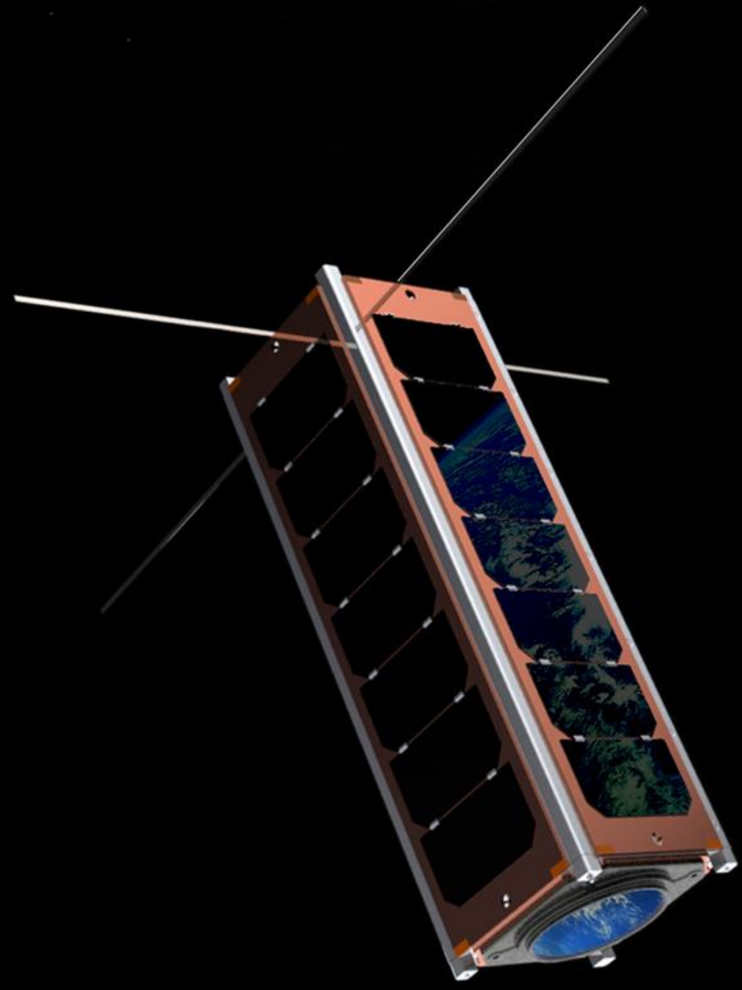

MEA_AM30 Space Technologies/Διαστημικές Τεχνολογίες

Prof V. Lappas, Prof V. Kostopoulos
Email: vlappas@upatras.gr

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ
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Course Content

- **Week 1:** Brief history & context: Background to the development of space, agencies, space history/policy, space economics, funding, future missions – case studies.
- **Week 2:** Introduction to space system design methodology: requirements, trade-off analysis, design specifications, system budgets. Introduction to space system architecture. Launch Vehicles.
- **Week 2:** Space and Spacecraft Environment: Radiation, vacuum, debris, spacecraft charging, material behaviour and outgassing.
- **Week 3:** Orbit Mechanics: celestial mechanics, orbits, trajectory design and spacecraft maneuvers
- **Weeks 4-10:** Spacecraft sub-systems design: **Structure & configuration**; Power, the power budget and solar array and battery sizing; Attitude determination and control; Orbit determination and control; Thermal control.

Basic Mechanical Concepts

- Load (F) - Φορτίο
- Static Loads - Loads (forces) that are constant (or relatively constant)
- Dynamic Loads - Loads that vary with time
- Axial loads - loads that are aligned with the longitudinal (long) axis of a structure – αξονικό φορτίο
- Lateral loads - loads that are orthogonal to the longitudinal axis – πλευρικό φορτίο
- Torsional loads - twisting loads that apply a torque to a structure – φορτίο στρέψης
- Compressive loads - loads that tend to compress (squeeze) a structure –θλιπτικό φορτίο (πίεση)
- Tensile (tension) loads - loads that tend to stretch (Pull) a structure – φορτίο εφελκισμού

Basic Mechanical Concepts

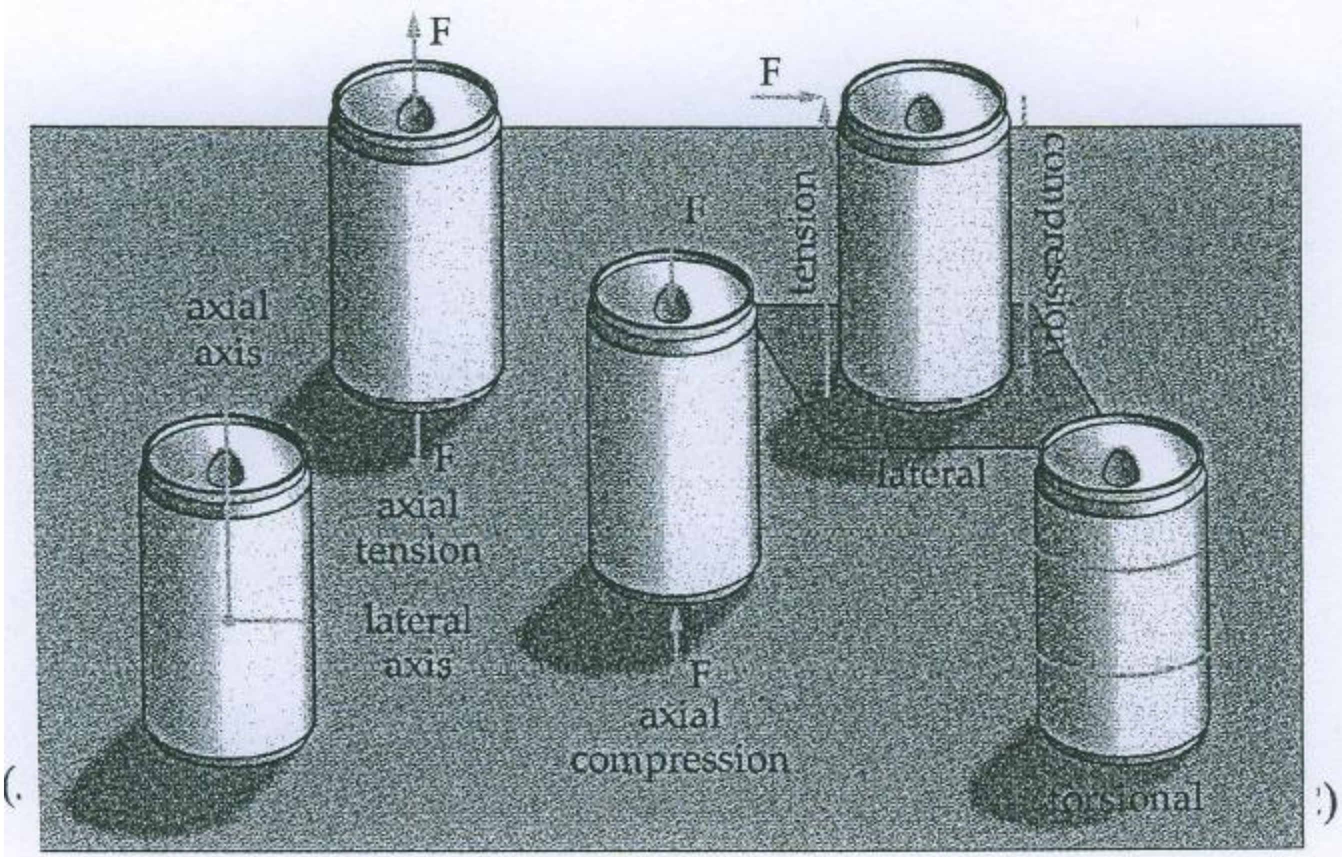


Figure 13-59. Types of Loads. We classify loads on any structure as axial (compression or tension), lateral, or torsional.

Fundamentals

- Bending Moments (M) – ροπή κάμψησσ
- A force, F, applied at some distance, from an attachment point will give a bending moment:

$$M = F\,d$$

- Stress (σ) – Τάση
- Stress = Force per unit Area
- $\sigma = F / A$
- Where σ = stress N/m^2
- F = force N
- A = area m^2

Fundamentals (II)

- Strain (ε) - Καταπόνηση
- Strain = Change in Length / Original Length

$$\varepsilon = \Delta L / L$$

- ε = strain m/m (dimensionless)
- ΔL = change in length m
- L = original length m

Mechanical Concepts

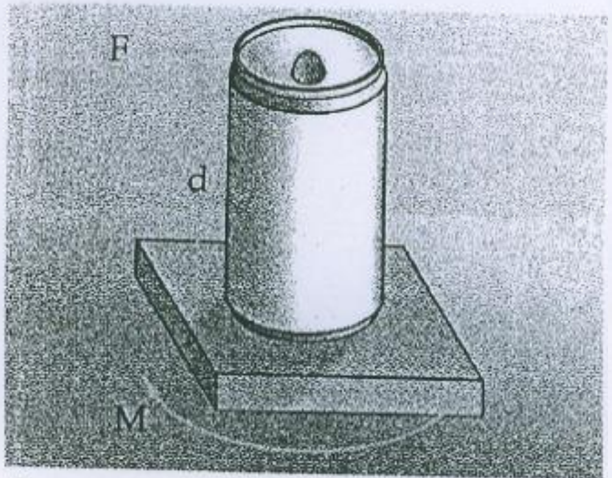


Figure 13-60. Bending Moment. The lateral load applied to the fixed soda can causes a bending moment, M, about the attachment point.

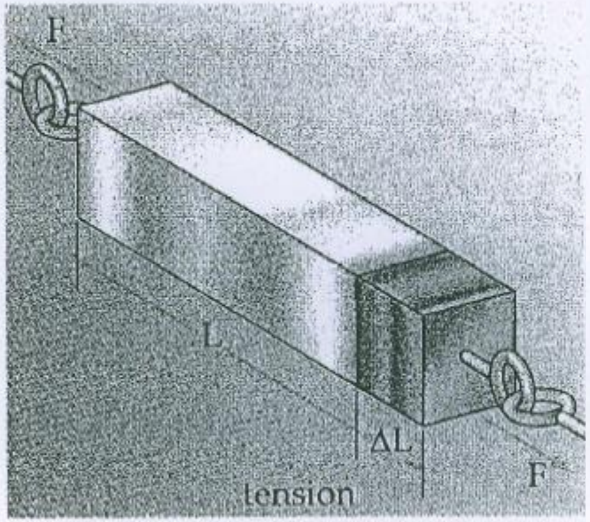


Figure 13-61. Strain. Strain describes how an object changes in length due to stress.

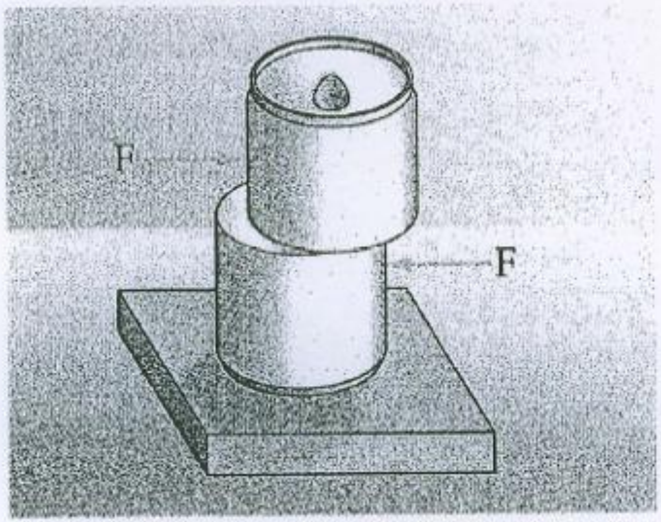


Figure 13-62. Shear. When we apply a transverse load, as shown above, to a structure, the resulting shear causes shear stress. Depending on how they're applied, torsional or axial loads may also cause shear.

Elastic (Young's) Modulus (E)

Young's Modulus = Stress / Strain

$$E = \sigma / \varepsilon \qquad Nm^{-2}$$

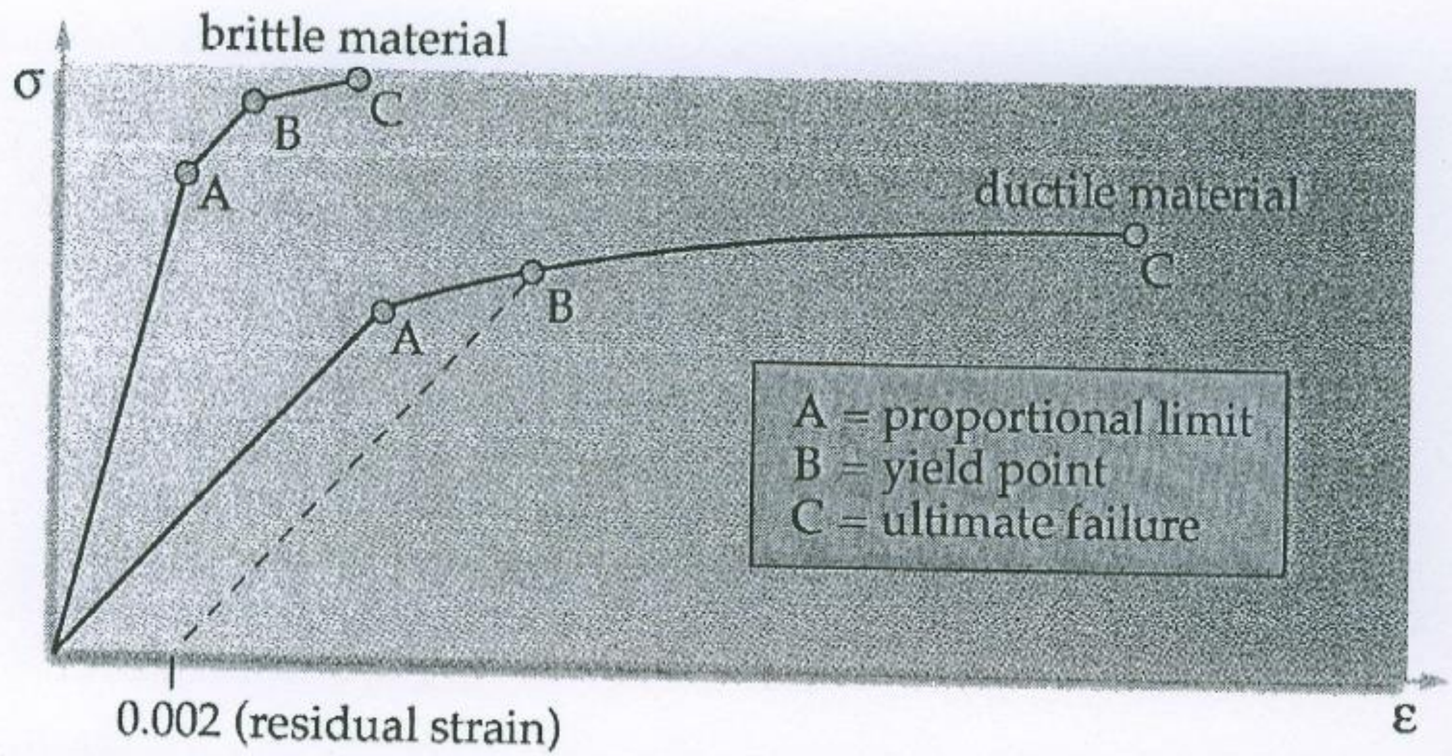


Figure 13-65. Stress-Strain Curves. Typical stress-strain curves show the difference between ductile and brittle materials.

Fundamentals (III)

- Q-Factor:
- The "Amplification" effect of vibrational energy when applied at, or near to, the resonant frequency of a structure.
- Safety Factor:
- The design margin applied to structures to ensure that they remain safe under the effect of the calculated loads - e.g. if the calculated maximum load on a particular structure is F, the structure may be designed to withstand a load of 1.5 F to ensure its safety.

Thermal Expansion (δ)

Material objects tend to expand when heated and contract when cooled.

The amount of expansion (or contraction) depends upon the object's coefficient of thermal expansion, α, its orginal length, L, and the temperature change, ΔT:

$$\delta = \alpha (\Delta T) L$$

where	δ = change in length	m
	α = coefficient of thermal expansion	K^{-1}
	ΔT = temperature change	K
	L = original length	m

Spring (stiffness) Constant (k)

When a tensile (or compressive) force, F, is applied to a spring of stiffness, k, it extends (or is compressed) by an amount x

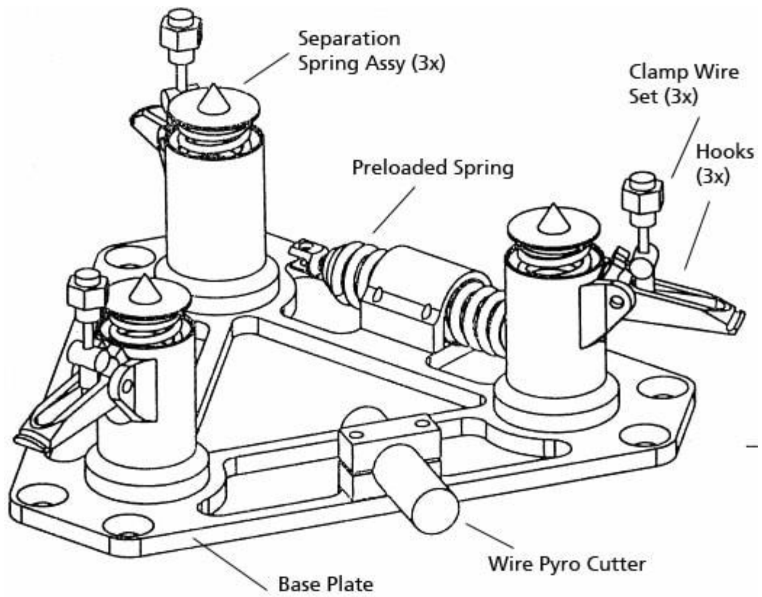
$$\mathbf{k = F / x}$$

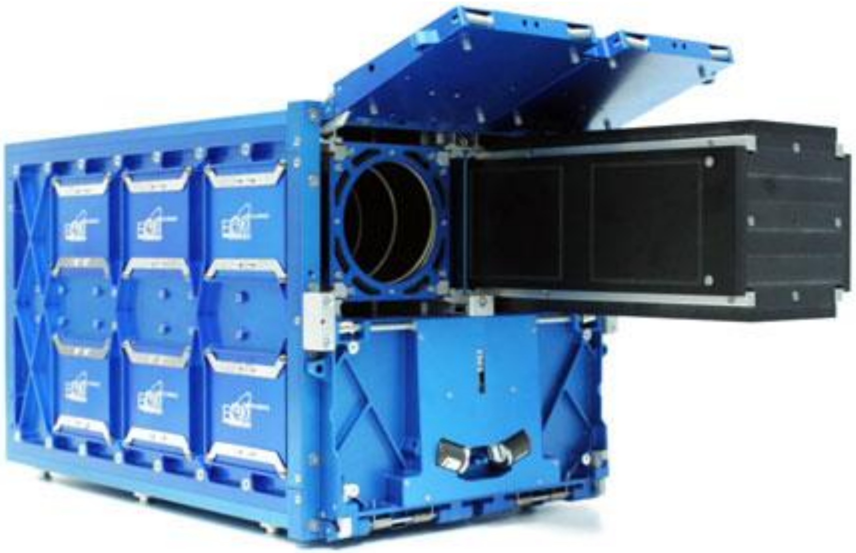
where	k = spring constant	Nm^{-1}
	F = force	N
	x = change in length	m

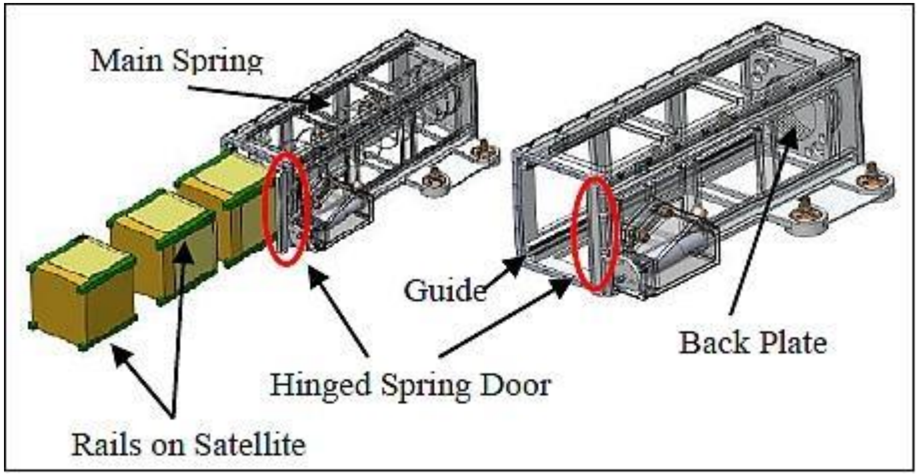
The energy stored in a spring, $\mathbf{E = \frac{1}{2} k x^2}$

Stiffness/Δυσκαμψία

Small Satellite Separation Systems







Fundamental Vibration Frequency (f)

- All objects vibrate at some fundamental natural frequency, f, also know as the resonant frequency:

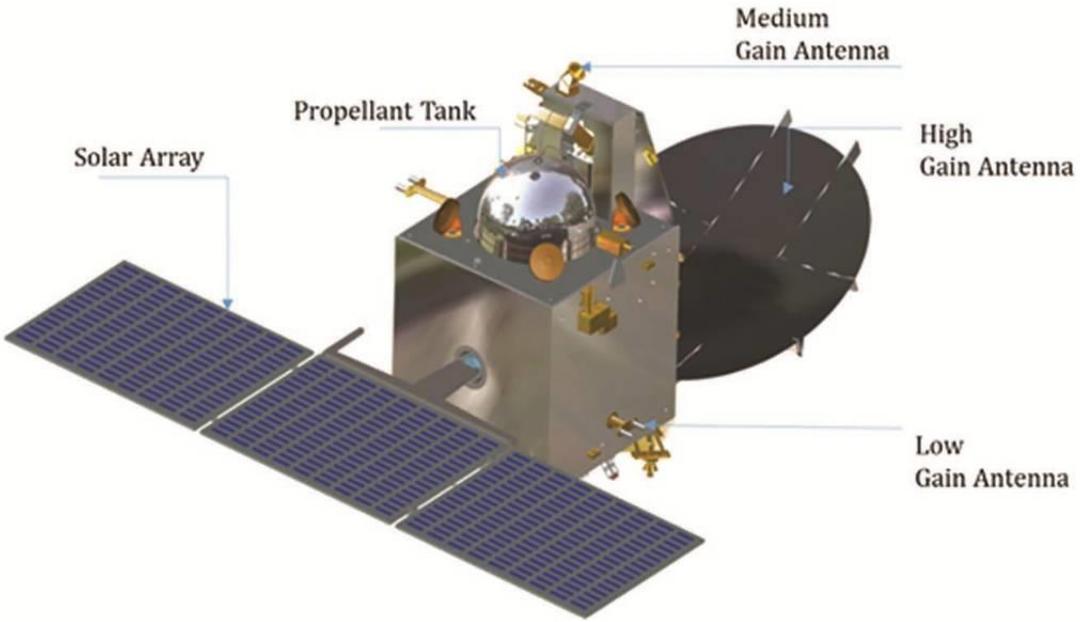
$$f = [1/(2\pi)]\mathrm{sqrt}(k/m)$$

- where f = the resonant frequency Hz
- k = the objects stiffness Nm^{-1}
- m = the objects inertia (mass) kg

Resonant Frequency

- A resonant frequency can be very sharp (we say such a structure has a high Q-factor), or it can be a small spread of frequencies (low Q-factor).
- If an object is forced to vibrate at its natural frequency, the oscillations can become very large -especially if it is a high-Q structure.
- Active or passive damping can limit a structure's response.

Spacecraft Structures

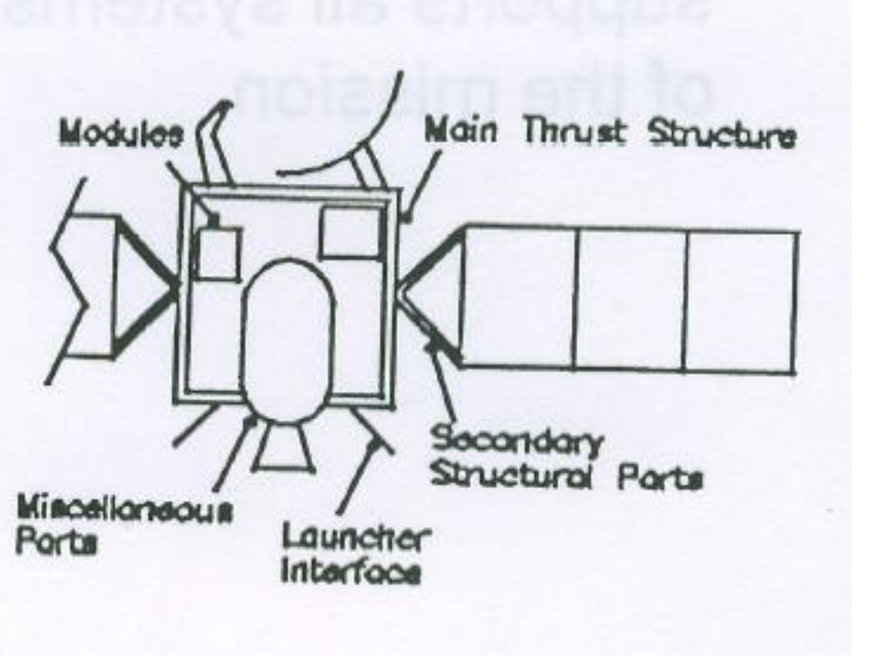


Contents

- General
- Functional requirements
- Structural requirements
- Sample structures
- Design
- Analysis
- Verification

Major Mechanical Parts

- Launcher interface
- Main thrust structure
- Secondary structural parts
- Miscellaneous parts
- Modules



Functional Requirements

- Support for bus and payload modules
- Interface to launch vehicle
- Alignment of units
- Thermal control
- Environmental shielding

Structural Requirements

- Structural loads
- Resonant frequencies
- Inertia Ratio and Axes
- Handling
- Integration
- Accessibility of sub-system

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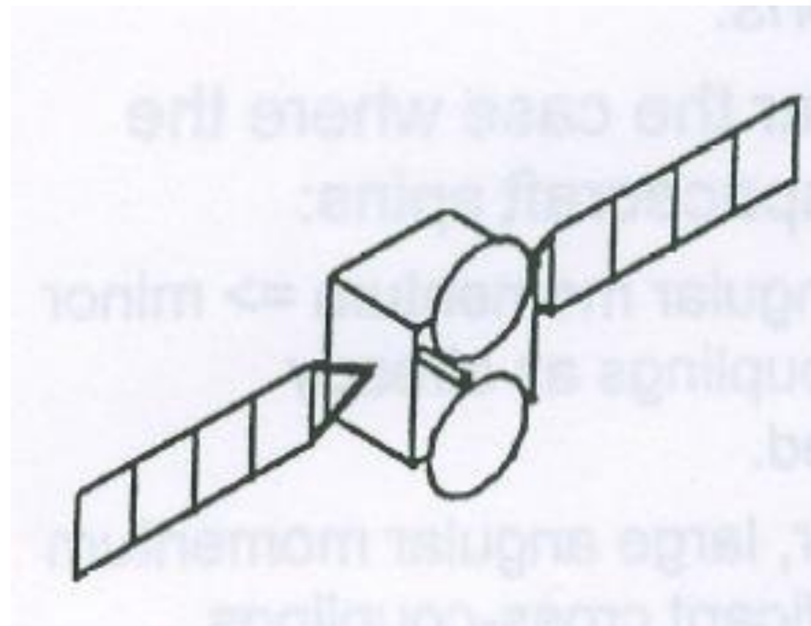
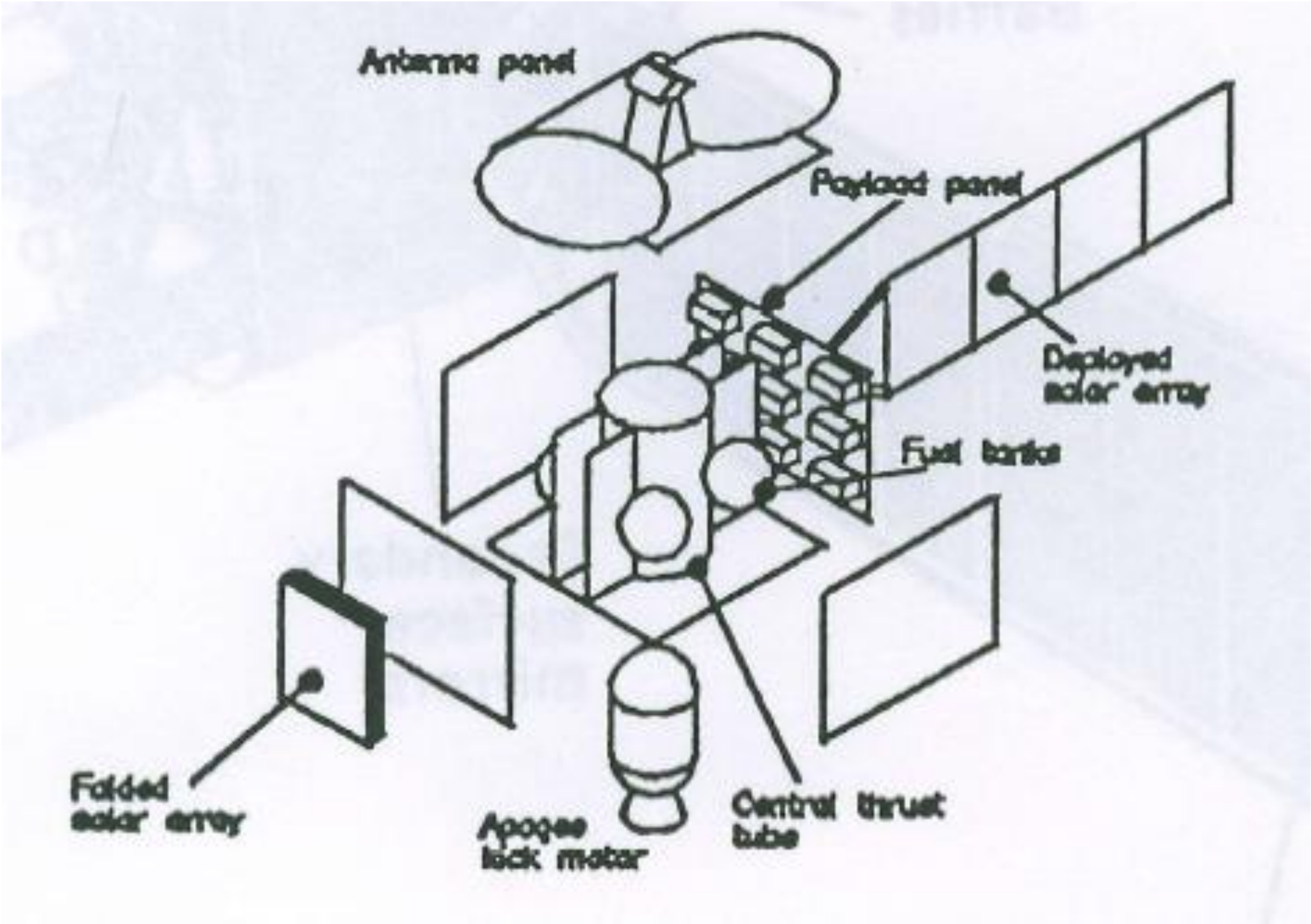
Box Structure

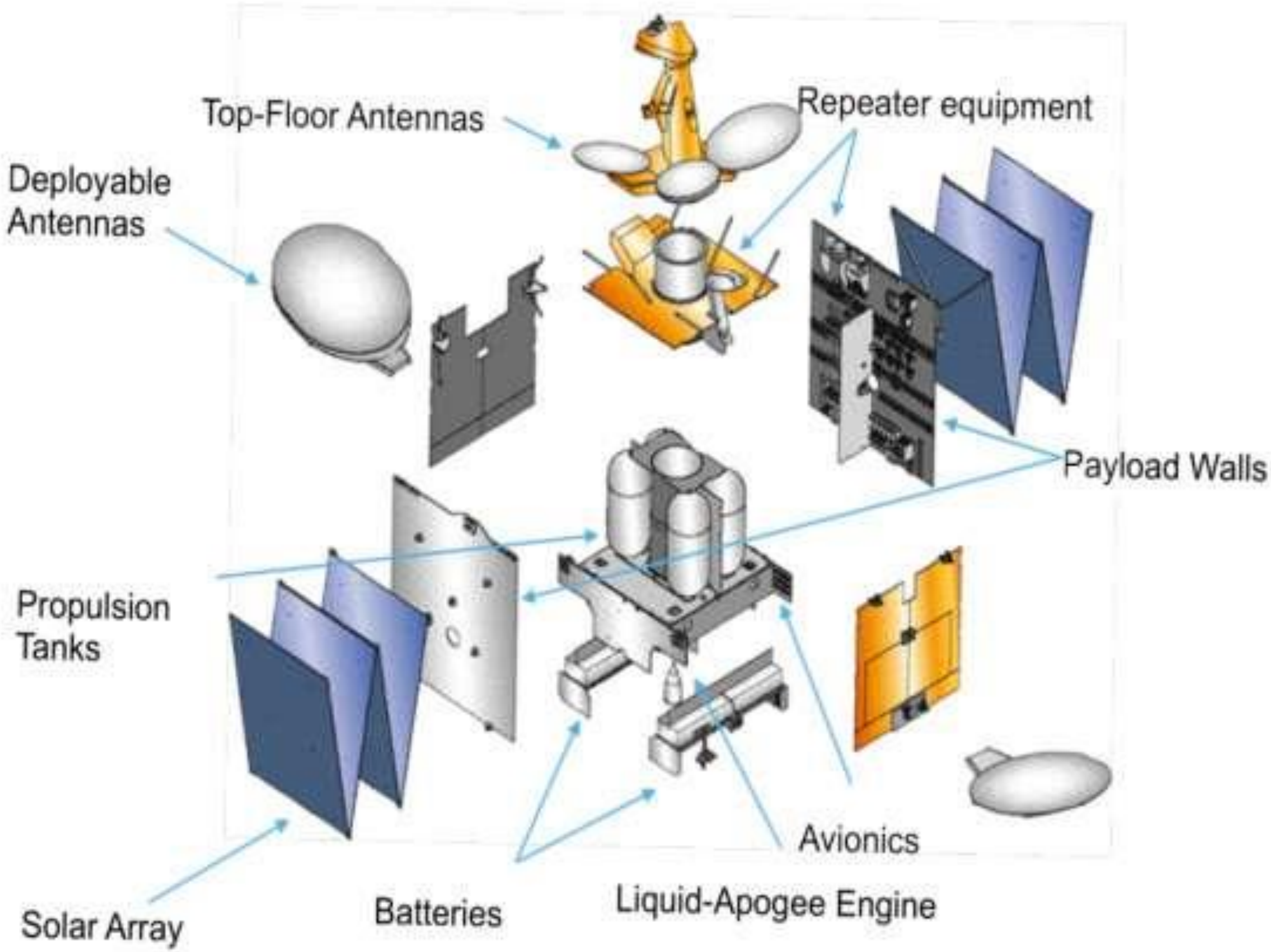
- Cuboid shape
- Structure build round kick motor
- Modules mounted on panels of box
- Tracking solar panels

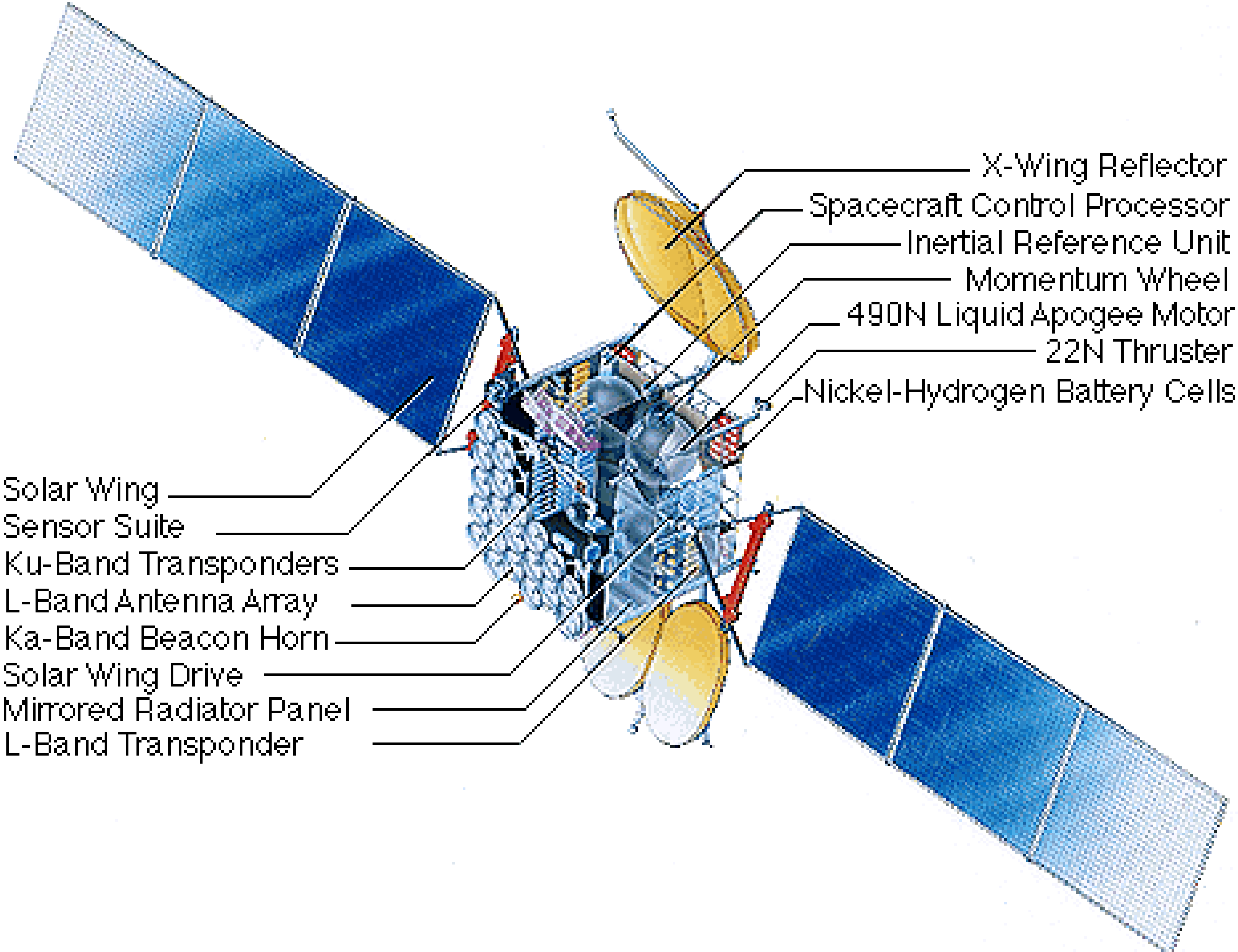


Box Satellite Internal View

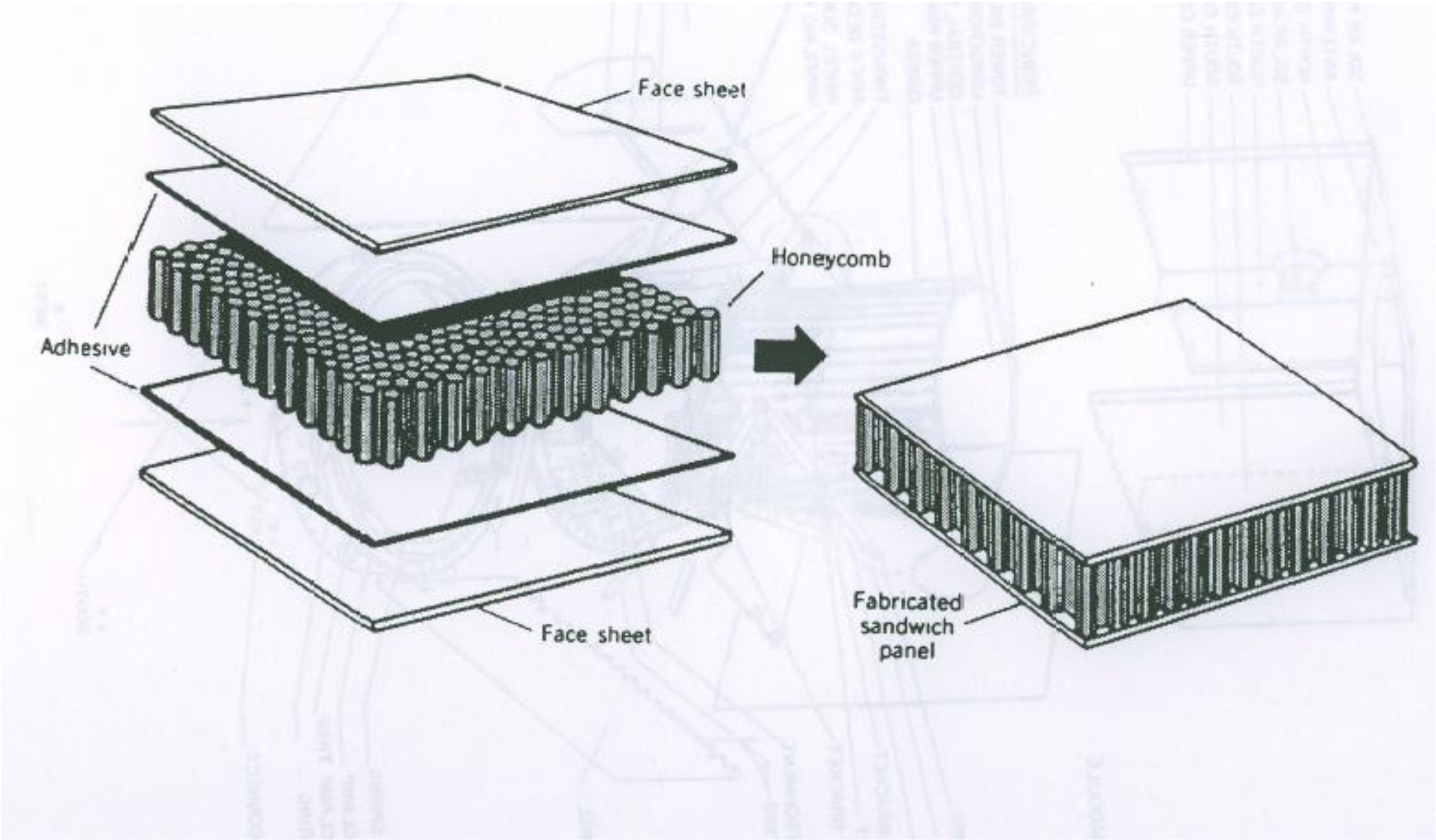


Ανατομία Δορυφόρου



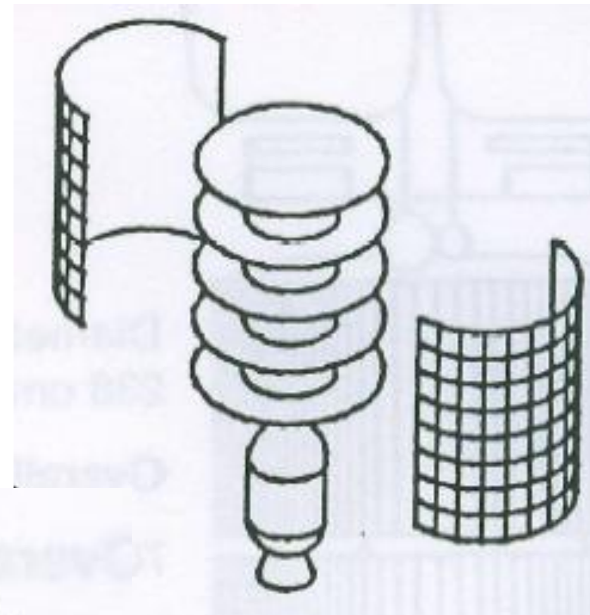

X-Wing Reflector
Spacecraft Control Processor
Inertial Reference Unit
Momentum Wheel
490N Liquid Apogee Motor
22N Thruster
Nickel-Hydrogen Battery Cells
Solar Wing
Sensor Suite
Ku-Band Transponders
L-Band Antenna Array
Ka-Band Beacon Horn
Solar Wing Drive
Mirrored Radiator Panel
L-Band Transponder

Honeycomb Space Structure

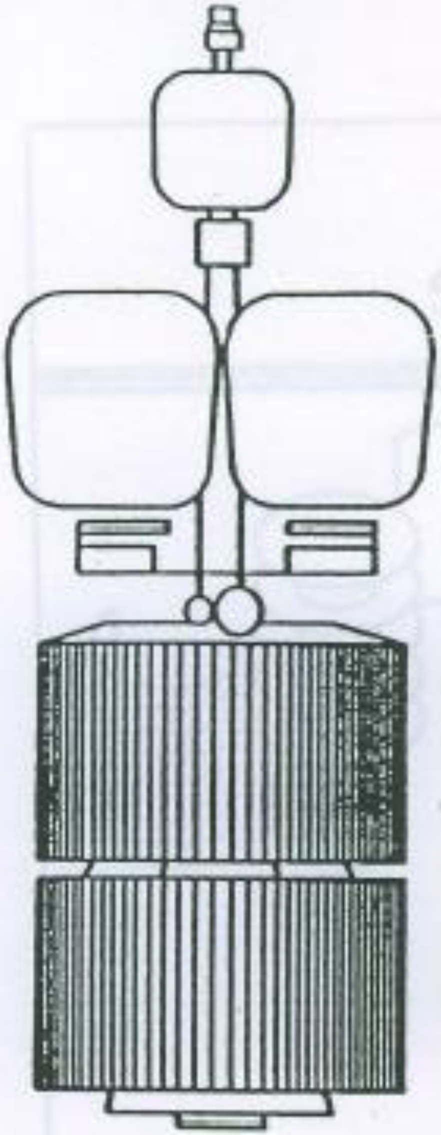


Spinning Satellite

- Cylindrical shape
- De-spun antenna platform
- Trays with equipment stacked



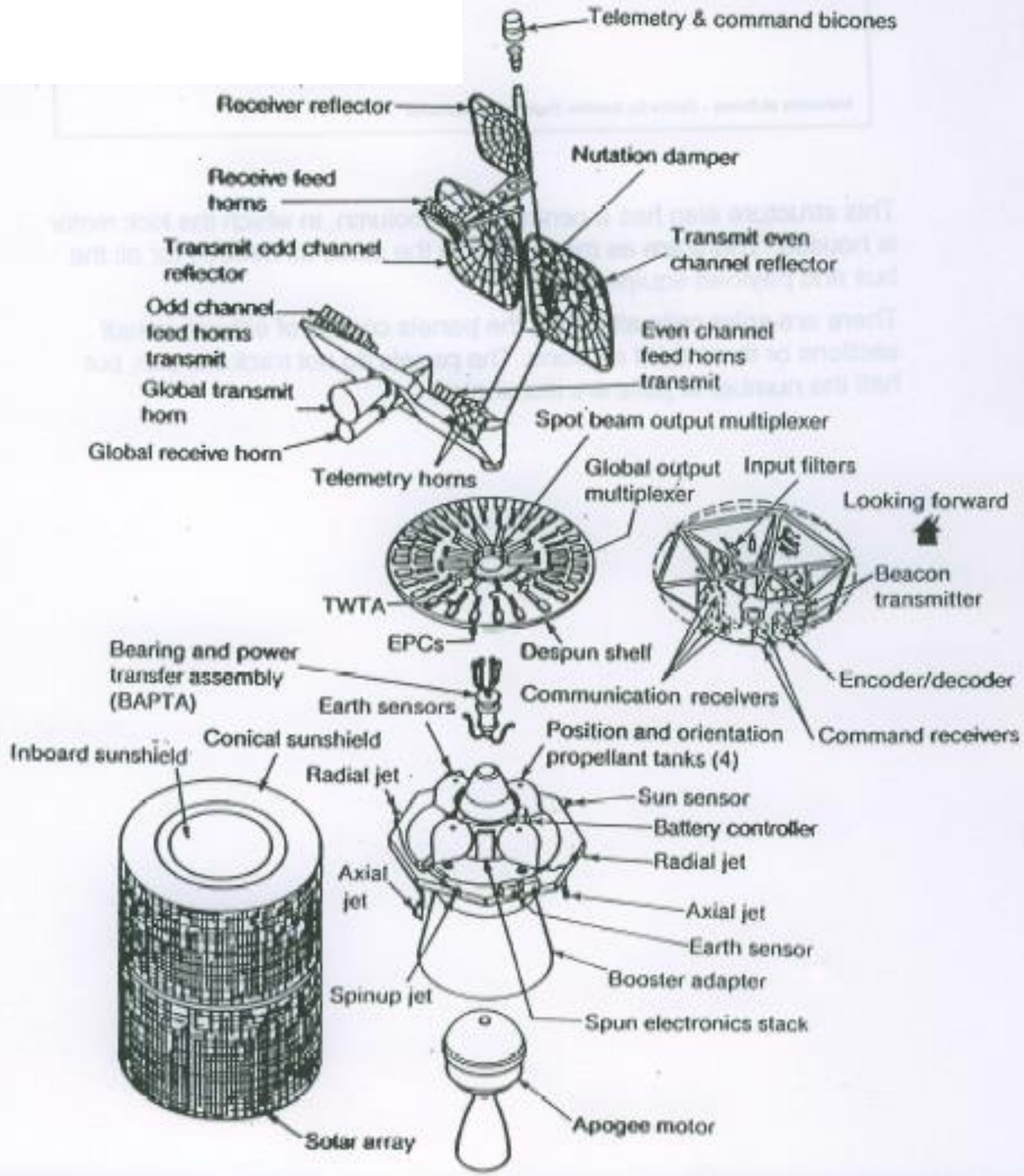
Spinning Satellite Examples

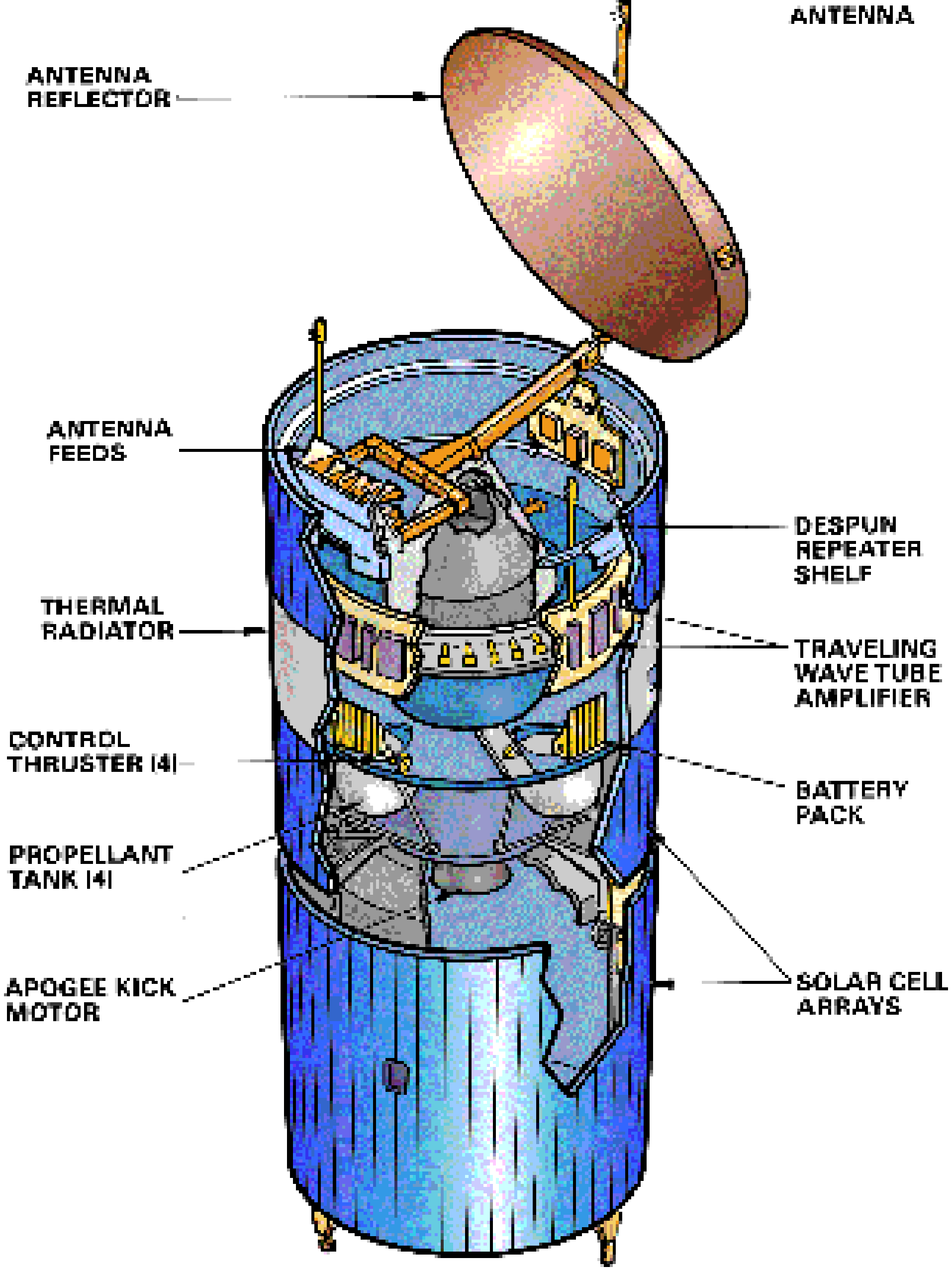


Diameter:
238 cm (93 in.)

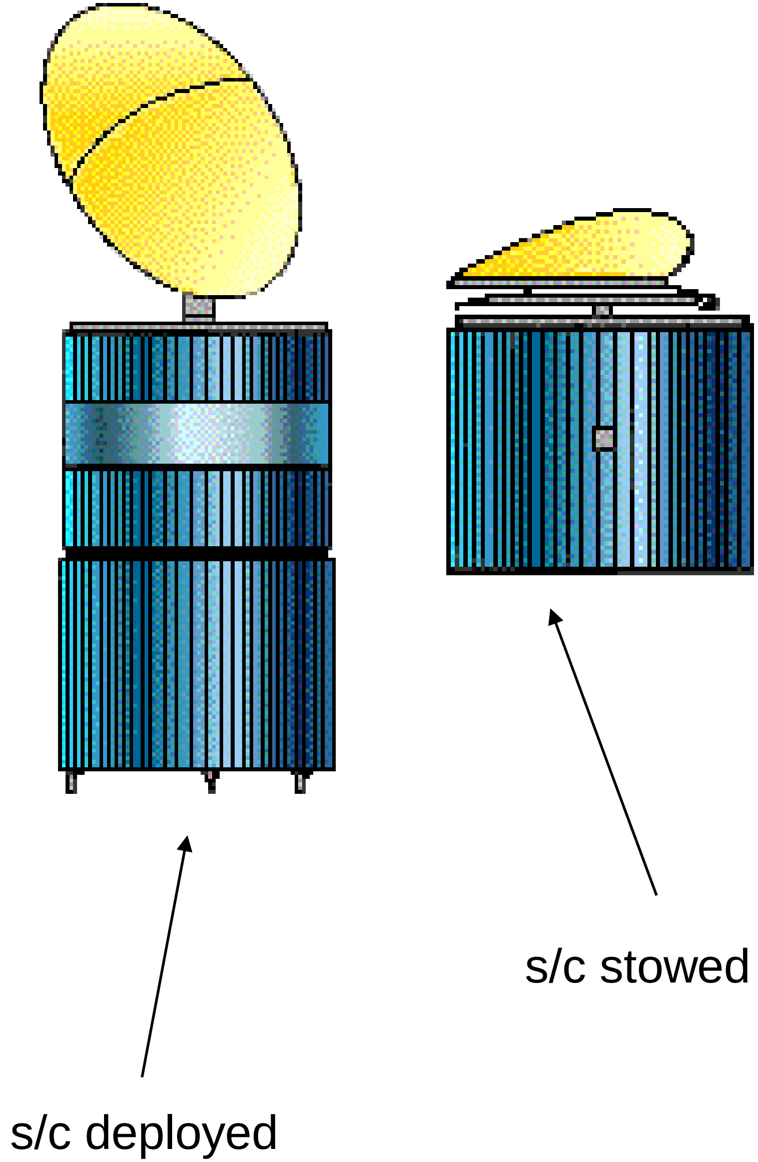
Overall Height:
701 cm (275 in.)

Weight:
785 kg in orbit
(1732 lb)





BOEING 376
SPACECRAFT CONFIGURATION



Example: Hayabusa (JAXA)

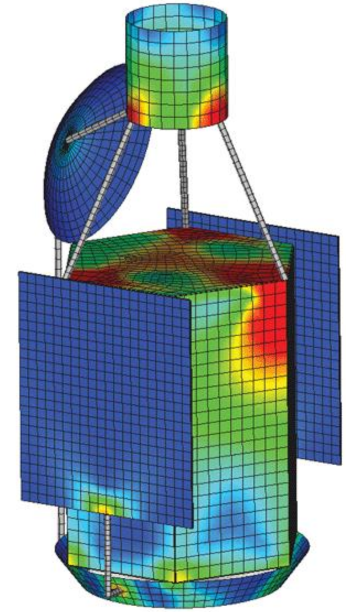
Design

- Iterative process
- Combine functional requirements and environmental constraints
- Design main structure, analyse, optimise
- The design is an iterative process, which has as inputs the mission requirements and the launcher constraints.
- The main structure gets designed, analysed and optimised to meet all the specifications.

Analysis

- Computer aided analysis
- Engineering models
- Coupled load analysis
- The design is analysed using computer models.
- These models have a mathematical description of the structure and parts of the spacecraft.

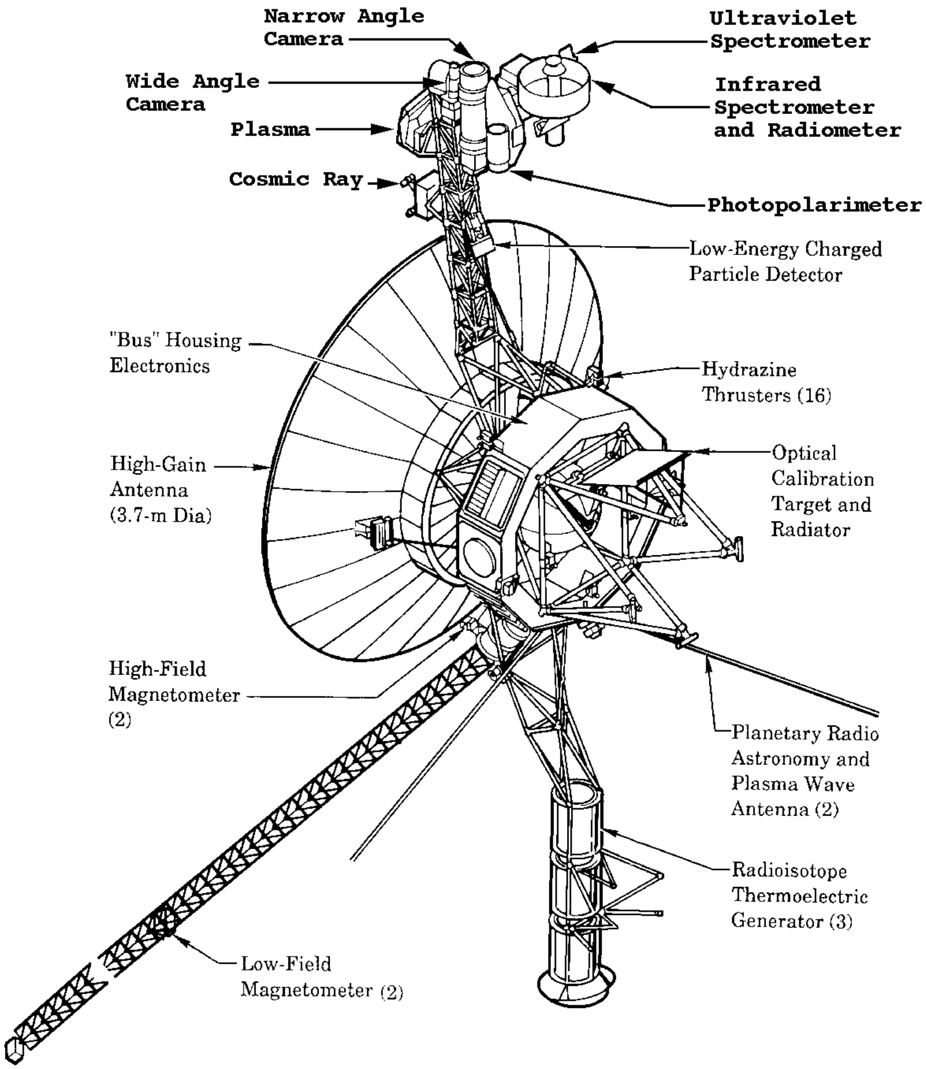
Analysis (III)



- NASTRAN FE Modelling.
- Spacecraft System Structural Dynamics.
- Acoustic Analysis.
- Fracture Mechanics.
- Microvibrations
- Hardware and Test Support

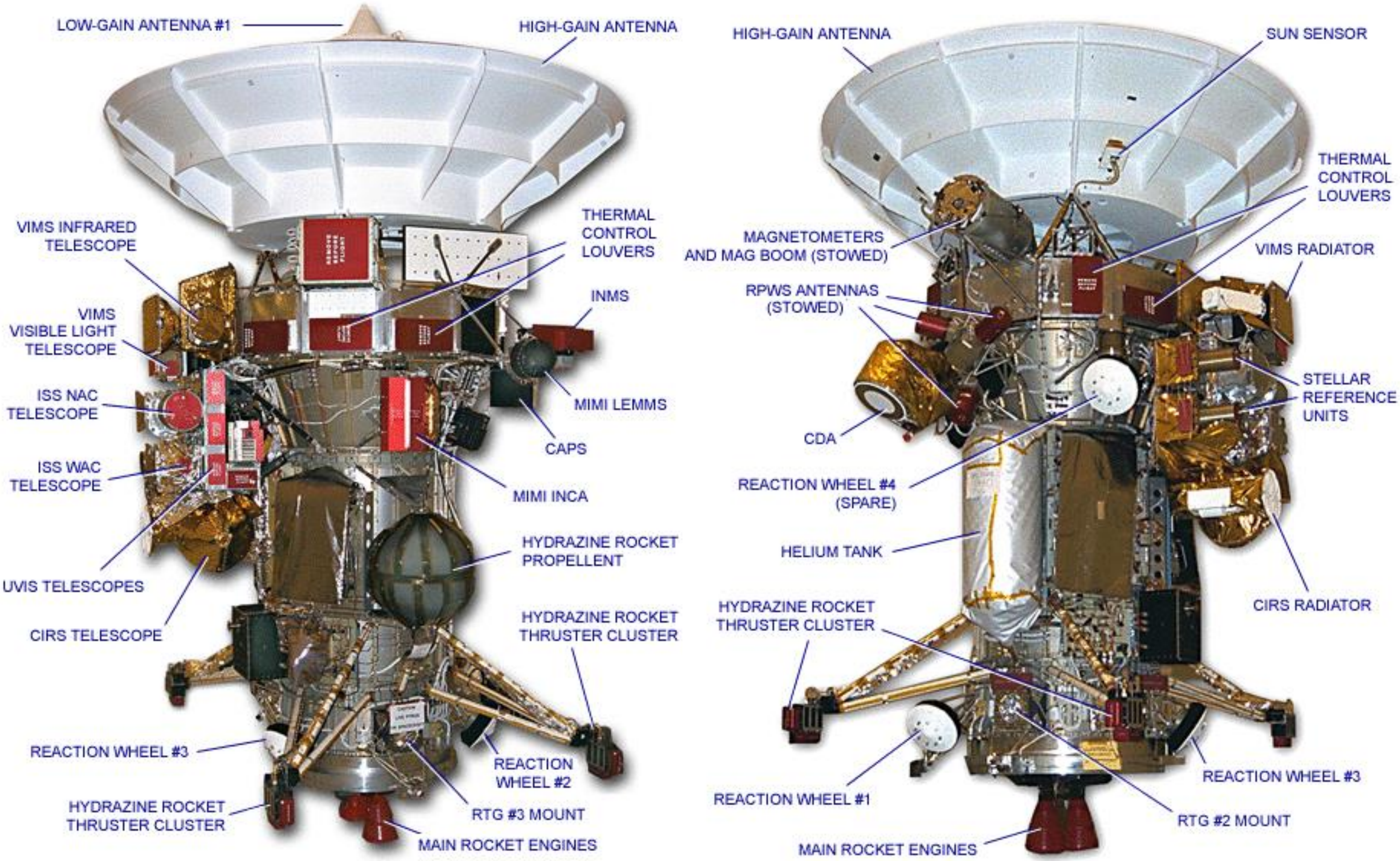
MATRA MARCONI SPACE

Further Satellite Structure Examples

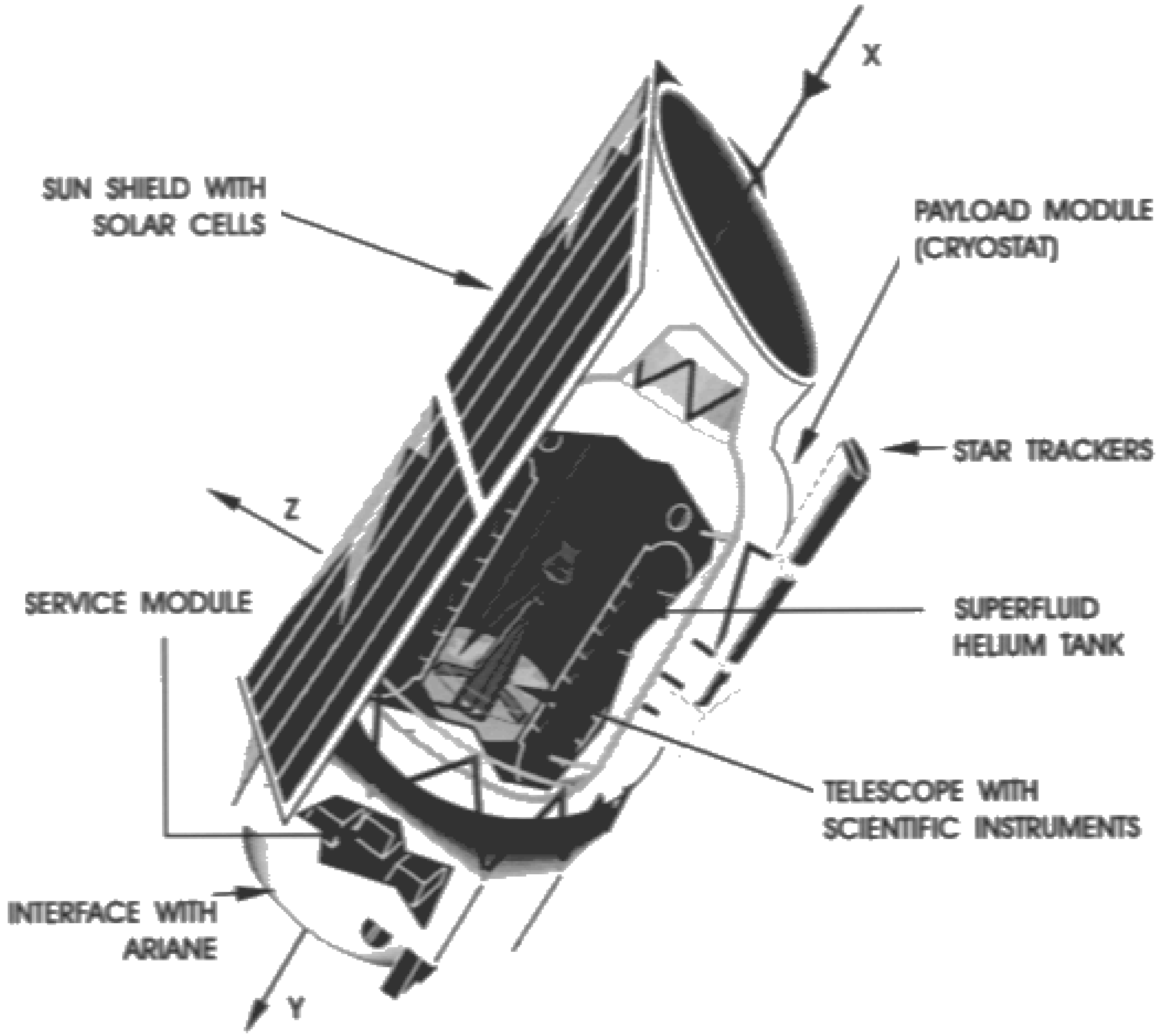


(Spacecraft Shown Without Thermal Blankets for Clarity)

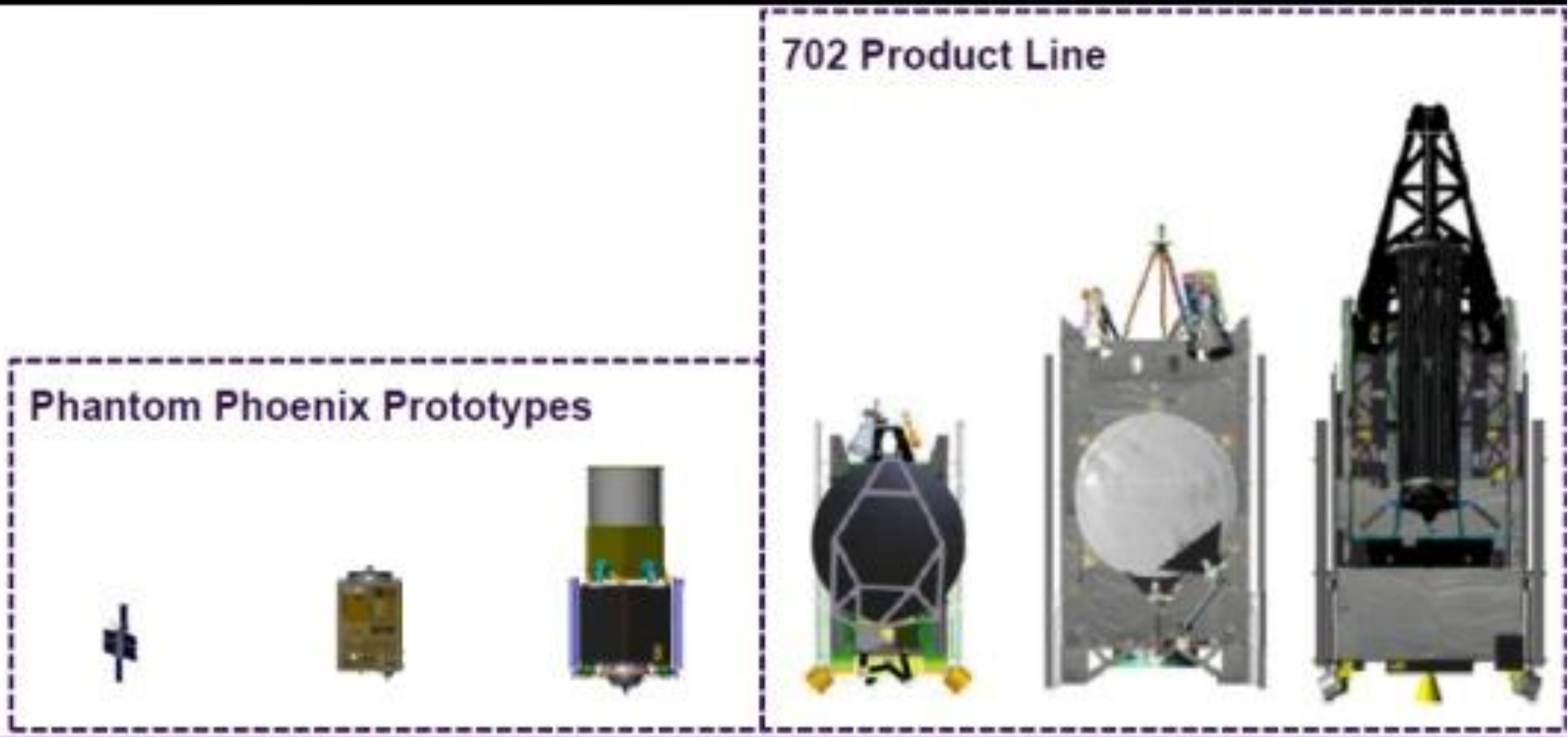
Cassini


LOW-GAIN ANTENNA #1
HIGH-GAIN ANTENNA
VIMS INFRARED TELESCOPE
THERMAL CONTROL LOUVERS
VIMS VISIBLE LIGHT TELESCOPE
INMS
ISS NAC TELESCOPE
MIMI LEMMS
CAPS
ISS WAC TELESCOPE
MIMI INCA
HYDRAZINE ROCKET PROPELLENT
UVIS TELESCOPES
CIRS TELESCOPE
HYDRAZINE ROCKET THRUSTER CLUSTER
REACTION WHEEL #3
REACTION WHEEL #2
HYDRAZINE ROCKET THRUSTER CLUSTER
RTG #3 MOUNT
MAIN ROCKET ENGINES
HIGH-GAIN ANTENNA
SUN SENSOR
THERMAL CONTROL LOUVERS
MAGNETOMETERS AND MAG BOOM (STOWED)
VIMS RADIATOR
RPWS ANTENNAS (STOWED)
STELLAR REFERENCE UNITS
CDA
REACTION WHEEL #4 (SPARE)
HELIUM TANK
CIRS RADIATOR
HYDRAZINE ROCKET THRUSTER CLUSTER
REACTION WHEEL #3
REACTION WHEEL #1
RTG #2 MOUNT
MAIN ROCKET ENGINES

Cryosat


X
SUN SHIELD WITH
SOLAR CELLS
PAYLOAD MODULE
(CRYOSTAT)
STAR TRACKERS
Z
SERVICE MODULE
SUPERFLUID
HELIUM TANK
TELESCOPE WITH
SCIENTIFIC INSTRUMENTS
INTERFACE WITH
ARIANE
Y

Satellite Sizes (Boeing)



Vehicle	Phoenix Nano	Phoenix ESPA	Phoenix	702SP	702MP	702HP
Payload Power (Cont./Peak)	36W /70W	90W /135 W	280W – 700+W	3.5kW – 7.5 kW	6.0kW – 12 kW	8kw – 12+kW
Total SV Mass	4 – 10 kg	180 kg	500 – 1000 kg	1500-2000 kg	5800-6100 kg	5400-5900 kg
Design Life	1 year	1-5 years	7+ years	15+ years	15+ years	15+ years

Verification

- Mechanical confirmation of computer analysis by testing engineering model
- Repeat coupled load analysis with computer model updated with engineering test data.
- Tests on flight model

Mechanical environment

- Satellites are subjected to a wide variety of external influences during their missions.
- They range from Political and technical to Electrical and Mechanical.
- A brief overview of the Mechanical environment is given here.
- This presentation aims to give an understanding of the wide range of mechanical influences on a satellite, from manufacture through launch and orbital operations.

External Environment

- General
- Ground
- Launch
- Space
- The external environment is what nature and technology throw at the satellite.
- The environment breaks down into four major areas: General, Ground, Launch and Space.
- These are sub-divided then into several areas for the description.

General - Design Brief

- Satellite payload requirement
- Launcher allowable mass
- Launcher payload volume
- Launcher interface
- Launcher dynamics

General-Materials

- Magnetic
- Outgassing
- Conductivity
- Strength/Weight ratio
- Corrosion
- Compatibility

Listed in order of decreasing condensed contaminants (CVCM).

Material type	Name	Use	Key	TML (%)	CVCM (%)
Silicone	PCB-Z	White matt paint, conductive		0.6	0.10
Urethane	A 276	White paint		0.99	0.08
	Thermofit RT 876	Wire, insulation sleeve	Th	0.8	0.08
Silicone rubber	Eccoshield SV-R	Conductive seals	E	0.3	0.08
Epoxy	Araldite AV 100 / HV 100	Adhesive	A	1.1	0.07
Grease	Braycote 602	Lubricant	B	0.15	0.06
Epoxy	Stycast 1090 / 9	Potting foam	St	0.55	0.04
PETP	Gude Space DPTH	Harness tape	H	0.5	0.04
Urethane	Aeroglaze Z 306	Black paint	Z	0.92	0.03
Polyester	Scotch 850 Silver	Thermal tape	Sc	0.6	0.03
Epoxy	Scotchweld 1838	Adhesive	Sw	0.65	0.03
Silicone	RTV 566	Sealant, adhesive	R	0.27	0.03
Polyimide	Kapton H	(Thermal) film	K	1.03	0.02
Fluorocarbon	Viton B910	Rubber seals	Vi	0.5	0.02
Polyacetyl	Delrin 550	Plastic parts	D	0.39	0.02
Urethane	Torrseal	Sealing resin	To	1.0	0.015
PETP	Mylar A	(Thermal) film	M	0.25	0.015
Epoxy-Carbon	Cycon C89 / HM-S (40/60)	Structure composite	C	0.6	0.01
Urethane	Solithane 113	Potting resin	So	0.37	0.01
Fluoralkylether	Fomblin Z 25	Lubricating oil	F	0.06	0.01
Polyimide	Vespel SP-3	Machined insulators	Ve	1.08	0
DAP		Connector bodies		0.44	0
PTFE/glass/MoS_2	Duroid 5813	Bearings, composite	Du	0.08	0
Glass, woven	Betacloth	Thermal blanket	W	0.03	0

Ground-Manufacture

- Toxicity
- Availability
- Machinability

General-Integration

- Gravity
- Cleaning
- Shocks and Stress
- Moving
- Access
- Mating and De-mating
- Dust, Humidity, Temperature

Ground Tests

- General Non-mechanical test
- Vibration
- Shock
- Unit deployment
- Mass properties

Launch-Operations

- Shipping
- Mating of Spacecraft, Fairing etc.
- Launcher transport
- Sun, Wind
- LH2, filling

Launch-Shocks

- Booster ignition
- Launcher release
- Stage separation
- Fairing separation
- Other payload separation
- Spacecraft separation

Launch-Accelerations

- Sine
- Acoustic
- Random

Launch-Accelerations-Ariane 4

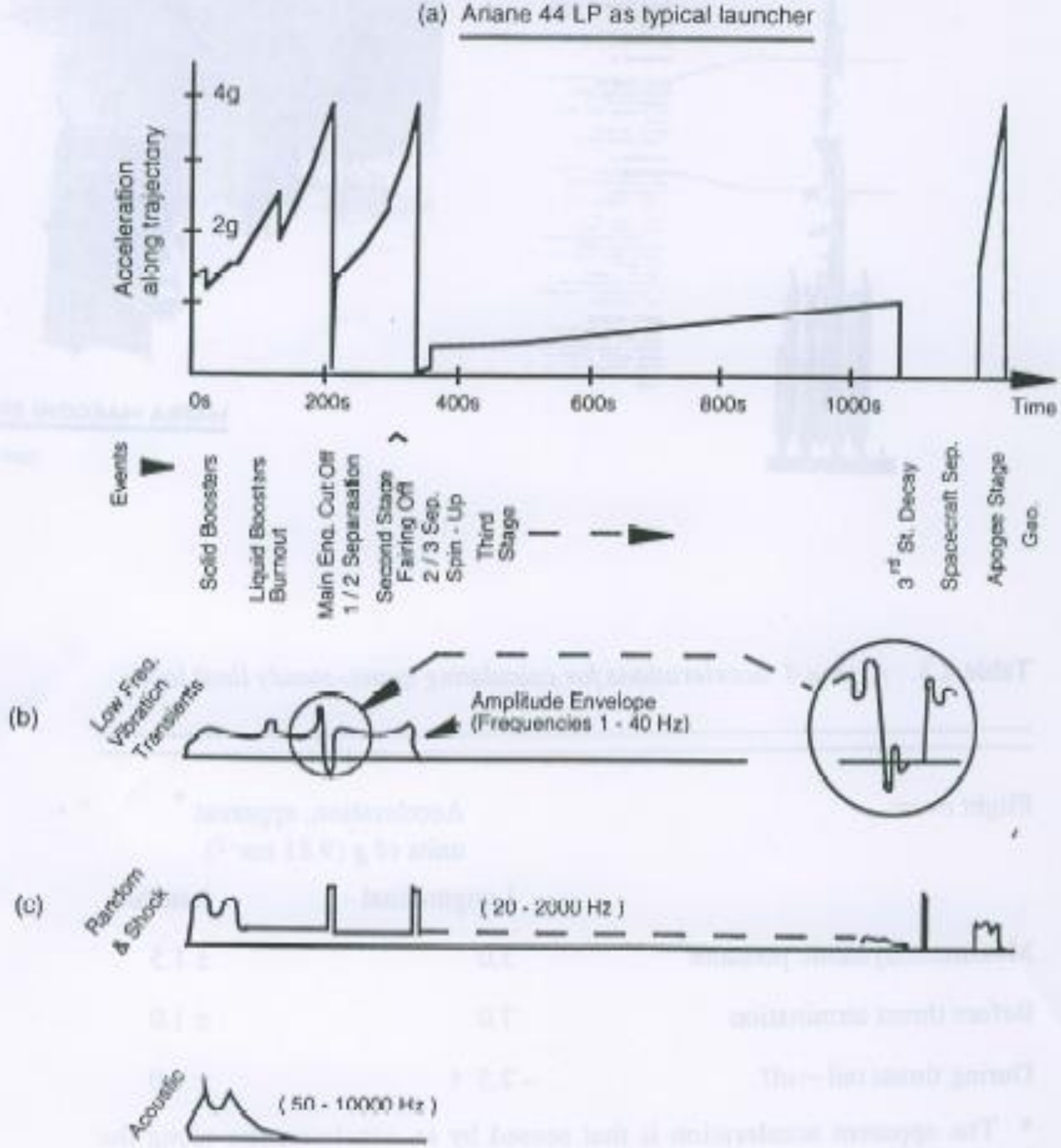
Table 2.3. *Ariane 4 accelerations for calculating quasi–steady limit loads*

Flight event	Acceleration, apparent * units of g ($9.81\ ms^{-2}$)	
	Longitudinal	Lateral
Maximum dynamic pressure	3.0	± 1.5
Before thrust termination	7.0	± 1.0
During thrust tail – off	– 2.5 †	± 1.0

* The apparent acceleration is that sensed by an accelerometer along the longitudinal or lateral axis, and is a component of the vector sum of the true (kinematic) acceleration and the acceleration due to gravity.

† The negative sign denotes a retardation of the spacecraft during a vibration half – cycle in which the launch vehicle is in tension rather than compression.

$g = 9.81\ ms^{-2}$.



(a) Ariane 44 LP as typical launcher
Acceleration along trajectory
4g
2g
0s
200s
400s
600s
800s
1000s
Time
Events
Solid Boosters
Liquid Boosters Burnout
Main Eng. Cut Off 1 / 2 Separation
Second Stage Fairing Off 2 / 3 Sep. Spin - Up
Third Stage
3rd St. Decay
Spacecraft Sep.
Apogee Stage Gao.
(b)
Low Freq. Vibration Transients
Amplitude Envelope (Frequencies 1 - 40 Hz)
(c)
Random & Shock
(20 - 2000 Hz)
Acoustic
(50 - 10000 Hz)

Launch-General

- Thermal shocks
- De-pressurization
- Gas flow
- Thermal radiation

Space - Vibration

- Kick motor burning
- Thruster firing
- Thermal vibrations
- Resonance

Space-Shocks

- Solar panel deployment
- Antenna deployment
- Kick motor ignition

Space-Undesired Forces

- Propellant valve operation
- Solar panel and Antenna trackers
- Propellant sloshing
- Tank stress
- Centrifugal forces
- Tape recorders
- Non-vented enclosures

Space-External

- Meteorites
- Solar pressure
- Radiation
- Gas
- Atomic oxygen

Space-External (III)

- Solar radiation puts a force on the satellite.
- Radiation can cause materials to degrade and lose strength.
- Free flowing gas molecules hitting the surfaces at 7 km/s put force on the satellite, causing orbit drift and attitude changes.
- Atomic oxygen is very corrosive, and can disintegrate structural parts of the satellite.

Space-Desired Forces

- Thrusters
- Magnetorquers
- Gravity Gradient
- Centrifugal force
- Momentum wheels
- Reaction wheels

Summary

- Each phase in a spacecraft project has its own specific environment.
- The influence of all the environmental factors must be taken into account at the design and development stage to ensure the satellite can fulfill its mission
- Because often the requirements for the different mission phases are contradictory, it is imperative that the all phases are fully understood before the detailed design process is started
- Only then will it be possible to achieve the correct compromises required for a successful design of the satellite.

Structures Problem (a)

(a) A University group designs a 1.0 kg pico-satellite that has to be deployed at a velocity of 0.3 m s^{-1} relative to the launch vehicle to which it is attached. This separation velocity is to be achieved by a spring, which can be compressed by 2.5 cm.

(i) Assuming that all the energy in the compressed spring is converted to kinetic energy of the satellite, calculate the "stiffness" of the spring (i.e. the spring constant, k) required.

(ii) If the spring is misaligned slightly such that its line of force acts through a point 1 mm displaced from the centre of mass of the spacecraft, calculate the average force and the resulting average torque acting on the satellite.

(iii) Given that the satellite has a moment of inertia of 6.0 x 10^{-4} kg m^2 about the appropriate axis, calculate the satellite's tumble rate upon separation (in revolutions per minute), and comment on need for accurately aligning the spring.

Structures Problem (b)

(b) The pico-satellite has six fixed, deployed solar panels, each with a mass of 20 g.

(i) Assuming that the panels have a stiffness constant, k = 1000 Nm^{-1}, calculate their resonant frequency and comment, with reasons, on whether or not they are likely to be damaged by the vibrations of launch.

(ii) The panels are made from aluminium, and are 8.5 cm long. Given that, once in orbit, the temperature of the panels varies from –60 ^{o}C to +30 ^{o}C, calculate the change in length due to thermal expansion.

Data: Thermal expansion coefficient of aluminium, $\alpha = 2.3 \times 10^{-5}\ K^{-1}$

(iii) Given that the aluminium panel has a much higher thermal expansion coefficient than that for the solar cells mounted on it, explain how the stress associated with this change is length can be relieved.

Structures Problem Solution (a)

(i) The KE of the separated satellite = $0.5\ mv^2 = 0.5 \times 1 \times 0.3^2 = 0.045$ J
Energy stored in the spring = $0.5\ k\ x^2$
Thus, equating these $k = 0.09/\ 0.025^2 = 144\ Nm^{-1}$

(ii) Force = Energy/distance moved = 0.045/ 0.025 = 1.8 N (not 3.6 N) (Another argument is that F= 3.6 N at start of push and zero at the end, so the average push is 1.8N).

Torque = F x displacement from CoM = $1.8 \times 1 \times 10^{-3}$ = 1.8×10^{-3} Nm

(iii) $T = I\ d\omega/dt \Rightarrow d\omega/dt = T/I = 1.8 \times 10^{-3}/6 \times 10^{-4} = 3\ rad\ s^{-2}$
This angular acceleration lasts for 2s/v = 2 x 0.025 / 0.3 = 0.167 s
But $\Delta\omega = d\omega/dt \times \Delta t$, $\Rightarrow \omega = 3 \times 0.167 = 0.5\ rad\ s^{-1}$
$= 0.5 \times (180/\pi) \times 60 / 360 =$ 4.77 rpm

A small alignment error can give a large tumble rate!

Structures Problem (b)

(i) Natural frequency = $(1/2\pi)$ sqrt (k/m) = $(1/2\pi)$ sqrt $(1000/20 \times 10^{-3})$
f = 35.6 Hz.

There is significant energy associated with launch vibration-frequencies in the few 10's of Hz range, so there is a potential problem.

(ii) For the aluminium:

$\delta = \alpha\ (\Delta T)\ L_{initial} = 23 \times 10^{-6}\ (90) \times 8.5 \times 10^{-2} = 1.76 \times 10^{-4}$ m

(iii) The glue that holds the cell to the panel has some give in it. This relieves the stress.