Last updated: November 1, 2026

🗺️ Four-year roadmap · Year 4, Spring · 🧱 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 senior aerospace capstone. It is modeled on the conceive-design-implement-operate approach of MIT 16.83X Space Systems Engineering (free on MIT OpenCourseWare) and on the NASA Systems Engineering Handbook, which we link where they help. Neither MIT nor NASA endorses this page.
>
> What we add: two parallel tracks (a small electric drone or a 3U CubeSat), every unit tied to real work with a cited public source, every number on the page re-computed by a checking script before it goes live, and every lab in a free spreadsheet.
>
> Work through it in order, alone or with a team. 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

Capstone teams build the satellites and aircraft that measure and protect the planet: student CubeSats fly through NASA’s CubeSat Launch Initiative, and small satellites like PREFIRE study how the Arctic sheds heat.

On the aircraft side, NASA’s Sustainable Flight National Partnership aims for 25–30% energy-efficiency gains. 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 490).
- 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

- Avionics & Systems Engineering: requirements, reliability and verification.
- Spacecraft Design: power, thermal and link budgets.
- Aircraft Performance: lift, drag, range and climb.
- Aerospace Structures: stress, safety factors and margins.

How to study

- Keep one design notebook or spreadsheet that every number flows from.
- Trace every design choice to a requirement.
- Close budgets with margin before adding detail.
- Hold short weekly reviews, even when working alone.
- Write as you go: every unit adds a section to your final report.
- Do every practice problem on paper before opening the answer, and retake the quizzes a few days later.

What you need

- Spreadsheet software (any free one works), or Python.
- The free NASA Systems Engineering Handbook in a web browser.
- Free slide software for your design reviews.
- A calculator.

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	Mission, Stakeholders and Requirements	Mission and requirements; Lab A	NASA SE Handbook
2	Concept Generation and Selection	Concept selection; Lab B	MIT 16.83X
3	Aircraft Track: Weight Sizing and Range	Aircraft weight sizing	NASA SFNP
4	Aircraft Track: Weight Sizing and Range	Range and sizing loop; Lab C	MIT 16.83X
5	Aircraft Track: Wing Loading and Power	Wing loading and power	NASA SFNP
6	CubeSat Track: Sizing and Orbit	CubeSat sizing and orbit; Lab D	NASA PREFIRE
7	CubeSat Track: Power and Link Budgets	Power and link budgets; Lab E; midterm practice	NASA SST SOA
8	Structural and Thermal Checks	Structural and thermal checks	MIT 16.83X
9	Cost, Schedule and Risk	WBS and schedule	NASA SE Handbook
10	Cost, Schedule and Risk	Earned value and risk; Lab F	NASA SE Handbook
11	Prototype, Test and Verification	Prototype planning	MIT 16.83X
12	Prototype, Test and Verification	Testing	NASA CSLI
13	Prototype, Test and Verification	Verification closure	NASA SE Handbook
14	Design Reviews and the Final Report	Critical design review	MIT 16.83X
15	Design Reviews and the Final Report	Final report; final practice	NASA SE Handbook

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

Mission, Stakeholders and Requirements

Choosing a track, defining the mission, identifying stakeholders, writing verifiable requirements and setting allocations with margin.

Learning objectives

By the end of this unit you can:

- Write a one-sentence mission statement.
- List stakeholders and their needs.
- Write verifiable requirements.
- Compute margin against an allocation.

Key concepts

- Pick one track: a small electric drone that carries a sensor, or a 3U CubeSat that observes Earth.
- A mission statement says who needs what and why; requirements make it measurable.
- Stakeholders include users, funders, launch or airspace authorities, and the team itself.
- Each requirement has a number, a unit and a verification method (test, analysis, inspection or demonstration).
- Allocations carry margin early, because estimates grow as designs mature.

Key equations

$$\text{Margin} = \frac{A - E}{E}$$

```
Margin=(A-E)/(E)
```

Margin of allocation over estimate

$$m_{alloc} = m_{est}(1 + M)$$

```
m_alloc=m_est(1+M)
```

Allocation with margin

$$m_{3U} \approx 3 \times 1.33\ \text{kg}$$

Textbook 3U mass allowance

$$\sum w_i = 1$$

```
w_i=1
```

Weights sum to one

Worked examples, step by step

Example 1.1 A 3U CubeSat has a 4.0 kg allocation (textbook value) and a 3.4 kg estimate. Margin?

1. (4.0 − 3.4)/3.4.

Answer: 17.6%.

Example 1.2 A drone sensor estimate is 0.8 kg. Allocate with 25% margin (sample values).

1. 0.8 × 1.25.

Answer: 1.0 kg.

Example 1.3 Write a verifiable requirement for drone endurance.

1. Number, unit, method.

Answer: “The drone shall fly at least 30 minutes at 15 m/s, verified by flight test.”

Practice problems

Work each on paper first, then check.

1. Margin if the estimate grows to 3.8 kg?

   5.26%.

2. Three textbook 1.33 kg units?

   3.99 kg, about 4 kg.

3. Name four stakeholders for a student CubeSat.

   For example: science users, the university, the launch provider and the radio regulator.

4. Is “the CubeSat shall be reliable” verifiable?

   No; add a number and a method.

Common misconceptions

Myth: Requirements describe the design.

Actually: They state needs, not solutions.

Myth: Margin can be added later.

Actually: It is cheapest to hold early.

Myth: One stakeholder is enough.

Actually: Missed stakeholders cause late surprises.

Flashcards

Mission statement

Who needs what and why.

Stakeholder

Anyone with a need or say.

Requirement

Verifiable need.

Allocation

Budgeted share.

Margin

Reserve over estimate.

Track

Drone or CubeSat project path.

Self-check quiz

1. Mass margin...

17.6%

15%

0.6%

85%

17.6%. (4.0 − 3.4)/3.4.

2. 0.8 kg + 25%...

1.0 kg

0.85 kg

1.25 kg

0.6 kg

1.0 kg. Multiply.

3. Verification methods...

test, analysis, inspection, demonstration

guess, hope, wait, ship

cost, schedule, risk, scope

PDR, CDR, TRR, FRR

test, analysis, inspection, demonstration. Four methods.

4. Mission statement says...

who needs what and why

the bolt sizes

the budget only

the launch date only

who needs what and why. Purpose.

Try this quiz again

How this helps save the planet

NASA’s CubeSat Launch Initiative provides opportunities for CubeSats built by U.S. educational institutions and non-profit organizations, including museums and science centers, to fly on upcoming launches; NASA says it has launched over 150 CubeSats.

NASA says its Announcement of Partnership Opportunity is typically released each August with proposals due in November, so a capstone can be shaped like a real proposal.

On Saving Planets: Spacecraft Design · Avionics & Systems Engineering

Sources: NASA: CubeSat Launch Initiative (https://www.nasa.gov/kennedy/launch-services-program/cubesat-launch-initiative/)

Free learning resources

- NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/): Free NASA handbook.
- NASA: CubeSat Launch Initiative (https://www.nasa.gov/kennedy/launch-services-program/cubesat-launch-initiative/): NASA CSLI.

☐ **I finished this unit**

Concept Generation and Selection

Brainstorming, morphological charts, Pugh matrices, weighted decision matrices and sensitivity to weights.

Learning objectives

By the end of this unit you can:

- Generate several concepts.
- Build a morphological chart.
- Score concepts in a weighted matrix.
- Test sensitivity to weights.

Key concepts

- Generate many concepts before judging any; quantity first, quality later.
- A morphological chart lists options for each function and combines them into concepts.
- A Pugh matrix compares concepts to a datum with +, 0 and −.
- A weighted decision matrix multiplies scores by weights and sums them.
- If small weight changes flip the winner, the decision needs more data.

Key equations

$$S = \sum w_i s_i$$

`S= w_is_i`

Weighted score

$$N = \prod n_i$$

`N= n_i`

Morphological combinations

$$P = n_+ - n_-$$

`P=n_+-n_-`

Pugh net score

$$\sum w_i = 1$$

`w_i=1`

Normalized weights

Worked examples, step by step

Example 2.1 Concept A scores 6 (cost), 9 (performance), 5 (risk); B scores 8, 6, 8. Weights 0.3, 0.5, 0.2. Winner?

1. A = 1.8 + 4.5 + 1.0 = 7.3.
2. B = 2.4 + 3.0 + 1.6 = 7.0.

Answer: A, 7.3 to 7.0.

Example 2.2 Change weights to 0.4, 0.3, 0.3.

1. A = 2.4 + 2.7 + 1.5 = 6.6.
2. B = 3.2 + 1.8 + 2.4 = 7.4.

Answer: B wins: the choice is sensitive to weights.

Example 2.3 A chart has 3 power options, 2 structures and 4 sensors. Combinations?

1. 3 × 2 × 4.

Answer: 24.

Practice problems

Work each on paper first, then check.

1. Pugh: 4 pluses, 1 minus. Net?

   +3.

2. Combinations for 2 × 3 × 3 × 2?

   36.

3. Why test weight sensitivity?

   To see if the winner is robust.

4. Why brainstorm before scoring?

   Early judging kills good ideas.

Common misconceptions

Myth: The highest score is always right.

Actually: Check sensitivity and assumptions.

Myth: Weights are objective.

Actually: They encode judgment.

Myth: One concept is enough.

Actually: Compare several.

Flashcards

Morphological chart

Options per function.

Pugh matrix

Compare to a datum.

Datum

Reference concept.

Weighted matrix

Scores times weights.

Sensitivity

How results change with inputs.

Down-select

Choosing a concept.

Self-check quiz

1. A's score...

7.3

7.0

6.6

20

7.3. Weighted sum.

2. B's score...

7.0

7.3

7.4

22

7.0. Weighted sum.

3. After reweighting...

B wins

A wins

tie

neither

B wins. 7.4 > 6.6.

4. Combinations...

24

9

12

48

24. 3 × 2 × 4.

Try this quiz again

How this helps save the planet

NASA's Sustainable Flight National Partnership works in three areas: advanced vehicle technologies, efficient airline operations and sustainable aviation fuels.

Weighing options across areas like these is a concept-selection problem: the right weights depend on what the stakeholders value, including emissions.

On Saving Planets: Solutions · Aircraft Performance

Sources: NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/)

Free learning resources

- MIT OpenCourseWare 16.83X Space Systems Engineering (Spring 2002 – Spring 2003) (https://ocw.mit.edu/courses/16-83x-space-systems-engineering-spring-2002-spring-2003/): Free MIT capstone materials.
- NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/): Free NASA handbook.

Watch the lecture

Session 4: System Architecture and Concept Generation (https://ocw.mit.edu/courses/16-842-fundamentals-of-systems-engineering-fall-2015/resources/session-4-system-architecture-and-concept-generation/) (in English)

MIT 16.842 Fundamentals of Systems Engineering (Fall 2015), MIT OpenCourseWare. License: CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/) · Terms of use (https://ocw.mit.edu/pages/privacy-and-terms-of-use/). Linked for free study only; Saving Planets is not affiliated with or endorsed by this university.

☐ **I finished this unit**

Aircraft Track: Weight Sizing and Range

Takeoff-weight estimation from weight fractions, the Breguet range equation, and how efficiency gains change range and fuel.

Learning objectives

By the end of this unit you can:

- Estimate takeoff weight from fractions.
- Apply the Breguet range equation.
- Show how L/D changes range.
- Iterate a sizing loop.

Key concepts

- Takeoff weight equals payload divided by one minus the empty and energy fractions.
- If the empty plus energy fractions approach 1, the design does not close.
- For jet aircraft, Breguet range is (V/c)(L/D) ln(W_i/W_f).
- Range is proportional to L/D, so a 30% L/D gain gives 30% more range at the same fuel fraction.
- Sizing is iterative: estimate, compute, update fractions, repeat until the weight converges.

Key equations

$$W_0 = \frac{W_{pay}}{1 - W_e/W_0 - W_f/W_0}$$

`W_0=_pay1-W_e/W_0-W_f/W_0`

Takeoff weight

$$R = \frac{V}{c}\frac{L}{D}\ln\frac{W_i}{W_f}$$

`R=V/cL/D(W_i)/(W_f)`

Breguet range (jet)

$$R \propto L/D$$

Range scales with L/D

$$W = mg$$

`W=mg`

Worked examples, step by step

Example 3.1 A drone carries 1 kg payload with empty fraction 0.5 and battery fraction 0.3 (sample values). Takeoff mass?

1. $1/(1 - 0.5 - 0.3)$.

Answer: 5 kg.

Example 3.2 A transport flies at 230 m/s with c = 0.6 per hour, L/D = 17 and W_i/W_f = 1.25 (textbook values). Range?

1. $c = 1.667 \times 10^{-4}\ s^{-1}$.
2. $R = (230/1.667 \times 10^{-4}) \times 17 \times \ln 1.25 = 1.38 \times 10^{6} \times 17 \times 0.2231$.

Answer: About 5235 km.

Example 3.3 Raise L/D by 30%.

1. Range scales with L/D.

Answer: About 6805 km.

Practice problems

Work each on paper first, then check.

1. Takeoff mass if the battery fraction rises to 0.35?

   6.67 kg.

2. Weight of the 5 kg drone?

   49.0 N.

3. Why can’t fractions sum to 1?

   Nothing would be left for payload.

4. ln 1.25?

0.223.

Common misconceptions

Myth: More battery always means more range.

Actually: It also raises weight; the fraction matters.

Myth: Breguet fits electric aircraft.

Actually: Batteries don’t get lighter; use an energy form.

Myth: One pass is enough.

Actually: Iterate until weight converges.

Flashcards

Empty fraction

Empty over takeoff weight.

Fuel fraction

Fuel over takeoff weight.

Breguet

Range equation.

L/D

Lift-to-drag ratio.

TSFC

Thrust-specific fuel consumption.

Sizing loop

Iterate to convergence.

Self-check quiz

1. Drone takeoff mass...

5 kg

2 kg

1.25 kg

10 kg

5 kg. 1/0.2.

2. Transport range...

≈ 5235 km

≈ 523 km

≈ 52,000 km

≈ 1380 km

≈ 5235 km. Breguet.

3. With +30% L/D...

≈ 6805 km

≈ 5235 km

≈ 4027 km

≈ 10,470 km

≈ 6805 km. × 1.3.

4. Range scales with...

L/D

c

W_f

drag

L/D. Breguet.

Try this quiz again

How this helps save the planet

NASA says the Sustainable Flight National Partnership aims to enable 25–30% energy-efficiency improvements in next-generation transports that can use 100% sustainable aviation fuel and fly

optimal trajectories.

Its centerpiece is a full-scale X-plane demonstrator testing an ultra-efficient aerodynamic design, with first flight no earlier than late 2026; higher L/D is exactly the lever this unit's Breguet equation rewards.

On Saving Planets: Aircraft Performance · Solutions

Sources: NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/)

Free learning resources

- NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/): NASA SFNP.
- MIT OpenCourseWare 16.83X Space Systems Engineering (Spring 2002 – Spring 2003) (https://ocw.mit.edu/courses/16-83x-space-systems-engineering-spring-2002-spring-2003/): Free MIT capstone materials.

☐ **I finished this unit**

Aircraft Track: Wing Loading and Power

Constraint sizing: wing loading from stall speed, wing area, and climb power for a small electric aircraft.

Learning objectives

By the end of this unit you can:

- Find wing loading from stall speed.
- Size the wing area.
- Compute climb power.
- Draw a simple constraint diagram.

Key concepts

- Stall speed sets the maximum wing loading: W/S = ½ρV_s²C_Lmax.
- Wing area follows from weight divided by wing loading.
- Shaft power for climb covers drag (W V/(L/D)) plus the climb term (W × rate of climb), divided by propulsive efficiency.
- Each requirement draws a line on a W/S versus power-to-weight plot; the design point lies in the region meeting all.
- Small drones fly at low Reynolds numbers, so check airfoil data for small scales.

Key equations

$$\frac{W}{S} = \frac{1}{2}\rho V_s^2 C_{L,max}$$

`W/S=12ρ V_s^2C_L,max`

Stall wing loading

$$S = \frac{W}{W/S}$$

`S=(W)/(W/S)`

Wing area

$$P = \frac{W}{\eta}\left(\frac{V}{L/D} + RC\right)$$

`P=(W)/()((V)/(L/D)+RC)`

Climb power

$$q = \tfrac{1}{2}\rho V^2$$

`q=12ρ V^2`

Dynamic pressure

Worked examples, step by step

Example 4.1 Stall at 12 m/s, C_Lmax = 1.2, sea level. Wing loading?

1. ½ × 1.225 × 144 × 1.2.

Answer: 105.8 N/m².

Example 4.2 Wing area for the 5 kg drone?

1. 49.03/105.84.

Answer: 0.463 m².

Example 4.3 Climb power at 15 m/s, L/D = 10, 2 m/s climb, η = 0.7?

1. 49.03 × (1.5 + 2) = 171.6 W.
2. 171.6/0.7.

Answer: 245 W.

Practice problems

Work each on paper first, then check.

1. Wing loading for a 10 m/s stall?

   73.5 N/m².

2. Power without the climb term?

   105.1 W.

3. Dynamic pressure at 15 m/s?

   137.8 Pa.

4. Why does stall set a maximum W/S?

   Higher W/S needs higher stall speed.

Common misconceptions

Myth: Bigger wings are always better.

Actually: They add weight and drag.

Myth: Climb power is small.

Actually: It can dominate small drones.

Myth: $\eta = 1$.

Actually: Propellers and motors lose energy.

Flashcards

Wing loading

Weight per wing area.

C_Lmax

Maximum lift coefficient.

Constraint diagram

Requirements on one plot.

Rate of climb

Vertical speed.

Propulsive efficiency

Useful power fraction.

Stall speed

Minimum steady speed.

Self-check quiz

1. W/S...

105.8 N/m²

88.2

1058

10.6

105.8 N/m². ½ρV²C_L.

2. Wing area…

0.463 m²

4.63 m²

0.0463 m²

1 m²

0.463 m². W/(W/S).

3. Climb power…

245 W

171.6 W

49 W

490 W

245 W. Divide by η.

4. Design point lies…

where all constraints are met

on any line

at the origin

outside

where all constraints are met. Feasible region.

Try this quiz again

How this helps save the planet

NASA's Sustainable Flight National Partnership also targets efficient airline operations and optimal trajectories, where power and climb choices meet fuel use.

Small electric drones sized well in this unit are already used for crop, forest and coastline surveys. Values in this unit are sample values.

On Saving Planets: Aircraft Performance · Aerodynamics I

Sources: NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/)

Free learning resources

- NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/): NASA SFNP.
- MIT OpenCourseWare 16.83X Space Systems Engineering (Spring 2002 – Spring 2003) (https://ocw.mit.edu/courses/16-83x-space-systems-engineering-spring-2002-spring-2003/): Free MIT capstone materials.

☐ **I finished this unit**

CubeSat Track: Sizing and Orbit

CubeSat form factors, mass allowance, orbit period, passes per day and eclipse fraction for a low Earth orbit.

Learning objectives

By the end of this unit you can:

- Size a 3U CubeSat mass budget.
- Compute orbit period.
- Compute orbits per day.
- Compute the worst-case eclipse.

Key concepts

- CubeSats come in 10 cm units (U); a 3U is about 10 × 10 × 34 cm (textbook value).
- Mass allowance is roughly 1.33 kg per U (textbook value); confirm with the launch provider.
- Orbit period depends only on the semi-major axis: T = 2π√(a³/μ).
- In the worst case (Sun in the orbit plane), eclipse fraction is asin(R_E/a)/π.
- Low orbits decay faster from drag; most student CubeSats re-enter within years.

Key equations

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

T=2π^3/μ

Orbital period

$$f_e = \frac{1}{\pi} \sin^{-1} \frac{R_E}{a}$$

f_e=(1)/(π)^-1(R_E)/(a)

Worst-case eclipse fraction

$$n = 1440/T$$

n=1440/T

Orbits per day (T in min)

$$a = R_E + h$$

a=R_E+h

Semi-major axis

Worked examples, step by step

Example 5.1 Period at 500 km altitude?

1. a = 6878.1 km.
2. $T = 2\pi\sqrt{(6878.1^3/398{,}600.4)}$.

Answer: 94.6 min.

Example 5.2 Orbits per day?

1. 1440/94.6.

Answer: 15.2.

Example 5.3 Worst-case eclipse?

1. $\text{asin}(6378.1/6878.1)/\pi = 0.378$.
2. 0.378×94.6.

Answer: 35.8 min.

Practice problems

Work each on paper first, then check.

1. 3U mass allowance at 1.33 kg/U?

   3.99 kg.

2. Sunlit time per orbit?

   58.9 min.

3. Does period depend on CubeSat mass?

   No.

4. Why do low orbits decay?

   Atmospheric drag.

Common misconceptions

Myth: Heavier satellites orbit slower.

Actually: Period depends only on a.

Myth: Eclipse is always 50%.

Actually: It depends on altitude and Sun angle.

Myth: Use altitude in Kepler's law.

Actually: Use a = R_E + h.

Flashcards

CubeSat

Standard small satellite in 10 cm units.

3U

Three-unit CubeSat.

Period

Time per orbit.

Eclipse fraction

Share of orbit in shadow.

Semi-major axis

R_E + h for circular orbits.

Decay

Orbit loss from drag.

Self-check quiz

1. Period...

94.6 min

90 min

100 min

84.4 min

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

2. Orbits per day...

15.2

14.5

16

24

15.2. 1440/T.

3. Eclipse...

35.8 min

47 min

20 min

0 min

35.8 min. 0.378 × 94.6.

4. 3U mass...

≈ 4 kg

≈ 1.33 kg

≈ 12 kg

≈ 40 kg

≈ 4 kg. 3 × 1.33.

Try this quiz again

How this helps save the planet

NASA says PREFIRE uses a pair of tiny satellites, CubeSats launched in May 2024, to measure a little-studied part of the radiant energy Earth emits, for clues about sea ice loss, ice-sheet melting

and a warming Arctic.

NASA calls the Arctic the region that behaves like our planet's thermostat, venting excess energy received in the tropics, which is why a pair of small satellites there matters.

On Saving Planets: Earth Observation · Orbital Mechanics

Sources: NASA Science: PREFIRE (Polar Radiant Energy in the Far-InfraRed Experiment) (https://science.nasa.gov/mission/prefire/)

Free learning resources

- NASA Science: PREFIRE (Polar Radiant Energy in the Far-InfraRed Experiment) (https://science.nasa.gov/mission/prefire/): NASA PREFIRE.
- NASA Small Spacecraft Technology State of the Art (https://www.nasa.gov/smallsat-institute/sst-soa/): Free NASA report.

- [ ] **I finished this unit**

CubeSat Track: Power and Link Budgets

Solar-array output, orbit-average power, battery sizing for eclipse, UHF link path loss and daily data volume.

Learning objectives

By the end of this unit you can:

- Compute array output in sunlight.
- Compute orbit-average power.
- Size a battery for eclipse.
- Estimate path loss and data per day.

Key concepts

- Array power is solar flux × cell efficiency × area × cos(angle).
- Orbit-average generation is reduced by the eclipse fraction (and by pointing in practice).
- The battery covers the eclipse load; limiting depth of discharge extends cycle life.
- Free-space path loss grows as 20 $\log_{10}(4\pi d/\lambda)$; UHF amateur bands are common for student CubeSats.
- Data volume per day is bit rate × pass time × passes.

Key equations

$$P = S\eta A\cos\theta$$

`P=S ηA cosθ`

Array output

$$\bar{P} = P(1 - f_e)$$

`P=P(1-f_e)`

Orbit-average generation

$$E = \frac{P_e t_e}{DoD}$$

`E=(P_et_e)/(DoD)`

Battery capacity

$$L = 20\log_{10}\frac{4\pi d}{\lambda}$$

`L=20_10(4π d)/()`

Path loss

Worked examples, step by step

Example 6.1 Panels of 0.06 m² with 28% cells face the Sun (sample values). Output?

1. 1361 × 0.28 × 0.06.

Answer: 22.9 W.

Example 6.2 Orbit average with Unit 5's eclipse fraction of 0.378?

1. 22.86 × 0.622.

Answer: 14.2 W.

Example 6.3 Battery for 8 W through a 35.8 min eclipse at 30% depth of discharge?

1. 8 × 35.75/60 = 4.77 Wh.
2. 4.77/0.3.

Answer: 15.9 Wh.

Practice problems

Work each on paper first, then check.

1. Path loss at 437 MHz over 1000 km?

   λ = 0.686 m; L = 145.3 dB.

2. Data per day at 9600 bit/s, four 10-minute passes?

   23.04 Mbit = 2.88 MB.

3. Output at a 60° Sun angle?

   11.4 W.

4. Why limit depth of discharge?

   More cycles before the battery wears out.

Common misconceptions

Myth: Sun power is constant around the orbit.

Actually: Eclipse and pointing cut it.

Myth: Battery = eclipse energy.

Actually: Divide by DoD.

Myth: More bits per second is free.

Actually: It needs more link margin.

Flashcards

Orbit-average power

Generation over a full orbit.

DoD

Depth of discharge.

Path loss

Spreading loss.

UHF

Ultra-high-frequency band.

Pass

Time a ground station sees the satellite.

Data volume

Bits downlinked per day.

Self-check quiz

1. Array output...

22.9 W

2.29 W

229 W

38 W

22.9 W. SηA.

2. Orbit average…

14.2 W

22.9 W

8.6 W

11.4 W

14.2 W. × 0.622.

3. Battery…

15.9 Wh

4.77 Wh

47.7 Wh

8 Wh

15.9 Wh. ÷ 0.3.

4. Path loss…

145.3 dB

125 dB

165 dB

14.5 dB

145.3 dB. 20 $\log_{10}(4\pi d/\lambda)$.

Try this quiz again

How this helps save the planet

NASA’s small spacecraft report says that when its first edition was published in 2013, 247 CubeSats and 105 other small spacecraft under 50 kg had been launched worldwide, less than 2% of the mass

launched to orbit.

NASA says small spacecraft have since become the primary means for commercial, government, private and academic institutions to access space, so careful power and link budgets now support a large share of Earth observation.

On Saving Planets: Spacecraft Design · Earth Observation

Sources: NASA Small Spacecraft Technology State of the Art (https://www.nasa.gov/smallsat-institute/sst-soa/)

Free learning resources

- NASA Small Spacecraft Technology State of the Art (https://www.nasa.gov/smallsat-institute/sst-soa/): Free NASA report.
- MIT OpenCourseWare 16.83X Space Systems Engineering (Spring 2002 – Spring 2003) (https://ocw.mit.edu/courses/16-83x-space-systems-engineering-spring-2002-spring-2003/): Free MIT capstone materials.

- [ ] **I finished this unit**

Structural and Thermal Checks

Load factors, margins of safety, launch and flight loads, and a first thermal equilibrium estimate for both tracks.

Learning objectives

By the end of this unit you can:

- Compute a design load from a load factor.
- Compute a margin of safety.
- Estimate equilibrium temperature.
- Decide what needs detailed analysis.

Key concepts

- Design loads are weight times a load factor (launch or maneuver), times a factor of safety.
- Margin of safety MS = allowable/(FS × applied) − 1 must be positive.
- Aluminum 6061-T6 yields near 276 MPa (textbook value), a common choice for both drones and CubeSat frames.
- A first thermal estimate balances absorbed sunlight with emitted infrared; for α = ε a sunlit body near Earth sits near 278 K on average.
- Hand checks find the critical cases; finite-element and thermal models then refine them.

Key equations

$$F = nmg$$

`F=nmg`

Load from load factor

$$MS = \frac{\sigma_{allow}}{FS \cdot \sigma} - 1$$

`MS=σ_allowFS·σ-1`

Margin of safety

$$T = \left(\frac{\alpha S}{4 \varepsilon \sigma} \right)^{1/4}$$

`T=((α S)/(4σ))^1/4`

Average equilibrium temperature

$$\sigma = F/A$$

Normal stress

Worked examples, step by step

Example 7.1 A 4 kg CubeSat sees 10 g (sample load factor). Load?

1. 10 × 4 × 9.80665.

Answer: 392 N.

Example 7.2 A rail sees 80 MPa; yield is 276 MPa; FS = 1.25. MS?

1. 276/(1.25 × 80) − 1.

Answer: 1.76, positive.

Example 7.3 Average equilibrium temperature with α = ε?

1. (1361/(4 × 5.670374419 × 10⁻⁸))^¼.

Answer: 278 K.

Practice problems

Work each on paper first, then check.

1. MS if stress rises to 200 MPa?

   0.10.

2. Load at 6 g on 5 kg?

   294 N.

3. In °C, 278.3 K is?

   5.2 °C.

4. Why a factor of safety?

   Uncertain loads, materials and analysis.

Common misconceptions

Myth: MS = 0 is fine.

Actually: Keep it positive.

Myth: Space is cold, so no thermal problem.

Actually: Sunlit parts can overheat.

Myth: Hand checks replace analysis.

Actually: They guide it.

Flashcards

Load factor

Multiple of weight.

Factor of safety

Multiplier on loads.

Margin of safety

Allowable over required minus one.

Yield strength

Stress for permanent set.

Equilibrium temperature

Absorbed = emitted.

FEA

Finite element analysis.

Self-check quiz

1. Load...

392 N

39 N

3920 N

40 N

392 N. nmg.

2. MS…

1.76

2.76

0.76

−0.24

1.76. 276/100 − 1.

3. Equilibrium T…

278 K

255 K

300 K

373 K

278 K. (S/4σ)^¼.

4. MS must be…

positive

negative

zero

above 10

positive. Definition.

Try this quiz again

How this helps save the planet

NASA says PREFIRE's twin CubeSats measure far-infrared emission from Earth, the same radiation this unit balances in its thermal estimate.

NASA reports the PREFIRE mission was extended so the twin satellites operate through at least September 2026, expanding focus from the poles to the whole planet, a payoff of a design that survived launch and orbit.

On Saving Planets: Aerospace Structures · Heat Transfer

Sources: NASA Science: PREFIRE (Polar Radiant Energy in the Far-InfraRed Experiment) (https://science.nasa.gov/mission/prefire/)

Free learning resources

- MIT OpenCourseWare 16.83X Space Systems Engineering (Spring 2002 – Spring 2003) (https://ocw.mit.edu/courses/16-83x-space-systems-engineering-spring-2002-spring-2003/): Free MIT capstone materials.
- NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/): Free NASA handbook.

Watch the lecture

Lecture 5: Orbiter Structure + Thermal Protection System (https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2005/resources/lecture-5/) (in English)

MIT 16.885J Aircraft Systems Engineering (Fall 2005), MIT OpenCourseWare. License: CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/) · Terms of use (https://ocw.mit.edu/pages/privacy-and-terms-of-use/). Linked for free study only; Saving Planets is not affiliated with or endorsed by this university.

☐ **I finished this unit**

Cost, Schedule and Risk

Work breakdown structures, critical-path schedules, earned value, risk matrices and mitigation plans.

Learning objectives

By the end of this unit you can:

- Build a work breakdown structure.
- Find the critical path.
- Compute CPI, SPI and estimate at completion.
- Score and mitigate risks.

Key concepts

- A work breakdown structure splits the project into deliverable pieces that can be estimated and assigned.
- The critical path is the longest chain of dependent tasks; any delay on it delays the project.
- Earned value compares planned value, earned value and actual cost.
- CPI = EV/AC and SPI = EV/PV; values under 1 mean over budget or behind schedule.
- Risks are scored likelihood × consequence and tracked with owners and mitigations.

Key equations

$$CPI = EV / AC$$

`CPI=EV/AC`

Cost performance index

$$SPI = EV / PV$$

`SPI=EV/PV`

Schedule performance index

$$EAC = BAC / CPI$$

`EAC=BAC/CPI`

Estimate at completion

$$R = L \times C$$

R=L× C

Risk score

Worked examples, step by step

Example 8.1 PV = $50k, EV = $45k, AC = $48k (sample values). CPI and SPI?

1. CPI = 45/48.
2. SPI = 45/50.

Answer: CPI = 0.9375, SPI = 0.90.

Example 8.2 Budget at completion is $100k. EAC?

1. 100/0.9375.

Answer: $106.7k.

Example 8.3 Tasks in sequence take 3, 4, 5 and 2 weeks in a 15-week term. Slack?

1. Path = 14 weeks.
2. 15 − 14.

Answer: 1 week.

Practice problems

Work each on paper first, then check.

1. Risk score for likelihood 4, consequence 5?

   20 of 25.

2. CPI = 1.1 means?

   Under budget.

3. Variance at completion for EAC $106.7k?

   −$6.7k.

4. What is a WBS?

Work breakdown structure.

Common misconceptions

Myth: Spending on plan means on schedule.

Actually: Compare earned value, not spend.

Myth: Every task is critical.

Actually: Only the longest path is.

Myth: Risks disappear when listed.

Actually: They need owners and actions.

Flashcards

WBS

Work breakdown structure.

Critical path

Longest dependent chain.

Earned value

Value of work done.

CPI

EV/AC.

SPI

EV/PV.

Risk matrix

Likelihood × consequence.

Self-check quiz

1. CPI...

0.9375

0.90

1.067

0.96

0.9375. EV/AC.

2. SPI…

0.90

0.9375

1.11

0.96

0.90. EV/PV.

3. EAC…

$106.7k

$100k

$93.8k

$111k

$106.7k. BAC/CPI.

4. Slack…

1 week

0 weeks

14 weeks

3 weeks

1 week. 15 − 14.

Try this quiz again

How this helps save the planet

NASA’s Systems Engineering Handbook includes a full section on crosscutting technical management, alongside system design and product realization.

Projects that stay on budget and schedule launch sooner, and Earth-observing data starts flowing sooner. Cost values in this unit are sample values.

On Saving Planets: Solutions · Avionics & Systems Engineering

Sources: NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/)

Free learning resources

- NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/): Free NASA handbook, Section 6.
- MIT OpenCourseWare 16.83X Space Systems Engineering (Spring 2002 – Spring 2003) (https://ocw.mit.edu/courses/16-83x-space-systems-engineering-spring-2002-spring-2003/): Free MIT capstone materials.

☐ **I finished this unit**

Prototype, Test and Verification

Verification matrices, test planning, measurement statistics, comparing results with predictions, and closing requirements.

Learning objectives

By the end of this unit you can:

- Build a verification matrix.
- Compute mean and standard deviation.
- Compare a measurement with an allocation.
- Close or waive a requirement.

Key concepts

- A verification matrix lists each requirement, its method, the test or analysis, and the result.
- Repeat measurements to estimate the mean and spread; report both.
- Compare results with predictions; large differences reveal model errors early.
- Test as you fly: use flight-like configurations and procedures.
- MIT's 16.83X follows conceive, design, implement and operate phases, ending with testing in the intended environment.

Key equations

$$\bar{x} = \frac{1}{n}\sum x_i$$

`x=1n x_i`

Mean

$$s = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}}$$

`s=((x_i- x)^2)/(n-1)`

Sample standard deviation

$$\text{Margin} = \frac{A - \bar{x}}{\bar{x}}$$

`Margin=(A- x)/( x)`

Measured margin

$$e = \frac{x_m - x_p}{x_p}$$

`e=(x_m-x_p)/(x_p)`

Prediction error

Worked examples, step by step

Example 9.1 Five mass measurements: 3.38, 3.42, 3.40, 3.45, 3.35 kg. Mean?

1. Sum 17.00/5.

Answer: 3.40 kg.

Example 9.2 Sample standard deviation?

1. Deviations −0.02, 0.02, 0, 0.05, −0.05.
2. √(0.0058/4).

Answer: 0.038 kg.

Example 9.3 Margin against the 4.0 kg allocation?

1. (4.0 − 3.40)/3.40.

Answer: 17.6%: the requirement closes.

Practice problems

Work each on paper first, then check.

1. Predicted 3.30 kg, measured 3.40 kg. Error?

   +3.03%.

2. Why repeat measurements?

   To estimate spread and catch mistakes.

3. What does “test as you fly” mean?

   Use flight-like hardware and procedures.

4. Who approves a waiver?

   The project's review board or customer.

Common misconceptions

Myth: One measurement is enough.

Actually: Report mean and spread.

Myth: Tests prove a design perfect.

Actually: They show it meets requirements under test conditions.

Myth: Disagreeing data is bad.

Actually: It teaches you about the model.

Flashcards

Verification matrix

Requirement-to-evidence table.

Mean

Average.

Standard deviation

Spread.

Test as you fly

Flight-like testing.

Waiver

Approved exception.

CDIO

Conceive, design, implement, operate.

Self-check quiz

1. Mean...

3.40 kg

3.38 kg

3.45 kg

17 kg

3.40 kg. Sum/n.

2. Std dev...

0.038 kg

0.38 kg

0.0058 kg

0.1 kg

0.038 kg. Sample formula.

3. Margin...

17.6%

15%

0.6%

−15%

17.6%. (4 − 3.4)/3.4.

4. Prediction error...

+3.03%

−3.03%

+0.1%

+30%

+3.03%. 0.1/3.3.

Try this quiz again

How this helps save the planet

MIT OpenCourseWare describes 16.83X as following a conceive-design-implement-operate model, with a final phase in which the system is tested and readied for its intended environment.

NASA's CubeSat Launch Initiative flies student satellites that pass this kind of testing, turning capstones into working instruments in orbit.

On Saving Planets: Avionics & Systems Engineering · Probability & Statistics

Sources: MIT OpenCourseWare 16.83X Space Systems Engineering (Spring 2002 – Spring 2003) (https://ocw.mit.edu/courses/16-83x-space-systems-engineering-spring-2002-spring-2003/) · NASA: CubeSat Launch Initiative (https://www.nasa.gov/kennedy/launch-services-program/cubesat-launch-initiative/)

Free learning resources

- MIT OpenCourseWare 16.83X Space Systems Engineering (Spring 2002 – Spring 2003) (https://ocw.mit.edu/courses/16-83x-space-systems-engineering-spring-2002-spring-2003/): Free MIT capstone materials.
- NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/): Free NASA handbook, Section 5.

☐ **I finished this unit**

Design Reviews and the Final Report

Preliminary and critical design reviews, presenting trades and budgets, answering questions, and writing the final report.

Learning objectives

By the end of this unit you can:

- Plan a design review.
- Present budgets with margins.
- Track review action items.
- Write a clear final report.

Key concepts

- A preliminary design review shows the concept meets requirements with margin; a critical design review shows the detailed design is ready to build.
- Lead with requirements, then the design, then budgets, risks, test plans and open issues.
- Every review produces action items with owners and due dates.
- The final report tells the story from need to verified design, with numbers that trace to the spreadsheet.
- Honest discussion of what didn’t work is part of good engineering.

Key equations

$$t_{talk} = n_{slides} \times t_{slide}$$

```
t_talk=n_slides× t_slide
```

Talk length

$$\text{Closure} = \frac{n_{closed}}{n_{total}}$$

```
Closure=_closedn_total
```

Action-item closure

$$\text{Margin} = \frac{A - E}{E}$$

```
Margin=(A-E)/(E)
```

Budget margin

$$\text{Coverage} = \frac{n_{verified}}{n_{req}}$$

`Coverage=_verifiedn_req`

Verification coverage

Worked examples, step by step

Example 10.1 A 20-minute review at 1.5 minutes per slide. Slides?

1. 20/1.5.

Answer: About 13.

Example 10.2 A review leaves 12 action items; 9 are closed. Closure?

1. 9/12.

Answer: 75%.

Example 10.3 30 of 32 requirements are verified. Coverage?

1. 30/32.

Answer: 93.75%.

Practice problems

Work each on paper first, then check.

1. Slides for a 30-minute review at 2 min each?

   15.

2. What follows PDR?

   CDR.

3. Closure with 11 of 12 closed?

   91.7%.

4. Why show open issues?

   Reviewers can help, and it builds trust.

Common misconceptions

Myth: Reviews are exams.

Actually: They help the project.

Myth: More slides is better.

Actually: Clarity beats volume.

Myth: Hide problems.

Actually: Show them with plans.

Flashcards

PDR

Preliminary design review.

CDR

Critical design review.

Action item

Task from a review.

Final report

Need-to-verification story.

Coverage

Share of verified requirements.

Lessons learned

What to do differently.

Self-check quiz

1. Slides...

≈ 13

20

30

5

≈ 13. 20/1.5.

2. Closure...

75%

9%

25%

133%

75%. 9/12.

3. Coverage...

93.75%

30%

96%

6.25%

93.75%. 30/32.

4. CDR shows...

design ready to build

first idea

launch done

budget only

design ready to build. Critical design.

Try this quiz again

How this helps save the planet

NASA says its Sustainable Flight National Partnership supports the aviation community's goal of net-zero carbon emissions by 2050.

NASA says PREFIRE's extended mission now looks at the whole planet; strong reviews and reports are how student and professional designs reach that kind of impact.

On Saving Planets: Solutions · Earth Observation

Sources: NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/) · NASA Science: PREFIRE (Polar Radiant Energy in the Far-InfraRed Experiment) (https://science.nasa.gov/mission/prefire/)

Free learning resources

- NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/): Free NASA handbook.
- MIT OpenCourseWare 16.83X Space Systems Engineering (Spring 2002 – Spring 2003) (https://ocw.mit.edu/courses/16-83x-space-systems-engineering-spring-2002-spring-2003/): Free MIT capstone materials.

☐ **I finished this unit**

Problem Sets

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

1. Mission, Stakeholders and Requirements
   4 problems
2. Concept Generation and Selection
   4 problems
3. Aircraft Track: Weight Sizing and Range
   4 problems
4. Aircraft Track: Wing Loading and Power
   4 problems
5. CubeSat Track: Sizing and Orbit
   4 problems
6. CubeSat Track: Power and Link Budgets
   4 problems
7. Structural and Thermal Checks
   4 problems
8. Cost, Schedule and Risk
   4 problems
9. Prototype, Test and Verification
   4 problems
10. Design Reviews and the Final Report
    4 problems

The lab (Design studio)

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

Every lab is a spreadsheet design tool, so there are no hazards. Do not build or fly a real drone, charge lithium batteries or handle launch hardware for this course without qualified supervision and local rules. 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: Requirements and margin tracker

WEEK 1

Goal: Build the requirements spreadsheet your whole project will use, with live margins.

$$\text{Margin} = (A - E)/E$$

```
Margin=(A-E)/E
```

Margin

Procedure

1. List 10–20 requirements with number, unit and verification method.
2. Enter a 4.0 kg mass allocation (textbook 3U value) or a 5 kg drone allocation.
3. Enter estimates of 3.4, 3.6 and 3.8 kg and compute margin.
4. Color margins under 10% red.

Data table

Estimate (kg)	Margin
3.4	17.6%
3.6	11.1%
3.8	5.26%

Computed sample values.

Sample calculation

1. (4.0 − 3.6)/3.6 = 11.1%.
2. (4.0 − 3.8)/3.8 = 5.26%.

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

Home or virtual alternative

- Any spreadsheet works.

NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/)

Planet link: NASA's CubeSat Launch Initiative has launched over 150 CubeSats. NASA: CubeSat Launch Initiative (https://www.nasa.gov/kennedy/launch-services-program/cubesat-launch-initiative/)

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

Lab B: Concept-selection matrix with sensitivity

WEEK 2

Goal: Score two concepts and test how weights change the winner.

$$S = \sum w_i s_i$$

`S= w_is_i`

Weighted score

Procedure

1. Enter Unit 2’s scores: A (6, 9, 5), B (8, 6, 8).
2. Score with three weight sets.
3. Plot the winner against the performance weight.
4. Write one paragraph defending your choice.

Data table

Weights (cost, perf., risk)	A	B
0.3, 0.5, 0.2	7.3	7.0
0.4, 0.3, 0.3	6.6	7.4
0.2, 0.6, 0.2	7.6	6.8

Computed sample values.

Sample calculation

1. A = 0.2 × 6 + 0.6 × 9 + 0.2 × 5 = 7.6.
2. B = 0.2 × 8 + 0.6 × 6 + 0.2 × 8 = 6.8.

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

Home or virtual alternative

- Any spreadsheet works.

MIT OpenCourseWare 16.83X Space Systems Engineering (Spring 2002 – Spring 2003) (https://ocw.mit.edu/courses/16-83x-space-systems-engineering-spring-2002-spring-2003/)

Planet link: NASA's SFNP works across vehicles, operations and sustainable fuels. NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/)

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

Lab C: Drone sizing loop

WEEK 4

Goal: Size the drone track's takeoff mass for several battery fractions.

$$W_0 = W_{pay}/(1 - f_e - f_b)$$

```
W_0=W_pay/(1-f_e-f_b)
```

Takeoff mass

Procedure

1. Enter 1 kg payload and empty fraction 0.5.
2. Compute takeoff mass for battery fractions 0.25, 0.30 and 0.35.
3. Add wing area from W/S = 105.84 N/m².
4. Pick a design point and justify it.

Data table

Battery fraction	Takeoff mass (kg)
0.25	4.0
0.30	5.0
0.35	6.67

Computed sample values.

Sample calculation

1. 1/(1 − 0.5 − 0.25) = 4.0 kg.
2. 1/(1 − 0.5 − 0.35) = 6.67 kg.

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

Home or virtual alternative

- Any spreadsheet works.

MIT OpenCourseWare 16.83X Space Systems Engineering (Spring 2002 – Spring 2003) (https://ocw.mit.edu/courses/16-83x-space-systems-engineering-spring-2002-spring-2003/)

Planet link: NASA's SFNP targets 25–30% energy-efficiency gains. NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/)

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

Lab D: CubeSat orbit and eclipse

WEEK 6

Goal: Compute period and worst-case eclipse for candidate altitudes.

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

T=2π^3/μ

Period

Procedure

1. Enter altitudes 400, 500 and 600 km.
2. Compute T and orbits per day.
3. Compute worst-case eclipse minutes.
4. Choose an altitude and note the drag-lifetime trade.

Data table

Altitude (km)	T (min)	Eclipse (min)
400	92.6	36.1
500	94.6	35.8
600	96.7	35.5

Computed sample values.

Sample calculation

1. T(600) = 2π√(6978.1³/398,600.4) = 96.7 min.
2. Eclipse(400) = 0.390 × 92.6 = 36.1 min.

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

Home or virtual alternative

- Any spreadsheet works.

NASA Small Spacecraft Technology State of the Art (https://www.nasa.gov/smallsat-institute/sst-soa/)

Planet link: NASA: PREFIRE's CubeSats launched in May 2024. NASA Science: PREFIRE (Polar Radiant Energy in the Far-InfraRed Experiment) (https://science.nasa.gov/mission/prefire/)

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

Lab E: Power and data budget

WEEK 7

Goal: Close the CubeSat power and data budgets with margin.

$$V = R_b t_p n_p$$

V=R_bt_pn_p

Daily data volume

Procedure

1. Enter array output 22.9 W and orbit average 14.2 W.
2. List loads and compare with the orbit average.
3. Compute data per day at 9600 bit/s for 2, 4 and 6 ten-minute passes.
4. Compare with your payload’s daily data.

Data table

Passes per day	Data (Mbit)
2	11.52
4	23.04
6	34.56

Computed sample values.

Sample calculation

1. 9600 × 600 × 2 = 11.52 Mbit.
2. 9600 × 600 × 6 = 34.56 Mbit.

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

Home or virtual alternative

- Any spreadsheet works.

NASA Small Spacecraft Technology State of the Art (https://www.nasa.gov/smallsat-institute/sst-soa/)

Planet link: NASA: small spacecraft are now the primary means for many groups to access space.
NASA Small Spacecraft Technology State of the Art (https://www.nasa.gov/smallsat-institute/sst-soa/)

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

Lab F: Earned-value tracker

WEEK 10

Goal: Track cost and schedule performance across three status dates.

$$CPI = EV/AC,\ SPI = EV/PV$$

`CPI=EV/AC,\ SPI=EV/PV`

Performance indices

Procedure

1. Enter PV, EV and AC for three dates.
2. Compute CPI and SPI.
3. Compute EAC with BAC = $100k.
4. Write a one-line status for each date.

Data table

PV, EV, AC ($k)	CPI	SPI
20, 20, 22	0.909	1.00
50, 45, 48	0.9375	0.90
80, 76, 80	0.95	0.95

Computed sample values.

Sample calculation

1. 20/22 = 0.909.
2. 76/80 = 0.95.

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

Home or virtual alternative

- Any spreadsheet works.

NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/)

Planet link: NASA's handbook covers crosscutting technical management. NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/)

- [ ] **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. Margin of a 4.0 kg allocation over a 3.6 kg estimate?

    1. 0.4/3.6.

    Answer: 11.1%.

2. Takeoff mass for 2 kg payload, empty 0.45, battery 0.3?

    1. 2/0.25.

    Answer: 8 kg.

3. Wing loading for a 14 m/s stall, C_Lmax 1.3?

    1. ½ × 1.225 × 196 × 1.3.

    Answer: 156.1 N/m².

4. Period at 400 km?

    1. a = 6778.1 km.

    Answer: 92.6 min.

5. Breguet range with L/D = 20 instead of 17 (Unit 3 values)?

    1. 5235 × 20/17.

    Answer: 6159 km.

Final practice set (Units 1–10)

1. Array of 0.09 m² at 30% efficiency?

    1. 1361 × 0.3 × 0.09.

    Answer: 36.7 W.

2. Battery for 10 W over 36 min at 25% DoD?

1. 10 × 0.6/0.25.

Answer: 24 Wh.

3. MS for 100 MPa, yield 276 MPa, FS 1.4?

    1. 276/140 − 1.

    Answer: 0.971.

4. EAC with BAC $200k, EV 60, AC 64?

    1. CPI = 0.9375.
    2. 200/0.9375.

    Answer: $213.3k.

5. Mean and sample std dev of 2, 4, 6?

    1. Mean 4.
    2. √(8/2).

    Answer: 4 and 2.

6. Verification coverage, 45 of 50?

    1. 45/50.

    Answer: 90%.

Formula sheet

$$\text{Margin} = (A - E)/E,\ m_{alloc} = m_{est}(1 + M)$$

$$S = \sum w_i s_i,\ N = \prod n_i$$

$$W_0 = W_{pay}/(1 - f_e - f_b),\ R = (V/c)(L/D)\ln(W_i$$

$$W/S = \tfrac{1}{2}\rho V_s^2 C_{L,max},\ P = W(V/(L/D) + RC)/\eta$$

$$T = 2\pi\sqrt{a^3/\mu},\ f_e = \sin^{-1}(R_E/a)/\pi$$

$$P = S\eta A\cos\theta,\ E = P_e t_e/DoD,\ L = 20\log_{10}(4\pi d$$

$$F = nmg,\ MS = \sigma_{allow}/(FS\,\sigma) - 1$$

$$CPI = EV/AC,\ SPI = EV/PV,\ EAC = BAC$$

$$\bar{x} = \sum x_i/n,\ s = \sqrt{\sum (x_i - \bar{x})^2/(n-1)}$$

$$\text{Coverage} = n_{verified}/n_{req}$$

Constants

Constant	Value
Earth’s gravitational parameter (textbook value)	$\mu = 398{,}600.4418\ km^3/s^2$
Earth’s equatorial radius (textbook value)	6378.137 km
Standard gravity	$g = 9.80665\ m/s^2$
Solar constant (textbook value)	$1361\ W/m^2$
Sea-level air density (textbook value)	$1.225\ kg/m^3$
Speed of light	c = 299,792,458 m/s (exact)

Source: NIST: CODATA value, speed of light in vacuum (https://physics.nist.gov/cgi-bin/cuu/Value?c)

Free texts and resources

Use these free handbooks, lectures and mission pages alongside the course.

- NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/): Free NASA handbook.
- MIT OpenCourseWare 16.83X Space Systems Engineering (Spring 2002 – Spring 2003) (https://ocw.mit.edu/courses/16-83x-space-systems-engineering-spring-2002-spring-2003/): Free MIT capstone materials.
- NASA Small Spacecraft Technology State of the Art (https://www.nasa.gov/smallsat-institute/sst-soa/): Free NASA small-spacecraft report.
- NASA: CubeSat Launch Initiative (https://www.nasa.gov/kennedy/launch-services-program/cubesat-launch-initiative/): NASA launch opportunities.
- NASA Science: PREFIRE (Polar Radiant Energy in the Far-InfraRed Experiment) (https://science.nasa.gov/mission/prefire/): NASA CubeSat mission.
- NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/): NASA sustainable aviation.

Glossary

Action item
Task assigned at a review.

Allocation
Budgeted share of a resource.

Breguet equation
Aircraft range equation.

CDR
Critical design review.

CPI
Cost performance index.

Constraint diagram
Requirements plotted against wing loading.

Critical path
Longest chain of dependent tasks.

CubeSat
Small satellite built in 10 cm units.

Depth of discharge
Share of battery capacity used.

Earned value
Budgeted value of work done.

Eclipse fraction
Share of an orbit in shadow.

Margin of safety
Allowable over required minus one.

Morphological chart
Options for each function.

PDR
Preliminary design review.

Pugh matrix
Comparison against a datum concept.

Requirement
Verifiable statement of need.

SPI
Schedule performance index.

Verification matrix
Requirement-to-evidence table.

Wing loading
Weight per wing area.

Work breakdown structure
Project split into deliverables.

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	Delivers a design that traces every number to a requirement, closes all budgets with margin, verifies requirements with evidence, and presents trades, risks and lessons clearly.
3 · Proficient	Closes most budgets with margin and presents a clear design with minor gaps.
2 · Developing	Has a concept and some budgets but weak requirement tracing or missing margins.
1 · Beginning	Presents a design without requirements, budgets or verification; needs to revisit the units.

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

- Avionics & Systems Engineering AERO 450
- Sustainable Aviation AERO 470
- Propulsion AERO 410
- All courses