Assessment and Selection Phase
Lecture P. Falkner

Elixir School 19-20 May 2011
ESTEC

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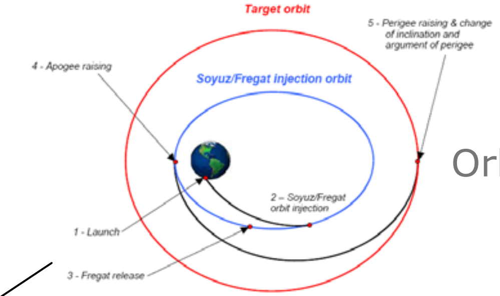
Space Mission Elements

Launcher



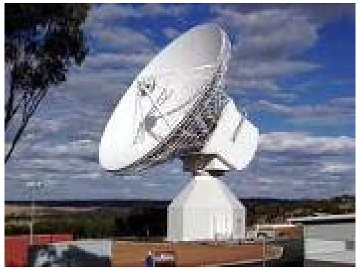
Orbit - Konstellation

Data Center

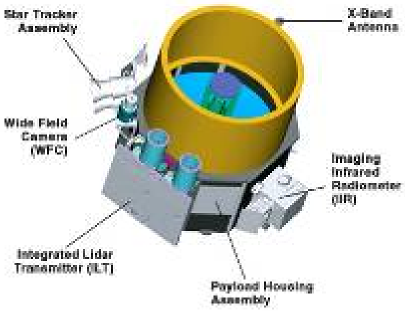
Space Mission

Spacecraft

Mission Operation

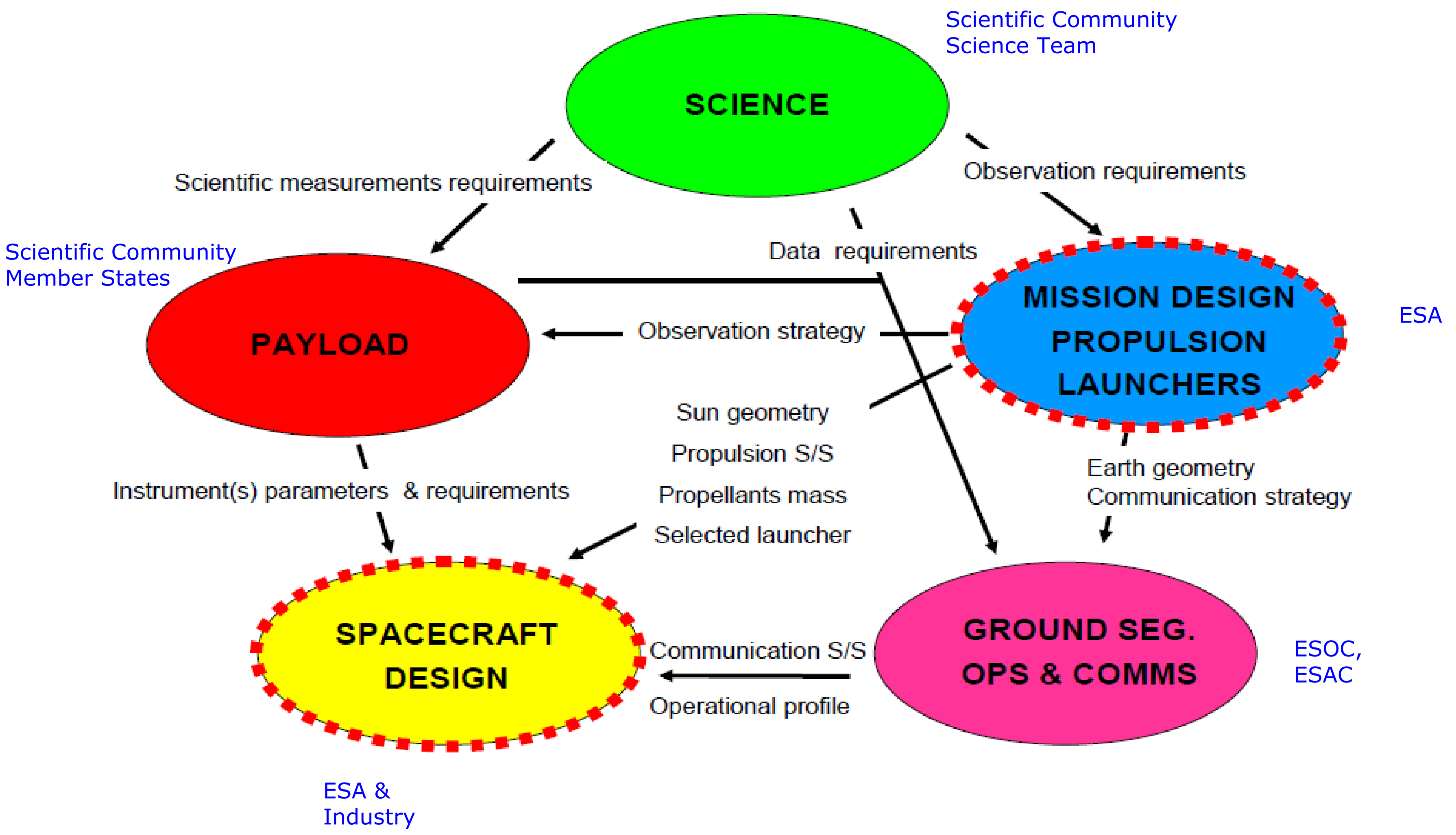


Ground Station



Payload

Mission Design Process



Adopted from D. Moura (2009)

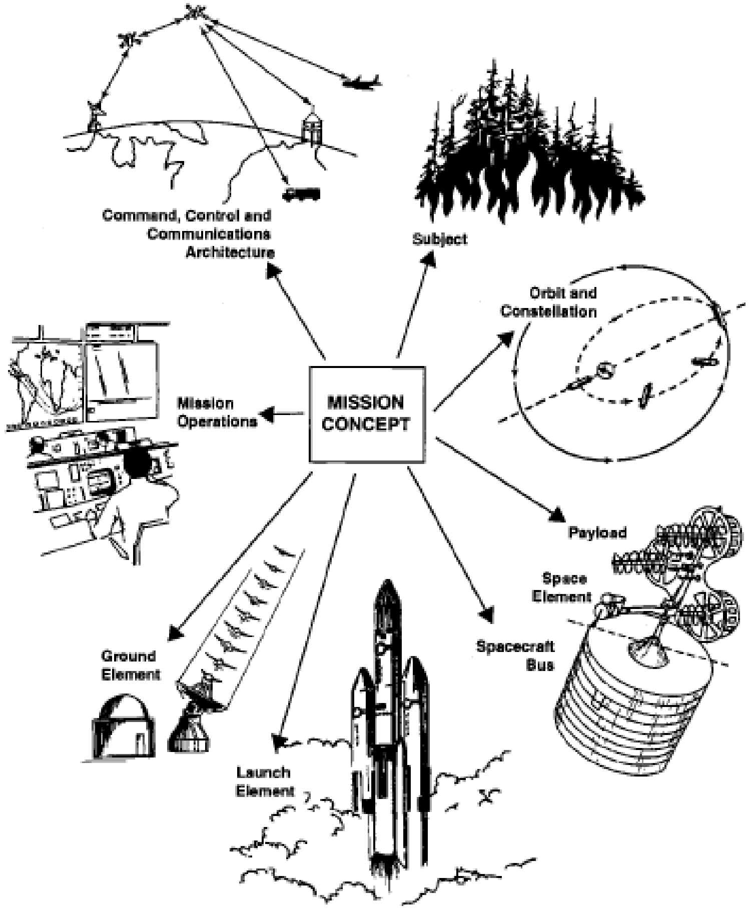
System Design / End-to-End view

Study Phase 0:

- Analysis of Mission Objectives
- Analysis of Mission Constraints
- Definition of Science Requirements
- Definition of Mission Architecture (s)
- Definition of payload / performance
- Analysis of Environment
- **Iteration / Trade phase**
- Cost, Risk, Schedule, Technology Development

Goal:

- **feasible mission profile**
- **satisfying requirements and constraints**



SMAD, p. 13 Space Mission Architecture

Launcher

- Provides access to Space
- **Main trade**: Performance/Cost (end-to-end view)
- Possibility of sharing launch (e.g. Herschel / Planck)
- Trade: direct transfer vs. optimisation of launcher insertion orbit
- (spacecraft design dependent)
- Attention (!): launch environment/constraints (incl. launch site)

- Soyuz Fregat-2B (~70 M€), Ariane 5 ECA (~150M€), VEGA

- Performance: SF-2B ~ 4900 kg SSO 650km
- A5 ~8000 kg SSO 800 km
- For performance => see launcher user manuals (web)

Launcher	Vega	Soyuz	Ariane-5 Generic	Ariane-5 ECA
Orbit	SSO/LEO	GTO	GTO	GTO
Payload mass, kg	1500 (700 km)	3000	6600	10000

SSO/LEO: Sun Synchronous Orbit/Low Earth Orbit, GTO: Geostationary Transfer Orbit

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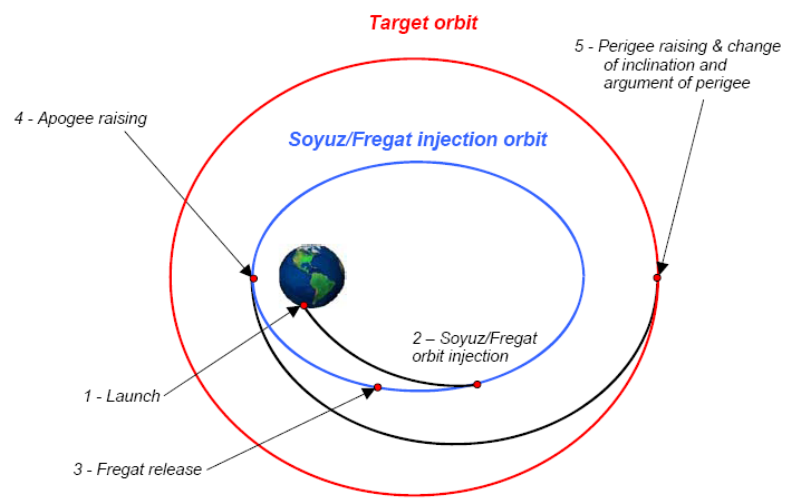
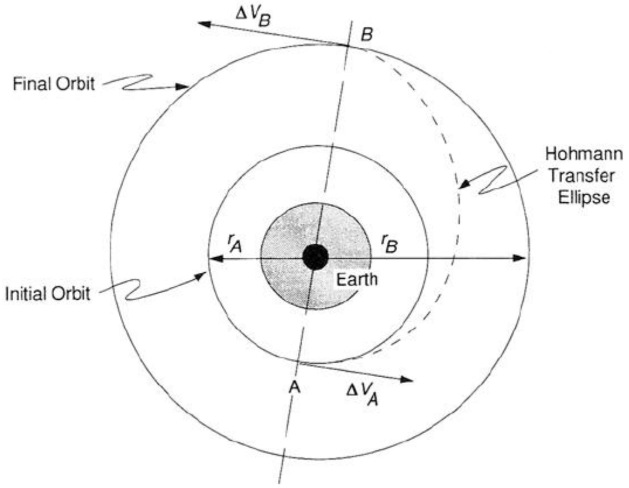
Orbit Design



Mission Analysis

- Launch and Transfer from Earth
- Insertion into target orbit
- Orbit and Maintenance
- End-of-Life disposal

- Important:
  Analysis of perturbations, e.g. third bodies, solar radiation pressure (translation, rotation), micrometeorites
  for LEO: atmospheric drag, J-factors



Hohmann Transfer. The Hohmann Transfer ellipse provides orbit transfer between two circular, co-planar orbits.

$$a_D = -(1/2)\rho\,(C_D\,A/m)V^2$$

ρ is atmospheric density, A is the satellite's cross-sectional area, m is the s/c mass, V is the satellite's velocity with respect to the atmosphere, and C_D is the drag coefficient

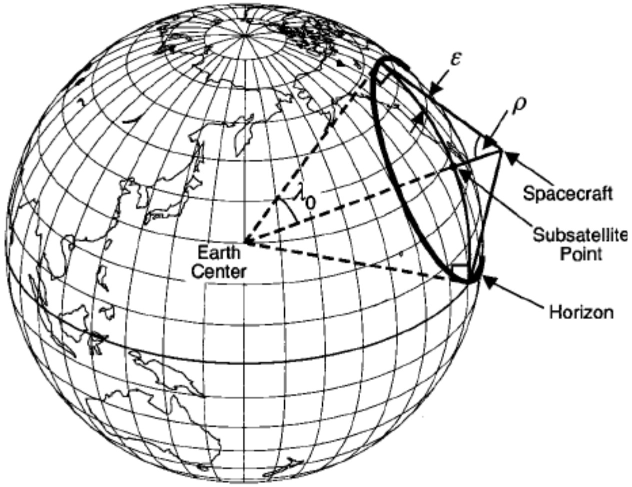
$$a_R \approx -4.5 \times 10^{-6}(1+r)\,A/m$$

Solar radiation: A is the satellite cross-sectional area exposed to the Sun in m^2 , m is the satellite mass in kg, and r is a reflection factor.

Target Orbit Selection

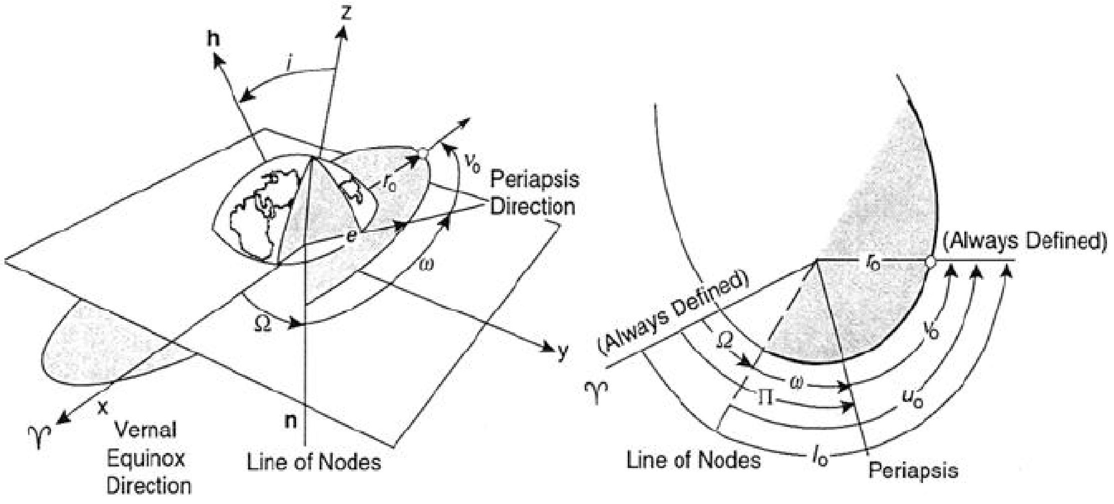
Driven by (contradicting) requirements:

- Resolution, revisit time, link budgets, visibility from ground stations, eclipse duration
- Cost of orbit acquisition and maintenance (e.g. drag, J-term perturbations, 3rd body perturbations etc…)
- Illumination conditions

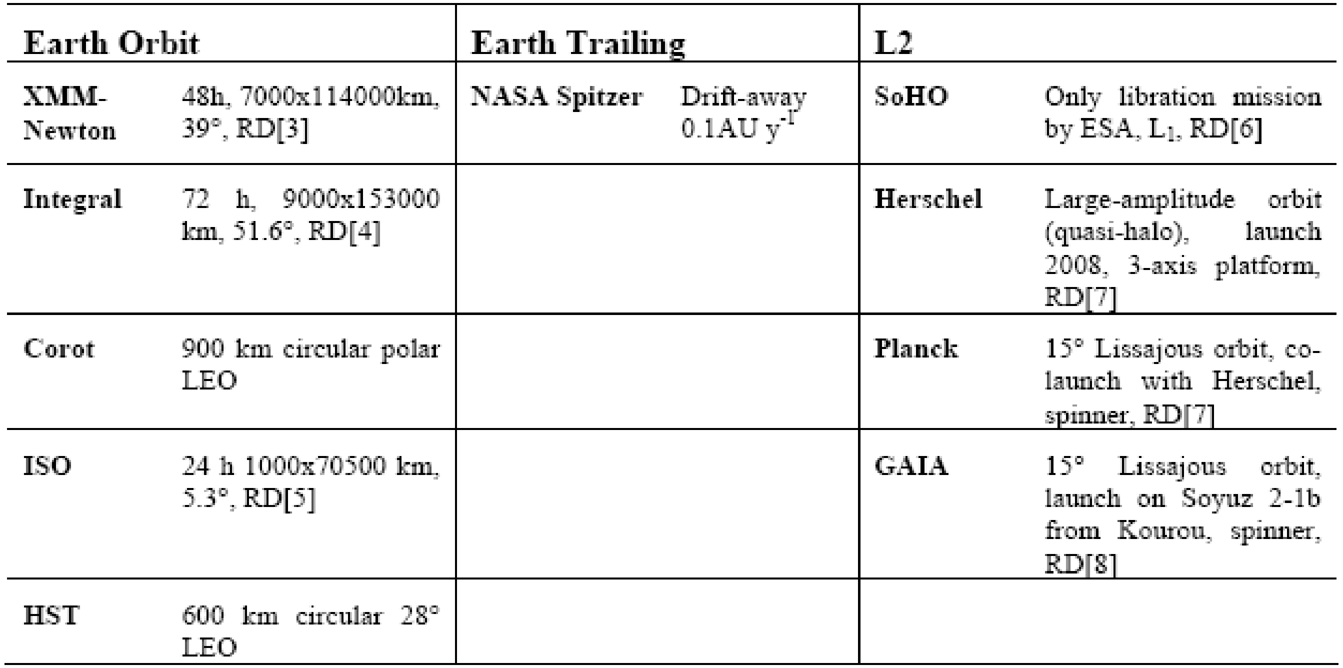


Relationship Between Geometry as Viewed from the Spacecraft and from the Center of the Earth. See also Fig. 5-12.

Definition of the Keplerian Orbital Elements of a Satellite In an Elliptic Orbit.



Some Examples

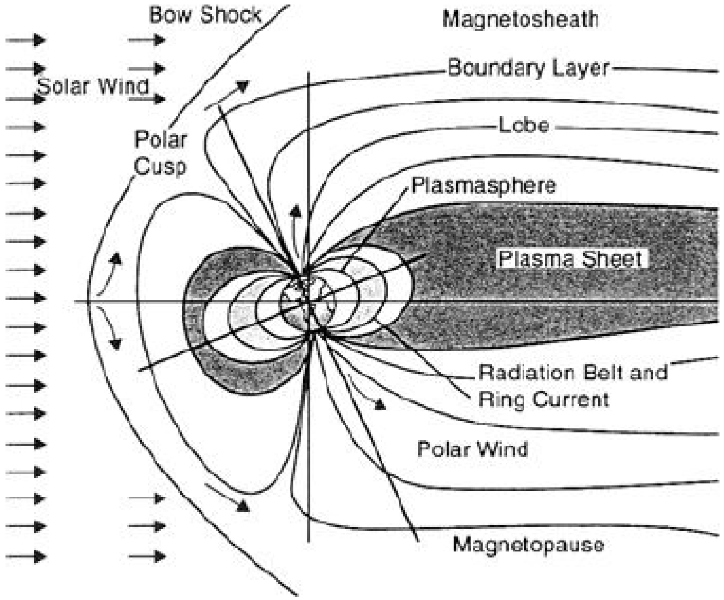


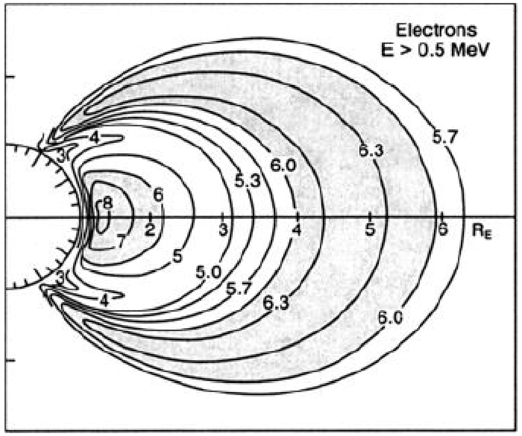
Earth Orbit		Earth Trailing		L2	
XMM-Newton	48h, 7000x114000km, 39°, RD[3]	**NASA Spitzer**	Drift-away 0.1AU y^{-1}	**SoHO**	Only libration mission by ESA, L_1, RD[6]
Integral	72 h, 9000x153000 km, 51.6°, RD[4]			**Herschel**	Large-amplitude orbit (quasi-halo), launch 2008, 3-axis platform, RD[7]
Corot	900 km circular polar LEO			**Planck**	15° Lissajous orbit, co-launch with Herschel, spinner, RD[7]
ISO	24 h 1000x70500 km, 5.3°, RD[5]			**GAIA**	15° Lissajous orbit, launch on Soyuz 2-1b from Kourou, spinner, RD[8]
HST	600 km circular 28° LEO				

Space Environment

- Solar cycle (11-years) – flares
  Solar Protons: 1 MeV to > 1 GeV
- Radiation belts of Earth
  electrons, protons
- Cosmic Rays
- Spacecraft charging
- Magnetic Field
- Solar Radiation Pressure
- Thermal environment
- Vacuum

- Radiation effects electronics, materials and increase noise in detectors

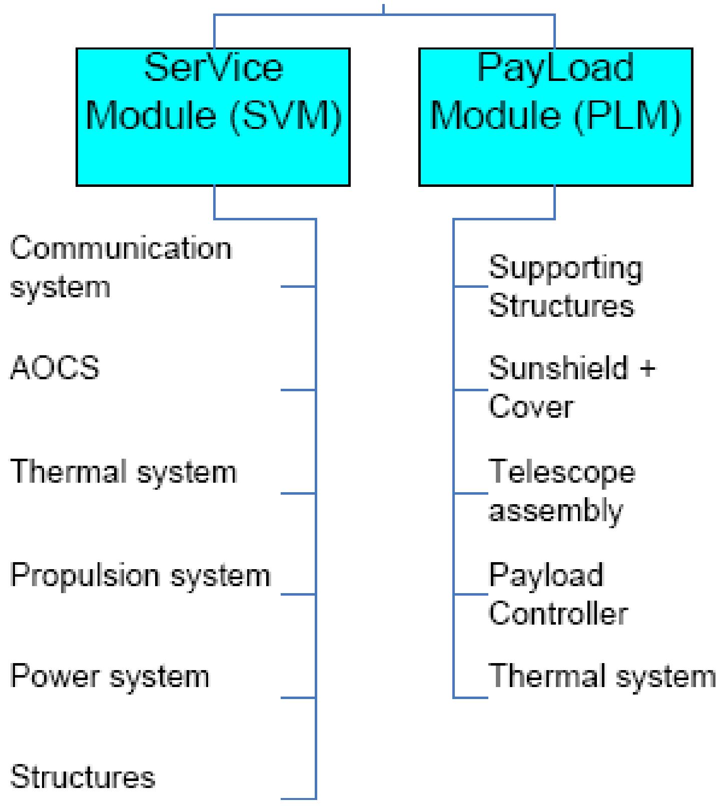




Spacecraft Subsystems

- Structures & Mechanism
- Propulsion
- AOCS
- Thermal
- Power
- Data Handling
- Communication (TT&C)
- **Payload**

Important: **Interrelation of Subsystems**



SerVice Module (SVM)

- Communication system
- AOCS
- Thermal system
- Propulsion system
- Power system
- Structures

PayLoad Module (PLM)

- Supporting Structures
- Sunshield + Cover
- Telescope assembly
- Payload Controller
- Thermal system

Structures

Distinguish:

- Primary structures (carrying s/c major loads)
- Secondary structures (carrying equipment) & appendages

- Structure need to provide stiffness in all mission modes
  (most driving launch, main propulsion manoeuvres, separation of stages, pyros firing etc.) <u>at lowest possible mass</u>
- **Sizing parameters**: acceleration, shock, vibration, acoustic noise (large surfaces!)
- **Critical parameter**: Strength, stiffness, density, thermal characteristics (expansion, conductivity), handling (machining), cost
- Thermal deformations / co-alignment requirements
- Eigenfrequencies > launcher induced frequencies = driving stiffness

$$\sigma \equiv \frac{\text{Load}}{\text{Area}} \equiv \frac{P}{A}$$

Stress σ [N/m^2]

$$\varepsilon \equiv \frac{\Delta L}{L}$$

Strain ε

$$\nu \equiv \frac{\varepsilon_{lateral}}{\varepsilon_{axial}}$$

Poisson's ratio

$$E \equiv \frac{\sigma}{\varepsilon}$$

Young Modulus
E [N/m2]

Mechanism

Moving parts:

- Reliability is critical (lubrication in space, long storage, thermal range)
- Introduce vibrations

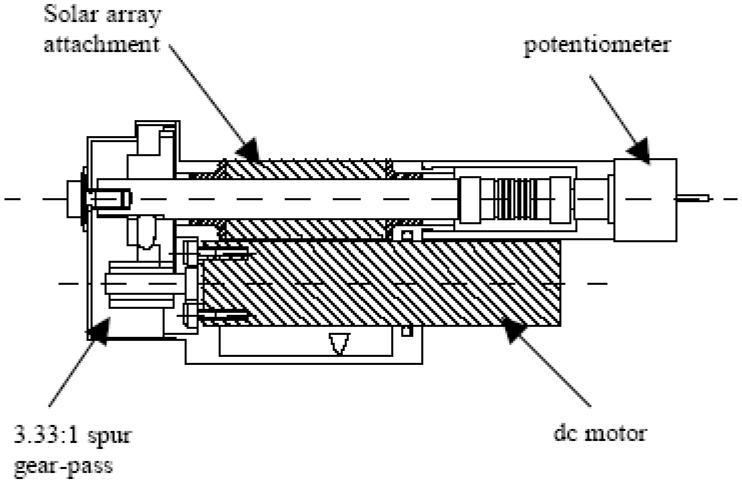
Examples:

- Launch lock mechanism (hold down release mechanism HDRM)
- Deployment of structure, appendages and booms
  (e.g. solar panel, sun shield, antennae, …)
- Separation mechanism (separation of stages, multiple s/c,..)
- Pointing mechanism (e.g. payload, HG-antenna, panels)
- Reaction wheels
- Deployable instrument covers

HDRM

Mechanism are a source of mechanical noise

- Motors and gears: e.g. Maxon
- Frangibolt® Actuator http://www.tiniaerospace.com/fbt/fbfc3-20-16sr2.html



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Propulsion

Provides: acceleration and torques
For: transfer, orbit insertion, attitude correction and orbit corrections

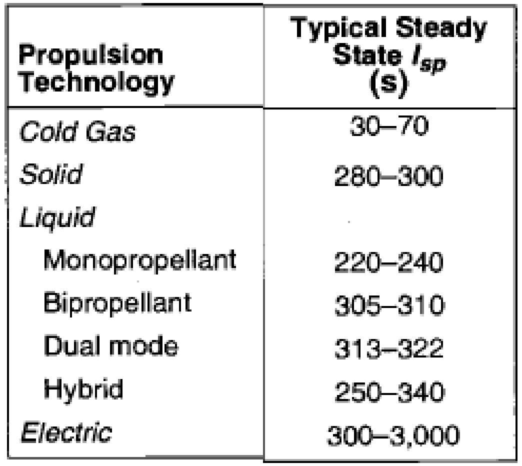
Main engines (e.g. 400 N engine, I_{sp} ~320)
  - large delta-v, large I_{sp}, drive propellant need
  - chemical (solid, liquid mon-, bi-prop),
  - electrical (I_{sp} 3000-4500s)

RCS-thruster
  - Chemical
  - Electrical
  - Cold gas

- Propulsion tanks + pressurant tanks
- Harness, piping

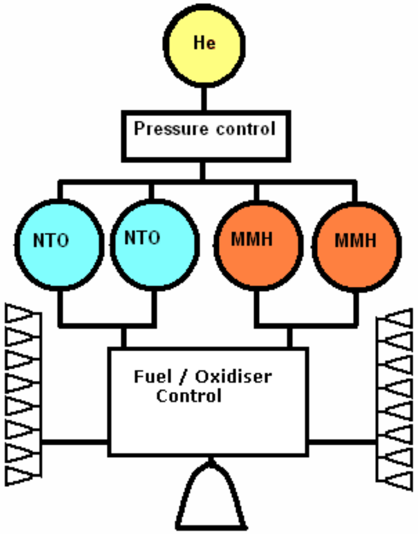
$$m_p = m_f\left[e^{(\Delta V / I_{sp} g)} - 1\right]$$

Rocket equation: m_f=dry mass, m_p=propellant

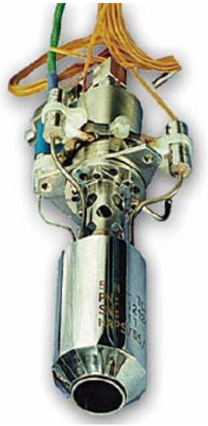


Propulsion Technology	Typical Steady State I_{sp} (s)
Cold Gas	30–70
Solid	280–300
Liquid	
Monopropellant	220–240
Bipropellant	305–310
Dual mode	313–322
Hybrid	250–340
Electric	300–3,000

main engine

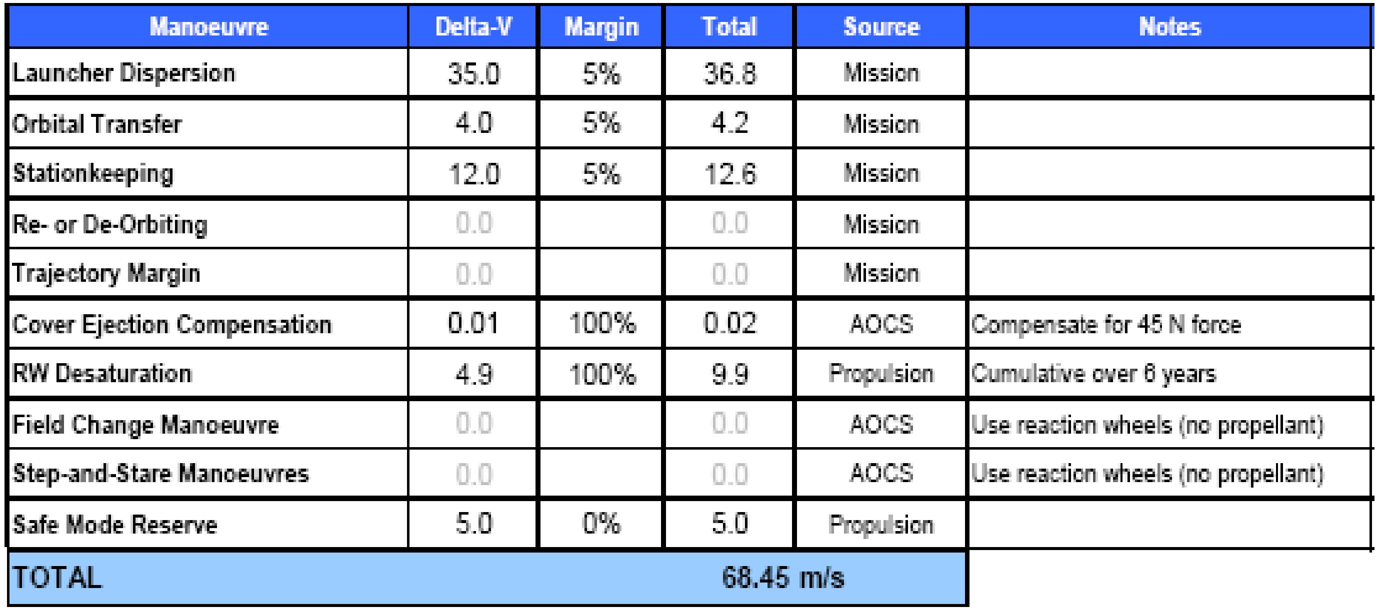


Propulsion system



RCS Thruster

Delta-v budget (example)



Manoeuvre	Delta-V	Margin	Total	Source	Notes
Launcher Dispersion	35.0	5%	36.8	Mission	
Orbital Transfer	4.0	5%	4.2	Mission	
Stationkeeping	12.0	5%	12.6	Mission	
Re- or De-Orbiting	0.0		0.0	Mission	
Trajectory Margin	0.0		0.0	Mission	
Cover Ejection Compensation	0.01	100%	0.02	AOCS	Compensate for 45 N force
RW Desaturation	4.9	100%	9.9	Propulsion	Cumulative over 6 years
Field Change Manoeuvre	0.0		0.0	AOCS	Use reaction wheels (no propellant)
Step-and-Stare Manoeuvres	0.0		0.0	AOCS	Use reaction wheels (no propellant)
Safe Mode Reserve	5.0	0%	5.0	Propulsion	
TOTAL			68.45 m/s		

AOCS (attitude and orbit control system)

Stabilizes the spacecraft against external (and internal) disturbances+
Orbit control and maintenance

- 3-axis or spin stabilized (‘gyroscopic stiffness’)
- Analysis of pointing requirements (payload, s/c subsystems like antennae, solar panels, etc.)
  - re-pointing (⇨APE) , duration of starring (⇨RPE)
  - safe modes, transfer phase,… ⇨ all modes need to be analysed
  - see ESA pointing requirements Handbook

Sensors:
Magnetometer, sun sensor, limb sensor, star tracker, accelerometer, payload, GPS (if available), gyroscopes , IMU

Actuators:
thruster (hot gas, cold gas, electric) ⇨ propulsion system
reaction or momentum wheels, control-moment gyros, magnetic-torquers, ‘natural’ perturbations, nutation dampers

Thermal

Controls spacecraft thermal environment (within operational, non-operational ranges) in various mission modes:

- Launch, transfer, science mode, safe mode, eclipse, etc…

- Driven by equipment and payload requirements
- Need careful analysis of all modes (internal dissipation and external input) under various aspect angles.

Sensors: temperature sensors

Control Components:

- Coatings, MLI, paint, radiators, sun shields, foam, heat pipes, optical reflectors, louvers, fillers, thermal insulators, cooler, cold plates, phase change devices, electrical heaters & thermostats, RHU’s,….
- Using of emission (ε), absorption (ɑ) values

- Requires: Geometrical Mathematical Model (GMM) and Thermal Mathematical Model (TMM) – e.g. ESATAN
- Need to understand the characteristics and dissipation of all s/c equipment

Attention (!) to: thermo-elastics (⇨co-alignment), outgasing

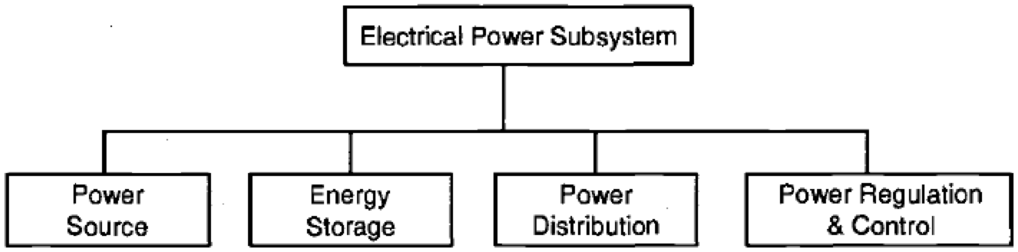
Power

Provides: electrical power to S/C bus and payload

Solar Panel (e.g. triple-Junction cell ~28-32% eff.)

  - panels need to point to the sun (dependent on orbit characteristics ⇨ pointing mechanism needed 1-2 DOF?)
  - body mounted (typ. spinner) or panel type (3-axis)
  - input at Earth: 1367 W/m^2 solar flux

- **Batteries**
  - Primary (up to ~300 Whr/kg) and Secondary (re-chargeable, e.g. Li-Ion ~120 Whr/kg)
  - Energy storage
  - needed for emergency (safe mode), eclipses,…
- **Alternative energy sources**
  - Nuclear Power (RTG, RHU’s, ASGR’s), …
- **Power Control and Distribution Unit (PCDU)**



Electrical Power Subsystem

Power Source

Energy Storage

Power Distribution

Power Regulation & Control

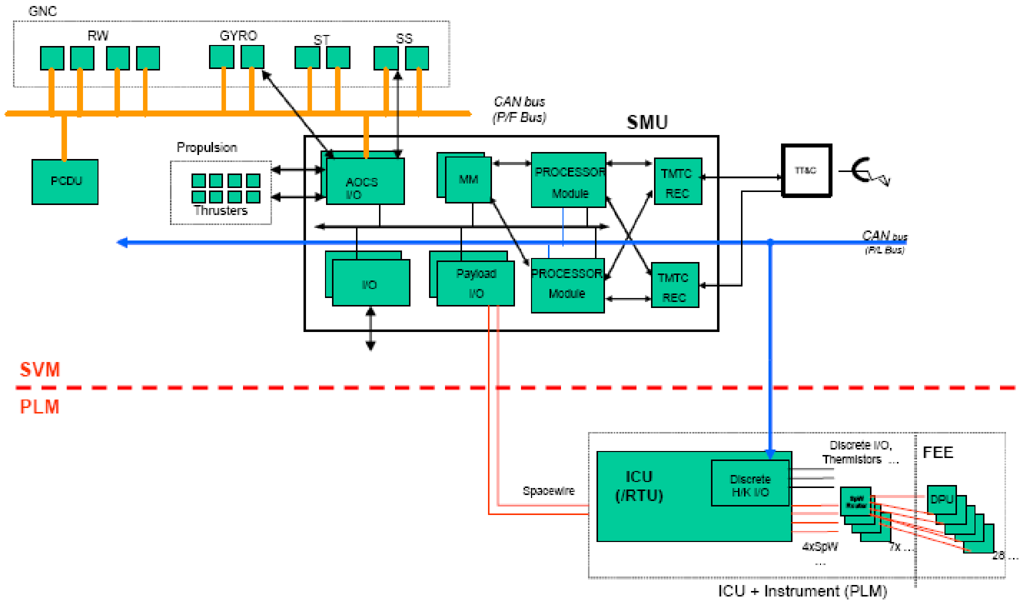
Simplified approach:

1) Define driving mode
2) Calculate power budget
3) Sizing of panels, batteries and PCDU

Data Handling & Control

Onboard Computer System and Memory

- Command Interpretation and execution
- **Data Handling, Processing and Storage**
- Housekeeping handling
- AOCS control algorithm
- Control functions (power, thermal, payload)
- Failure Detection Isolation and recovery (FDIR)



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Communication and tracking

Provides communication (RF- or optical link) for:

- Commanding, housekeeping
- Data download
- Radio-Science
- Tracking (location (range), velocity (doppler))

Ground station to/from spacecraft

For longer slant range: X- or Ka-band (others S, UHF)

Understanding of required data rates ⇨drives RF system

– VHF:	30 - 225 MHz
– UHF:	225 - 1000 MHz
– L-Band:	1.0 - 2.0 GHz
– S-Band:	2.0 - 4.0 GHz
– C-Band:	4.0 - 8.0 GHz
– X-Band:	8.0 - 12.4 GHz
– Ku-Band:	12.4 - 18.0 GHz
– K-Band:	18.0 - 26.5 GHz
– Ka-Band:	26.5 - 40.0 GHz
– Q-Band:	40.0 - 60.0 GHz
– V-Band:	60.0 - 75.0 GHz
– W-Band:	75.0 - 110 GHz

Link budget:

$$\frac{E_b}{N_o} = \frac{P L_l G_t L_s L_a G_r}{k T_s R} = \frac{[\mathrm{EIRP}] L_s L_a}{k R} \left(\frac{G_r}{T_s} \right)$$

Energy per bit over noise >3 dB

P = transmitter power
L_l = Line loss
G_t =Antenna Gain Tx
L_s = space loss
L_a = transmission path loss
G_r = Gain receiver antenna
T_s = Receiver system noise temperature
k = Boltzmann constant
R = data Rate
λ = wave length
S = path length (distance)

$$G \simeq \frac{\pi^2 D^2 \eta}{\lambda^2}$$

Antenna Gain

$$\theta = \frac{21}{f_{GHz} D}$$

3-dB beamwidth
θ in degrees

$$L_s = \left(\frac{\lambda}{4 \pi S} \right)^2$$

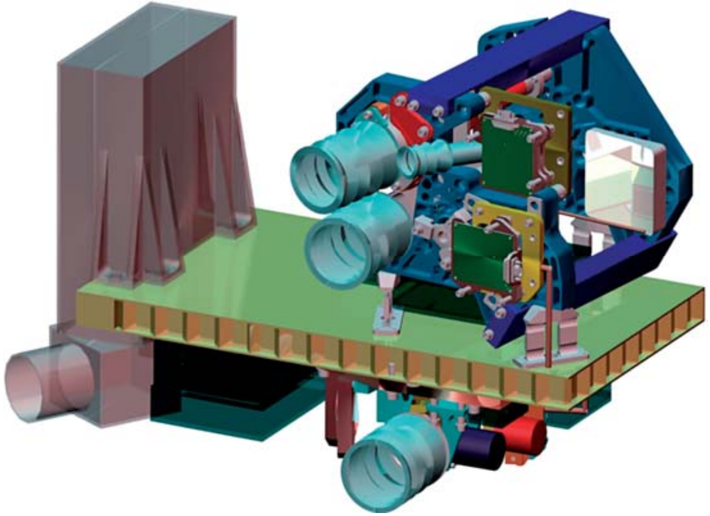
Space loss

Payload & Accommodation

- Science & Measurement requirements drive the Payload Definition

- Specific measurement principles – as discussed in other lectures
  ⇨ drive the instrument selection and s/c design

- Accommodation (all s/c subsystems might be affected):
  - Mass (Launcher, structure, propulsion system, etc…)
  - Power (power, cleanliness, etc.)
  - Data Rate (DHS, TT&C system, ground station, orbit)
  - Pointing requirements (AOCS and configuration, thermal)
  - Thermal ranges (op/non-op), **cooling required? Active / Passive**
  - Deployment needed (covers, baffles, sun shields…)?
  - Operation / commanding (complexity of modes, calibration)
  - EMC
  - Protection against heat/ radiation / stray light etc.



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Operations

- Spacecraft and Instruments need to be controlled from Ground
- Launcher authority takes control until successful launcher insertion orbit and separation from upper/transfer stage

ESA missions:

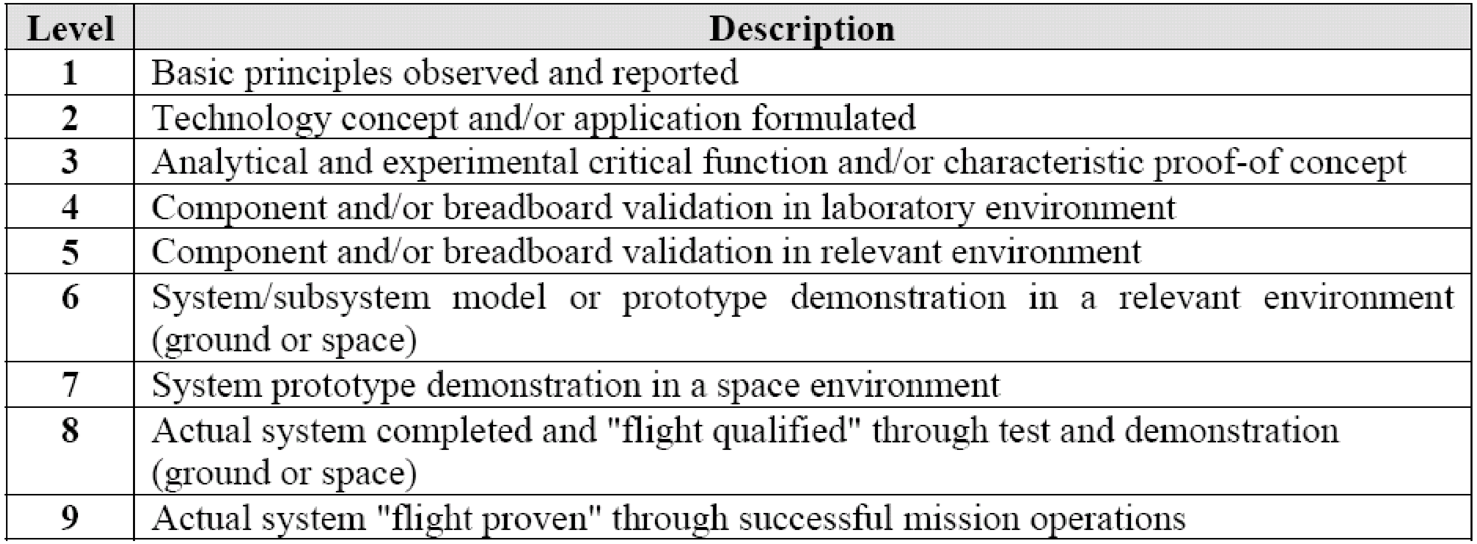
- Mission Operations done by ESOC
  - Navigation and tracking, commissioning, control of s/c, upload of commands, monitoring of health status, planning of manoeuvres etc.
  - Organise download of data for next passes
- Science Operations done by ESAC
  - Instrument control, definition of instrument commands
- Science data distribution centres
  - Distribution of onboard data together with housekeeping to interested scientists
- Definition of observation cycles/modes

☝ Do not underestimate cost of mission operation and data management

Technology Development

- Technology Readiness is a key system driver
- Assessment of efforts required to reach flight status is difficult
- Assessment done according to the table below
- Non availability of Technology can be detrimental to the schedule and cost

Technology Readiness Levels (TRL):



Level	Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
7	System prototype demonstration in a space environment
8	Actual system completed and "flight qualified" through test and demonstration (ground or space)
9	Actual system "flight proven" through successful mission operations

Cost, Risk and Schedule

Cost estimate is very difficult !

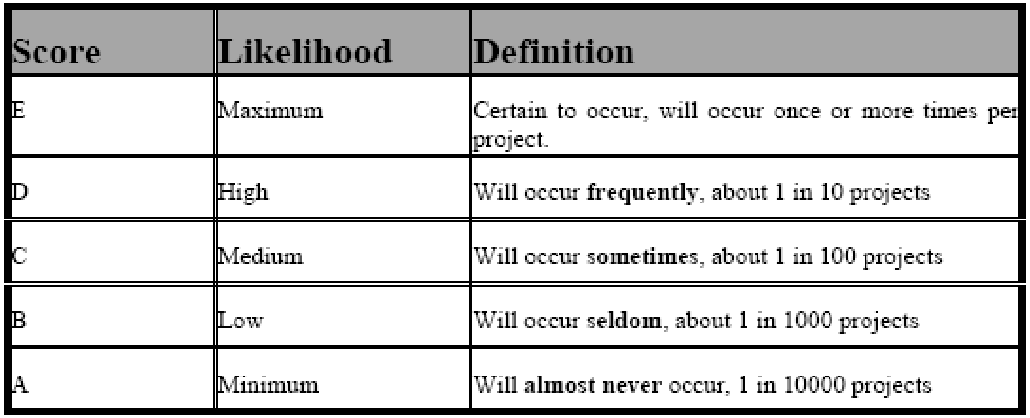
- **3 methods:** Bottom up approach, parametric analysis or by analogy with other missions
- Need cost model and data base with cost info
- Most difficult is the estimate on engineering cost, manpower etc. **cost of technology TRL upgrade**
- Cost is driven by complexity of mission

Cost at completion comprises:

- Development cost
- Procurement cost of the space segment (industrial cost)
- Test facilities cost
- Launch cost
- Mission operation cost
- Science operations cost (Data analysis, distribution and archiving)
- Agency cost and margins
- Management costs
- Payload cost
- …

Risk

- Space missions are large investments
- Understanding and analysis of risk is important to avoid catastrophic events as much as possible
- Identification of risk followed by risk mitigation is the approach
- Make a risk Register with main risks
- Rated with likelihood (1-5) and severity (A-E)



Score	Likelihood	Definition
E	Maximum	Certain to occur, will occur once or more times per project.
D	High	Will occur **frequently**, about 1 in 10 projects
C	Medium	Will occur **sometimes**, about 1 in 100 projects
B	Low	Will occur **seldom**, about 1 in 1000 projects
A	Minimum	Will **almost never** occur, 1 in 10000 projects

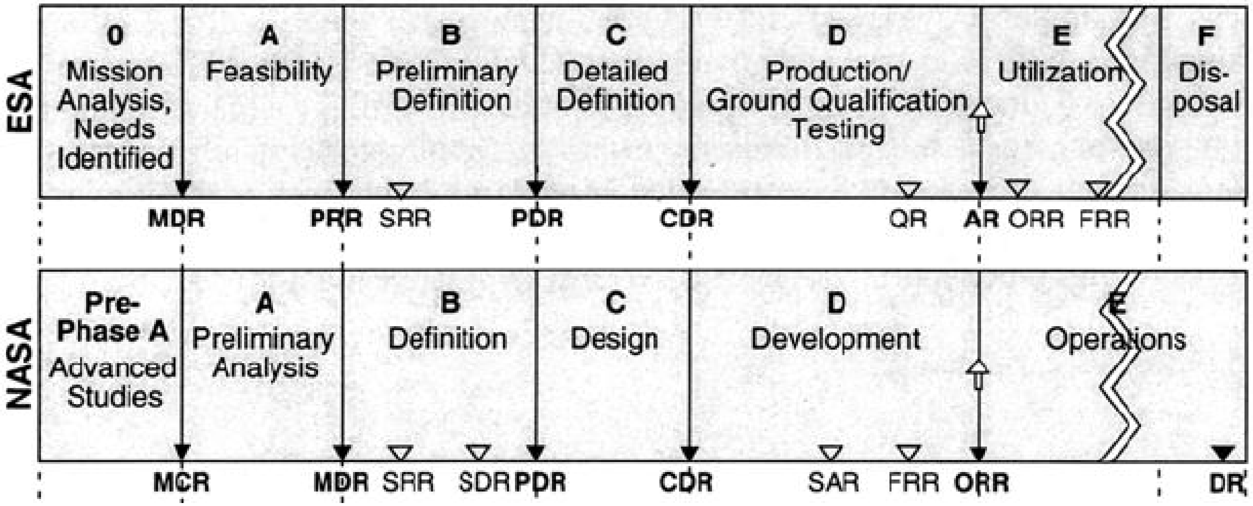
Risk Severity (1-5)

5

1

Severity	Schedule	Science	Technical (ECSS-Q-30 and ECSS-Q-40)	Cost
Catastrophic	Launch opportunity lost	Failure leading to the impossibility of fulfilling the mission's scientific objectives	Safety: Loss of system, launcher or launch facilities. Loss of life, life-threatening or permanently disabling injury or occupational illness; Severe detrimental environmental effects.	Cost increase result in project cancellation
Critical	Launch delayed (TBD) months	Failure results in a major reduction (70-90%) of mission's science return	Dependability: Loss of mission. Safety: Major damage to flight systems, major damage to ground facilities; Major damage to public or private property; Temporarily disabling but not life-threatening injury, or temporary occupational illness; Major detrimental environmental effects.	Critical increase in estimated cost
Major	Launch delayed (TBD) months	Failure results in an important reduction (30-70%) of the mission's science return	Dependability: Major degradation of the system. Safety: Minor injury, minor disability, minor occupational illness. Minor system or environmental damage.	Major increase in estimated cost
Significant	Launch delayed (TBD) months	Failure results in a substantial reduction (<30%) of the mission's science return	Dependability: Minor degradation of system (e.g.: system is still able to control the consequences) Safety: Impact less than minor	Significant increase in estimated cost
Minimum	No/ minimal consequences	No/ minimal consequences.	No/ minimal consequences.	No/ minimal consequences.

Mission Phases



◇	DoD Milestone
▼	Major Review (Control Gate)
▽	Review
⇧	Launch
AR	Acceptance Review
CDR	Critical Design Review
DR	Decommissioning Review
FRR	Flight Readiness Review
MCR	Mission Concept Review
MDR	Mission Definition Review
ORR	Operational Readiness Review
PDR	Preliminary Design Review
PRR	Preliminary Requirements Review
QR	Qualification Review
SAR	System Acceptance Review
SDR	System Definition Review
SRR	System Requirements Review

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