Spacecraft mechanical systems

by

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Spacecraft Mechanical Systems learning outcomes

1. Configuration
   - Define and list drivers
2. Structure
   - Define difference bet. primary and secondary structure
   - Consider design constraints
   - List load sources
   - List materials used on satellites and their applications
   - Explain modelling and testing philosophy
3. Mechanisms
   - List types of mechanisms (one shot, continuous)
   - Know design constraints

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These are the learning objectives for this lecture. Mechanical systems comprises configuration, structures and mechanisms. If you go into the mechanical design department in spacecraft industry there will be mechanical systems, structures, thermal, propulsion and mechanisms departments.

Mechanical systems links

- Orbit drives launcher choice which determines configuration and structure
- Comms drives size of antenna which may determine configuration
- Thermal can affect position and size of radiator and CTE's affect material choice
- Payload determines configuration and structure
- Power determines whether deployable solar arrays are needed (mechanisms)

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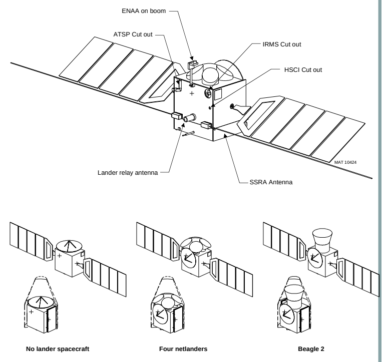
These are the links between the mechanical subsystem and the other subsystems in order for you to be able to link them up together. This is important when considering the design of a full spacecraft.

CTE=coefficient of thermal expansion.

1. Configuration

- Configuration = arrangement = architecture
- Answer: a GA

Example of Mars Express mission and launch configuration sketches



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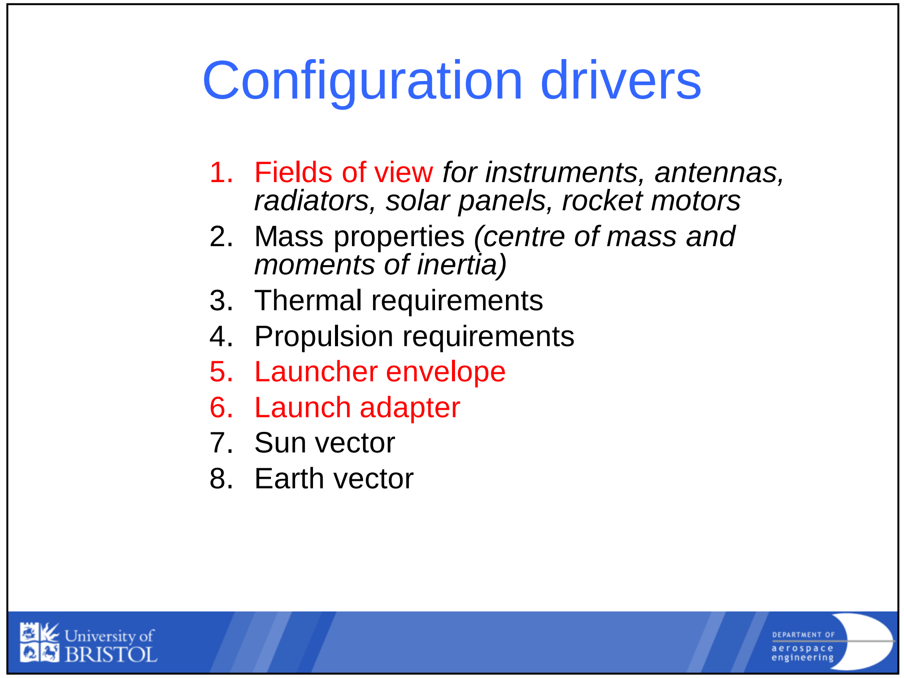
Configuration is the arrangement of the spacecraft. In french: ‘architecture’ ie: what equipment you include on the spacecraft and where you locate it. The answer to the question “what is the configuration of the spacecraft?” is given via a general arrangement drawing. There are 2 types of GA’s provided, the mission and the launch configuration ie: deployed and stowed.



Pointing and Fields of view - for instruments, antennas, radiators, solar panels, rocket motors

Mass properties – the centre of mass has to be within a few cm of the centreline of the launcher and moments of inertia are also closely controlled

Thermal requirements – is a thermal shield required, how can we keep the electronics and fuel tanks warm?

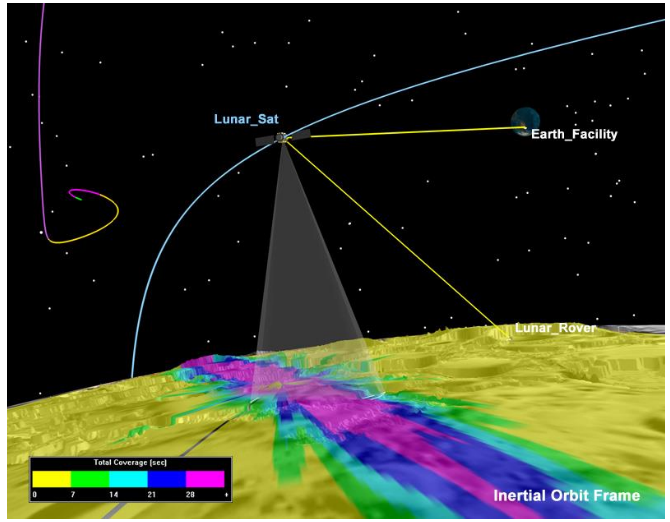
Propulsion requirements – location of thrusters and engine

Launcher envelope – the diameter of the launcher limits the size of the undeployed spacecraft

Sun vector – solar panels will need to see Sun, should they be tracking it? In which case they need to rotate.

Earth vector – the spacecraft will need to communicate with the Earth

1. Fields of view



Example of FoVs: this lunar orbiter has FoVs to Moon, rover and Earth

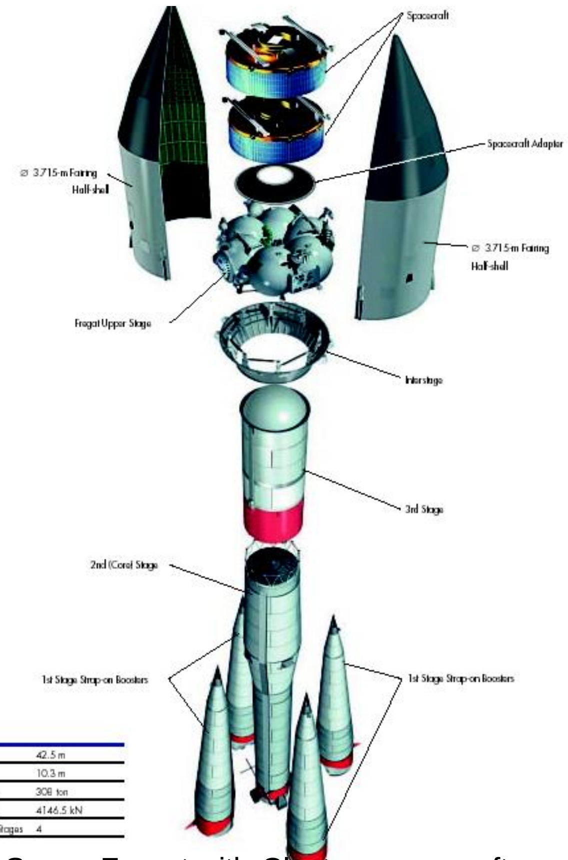
Fields of view will limit where certain items of equipment and payload can be positioned on the spacecraft ie: the configuration. Sometimes it is not possible to fulfil all the FoVs at the same time.

5. Launcher envelope

Payload fairing:

3.5 to 4.5m dia.

Why is the design envelope smaller than the space inside the fairing?



Soyuz	
Length	42.5 m
Diameter	10.3 m
Liftoff Mass	308 ton
Liftoff Thrust	4146.5 kN
Number of Stages	4

Soyuz-Fregat with Cluster spacecraft

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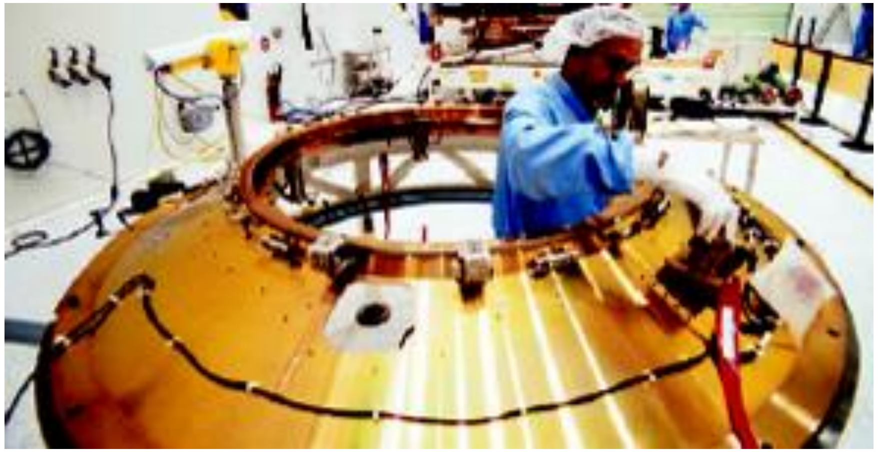
Here we see the Soyuz Fregat rocket with 2 Cluster spacecraft mounted. Note the Fregat upper stage and the LVA (launch vehicle adaptor) or ‘spacecraft adaptor’.

Why is the envelope smaller than the shape of the fairing? Dynamics of launch mean that vibration causes spacecraft to move and so envelope is smaller.

6. Launch adapter

Launch Vehicle Adapter (LVA) forms mechanical and electrical junction between spacecraft and launcher.



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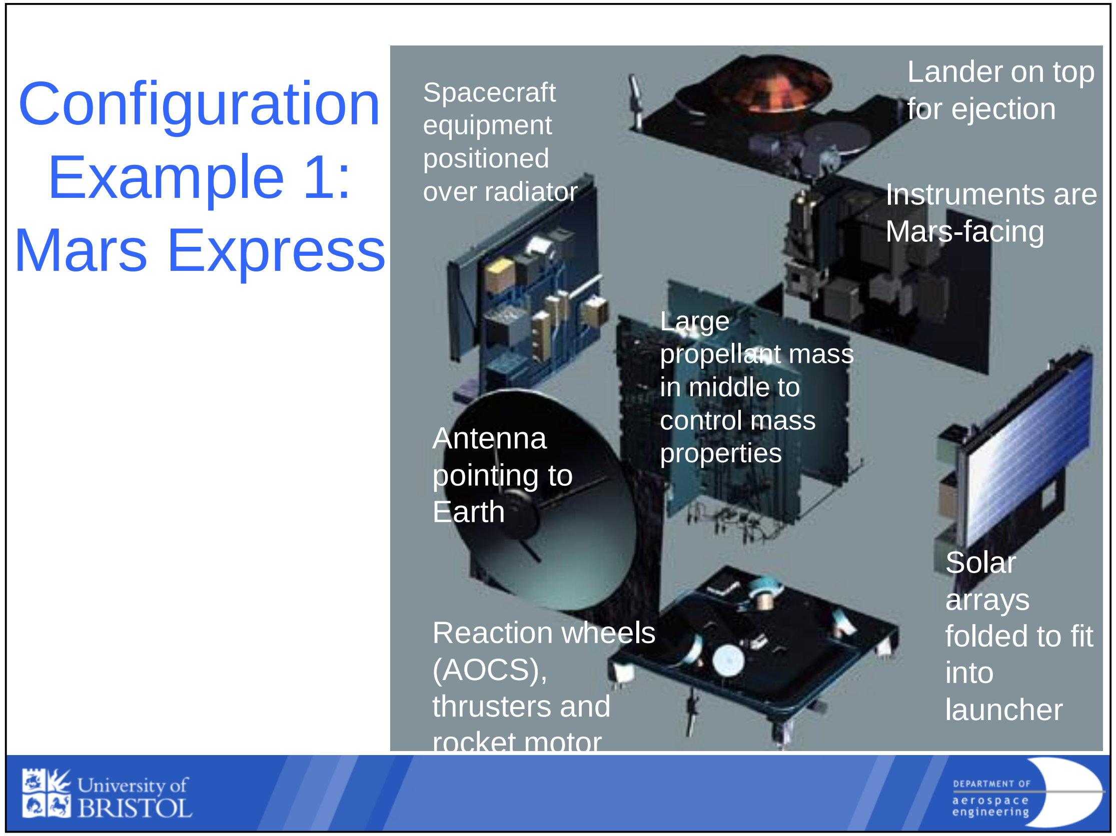
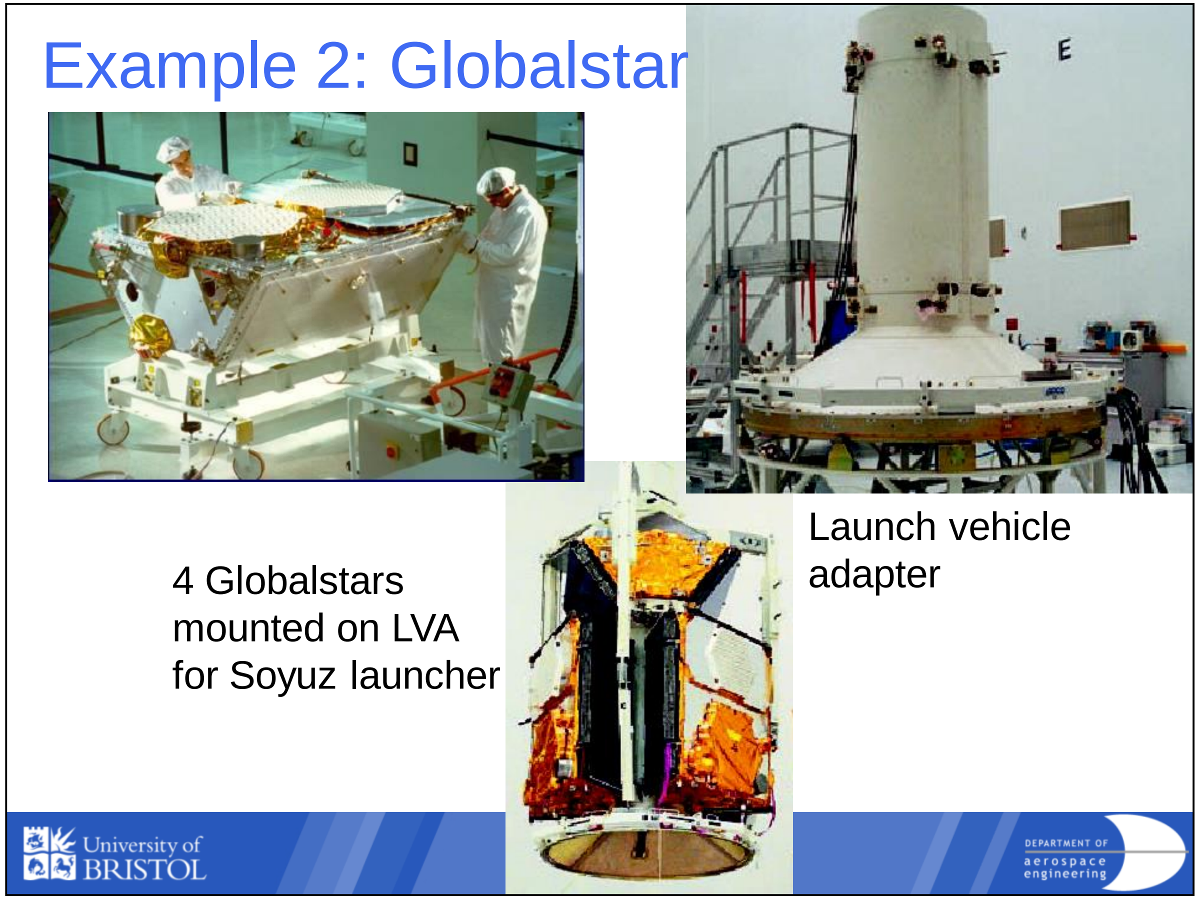
The launch adapter forms the junction between spacecraft and launcher and is provided by the Launch vehicle company. Many different adapters are available depending on size of spacecraft. The LVA mass may be 50-100kg and must be allowed for in the mass budget.



Mars Express has to accommodate 7 instruments, many of which have fields of view (ie: angles at which they have to view Mars). In particular the high resolution camera has a high pointing accuracy of 0.15degrees. A lander (Beagle 2) was ejected before the Mars capture manoeuvre and this has to be placed on the outside of the spacecraft where its ejection will not affect any other subsystems. To get to Mars you need a significant amount of propellant, so tanks and a rocket motor are required. To provide power, a large solar array area is needed and these need to be deployable so that they can fold up inside the launcher. The largest possible antenna enables the maximum amount of science data to be returned to Earth.



Globalstar is a set of 48 LEO telecommunication satellites. They are expensive to launch so 4 were fitted on each launcher to economise and this drove the shape of the satellites. This required a special LVA.

2. Structures

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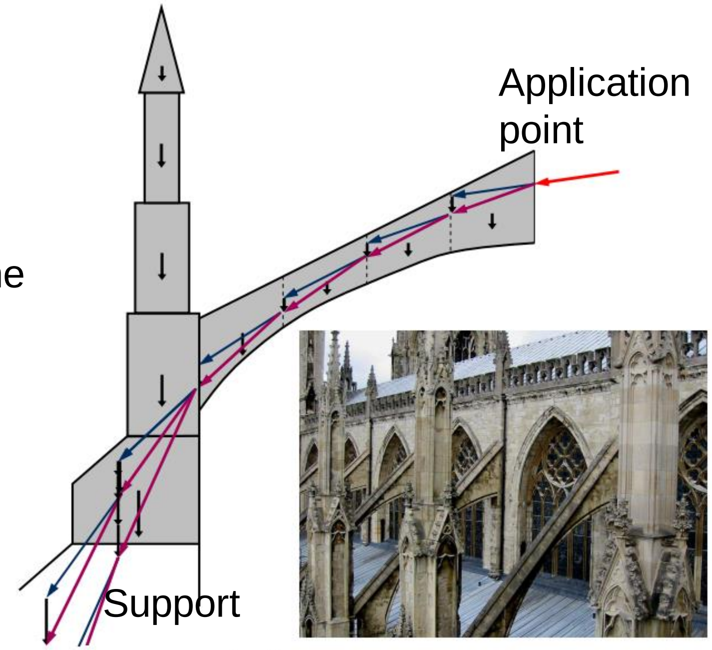
Concept of load path

Load path:

how a load is transferred from its application point to the support / equilibrium



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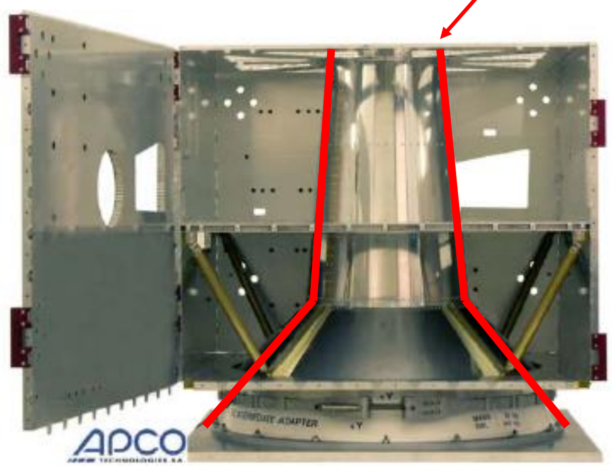
Example: the flying buttresses of Notre Dame in Paris. Why is this important in spacecraft? Because the loads come from launch and it is important how we transfer them through the spacecraft to the support.

Difference between Primary and Secondary Structure

- Primary structure carries the load path
- Secondary does not



Aluminium structure of SMART-1 spacecraft

Primary structure is the cone which takes the load from the launcher and the load of the propellant tanks. The secondary structure is the box around it and this supports merely the equipment, payload etc.

Structures provide:

1. Load paths
2. Mounting location
3. Stiffness
4. Environmental protection
5. Alignment
6. Thermal and electrical paths
7. Accessibility

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These are the requirements for the spacecraft structure. The structure must provide all the things on the list. Alignment is for cameras and other instruments typically. Accessibility is for ease of manufacture.

Definitions

Reminder:

STATICS – Constant loads

DYNAMICS - Loads that vary rapidly with time

However, in spacecraft analysis we have:

'QUASISTATICS' – a dynamic load, launch acceleration, which varies slowly enough to be treated as static.

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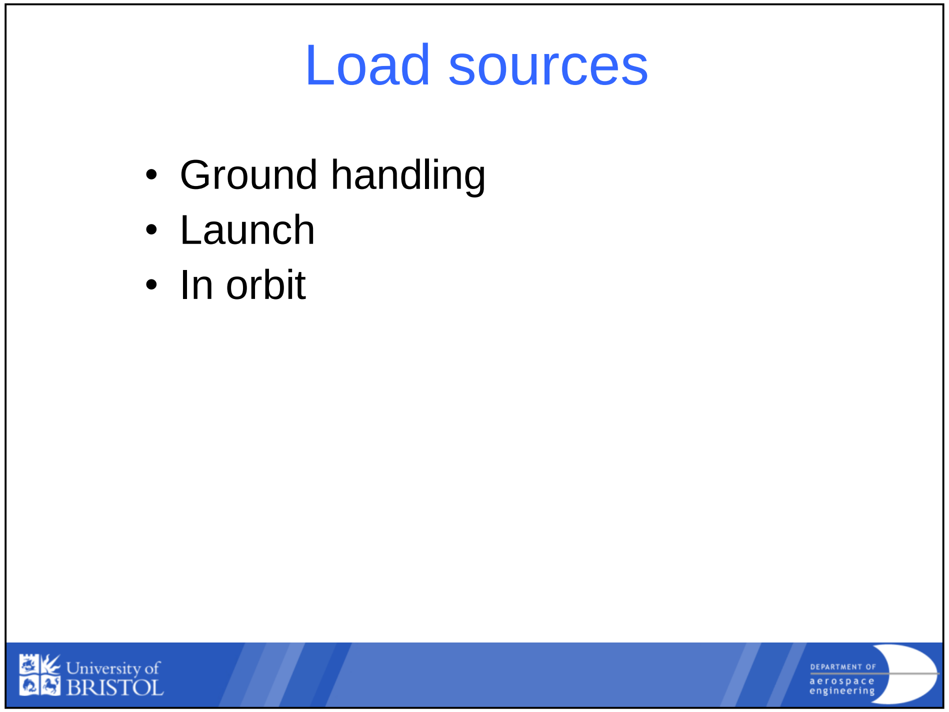
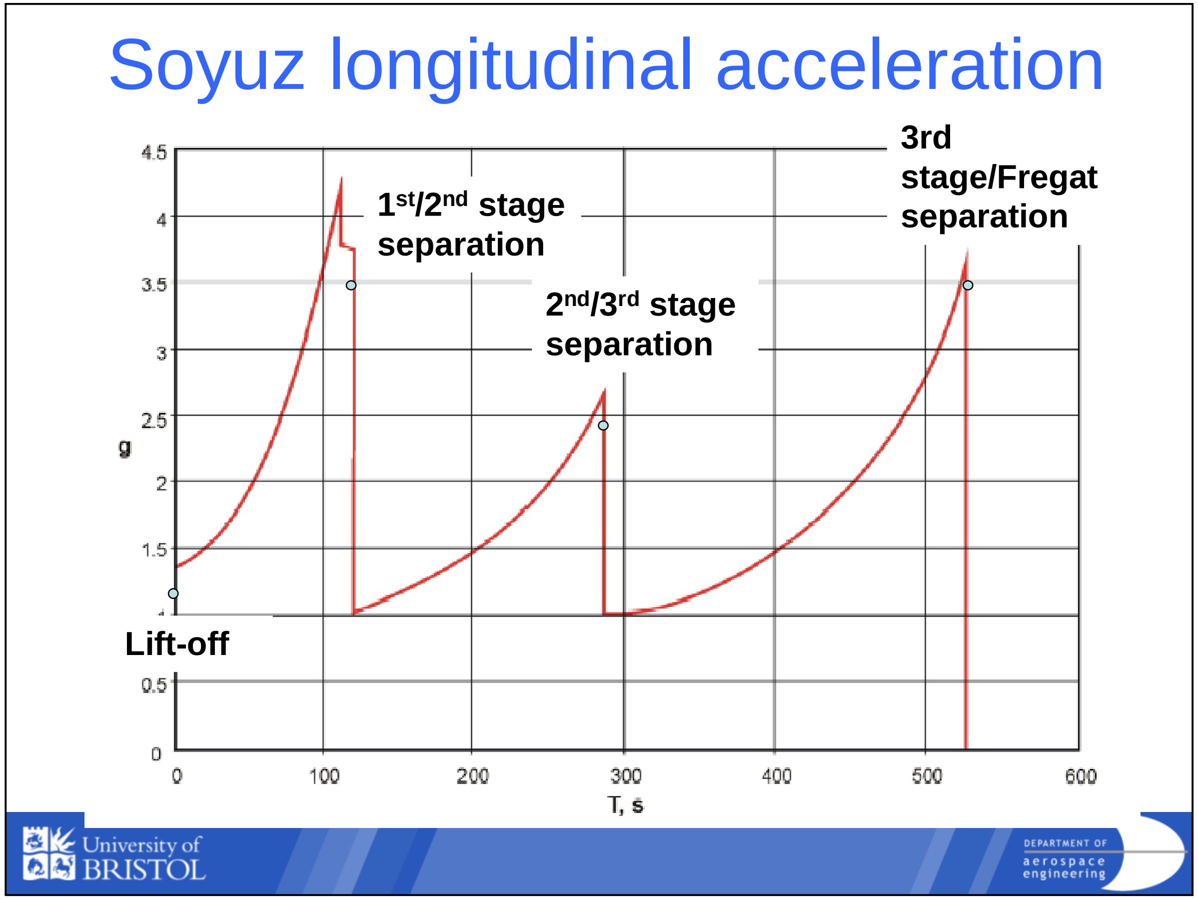
Because launch acceleration along the axis of the launcher varies relatively slowly, it is treated as a static load.



During **ground handling**, shocks to the spacecraft are caused by eg: transportation. During **Launch** there are 'quasistatic' loads. Also shocks from ignition of engines, stage separations and clamp band release when the spacecraft separates from the launch adapter. High velocity gases are ejected from the motor and reflected from the ground, creating turbulence in the surrounding air and inducing a vibratory response of the rocket structure. As the vehicle accelerates through the atmosphere to high velocity, aerodynamic turbulence induces pressure fluctuations increasing in severity as the vehicle approaches and passes through the speed of sound. The high-level acoustic noise environment continues during supersonic flight until the maximum dynamic pressure, or max Q, condition is reached. The spacecraft is therefore designed to avoid launcher resonant frequencies ($f_{spacecraft}$ > 30Hz longitudinally, $f_{spacecraft}$ > 10Hz lateral). In **orbit** the spacecraft solar array/antenna/boom deployment causes loads, as does manoeuvring by the spacecraft motor and thrusters.



We have discussed the shocks caused by release of the stages. You can see here the g levels (acceleration) over time for the different stages of separation for the Soyuz rocket. Early rockets pulled 20g. Fregat is the 4th or 'Upper' stage used for boosting to GEO or to interplanetary orbits. The fairing is the protective cover that goes over the payload.

Materials used

- Aluminium Alloys
  - Sandwich panel face-skins
  - Forged rings
  - Brackets
  - Honeycomb
- Composites
  - Primary structures (CFRP)
  - Struts (CFRP)
  - Antenna reflectors (CFRP & kevlar)
  - Brackets (Glass Fibre RP)
  - Honeycomb (Nomex, kevlar)
- Titanium
  - Bolts
  - Strut fittings
  - Special brackets
- Beryllium
  - Mechanisms

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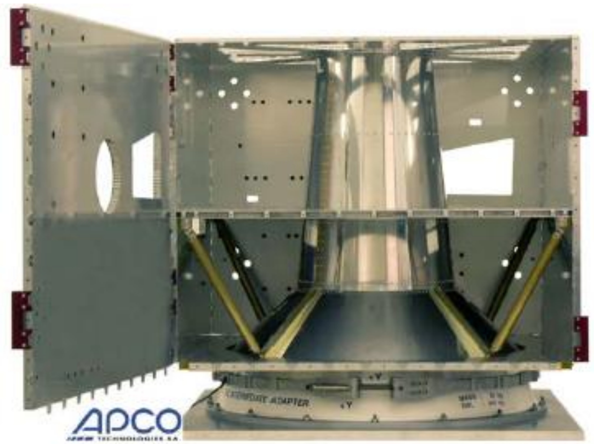
CFRP=Carbon Fibre Reinforced Plastic. Examples to be shown in class. *Titanium* is as strong as steel but much less dense and it is extremely good at high temperatures. Beryllium has a combination of high flexural rigidity, thermal stability, thermal conductivity and low density, but is unfortunately rather toxic to handle.

Elements of structure

The main structural elements of a spacecraft are:

- Panels
- Cones
- Cylinders
- Struts
- Tanks



Aluminium structure of SMART-1 spacecraft

SMART-1 was a technical demonstration spacecraft built by ESA to fly to the Moon. It was built mostly of aluminium and aluminium honeycomb. Note that the primary load path of a spacecraft is usually through a central cone or cylinder. It is this that supports the heavy propellant tanks. The walls are mostly just for mounting equipment.

Testing models

1. Structural Test Model

2. Protoflight Model

3. Qualify by Similarity

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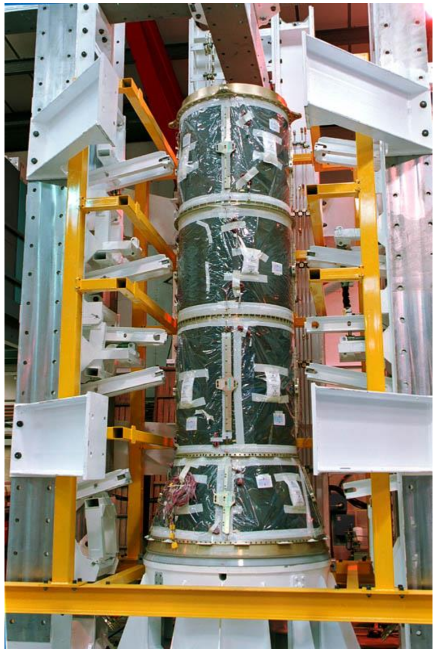
There are 3 different ways of testing spacecraft, depending on whether you have built any before. 1. If we want to be really confident of our design, we build various test models before building the real thing, including a structural test model which we can test to destruction. 2. If we have less money, we can built a protoflight, ie: build an experimental model, test it (not to critical levels) and then fly it. 3. If you already have built multiple spacecraft then you can ‘qualify’ your spacecraft by similarity ie: as we have built this before, we know the next one should work (assuming it was built to the same quality).

Structural testing



Tensile testing of Envisat central cylinder

The same kind of structural tests are performed on a spacecraft as you have performed in your course. Compressive, tensile tests. The aim is to verify whether the FE modelling is correct. However, there are several new tests which are performed which you have not yet seen: vibration, acoustic and thermal vacuum.

Vibration testing

http://www.youtube.com/watch?v=DczJ1uZ_Cc8

Vibration testing of Antenna and its steering mechanism

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Vibration testing is accomplished by introducing a forcing function such as a sine wave into a structure, usually by attaching the structure to the "table" of a shaker. The sine wave amplitude and frequency can be varied. ‘Random’ testing is also performed, this is where all frequencies at once are fed into the structure and its response measured.

Acoustic testing

Acoustic testing of Envisat

Up to 140dB of noise is used to simulate the noise of launch in a special acoustic room to see if the structure (in this case of Envisat) responds as predicted.

Image credit: Airbus Defense and Space.

As the NOAA-N Prime spacecraft was being repositioned from vertical to horizontal on the "turn over cart" it slipped off the fixture, causing severe damage.

Two errors occurred. Firstly, technicians from another satellite program that uses the same type of "turn over cart" removed the 24 bolts from the NOAA cart without proper documentation. Secondly, the NOAA team failed to follow the procedure to verify the configuration of the NOAA "turn over cart" since they had used it a few days earlier.

3. Mechanisms

•Need for mechanisms comes from need to fold up spacecraft to get it into launcher fairing

•And from need to point components

•Thermal vacuum envt influences selection of materials, lubricants, coatings

Mechanisms

Pointing mechanism

1. Continuous
   Eg: antenna pointing mechanism

2. One-shot
   Eg:?

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1. Continuous or used frequently
   - Antenna pointing and tracking
   - Solar array pointing and tracking
   - Attitude control reaction wheels

- Boom extensions

2. One-shot ie: used once only for deploying an appendage
   - Antenna launch retention and deployment
   - Solar array retention and deployment
   - Launch vehicle separation

Mechanisms design constraints

- Precision pointing
- Operation life
- Torques or forces and operating rates.
- Volume
- Mech/elec. interfaces
- Structural stiffness
- Launch and in orbit environment.

These are the constraints which will drive the design of any spacecraft mechanism. The first two are particular to mechanisms, the next four apply to all parts of the spacecraft. : thermal loads caused by CTE differences and vacuum which influences selection of materials, lubricants and coatings

Spacecraft gone bad!

(mechanism failure examples)

Galileo	1989	High-gain antenna failed to deploy	Cold welding in ball and socket joint
Galileo	1989	Instrument cover jettisoned late	Thermal binding
Magellan	1989	Solar array failed to latch at end of travel	Microswitch misadjusted
Ulysses	1990	Spin-stabilized spacecraft wobbled	Antenna boom thermal distortion caused spacecraft CoG offset
Hubble	1990	Solar array booms jittered as telescope went between sun and shade	Thermal gradient across boom diameter
GOES 10	1997	Solar Array Drive malfunctioned	Block fastening or gear jam
SOHO	2003	HGA pointing mechanism	Undetermined mechanical anomaly

Generally we avoid using mechanisms on spacecraft designs if possible. Because they are complex, hard to test and function differently in the space environment, they fail more often than other parts of satellites. Here are some examples.

The Future

- Embedded heat pipes
- Embedded sensors
- Foil for wiring channel
- Self healing composites
- Spacecraft on a chip: silicon as structure, heat transfer system, radiation shield, optics, and semiconductor substrate

SSTL nanosat 6kg

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The drive towards low mass means that if two functions on a spacecraft can be combined then they will be. UoB has particular expertise in self-healing composites.

Summary

- The *configuration* is the *arrangement* of the spacecraft.
- Primary structure carries the load
- Spacecraft are designed for stiffness during launch. But loads also come from ground and orbit.
- Materials are carefully selected for space bearing in mind mass, stiffness, CTEs and outgassing.
- Testing philosophy is: STM, Protoflight or similarity
- Types of testing include: structural, vibration, acoustic, thermal vacuum, life, deployment.
- Mechanisms are either one-shot (eg: boom deployment) or continuous (eg: solar array drive mechanism)

CTE=Coefficient of Thermal expansion

CTE=Coefficient of Thermal expansion

Test Yourself! (Feedback)

1. What is the definition of the configuration of a spacecraft?
2. What might drive the configuration of a spacecraft going to Mars, Mercury, a comet?
3. What are quasistatics?
4. What model philosophies can be used for spacecraft?
5. How would you test a spacecraft structure?
6. Name types of continuous and one-shot mechanisms.