction of satellite motion

c. calculated from the specific mechanical energy

d. tells us the tilt of our orbit plane

e. the only COE that constantly changes

f. tells us the swivel of our orbit plane with respect to the vernal equinox

Lesson 5 - Describing and Using Orbits Part 2

Review

‣ Orbital geometry helps us understand what a satellite in a given orbit can see and when. Key parameters include:

- Field of Regard (FOR): The angle that describes the potential cone of visibility for a satellite or sensor limited by geometric constraints (e.g. edge of radio horizon)
- Field of View (FOV): The angle that describes the actual cone (or other shape) of visibility for a sensor limited by physical constraints (e.g. the lens, image plane or antenna beam pattern)
- Elevation angle, ε, angle measured from local horizon at the edge of the FOR to the satellite or sensor

‣ A ground track is the path a spacecraft traces on Earth's surface as it orbits. Because a spacecraft orbits around Earth's center, the orbital plane
slices through the center.

‣ When the spherically-shaped Earth is spread out on a two-dimensional, unprojected equal latitude and longitude map, the orbital ground track resembles a sine wave for orbits with periods less than 24 hours

‣ Because orbital planes are fixed in inertial space and Earth rotates beneath them, ground tracks appear to shift westward during successive orbits

‣ From a ground track, you can find several orbital parameters

- Orbital period—by measuring the westward shift of the ground track
- Inclination of a spacecraft's orbit—by looking at the highest latitude reached on the ground track (for direct orbits)
- Approximate eccentricity of the orbit—(nearly) circular orbits appear symmetrical, whereas eccentric orbits appear lopsided
- Location of perigee—by looking at the point where the ground track is spread out the most

‣ Basic orbits include:

- Low Earth Orbit (LEO)
- Geostationary Orbit (GEO)

Key Terms

• Elevation angle	GEO and LEO
• Field of Regard (FOR)	Ground Track
• Field of View (FOV)	Swath

Lesson 5 - Mission Problems

1. Given a rotating Earth, if the inclination stays the same but the orbital size increases or decreases, does the ground track change? Why or why not? Describe what, if anything, happens to the ground track.

2. What type of ground track does a geosynchronous spacecraft with a 30 degree inclination have?

3. Match the following terms with the best description below: Sine wave, point on the equator, 60 degrees, "scrunch it"

a. If we raise a spacecraft's orbit, we do this to its ground track.

b. Low-Earth, circular orbits trace this kind of ground track on a flat Mercator projection.

c. Minimum inclination for a spacecraft to pass over Oslo, Norway (about 60° N latitude)

d. A geostationary orbit has this kind of a ground track.

4. Define the following terms:

FOR

FOV

Swath

Lesson 6 - Predicting Orbits

Review

- Satellite tracking requires we
  - First determine where a satellite is (its COEs)
  - Second predict where it will be in the future
- Kepler's Equation gives us the solution to two problems
  - Finding the time of flight between two known orbital positions
  - Finding a future orbital position, given the time of flight
- Perturbations resulting from small disturbing forces cause our two-body orbit to vary.
  - These include: drag, oblateness (J2), solar pressure, and 3rd body effects.
  - We take advantage of these effects for sun-synchronous and Molniya (HEO) orbits
- Real-world orbit design involves balancing competing requirements to select an orbit that is the best compromise for a given mission.

Key Terms

- Atmospheric drag
- Azimuth
- Eccentric anomaly, E
- Elevation
- J2 effect
- Mean anomaly, M
- Mean motion, n
- Molniya
- Oblateness
- Perturbations
- Precession
- Range
- Sunsynchronous

Lesson 6 - Mission Problems

1. Briefly describe how to track and predict an orbit.

2. Describe the effects of atmospheric drag on the orbits of spacecraft in low-Earth orbit (LEO).

3. Describe the effects of an oblate Earth on the orbits of spacecraft in low-Earth orbit (LEO).

4. Match the following terms with the best description below: solar radiation pressure, 3rd body effects, Range, Azimuth, Elevation.

a. Radar's angle along the horizontal plane from true north to a spacecraft

b. Gravitational effects of the Moon, Sun and other planets which can perturb orbits at high altitudes

c. Distance between a tracking site and a spacecraft

d. Radar's angle above the horizon to a spacecraft

e. Can cause long-term orbital perturbations and unwanted spacecraft rotation

Lesson 7 - Maneuvering in Space

Review

‣ The Hohmann Transfer moves a spacecraft from one orbit to another in the same plane. It's the simplest kind of orbital maneuver because it focuses only on changing the spacecraft's specific mechanical energy, ε.
‣ The Hohmann Transfer consists of two separate ΔVs
- The first, $\Delta V1$, accelerates the spacecraft from its initial orbit into an elliptical transfer orbit
- The second, $\Delta V2$, accelerates the spacecraft from the elliptical transfer orbit into the final orbit

‣ We need plane change maneuvers to move a spacecraft from one orbital plane to another
- Simple plane changes alter only the direction, not the magnitude, of the velocity vector for the original orbit
- A combined plane change alters the magnitude and direction of the original velocity vector
  - It's always cheaper (in terms of ΔV) to do a combined plane change than to do a simple plane change followed by a Hohmann Transfer burn
- It's cheaper (in terms of ΔV) to change planes when the orbital velocity is slowest, which is at apogee for elliptical transfer orbits

‣ Rendezvous is the problem of arranging for two or more spacecraft to arrive at the same point in an orbit at the same time
- The rendezvous problem is very similar to the problem quarterbacks face when they must "lead" a receiver with a pass. But because the interceptor and target spacecraft travel in circular orbits, the proper relative positions for rendezvous repeat periodically.
- We assume spacecraft rendezvous uses a Hohmann Transfer

Key Terms

- Combined plane change
- Coplanar orbit
- Lead angle
- Hohmann Transfer
- Phase angle

Phasing Orbit
Rendezvous
Simple plane change
Tangent
Transfer orbit

Lesson 7 - Mission Problems

1. List and briefly describe the assumptions that allow us to use a Hohmann Transfer.

2. When going from a smaller circular orbit to a larger one, why do we speed up twice but end up with a slower velocity in the final orbit?

3. Match the following terms with the best description below: Lead angle, Initial Phase angle, Simple plane change, Combined plane change.

a. An orbital adjustment that only alters the direction of the velocity vector, not its magnitude.

b. The cheapest way to change inclination and orbit size; requires only one Hohmann burn to complete orbit resize.

c. The orbital distance that an interceptor spacecraft must aim ahead of a target to rendezvous with it.

d. The orbital distance between an interceptor spacecraft and a target spacecraft at the beginning of a Hohmann-transfer-rendezvous maneuver.

4. Define the following terms:

Hohmann Transfer

Rendezvous

Lesson 8 - Launch & Re-entry

Review

‣ A launch window is the period during which we can launch directly into a desired orbit from a particular launch site

- For a launch window to exist at a given launch site, the latitude of the launch site, Lo, must be less than or equal to the inclination of the desired orbit ($Lo \leq i$).

‣ We design a launch vehicle to go from a given launch site and deliver a spacecraft of a certain size into a specified orbit. It does this in four phases: Vertical ascent, Pitch over, Gravity turn, and Vacuum

‣ Because Earth is rotating eastward, a launch vehicle sitting on the launch pad already has some velocity in the eastward direction. Thus,

- A launch vehicle has a “head start” for launching into direct orbits
- A launch vehicle must overcome Earth’s rotation to get into a retrograde orbit
- The velocity of a launch site depends on the launch-site’s latitude and is in the eastward direction

‣ Launch vehicles must meet two primary objectives

- Increase altitude to orbital altitude
- Increase velocity to orbital velocity, ~9.3 km/s including losses

‣ Re-entry design must balance three competing requirements: Deceleration; Heating; and Accuracy

‣ We can meet re-entry mission requirements on the trajectory front by changing

- Re-entry velocity, $V_{re\text{-}entry}$
- Re-entry flight-path angle, γ

‣ We can meet mission requirements on the design front by changing

- Vehicle size and shape, BC
- Vehicle thermal-protection systems (TPS)

Key Terms

- Ablation
- Accuracy
- Aerobraking
- Ballistic coefficient (BC)
- Deceleration
- Delta V design
- Delta V losses
- Flight-path angle
- Gravity turn
- Heating
- Launch azimuth
- Launch site latitude
- Launch window
- Lifting entry
- Pitch over
- Retrograde orbit
- Thermal-protection systems (TPS)
- Vertical ascent

Lesson 8 - Mission Problems

1. Mission planners want to launch the Space Shuttle from Kennedy Space Center (Lo = 28.5°) into an orbit with an inclination of 28.5°. How many launch windows will there be each day? Draw a diagram to illustrate this case. How would this change if the desired inclination were 57°? Draw a diagram to illustrate this case.

2. List and briefly describe the two approaches we can use to balance competing re-entry requirements?

3. Match the following terms with the best description below: delta V design, lifting entry, low BC, delta V losses

a. light and/or blunt vehicle which slows down quickly

b. the total velocity we need our launch vehicle to provide in order to overcome losses and still achieve our desired orbit

c. velocity required to overcome significant air drag, back pressure and steering losses encountered on the way from the launch pad into orbit

d. allows us to stretch the size of the re-entry corridor and improve accuracy by flying the vehicle to the landing site

4. Define the following terms:

Ballistic Coefficient

Ablation