An Introduction to Astronautics
and
Space Systems

Block 3 Study Guide

Lesson 1 - Payload and Spacecraft Design

Review

- A spacecraft can be divided into the payload and the bus
    - The payload's job is to collect all mission data or interact with users on the ground
    - The spacecraft bus provides all the housekeeping functions needed to run the payload and get data to users. The bus consists of a number of critical subsystem functions:
        - Attitude determination and control keeps the spacecraft pointed in the right direction
        - Navigation, guidance and control maintains our orbits or takes us to new ones
        - Communication to send payload data and other telemetry and receive commands from the ground
        - Data handling to collect, process, store and distribute commands, mission data and telemetry
        - Electrical power to generate, store, convert, distribute and regulate power around the spacecraft
        - Thermal control to maintain the payload and subsystems at their optimal temperature
        - Structures to hold together all the other subsystems and payload; withstands launch and mission loads along with a variety of mechanisms which may also deploy and retract throughout the mission.
        - Rocket propulsion generates thrust to change our orbit or torque to change our attitude
- The spacecraft design process starts with the payload and is inherently iterative as changes made in one subsystem can affect the design of all other subsystems
- To "look" and "listen" from space we use the electro-magnetic (EM) spectrum
    - We apply principles of black-body radiation, and understand how EM radiation is affected by the atmosphere.
        - The Stefan-Boltzmann Equation identifies the total energy radiated by the blackbody
        - Wien's Law defines the wavelength of peak energy emission
- Sensor spatial resolution refers to the smallest object a sensor can detect
    - A function of: wavelength; distance to the subject; diameter of the sensor's aperture; and the number of pixels on the sensor's detector array.
- To estimate key payload design parameters (mass, power, volume, data) we scale from existing similar payloads based on sensor aperture.
    - We then can determine subsystem performance budgets that will form the basis for the initial spacecraft design.

Key Terms

- Aperture
- Atmospheric windows
- Black-body radiation
- Electro-magnetic radiation
- Emissivity, ε
- Field of view
- Frequency
- Payload
- Planck's Law
- Remote sensing
- Requirements
- Resolution
- Spacecraft bus
- Stakeholder expectations
- Swath width
- Stefan-Boltzmann constant
- Wavelength
- Wien's Law

Lesson 1 - Mission Problems

1. List the major spacecraft subsystems and their function.

2. Describe the difference between passive and active sensors and give examples of each.

3. Match the following terms with the appropriate statement below: Wien's Law, Planck's Law, and Stefan-Boltzman Equation

a. identifies the total energy radiated by a blackbody
b. the amount of energy given off by an object is related to its temperature
c. relates the wavelength of maximum output an object will emit to its temperature

4. Define the following terms:

- Atmospheric Windows

- Sensor resolution

Lesson 2 - Electrical Power Subsystems

Review

‣ The basic function of the electrical power subsystem (EPS) is to convert some raw energy source-such as solar energy- into usable electrical power (at the right current and voltage) to operate the payload and all other subsystems.
‣ Energy sources available to spacecraft include: the Sun (photovoltaic), chemical systems (batteries and fuel cells); and nuclear systems (radioisotope thermoelectric generators).
‣ There are three key functions within the EPS process:

- Power supply - from some primary source e.g. the Sun
- Power storage - as in secondary batteries
- Power conditioning and distribution - voltage regulation, protection and delivery to users

‣ The overall spacecraft power budget drives the EPS design. In addition, we must account for:

- Lifetime degradation and losses due to the space environment
- Duty cycle issues
- Peak power
- Orbit average power
- Integrated testing

Key Terms

- Angle of incidence, θ
- Charge
- Chemical energy
- Coulomb's Law
- Current
- Duty cycle
- Eclipse
- Fuel cells
- Orbit average power
- Peak power
- Photovoltaic, PV
- Power budget
- Primary batteries
- Radioisotope thermoelectric generators (RTGs)

Secondary batteries
Solar cells
Solar cell efficiency, η
Voltage

Lesson 2 - Mission Problems

1. List and briefly describe the three key functions within the EPS.

2. Define duty cycle, peak power and orbit average power as they relate to the overall spacecraft power budget which drives the EPS design.

3. Match the following terms or values to the appropriate descriptions below: Charge, Voltage, Current, Power

a. the amount of energy that is delivered to a unit of charge
b. the rate at which charges flow through a given area, such as the cross section of a wire
c. the basic unit of electricity; it can be positive or negative
d. the amount of energy delivered per unit time

4. Briefly describe the following:

- Coulomb's Law

- Ohm's Law

Lesson 3 - Attitude and Orbit Control Subsystems

Review

‣ Control systems are critical to spacecraft, they manage and control power, data, temperature, attitude and orbits.

- Open-loop systems are simple but not adaptive.
- Closed-loop systems use feedback to react to changes in the environment.

‣ Spacecraft attitude determination & control systems (ADCS) overcome disturbance torques (gravity gradient, solar pressure, magnetic or drag) to point in the right direction by using sensors (Earth, sun, star, gyros, magnetometers) and actuators (thrusters, magnetorquers, momentum wheels, reaction wheels or control moment gyros).

‣ Navigation, guidance and control (NGC) is the process of determining our orbit then using rockets to guide into a new orbit.

Key Terms

- Active control
- Actuators
- Attitude Determination and Control System (ADCS)
- Block Diagram
- Closed-loop
- Dampers
- Disturbance torque
- Gravity gradient
- Guidance
- Gyroscope
- Magnetometer
- Momentum control devices
- Navigation, guidance and control (NGC)
- Open-loop
- Passive control
- Pointing accuracy, Ψ
- Precession
- Sensors
- Spin stabilization

Lesson 3 - Mission Problems

1. List and briefly describe the four basic tasks all control systems must perform.

2. Describe open-loop and closed-loop control systems and give an example of each.

3. Match the following terms with the correct description below: Pointing Accuracy, Disturbance Torques, Star Sensor, Gyroscope, Magnetometer

a. a spacecraft's attitude measuring instrument that uses a sensitive electromagnet to measure Earth's magnetic field direction and determine a spacecraft's attitude
b. a spacecraft's attitude measuring instrument that uses a spinning mass to maintain a constant orientation so that it can measure any spacecraft rotation around it
c. the ability of a spacecraft's attitude control system to point sensors and antennas within angular constraints.
d. environmental effects that drive a spacecraft away from its original attitude
e. a spacecraft's attitude measuring instrument that looks out the window at known star locations.

4. Define the following:

- ADCS

- NGC

Lesson 4 - Communication Subsystems

Review

- The communication subsystem is the "ears and mouth" of the spacecraft.
  - Sends payload and subsystem information to the ground station and receives commands in return
  - Consists of modulators/demodulators ("MODEMS"), transmitters, receivers, and antennas
- The communication subsystem works as part of an overall communication architecture
  - The communication architecture is the configuration of satellites and ground station nodes in a space system and the network that links them together.
  - Communication subsystems create all of the links between these nodes
- Radio Frequency (RF) Communication is the process of modulating an information signal put onto a carrier signal and then retrieving that information at the receiver
- The link budget accounts for the data rate and other factors that contribute to the basic ability for the spacecraft and ground system to communicate effectively. Five key issues are important:
  - Distance - Characterized as Space Losses
  - Language - Characterized by Modulation method (e.g. AM or FM)
  - Speed - Defined to be the Data Rate
  - Environment - Which produces Noise
  - Carrier Frequency - Regulated & controlled at the national and international level
- Link Budget analysis helps us determine if there is enough energy in each bit we send so that the receiver can distinguish between a "1" and a "0" in the presence of background noise
- Key limitations in communication subsystem design include:
  - Physical limits, Technical limits, Legal limits
- System design must manage a variety of trade-offs to best ensure the message gets through

Key Terms

- Carrier Frequency
- Data Rate
- Distance
- Eb/No
- Environment
- Frequency Allocation
- Language
- Link Budget
- Modulators/demodulators ("MODEMs")
- Radio frequencies (rf)
- Receiver
- Speed
- Transmitter

Lesson 4 - Mission Problems

1. List and briefly describe the five key issues the we must focus on to be "heard and understood".

2. List and describe the three main areas of limitations which impact Communication Subsystem design.

3. Match the following with the appropriate descriptions below: Eb/No, link budget analysis, data rate, modulator

a. the number of bits per second that the communication and data handling subsystem must transmit during a pass over the ground station.

b. helps us determine if there is enough energy in each bit we send so that the receiver can distinguish between a "1" and a "0" in the presence of background noise.

c. the ratio of the received energy per bit to noise density ratio

d. an electronic device that add a message's electronic signal to a carrier wave before transmitting it.

4. List five things that designers can do to increase Eb/No and the associated constraint (s).

Lesson 5 - Data Handling Subsystems

Review

‣ The data handling subsystem (DHS) acts as the "brains" of the spacecraft. It's purpose is to manage, store and control all ground commands, payload data and telemetry during every phase of the mission. It needs to:

- Respond to ground commands
- Collect, process, store and format subsystem telemetry and payload data
- Autonomously Boot up and Self-test, Detect & correct errors and go into a safe mode if necessary
- Control attitude, orbit, temperature, power and every other process onboard the spacecraft
- Allow for on-orbit corrections, updates and upgrades to functionality

‣ The DHS is one part of an integrated mission concept of operations that involves both ground and space data systems

‣ The DHS consists of:

- Central Processing Unit (CPU) - Where the "thinking" takes place
- Memory - RAM, ROM and other solid state memory devices store the operating system, application programs, health and status telemetry data as well as payload data
- Data storage has become basically "free" as terabits can now readily be stored onboard even small satellites.
- Input/Output - Data lines that interface to sensors and other subsystems
- Other Components such as transducers, FPGAs and ASICs
- Software - To execute all key functions

‣ Software drives all data handling functions - Spacecraft have become "flying software"

- The amount and complexity of software in space systems (and terrestrial systems for that matter) is exploding
- The more we depend on software, the more likely software will contribute to failures

Key Terms

- Autonomy
- Central Processing Unit (CPU)
- Data Handling Subsystem (DHS)
- Sampling
- Software
- Single event latch-ups (SEL)
- Single event upsets (SEU)
- Random access memory (RAM)
- Read only memory (ROM)

Lesson 5 - Mission Problems

1. Draw the input/output diagram for a simple data-handling subsystem and define all of its components.

2. What are the two types of software in a data-handling subsystem? What does each do?

3. Match the following terms with the best description below: CPU, RAM, ROM, SEU

a. a computer memory change caused by charged particle impacts

b. a computer's short-term electronic storage locations for access by the central processing unit; volatile memory that erases when power is off

c. a computer's electronic locations to store fixed programs and data that don't change during the mission; non-volatile memory that stays constant when power is on or off

d. one of three main components of a data-handling subsystem

Lesson 6 - Structure and Thermal Subsystems

Review

- The structure typically accounts for 10%-20% of the dry mass of the entire spacecraft
  - The primary structure carries all the major loads: Pushing (compression) or pulling (tension); Bending; Changes in temperature - heating causes expansion; cooling causes contraction; Vibrations
  - The secondary structure hold all the subsystems together
- Must define structural requirements and constraints for:
  - Strength - minimum necessary to ensure the structure won't break
  - Stiffness (and natural frequency) - avoid resonance with the launch vehicle's vibration modes
  - Stability - minimum necessary to ensure the structure doesn't permanently deform after being subjected to loads
  - Mass properties - mass, volume, center of gravity, and moments of inertia
  - Mechanical interfaces - what needs to attach, where and how
  - The launch vehicle environment is typically the biggest driver of structural requirements
- Structural design balances requirements of mechanical configuration (mass, volume, layout imposed by the payload, subsystems and launch vehicle with the equally important requirements for mechanical behavior
- The thermal control subsystem regulates and controls the amount of heat that gets in, out, and moves around inside of a spacecraft: Heat Out = Heat In +Internal Heat (for thermal equilibrium)
- Radiation is the primary means for heat to get in/out of a spacecraft
  - Most of our thermal control effort is aimed at controlling how heat is absorbed, α, or emitted, ε
  - ~80-100% of spacecraft thermal control can be done using passive means (e.g. insulations, coatings, radiators)
  - Active thermal control methods include heaters, louvers and cryopumps
- To model spacecraft thermal control, engineers define a series of interconnected nodes on the spacecraft
- Spacecraft thermal control subsystem testing involves subjecting systems to thermal cycling, as well as combined, thermal-vacuum cycling.

Key Terms

- Absorptivity, α
- Compression
- Conduction
- Convection
- Dynamic loads
- Emissivity, ε
- Expansion
- Fatigue
- Primary structure
- Radiation
- Resonance
- Secondary structure
- Static loads
- Tension
- Thermal Equilibrium

Lesson 6 - Mission Problems

1. List and briefly describe the loads that a spacecraft structure may be subjected to.

2. Match the following terms with the best description below: primary structure, secondary structure, low-cycle mechanisms, high-cycle mechanisms

a. operate repeatedly during a mission, i.e. solar array pointing devices, reaction wheels and other moving parts

b. carries all of the major loads

c. operate only once or a few times to deploy booms and solar panels or open (or close) propellant valves

d. holds all of the subsystems together

3. Briefly describe passive and active thermal control and list techniques

4. Match the following terms with the best description below: conduction, convection, radiation

a. energy transfer via electromagnetic energy (e.g. infrared)

b. thermal energy transfer between a flowing fluid and a solid surface

c. thermal energy transfer through matter in the absence of fluid motion

Lesson 7 - Rocket Science

Review

- Rockets take in mass and energy and convert them into thrust
  - Rocket thrust is described by Newton's Third Law "For every action, there is an equal but opposite reaction". Rockets eject high-velocity mass in one direction causing the rocket to accelerate in the other direction.
  - Total thrust delivered depends on how much mass is ejected in a given time (mass flow rate) and the velocity of the mass ejected (effective exhaust velocity, C).
  - Specific impulse, Isp, measures a rocket's efficiency in terms of propellant mass needed to deliver a given thrust.
    - The higher the Isp, the less propellant mass needed to deliver the same total impulse. Isp is a function of a rocket's exhaust velocity.
  - You can find the amount of velocity change, ΔV, a rocket delivers for a given amount of propellant using the rocket equation
- We classify rockets based on the form of energy they use
  - Thermodynamic rockets - rely on thermodynamic energy (heat and pressure). These include:
    - Chemical Rockets - Liquid Mono-propellant, Liquid Bi-propellant, Solid Rockets and Hybrid Rockets
    - Electro-thermal Rockets - Resistojets and Arcjets
    - Nuclear Thermal Rockets
  - Electrodynamic rockets - rely on electric and/or magnetic fields to accelerate charged particles to high velocity. These include:
    - Ion (also called electrostatic) rocket engines
    - Hall Effect thrusters (HET)
    - Pulsed-Plasma Thrusters (PPT)
- A variety of factors must be considered when choosing the "best" type of rocket for a given application (e.g. mass, volume, power, time, safety, etc.)

Key Terms

- Effective Exhaust Velocity, C
- Electrodynamic
- Ideal Rocket Equation
- Momentum
- Specific Impulse, Isp
- Thermodynamic
- Thrust

Lesson 7 - Mission Problems

1. Define rocket thrust and explain where it comes from in terms of Newton's 3rd Law of Motion.

2. What are the two main categories of rockets in current use and how are they classified?

3. Describe the basic operating principle of a hybrid rocket. Compare their advantages and disadvantages to chemical bipropellant systems.

4. List the various factors that we must consider when determining the total cost of a particular propulsion subsystem option. Describe how the relative importance of these factors would differ between an experimental-science mission conducted by university students and a communication mission conducted by a commercial aerospace company.

Lesson 8 - Launch Vehicles

Review

‣ Launch-vehicle subsystems are similar in many ways to spacecraft subsystems. The primary differences include:
- Total lifetime (minutes to hours rather than years)
- Propulsion subsystem requirements

‣ Launch-vehicle propulsion subsystems must be designed for
- Thrust-to-weight ratio greater than 1.0
- Throttling and thrust-vector control
- Optimized nozzle expansion ratio

‣ By staging launch vehicles, we can
- Reduce the total vehicle mass for a given payload and ΔV requirement
- Increase the total mass of the payload delivered to space for the same-sized vehicle
- Increase the total velocity achieved for the same-sized vehicle
- Decrease the engine efficiency (Isp) required to deliver a same-sized payload to orbit
- Optimize the nozzle expansion for each stage to its operational altitude range

‣ But staging also has several disadvantages
- Increased complexity, because the vehicle needs extra engines and plumbing
- Decreased reliability, because we add extra sets of engines and the plumbing for the upper stages
- Increased total cost, because a more complex vehicle costs more to build and launch

‣ Selection of launch system services is a major driver of spacecraft and other mission requirements
- There are a wide variety of world launch vehicles available with different performance, price and reliability

‣ Launch vehicles typically require complex support infrastructure to operate including: pads, processing facilities and ranges

Key Terms

- Delta V, ΔV
- Final mass
- Inert mass
- Initial mass
- Staging
- Throttling
- Thrust-to-weight ratio
- Thrust-vector control

Lesson 8 - Mission Problems

1. What are the two biggest differences affecting the design of launch vehicles versus spacecraft?

2. List and briefly describe the advantages and disadvantages of staging.

3. Match the following terms with the best description below: initial mass, final mass, and inert mass

a. anything that is not payload or propellant

b. mass of the entire vehicle at lift-off

c. mass of the vehicle minus propellant mass

4. Give three examples of why launch vehicle selection is a major driver in spacecraft design.