Last updated: November 1, 2026

🗺️ Four-year roadmap · Year 3, Fall · 🧮 Built-in calculator

About this course

This free course has 10 units and 6 labs. Those are the real counts, not a longer syllabus cut short.

A check is one number or code result on a course page that a script recomputes before the page is published. The printed number and the recomputed number have to match.

> This is a free self-study course outline written by Saving Planets. It is not a university course, it carries no academic credit, and no school is involved.
>
> Its scope follows a one-semester junior orbital mechanics course. It is modeled on the topics and depth of MIT 16.346 Astrodynamics and the orbital parts of MIT 16.07 Dynamics (free on MIT OpenCourseWare), and on courses such as Purdue AAE 340 and Georgia Tech AE 3330, using NASA's free Basics of Space Flight and OpenStax University Physics, which we link where they help. None of those authors, schools or agencies endorses this page.
>
> What we add: every unit ties to real work with a cited public source (Landsat, GOES weather satellites, NASA's DART planetary-defense test and orbital-debris rules), every number on the page is re-computed by a checking script before it goes live, and every lab has a free simulation or a spreadsheet.
>
> Work through it in order. Each unit has goals, key ideas, equations, step-by-step examples, practice with full answers, common mistakes, flashcards and a quiz. Your progress is saved only in this browser.

How this course helps save the planet

Orbits are how we watch our planet: Earth-observing satellites in low orbits map forests, crops and water, and geostationary weather satellites watch storms around the clock. Choosing those orbits is pure orbital mechanics.

Orbits are also a shared, limited resource. Debris left in space threatens the satellites we rely on, so responsible mission design now includes a plan to leave orbit. Each unit ends with a short, sourced section. Values that are not from a source are labeled as sample or textbook values.

For instructors

You can teach this course, or let a student work through it alone. It is free. Saving Planets does not give a grade or school credit.

- This page is the whole course: 10 units and 6 labs (AERO 340).
- Plan on 15 weeks, about 6 to 9 hours a week, including the lab weeks.
- Follow the 15-week schedule. Read the unit, do the practice on paper, then open the answer. In a lab week, do the lab or the home version.
- A check is one number or code result on the page that a script recomputes before we publish. The number you see and the recomputed number have to match.
- Use Print this page, or download the PDF study guide. The formula sheet is near the end.
- Ask: how does this unit help people and the planet? Each unit has a green box with a sourced fact.
- Copy the teacher guide template and write in your class name, the time you have, and the questions you will ask. Open the teacher guide template

Before you start

Prerequisites

- Dynamics: Newton’s laws, angular momentum and energy.
- Calculus III and Differential Equations: vectors, gradients and ODEs.
- Linear Algebra: vectors, rotations and coordinate frames.
- Physics I: universal gravitation.

How to study

- Start every problem with a sketch of the orbit: central body, periapsis, apoapsis and the spacecraft’s position.
- Write the vis-viva equation first; it answers most speed questions.
- Keep units in metres and seconds, and μ in m^3/s^2; convert to km only at the end.
- Draw each maneuver as a velocity triangle before computing Δv.
- Check limits: a circular orbit has $e = 0$; escape has zero total energy.
- Do every practice problem on paper before opening the answer, and retake the quizzes a few days later.

What you need

- A computer or tablet for the free PhET Gravity and Orbits, Kepler’s Laws and My Solar System simulations.
- NASA’s Eyes on the Solar System in a web browser.
- Spreadsheet software for the transfer, rocket-equation and ground-track labs.

- A calculator with trigonometric functions.

Suggested 15-week schedule

About 6 to 9 hours a week: reading, practice problems and, in lab weeks, the lab.

Week	Unit	Topics	Reading
1	Gravity, the Two-Body Problem and Circular Orbits	Gravity, two-body problem, circular orbits; Lab A	OpenStax UP1 13.4–13.5
2	Conic Sections, Energy and Orbital Elements	Energy, angular momentum, conics	MIT 16.346
3	Conic Sections, Energy and Orbital Elements	Vis-viva and orbital elements; Lab B	NASA Basics of Space Flight
4	Kepler’s Equation and Time of Flight	Kepler’s equation and time of flight	MIT 16.346
5	Orbit Transfers: Hohmann and Beyond	Impulsive maneuvers and Hohmann transfers	MIT 16.346
6	Orbit Transfers: Hohmann and Beyond	Bi-elliptic, phasing, deorbit; Lab C	MIT 16.346
7	Plane Changes and Combined Maneuvers	Plane changes and combined burns; midterm practice	MIT 16.346
8	Rockets, Δv Budgets and Staging	Rocket equation, staging, Δv budgets; Lab D	OpenStax UP1 9.7
9	Perturbations: Earth’s Bulge, Drag and Sun-Synchronous Orbits	J_2 and nodal regression	MIT 16.346
10	Perturbations: Earth’s Bulge, Drag and Sun-Synchronous Orbits	Sun-synchronous orbits and drag; Lab E	NASA Landsat 9
11	Ground Tracks, Coverage and Constellations	Ground tracks, coverage, constellations; Lab F	NASA Eyes
12	Interplanetary Transfers and Patched Conics	Heliocentric transfers and patched conics	NASA Basics of Space Flight
13	Interplanetary Transfers and Patched Conics	Launch windows and gravity assists	NASA Basics of Space Flight
14	Space Sustainability: Debris, Disposal and Planetary Defense	Debris, disposal and collision avoidance	NASA ODPO; FCC

Week	Unit	Topics	Reading
15	Space Sustainability: Debris, Disposal and Planetary Defense	Planetary defense; final practice	NASA DART

Your progress

Tick units and labs as you finish them, and take the quizzes. Progress and quiz scores are saved only in this browser, never sent to us.

Units

Gravity, the Two-Body Problem and Circular Orbits

Newton’s law of gravitation, the gravitational parameter μ, the two-body equation of motion, circular orbit speed and period, escape speed, Kepler’s three laws, and low, medium and geostationary orbits.

Learning objectives

By the end of this unit you can:

- Write the two-body equation of motion.
- Compute circular orbit speed and period.
- Compute escape speed.
- Find the geostationary radius.

Key concepts

- Newton’s gravity gives the two-body equation r̈ = −μr/r³, with μ = GM. For Earth μ = 3.986 × 10¹⁴ m³/s².
- A circular orbit has speed v = √(μ/r) and period T = 2π√(r³/μ): higher orbits are slower and take longer.
- Escape speed is √2 times circular speed at the same radius: v_esc = √(2μ/r).
- Kepler’s laws: orbits are ellipses with the central body at a focus; the radius sweeps equal areas in equal times; and T² is proportional to a³.
- A geostationary orbit has a period of one sidereal day (86,164.1 s) and lies over the equator, so the satellite stays over the same spot.

Key equations

$$\ddot{\mathbf{r}} = -\frac{\mu}{r^3}\mathbf{r}$$

```
r=-(μ)/(r^3) r
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Two-body equation

$$v_c = \sqrt{\frac{\mu}{r}}$$

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v_c=(μ)/(r)
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Circular speed

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

T=2π(a^3)/(μ)

Period

$$v_{esc} = \sqrt{\frac{2\mu}{r}}$$

v_esc=(2μ)/(r)

Escape speed

Worked examples, step by step

Example 1.1 Find the speed and period of a circular orbit 400 km up.

1. r = 6378 + 400 = 6778 km.
2. v = √(3.986 × 10¹⁴/6.778 × 10⁶).
3. T = 2π√(r³/μ).

Answer: v = 7.67 km/s; T = 92.6 min.

Example 1.2 Find escape speed from that altitude.

1. v_esc = √2 × 7.669.

Answer: v_esc = 10.85 km/s.

Example 1.3 Find the geostationary radius and altitude.

1. r = (μT²/(4π²))^(1/3) with T = 86,164.1 s.
2. Altitude = 42,164 − 6378.

Answer: r = 42,164 km; altitude 35,786 km (22,236 miles); v = 3.07 km/s.

Practice problems

Work each on paper first, then check.

1. Find the period of a circular orbit 705 km up.

   98.9 min.

2. Find the speed there.

7.50 km/s.

3. How many orbits a day is that?

   1440/98.87 = 14.56.

4. Convert 7.67 km/s to mph.

   17,154 mph.

Common misconceptions

Myth: Higher orbits are faster.
Actually: They are slower.

Myth: Astronauts float because there is no gravity.
Actually: They are in free fall around Earth.

Myth: A geostationary orbit can be over any city.
Actually: It must be over the equator.

Flashcards

μ

GM = 3.986 × 10^{14} m^3/s^2.

Circular speed

√(μ/r).

Period

$2\pi\sqrt{(a^3/\mu)}$.

Escape

√(2μ/r).

Kepler 3

$T^2 \propto a^3$.

GEO

42,164 km radius.

Self-check quiz

1. Circular speed is...

√(μ/r)

μ/r

√(2μ/r)

μr

√(μ/r). Gravity = centripetal.

2. Escape speed is … times circular.

√2

2

1

½

√2. Energy.

3. Kepler’s third law relates…

T^2 and a^3

T and a

v and r

e and a

T^2 and a^3. Harmonic law.

4. GEO period is…

one sidereal day

12 h

90 min

1 year

one sidereal day. Matches rotation.

Try this quiz again

How this helps save the planet

NOAA explains that GOES weather satellites orbit 22,236 miles above Earth's equator at speeds equal to Earth's rotation, so they stay over the same regions and give continuous coverage. Together, GOES East and GOES West watch over more than half the globe, from the west coast of Africa to New Zealand.

The GOES-R series imager can image storms as often as every 30 seconds, and the series carries the first operational lightning mapper in geostationary orbit. The 22,236-mile altitude is exactly this unit's geostationary radius minus Earth's radius.

On Saving Planets: Earth Observation · Physics I

Sources: NOAA NESDIS: GOES-R Series mission (https://www.goes-r.gov/mission/mission.html)

Free learning resources

- OpenStax UP1, 13.5 Kepler's laws of planetary motion (https://openstax.org/books/university-physics-volume-1/pages/13-5-keplers-laws-of-planetary-motion): Free textbook section.
- OpenStax UP1, 13.4 Satellite orbits and energy (https://openstax.org/books/university-physics-volume-1/pages/13-4-satellite-orbits-and-energy): Free textbook section.
- NASA Basics of Space Flight, Chapter 5: Planetary orbits (https://science.nasa.gov/learn/basics-of-space-flight/chapter5-1/): Free NASA chapter.
- PhET: Gravity and Orbits (https://phet.colorado.edu/en/simulations/gravity-and-orbits): Orbits interactively.

☐ **I finished this unit**

Conic Sections, Energy and Orbital Elements

Conservation of energy and angular momentum, the orbit equation, ellipses, parabolas and hyperbolas, eccentricity, the vis-viva equation, periapsis and apoapsis speeds, and the six classical orbital elements.

Learning objectives

By the end of this unit you can:

- Use vis-viva to find speeds.
- Relate eccentricity to periapsis and apoapsis.
- Compute specific energy and angular momentum.
- Name and interpret the six orbital elements.

Key concepts

- Specific energy ε = v²/2 − μ/r = −μ/(2a) is constant: negative for ellipses, zero for parabolas and positive for hyperbolas.
- Specific angular momentum h = r × v is constant, so the orbit lies in a fixed plane.
- The orbit equation r = (h²/μ)/(1 + e cos ν) gives the radius at true anomaly ν. Eccentricity e = (r_a − r_p)/(r_a + r_p) for an ellipse.
- The vis-viva equation v² = μ(2/r − 1/a) gives the speed anywhere on any orbit.
- Six classical elements fix an orbit: semi-major axis a, eccentricity e, inclination i, right ascension of the ascending node Ω, argument of periapsis ω and true anomaly ν.

Key equations

$$\varepsilon = \frac{v^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a}$$

`=(v^2)/(2)-(μ)/(r)=-(μ)/(2a)`

Specific energy

$$v^2 = \mu\left(\frac{2}{r} - \frac{1}{a}\right)$$

`v^2=μ(2r-1a)`

Vis-viva

$$r = \frac{h^2/\mu}{1 + e\cos\nu}$$

`r=(h^2/μ)/(1+eν)`

Orbit equation

$$e = \frac{r_a - r_p}{r_a + r_p}$$

`e=(r_a-r_p)/(r_a+r_p)`

Eccentricity

Worked examples, step by step

Example 2.1 An orbit has perigee radius 6778 km and apogee radius 42,164 km. Find a and e.

1. a = (6778 + 42,164)/2 = 24,471 km.
2. e = (42,164 − 6778)/(42,164 + 6778).

Answer: a = 24,471 km; e = 0.723.

Example 2.2 Find its specific energy.

1. ε = −3.986 × 10^{14}/(2 × 2.4471 × 10^{7}).

Answer: ε = −8.14 MJ/kg.

Example 2.3 Find the speeds at perigee and apogee.

1. v_p = √(μ(2/r_p − 1/a)).
2. v_a = √(μ(2/r_a − 1/a)).

Answer: v_p = 10.07 km/s; v_a = 1.62 km/s.

Practice problems

Work each on paper first, then check.

1. Find h at perigee.

   r_p v_p = 6.778 × 10^{6} × 10,066 = 6.82 × 10^{10} m^2/s.

2. What is e for a circle?

0.

3. What sign is ε for an escape trajectory?

   Zero or positive.

4. Find the period of the orbit above.

   $2\pi\sqrt{(a^3/\mu)} = 10.58$ h.

Common misconceptions

Myth: The satellite moves at constant speed on an ellipse.
Actually: Fastest at periapsis, slowest at apoapsis.

Myth: Inclination is measured from the North Pole.
Actually: From the equator plane.

Myth: Energy depends on eccentricity.
Actually: Only on a.

Flashcards

Energy

$-\mu/(2a)$.

Vis-viva

$v^2 = \mu(2/r - 1/a)$.

Angular momentum

$h = r \times v$.

Orbit equation

$r = (h^2/\mu)/(1 + e \cos \nu)$.

Eccentricity

$(r_a - r_p)/(r_a + r_p)$.

Elements

a, e, i, Ω, ω, ν.

Self-check quiz

1. Vis-viva gives...

speed

period

inclination

node

speed. $v^2 = \mu(2/r - 1/a)$.

2. An ellipse has...

$\varepsilon < 0$

$\varepsilon = 0$

$\varepsilon > 0$

$e > 1$

$\varepsilon < 0$. Bound orbit.

3. Speed is highest at...

periapsis

apoapsis

the node

everywhere

periapsis. Angular momentum.

4. How many classical elements?

6

3

4

9

6. a, e, i, Ω, ω, ν.

Try this quiz again

How this helps save the planet

NASA lists Landsat 9's orbit as near-polar and sun-synchronous, at 705 km altitude and 98.2° inclination, with a period of 99 minutes, about 14.5 orbits a day, and a nominal equator crossing at 10:12 a.m. local time on the descending pass.

Those few numbers are orbital elements: a from the altitude, e near zero, i = 98.2°, and a node chosen to fix the local crossing time. The steady geometry is what lets Landsat compare images across more than five decades of its record.

On Saving Planets: Earth Observation · Calculus III

Sources: NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/)

Free learning resources

- OpenStax UP1, 13.4 Satellite orbits and energy (https://openstax.org/books/university-physics-volume-1/pages/13-4-satellite-orbits-and-energy): Free textbook section.
- MIT OpenCourseWare 16.346 Astrodynamics (Fall 2008) (https://ocw.mit.edu/courses/16-346-astrodynamics-fall-2008/): MIT notes on conics.
- NASA Basics of Space Flight, Chapter 5: Planetary orbits (https://science.nasa.gov/learn/basics-of-space-flight/chapter5-1/): Free NASA chapter.
- PhET: Kepler's Laws (https://phet.colorado.edu/en/simulations/keplers-laws): Ellipses interactively.

☐ **I finished this unit**

Kepler’s Equation and Time of Flight

Mean motion, mean, eccentric and true anomaly, Kepler’s equation M = E − e sin E, solving it with Newton’s method, time of flight between two points, and position at a given time.

Learning objectives

By the end of this unit you can:

- Relate mean, eccentric and true anomaly.
- Solve Kepler’s equation iteratively.
- Find the time to fly between two true anomalies.
- Predict a satellite’s position at a later time.

Key concepts

- Mean motion n = √(μ/a³) is the average angular rate. Mean anomaly M = n(t − t_p) grows uniformly with time.
- Kepler’s equation links time to geometry: M = E − e sin E, where E is the eccentric anomaly.
- True anomaly follows from tan(ν/2) = √((1 + e)/(1 − e)) tan(E/2).
- Kepler’s equation has no closed-form solution for E; Newton’s method, E ← E − (E − e sin E − M)/(1 − e cos E), converges in a few steps.
- Time of flight from ν_1 to ν_2: find E_1, E_2, then M_1, M_2, and divide the difference by n.

Key equations

$$n = \sqrt{\frac{\mu}{a^3}}$$

`n=(μ)/(a^3)`

Mean motion

$$M = E - e \sin E$$

`M=E-e E`

Kepler’s equation

$$\tan \frac{\nu}{2} = \sqrt{\frac{1+e}{1-e}} \tan \frac{E}{2}$$

`ν2=(1+e)/(1-e) E2`

True anomaly

$$t - t_p = \frac{M}{n}$$

`t-t_p= Mn`

Time since periapsis

Worked examples, step by step

Example 3.1 For e = 0.3, find M when E = π/2.

1. M = 1.5708 − 0.3 × 1.

Answer: M = 1.271 rad.

Example 3.2 For e = 0.3 and M = 1 rad, solve Kepler’s equation.

1. Start E = 1; apply Newton’s method until it settles.

Answer: E = 1.288 rad.

Example 3.3 Find the true anomaly for that E.

1. tan(ν/2) = √(1.3/0.7) × tan(0.644).

Answer: ν = 1.594 rad (91.3°).

Practice problems

Work each on paper first, then check.

1. How long does a LEO-to-GEO transfer take (half of a 10.58 h orbit)?

   5.29 h.

2. For a circle, how are M, E and ν related?

   They are equal.

3. Why can’t we solve for E directly?

   Kepler’s equation is transcendental.

4. What is the mean motion of a 92.6 min orbit in rev/day?

   1440/92.56 = 15.56.

Common misconceptions

Myth: True anomaly grows uniformly with time.

Actually: Mean anomaly does.

Myth: Kepler’s equation applies to hyperbolas unchanged.

Actually: Hyperbolas use a hyperbolic form.

Myth: Newton’s method needs many iterations.

Actually: Usually 3–5.

Flashcards

Mean motion

$n = \sqrt{(\mu/a^3)}$.

Mean anomaly

$M = n(t - t_p)$.

Kepler’s equation

$M = E - e \sin E$.

True anomaly

From $\tan(\nu/2)$.

Newton step

$E - f/f'$.

Time of flight

$\Delta M/n$.

Self-check quiz

1. Kepler’s equation is…

$M = E - e \sin E$

$M = E + e$

$E = \nu$

$n = M/E$

M = E − e sin E. Definition.

2. Mean motion is…

√(μ/a³)

μ/a

√(μa)

a/μ

√(μ/a³). 2π/T.

3. Which anomaly grows uniformly?

mean

true

eccentric

none

mean. M = nt.

4. Kepler’s equation is solved…

iteratively

directly

graphically only

never

iteratively. Newton’s method.

Try this quiz again

How this helps save the planet

NASA reports that before DART's impact, the moonlet Dimorphos took 11 hours and 55 minutes to orbit its parent asteroid Didymos, and that after the impact on September 26, 2022 the period was 11 hours and 23 minutes, a change of 32 minutes (uncertainty about ±2 minutes).

Astronomers measured that change by timing the moonlet's orbit from telescopes on Earth: Kepler's laws turn a small timing shift into proof that the orbit had changed.

On Saving Planets: Calculus II · Earth Observation

Sources: NASA: NASA Confirms DART Mission Impact Changed Asteroid's Motion in Space (Oct. 11, 2022) (https://www.nasa.gov/news-release/nasa-confirms-dart-mission-impact-changed-asteroids-motion-in-space/)

Free learning resources

- MIT OpenCourseWare 16.346 Astrodynamics (Fall 2008) (https://ocw.mit.edu/courses/16-346-astrodynamics-fall-2008/): MIT notes on Kepler's equation.
- OpenStax UP1, 13.5 Kepler's laws of planetary motion (https://openstax.org/books/university-physics-volume-1/pages/13-5-keplers-laws-of-planetary-motion): Free textbook section.
- NASA Basics of Space Flight, Chapter 5: Planetary orbits (https://science.nasa.gov/learn/basics-of-space-flight/chapter5-1/): Free NASA chapter.
- MIT OpenCourseWare 16.07 Dynamics (Fall 2009) (https://ocw.mit.edu/courses/16-07-dynamics-fall-2009/): MIT dynamics notes.

- [ ] **I finished this unit**

Orbit Transfers: Hohmann and Beyond

Impulsive maneuvers and Δv, the Hohmann transfer between circular orbits, transfer time, bi-elliptic transfers, phasing and rendezvous, and raising and lowering orbits.

Learning objectives

By the end of this unit you can:

- Compute Δv for a Hohmann transfer.
- Find the transfer time.
- Explain when bi-elliptic transfers save Δv.
- Plan a simple phasing maneuver.

Key concepts

- An impulsive burn changes velocity instantly by Δv; the orbit after the burn follows from vis-viva.
- The Hohmann transfer uses an ellipse tangent to both circles: burn at the inner orbit to enter the ellipse, and burn again at apoapsis to circularize.
- Transfer time is half the period of the transfer ellipse.
- For very large radius ratios (above about 11.9), a three-burn bi-elliptic transfer can use less Δv, at the cost of much more time.
- Phasing: to catch a target in the same orbit, enter a slightly smaller or larger orbit for one or more revolutions, then return.

Key equations

$$\Delta v_1 = \sqrt{\mu\left(\frac{2}{r_1} - \frac{1}{a}\right)} - \sqrt{\frac{\mu}{r_1}}$$

```
Δ v_1=μ(2r_1-1a)-μr_1
```

First burn

$$\Delta v_2 = \sqrt{\frac{\mu}{r_2}} - \sqrt{\mu\left(\frac{2}{r_2} - \frac{1}{a}\right)}$$

```
Δ v_2=μr_2-μ(2r_2-1a)
```

Second burn

$$a = \frac{r_1 + r_2}{2}$$

```
a=(r_1+r_2)/(2)
```

Transfer ellipse

$$t = \pi\sqrt{\frac{a^3}{\mu}}$$

t=π(a^3)/(μ)

Transfer time

Worked examples, step by step

Example 4.1 Find the Δv for a Hohmann transfer from a 400 km circular orbit to GEO (in the same plane).

1. Δv_1 = 10.066 − 7.669 = 2.398 km/s.
2. Δv_2 = 3.075 − 1.618 = 1.456 km/s.

Answer: Total Δv = 3.85 km/s.

Example 4.2 Find the transfer time.

1. t = π√(24,471,000³/μ).

Answer: t = 5.29 h.

Example 4.3 A deorbit burn at 700 km lowers perigee to 200 km. Find Δv.

1. v_c = √(μ/7078 km).
2. v_a on the 7078 × 6578 km ellipse from vis-viva.

Answer: Δv = 139 m/s.

Practice problems

Work each on paper first, then check.

1. Which burn is larger in the LEO-to-GEO Hohmann?

   The first, 2.40 km/s.

2. Above what radius ratio can bi-elliptic win?

About 11.9.

3. To catch up to a target ahead in the same orbit, go higher or lower?

   Lower (shorter period).

4. Which way do you burn to lower an orbit?

   Retrograde.

Common misconceptions

Myth: To speed up in orbit, burn forward and stay faster.
Actually: Raising the orbit makes you slower overall.

Myth: Hohmann is always the cheapest.
Actually: Not for very large ratios.

Myth: Transfer time is a full period.
Actually: Half a period.

Flashcards

Δv

Velocity change.

Hohmann

Two tangent burns.

Transfer a

$(r_1 + r_2)/2$.

Transfer time

$\pi\sqrt{(a^3/\mu)}$.

Bi-elliptic

Three burns, large ratios.

Phasing

Lower to catch up.

Self-check quiz

1. Hohmann uses ... burns.

2

1

3

4

2. Tangent burns.

2. Transfer time is...

half the transfer period

full period

zero

one day

half the transfer period. Periapsis to apoapsis.

3. To catch a target ahead, go...

lower

higher

polar

nowhere

lower. Shorter period.

4. Transfer ellipse a is...

$(r_1 + r_2)/2$

$r_1 r_2$

$r_2 - r_1$

$\sqrt{(r_1 r_2)}$

$(r_1 + r_2)/2$. Tangent ellipse.

Try this quiz again

How this helps save the planet

The FCC adopted a rule in September 2022 requiring satellite operators in low Earth orbit to dispose of their satellites within 5 years of completing their missions (Report and Order FCC-22-74).

A deorbit burn is just a Hohmann-style half maneuver: lower the perigee into the upper atmosphere so drag finishes the job. From 700 km, lowering perigee to 200 km takes only about 139 m/s in this unit's example.

On Saving Planets: Dynamics · Solutions

Sources: FCC: FCC Adopts New '5-Year Rule' for Deorbiting Satellites (Report and Order FCC-22-74) (https://www.fcc.gov/document/fcc-adopts-new-5-year-rule-deorbiting-satellites-0)

Free learning resources

- MIT OpenCourseWare 16.346 Astrodynamics (Fall 2008) (https://ocw.mit.edu/courses/16-346-astrodynamics-fall-2008/): MIT notes on transfers.
- NASA: Basics of Space Flight (https://science.nasa.gov/learn/basics-of-space-flight/): Free NASA guide.
- OpenStax UP1, 13.4 Satellite orbits and energy (https://openstax.org/books/university-physics-volume-1/pages/13-4-satellite-orbits-and-energy): Free textbook section.
- NASA's Eyes on the Solar System (https://eyes.nasa.gov/apps/solar-system/): Real trajectories.

☐ **I finished this unit**

Plane Changes and Combined Maneuvers

Inclination and node changes, the simple plane-change Δv, why plane changes are expensive in low orbit, combining a plane change with a Hohmann burn, and launch site latitude.

Learning objectives

By the end of this unit you can:

- Compute a simple plane-change Δv.
- Combine a plane change with a circularization burn.
- Explain why plane changes are done at high altitude.
- Relate launch latitude to the minimum inclination.

Key concepts

- Rotating the orbit plane by Δi at speed v costs Δv = 2v sin(Δi/2), with no change in speed.
- Because the cost scales with speed, plane changes are cheapest where the spacecraft is slowest: at apoapsis or in high orbits.
- Combining a plane change with a speed change in one burn uses the law of cosines: Δv = √(v_1^2 + v_2^2 − 2v_1v_2 cos Δi), which is cheaper than doing them separately.
- A direct launch reaches an inclination no lower than the launch site's latitude, so GEO satellites launched from mid-latitudes must remove inclination later.
- Node changes and combined inclination-and-node changes use the same velocity-triangle idea with spherical trigonometry.

Key equations

$$\Delta v = 2v \sin \frac{\Delta i}{2}$$

`Δ v=2v(Δ i)/(2)`

Simple plane change

$$\Delta v = \sqrt{v_1^2 + v_2^2 - 2v_1 v_2 \cos \Delta i}$$

`Δ v=_1^2+v_2^2-2v_1v_2Δ i`

Combined maneuver

$$i_{min} = \phi_{launch}$$

`i_min=_launch`

Minimum direct inclination

$$\cos i = \cos \phi \sin \beta$$

Launch azimuth β

Worked examples, step by step

Example 5.1 Find the Δv to remove 28.5° of inclination at GEO (v = 3.075 km/s).

1. Δv = 2 × 3.075 × sin 14.25°.

Answer: Δv = 1.51 km/s.

Example 5.2 Combine that plane change with the GEO circularization burn (v_a = 1.618 km/s).

1. Δv = √(1.618² + 3.075² − 2 × 1.618 × 3.075 × cos 28.5°).

Answer: Δv = 1.82 km/s, saving 1.15 km/s over separate burns (1.51 + 1.46).

Example 5.3 Find the cost of a 10° plane change in a 400 km orbit.

1. Δv = 2 × 7.669 × sin 5°.

Answer: Δv = 1.34 km/s.

Practice problems

Work each on paper first, then check.

1. Total LEO-to-GEO Δv with the combined final burn?

   2.40 + 1.82 = 4.22 km/s.

2. Where is the cheapest place to change planes on an ellipse?

   Apoapsis.

3. A 60° plane change costs how many times v?

   2 sin 30° = 1 × v.

4. Can a direct launch from 28.5° latitude reach 0° inclination?

   No.

Common misconceptions

Myth: Plane changes are cheap.

Actually: In LEO, 10° costs 1.34 km/s.

Myth: Separate burns are as good as combined.

Actually: Combined burns save Δv.

Myth: Any launch site can reach any inclination directly.

Actually: Not below its latitude.

Flashcards

Plane change

2v sin(Δi/2).

Combined

Law of cosines.

Where

At low speed.

Launch latitude

Minimum inclination.

Node change

Spherical trig.

GEO

Remove inclination at apogee.

Self-check quiz

1. Simple plane change costs...

2v sin(Δi/2)

$v\Delta i^2$

v cos Δi

0

2v sin(Δi/2). Velocity triangle.

2. Best place for a plane change…

apoapsis

periapsis

node only

anywhere

apoapsis. Lowest speed.

3. Combined burns are…

cheaper

costlier

the same

impossible

cheaper. Law of cosines.

4. Minimum direct inclination equals…

launch latitude

0

90°

longitude

launch latitude. Geometry.

Try this quiz again

How this helps save the planet

NASA's Landsat 9 page notes that the satellite was launched into Landsat 7's orbit to keep 8-day repeat coverage together with Landsat 8, and that the spacecraft carries enough fuel to operate for at least 10 years against a 5-year design life.

Placing a satellite precisely in another's orbit plane, and keeping it there, is plane-change and phasing work. Fuel saved by good maneuver planning becomes extra years of free Earth data.

On Saving Planets: Earth Observation · Linear Algebra

Sources: NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/)

Free learning resources

- MIT OpenCourseWare 16.346 Astrodynamics (Fall 2008) (https://ocw.mit.edu/courses/16-346-astrodynamics-fall-2008/): MIT notes on plane changes.
- NASA: Basics of Space Flight (https://science.nasa.gov/learn/basics-of-space-flight/): Free NASA guide.
- MIT OpenCourseWare 16.07 Dynamics (Fall 2009) (https://ocw.mit.edu/courses/16-07-dynamics-fall-2009/): MIT dynamics.
- OpenStax UP1, 13.4 Satellite orbits and energy (https://openstax.org/books/university-physics-volume-1/pages/13-4-satellite-orbits-and-energy): Free textbook section.

☐ **I finished this unit**

Rockets, Δv Budgets and Staging

The Tsiolkovsky rocket equation, specific impulse and exhaust speed, mass ratio and propellant fraction, thrust, staging, gravity and drag losses on ascent, and building a mission Δv budget.

Learning objectives

By the end of this unit you can:

- Apply the rocket equation.
- Relate specific impulse, exhaust speed and thrust.
- Show why staging helps.
- Build a simple Δv budget.

Key concepts

- The rocket equation: Δv = I_sp g_0 ln(m_0/m_f), where m_0/m_f is the mass ratio. Exhaust speed v_e = I_sp g_0.
- Thrust F = $\dot{m}$ v_e = $\dot{m}$ I_sp g_0.
- Because Δv grows only with the log of the mass ratio, a single stage to orbit needs most of its mass to be propellant. Staging drops empty tanks and engines so later stages push less dead mass.
- Reaching low orbit takes about 9.3–10 km/s of Δv in practice (a textbook range): about 7.7–7.8 km/s of orbital speed plus gravity and drag losses, less a boost from Earth's rotation for eastward launches.
- A mission Δv budget adds every maneuver: launch, transfers, plane changes, station-keeping and disposal, plus margin.

Key equations

$$\Delta v = I_{sp} g_0 \ln \frac{m_0}{m_f}$$

```
Δ v=I_spg_0(m_0)/(m_f)
```

Rocket equation

$$v_e = I_{sp} g_0$$

```
v_e=I_spg_0
```

Exhaust speed

$$F = \dot{m}\, I_{sp} g_0$$

```
F= m I_spg_0
```

Thrust

$$\frac{m_0}{m_f} = e^{\Delta v/(I_{sp} g_0)}$$

`(m_0)/(m_f)=e^Δ v/(I_spg_0)`

Required mass ratio

Worked examples, step by step

Example 6.1 A stage with I_sp = 300 s has a mass ratio of 4. Find Δv.

1. Δv = 300 × 9.80665 × ln 4.

Answer: Δv = 4.08 km/s.

Example 6.2 What mass ratio gives 9.4 km/s with I_sp = 350 s in one stage?

1. $m_0/m_f = \exp(9400/(350 \times 9.80665))$.

Answer: 15.5, so 93.5% of liftoff mass is propellant.

Example 6.3 Two stages, each I_sp = 300 s and mass ratio 3. Total Δv?

1. Δv = 2 × 300 × 9.80665 × ln 3.

Answer: Δv = 6.46 km/s.

Practice problems

Work each on paper first, then check.

1. Find the thrust for $\dot{m}$ = 100 kg/s at I_sp = 300 s.

   294 kN.

2. Find v_e for I_sp = 450 s.

   4.41 km/s.

3. Double the mass ratio from 4 to 8. Δv?

Rises by 300 × 9.807 × ln 2 = 2.04 km/s, not doubled.

4. Why does staging help?

   Later stages do not carry empty tanks.

Common misconceptions

Myth: Doubling propellant doubles Δv.
Actually: Δv grows with the log of mass ratio.

Myth: I_sp is measured in m/s.
Actually: In seconds; v_e = I_spg_0.

Myth: Orbit needs only 7.7 km/s.
Actually: Losses add 1.5–2 km/s.

Flashcards

Rocket equation

Δv = v_e ln(m_0/m_f).

I_sp

Seconds; v_e/g_0.

Thrust

$\dot{m}$ v_e.

Mass ratio

m_0/m_f.

Staging

Drop empty mass.

Δv budget

Sum of all maneuvers + margin.

Self-check quiz

1. Δv = …

I_sp g_0 ln(m_0/m_f)

I_sp m_0

g_0 m_f

m_0/m_f

$I_{sp}\, g_0 \ln(m_0/m_f)$. Tsiolkovsky.

2. Thrust = ...

$\dot{m}\, I_{sp}\, g_0$

$m\, g_0$

$I_{sp}/\dot{m}$

$\Delta v/t$

$\dot{m}\, I_{sp}\, g_0$. Momentum flux.

3. Staging helps by...

dropping dead mass

adding fuel

raising g_0

nothing

dropping dead mass. Mass ratio.

4. Low-orbit Δv is about...

9.4 km/s

3 km/s

20 km/s

1 km/s

9.4 km/s. With losses.

Try this quiz again

How this helps save the planet

NASA reports that DART launched on November 24, 2021 (EST) on a SpaceX Falcon 9 from Vandenberg Space Force Base in California, and struck Dimorphos, a moonlet just 160 meters across orbiting the 780-meter asteroid Didymos, on September 26, 2022.

NASA notes the collision happened at roughly 22,530 km/h. Getting a spacecraft there at that speed and on the right path started with this unit's Δv budget.

On Saving Planets: Thermodynamics · Intro to Aerospace Engineering

Sources: NASA Science: Double Asteroid Redirection Test (DART) (https://science.nasa.gov/mission/dart/) · NASA: NASA Confirms DART Mission Impact Changed Asteroid's Motion in Space (Oct. 11, 2022) (https://www.nasa.gov/news-release/nasa-confirms-dart-mission-impact-changed-asteroids-motion-in-space/)

Free learning resources

- OpenStax UP1, 9.7 Rocket propulsion (https://openstax.org/books/university-physics-volume-1/pages/9-7-rocket-propulsion): Free textbook section.
- NASA Glenn: Rocket thrust (https://www.grc.nasa.gov/www/k-12/rocket/rktpow.html): Free NASA page.
- NASA: Basics of Space Flight (https://science.nasa.gov/learn/basics-of-space-flight/): Free NASA guide.
- MIT OpenCourseWare 16.346 Astrodynamics (Fall 2008) (https://ocw.mit.edu/courses/16-346-astrodynamics-fall-2008/): MIT notes.

☐ **I finished this unit**

Perturbations: Earth’s Bulge, Drag and Sun-Synchronous Orbits

Why real orbits drift, Earth’s oblateness and J_2, regression of the node and rotation of periapsis, sun-synchronous orbits, frozen and critically inclined orbits, atmospheric drag and orbit decay, and third-body and solar pressure effects.

Learning objectives

By the end of this unit you can:

- Compute nodal regression from J_2.
- Find the inclination for a sun-synchronous orbit.
- Explain orbit decay from drag.
- Name other perturbations.

Key concepts

- Earth bulges at the equator. Its J_2 term (1.0826×10^{-3}) makes the orbit plane precess: $d\Omega/dt = -1.5\, n\, J_2\, (R/p)^2 \cos i$, with $p = a(1 - e^2)$.
- Prograde orbits ($i < 90°$) regress westward; retrograde orbits ($i > 90°$) advance eastward.
- A sun-synchronous orbit picks i so the plane advances 360° per year, about 0.9856° per day, keeping the same local solar time at each pass.
- In low orbit, atmospheric drag slowly removes energy, lowering the orbit until the spacecraft reenters. Drag grows sharply when solar activity heats the upper atmosphere.
- Other perturbations: Moon and Sun gravity (important for GEO), solar radiation pressure, and higher gravity harmonics.

Key equations

$$\dot{\Omega} = -\frac{3}{2} n J_2 \left(\frac{R}{p}\right)^2 \cos i$$

```
=-32nJ_2( Rp)^2 i
```

Nodal regression

$$\dot{\Omega}_{SS} = \frac{360^\circ}{365.2422\ \mathrm{d}}$$

```
_SS=360°365.2422\ d
```

Sun-synchronous rate

$$\cos i = -\frac{\dot{\Omega}_{SS}}{1.5 n J_2 (R/p)^2}$$

i=-_SS1.5nJ_2(R/p)^2

Sun-synchronous inclination

$$n = \sqrt{\mu / a^3}$$

n=μ/a^3

Mean motion

Worked examples, step by step

Example 7.1 Find the inclination for a sun-synchronous circular orbit at 705 km.

1. r = 7083 km; n = √(μ/r³).
2. Required rate 0.9856°/day = 1.991 × 10⁻⁷ rad/s.
3. cos i = −rate/(1.5nJ$_2$(R/r)²).

Answer: i = 98.2°, exactly Landsat 9's inclination.

Example 7.2 Check the nodal rate for Landsat 9 (705 km, 98.2°).

1. dΩ/dt = −1.5nJ$_2$(R/r)² cos 98.2°.

Answer: +0.985° per day, matching the 0.9856° per day the Sun moves.

Example 7.3 Find the nodal regression of a 400 km orbit at 51.6°.

1. Same formula with r = 6778 km and cos 51.6°.

Answer: −5.00° per day (westward).

Practice problems

Work each on paper first, then check.

1. Is a sun-synchronous orbit prograde or retrograde?

   Slightly retrograde (i > 90°).

2. What does J_2 do to a polar orbit (i = 90°)?

   Nothing to the node: cos 90° = 0.

3. Why do low satellites need reboosts?

   Drag lowers them.

4. Which perturbation matters most for GEO inclination?

   Moon and Sun gravity.

Common misconceptions

Myth: Orbit planes are fixed in space.
Actually: J_2 makes them precess.

Myth: Sun-synchronous means the satellite sees the Sun all the time.
Actually: It means the same local solar time each pass.

Myth: Drag only matters below 100 km.
Actually: It shapes orbits up to several hundred km.

Flashcards

J_2

1.0826×10^{-3}.

Nodal rate

$-1.5nJ_2(R/p)^2 \cos i$.

Sun-synchronous

+0.9856°/day.

Retrograde node

Advances east.

Drag

Decay and reentry.

GEO perturbation

Sun and Moon.

Self-check quiz

1. J_2 causes...

nodal precession

escape

more mass

nothing

nodal precession. Oblateness.

2. Sun-synchronous node rate...

0.9856°/day

0

360°/day

1°/hour

0.9856°/day. One cycle per year.

3. Sun-synchronous inclinations are...

slightly over 90°

near 0°

45°

28.5°

slightly over 90°. cos i < 0.

4. Drag makes LEO orbits...

decay

grow

stay

tilt

decay. Energy loss.

Try this quiz again

How this helps save the planet

NASA lists Landsat 9 in a near-polar, sun-synchronous orbit at 705 km and 98.2° inclination, crossing the equator at about 10:12 a.m. local time. Landsat 9 and Landsat 8 together image the same place every 8 days, enabling near-weekly deforestation alerts, water-quality monitoring and crop reports.

NASA notes that Landsat's free, public data contributed an estimated $25.6 billion to the U.S. economy in 2023. The steady morning light that makes those images comparable comes straight from J_2 and this unit's sun-synchronous condition.

On Saving Planets: Earth Observation · Oceans

Sources: NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/)

Free learning resources

- MIT OpenCourseWare 16.346 Astrodynamics (Fall 2008) (https://ocw.mit.edu/courses/16-346-astrodynamics-fall-2008/): MIT notes on perturbations.
- NASA Basics of Space Flight, Chapter 5: Planetary orbits (https://science.nasa.gov/learn/basics-of-space-flight/chapter5-1/): Free NASA chapter.
- NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/): Landsat 9 orbit facts.
- MIT OpenCourseWare 16.07 Dynamics (Fall 2009) (https://ocw.mit.edu/courses/16-07-dynamics-fall-2009/): MIT dynamics.

☐ **I finished this unit**

Ground Tracks, Coverage and Constellations

Ground tracks and the westward shift per orbit, repeat-ground-track orbits, swath width and revisit time, coverage from GEO, and designing constellations for revisit and coverage.

Learning objectives

By the end of this unit you can:

- Compute the ground-track shift per orbit.
- Find orbits per repeat cycle.
- Relate swath width to revisit.
- Explain why two satellites halve revisit time.

Key concepts

- As Earth turns beneath an orbit, each ground track shifts west by Δλ = 360° × T/T_sidereal per orbit.
- A repeat-ground-track orbit makes a whole number of orbits in a whole number of days, so the pattern repeats exactly.
- A sensor with swath width w covers the equator in roughly (circumference)/w passes, which sets the minimum repeat cycle.
- Adding satellites in the same orbit, evenly spaced, divides the revisit time.
- A single GEO satellite sees roughly 40% of Earth’s surface (a textbook value), but at low resolution near the edges; a few spaced around the equator cover all longitudes except the polar regions.

Key equations

$$\Delta\lambda = 360^\circ \frac{T}{T_{sid}}$$

`Δ=360°_sid`

Ground-track shift

$$kT = jT_{day}$$

`kT=jT_day`

Repeat condition

$$N_{pass} \approx \frac{2\pi R}{w}$$

Passes to cover the equator

$$t_{revisit} = \frac{t_{repeat}}{N_{sat}}$$

```
t_revisit=_repeatN_sat
```

Constellation revisit

Worked examples, step by step

Example 8.1 Find the ground-track shift per orbit for a 98.87 min orbit.

1. Δλ = 360 × 98.87 × 60/86,164.1.

Answer: Δλ = 24.8°, about 2760 km at the equator.

Example 8.2 How many orbits does that satellite make in 16 days?

1. 16 × 14.564.

Answer: About 233 orbits, so a 16-day repeat cycle fits.

Example 8.3 Two identical satellites share a 16-day repeat orbit, evenly spaced. Revisit?

1. 16/2.

Answer: 8 days, as NASA reports for Landsat 8 and 9.

Practice problems

Work each on paper first, then check.

1. How many 185 km swaths span the equator (40,075 km)?

   40,075/185 = 216.6, so about 217.

2. Why do ground tracks shift west?

   Earth rotates east under the orbit.

3. What does a GEO ground track look like?

   A point (or small figure-eight if inclined).

4. How would three satellites change the 16-day revisit?

   About 5.33 days.

Common misconceptions

Myth: Ground tracks repeat every orbit.

Actually: Only after a whole repeat cycle.

Myth: More altitude always means better coverage.

Actually: Resolution falls with altitude.

Myth: GEO sees the whole Earth.

Actually: About 40%, poorly near the poles.

Flashcards

Track shift

360°T/T_sid.

Repeat orbit

kT = jT_day.

Swath

Width imaged.

Revisit

Repeat/N_sat.

GEO view

≈ 40% of Earth.

Constellation

Spaced satellites.

Self-check quiz

1. Ground tracks shift...

west

east

north

not at all

west. Earth rotates east.

2. Shift per orbit is...

360°T/T_sid

T/360

0

15°

360°T/T_sid. Earth rotation.

3. Two evenly spaced satellites...

halve revisit

double revisit

no change

quadruple

halve revisit. Spacing.

4. A repeat orbit has...

whole orbits in whole days

e = 1

i = 0

T = 1 day only

whole orbits in whole days. Definition.

Try this quiz again

How this helps save the planet

NASA reports that Landsat 9 has a 16-day repeat cycle with a 185 km swath, collects about 740 scenes a day (almost double its 400-scene requirement), and together with Landsat 8 observes the same location every 8 days.

NOAA notes that GOES East and GOES West together cover more than half the globe from geostationary orbit. Low polar orbits give sharp, repeated maps; GEO gives constant watch. Good Earth monitoring uses both.

On Saving Planets: Earth Observation · Oceans

Sources: NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/) · NOAA NESDIS: GOES-R Series mission (https://www.goes-r.gov/mission/mission.html)

Free learning resources

- NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/): Landsat 9 coverage facts.
- NOAA NESDIS: GOES-R Series mission (https://www.goes-r.gov/mission/mission.html): NOAA GOES-R facts.
- NASA: Basics of Space Flight (https://science.nasa.gov/learn/basics-of-space-flight/): Free NASA guide.
- MIT OpenCourseWare 16.346 Astrodynamics (Fall 2008) (https://ocw.mit.edu/courses/16-346-astrodynamics-fall-2008/): MIT notes.

☐ **I finished this unit**

Interplanetary Transfers and Patched Conics

Heliocentric Hohmann transfers, transfer time to Mars, departure v∞ and C_3, the patched-conic method, spheres of influence, escape from a parking orbit, synodic periods and launch windows, and gravity assists.

Learning objectives

By the end of this unit you can:

- Compute an Earth–Mars Hohmann transfer.
- Find v∞ and C_3.
- Find the Δv to depart from low Earth orbit.
- Compute synodic periods and explain launch windows.

Key concepts

- Far from planets, a spacecraft follows a heliocentric conic with μ_Sun = 1.327 × 10^{20} m^3/s^2. An Earth–Mars Hohmann transfer is an ellipse from 1 AU to 1.524 AU.
- Patched conics: near each planet, use a hyperbola relative to the planet; far away, use the heliocentric ellipse; match velocities at the sphere of influence.
- The departure hyperbolic excess speed v∞ is the heliocentric speed needed minus Earth's orbital speed. $C_3 = v_\infty^2$ is the launch energy.
- From a circular parking orbit, the departure burn is $\Delta v = \sqrt{v_\infty^2 + 2\mu/r} - \sqrt{\mu/r}$, using the Oberth effect of burning deep in the gravity well.
- Launch windows repeat every synodic period, $1/(1/T_1 - 1/T_2)$: about 2.1 years for Mars. Gravity assists change a spacecraft's heliocentric speed for free by flying past a planet.

Key equations

$$t = \pi\sqrt{\frac{a^3}{\mu_\odot}}$$

`t=π(a^3)/(μ_)`

Transfer time

$$v_\infty = \sqrt{\mu_\odot\left(\frac{2}{r_1} - \frac{1}{a}\right)} - \sqrt{\frac{\mu_\odot}{r_1}}$$

`v_∞=μ_(2r_1-1a)-(μ_)/(r_1)`

Departure excess speed

$$\Delta v = \sqrt{v_\infty^2 + \frac{2\mu}{r}} - \sqrt{\frac{\mu}{r}}$$

`Δ v=_∞^2+(2μ)/(r)-μ r`

Departure burn

$$S = \frac{1}{1/T_1 - 1/T_2}$$

`S=(1)/(1/T_1-1/T_2)`

Synodic period

Worked examples, step by step

Example 9.1 Find the Earth–Mars Hohmann transfer time.

1. a = (1 + 1.524)/2 AU = 1.888 × 10^{11} m.
2. t = π√(a^3/μ_Sun).

Answer: t = 259 days.

Example 9.2 Find v∞ and C_3 at departure.

1. Earth's speed √(μ_Sun/1 AU) = 29.78 km/s.
2. Transfer perihelion speed from vis-viva.

Answer: v∞ = 2.95 km/s; C_3 = 8.68 km^2/s^2.

Example 9.3 Find the departure burn from a 400 km parking orbit.

1. Δv = √(2946² + 2μ/6.778 × 10^6) − 7669.

Answer: Δv = 3.57 km/s.

Practice problems

Work each on paper first, then check.

1. Find Mars's orbital period from Kepler's third law.

1.524^1.5 = 1.88 years.

2. Find the Earth–Mars synodic period.

   1/(1 − 1/1.881) = 2.13 years.

3. Why burn deep in a gravity well?

   The Oberth effect: more kinetic energy per Δv.

4. Does a gravity assist change speed relative to the planet?

   No, only relative to the Sun.

Common misconceptions

Myth: You can launch to Mars any time cheaply.
Actually: Only in windows every 2.1 years.

Myth: v∞ equals the burn Δv.
Actually: The burn from LEO is larger.

Myth: Gravity assists break energy conservation.
Actually: The planet loses a tiny amount.

Flashcards

Heliocentric

μ_Sun = 1.327 × 10^{20}.

Patched conics

Hyperbola + ellipse.

v∞

Excess speed.

C_3

v_∞^2.

Synodic period

$1/(1/T_1 - 1/T_2)$.

Gravity assist

Free heliocentric Δv.

Self-check quiz

1. Earth–Mars Hohmann takes about…

259 days

30 days

3 years

1 day

259 days. Half the ellipse period.

2. C_3 is...

v_∞^2

v_∞

Δv^2

μ/r

v_∞^2. Launch energy.

3. Mars windows repeat every...

2.1 years

1 year

6 months

10 years

2.1 years. Synodic period.

4. Patched conics switch frames at...

the sphere of influence

apoapsis

the Moon

random

the sphere of influence. Definition.

Try this quiz again

How this helps save the planet

NASA calls DART the first-ever mission dedicated to demonstrating asteroid deflection by changing an asteroid's motion through kinetic impact. Before the encounter, NASA defined success as a change in Dimorphos' orbit period of 73 seconds or more; the measured change of 32 minutes exceeded that by more than 25 times.

NASA notes that neither Dimorphos nor Didymos posed any hazard to Earth before or after the test. Planetary defense depends on exactly the interplanetary trajectory tools in this unit.

On Saving Planets: Physics I · Solutions

Sources: NASA: NASA Confirms DART Mission Impact Changed Asteroid's Motion in Space (Oct. 11, 2022) (https://www.nasa.gov/news-release/nasa-confirms-dart-mission-impact-changed-asteroids-motion-in-space/)

Free learning resources

- NASA: Basics of Space Flight (https://science.nasa.gov/learn/basics-of-space-flight/): Free NASA guide to interplanetary trajectories.
- NASA's Eyes on the Solar System (https://eyes.nasa.gov/apps/solar-system/): Real interplanetary paths.
- MIT OpenCourseWare 16.346 Astrodynamics (Fall 2008) (https://ocw.mit.edu/courses/16-346-astrodynamics-fall-2008/): MIT notes.
- PhET: My Solar System (https://phet.colorado.edu/en/simulations/my-solar-system): Multi-body orbits.

☐ **I finished this unit**

UNIT 10 · WEEKS 14–15

Space Sustainability: Debris, Disposal and Planetary Defense

The orbital debris environment, collision speeds and energies, the Kessler cascade, end-of-life disposal and deorbit Δv, graveyard orbits for GEO, conjunction screening and collision avoidance, and kinetic-impact planetary defense.

Learning objectives

By the end of this unit you can:

- Compute the energy of a debris impact.
- Size a deorbit burn.
- Explain the Kessler cascade.
- Quantify the DART result.

Key concepts

- Low Earth orbit holds millions of pieces of debris: dead satellites, rocket parts, fragments and paint flecks. At orbital speeds even tiny pieces carry enormous energy.
- Kinetic energy ½mv² grows with the square of speed: a 1 g fragment at 10 km/s (a sample relative speed) carries 50 kJ.
- Collisions make more fragments, which cause more collisions: the Kessler cascade. Limiting new debris is far cheaper than removing it.
- Disposal: LEO satellites lower their perigee so drag brings them down; GEO satellites are raised to a graveyard orbit a few hundred kilometres higher.
- Operators screen for close approaches (conjunctions) and make small avoidance burns when the collision probability is too high.

Key equations

$$E_k = \tfrac{1}{2} m v^2$$

`E_k=12mv^2`

Impact energy

$$\Delta v_{deorbit} = v_c - v_a$$

`Δ v_deorbit=v_c-v_a`

Perigee-lowering burn

$$\frac{\Delta T}{T}$$

Fractional period change

$$v_a = \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)}$$

`v_a=μ(2r-1a)`

Vis-viva after the burn

Worked examples, step by step

Example 10.1 Convert NASA's 18,000 mph debris speed to km/s.

1. 18,000 × 0.44704 m/s.

Answer: 8.05 km/s.

Example 10.2 Find the kinetic energy of a 1 g fragment at a 10 km/s relative speed (sample value).

1. E = ½ × 0.001 × 10,000².

Answer: E = 50 kJ from a fragment the mass of a paper clip.

Example 10.3 DART shortened Dimorphos' 11 h 55 min (715 min) orbit by 32 minutes. Find the fractional change and the margin over NASA's 73 s success threshold.

1. 32/715.
2. 1920 s/73 s.

Answer: 4.48% shorter; 26.3 times the threshold.

Practice problems

Work each on paper first, then check.

1. Find the deorbit Δv from 700 km to a 200 km perigee.

   139 m/s (Unit 4).

2. Within how many years must LEO satellites be disposed of under the FCC rule?

   5 years after mission end.

3. Why is preventing debris cheaper than removing it?

   Removal needs a dedicated spacecraft for each object.

4. Where do GEO satellites go at end of life?

   A graveyard orbit above GEO.

Common misconceptions

Myth: Space is too big to fill up.
Actually: Useful orbits are limited and crowded.

Myth: Small debris is harmless.
Actually: Energy grows with v^2.

Myth: Deorbiting needs huge burns.
Actually: Lowering perigee from 700 km takes about 139 m/s.

Flashcards

Debris

Millions of pieces in LEO.

Impact energy

$\frac{1}{2}mv^2$.

Kessler

Cascade of collisions.

Deorbit

Lower perigee.

Graveyard

Above GEO.

DART

32-minute period change.

Self-check quiz

1. Debris energy grows with...

v^2

v

$\sqrt{v}$

1/v

v^2. $\frac{1}{2}mv^2$.

2. The Kessler cascade is…

collisions making more debris

a launch

a transfer

drag

collisions making more debris. Chain reaction.

3. FCC LEO disposal rule…

5 years

25 years

1 year

none

5 years. FCC-22-74.

4. DART changed the period by…

32 min

73 s

12 h

0

32 min. NASA result.

Try this quiz again

How this helps save the planet

NASA's Headquarters Library notes that there are millions of pieces of space junk in low Earth orbit, moving as fast as 18,000 miles per hour, almost seven times faster than a bullet, with close to 6,000 tons of material in low Earth orbit. NASA's Orbital Debris Program began in 1979 at Johnson Space Center.

The FCC's 2022 rule requires low-Earth-orbit operators to dispose of satellites within 5 years of completing their missions. Planning that disposal burn from day one is now part of responsible mission design.

On Saving Planets: Solutions · Earth Observation

Sources: NASA Headquarters Library: Space Debris (https://www.nasa.gov/headquarters/library/find/bibliographies/space-debris/) · FCC: FCC Adopts New '5-Year Rule' for Deorbiting Satellites (Report and Order FCC-22-74) (https://www.fcc.gov/document/fcc-adopts-new-5-year-rule-deorbiting-satellites-0)

Free learning resources

- NASA Orbital Debris Program Office (https://orbitaldebris.jsc.nasa.gov/): NASA Orbital Debris Program Office.
- NASA Headquarters Library: Space Debris (https://www.nasa.gov/headquarters/library/find/bibliographies/space-debris/): NASA debris reading list.
- NASA: NASA Confirms DART Mission Impact Changed Asteroid's Motion in Space (Oct. 11, 2022) (https://www.nasa.gov/news-release/nasa-confirms-dart-mission-impact-changed-asteroids-motion-in-space/): NASA DART result.
- MIT OpenCourseWare 16.346 Astrodynamics (Fall 2008) (https://ocw.mit.edu/courses/16-346-astrodynamics-fall-2008/): MIT notes.

☐ **I finished this unit**

Problem Sets

These practice problems live inside each unit. Work on paper first, then open the answer.

1. Gravity, the Two-Body Problem and Circular Orbits
   4 problems
2. Conic Sections, Energy and Orbital Elements
   4 problems
3. Kepler's Equation and Time of Flight
   4 problems
4. Orbit Transfers: Hohmann and Beyond
   4 problems
5. Plane Changes and Combined Maneuvers
   4 problems

6. Rockets, Δv Budgets and Staging
   4 problems
7. Perturbations: Earth’s Bulge, Drag and Sun-Synchronous Orbits
   4 problems
8. Ground Tracks, Coverage and Constellations
   4 problems
9. Interplanetary Transfers and Patched Conics
   4 problems
10. Space Sustainability: Debris, Disposal and Planetary Defense
    4 problems

The lab (Astrodynamics lab)

The lab is the hands-on part of the course. Here it is free and for practice only, with no credit.

Every lab runs in a free simulation or a spreadsheet, so there are no physical hazards. Take screen breaks, sit with good posture, and keep cables out of walkways.

Safety reference: OSHA: Walking-working surfaces (slip, trip and fall hazards) (https://www.osha.gov/walking-working-surfaces)

Lab A: Circular orbits in PhET

WEEK 1

Goal: Explore how orbit speed and period change with distance in PhET Gravity and Orbits, then compute real Earth orbits.

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

v_c=μ/r,\ \ T=2π^3/μ

Circular orbits

Procedure

1. Open PhET Gravity and Orbits; launch the satellite at different distances and speeds.
2. Find the speed that gives a circle at each distance.
3. Compute v and T for a 400 km orbit, Landsat's 705 km orbit and GEO.
4. Compare the trend with the simulation.

Data table

Orbit	v (km/s)	T
400 km	7.67	92.6 min
705 km	7.50	98.9 min
GEO (35,786 km)	3.07	23.93 h

Computed values.

Sample calculation

1. v(705 km) = √(3.986 × 10^{14}/7.083 × 10^{6}) = 7.50 km/s.
2. T(GEO) = 86,164 s = 23.93 h.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any browser works.

PhET: Gravity and Orbits (https://phet.colorado.edu/en/simulations/gravity-and-orbits)

Planet link: NOAA notes GOES satellites orbit 22,236 miles above the equator. NOAA NESDIS: GOES-R Series mission (https://www.goes-r.gov/mission/mission.html)

- [ ] **I completed this lab (wet or virtual)**

Lab B: Kepler’s third law with real planets

WEEK 3

Goal: Check $T^2 \propto a^3$ for planets and explore elliptical orbits in PhET Kepler’s Laws.

$$T_{yr} = a_{AU}^{3/2}$$

```
T_yr=a_AU^3/2
```

Kepler’s third law (Sun)

Procedure

1. Explore PhET Kepler’s Laws: change eccentricity and watch equal areas swept in equal times.
2. Enter planet semi-major axes in AU.
3. Compute T = a^1.5 in years.
4. Plot log T against log a and find the slope.

Data table

Planet	a (AU)	T (years)
Earth	1.000	1.000
Mars	1.524	1.881
Jupiter	5.203	11.87

Semi-major axes are textbook values; the slope of log T against log a is 1.5.

Sample calculation

1. T(Mars) = 1.524^1.5 = 1.881 years.
2. T(Jupiter) = 5.203^1.5 = 11.87 years.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any browser and spreadsheet work.

PhET: Kepler’s Laws (https://phet.colorado.edu/en/simulations/keplers-laws) · PhET: My Solar System (https://phet.colorado.edu/en/simulations/my-solar-system)

Planet link: NASA timed Dimorphos' orbit before and after DART to measure a 32-minute change. NASA: NASA Confirms DART Mission Impact Changed Asteroid's Motion in Space (Oct. 11, 2022) (https://www.nasa.gov/news-release/nasa-confirms-dart-mission-impact-changed-asteroids-motion-in-space/)

- [ ] **I completed this lab (wet or virtual)**

Lab C: Hohmann transfer calculator

WEEK 6

Goal: Build a spreadsheet that computes both burns, total Δv and transfer time for any pair of circular orbits.

$$a = \frac{r_1 + r_2}{2}, \;\; v^2 = \mu\left(\frac{2}{r} - \frac{1}{a}\right)$$

a=(r_1+r_2)/(2),\ \ v^2=μ(2r-1a)

Hohmann transfer

Procedure

1. Enter μ and the two radii.
2. Compute circular speeds, transfer-orbit speeds, both burns and the transfer time.
3. Run LEO (400 km) to GEO and LEO to a 20,200 km medium orbit.
4. Add a plane-change option for the second burn.

Data table

Transfer	Δv_1 (km/s)	Δv_2 (km/s)	Total	Time (h)
400 km → GEO	2.398	1.456	3.854	5.29
400 km → 20,200 km	2.012	1.404	3.416	2.98

Computed values, coplanar.

Sample calculation

1. Δv_1(GEO) = 10.066 − 7.669 = 2.398 km/s.
2. Time(20,200 km) = $\pi\sqrt{a^3/\mu}$ = 2.98 h.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

NASA’s Eyes on the Solar System (https://eyes.nasa.gov/apps/solar-system/)

Planet link: The FCC requires LEO satellites to be disposed of within 5 years of mission end. FCC: FCC Adopts New ‘5-Year Rule’ for Deorbiting Satellites (Report and Order FCC-22-74) (https://www.fcc.go

v/document/fcc-adopts-new-5-year-rule-deorbiting-satellites-0)

- [ ] **I completed this lab (wet or virtual)**

Lab D: Rocket equation and staging

WEEK 8

Goal: See how Δv grows with mass ratio and how staging beats a single stage.

$$\Delta v = I_{sp} g_0 \ln \frac{m_0}{m_f}$$

`Δ v=I_spg_0(m_0)/(m_f)`

Rocket equation

Procedure

1. Set I_sp = 300 s.
2. Compute Δv for mass ratios 2, 4 and 8.
3. Compare one stage of ratio 9 with two stages of ratio 3.
4. Find the mass ratio for 9.4 km/s at I_sp = 350 s.

Data table

Mass ratio	Δv (km/s)
2	2.04
4	4.08
8	6.12

Computed values; one stage of ratio 9 and two stages of ratio 3 give the same ideal Δv (6.46 km/s), but the staged rocket needs far less structure per stage.

Sample calculation

1. Δv(8) = 300 × 9.80665 × ln 8 = 6.12 km/s.
2. Two stages of 3: 2 × 300 × 9.80665 × ln 3 = 6.46 km/s.

> **Safety**
>
> - Computer only. Do not build or fly propellant rockets for this lab.

Home or virtual alternative

- Any spreadsheet works.

NASA Glenn: Rocket thrust (https://www.grc.nasa.gov/www/k-12/rocket/rktpow.html)

Planet link: NASA's DART launched on a Falcon 9 from Vandenberg in November 2021. NASA Science: Double Asteroid Redirection Test (DART) (https://science.nasa.gov/mission/dart/)

- [ ] **I completed this lab (wet or virtual)**

Lab E: Designing a sun-synchronous orbit

WEEK 10

Goal: Compute the sun-synchronous inclination for several altitudes and check it against Landsat 9.

$$\cos i = -\frac{\dot{\Omega}_{SS}}{1.5 n J_2 (R/r)^2}$$

```
i=-_SS1.5nJ_2(R/r)^2
```

Sun-synchronous condition

Procedure

1. Enter μ, R, J_2 and the required 0.9856°/day.
2. Compute i for circular orbits at 500, 705 and 800 km.
3. Compare 705 km with Landsat 9's published 98.2°.
4. Plot i against altitude.

Data table

Altitude (km)	i (deg)
500	97.40
705	98.21
800	98.60

Computed values; Landsat 9's published inclination is 98.2°.

Sample calculation

1. n(705 km) = √(μ/7.083³ × 10¹⁸) = 1.059 × 10⁻³ rad/s.
2. i(705) = 98.21°.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/)

Planet link: NASA says Landsat 9 crosses the equator at about 10:12 a.m. local time. NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/)

- [ ] **I completed this lab (wet or virtual)**

Lab F: Ground tracks in NASA’s Eyes

WEEK 11

Goal: Watch real Earth-observing satellites in NASA’s Eyes and compute their ground-track shift and repeat cycle.

$$\Delta\lambda = 360^\circ \frac{T}{T_{sid}}$$

`Δ=360°_sid`

Ground-track shift

Procedure

1. Open NASA’s Eyes and follow an Earth-observing satellite for a few orbits.
2. Note how each track lands west of the last.
3. Compute the shift for a 98.87 min orbit.
4. Find how many orbits fit in 16 days.

Data table

Quantity	Value
Period	98.87 min
Shift per orbit	24.8°
Shift at equator	2760 km
Orbits in 16 days	233

Computed for a 705 km circular orbit.

Sample calculation

1. Δλ = 360 × 5932/86,164 = 24.8°.
2. 16 × 14.564 = 233 orbits.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any browser works.

NASA’s Eyes on the Solar System (https://eyes.nasa.gov/apps/solar-system/)

Planet link: NASA reports Landsat 8 and 9 together revisit every place every 8 days. NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/)

☐ **I completed this lab (wet or virtual)**

Exam prep practice sets

Time yourself: about 10 minutes per problem. Then compare with the full solutions.

Midterm practice set (Units 1–5)

1. Find the circular speed 1000 km above Earth.
    1. $\sqrt{(3.986 \times 10^{14}/7.378 \times 10^{6})}$.

    Answer: 7.35 km/s.
2. Find the period of that orbit.
    1. $2\pi\sqrt{(r^{3}/\mu)}$.

    Answer: 105.1 min.
3. An orbit has r_p = 7000 km and r_a = 14,000 km. Find e.
    1. 7000/21,000.

    Answer: 0.333.
4. Find the speed at perigee of that orbit.
    1. $\sqrt{(\mu(2/7 \times 10^{6} - 1/1.05 \times 10^{7}))}$.

    Answer: 8.71 km/s.
5. Find the Δv to change inclination by 5° at 7.5 km/s.
    1. 2 × 7.5 × sin 2.5°.

    Answer: 0.654 km/s.

Final practice set (all units)

1. Find Δv for I_sp = 320 s and mass ratio 5.
    1. 320 × 9.80665 × ln 5.

    Answer: 5.05 km/s.

2. Find the nodal rate at 600 km, i = 97.8°.

    1. −1.5nJ$_2$(R/r)² cos i.

    Answer: +0.987°/day.

3. Find the ground-track shift per orbit for a 100 min orbit.

    1. 360 × 6000/86,164.1.

    Answer: 25.1°.

4. Find the Earth–Venus Hohmann transfer time (Venus at 0.723 AU).

    1. π√(a³/μ_Sun) with a = 0.8615 AU.

    Answer: 146 days.

5. Find the energy of a 10 g fragment at 8 km/s.

    1. ½ × 0.01 × 8000².

    Answer: 320 kJ.

6. Find the synodic period of Earth and Jupiter (11.87 years).

    1. 1/(1 − 1/11.87).

    Answer: 1.092 years.

Formula sheet

$$v_c = \sqrt{\mu/r},\ T = 2\pi\sqrt{a^3/\mu},\ v_{esc} = \sqrt{2\mu/r}$$

$$\varepsilon = -\mu/(2a),\ v^2 = \mu(2/r - 1/a)$$

$$r = (h^2/\mu)/(1 + e\cos\nu),\ e = (r_a - r_p)/(r_a + r_p)$$

$$M = E - e\sin E,\ n = \sqrt{\mu/a^3}$$

$$\Delta v_{Hohmann} = (v_p - v_{c1}) + (v_{c2} - v_a)$$

$$\Delta v = 2v\sin(\Delta i/2),\ \Delta v^2 = v_1^2 + v_2^2 - 2v_1 v_2\cos\Delta i$$

$$\Delta v = I_{sp} g_0 \ln(m_0/m_f)$$

$$\dot{\Omega} = -\tfrac{3}{2} n J_2 (R/p)^2 \cos i$$

$$\Delta\lambda = 360^\circ T/T_{sid}$$

$$v_\infty = v_{transfer} - v_{planet},\ C_3 = v_\infty^2,\ S = 1/(1/T_1 -$$

$$E_k = \tfrac{1}{2} m v^2$$

Constants

Constant	Value
Earth (textbook values)	$\mu = 3.986 \times 10^{14}$ m³/s², R = 6378 km, $J_2 = 1.0826 \times 10^{-3}$, sidereal day 86,164.1 s
Sun (textbook value)	$\mu = 1.327 \times 10^{20}$ m³/s², 1 AU = 1.496×10^{11} m
Mars orbit (textbook value)	a = 1.524 AU
Standard gravity	$g_0 = 9.80665$ m/s²
1 mile	1.609344 km
1 mph	0.44704 m/s

Source: NIST Guide to the SI, Appendix B.9: conversion factors (https://www.nist.gov/pml/special-publication-811/nist-guide-si-appendix-b-conversion-factors/nist-guide-si-appendix-b9)

Free texts and simulations

Use these free lectures, NASA guides and simulations alongside the course.

- MIT OpenCourseWare 16.346 Astrodynamics (Fall 2008) (https://ocw.mit.edu/courses/16-346-astrodynamics-fall-2008/): Free MIT astrodynamics lectures and problem sets.
- MIT OpenCourseWare 16.07 Dynamics (Fall 2009) (https://ocw.mit.edu/courses/16-07-dynamics-fall-2009/): Free MIT dynamics notes on orbits.
- NASA: Basics of Space Flight (https://science.nasa.gov/learn/basics-of-space-flight/): Free NASA guide to orbits and missions.
- OpenStax University Physics Volume 1, 13.5 Kepler's laws (https://openstax.org/books/university-physics-volume-1/pages/13-5-keplers-laws-of-planetary-motion): Free textbook section.
- PhET: Gravity and Orbits (https://phet.colorado.edu/en/simulations/gravity-and-orbits): Orbits interactively.
- NASA's Eyes on the Solar System (https://eyes.nasa.gov/apps/solar-system/): Real spacecraft trajectories in 3D.

Glossary

Apoapsis
Farthest point of an orbit.

Conjunction
Close approach between two space objects.

C_3
Launch energy, the square of v_∞.

Eccentricity
How stretched an orbit is.

Geostationary orbit
Equatorial orbit with a one-sidereal-day period.

Ground track
Path of the point directly below a satellite.

Hohmann transfer
Two-burn transfer on a tangent ellipse.

Inclination
Tilt of the orbit plane from the equator.

J_2
Earth's oblateness term.

Kepler's equation
$M = E - e \sin E$.

Kessler cascade
Chain reaction of debris collisions.

Mean anomaly
Angle that grows uniformly with time.

Patched conics
Joining planet-centered and Sun-centered conics.

Periapsis
Closest point of an orbit.

Specific impulse
Thrust per propellant weight flow, in seconds.

Sun-synchronous orbit
Orbit whose plane keeps a fixed angle to the Sun.

Synodic period
Time between repeat alignments of two orbiting bodies.

True anomaly
Angle from periapsis to the spacecraft.

Vis-viva equation
$v^2 = \mu(2/r - 1/a)$.

Δv
Change in velocity a maneuver requires.

Self-assessment rubric

No grade or credit is given. Use this to judge honestly where you are in each unit.

Level	What it looks like
4 · Mastery	Sketches the orbit and maneuvers, picks vis-viva, Kepler or the rocket equation correctly, keeps units in SI, and checks answers against limits.
3 · Proficient	Solves the practice problems with occasional unit slips.
2 · Developing	Follows worked examples but mixes up circular and transfer speeds.
1 · Beginning	Plugs numbers into formulas without a sketch; needs to revisit the unit.

Suggested weighting if you want a score

Part	Weight
Practice problems	20%
Labs	25%
Midterm practice set	25%
Final practice set	30%

Aim for level 3 or better in every unit before moving to the next course.

Related courses

- Aerospace Structures AERO 330
- Numerical Methods MATH 340
- Aerodynamics I AERO 310
- All courses