ELIXIR Course

Structural Design

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(JWST NIRSpec & MIRI Mechanical Eng.)

Structural Design

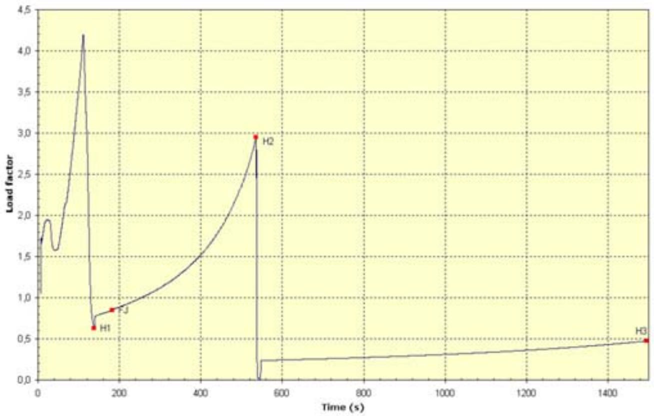
- Why a structure?
- Structural Requirements & Design Drivers
- Materials
- Analyses
- Verification & Testing

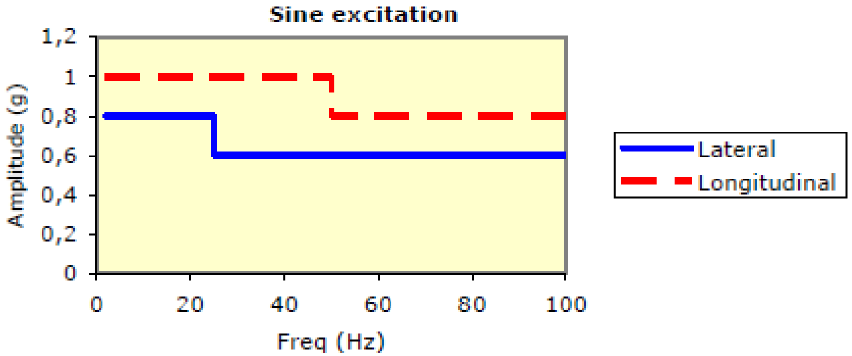
Why a structure?

- ECSS says: "*set of mechanical components or assemblies designed to sustain loads or pressures, provide stiffness or stability, or provide support or containment*"
- So, some kind of shelf or bracket…
- Sounds trivial but not so much taking into account…
  - The launcher environment (QSL & vibrations!)
  - The space environment (temperatures, vacuum / depressurisation, radiations, micro-meteorites, re-entry, etc)
  - The very stringent requirements: mass, volume, access, stiffness, strength, stability, low WFE, etc.

Launcher Environment

- Static loads (up to ~4.5g)
- Low frequency loads (<1g, up to 100Hz)



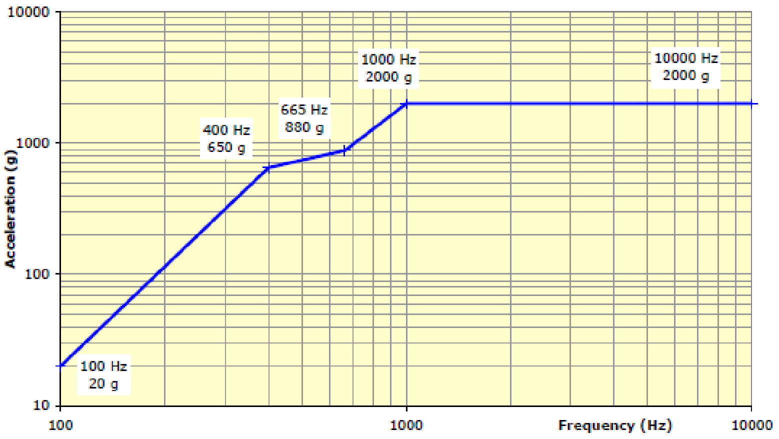


Structural Design

Launcher Environment

- –Acoustic noise (140dB, up to 2000Hz)
- –Shocks (eg booster & fairing separations)

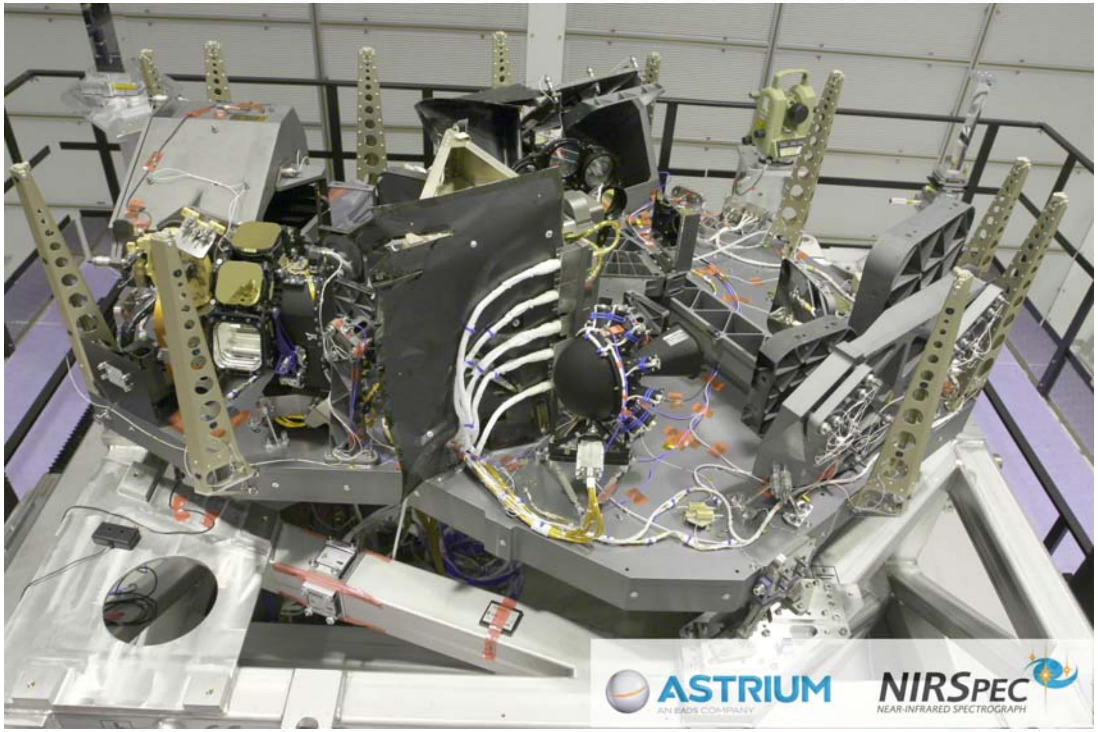
Octave center frequency (Hz)	Flight limit level (dB) (reference: 0 dB = 2 x 10^{-5} Pa)
31.5	128
63	131
125	136
250	133
500	129
1000	123
2000	116
OASPL (20 – 2828 Hz)	139.5



Structural Design

Structural Requirements & Design Drivers

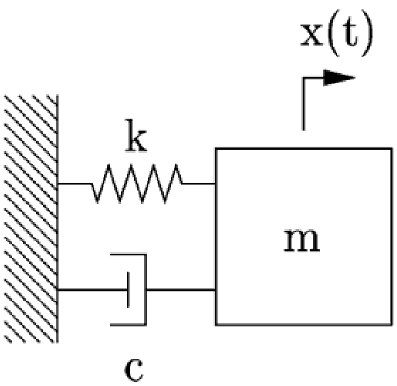
- Mass: Limitation from the launcher lift-off capability
- Envelope & interfaces:
  - The spacecraft has to fit within the launcher fairing
  - The internal instruments have to fit within the S/C
  - The sub-systems have to fit within the instrument



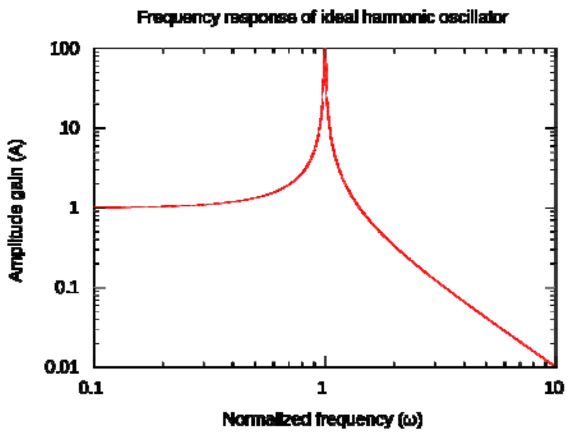
Structural Design

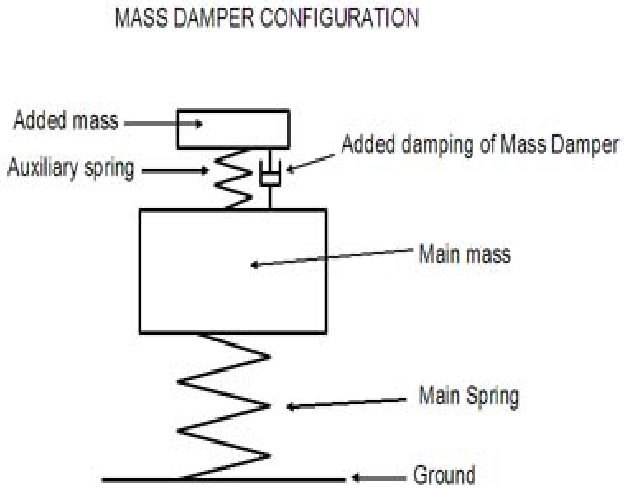
Structural Requirements & Design Drivers

– Stiffness & decoupling:
  - A unit can be seen as a mass + spring system
  - Its resonance frequency shall not couple with the one of its “support”



$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{T}.$$

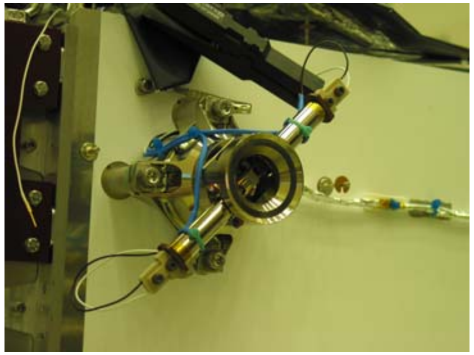




Structural Design

Structural Requirements & Design Drivers

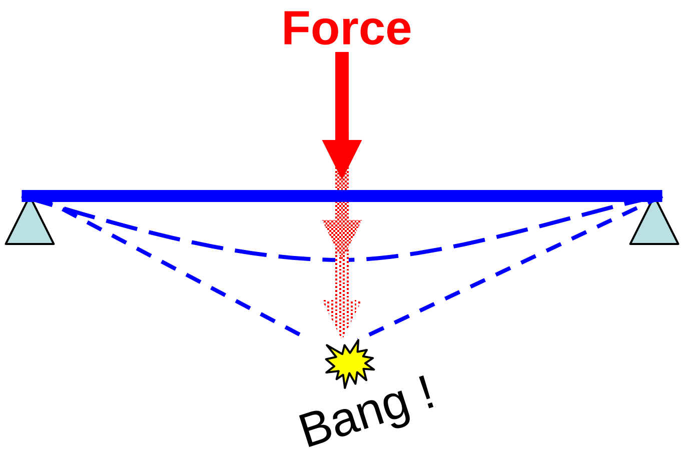
- Strength vs design loads
  - The S/C structure has to cope safely with the launcher static & dynamic loads
  - The Payload units as well … including the amplifications coming from the S/C
  - Thermo-elastic loads are very often very severe and can be dimensioning
- Shocks:
  - Are generated by the launcher (eg booster or fairing separation)
  - But also by the release of internal (S/C) devices like antennae (pyro nuts)
- And also…
  - Opto-mechanical (WFE), stability constrains
  - Thermal constrains
  - Micro-vibrations (eg reaction wheels)
  - EMC, magnetic constrains (P/L needs)
  - Integration & access (AIT)
  - Manufacturing limitations
  - Transportation (i/f, loads, horizontal)
  - Availability / schedule / risks / costs

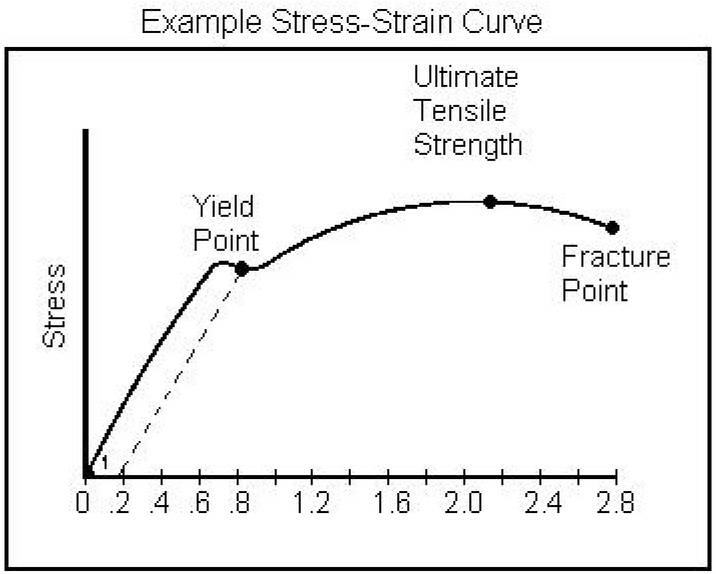


Thermal cutter
for Solar Array

Materials

- Strain stress law





Materials

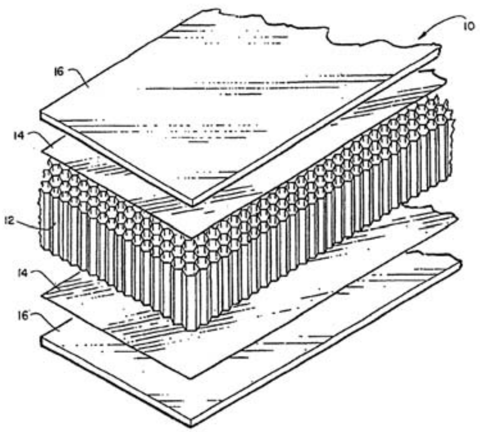
- Metals: recommended as far as possible, and aluminium if possible!
- Lots of experience, well characterised
- Easy to machine … and in many places
- Low safety factors (less conservative dimensioning)
- Can be repaired, modified at a late stage, etc
- Cheap and easily available

Structural Design

Materials

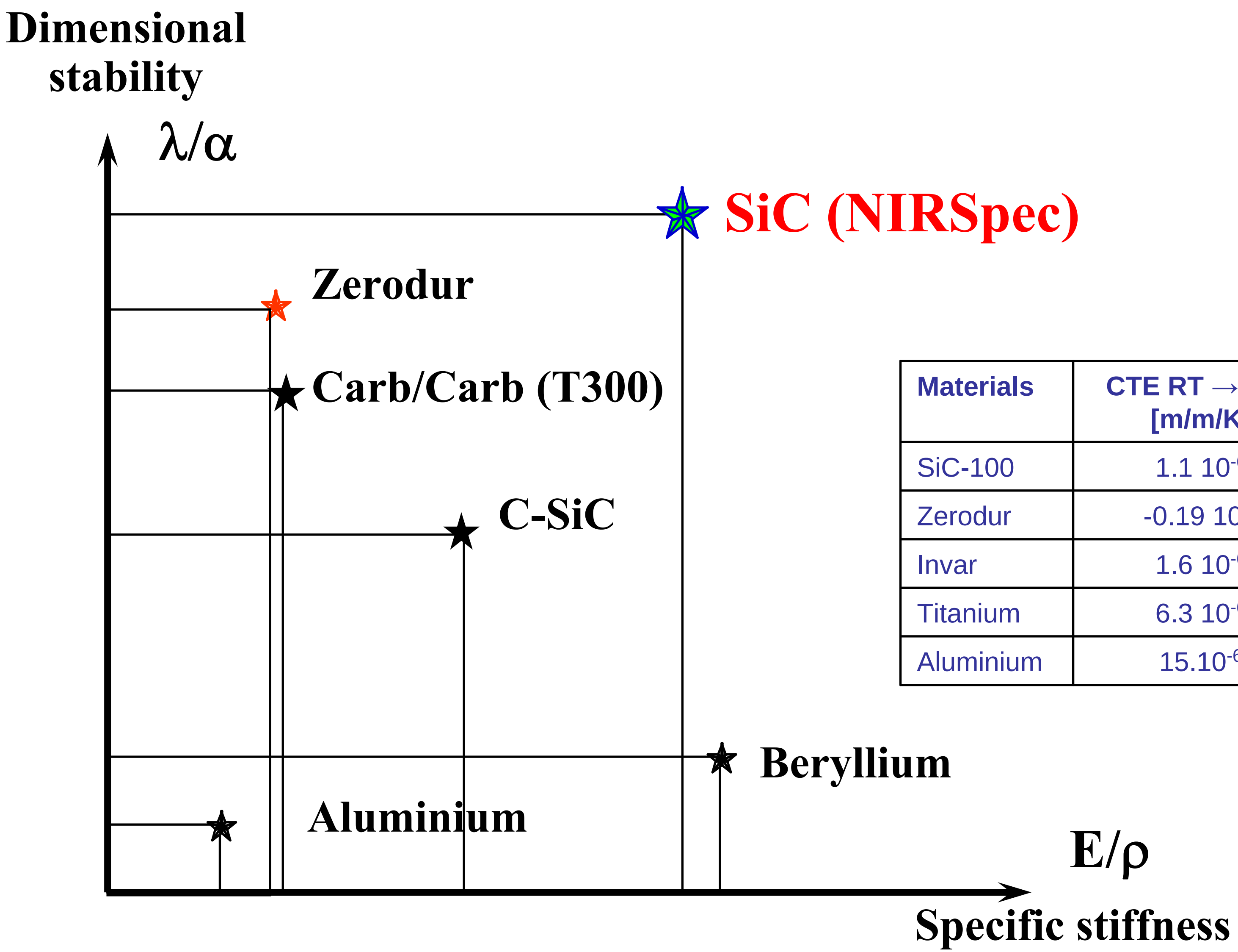
– Sandwich panels or cylinders are commonly used for the S/C structure for their favourable stiffness to mass ratio

– If mass or performances cannot be met with standard metals, think about:
  - Fibres (CFRP, GFPP, Kevlar, etc)
  - Ceramics and glasses



SMART Primary Structure

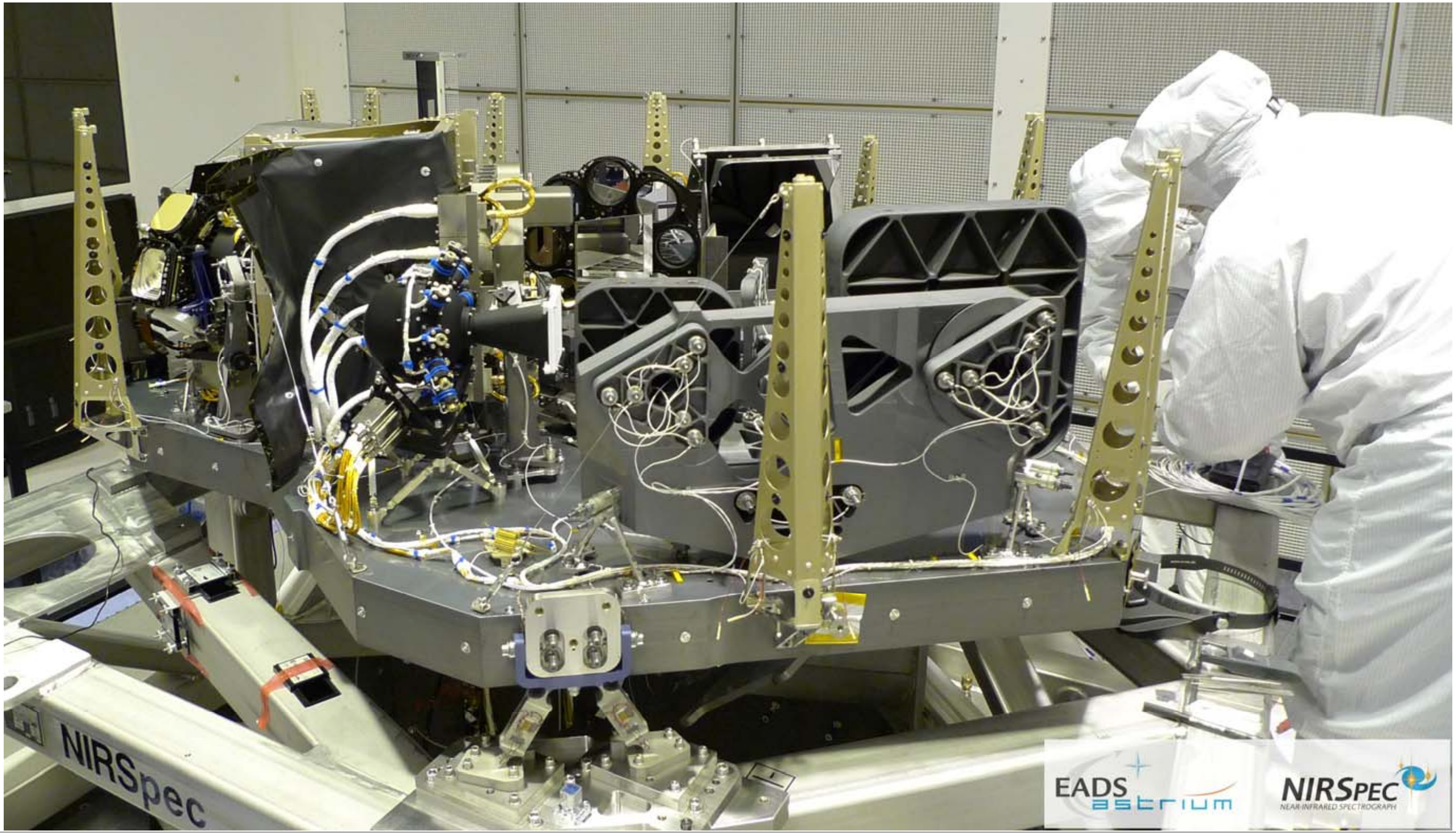
Structural Design



Materials	CTE RT → 30K [m/m/K]	CTE at 30K [m/m/K]
SiC-100	$1.1\ 10^{-6}$	$0.2\ 10^{-6}$
Zerodur	$-0.19\ 10^{-6}$	$-0.4\ 10^{-6}$
Invar	$1.6\ 10^{-6}$	$-0.8\ 10^{-6}$
Titanium	$6.3\ 10^{-6}$	$1.0\ 10^{-6}$
Aluminium	15.10^{-6}	$1.0\ 10^{-6}$

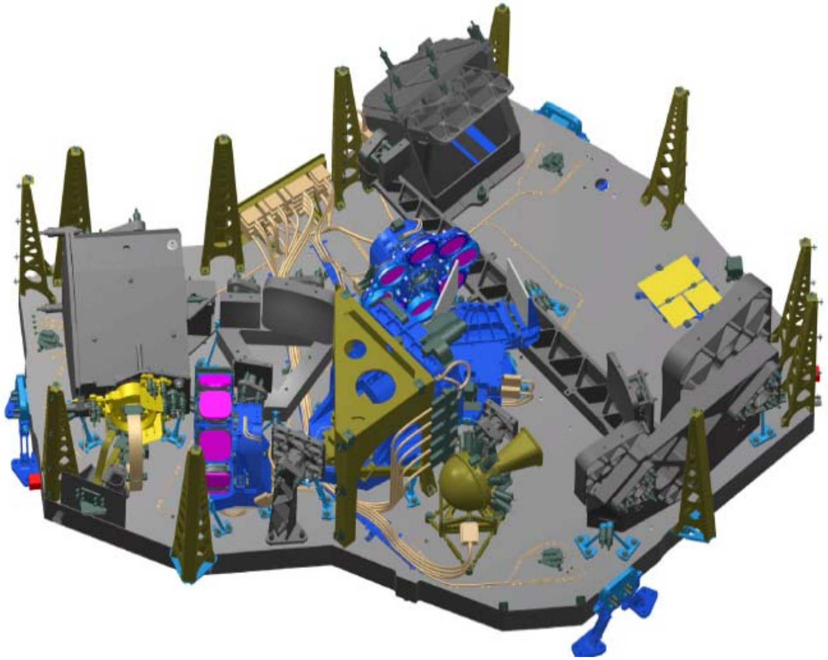
Structural Design

➔ ~60% of the **NIRSpec** mass in SiC-100



CAD = Computer Aided Design

3D geometrical modelling software
The accommodation is done with CAD S/W like CATIA



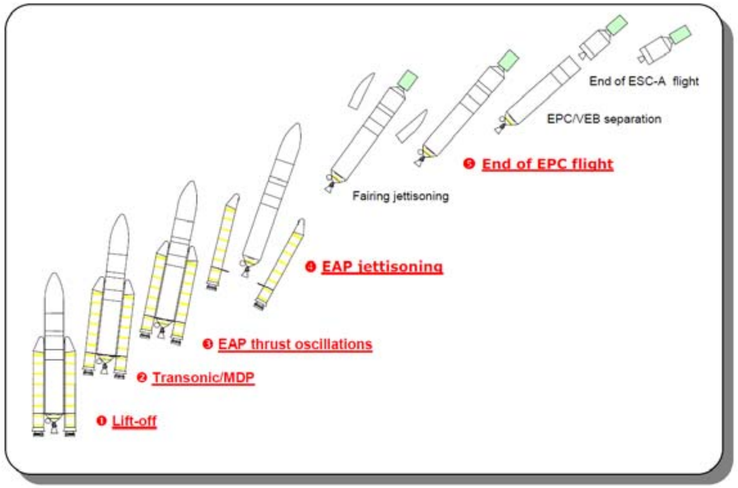
Very powerful tool to ensure proper interface allocations, integration access, etc … but some surprises can be seen on the actual hardware!

Structural Design

Analyses

– **FEM** & Types of analyses (NASTRAN)
  - Predictions are made with **finite element models** (FEM) - NASTRAN is the most common tool
  - Static, modal, dynamic, acoustic, shocks can be predicted for the dimensioning, for the test campaign and for flight (CLA)

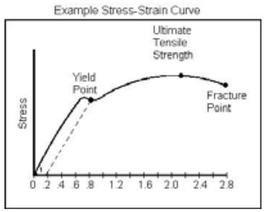
– **CLA** = Coupled Loads Analysis: Dynamic analysis of the S/C inside the Launcher with all the flight events like ignition of engines, booster ejection, gust, etc. Predicts the flight loads against which the S/C has to be qualified (= safely survive with margins)



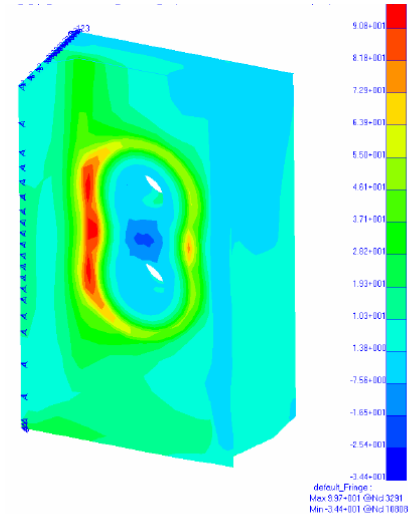
Structural Design

Analyses

- Strength analyses: the parts shall not distort and even less break under transportation, handling, **test**, and launch loads.
- Safety factors & Margin of Safety (MoS)
  - The ESA standards (ECSS) requires the structures to show positive margin of safety including factors that are material dependant:



$$MOS = \frac{design\ allowable\ load}{design\ limit\ load \times FOS} - 1$$



Structure type and sizing case	FOS Yield	FOS Ultimate
Metallic structures	1.1	1.25
Composite structures. Uniform material, brittle	-	1.25
Sandwich structures	-	1.25
Glass & Ceramic structures	-	2.5
Composite structures discontinuities	-	1.5
Joints and inserts	-	1.25
Global buckling	-	2.0

Allowable load	allowable load under specified functional conditions (e.g. yield, buckling, ultimate)
Limit load	computed or measured load under defined load condition (e.g. design limit load, vibration load, thermal load)
FOS	Factor of safety applicable to the specified functional conditions including the specified load conditions (e.g. yield, ultimate, buckling) as defined in Table 11

Structural Design

Verification & Testing

- Static tests or very low frequency vibration test
  - Done on a dedicated jig with hydraulic pullers / pushers, masses & pulleys, or on a shaker
- Sinusoidal vibration tests
  - Done on a shaker
  - Excites (sweeps) the structure up to typically 100Hz to cover the low freq launcher excitations
- Random vibration tests
  - Done on a shaker, all freq excited simultaneously, 20Hz to 2000Hz
  - Typically not done at S/C level (high freq are covered by the acoustic test) but very common at unit level

Rosetta S/C

Structural Design

Verification & Testing

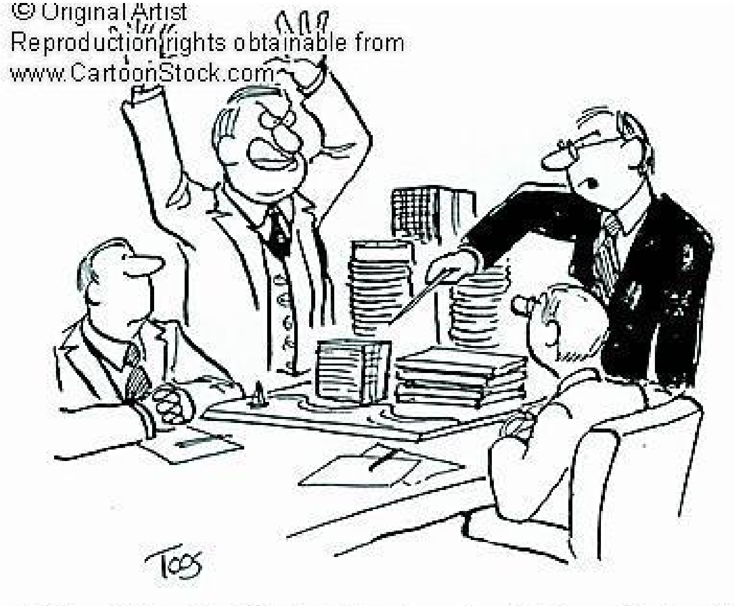
– Sinusoidal vibration tests

Verification & Testing

- Acoustic test
  - Done in a dedicated acoustic chamber, typically up to 2000Hz
- Shock test
  - Clampband release done at S/C level, sometimes a SHOGUN test is also perform to address the L/V shocks
  - For units, a shock test on a ringing table can be performed
- Thermo-elastic tests
  - Covered as part of the thermal vacuum test → See Thermal Design Presentation
- Proof tests
  - For some critical parts (e.g. kinematic mounts / flexures) or for fragile materials like glass or ceramics
  - Generally done at part level
- Micro-vibrations
  - Done at unit level for sensitive units, not very common

Structural Design

Now, you cannot probably make a S/C or Payload structure yet…



"Bob will be Godzilla in this structural integrity test."

… but you should be able to talk with better confidence to a structural engineer!

ELIXIR Course

Mechanisms

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Mechanisms

- Rule number 1
- Why using mechanisms?
- Design drivers
- Analyses
- Verification and Testing

Mechanisms

Design Rule Nº 1:

Do not use mechanisms

(as far as you can…)

It's a source of problems, delays, costs…
Forget about flight heritage in 99% of the cases!

Mechanisms

Why using mechanisms?

- Because there is no other choice
- Examples: SADM, APM, FWA, RMA

Mechanisms

2009 JWST HD
Animation B-Roll

Deployment #1
Solar Array & HGA

Runtime: 00:20:00
Resolution: HD 1920x1080

Mechanisms

Design drivers

- Same as for structures (stiffness, strength)
- Motorisation margins (shall move)
- Lifetime (shall move … up to the end!)
- Power consumptions
- Performances including opto-mechanical, stability, position accuracy, repeatability, etc.
- Available technologies (e.g. sensors, motors, bearings, tribology/lubricants)
- Reliability (redundancy!)
- Cleanliness
- Costs (expensive!)

Mechanisms

Design drivers

– Motorisation margins (extract of ECSS for Mechanisms):

The minimum actuation torque (T_{min}) shall be derived by the equation:

$$T_{\min} = 2 \times (1{,}1\, I + 1{,}2\, S + 1{,}5\, H_M + 3\, F_R + 3\, H_Y + 3\, H_A + 3\, H_D) + 1{,}25\, T_D + T_L$$

where:

- *I* is the inertial torque applied to a mechanism subjected to acceleration in an inertial frame of reference (e.g. spinning spacecraft, payload or other).
- *TD* is the inertial resistance torque caused by the worst-case acceleration function specified by the customer at the mechanism level.
-*TL* is the deliverable output torque, when specified by the customer.

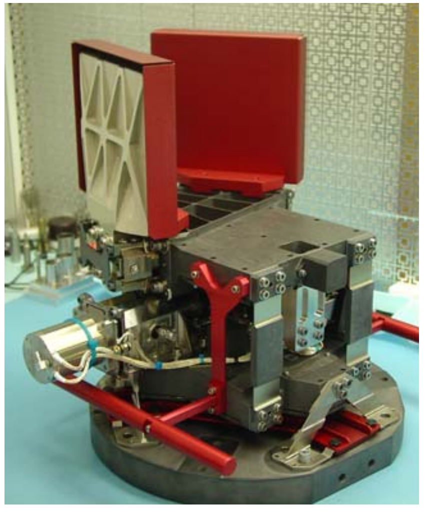


Table 4-2: Minimum uncertainty factors

Component of resistance	Symbol	Theoretical Factor	Measured Factor
Inertia	I	1,1	1,1
Spring	S	1,2	1,2
Motor mag. losses	H_M	1,5	1,2
Friction	F_R	3	1,5
Hysteresis	H_Y	3	1,5
Others (Harness)	H_A	3	1,5
Adhesion	H_D	3	3

Mechanisms

Design drivers

– Lifetime (extract of ECSS for Mechanisms):

a. The lifetime qualification shall be verified using the factored sum of the predicted nominal ground test cycles and the in-orbit operation cycles.

b. For the test verification, the number of expected cycles shall be multiplied by the factors in Table 4-3.

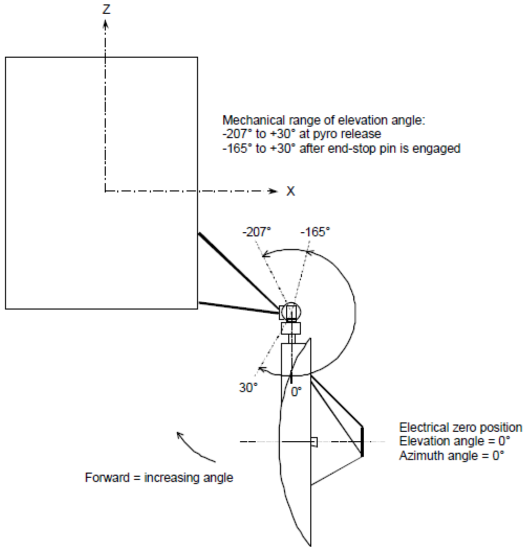
Table 4-3: Life test duration factors

Type	Number of expected cycles	Factor
Ground testing (minimum 10 cycles to be tested)	1 to 1 000 cycles	4
	1 001 to 100 000 cycles	2
	> 100 000 cycles	1,25
In-orbit	1 to 10 cycles	10
	11 to 1 000 cycles	4
	1 001 to 100 000 cycles	2
	> 100 000 cycles	1,25

Mechanisms

- **Analysis**
  - Same as for structures: FEM used to assess the structural performances
  - Kinematics - Deployments: risks of hitting something on the way (eg antenna), definition of envelopes (eg shutters, doors)
  - Kinematics - Characterisation of motions: ex reactive torque due to the rotation of the wheel ➔ can impact a fine pointing system

- **Verification & Testing**
  - Same as for structures (vibrations, shock, thermal cycling)
  - Lifetime test
  - Functional & Performance tests



Reminder of Design Rule Nº 1:

Do not use mechanisms!

(as far as you can...)

QUESTIONS?