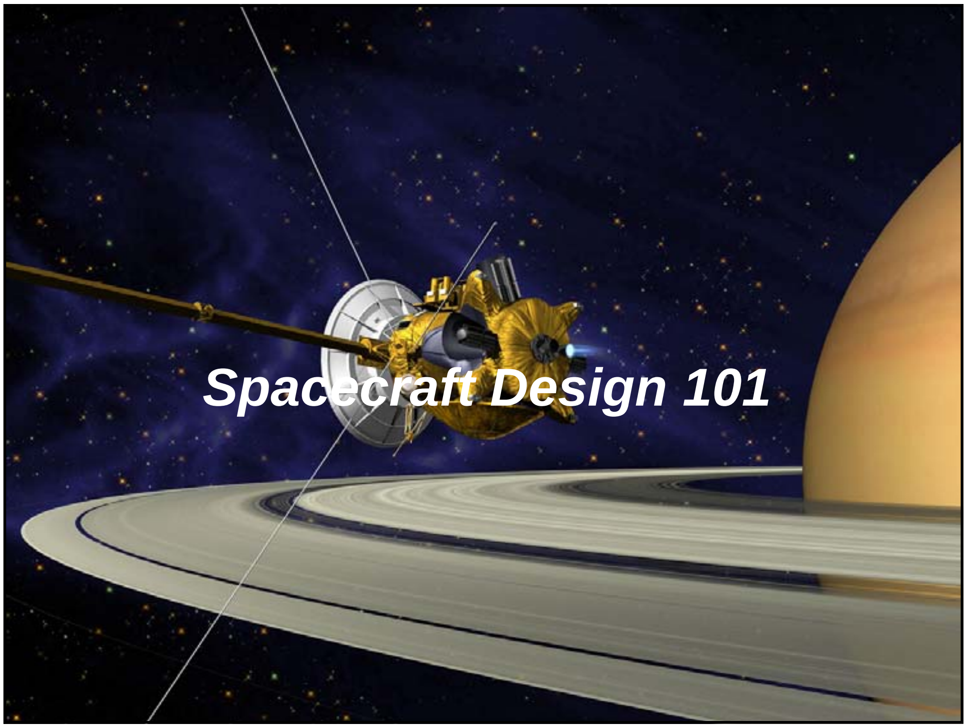

Agenda

- Requirements, constraints, and design process
- Spacecraft configuration
- Design budgets
- Designing spacecraft bus
- Integrating spacecraft design

2

Spacecraft Design and Sizing

- To design a spacecraft we must understand the mission, including the payload's size and characteristics, plus significant systems constraints such as orbit, lifetime, and operations
- We then configure a vehicle to carry the payload equipment and provide functions necessary for mission success
- Unmanned spacecraft consists of at least three elements: payload, spacecraft bus, and booster adapter

3

Spacecraft Design and Sizing

- Payload – mission-peculiar equipment or instruments
- Spacecraft bus – carries payload and provides housekeeping functions
- Booster adapter – provides load-carrying interface with the boost vehicle
- Propellant – either compressed gas, liquid or solid fuel, is used for velocity corrections and attitude control
- Kick stage – separate motor or liquid stage used to inject spacecraft into its mission orbit

4

Spacecraft Design and Sizing

1. Prepare list of design requirements and constraints
2. Select preliminary spacecraft design approach and overall configuration based on above list
3. Establish budgets for spacecraft propellant, power, and weight
4. Develop preliminary subsystem designs
5. Develop baseline spacecraft configuration
6. Iterate, negotiate, and update requirements, constraints, and design budgets

5

Spacecraft Design and Sizing

- Top-level requirements and constraints are dictated by mission concept, mission architecture, and payload operation
- Spacecraft bus functions
  - Support payload mass
  - Point payload correctly
  - Keep payload at right temperature
  - Provide electric power, commands, and telemetry
  - Put payload in correct orbit and keep it there
  - Provide data storage and communications

6

Spacecraft Design and Sizing

- Propulsion subsystem
  - Provides thrust for changing spacecraft's translational velocity or applying torques to change its angular momentum
  - Simplest spacecraft do not require thrust and hence have no propulsion system
  - Most require propulsion – called "metered" propulsion – can be turned on and off in small increments
  - Equipment needed: propellant, tankage, distribution system, pressurant, propellant controls, thrusters/engines
  - Sizing parameters: total impulse, number, orientation, and thrust levels of thrusters

7

Spacecraft Design and Sizing

- Attitude determination and control subsystem
  - Measures and controls spacecraft's angular orientation
  - Simplest spacecraft are either uncontrolled or achieve control by passive methods such as spinning or interacting with Earth's magnetic or gravity fields
  - May or may not use sensors to measure attitude and position
  - Capability of attitude control system depends on the number of body axes and appendages to be controlled, control accuracy and speed of response, maneuvering requirements, and disturbance environment

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Spacecraft Design and Sizing

- Communications subsystem
  - Links spacecraft with ground or other spacecraft
  - Information flowing to spacecraft consists of commands and ranging tones
  - Information flowing from spacecraft consists of status telemetry, ranging tones, and payload data
  - Basics: receiver, transmitter, wide-angle antenna
  - Receives and demodulates commands, modulates and transmits telemetry and payload data, and receives and retransmits range tones
  - Data rate, allowable error rate, communication path length, and RF frequency determine size

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Spacecraft Design and Sizing

- Command and data handling subsystem
  - Distributes command and accumulates, stores, and formats data from spacecraft and payload
  - Could be combined with communication to form tracking, telemetry, and command subsystem
  - Includes: general processor (computer), data buses, remote interface units, and data storage units
  - Data rate and data volume determine size

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Spacecraft Design and Sizing

- Power subsystem
  - Provides electric power for equipment on spacecraft and payload
  - Consists: power source (solar cells, RTG), power storage (battery), power conversion and distribution equipment
  - Power needed to operate equipment and power duty cycle determine subsystems' size
    - Must consider power requirements during eclipses and peak power consumption
  - Must account for solar cell and battery life limits
    - Beginning-of-life (BOL)
    - End-of-life (EOL)

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Spacecraft Design and Sizing

- Thermal subsystem
  - Controls spacecraft equipment's temperatures
  - Ways
    - Passive
    - Active
  - Passive
    - Physical arrangement of equipment
    - Thermal insulation and coatings
  - Active
    - Electrical heaters, high-capacity heat conductors, heat pipes
  - Amount of heat dissipation and temperature required for equipment to operate and survive determine size

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Spacecraft Design and Sizing

- Structural subsystem
  - Carries, supports, and mechanically aligns spacecraft equipment
  - Cages and protects folded components during boost and deploys them in orbit
  - Primary structure – load-carrying structure sized by
    - Strength needed to carry spacecraft mass through launch accelerations and transient events during launch
    - Stiffness needed to avoid dynamic interaction between spacecraft and launch vehicle structures
  - Secondary structure – consists of deployables and supports for components, designed for compact packaging and convenience of assembly

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Requirements, Constraints, and Design Process

- Begin by developing baseline requirements and constraints
- For successful design, must document all assumptions and revisit them until we establish an acceptable baseline
- 1st – understand space mission: concept of operations, duration, overall architecture, and constraints on cost and schedule
- Payload is single most significant driver of spacecraft design

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Requirements, Constraints, and Design Process

- Physical parameters – size, weight, and power – dominate physical parameters of spacecraft
- Payload operations and support are key requirements for spacecraft subsystems
- Payload may also impost significant special requirements that drive design approach
- Usually understand payload characteristics better than spacecraft overall characteristics in early design phases
- Orbit affects propulsion, attitude control, thermal design, and electric power subsystem

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Requirements, Constraints, and Design Process

- Most are secondary to effect on payload performance
- Select orbit based on mission and payload performance
- Then compute performance characteristics needed for spacecraft
- Size spacecraft to meet these needs
- Radiation limits two aspects of spacecraft design: usable materials and lifetime
- Radiation levels and dose do not normally affect system’s configuration or ability

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Requirements, Constraints, and Design Process

- Selecting a boost vehicle and possible kick stage are central issues in designing spacecraft
- Need to select booster that can put up at least minimum version of spacecraft into required orbit
- Perigee kick motor – kick stage used to inject a spacecraft into transfer orbit
- Apogee kick motor – kick stage used to circularize at high altitude
- Booster vehicle also affects spacecraft linear dimensions

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Requirements, Constraints, and Design Process

- Fairing diameter and length limit spacecraft size – while its attached to booster
- If on-orbit spacecraft is larger than fairing – must be folded or stowed to fit within fairing and unfolded or deployed on orbit
- Design deployables to be as light as possible, fold it and protect it during boost, deploy it on orbit
  - Most common: solar arrays and antennas
- Ground system interface determines how much ground operators and spacecraft can interact

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Initial Spacecraft Design Decisions

Design Approach or Aspect	Principal Options or Key Issues
Spacecraft Weight	Must allow for spacecraft busy weight and payload weight
Spacecraft Power	Must meet power requirements of payload and bus
Spacecraft Size	Is there an item such as a payload antenna or optical system that dominates the spacecraft's physical size? Can the spacecraft be folded to fit within the booster diameter? Spacecraft size can be estimated from weight and power requirements
Attitude Control Approach	Options include no control, spin stabilization, 3-axis control: selection of sensors and control torquers. Key issues are number of items to be controlled, accuracy, and amount of scanning or slewing required.

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Initial Spacecraft Design Decisions

Design Approach or Aspect	Principal Options or Key Issues
Solar Array Approach	Options include planar, cylindrical, and omnidirectional arrays either body mounted or offset
Kick Stage Use	Use of a kick stage can raise injected weight. Options include solid and liquid stages
Propulsion Approach	Is metered propulsion required? Options include no propulsion, compressed gas, liquid monopropellant or bipropellant

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Spacecraft Configurations

- To estimate size and structure of spacecraft we select a design approach, develop a spacecraft configuration, and make performance allocations to the subsystems
- Evaluate resulting design and reconfigure or reallocate as needed
- Subsequent iterations add design detail and provide better allocations
- Top-down approach – allocated design requirements are dictated by considering the overall spacecraft design

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Spacecraft Configurations

- Bottom-up approach – allocated design requirements are developed by gathering detailed design information
- Spacecraft configurations (Fig. 10-1)
  - Each spacecraft has a central body or equipment compartment that houses most of spacecraft equipment
  - All have solar arrays either mounted on external panels or on skin of equipment compartment
  - Some spacecraft have appendages carrying instruments or antennas attached to main compartment

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Spacecraft Configuration Drivers

Configuration Driver	Effect	Rule of Thumb
Payload Weight	Spacecraft dry weight	Payload weight is between 17% and 50% of spacecraft dry weight. Average is 30%
Payload Size and Shape	Spacecraft size	Spacecraft dimensions must accommodate payload dimensions
Payload Power	Spacecraft power	Spacecraft power is equal to payload power plus an allowance for the spacecraft bus and battery recharging
Spacecraft Weight	Spacecraft size	Spacecraft density will be between 20 kg/m^3 and 172 kg/m^3. Average is 79 kg/m^3.

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Spacecraft Configuration Drivers

Configuration Driver	Effect	Rule of Thumb
Spacecraft Power	Solar array area	Solar array will produce approximately 100 w/m^2 of projected area
Solar Array Area	Solar array type	If required solar array area is larger than area available on equipment compartment, then external panels are required
Booster Diameter	Spacecraft diameter	Spacecraft diameter is generally less than the booster diameter
Pointing Requirements	Spacecraft body orientation and number of articulated joints	Two axes of control are required for each article to be pointed. Attitude control of the spacecraft body provides 3 axes of control

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Estimating Spacecraft Equipment Compartment Dimensions

Step	Procedure	Comments
1. Payload Weight	Starting point	
2. Estimate Spacecraft Dry Weight	Multiply payload weight by between 2 and 7	Average is 3.3
3. Estimate Spacecraft Propellant	Prepare a bottom-up propellant budget or arbitrarily select a weight	Normal range is 0% to 25% of spacecraft dry weight
4. Estimate Spacecraft Volume	Divide spacecraft loaded weight by estimated density	Range of density is 20-172 kg/m^3, average is 79 kg/m^3
5. Select Equipment Compartment Shape and Dimensions	Shape and dimensions should match payload dimensions and fit within the booster diameter	In the folded configuration, spacecraft are cylindrically symmetric about the booster thrust axis. Cross-sectional shapes range from triangular to circular

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Design Budgets

- Begin allocating performance by establishing budgets for propellant, power, weight, and reliability
- Derive propellant budget by estimating propellant requirements for velocity changes and attitude control
- Estimate power budget by adding payload's power requirements to power estimates for spacecraft bus subsystems
- Derive weight budget by adding payload weight to estimates for spacecraft bus, including propulsion components and power components
- Reliability budget by defining probability of achieving acceptable spacecraft performance and lifetime

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Propellant Budget

Elements	Reference
Velocity Correction and Control	(ΔV for rocket equation)
Attitude Control •Spinup and despin •Maneuvering while spinning •Cancelling disturbance torque •Control during ΔV thrusting •Attitude maneuvering •Limit cycling	
Nominal Propellant	Sum of above
Margin	10-25% of nominal
Residual	1-2% of total
Total Propellant	Sum of above

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Steps in Preparing Power Budget

Step	What's Involved	Comments
1. Prepare Operating Power Budget	Estimate power requirements for payload and each spacecraft bus subsystem	
2. Size the battery	• Estimate power level that the battery must supply • Compute discharge cycle duration, charge cycle duration, and number of charge-discharge cycles • Select depth of discharge • Select charge rate • Computer battery recharge power	• Generally equal to or less than operating power level • Determined by orbit selection and mission duration
3. Estimate Power Degradation Over Mission Life	Compute degradation of power system from orbital environment	30% is typical for 10 years at GEO

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Estimating Power (AIAA)

- Second most critical resource – next to mass
- Start with payload requirements
  - Total spacecraft power strong function of payload required power
- Add contingency
- Margin = Total capability – Current best estimate

$$\%\textbf{margin} = \frac{\textbf{margin}}{\textbf{capability}} x100$$

- Total capability – total power capability of power system – maximum output of power source

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Spacecraft Total Power Required

- Communications

$$P_t = 1.1568 P_{PL} + 55.497$$

- Meteorology

$$P_t = 602.18 \ln(P_{PL}) - 2761.4$$

- Planetary

$$P_t = 332.93 \ln(P_{PL}) - 1046.6$$

- Other missions

$$P_t = 210 + 1.3 P_{PL}$$

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AIAA Power Contingencies

Category	Bid			CoDR			PDR		
	Class			Class			Class		
	1	2	3	1	2	3	1	2	3
AP 0-500 W	90	40	13	75	25	12	45	20	9
BP 500-1500 W	80	35	13	65	22	12	40	15	9
CP 1500-5000 W	70	30	13	60	20	12	30	15	9
DP 5000+ W	40	25	13	35	20	11	20	15	9

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AIAA Power Contingencies

Category	CDR			PRR		
	Class			Class		
	1	2	3	1	2	3
AP 0-500 W	20	15	7	5	5	5
BP 500-1500 W	15	10	7	5	5	5
CP 1500-5000 W	15	10	7	5	5	5
DP 5000+ W	10	7	7	5	5	5

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Subsystem Power Allocation Guide

Subsystem	Comsats	Metsats	Planetary	Other
Thermal Control	30	48	28	33
Attitude Control	28	19	20	11
Power	16	5	10	2
CDS	19	13	17	15
Communications	0	15	23	30
Propulsion	7	0	1	4
Mechanisms	0	0	1	5

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Weight (Mass) Budget

- Ratio of spacecraft weight to payload weight in range of 2:1 to 7:1
  - Payload weight is typically less than half of dry weight and may be as little as 15% of dry weight
- Spacecraft structure between 15-25% of spacecraft dry weight
  - Also 8-12% of injected weight (dry weight + propellant + injection stage)
- For uncertainties add 25% to weights for new equipment, 5% or less for known hardware
- Hold allowance of 1-2% at system level to account for integration hardware

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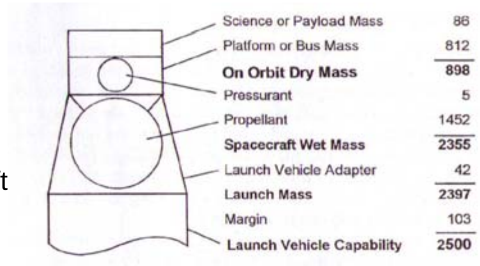
Mass Definitions

- Science (payload) mass – science instruments mass + all equipment used in direct support of instruments (mounting structure, cabling, engineering instrumentation, thermal control heaters, blankets, radiators)
- Bus (platform) mass – total, on-orbit dry mass of spacecraft – science, propellants, and gases are not included
- Launch vehicle adapter mass – mass of structure, separation devices, cabling, thermal control equipment necessary to adapt spacecraft to launch vehicle



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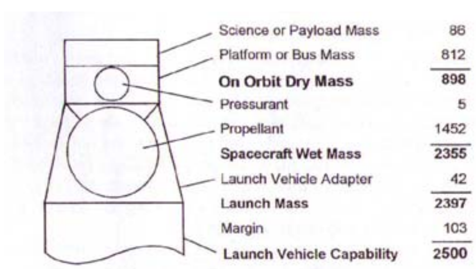
Mass Definitions

- Injected mass – planetary spacecraft mass that is accelerated to Earth departure velocity
- Launch mass – total mass of spacecraft as it rests on the launch vehicle
- Cruise mass – wet or dry mass in interplanetary cruise configuration – launch mass minus adapter mass
- On-orbit dry mass
  - Science instruments
  - Platform/bus



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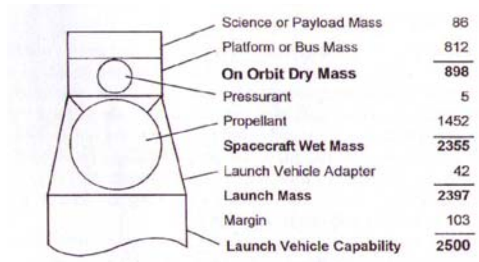
Mass Definitions

- Burn-out mass – mass after shutdown from propulsion event – spacecraft + gas + remaining propellant
- Mass uncertainty – mass growth estimate from a given time to launch
- Mass maturity – degrees of maturity
  - Estimated - history
  - Calculated – engineering calculation
  - Actual – weight measurement
- Mass margin – difference between spacecraft estimate and launch vehicle capability



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Design Budget (Dry Mass)

1. Determine maximum spacecraft launch mass from mission
2. Deduct launch vehicle adapter mass from launch mass
3. Determine propellants and pressurants required for mission
4. Determine total allowable on-orbit dry mass
5. Establish total allowable payload weight
6. Evaluate mass margin to be set aside
7. Allocate mass budgets to each subsystem

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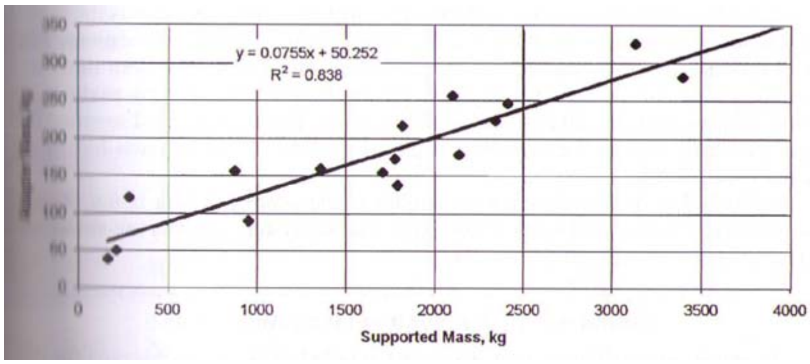
Launch Vehicle Adapter Mass

LVA = 0.0755LM + 50



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AIAA Recommended Mass Margins

- Mass margin
  - Margin = Total capability – Current best estimate

$$\%\boldsymbol{margin} = \frac{\boldsymbol{margin}}{\boldsymbol{capability}} x100$$

- Classes
  - 1 – new spacecraft
  - 2 – next-generation spacecraft based on previously development family
  - 3 – production-level development on an existing design

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AIAA Recommended Mass Margins

Category	Bid			CoDR		
	Class			Class		
	1	2	3	1	2	3
AW 0-50 kg	50	30	4	35	25	3
BW 50-500 kg	35	25	4	30	20	3
CW 500-2500 kg	30	20	2	25	15	1
DW 2500+ kg	28	18	1	22	12	0.8

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AIAA Recommended Mass Margins

Category	PDR			CDR		
	Class			Class		
	1	2	3	1	2	3
AW 0-50 kg	25	20	2	15	12	1
BW 50-500 kg	20	15	2	10	10	1
CW 500-2500 kg	20	10	0.8	10	5	0.5
DW 2500+ kg	15	10	0.6	10	5	0.5

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Subsystem Mass Allocation Guide

- Subsystem on-orbit dry mass allocation guide
- 2 conditions
  - Payload supplied by spacecraft team
  - Customer-supplied payload

Subsystem Mass Allocation Guide

Subsystem	Comsats		Metsats		Planetary		Other	
	with P/L	GFE P/L	with P/L	GFE P/L	with P/L	GFE P/L	with P/L	GFE P/L
Structure	21	29	20	29	26	29	21	30
Thermal	4	6	3	4	3	3	3	4
ACS	7	10	9	13	9	10	8	11
Power	26	35	16	23	19	21	21	29
Cabling	3	4	8	12	7	8	5	7
Propulsion	7	10	5	7	13	15	5	7
Telecom	-	-	4	6	6	7	4	6
CDS	4	6	4	6	6	7	4	6
Payload	28	-	31	-	11	-	29	-

Reliability Budget

- Must design our hardware and software to achieve reliable operation
- Design-for-reliability starts in conceptual design phase with determination of system reliability requirements and allocation of these requirements to spacecraft subsystems
- 1st – establish mission success criteria – list of events and operations that together constitute success

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Reliability Budget

- 2nd – assign a numerical probability to meeting each element of mission success criteria and select a set of ground rules for computing probability of success
- 3rd – allocate reliability requirements to all spacecraft hardware and software
- 4th – evaluate system reliability and iterate design to maximize reliability assessment, and identify and eliminate failure modes

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Designing Spacecraft Bus - Propulsion

- Propulsion equipment includes
  - Tankage to hold propellant
  - Lines and pressure-regulating equipment
  - Engines or thrusters
- Common propellants
  - Pressurized gas (N_2, He)
  - Monopropellants (N_2H_4, H_2O_2)
  - Bipropellants (N_2O_4/N_2H_4, LOX/LH_2)
- Pressurization
  - Pressure regulated
  - Blow down
- Design parameters
  - Number, orientation, and location of thrusters
  - Thrust level
  - Amount of impulse required

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Designing Spacecraft Bus - Propulsion

- Propulsion tanks rest at or near CG of spacecraft to avoid shifting center of mass as propellant is burned
- Engines for translational control are aligned to thrust through center of mass
- Engines for attitude control thrust tangentially and are mounted as far away from center of mass as possible to increase lever arm and thus increase torque per unit thrust
- 3 axis control requires minimum of 6 attitude control thrusters
- Many designs use 8 to 12 plus backup units

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Designing Spacecraft Bus - Propulsion

- Propulsion subsystem does not use much electrical power
- Power requirements
  - Heated catalyst beds
  - Heated thrusters (common)
  - Electric propulsion (rare)
- Propulsion lines and tanks – power allocated to thermal subsystem
- Electrically operated solenoid valves control propellant flow to thrusters – account for their power in ADC subsystem

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Propulsion Weight and Power Budget

Component	Weight (kg)	Power (W)	Comments
Propellant	Calculated		Added to overall budget, not part of propulsion subsystem
Tank	10% of propellant weight		Tanks for compressed gas may be up to 50% of gas weight
Thrusters	0.35-0.4 kg for 0.44 to 4.4 N hydrazine units	5 W per thruster when firing	
Lines, Valves, & Fittings	Dependent on detailed spacecraft design		Examples 6.8 kg (HEAO) 7.5 kg (FLTSATCOM)

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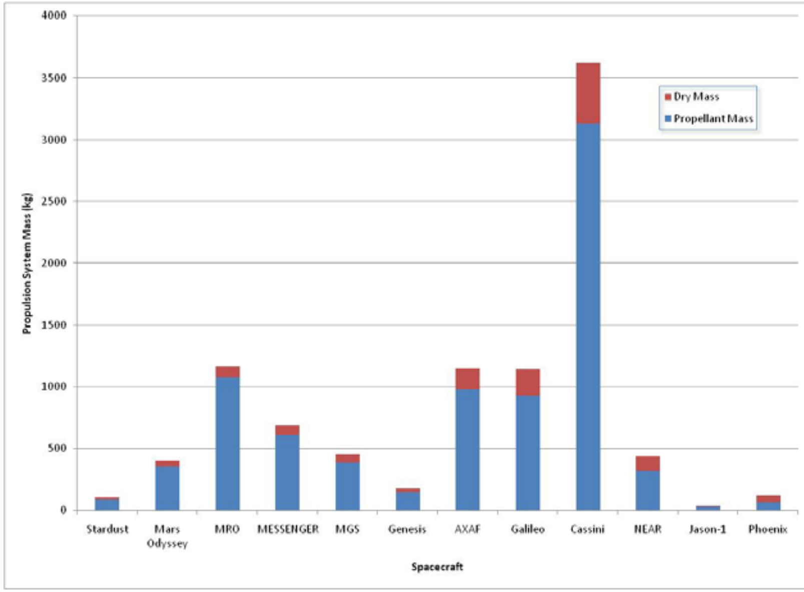
Historical Propellant Mass Ratio



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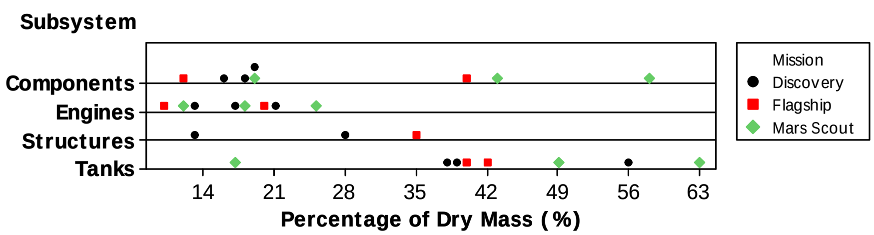
Historical Propulsion Components



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Designing Spacecraft Bus - ADCS

- Control requirements based on payload pointing and spacecraft bus pointing
- If payload attitude is controlled must decide
  – Point entire spacecraft
  – Articulate payload or part of payload
- Either spin stabilization or 3-axis control using sensors and torquers can be used to control spacecraft's attitude
- Spin stabilization (kick stage firing)
  – Passive spin – spin with precession control
  – Dual spin – spin with a despun platform

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Designing Spacecraft Bus - ADCS

- 3-axis approaches
  – Passive control – use gravity gradient or magnetics
    - Supports low accuracy pointing requirements and simple spacecraft
  – Full active control – propulsion thrusters and wheels
    - Highly accurate pointing control
    - Pointing of several payloads or spacecraft appendages
    - But, more complex and usually heavier

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Designing Spacecraft Bus - Comm

- Communications subsystem receives and demodulates uplink signals and modulates and transmits downlink signals
- Can also track spacecraft by retransmitting received range tones or by providing coherence between received and transmitted signals
- Considerations
  - Access – ability to communicate with spacecraft requires clear field of view to receiving antenna and appropriate antenna gain; need to select a level of transmit power and receiver sensitivity that allow detection of signals with an acceptable error rate

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Designing Spacecraft Bus - Comm

- Considerations, cont'd
  - Frequency – selection based on bands approved for spacecraft use by international agreement – S (2 GHz), X (8 GHz), Ku (12 GHz)
  - Baseband data characteristics – data bandwidth and allowable error rate determine RF power level for communications; rates between 100 bits/sec to 100 kbits/sec; rate depends on mission considerations and sets communications subsystem's bandwidth – which establishes received power required to detect signals
- If data can fit within a low-bandwidth link – use widebeam antenna

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Designing Spacecraft Bus - Comm

- Data over high bandwidth requires high-gain, directional antenna and a low-bandwidth mode for widebeam coverage
- Design process
  - Identify data rate
  - Select frequencies – decide which of the allowed bands to use
  - Prepare RF power budget – analyze characteristics of RF links
  - Select equipment

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Designing Spacecraft Bus – CD&H

- Receives and distributes commands
- Collects, formats, and delivers telemetry for standard spacecraft operations and payload operations
- Housekeeping data intermittently @ low rates (<1000 bits/sec)
- Payload commanding and telemetry depend on payload design – could be high & require storage

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Designing Spacecraft Bus – CD&H

- Sizing steps
  - Prepare command list – prepare a complete list of commands for payload and each spacecraft subsystem – include commands for each redundancy options and each commandable operation
  - Prepare telemetry list – analyze spacecraft operation to select telemetry measurement points that completely characterize it – include signals to identify redundancy configuration and command receipt
  - Analyze timing – analyze spacecraft operation to identify time-critical operations, and timeliness needed for telemetry data

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Designing Spacecraft Bus – CD&H

- Sizing steps, cont'd
  - Select data rates – choose data rates that support command and telemetry requirements and time-critical operations
  - Identify processing requirements – examine need for encryption, decryption, sequencing, and processing of commands and telemetry
  - Identify storage requirement – compare data rates of payload and spacecraft to communications subsystem's ability
  - Select equipment – configure subsystem and select components to meet requirements

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Designing Spacecraft Bus – Thermal

- Need to identify sources of heat and designing paths for transporting and rejecting heat so components will stay within required temperatures
- Heat sources
  – Solar radiation
  – Earth-reflection and infrared radiation
  – Electrical energy dissipated in electrical components
- Component temperature ranges
  – Electronics 25°C ± 20°C
  – Batteries 5°C to 20°C

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Designing Spacecraft Bus – Thermal

- Two types
  – Passive (thermal coatings, MLI)
  – Active (heaters, heat pipes)

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Designing Spacecraft Bus – Power

- Generates power, conditions and regulates it, stores it for periods of peak demand or eclipse operation, and distributes it throughout spacecraft
- May need to covert and regulate voltage levels or supply multiple voltage levels

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Designing Spacecraft Bus – Power

- Sizing steps
  - Determine power required (spacecraft power)
  - Select a solar array approach
  - Size solar array
  - Size batteries and components that control charging
  - Size equipment for distributing and converting power

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Designing Spacecraft Bus – Power

- Planar solar array area
  - $A_a = 0.01\ P$
    - A_a (m^2), P(W)
- Planar solar array mass
  - $M_a = 0.04\ P$
    - M_a (kg), P(W)
- Batteries
  - $M_B = C/35$ (NiCd)
  - $M_B = C/45$ (NiH2)
    - M_B (kg), C (W-hrs)
- Power control unit
  - $M_{PCU} = 0.02\ P$
    - M_{PCU} (kg), P (W)
- Regulators/Conv
  - $M_{RC} = 0.025\ P$
    - M_{RC} (kg), P (W)
- Wiring
  - $M_W = 0.01\text{-}0.04\ M_{dry}$

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Designing Spacecraft Bus – Struct

- Carries and protects spacecraft and payload equipment through launch environment and deploys spacecraft after orbit insertion
- Types
  - Primary – load carrying; sized based on launch loads with strength and stiffness dominating design
  - Secondary – brackets, closeout panels, most deployable components; sizing depends on on-orbit factors

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Integrating Spacecraft

- Spacecraft volume
  - V=0.01M
- Linear Dimension
  - $S = 0.25\ M^{1/3}$
- Body area
  - $Ab = s^2$
- Moment of inertia
  - $I = 0.01\ M^{5/3}$
- M = spacecraft loaded mass (kg)

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