Here is a summary of each part of the "SSEO notes.pdf" document, focusing on key concepts and important details while omitting formulas and calculations for now.

Space Systems Engineering and Operation

This document compiles information from Professor Lavagna's slides and lecture content to provide theoretical notes on space systems engineering and operations.

1. Introduction

System Engineering is an interdisciplinary approach that converts requirements into system solutions, ensuring customer needs are met throughout a system's life cycle. System engineers are responsible for the overall design and life cycle of a space system, possessing **holistic knowledge** of all subsystems and their interdependencies. They define budgets (mass, power, cost, schedule), monitor process evolution, drive development to limit risks, make decisions, lead testing, manage activities (trade-offs, models, simulators), manage planning, databases, documentation, and interfaces (internal and external). They also consider **technology readiness level (TRL)** and manage risk data.

Phases outline the project's progression. The **top-down process** defines objectives and requirements, leading to a detailed design. The **bottom-up process** involves designing, manufacturing, and testing individual parts, then gradually building and testing the complete system. Both processes check compliance with requirements iteratively. Each phase has iterative "looping rectangles" for convergence and includes **milestones and reviews** to decide whether to continue, stop, or postpone the project. Documentation is standardized, and management aspects like cost, risk, and planning are crucial from the start.

- **Phase 0 (Pre-Phase A)**: This is the **conceptual analysis phase** where high-level goals and project feasibility are examined. It helps identify bottlenecks, criticalities, and risks to guide decision-making. It concludes with the Mission Definition Review (MDR).
- **Phase A**: Involves **preliminary mission design**, defining mission requirements, disposal regulations, and assessing feasibility. General system-level solutions, such as potential architectures, are proposed, but the design is not fully detailed. This is a conceptual phase for quantifying requirements and discussing solutions. It concludes with the Preliminary Requirements Review (PRR).
- **Phase B**: Focuses on **detailed design work**, where different system and subsystem alternatives are sized and analyzed. Extensive analysis (e.g., finite elements) is performed. Alternatives from Phase A are confirmed, and requirements are finalized at the subsystem level. Technology should be at **TRL 6** or higher. It concludes with the Systems Requirements Review and Preliminary Design Review (PDR), after which implementation (Phase C) can begin.
- **Phase C**: This is the **"product realization process"** which consolidates the design. No component changes are allowed after completion of this phase. Engineering prototypes may be created for testing. A critical step is the Critical Design Review (CDR), where detailed designs of all subsystems, software, and plans are presented and approved.
- **Phase D**: Involves **manufacturing, building, and testing** the system. Tests are conducted in the actual environment the system will encounter, following standardized procedures for aspects like mass, temperature, dynamics, and electromagnetic compatibility. This phase ensures the system is flight-ready and includes the Qualification Review (QR), Acceptance Review (AR), and Operational Readiness Review (ORR). The system is then delivered for launch.
- **Phase E**: Covers the **in-space operations** of the mission. It addresses resolving non-nominalities (deviations from normal conditions). Key reviews include Flight Readiness Review (FRR), Launch Readiness Review (LRR), Commissioning Result Review (CRR), and End-of-Life Review (ELR).
- **Phase F**: This is the **disposal phase**, covering all events from the end of the mission's operational life until the final disposal of the product. The Mission Close-out Review (MCR) confirms the completion of all disposal

activities.

Life cycle models provide frameworks for managing projects, chosen based on criteria like development scheme, timeline, requirement robustness, risk sensitivity, system complexity, and environment stability.

Sequential/Waterfall model : A linear approach where each phase is completed before the next begins. Originally without feedback loops, later modifications incorporated them. Suitable for simple systems with stable, well-defined requirements and low risks, delivering one product at a time.
Incremental model : The system architecture and requirements are well-defined and unchanged , but the design is implemented in increments, with each adding useful operational capability. Examples include EGNOS-Galileo and Starlink constellations, where systems are delivered in multiple stages.
Evolutionary model : The final design is not fixed early . The basic life cycle repeats to deliver successive product versions, gradually increasing functionality over time based on user feedback. Beneficial for complex interfaces, rapidly changing environments, or pioneering systems, like Sentinel fleet and Artemis missions.
Spiral model : Combines the evolutionary model with risk assessment . It progresses in cycles, with each cycle identifying objectives, assessing and resolving risks (often using prototyping), designing, developing, verifying, and planning the next cycle. Common in high-risk software development.
V-Diagram : Reorganizes the simple life cycle to emphasize verification and validation . The left side represents requirements decomposition and system specification, while the right side represents integration and validation. It stresses checking deliverables against requirements (verification) and ensuring the complete system meets user needs (validation).
Robust design : A critical output from comprehensive trade-space analysis, aimed at protecting later, more expensive phases from unavoidable changes . It involves establishing a well-defined plan early, setting clear requirements, and carefully identifying suitable architectures, as early costs are low but increase exponentially later.

Functional analysis systematically identifies, describes, and establishes relationships between essential system functions to achieve high-level objectives. It defines what functions need to be done . Functional decomposition , a complementary method, identifies actions related to functionalities and organizes them sequentially or in parallel, generating tools like the Work Breakdown Structure (WBS) and Product Breakdown Structure (PBS).

Product Breakdown Structure (PBS) : A hierarchical tool that details the physical components of a product or system . It's built once requirements are fixed and helps track all elements, from the flight segment to specific physical components. It differs from the Work Breakdown Structure (WBS), which defines system engineering activities and assigns responsibilities.

Conops (Conceptual Operations) defines the work by identifying time-critical requirements , establishing the temporal arrangement of functions (concurrency, overlapping, sequential), generating alternative architectures, and defining mission phases and modes (e.g., launch, disposal, communication mode).

Definition of operation highlights various operational phases: Integration and test operations (thorough system testing, simulations), Launch operation (countdown, ascent, orbit injection, spacecraft deployment), Science operation (primary operational phase), Safe-hold operations (activated by faults, maintains power/thermal stability), Anomaly resolution and maintenance (requires additional resources), and Disposal operations (controlled re-entry or disposal orbit at end of life).
Definition of architecture involves establishing the association between functionalities and responsible parties, particularly for the ground architecture, becoming crucial in the final mission design.

Setting criteria involves defining clear, measurable quantities for decision-making and selecting alternatives. These criteria, such as mass, radiation, cost, or time to flight, must align with the mission's objectives and vary in importance between scientific and commercial missions.

Requirements serve as the foundation for mission objectives and are shaped through quantification.

Functional Requirements : Outline "what has to be done" by the system or subsystems. They are specified at various hierarchical levels and are frozen by Phase B.

Operational and Performance Requirements : Address "how" tasks are performed and "how well" they must be satisfied, often with numerical parameters. These are typically derived iteratively.

Verification : Pertains to "how" the system's adherence to requirements will be validated , specifying methods like numerical analysis or testing campaigns.

Mandatory Requirements : These are crucial and must be met ("shall" statements) without exception for mission success. They are pass-fail criteria and not subject to trade-offs.

Preference Requirements : These are "nice to have" ("should" statements) , aiming to enhance customer satisfaction. They are evaluated using scoring functions and may involve trade-offs. They can be omitted if not feasible.

Essential characteristics for effective requirements : They must be achievable (technically/economically feasible), affordable , justified (rational basis), classified and clear (unambiguous), traceable (clear sources), not contradictory , verifiable (methods specified), avoid negative statements, and have a responsible entity (ownership).

Path to follow : Involves developing an understanding of the problem from external goals to quantifiable requirements, exploring potential solutions, and examining technology feasibility, all while ensuring alignment with mission objectives.

Verification and Validation : An early step to ensure the final system complies. Verification ensures the system is built correctly and is testable, while validation ensures the system meets the mission objectives and user needs.

Drivers are specific mandatory requirements that heavily influence and constrain the system design process. They hold greater importance than regular requirements and must be addressed with top priority early in the project to prevent chaos.

Interfaces are crucial for any interaction with external entities (e.g., launcher, ground station) and between internal subsystems. They must be clear, unambiguous, and limited to minimize information exchange and ensure compliance.

The model philosophy in space equipment development involves a staged development schedule to reduce risk, leading to a space-qualified product. Stages include:

Breadboard : A low-fidelity unit used in early development to demonstrate basic functionality and prove the instrument concept. It may not resemble the final product.

Structural and Thermal model : Replicates the mechanical and thermal properties of the final instrument.

Electrical model : Demonstrates the integration of the instrument design with the spacecraft's data and power buses.

Qualification model : A fully representative model using flight-spec components, designed to withstand the harsh space environment and subjected to extensive testing under specified operational and non-operational environmental conditions.

Flight Model : The actual instrument that will fly on the spacecraft, sharing the same design and components as the Qualification Model, but tested under Acceptance Level environmental conditions (broader than operating conditions, but not as extreme as Qualification levels).

Other units include Brassboard (medium-fidelity functional unit for simulated environments), Engineering Unit (high-fidelity unit resembling the final product for design functionality confidence), and Prototype Unit (demonstrates form, fit, and function on a representative scale in operational environment). A Protoflight Unit is a flight unit that undergoes a limited version of qualification tests and will be flown.

Trading off alternatives is essential to identify the most favorable design options that meet requirements, considering performance and cost. This involves a step-by-step process of estimates, models, simulations, prototypes, and tests. This iterative approach ensures robustness and adaptability during the design phase.

The Design process emphasizes reusability (exploring existing solutions) and make or buy decisions for components, which impact time and cost. Flexibility is often prioritized over optimality. The process follows milestones where design and requirements are frozen, leading to the implementation phase of acquiring, testing, and assembling components.

Product implementation focuses on hardware trade-offs and defining criteria for all subsystems. Hardware progresses from low-fidelity models (breadboards) to the flight unit, with increasing manufacturing complexity often requiring clean room environments. Key decision points are the qualification unit (identical to flight unit, tested to extremes, not flown) and the flight unit (actual unit flown, tested to mission-specific stresses).

Technology Readiness Level (TRL) is a 9-level scale (1 being basic principles, 9 being proven in operational environment) used to classify technology maturity. A clear understanding of TRLs is crucial for decision-making regarding model usage and testing. For a system to be flight-worthy, all its technologies must be at least at TRL 6 . Changes to an existing unit can affect and potentially lower its TRL.

Verification methods and IV/V (Integration, Verification, Validation) stages ensure that the detailed design aligns with mission goals and fulfills all requirements. This process relies on standardized specifications. There are four primary verification methods:

Inspection : A visual examination of documentation, drawings, or the physical item to ensure compliance with requirements, especially for physical attributes not easily tested.

Analysis : Involves evaluating data using established analytical techniques (e.g., simulations, mathematical modeling) to determine if the system meets requirements, often used when testing is challenging.

Demonstration : Assesses system conformance by operating, adjusting, or reconfiguring a test article . It relies on observing functional operations without elaborate instrumentation.

Tests : A crucial method for evaluating system components under controlled conditions to determine compliance with quantitative design or performance requirements. Tests are conducted at different assembly levels and are preferred when analytical techniques are insufficient or for critical system interfaces. Testing is standardized and includes environmental conditions, but is generally avoided in the final mission phase to prevent last-minute issues.

2. Space Environment

The space environment significantly influences spacecraft design, with factors varying based on the mission's location. These factors include the Sun, Earth's magnetic field, thermal conditions, the neutral atmosphere, the plasma zone, radiation levels, microgravity conditions, vacuum conditions, debris/micrometeorites, planetary-specific environmental factors, and launchers.

The Sun acts as a powerful thermonuclear reactor, emitting immense power primarily as protons and electrons. It has an 11-year activity cycle, influencing sunspots and flares, which lead to electromagnetic and mass emissions (like Corona Mass Ejections). The solar wind, composed of plasma, generates the Interplanetary Magnetic Field (IMF) that profoundly affects the space environment.

Sun activity primarily involves electromagnetic (EM) radiation (challenging for payloads, requiring temporary shutdowns during solar passage) and emitted particles. Low-to-medium energy particles (X-rays, EUV) can cause geomagnetic storms, disrupting satellite communications and causing drag. High-energy particles (ions, protons) can affect instrument reliability (e.g., GPS).

Solar activity modeling uses indices like sunspot number (R) and 10.7 cm radio flux (F10,7) to represent the 11-year cycle. Understanding UV spectrum is vital for shielding material selection, and Far-Infrared (FIR) for thermal control.

Planet/Sun EM radiation effects:

TCS effects: The Sun is the main thermal perturbation source. Albedo (reflected solar radiation) and Infrared (IR) radiation from planets also contribute. Thermal exchange in space primarily occurs through radiation. These external heat sources dictate the thermal design.

UV band effects: UV radiation causes erosion and brittleness in organic materials (e.g., Teflon, Mylar) and changes in their optical/mechanical properties. Material selection, coatings, and mission lifespan studies are crucial, with protective layers like aluminum often used.

Earthâ ™s magnetic field comprises an internal field (from geodynamic interactions) and an external field (from outer atmosphere/solar wind interactions). Indices like Kp and Ap show solar activity's relation to atmospheric electrical intensity. The South Atlantic Anomaly (SAA) is a region of weakened magnetic field where trapped protons and electrons can penetrate deeper, posing a hazard to electronic devices and requiring design considerations like temporary electronic shutdowns. Other planets like Jupiter and Saturn have significant magnetic fields, trapping radiation, while Mercury, Moon, Mars, and Uranus have almost inactive fields.

The Atmosphere affects space missions through drag, contamination, and erosion by atomic oxygen. Its thickness and ionized particles are influenced by the Sun. Temperature varies significantly with solar activity, leading to differential expansion of materials. Atmospheric density, influenced by solar activity, impacts orbit decay, fuel budget, and mission lifetime.

The ionosphere is a layer where high-energy UV radiation dissociates oxygen. It acts as a barrier for radio signals below 100 MHz but can be used for signal reflection to non-visible Earth locations.

Atomic Oxygen (AO), abundant above 150 km, causes material erosion and changes optical properties of spacecraft surfaces. Its density increases with solar activity, affecting mission lifetime. Materials like Mylar and graphite composites are highly susceptible. Protection strategies include oxide layers (gold, platinum, aluminum) or silicone-based coatings. Solar activity needs to be considered for material selection and flight attitude adjustments.

Plasma is a partially or fully ionized gas whose particles respond collectively to magnetic and electric fields. Spacecraft encounter cold plasma in the ionosphere, hotter plasma in the magnetosphere, and solar wind. Plasma interactions can cause parasitic currents, electrostatic charge buildup (leading to arcs and electronic damage), and contamination (sputtering from ion impacts, deposition from ionized neutral atoms). Solar panels are particularly vulnerable to plasma effects, requiring decoupling from the spacecraft or conductive paths on outer surfaces, though this may conflict with thermal insulation goals. Design requirements primarily focus on grounding and electrical continuity to manage charging levels, specifying maximum voltages and electric fields, and assessing discharge risks.

Particles and radiation significantly influence spacecraft design. Key considerations are the particle flux (quantity) and energy. Generally, high energy corresponds to low flux. Ionizing radiation comes from:

- Galactic Cosmic Rays (GCR): High-energy, low-flux particles present throughout space, primarily protons and alpha particles. Their impact is inversely related to the solar cycle (more rejected during high solar activity).
- Radiation Belt Particles: Protons and electrons trapped by the magnetic fields of celestial objects, notably Earth's Van Allen belts. These belts are hazardous regions where electronics are vulnerable, with protons posing a greater danger in Medium Earth Orbit (MEO) and electrons just before Geostationary Earth Orbit (GEO).
- Free Solar Particles from the Solar Wind: Particles emitted by the Sun that travel freely.

Radiation can cause damage through three mechanisms:

- Ionization: Direct interaction with atoms, causing electron removal or excitation. The Total Ionizing Dose (TID) measures this effect.
- Atomic Displacement: A non-ionizing effect where atoms move from their lattice positions, primarily caused by energetic protons, which can significantly damage solar cells.
- Prompt Effects (Single Event Effects - SEE): Anomalies caused by a single energetic particle striking an electronic device, creating an ionized track. These can be transient (non-disruptive) or permanent (disruptive).
    - Single Event Upset (SEU): A transient effect where a particle causes a change in a digital device's logic state (e.g., bit-flip), which can be restored. Counteracted by immune materials, reset mechanisms, or error correction algorithms.
    - Single Event Latchup (SEL): A more severe SEU that can lead to a permanent change and device burnout if current is not turned off. It induces unexpected parasitic current peaks. Mitigation includes immune materials, current-limiting circuits, or turning off devices in hazardous regions like the SAA.
    - Single Event Transient (SET): Affects analog components, causing temporary output signal disturbances. Mitigated by immune materials or software filters.
    - Single Event Burnout (SEB) and Single Event Gate Rupture (SEGR) are permanent destructive effects.
    - Components' susceptibility to SEE is assessed by their Linear Energy Transfer (LET) threshold.

Shielding is critical in spacecraft design against energetic particles and radiation. Thicker shields generally reduce radiation levels, and placing electronics at the spacecraft's center provides additional shielding from the metallic structure. Water can be an effective shielding element for manned missions. Radiation environment analysis, including particle energy spectra and fluences, is required during Phase A of a mission.

Microgravity refers to the free-fall state experienced by orbiting spacecraft, where factors like atmospheric drag and solar pressure still cause small accelerations.

- Scientific Implications: Microgravity leads to unique phenomena such as substances not floating relative to each other, absence of convection in chemical reactions, and altered fluid dynamics, benefiting scientific experiments. However, it poses challenges for humans, including fluid shifts, bone loss, and space sickness.
- System Considerations: Design must account for liquid control (e.g., pressurized systems for fuel), solid components for friction, and adapting to the absence of convection. Components designed for microgravity may face issues in gravity.
- Technical Considerations: Simulating microgravity for ground tests is challenging, requiring specialized facilities like deploying extendable parts (with scaling considerations), dropping towers, parabolic flights, and sounding

rockets (offering the longest microgravity durations, ~14 minutes).

Vacuum in space leads to outgassing, the sublimation of surface atoms from materials at very low pressures. This causes loss of material and mechanical properties (e.g., structural protection, solar panel efficiency) and deterioration due to condensation of sublimated material on other surfaces (e.g., optical surfaces). Materials are selected based on low outgassing criteria (e.g., CVCM < 0.1%, TML < 1%), verified through dedicated tests.

Debris in space, including metallic elements, asteroids, and natural objects, has become a significant concern. The highest concentration is in Low Earth Orbit (LEO). Debris can originate from mission-related objects, rocket bodies, inactive satellites, and especially fragments from explosions. A collision can trigger the Kessler effect, a cascading impact scenario.

- Mitigation strategies aim to prevent new debris (e.g., controlled de-orbiting, graveyard orbits, emptying propellants).
- Remediation (Active Debris Removal - ADR) focuses on removing existing debris and protecting new systems (e.g., ground control avoidance maneuvers, specialized shields). The ESA CleanSpace program is studying ADR techniques. Collision risk analysis is crucial for pressurized subsystems.

Planetary protection involves regulations to prevent biological contamination of target celestial bodies and Earth (during sample-return missions). COSPAR (Committee on Space Research) classifies missions into five categories based on contamination risk and astrobiological interest:

- Category I : Minimal attention, standard cleanliness. For bodies with no direct interest in chemical processes or origin of life (e.g., Mercury, Io).
- Category II : Bodies of interest for chemical evolution/life, but low chance of contamination. Simple documentation (e.g., planetary protection plan) is sufficient (e.g., Venus, Moon, Jupiter).
- Category III : Highly significant for biological evolution, notable chance of contamination. Requires specific procedures, higher clean room standards, and sometimes sterilization. Applies to fly-by and orbiter missions (e.g., Mars, Europa, Enceladus).
- Category IV : Involves surface contact, atmospheric entry, or landing on astrobiologically interesting bodies. Requires a bio shield for hardware in direct contact and detailed documentation, including bioassay and contamination analysis (e.g., Mars, Europa, Enceladus).
- Category V : Earth-return missions, posing the most dangerous scenario due to back contamination risk. Requires strict containment measures for returned hardware and timely analysis under containment. Divided into "restricted" (e.g., Mars samples) and "unrestricted" (e.g., Moon samples) returns.

3. Propulsion Subsystem

Onboard spacecraft, there are two main types of propulsion units: primary propulsion for critical maneuvers (e.g., orbital adjustments, plane changes, reaching final orbit) and secondary propulsion for station-keeping, relative maneuvers (e.g., formation flights), and serving as the Reaction Control System (RCS) for attitude control. Spacecraft often use a dual propulsion architecture (e.g., chemical and electrical) depending on mission requirements.

- DeltaV of maneuvers is a crucial requirement that determines the class of thrusters needed. Different maneuvers, from LEO insertion (low DeltaV) to deep space maneuvers (high DeltaV), have specific velocity change requirements.

Types of propulsion include chemical and electrical.

- Chemical propulsion systems involve components like propellant storage, feed systems, thrusters, valves, and electrical control units.

Electrical propulsion systems have a critical Power Processing Unit (PPU), which is typically the heaviest component due to its high voltage operation, requiring significant power from the Electrical Power System (EPS). While electrical thrusters offer a significant advantage in specific impulse (2000s for electrical vs. 200-300s for chemical), reducing fuel mass, they demand substantially more power (500-1000W vs. 10-30W for chemical), increasing the mass of power-related components.

The propulsion system anatomy covers chemical and electrical systems. Chemical propulsion uses high-mass, low-velocity particles, while electrical propulsion uses low-mass, high-velocity ions. For chemical systems, propellant freezing temperatures and tank temperature control (often with Multi-Layer Insulation) are essential. Propellants have specific energy and physical requirements (e.g., high reaction heat, low freezing temperature, low toxicity).

Chemical propulsion :

Solid propulsion : Primarily used in launchers or for an extra boost in orbit. It provides high thrust and low impulse in a single burn, but it does not support multiple burns, restarting, or throttling , making it unsuitable for precise in-orbit maneuvers.

Cold gas : The simplest and cheapest option, using pressurized inert gas (e.g., nitrogen). It offers very low impulse and thrust and no throttling, but allows multiple starts and pulsing. It's used for attitude control and fine control, especially for nano-platforms. Tanks need to be easily accessible for filling before launch.

Monopropellant : Offers a good combination of specific impulse, suitable for secondary or even primary propulsion. It provides a large thrust range (1-20N or more) , restart capability , and throttling ability . Thrust decreases as fuel is used due to decreasing pressurization. Hydrazine is common but toxic. Redundancy is achieved by splitting the system.

Bipropellant : The most complex type, combining an oxidizer and a fuel for high-impulse burns. It requires a dedicated pressurizing system to ensure uniform pressures and constant thrust. This architecture allows feeding different thrusters for various applications. Cryogenic solutions are not preferred for satellite missions due to temperature maintenance challenges.

Electric propulsion (EP) accelerates particles using electrical power.

Electrothermal : Accelerates ions using thermal energy (e.g., Arcjets, Resistojets). Used for station keeping and attitude control, offering higher impulse than chemical but lower than other electric types. Arcjets use an electric arc, Resistojets use resistance to heat propellants.

Electrostatic : Ionizes propellant and accelerates particles using an electrostatic field (e.g., Ion Engines, FEEP). Characterized by very high specific impulse (3,000-10,000 s) and high thrust efficiency (>60%). Propellants like Xenon are common. A key challenge is grid erosion due to high-speed ion impingement, limiting lifetime. Neutralizers are crucial to prevent thrust loss.

Field Emission Electric Propulsion (FEEP) thrusters are designed for precision secondary propulsion, offering very low thrust (micro to milli newton), instantaneous on/off, and high specific impulses (6000-10000s).

Electromagnetic : Utilizes both electric and magnetic fields for ionization and acceleration (e.g., Hall Effect Thrusters, Pulsed Plasma Thrusters).

Hall Effect Thrusters : Use an electromagnetic field to accelerate charged particles. They require less power than gridded ion engines, making them lighter. Degradation includes erosion in the central element. Can be employed in parallel for increased thrust or extended lifetime.

Pulsed Plasma Thrusters (PPT) : Offer high specific impulse, low power, and minimal fuel, ideal for pulsing applications in station-keeping and attitude control, especially for small satellites. They use a solid propellant (e.g., Teflon), which is vaporized and ionized by an electric arc, then accelerated by Lorentz forces.

The feeding system design focuses on determining the mass and volume of the pressurant and sizing the tanks. A key challenge for liquid propellant systems is preventing bubbles and gaseous pockets in tanks, addressed by methods like spinning the spacecraft or using internal devices (sponges, diaphragms, bladders, bellows).

The pressurization system controls gas pressure in tanks for correct chamber pressure during propulsion operations. The two main solutions are blowdown systems and regulated systems .

Blowdown systems are simpler and more cost-effective, typically used with monopropellants where constant thrust is not required, as pressure, thrust, and mass flow vary over time.

Regulated systems maintain a constant pressure, thrust, and mass flow rate by using a pressure regulator valve. They are more complex and result in heavier tanks due to higher internal pressures.

Pressure losses along the feeding lines must be accounted for to ensure tank pressure meets combustion chamber requirements.

Electric power for propulsion is increasingly using low-thrust solutions for trajectory adjustments. Electric Orbit Topping (EOT) , using electric propulsion to increase apoapsis, can significantly reduce launch mass or save dry mass for other components. Hall effect thrusters, while less efficient, demand lower power compared to gridded systems. In architecture, one Power Processing Unit (PPU) can manage a maximum of two thrusters to optimize mass.

The Design process for the propulsion subsystem involves identifying requirements (Delta-V budget, maneuver time/type, thrust level), selecting components (engines, propellant, feeding system, tanks), sizing the system and architecture (number of engines, tanks, redundancy), creating schematics, and establishing budgets (mass, power, data). Chemical propulsion is chosen for large propellant inventory authority, while electrical solutions are for short burns or pulsing maneuvers where timeliness is less critical. Power budget for chemical systems accounts for valve actuation, sensors, and catalytic bed warm-up.

Propulsion Subsystem Mass Margins and Estimates are crucial. For chemical propellants, volume is sized with at least a 10% margin, and pressurant with 20%. For electric propulsion, a safety factor of 1.5 is applied to total impulse, lifetime, and cycles, assuming a 90% duty cycle. Certified lifetime hours (typically 10,000-20,000) are a key parameter, and operating beyond these introduces risk.

4. Telecom Subsystem

The TTM&TC (Telemetry Tracking Telecommand Subsystem) establishes connections between the space system and other systems (e.g., ground station, other satellites) for data transmission and tracking. Tracking involves reconstructing the spacecraft's position (e.g., via Doppler shift, ranging for deep space, GPS for near-Earth). Key considerations include limited visibility windows, potential weak signal strength due to environmental stresses, and thermal sensitivity of antennas. Collaboration with Mission Analysis (MA) is crucial for visibility windows and Ground Station (GS) selection.

Data transmission occurs in two directions:

Downlink (Space Segment to Ground Segment) : More common, includes engineering data (temperatures, voltages, sensor outputs) and science payload data. The trend is towards digital data.

Uplink (Ground Segment to Space Segment) : Less frequent but essential for sending commands (activity planning, updates), especially for non-nominal situations or software patches.

The signal elaboration process involves several steps: data source, Analog-to-Digital conversion (if needed), encryption (for classified missions), multiplexing, data storage, encoding, and finally, the transmit block (modulation, amplification, transmission).

Sampling and digital conversion are initial steps. Sampling discretizes analog signals into snapshots at regular intervals, adhering to Nyquist's sampling theorem (sampling frequency at least 2.2 times the maximum analog signal frequency) to avoid aliasing. Quantization then maps sampled values to discrete levels, introducing quantization error, which can be reduced by increasing bit resolution.

Channel capacity refers to the maximum reliable data rate over a communication channel without errors, determined by Shannon's theorem : it depends on bandwidth and Signal-to-Noise Ratio (SNR) . The datarate is the actual transmission rate, which must be less than or equal to the channel capacity.

Encoding processes data to protect against errors by adding control bits. Its scope is to detect and correct corrupted bits.

Block Code : Creates blocks of data bits and adds parity bits. Can detect errors (horizontal parity) or detect, locate, and correct them (horizontal and vertical parity). Examples include Hamming code (detects/corrects single-bit errors) and Reed-Solomon code (higher error correction capability).

Convolutional Encoding : Offers advantages in hardware implementation, providing a lower Bit Error Rate (BER) for the same SNR. It is not block-based but determines output bits from logic operations on present and previous bits in a stream. Encoding is necessary to achieve lower BER for a given SNR.

Modulation is required to transmit low-frequency, high-wavelength onboard signals over greater distances and with resistance to interference. It involves manipulating a high-frequency carrier wave. Types include Amplitude Modulation (AM) (amplitude varies), Frequency Modulation (FM) (frequency varies), and Phase Modulation (PM) (phase varies). Channel bandwidth is the range of frequencies a channel can carry without significant distortion and influences its information capacity. Carson's rule approximates the bandwidth for FM signals. Pulse Code Modulation (PCM) is an encoding technique that converts analog signals to digital through sampling, quantization, and encoding. Common PCM encoding schemes include NRZ-M and UNI-RZ . Alternatives to PCM include ASK, FSK, and PSK , which vary the carrier signal's amplitude, frequency, or phase to transmit digital information. More specific modulation schemes like BPSK, QPSK, 8FSK, and MSK are also used, each with different characteristics regarding bits per time and noise robustness.

Amplification increases the signal's power for transmission. This occurs in both the transmitter and receiver. Common amplifier classes are Solid State Amplifiers (SSAs) , preferred for lower power outputs (5-10W) due to their efficiency and compactness, and Travelling Wave Tube Amplifiers (TWTAs) , which are heavier but provide higher output power.

Antenna design involves selecting appropriate configurations. An Isotropic Antenna emits uniformly but is not powerful. Directional Antennas concentrate the signal in specific directions, offering higher gain and a defined beamwidth (field of view). A masking angle is used to account for environmental imperfections. Omnidirectional antennas are essential for initial mission phases or safe mode when precise pointing isn't feasible. More advanced solutions like electronically steered phased arrays offer high precision but at the cost of increased electronics, mass, and thermal control requirements.

Losses during signal transmission must be considered:

Transmission Losses : Include free space losses (signal spreading, dependent on frequency and distance), misalignment losses (due to imperfect pointing between transmitter and receiver), and atmospheric losses (interaction with gases, affected by elevation angle and frequency choice, minimized by dry, high-altitude ground stations).

Noise : Primarily from thermal sources , represented by equivalent noise temperature, which accounts for thermal sources, passive devices, and active devices. Ground stations are often cooled to minimize receiver noise, making onboard devices a primary noise source.

The Link budget is a crucial calculation that correlates the energy per bit to the noise per bit , accounting for all gains and losses in the communication link. It's used to evaluate system accuracy and requires a safety margin (typically 3dB) to ensure robust communication. If the margin is too high, the system might be over-engineered.

Design steps for the Telecom Subsystem involve integrating all components based on data collection, timing, size, and orbital dynamics. This helps in selecting the optimal ground network configuration. Data transmission timing is flexible, except for telemetry, which is sent regularly. Coordination with On-Board Data Handling (OBDH) is vital for efficient data storage. Compliance with international regulations (ITU) regarding frequency allocation is crucial.

Data rates vary: housekeeping data is in kilobits per second (kbps), attitude data can reach megabits per second (Mbps) or gigabits per second (Gbps) for critical phases, and payload data typically requires Mbps or Gbps. It's important to distinguish between acquisition data rate (onboard generation) and downlink data rate (transmission to ground).

Frequency bands are chosen considering atmospheric attenuation and ITU regulations.

The Ground segment architecture involves connections between the Ground Station Network (GSN) , Mission Operations Center (MOC) , and Science Operations Center (SOC) . The GSN interfaces with the spacecraft for tracking, telemetry (housekeeping and payload data), and telecommand. Selection of a ground station network is based on the number of antennas, number of stations for coverage, and uniformity of antennae (single provider for centralized control). Both ESA and NASA operate extensive GSNs, with strategically placed stations (e.g., Polar stations for sun-synchronous orbits, deep space networks with 35m or 70m dishes for continuous coverage). Commercial services like Ground Segment as a Service (GSaaS) and inter-satellite connectivity are increasingly popular, offering flexibility and cost reduction by providing GSN and MOC services to third-party satellites.

5. Mission Analysis

Deep space maneuvering involves constructing Multiple Gravity Assist (MGA) trajectories to minimize total velocity change (DeltaV) by optimizing subphase lengths, departure times, and velocities. The model can be enhanced by incorporating Deep Space Maneuvers (DSMs) , which add a Lambert arc at an unknown position in deep space, allowing for more versatile trajectory optimization. The model has degrees of uncertainty regarding the precise point of application of the outgoing velocity vector, leading to a family of possible hyperbolic trajectories.

The B-plane is a flat coordinate system perpendicular to the incoming asymptote of a hyperbolic trajectory, valuable for precision targeting during fly-bys . The B vector governs the design of the hyperbolic plane, and by specifying a point on the B-plane, post-gravity assist conditions are fully determined. Trajectory Correction Maneuvers (TCMs) are computed in flight to target the incoming asymptote on its B-plane and reduce dispersion.

6. ADCS Subsystem

The Attitude Determination and Control Subsystem (ADCS) is part of the broader AOCS (Attitude and Orbit Control Subsystem), responsible for managing a satellite's attitude (orientation) and orbit. GNC (Guidance, Navigation, and Control) is a more encompassing term used for on-board control when the satellite's position is controlled in a closed-loop manner.

Requirements for ADCS include:

Functional requirements : Hardware and software capabilities for attitude measurement, estimation, guidance, and control; orbit control maneuvers; safety assurance (including emergency and anomaly situations); and mission availability. It must acquire and maintain necessary attitudes throughout all mission phases, autonomously determine attitude and orbit (if navigation is needed), ensure mission pointing, execute orbit control maneuvers, and autonomously enter a safe mode in case of anomalies (which can also be initiated/deactivated by ground command).

Performance requirements : Specifies accuracies for absolute pointing (APE), attitude knowledge (AKE), relative pointing (RPE), and orbit knowledge, typically in microradians or meters, with confidence levels (e.g., 90% probability). These requirements can be interpreted statistically (ensemble, temporal, or mixed). Other performance aspects include stability, transient response, robustness, jitter (high-frequency angular motion), and drift (slow, low-frequency angular motion).

Budgets : ADCS provides detailed allocations for absolute performance, attitude knowledge, relative performance, duration (mode transitions, agility), propulsion-related impacts, and orbit correction performance.

The Design Process for ADCS involves defining control modes, summarizing pointing requirements, quantifying disturbance torques, selecting architecture and hardware, defining algorithms, and conducting trade-off studies. Sensor and actuator selection depends on the required pointing and knowledge accuracy.

Control Modes : Specific configurations of the AOCS used to achieve mission pointing requirements, tailored to payload needs, mission phases, and onboard systems. Common modes include Safe Hold Mode (detumble, Sun-pointing, autonomous, minimal power), Standby Mode (solar panel/antenna alignment, better pointing than safe mode), Operational Mode (primary mission objectives, precise hardware, often ground-assisted), Orbit Control Mode (orbital maneuvers, propulsion systems), and Transfer Mode (attitude/orbit control during long transfers). Modes are established based on flexibility, autonomy, redundancy, and performance. Standard modes include Orbit Insertion, Acquisition, Normal On-station, and Contingency/Safe Mode. Special modes are mission-specific, but increasing their number adds complexity and cost.

Transition between modes can be autonomous (event-driven, e.g., Fault Detection, Isolation, and Recovery - FDIR) or automatic (time-driven). Finite State Machines (FSM) are used to organize control mode architecture and transitions.

The Pointing budget compiles all mission-specific pointing directions, rates, and performance requirements, guiding ADCS design for accurate and precise pointing. Errors can be systematic, random, parametrization errors (bias, scale factor, nonlinearity, noise, quantization), or time response errors (delay, dead time).

Disturbance torques on spacecraft can be external (gravity gradient, atmospheric drag, solar radiation pressure, magnetic moment) or internal (actuator/sensor misalignment, thruster mismatch, center of mass uncertainty, structural dynamics, fluid slosh).

ADCS architecture choices depend on payload pointing, thermal/power requirements, thrust vector control, maneuver rates, and solar panel area.

Zero Momentum : Uses three reaction wheels for unrestricted pointing and high maneuverability, suitable for orbits below 1000 km. Offers excellent accuracy but is complex, heavy, power-consuming, and expensive.

Gravity Gradient + Momentum Bias : Effective for orbits below 1000 km, actively controlling roll and pitch, with yaw stabilized by a momentum wheel. Economical and robust but with limited pointing accuracy.

Momentum Bias : Uses a momentum wheel spinning at high speed for inertial stiffness in two axes, with the third axis controlled by wheel speed. Ideal for long-duration missions with good accuracy in one axis.

Spin Stabilized : Stabilizes the spacecraft by maintaining constant angular velocity around an axis. Simple and cost-effective, useful for scanning instruments and propellant control, but provides low pointing accuracy on two axes and poor maneuverability.

Dual Spin Stabilized : Spins the main mass while de-spinning a platform with payloads or antennas, offering versatility but being expensive and complex.

Preliminary sizing involves selecting sensors and actuators based on required accuracy.

Sensors : Sun sensors (Sun direction), Star Sensors (accurate 2-3 axis attitude, needs initialization), Horizon (Earth) Sensors (Earth-relative info), Magnetometers (magnetic field direction/magnitude, good for magnetic torquers), Gyroscopes (angular rates, attitude evolution, key for bias drift stability), Global Navigation Satellite Systems (GNSS) (orbit position, differential GNSS for attitude), Accelerometers (acceleration for orbit propagation/determination), and Inertial Measurement Units (IMU) (combines gyros and accelerometers for comprehensive sensing). Any two vector measurements from these sensors allow attitude determination.

Actuators : Provide torque to maintain orientation. Reaction Wheels (adjust rotor speed for one-axis control, nominal zero momentum), Momentum Wheels (similar but with non-zero nominal spin, stiffness on two axes), Control Moment Gyros (CMG) (generate torque by altering spin axis direction, for large torques/fast maneuvers, more efficient than RW but more massive and can suffer from singularities and saturation), Thrusters (provide torque with propellant, require 3-axis control during firing for misalignment), and Magnetic torques (Magnetorquers) (use Earth's magnetic field to control orientation without propellant, but dependence on field strength limits effectiveness).

ADCS Maneuvering sizing typically assumes constant angular velocity and single-axis maneuvering. Propellant required for thruster maneuvers is inversely proportional to specific impulse. Slew maneuvers can be performed with constant acceleration/braking. Reaction wheels may need desaturation.

7. Electrical and Power Subsystem (EPS)

The Electrical Power System (EPS) ensures an uninterrupted supply of electrical power to all spacecraft loads throughout all mission phases. Its purpose includes managing and allocating power, meeting average and peak demands, supplying converters for AC/DC distribution, enabling command/telemetry/control of EPS health, safeguarding payload from failures, and mitigating voltage fluctuations.

EPS Components include: Energy Sources (converting diverse energy into electrical power), Energy Storage (capturing surplus energy for continuous supply during primary source unavailability or high demand), Power Distribution (interfacing with loads and sources), and Power Regulation and Control (adjusting voltage and current to meet load specifications, managing battery cycles, and adapting to power source degradation).

The Design process for EPS requires defining mission phases and modes and understanding all components. Key information needed includes mission profile, solar irradiance/eclipse durations, spacecraft design, power demands, launcher requirements, and the thermal environment. This leads to identifying subsystem requirements, selecting and sizing power sources and energy storage, and choosing power regulation/control architectures. Outputs include the EPS schematic, power budget allocation, overall system budgets (mass and power), and an equipment list. The power budget allocation is a fundamental step.

Electric power sources include:

Primary Batteries : Store chemical energy, useful for short-term missions or emergencies. Not rechargeable, high specific energy but short lifespan and narrow temperature range (e.g., Silver-Zinc, Lithium batteries).

Solar Cells (Photovoltaic Generator) : Convert sunlight directly to electricity, commonly used in long-term missions. Efficiency increases as temperature decreases. Types include mono-crystalline silicon (lower efficiency, high radiation resistance) and multi-junction cells (higher efficiency, more vulnerable to degradation). Thin-film cells are flexible and rollable. Solar panel performance is affected by solar angle, solar radiation, temperature, and solar distance. Degradation occurs over time due to UV/space radiation, temperature cycling, micro-meteoroids, contamination, and aging, particularly significant in GEO and LEO. Coverglass protects from these effects. Solar concentrators (e.g., Fresnel's lenses) can augment solar flux, reducing array area and mass while increasing output, but may raise temperature.

GPHS â “ RTGs (General Purpose Heat Source â “ Radioisotope Generators) : Convert heat from radioactive decay (e.g., Plutonium-238, 86.8 years half-life) into electrical energy using the thermoelectric (Seebeck) effect. They provide a continuous power source for long durations, used in deep-space missions where solar energy is limited. RTGs typically have low efficiency (7%, up to 20% for newer generations) and are quite massive, requiring shielding and radiators to dissipate unused heat. Power degrades exponentially over time due to radioactive decay. Multi Mission RTGs (MMRTGs) are smaller and more adaptable units. Stirling Radioisotope Generators (SRGs) use a Stirling thermodynamic cycle for heat-to-mechanical-to-electrical conversion, offering higher efficiency (20-25%) but involving moving parts.

Fuel Cells : Convert chemical energy to electrical, extending autonomy.

Nuclear Reactors : Utilize nuclear fission for heat, powerful but complex.

Selection drivers for power sources include power level/density, mission lifetime, source availability, sensitivity to Sun distance, radiation hardness, degradation, reliability, and cost.

Power distribution involves wiring, safety measures (fault protection), and command decoders. Architectures can be Distributed (each load has dedicated feeding) or Centralized (managed by a central bus). Bus voltage selection (e.g., 28V for <2kW, 100-150V for >2kW) minimizes losses, noting that cabling can be a significant portion of EPS mass.

The regulation and control system ensures correct current-voltage (I-V) to loads. Power regulation can be achieved with the primary source and the bus, with three main topologies:

Unregulated Bus Voltage Power System : Direct link from sources to bus, risky as loads experience fluctuating voltage.

Sunlight/Quasi Regulated Bus Voltage Power System : Regulates bus voltage during battery charging (Sun-regulated) and tracks battery voltage during eclipse.

Regulated Bus Voltage Power System : Most robust, maintains voltage within narrow band using DC/DC converters.

Energy source regulation can be Direct Energy Transfer (DET) or Peak Power Tracking (PPT) .

DET : Maintains constant voltage by shunting excess current. Simple, lightweight, efficient at end-of-life, suitable for medium-long missions.

PPT : Uses a DC/DC converter to dynamically adjust voltage and current to track the peak power point of the solar array. Heavier and less efficient than DET but suitable for shorter missions with many cycles.

A fully regulated bus offers flexibility, avoids lock-up issues, and is suitable for larger satellites with high voltages and rapidly changing power demands.

8. Thermal Subsystem (TCS)

The Thermal Subsystem (TCS) manages heat in spacecraft. The three thermal mechanisms are conduction , convection (less relevant in space), and radiation . In space, thermal control primarily relies on radiation , which depends on optical properties (absorptance, emissivity, reflectance), area, and view factor.

Radiation : System behavior is characterized by absorptivity (Î±) (how much energy is absorbed) and emissivity (Ïµ) (how much thermal energy is emitted). High absorptivity is for heating (high-frequency sources like Sun), while high emissivity is for cooling (low-frequency infrared radiation). Optical properties vary with incidence angle and material (metals vs. non-metals).

The View Factor is a geometric fraction representing the portion of energy leaving one surface that is directly intercepted by another. It's crucial for evaluating radiative heat exchange between the spacecraft and celestial bodies.

Heat sources in the space environment include solar radiation (high-frequency), Albedo (solar radiation reflected by planets, high-frequency), Infrared (IR) emission (low-frequency radiation from planets), and internal dissipation (heat generated by onboard components due to inefficiencies). The Beta angle describes the angle between the orbit and the solar vector, influencing solar flux exposure and eclipse durations. Eclipses significantly alter the thermal situation, as the system receives only IR radiation from the planet.

The Thermal analysis and design process involves selecting worst-case temperature conditions (hot and cold), computing thermal behavior, choosing a thermal control strategy (passive or active), selecting components, performing thermal analysis (often starting with a preliminary single-node approach), sizing and locating radiators and heat pipes, and conducting tests. In the single-node steady-state approach, the goal is to balance total input, internal, and output heat. If initial computations show temperatures outside the desired range, passive controls like adjusting emissivity, absorptivity, or area are attempted, or internal power is adjusted. If passive controls are insufficient, active control may be needed. A significant margin (e.g., 15 K in Phase A) is accounted for temperature uncertainties in early design phases.

Thermal control components can be passive (preferred for simplicity, reliability, cost-effectiveness) or active (for precise temperature regulation in variable conditions).

- Passive components :
  - Coating : Manipulating absorptivity and emissivity with paints (e.g., white paint for cooling, black paint for both absorption and emission) or metal finishes. Coatings degrade over time due to UV, charged particles, and atomic oxygen.
  - Secondary Surface Mirrors (SSM) / Optical Solar Reflectors (OSR) : Two-layered materials (e.g., Polyimide/Teflon/glass on top, Silver/Gold/Aluminum on bottom) to limit incoming heat and maximize emission.
  - Louvers : Thermally activated shutters (bi-metallic sensors driving aluminum blades) that open/close to regulate heat dissipation, providing adjustable effective emittance.
  - Multi-Layer Insulation (MLI) : Thermal blankets with multiple reflective layers, kept detached by Dacron elements to block and reflect thermal energy, creating an adiabatic scenario. Designed with small valves for venting during launch.
  - Radiators : Surfaces designed to dissipate waste heat to space primarily through radiation. They can be structural panels or deployable appendages.
  - Phase Change Materials (PCMs) : Substances that undergo phase transitions (solid-liquid) to store and release latent heat, maintaining nearly constant temperature in cyclically operating components (e.g., in LEO for dampening variations).
  - Filters (for conduction) : Manipulating surface roughness or using materials between surfaces (fillers to enhance conduction, washers to reduce it).
  - Bolts, straps, braids : Used to establish conductive connections for heat transport from internal components to external radiators.
  - Thermal structures : Selecting materials with appropriate thermal conductivity and low Coefficient of Thermal Expansion (CTE) is important for effective coupling.
- Active components :
  - Heaters : Resistors that generate heat to warm equipment or compensate for heat dissipation, controlled by thermostats.
  - Peltier elements (TEC) : Utilize the inverse Seebeck effect to pump heat from a cold to a warm junction using electric current. Compact, lightweight, vibrationless, but with relatively low efficiency.

Radioisotope Heating Units (RHU) : Small devices based on plutonium decay that provide direct heat to warm spacecraft components, often used for deep-space missions where solar energy is insufficient. They cannot be stopped once activated.

Heat pipes : A versatile mechanism that can act as both passive and active control. They use fluid phase change and capillary action to transport heat from a hot end to a cold end (e.g., for radiators).

9. OBDH and Configuration

OBDH (On-Board Data Handling) refers to the system within a spacecraft that manages and processes data from onboard sensors, instruments, and systems. Its key responsibilities include data acquisition, processing, storage, control/monitoring, communication, and autonomous control.

Design steps for OBDH involve assessing environmental factors (especially radiation), mission phases/modes, data storage/processing needs, and available electric power. Objectives include identifying data management functionalities, deriving requirements, conducting trade-off analyses, analyzing components, estimating memory size and Performance Control Unit (PCU) capabilities, defining architecture, refining software, and selecting components/data bus. Outputs include system/subsystem architecture, equipment lists, and budget assessments (power, mass, data).

Defining requirements involves mission requirements (customer needs, number of satellites, programmatic aspects) and system-level processing requirements (functional capabilities, partitioning, physical features, communication protocol). Computer-level requirements include throughput, memory, radiation hardness, and development tools.

Partitioning Functionalities : Processing tasks are partitioned between in space or on ground (trade-offs for autonomy, time criticality, bandwidth), hardware (HW) or software (SW) (trade-offs for performance, complexity, changes), between the Service Module (SM) and Payload (P/L), or along organizational lines.

Architectural building blocks include Telecommand/Telemetry Modules, On-Board Computers, Data Storage/Mass Memory, Remote Terminal Units, and Communication Protocols/Buses.

Data flow architecture alternatives :

Central Processor : A central CPU communicates point-to-point with every device. It is highly reliable and specialized but has challenges with scalability and cabling complexity.

Ring : A closed-loop structure with arbitration mechanisms (e.g., token-passing). It offers easier node addition but has lower reliability as a single node failure can disrupt the entire ring.

Bus : A shared communication channel between processors and devices, controlled by protocol software. It includes Federated Bus (hybrid approach, deterministic transmission but specific interfaces required) and Distributed Bus (software stored in non-volatile memory, high redundancy, but complex testing).

Hardware redundancy is a solution to mitigate electronic risk in harsh radiation environments (Single Event Effects - SEE). This can involve identical backup hardware units (adds mass, requires in-flight decision logic, e.g., triple modulator redundancy) or software redundancy (transmitting data multiple times for voting logic). Distributed processing distributes computational tasks across multiple nodes, reducing mass and optimizing power but increasing software complexity.

The CPU (Central Processor Unit) is critical for onboard control, executing programs, interpreting commands, maintaining system health data, formatting telemetry, and delegating tasks to peripheral processors.

CPU sizing involves identifying functionalities, evaluating Instruction Set Architecture (ISA), selecting software languages, assessing software needs (e.g., central system, system management, mission data, operating software), estimating software size, and applying margins (e.g., 400% initially, decreasing to 100% at launch). The goal is to keep Cycles Per Instruction (CPI) low to minimize power and heat.

Memory in OBDH systems includes:

- RAM (Random Access Memory) : Volatile, high-speed, used for quick data read/write. Data is lost if power is interrupted.
- ROM (Read-Only Memory) : Non-volatile, stores permanent data (programs, constants) that cannot be easily modified.

Mass storage is essential for storing large volumes of data, as RAM has limited capacity. While traditional disks are less common in space due to mechanical vulnerabilities, Solid-State Mass Storage (large banks of RAM and integrated circuits) is widely used. It offers high-speed data access and density (gigabytes of storage) but has high power demand and cost. Flash memory is a common technology for mass storage, known for high density and speed, though with radiation immunity limitations.

Microcontrollers are highly integrated computer systems on a single chip, combining a CPU, memory, I/O interfaces, and A/D converters. They are compact, offer flexibility, and provide autonomous control for various subsystems like Power Systems, EPS, AOCS, and RTU control.
Microprocessors are general-purpose CPUs with complex architectures, including ALU, Control Unit, Registers, and Cache Memory. They execute a wide range of tasks and run complex operating systems, typically requiring external components for full functionality.

The BUS is the onboard command and control channel, facilitating data acquisition from sensors, commanding actuators, data transfer between instruments and computers, and time information distribution. Flight control systems are evolving towards distributed processing, using specialized microcontrollers. Common bus protocols include MIL-STD-1553B (1 Mbit/s) and CAN (Controller Area Network) (up to 5 Mbit/s).

The Remote Terminal Unit (RTU) is a critical component in distributed control systems, offloading tasks from the On-Board Computer (OBC), particularly analog and discrete digital data acquisition and actuator control. RTUs are typically non-intelligent units that perform predefined functions, gathering telemetry, controlling AOCS actuators/sensors, Power Systems, SA equipment, and distributing power to heaters and loads. They are found on medium to large-sized spacecraft.

Learning about space systems engineering and operations is like understanding how a complex orchestra works. Each instrument (subsystem) has its role, but it's the conductor (system engineer) who ensures they all play in harmony, following a precise score (requirements and phases) to deliver a beautiful, coherent performance (a successful mission) that stands the test of time and the unpredictable cosmic stage.