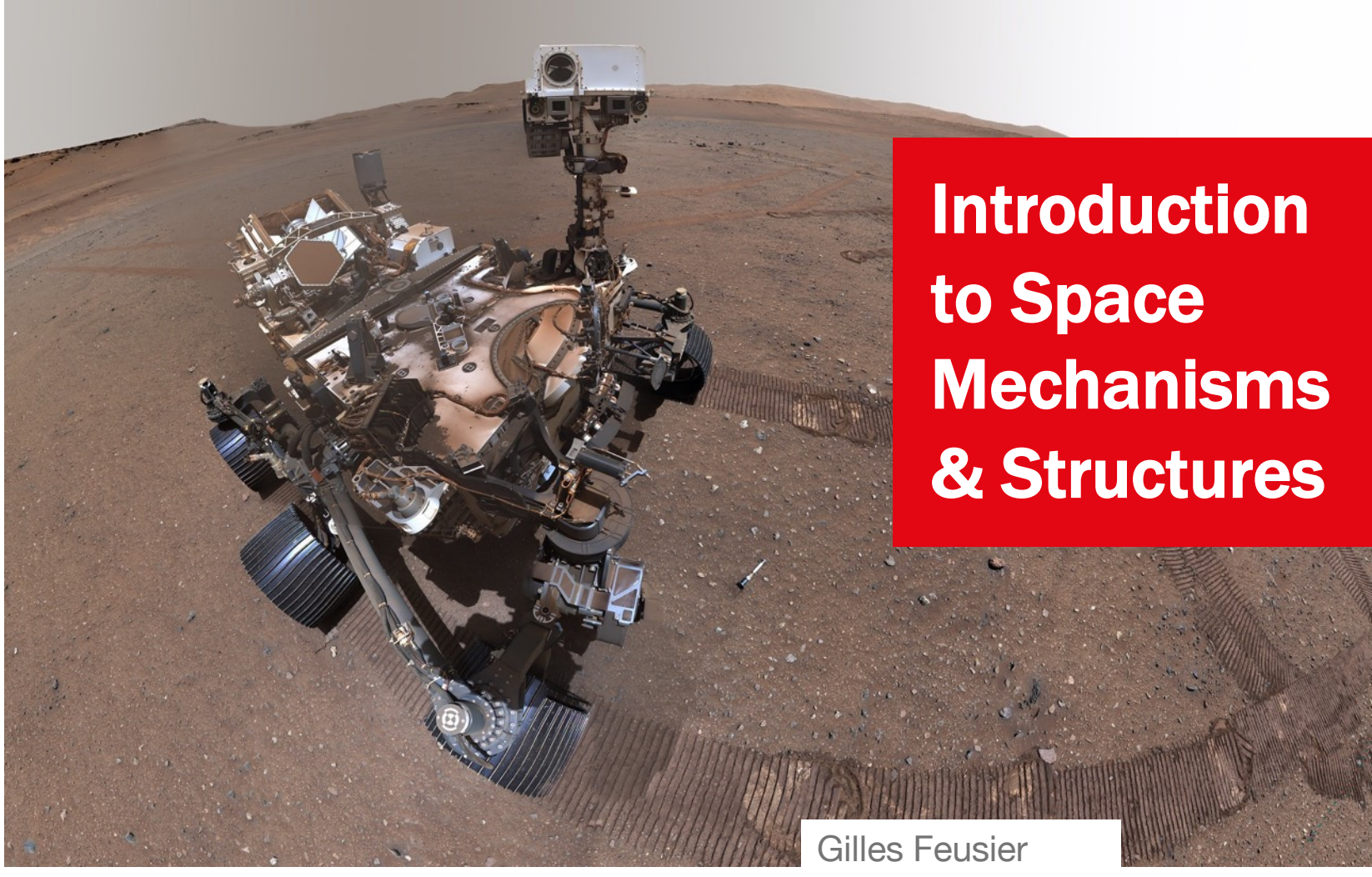
Introduction to Space Mechanisms & Structures



Source: NASA, JPL-Caltech, Kevin M. Gill

Gilles Feusier

Head of Technology and Science
Space Innovation

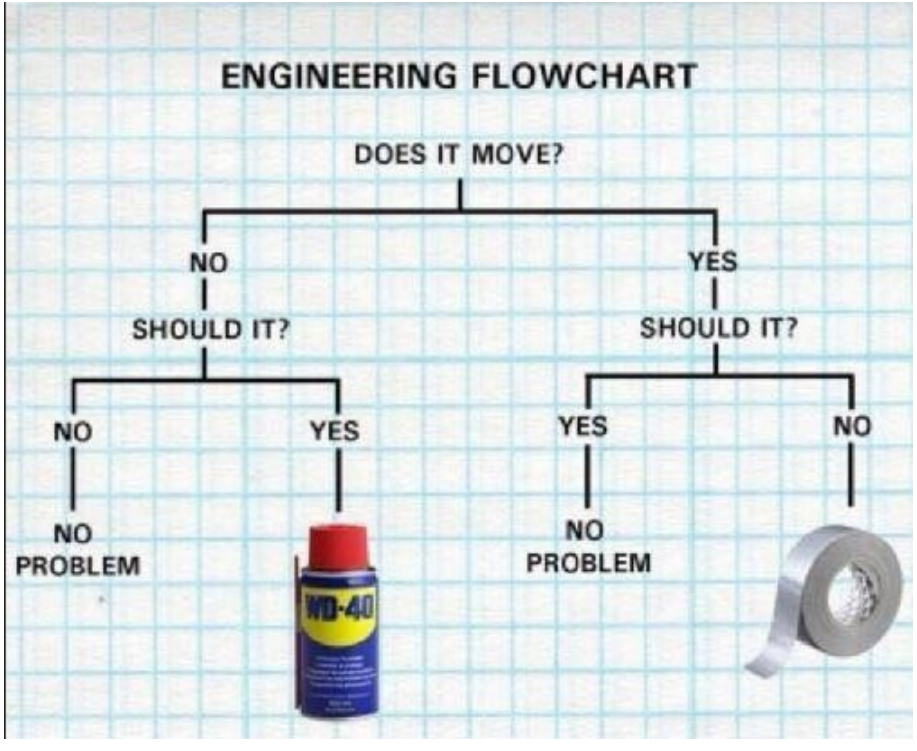
Gilles Feusier

EE580 “Introduction to the Design of Space Mechanisms”

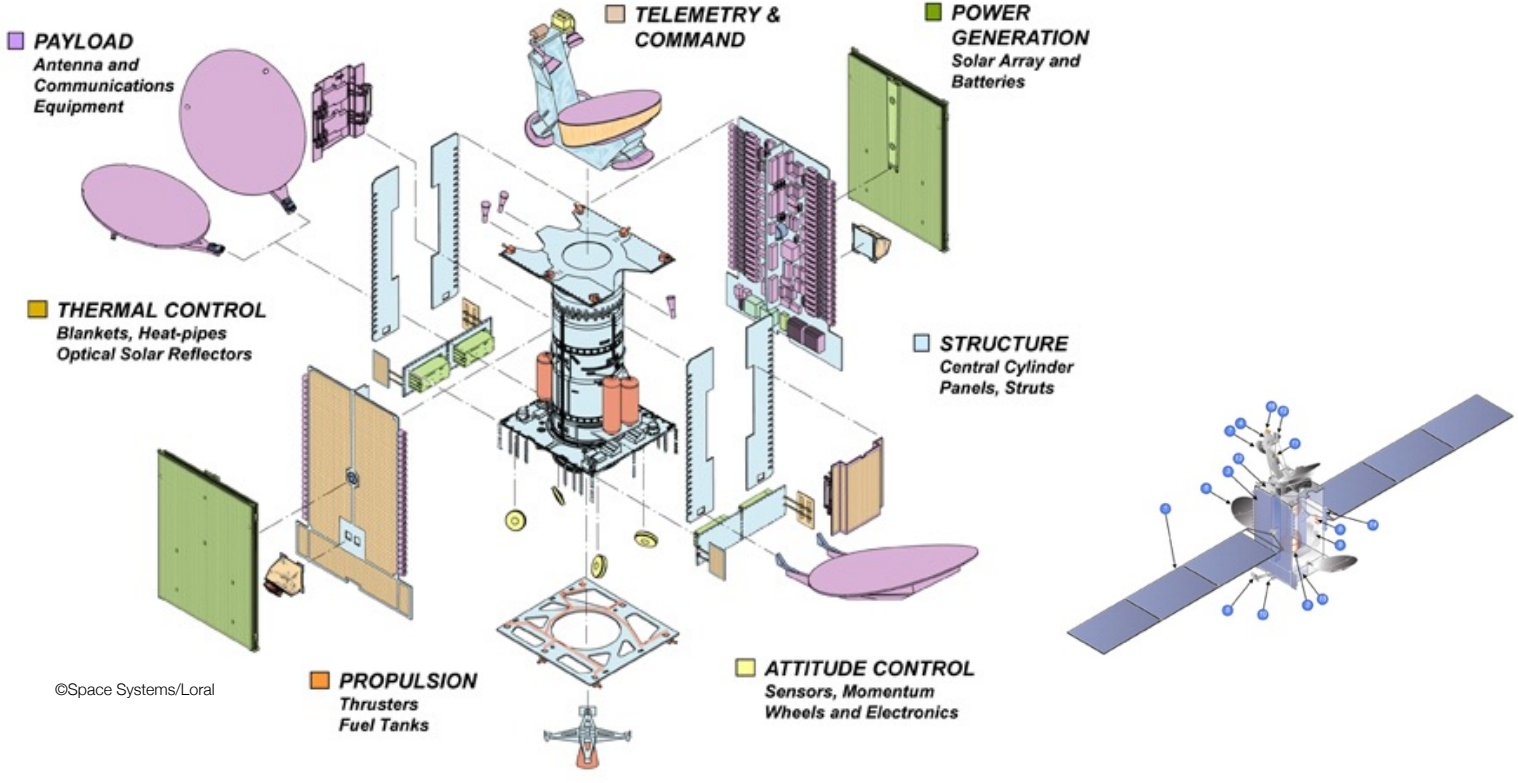
- Dipl. Ing. Physicist – EPFL 1993
- PhD in Solid State Physics – EPFL 1997
- Project Manager, MECANEX SA – Nyon (1997 -2001)
- Technical Director, MECANEX SA – Nyon (2001-2006)
- Head of development and innovation, RUAG AEROSPACE SA – Nyon (2007-2008)
- CTO, VOUMARD MACHINES SA – Hauterive (2008-2011)
- Product structure responsible, SCHOTT Suisse SA – Yverdon-les-bains (2011-2012)
- Member of the committee of the European Space Mechanisms and Tribology Symposium (ESMATS)
- Head of Technology and Science, Space Innovation – EPFL Space Center (since 2013)

gilles.feusier@epfl.ch

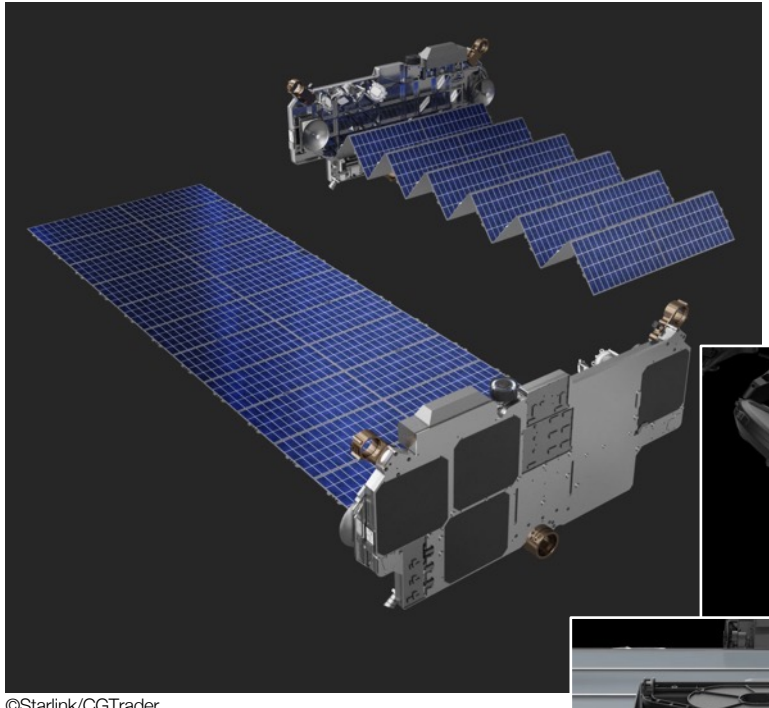
Mechanisms, Structures?



Telecom Satellite Platform (GEO)



Telecom Satellite Platform (constellations, e.g. Starlink)



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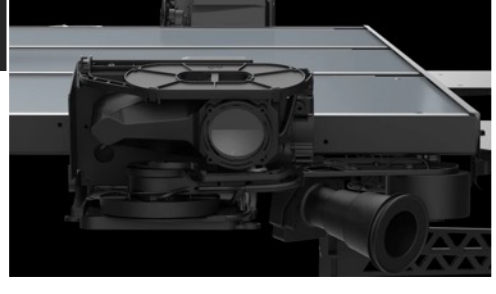

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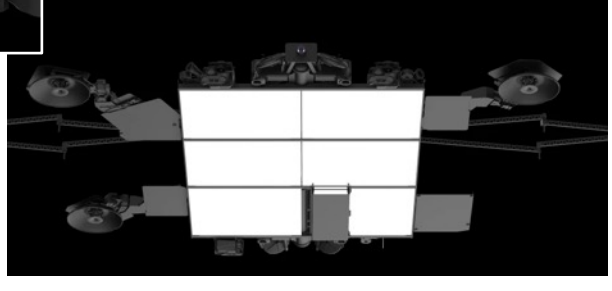
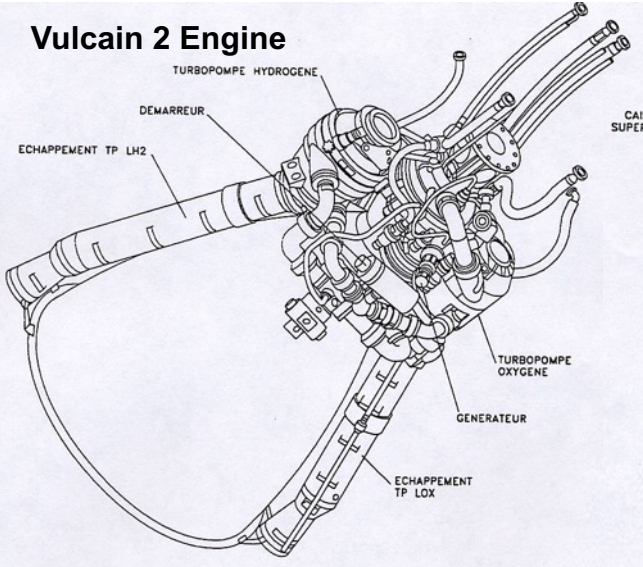


Space Mechanisms

- **Launch and Re-Entry Vehicles**
  - Separation systems
  - Engine/propulsion regulation, gimballing devices, turbo pumps
  - Flap controls, parachute deployment systems
- **Spacecraft equipment**
  - Wheels, mechanical coolers, pumps, valves, solar array drive mechanisms …
  - Hold-down/release, deployment, …
  - Pointing, …
- **Science Observatories, Earth Remote Sensing, and Planetary Exploration Mechanisms, In-Orbit Maintenance**
  - Mechanisms for manipulations, robots, rovers
  - Sampling systems and in-situ analysis devices, bioreactors, lab equipment
  - Mechanical devices for science and remote sensing instruments

Engine gimbals, turbopumps, valves

Vulcain 2 Engine



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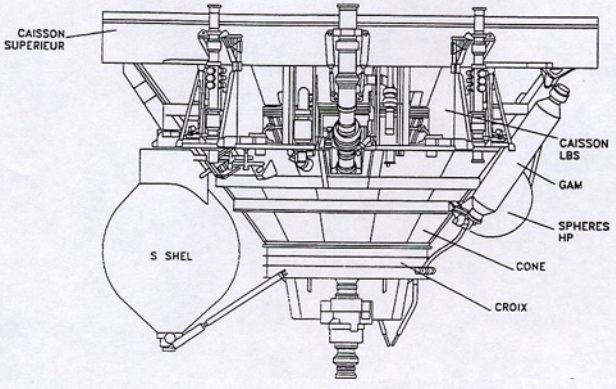
Engine Support Frame
Bâti Moteur Equipé (BME)



SLS Main Engine

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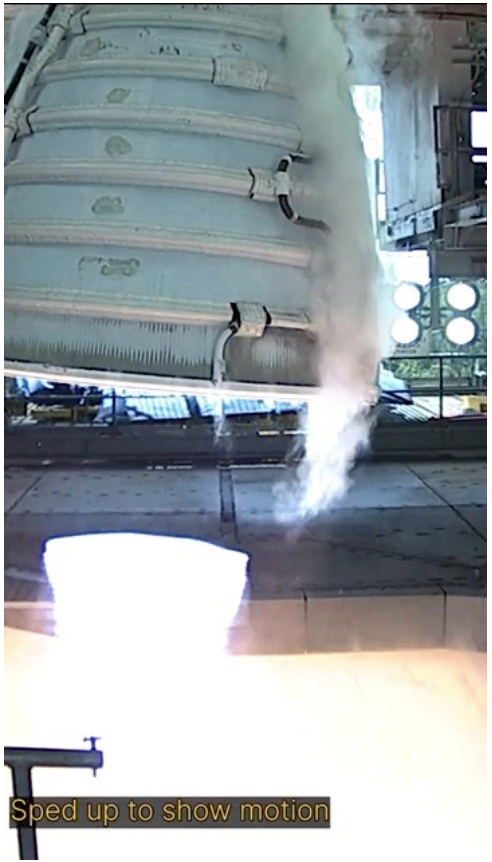

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Engine gimbals, turbopumps, valves

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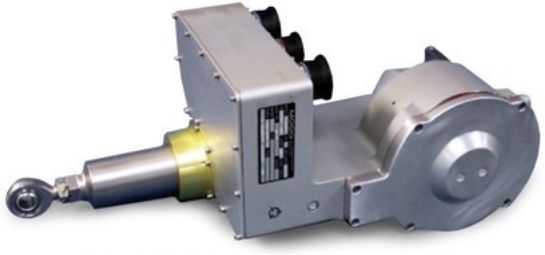

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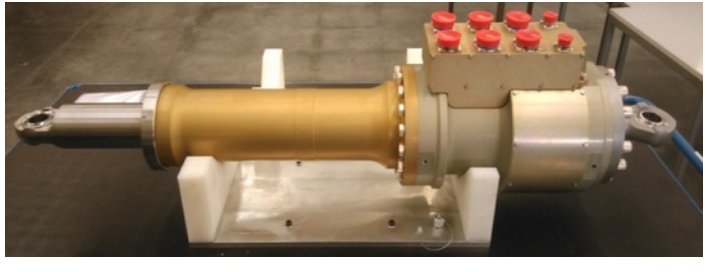

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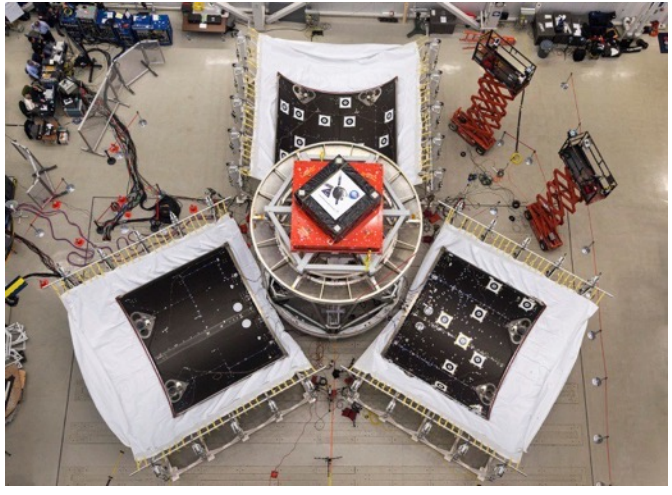
Separation Systems

©H. Martinez et al., 42nd AMS, 2014



Orion fairing separation test

Ariane 5 fairing separation test

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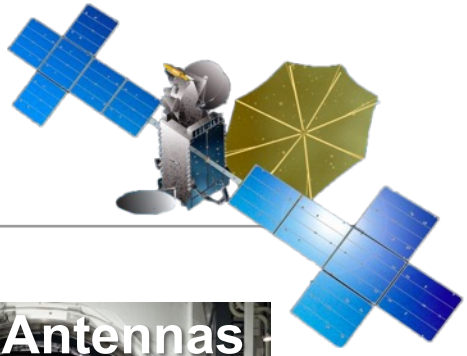
Deployment, release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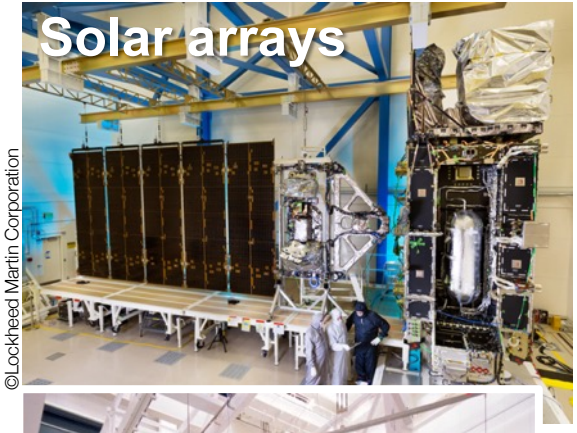
Solar arrays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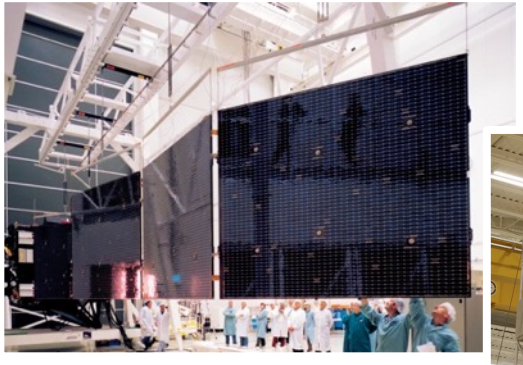
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Antennas


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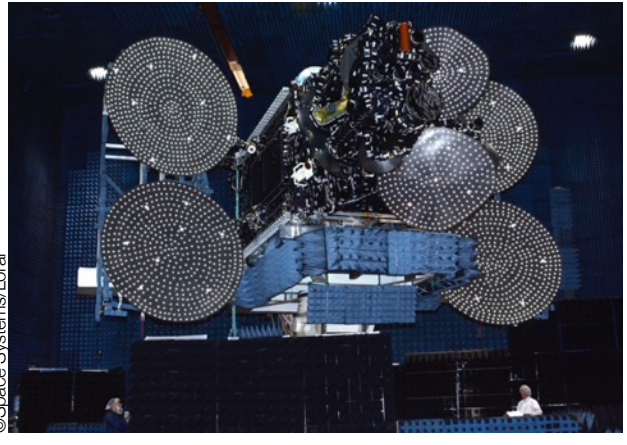
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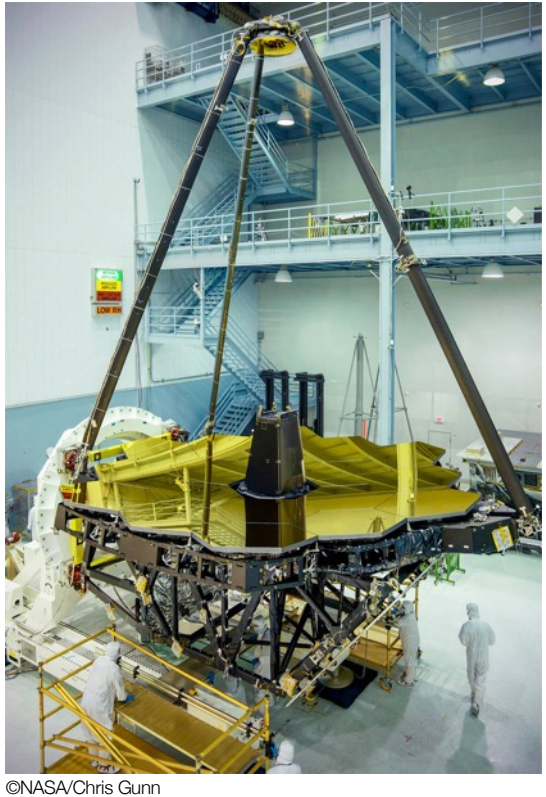
Deployment, release



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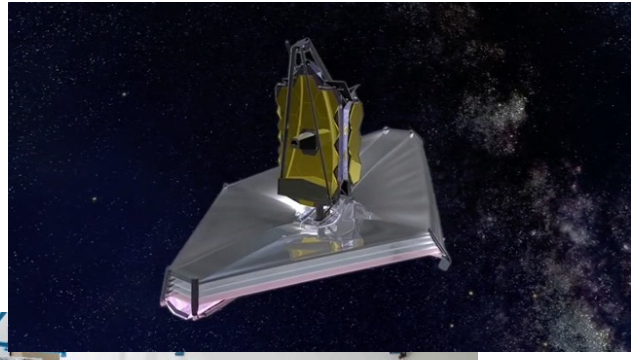

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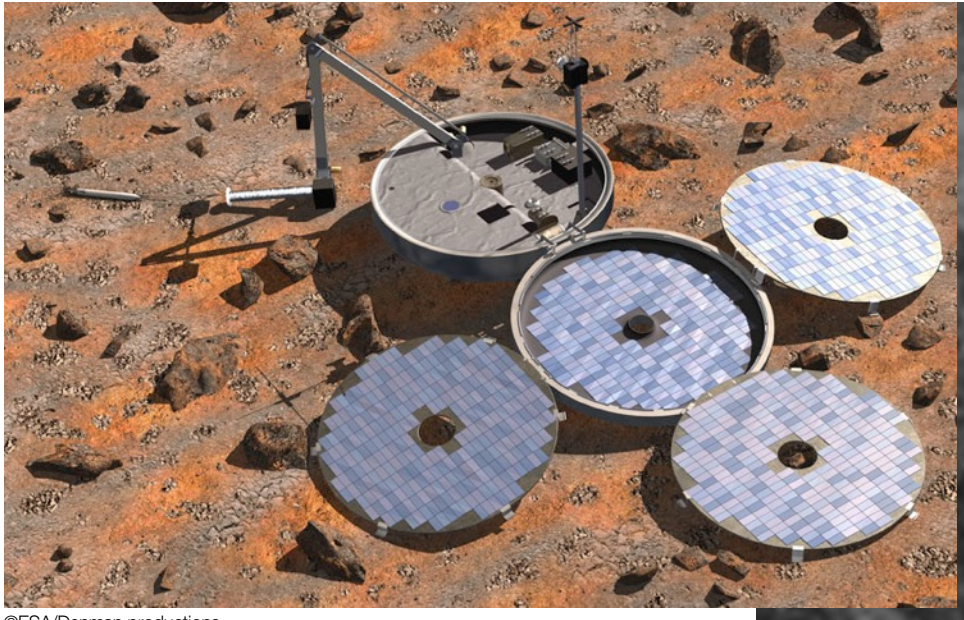
Deployment: failure



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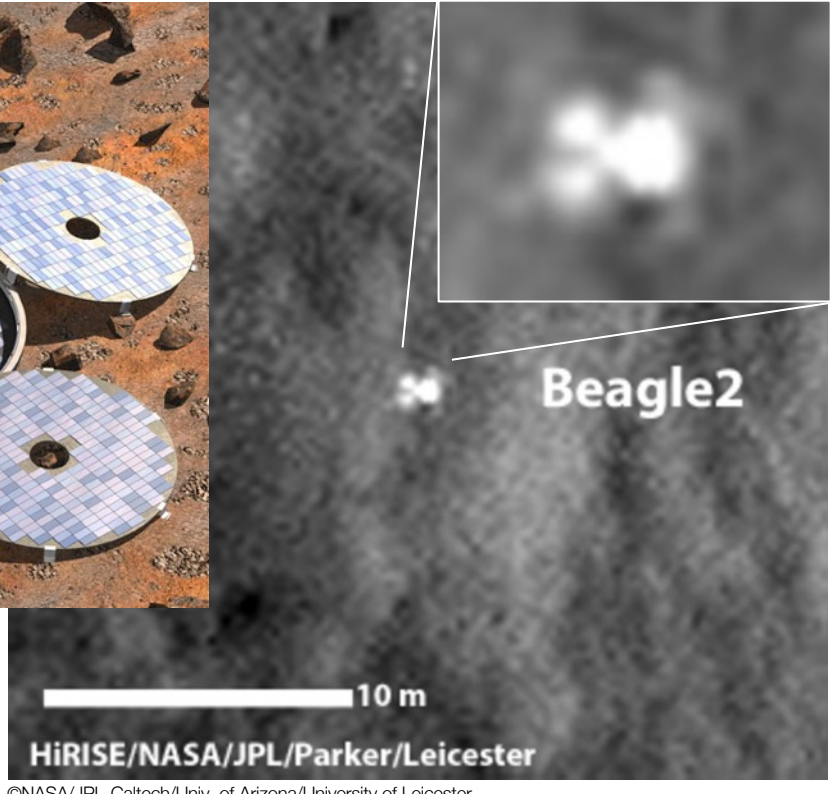

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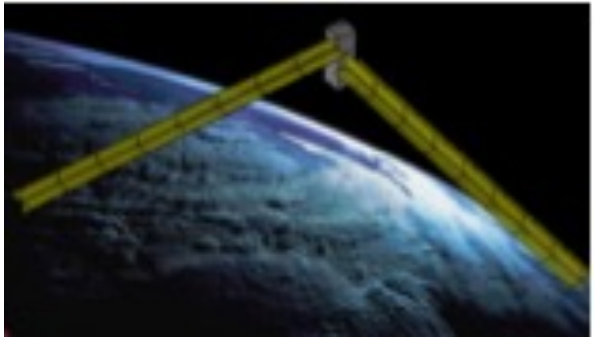
Deployment of solar sails

©D. Turse et al., 42nd Aerospace Mechanisms Symposium, 2014



S. A. Zirbel et al., 42nd Aerospace Mechanisms Symposium, 2014
Origami-Inspired

Drive mechanisms, power transfer

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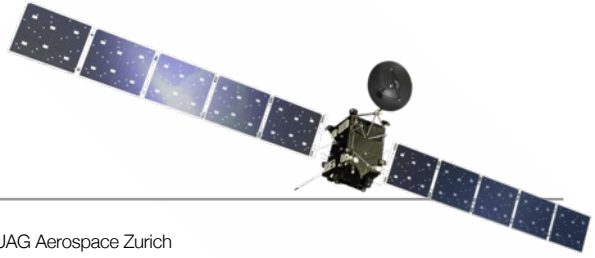

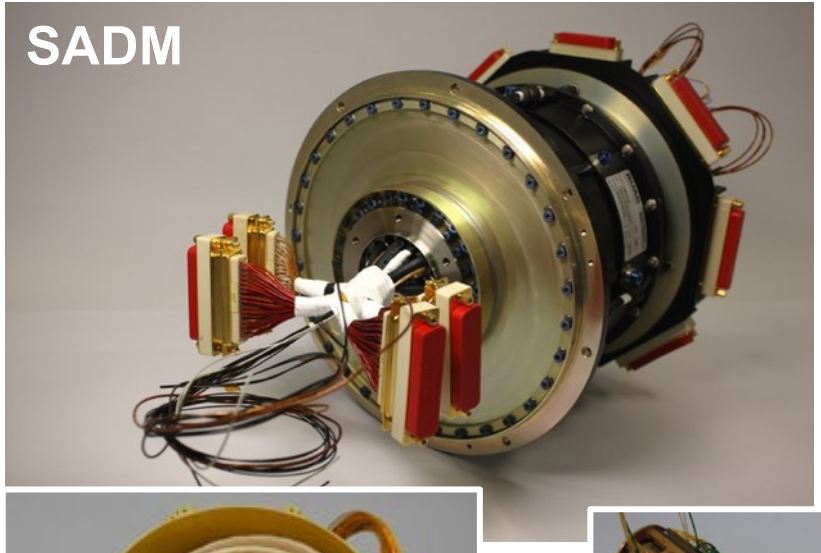

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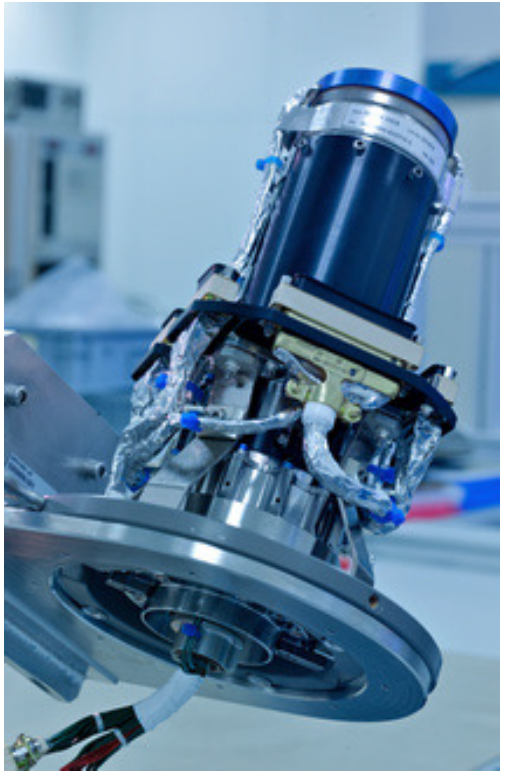

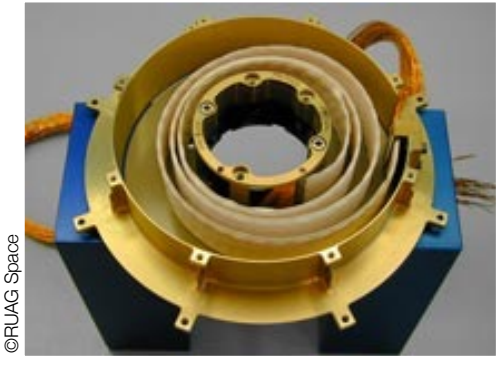

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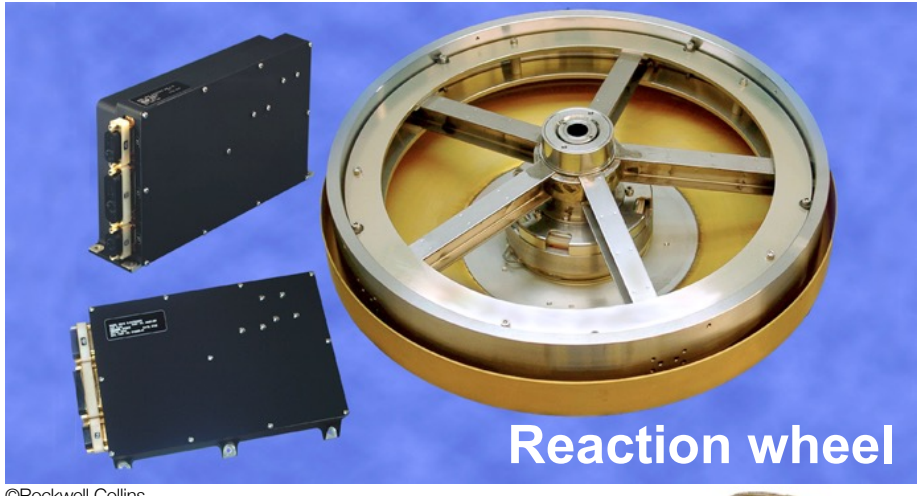
©C. Courtois et al., 16th ESMATS

Attitude control



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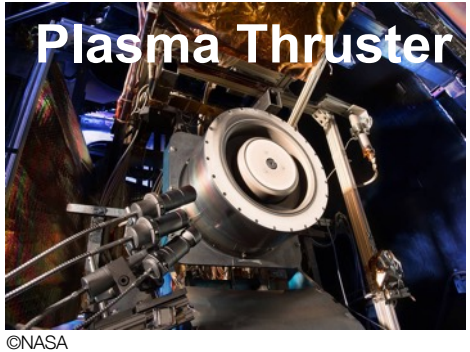

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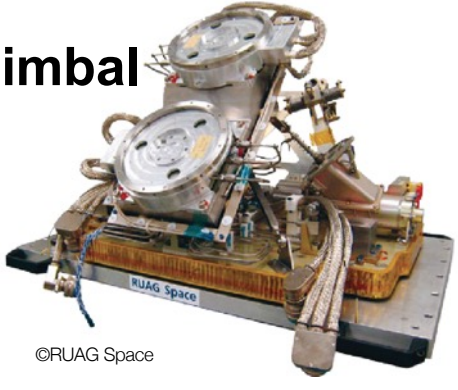
gimbal



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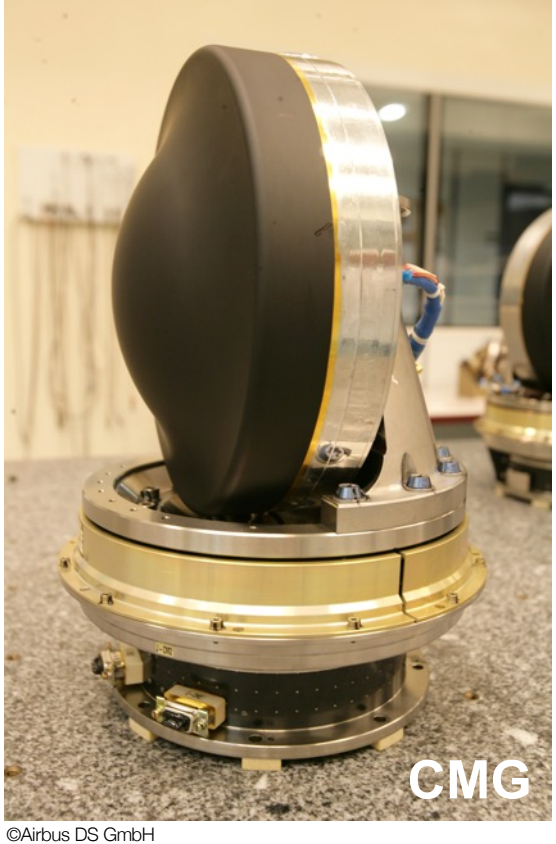

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Fluidic: valves for spacecraft propulsion

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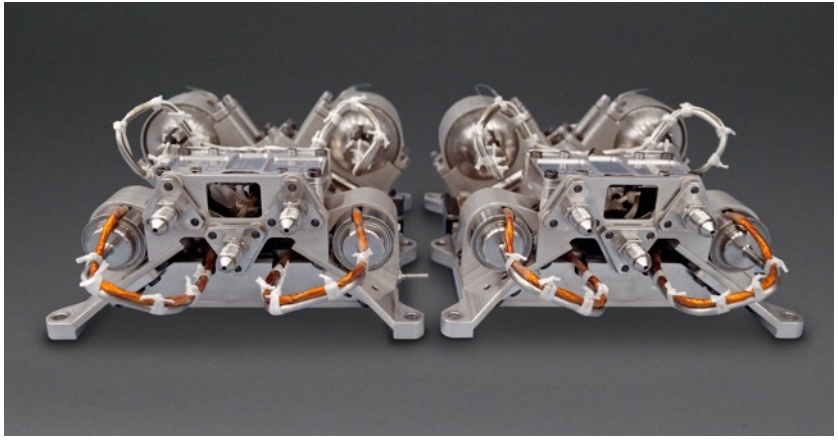

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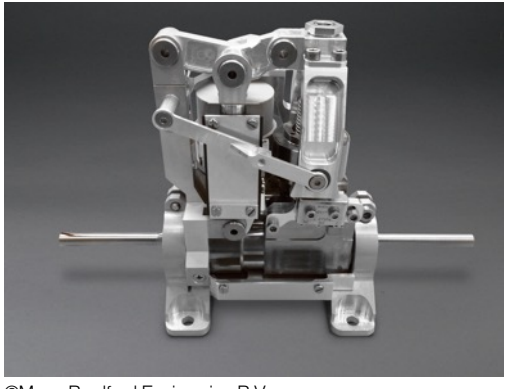

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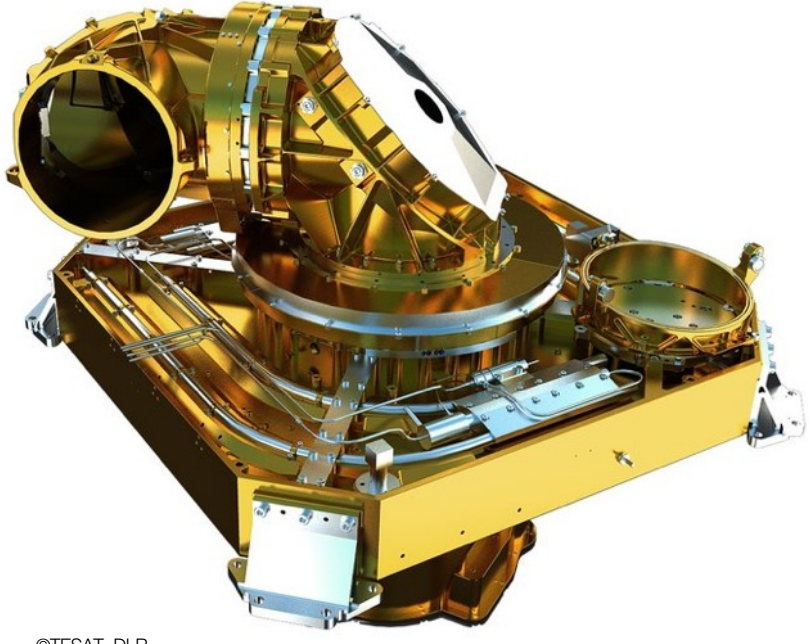
Payloads, communication



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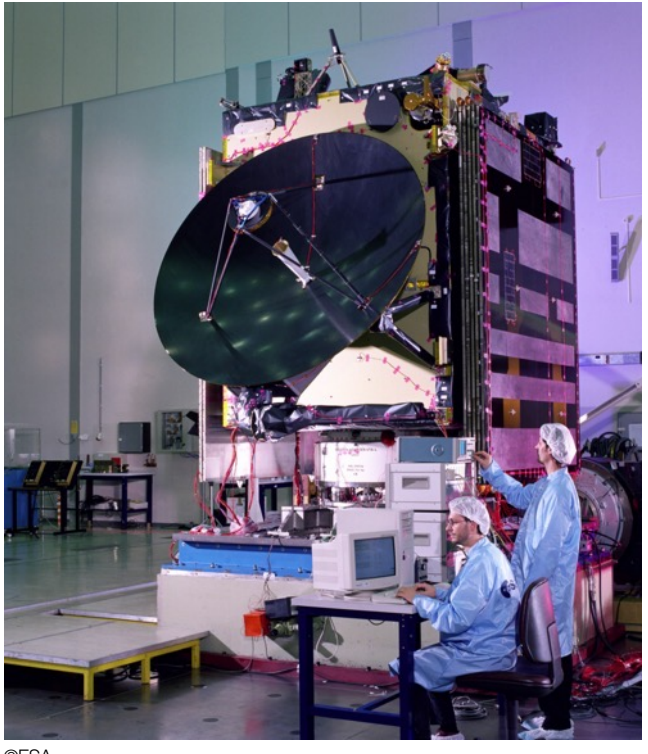
Optical

RF



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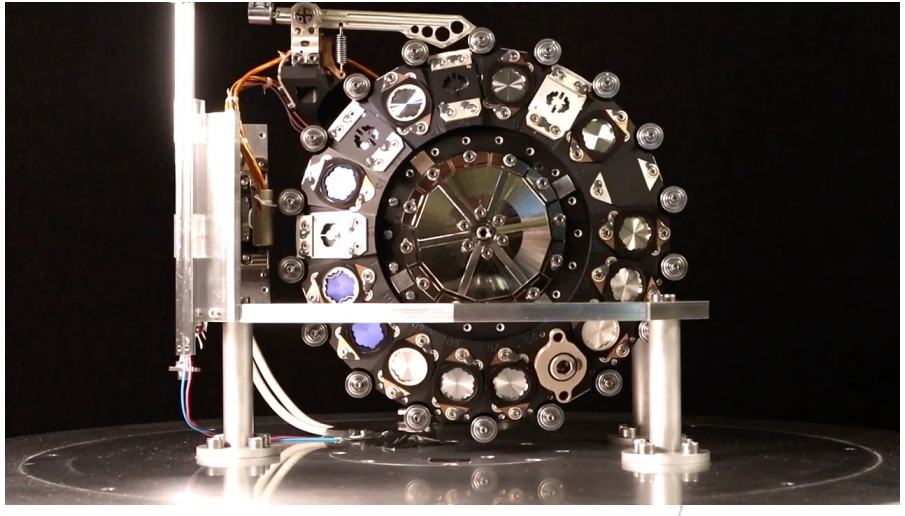
Optical payload – Filter assemblies



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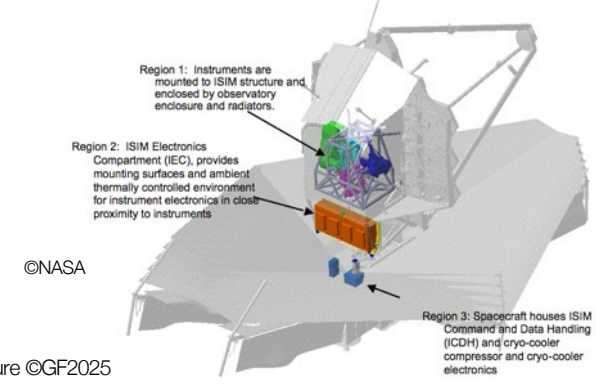

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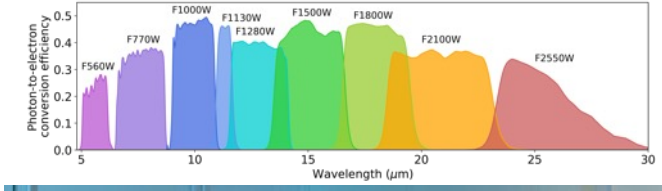
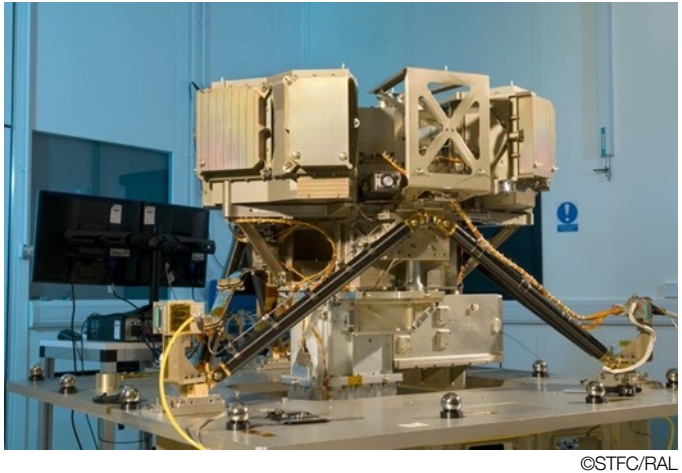
JWST MIRI Filter Wheel

Qualification Model



JWST User Doc



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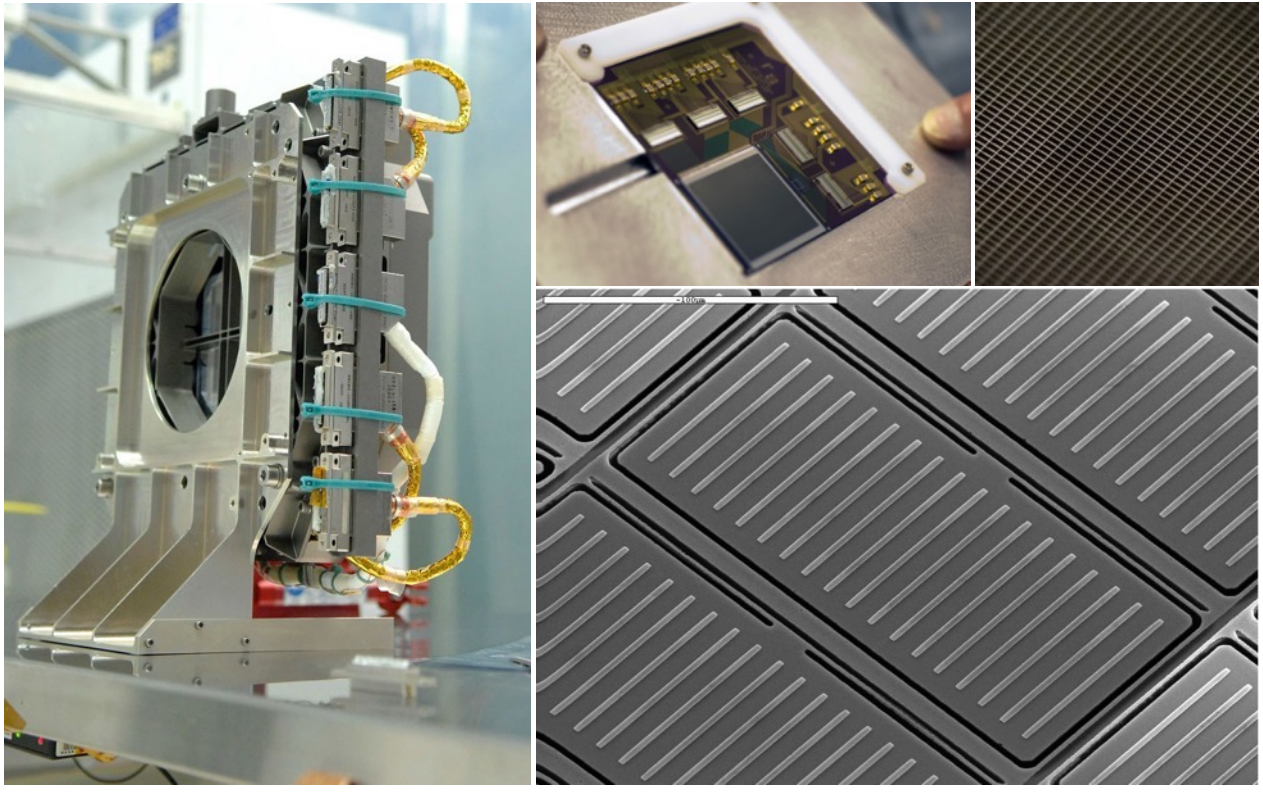
Optical payload – JWST: NIRSpec instrument microshutter (MEMS)



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Space Laboratory

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Columbus

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KUBIK

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Bioreactors

Biolab

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ISS Lab

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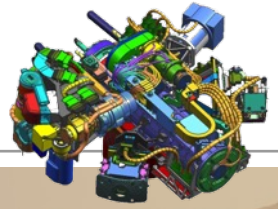
Planet exploration, robotic



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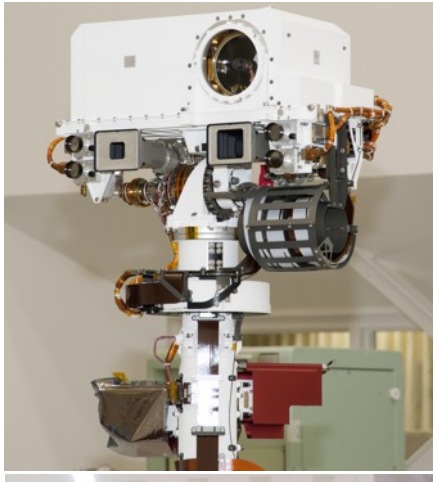
Mars Sample Return



MSL: Curiosity

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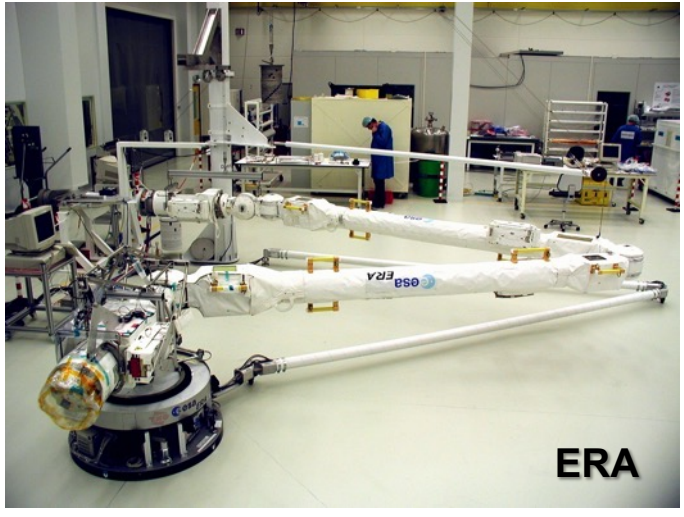
Space Robotic



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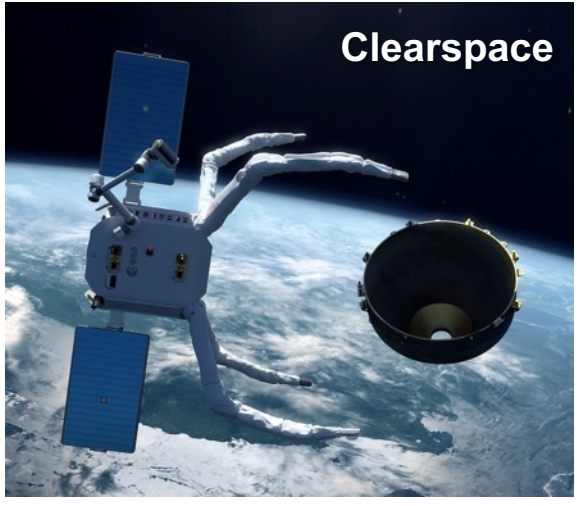

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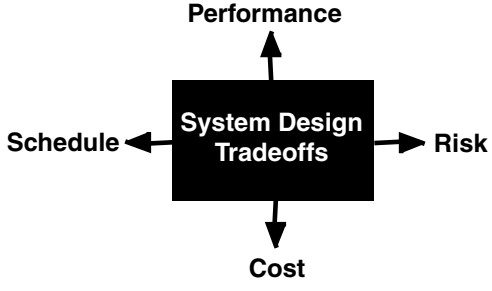
Parameters - Sizing

- Interfaces
- Thermal stability and loads
- Structural strength
- Tribology, wear
- Micro-vibration and noise
- Multi-body dynamics
- Cynematic



Mass ⟺ Size ⟺ Function ⟺ Reliability

Complexity ⇒ Risk

Bearings

- **Bearing types**
  - **Ball-bearings**
  - **Plain bearings**
  - **Flexure bearings**
  - **Magnetic bearings**

Credits for the images: Igus, Riverhawk Company, Schneeberger AG, SKF, S. Henein et al., Nanobeam 2002.

- **Ball-bearing materials:**
  - **440C stainless steel** is a martensitic high-carbon steel with up to 18 percent chromium, HRC 58.
  - **52100 high-carbon steel** is a 1 ½ percent chromium steel, HRC 60, greater wear resistance (gyros, ...) – Corrosion -> ***not recommended for space***
  - **Ceramic** (e.g. Si_3N_4) – Fragile

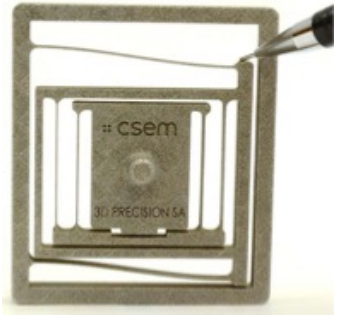
- **Limited electrical and heat conductivity** (λ ~ few hundredth of W/K). Depends on preload, material, lubricant. Varies with the rotation speed.
- **Drag torque, torque noise, running noise** -> control + microvibrations
- **Wear**

Compliant Mechanisms

Source: FreeFlex Pivot

Source: Ruland

Source: Almatech



Source: CSEM

Source: ESA

Compliant Mechanisms

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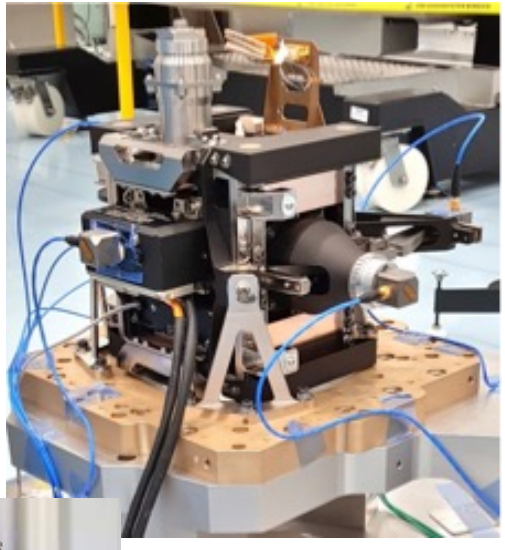

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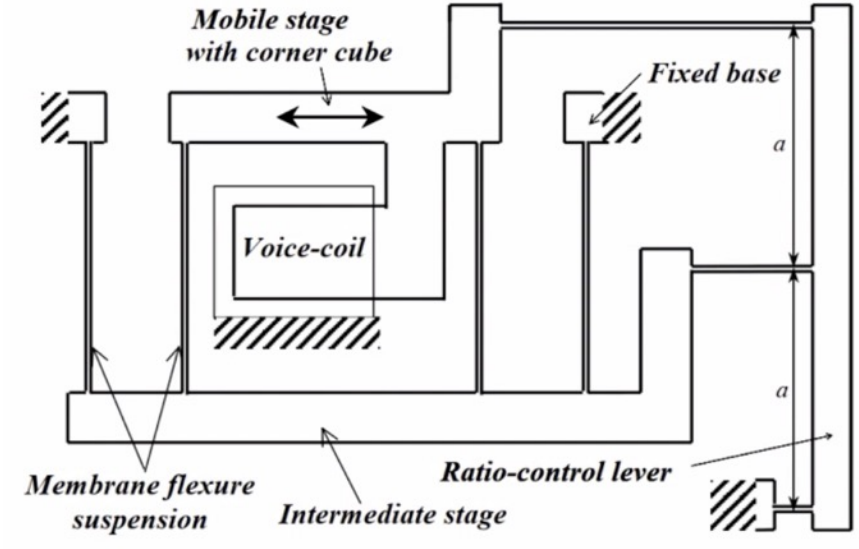
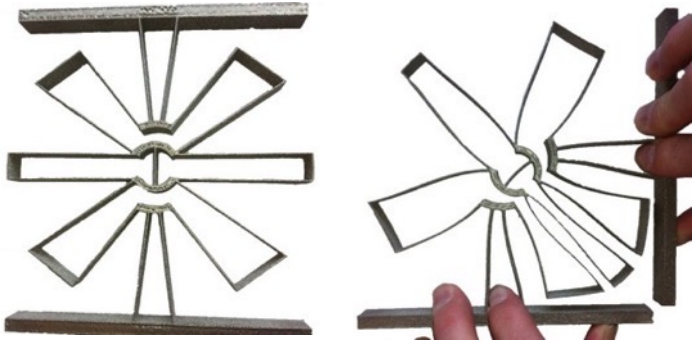


Source:
P. Spanoudakis et al. "*Design and Production of the METOP Satellite IASI Corner Cube Mechanisms*", European Space Mechanisms and Tribology Symposium, San Sebastian (2003)

ALM (3D printing)

Additive Layer Manufacturing



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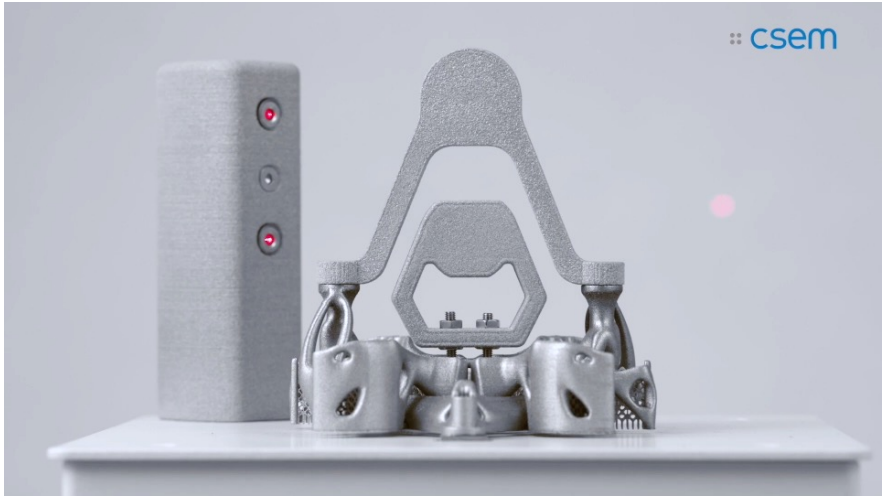
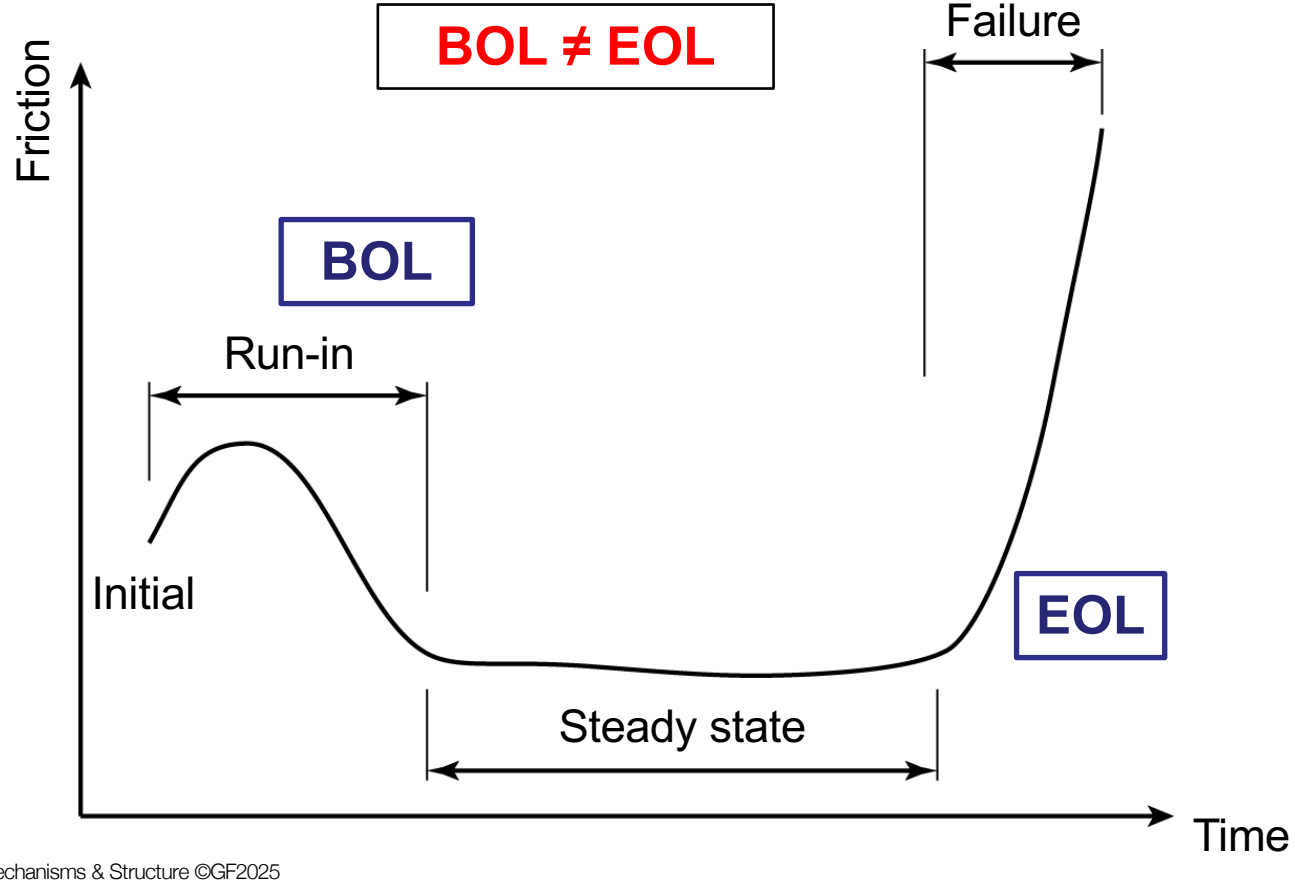


©CSEM

Wear of tribological contacts

- **Friction and Wear are function of:**
  - Contact load/stress
  - Hardness of the contact materials
  - Oxidation of the contact surfaces, oxidation film
  - Temperature
  - Atmospheric pressure (vacuum, ambient)
  - Environment (humidity, contamination, …)
  - Working conditions: vibrations, speed
  - Surface microstructure and condition
  - Pairing of the materials (e.g. electrochemical corrosion, cold welding …)
  - …

Wear of tribological contacts



Lubricants for space applications

- Volatility, evaporation: **outgassing**
- **Migration** (Creep: tendency of liquid lubricant to creep or migrate)
- **Viscosity** as a function of temperature
- Chemical **degradation**

  - **Maintenance free … (long lifetime …)**

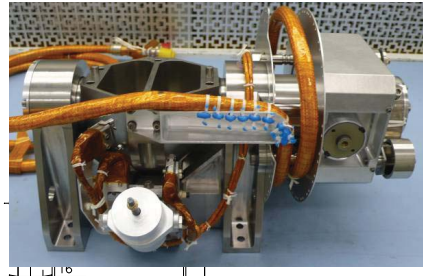
Lubricants for space applications

- **Dry Lubricants (Solid Lubricants)**
  - MoS_2, WS_2, ... Pb, Au, Ag …
- **Grease, oil** (specific ones, with low outgassing properties)
- **Ionic Liquids**
- **Self Lubricating Materials**
  - Polymers: PTFE (Teflon®), Polyamide (Vespel®), Phenolic, Torlon®, Peek® …
  - Metals: Bronzes
- **Coatings**
  - Resin bonded, Anodizing, Plasma coating, PVD, CVD, …

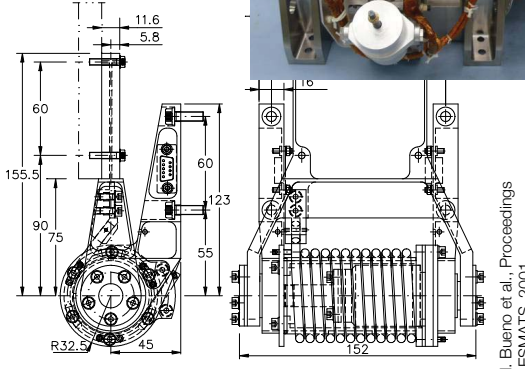
Actuators

- **Rotary**
- **Linear**

- **Types:**
  - **Electric and Magnetic**
  - **Hydraulic**
  - **Elastic Energy**
    - *Spring motor*
    - *Compliant structure, self deployable structure*
  - **Thermal**
    - *Bimetal*
    - *Paraffin actuator (volume expansion of solid-to-liquid phase change)*
    - *Shape memory alloy (SMA)*
  - **Pyrotechnic**

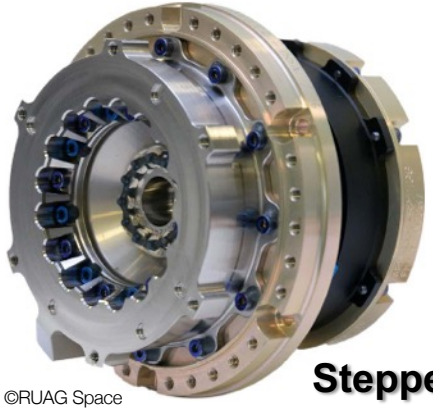


©J. A. Johnson, Proceedings of the 39th AMS, NASA Marshall Space Flight Center, 2008.



Source J.I. Bueno et al., Proceedings of the 9th ESMATS, 2001

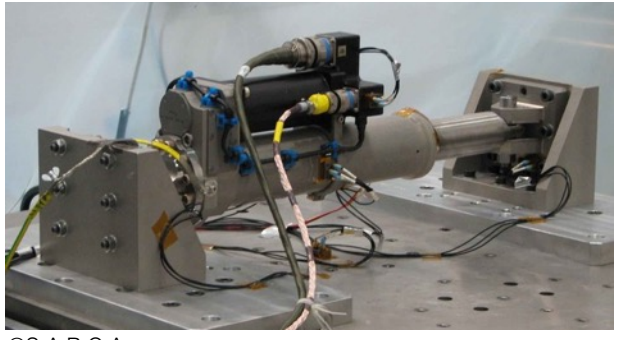
Electromagnetic Actuators



©RUAG Space

Stepper

©Harmonic Drive



©S.A.B.C.A.

Brushed DC
(encapsulated)

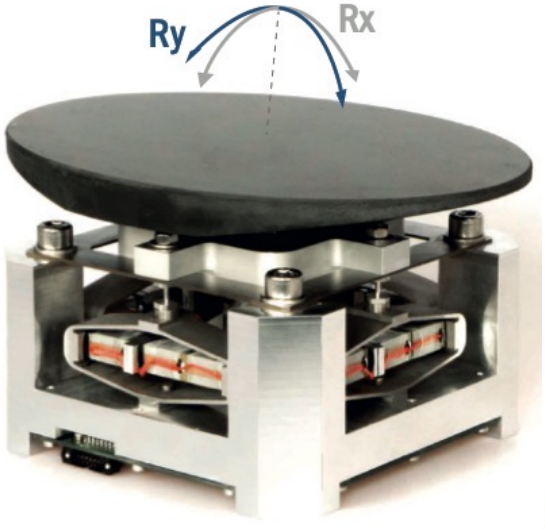
©Soterem

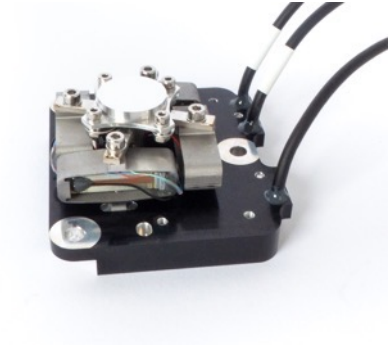
©Avior Contol Technologies, Inc.

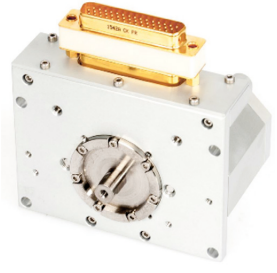
©CEDRAT Technologies

©CEDRAT Technologies

Piezo-electric Actuator







Sources: Cedrat Technologies

Cf. https://www.cedrat-technologies.com/en/technologies/actuators.html

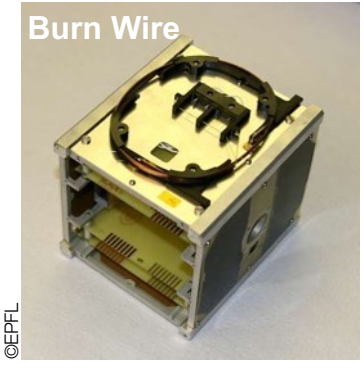
Thermal Actuator

©A. Blanc et al., 15th ESMATS

©Sierra Nevada Corporation

©TiNi Alloy Company

©Arquimea



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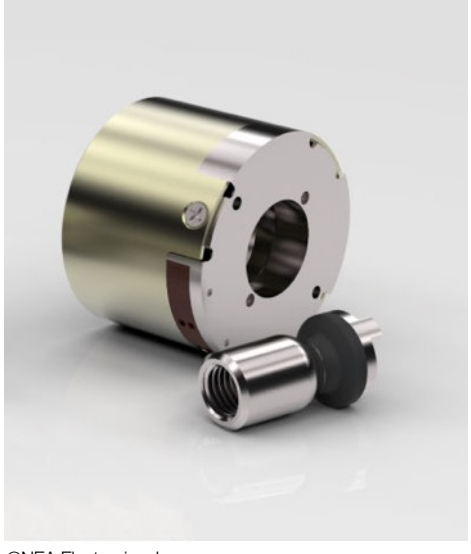
SMA: Shape Memory Alloy

Pyro-actuators

Hold Down & Release Mechanism

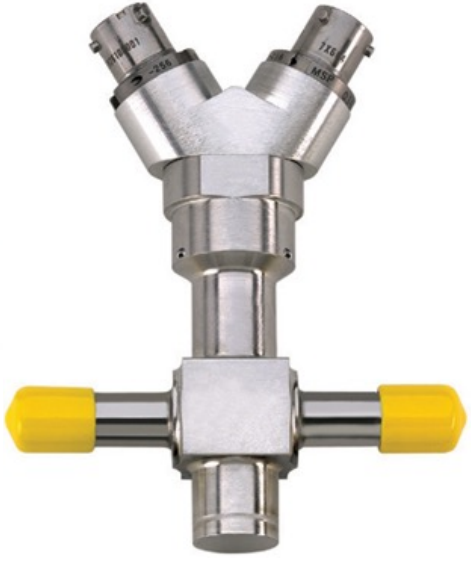


©NEA Electronics, Inc.

Cable cutter

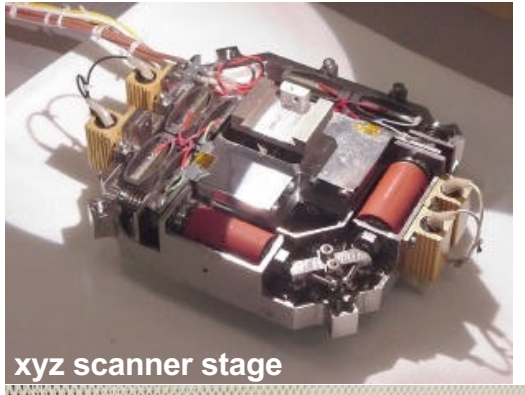
©PSEMC

Pyrovalve

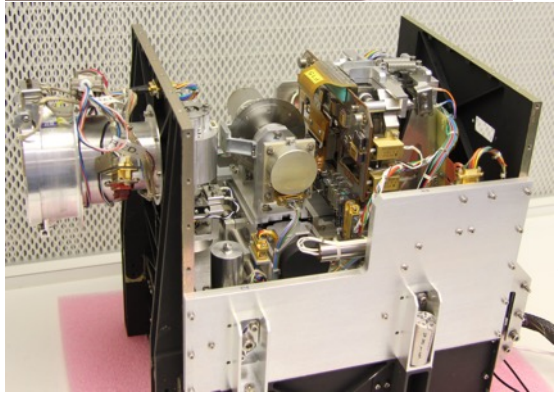


©Cobham Group

Example: ROSETTA – MIDAS Instrument



©H. Arends et al., 9th ESMATS

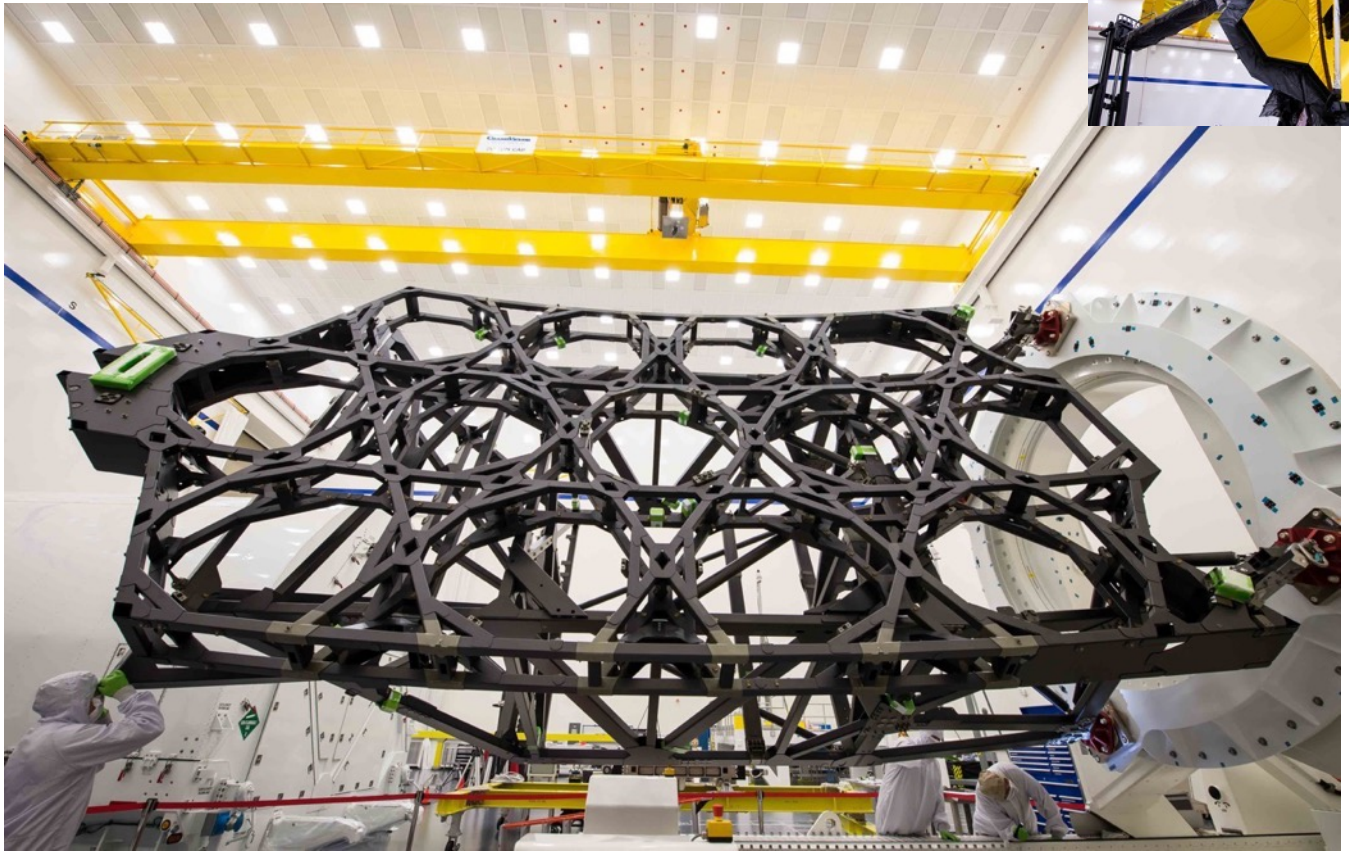


©Mark Bentley/Institut für Weltraumforschung, Österreichische Akademie der Wissenschaften, Graz, Austria

The MIDAS instrument contains 7 different mechanisms:

1. Cover to keep the funnel closed and clean in prelaunch and launch conditions. Released with a **Pyro-Piston Actuator**.
2. Shutter to control deposition time of the dust flux on the target wheel. Operated by a **Piezo-Electric motor**.
3. Wheel assembly includes a **Piezo-Electric motor** and an Incremental Encoder.
4. Translation stage for tip selection. Operated by a **Piezo-Electric motor**.
5. Approach mechanism for the coarse approach of the tips to the samples. Operated by a **DC brush-motor** in a hermetically sealed pressurised container.
6. XYZ scanner for three-dimensional scanning of the sample. Operated with three **Piezo-electric actuators**. Two **SMA**'s are implemented for launch-lock of the X and Y scanner.
7. Clamping mechanism to fix the AFM-baseplate before and during the launch. Two **paraffin actuators** release all 4 clamps.

Structures



© Chris Gunn, NASA's Goddard Space Flight Center

Reducing the mass: material selection

- *Ideal case:*
  - **Maximum strength**
    - σ_{max} as high as possible
    - σ_{max} can be $\sigma_{0.2}$ (yield strength) or σ_u (ultimate strength)
  - **Minimum mass**
    - ρ minimum (low specific mass)

$$\frac{\sigma_{max}}{\rho}$$ as high as possible

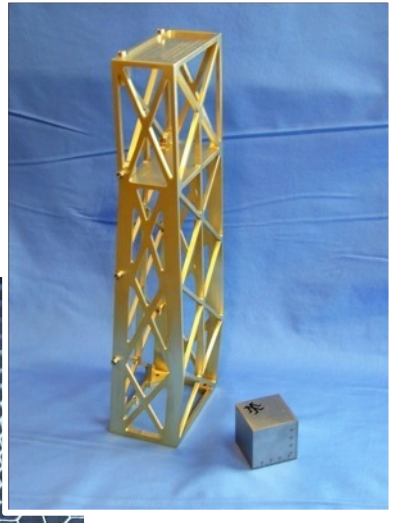
Various sources, for order of magnitude only

Material	σ_{max} [MPa]	ρ [kg/m^3]	σ_{max} / ρ	Comments
Polyimide (Vespel SP-1)	86.2	1430	0.06	@ room temperature
INCONEL 718	980	8190	0.12	@ 650° C
Beryllium	240	1844	0.13	Very high stiffness, very brittle
Al-Li 8090 T8151	370	2540	0.15	Difficult supply, low corrosion strength
High strength stainless steel (15-5-PH)	1140	7800	0.15	Metallurgical state > H1000 or limited corrosion strength
Aluminum Series 7000 T73	435	2810	0.15	Limited stress corrosion cracking strength
Stainless steel (440C)	1280	7800	0.16	
TA6V	1000	4430	0.23	Solution treated and aged
Carbon Fiber Reinforced Polymer (CFRP)	400-2800	1500-1800	0.27-1.9	Complex technology

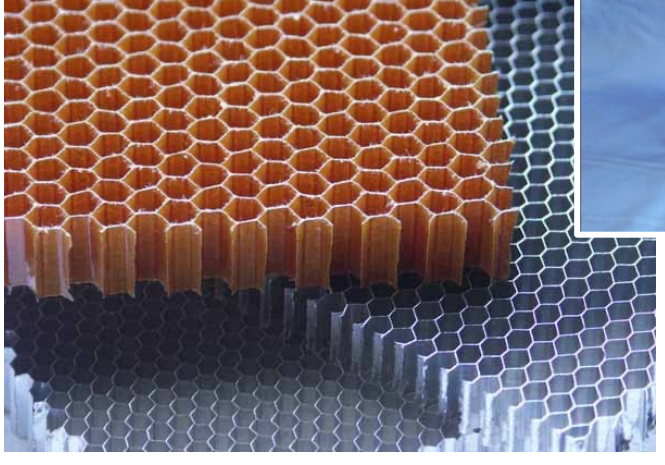
Reducing the mass: adapting the geometry

- Remove excess mass
  - Machining of pockets
  - Thin parts with ribs
  - Suitable assembly methods
    - Monolithic
    - Welding
    - Riveting
    - Gluing
    - Screwing
  - Additive manufacturing
  - Use of advanced composite materials
    - Honeycomb
    - Structural polymers
    - Carbon Fiber Reinforced Polymer (CFRP)

Source: M.E. Orme et al. “Additive Manufacturing of Lightweight, Optimized, Metallic Components Suitable for Space Flight”, Journal of Spacecraft and Rockets Vol. 54, No. 5, September–October 2017



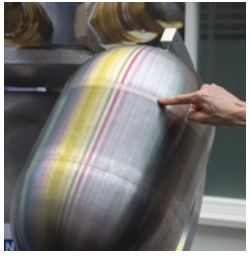
: ©Mecanex SA



Assembly of structures

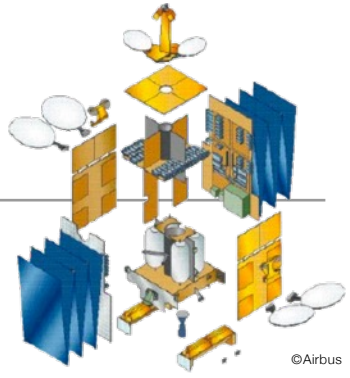
- **Monolithic**
  - Machined from billet
    - ***Advantage:*** no assembly elements (always critical)
    - ***Drawback:*** complex machining
  - Additive Manufacturing
    - ***Advantage:*** very complex geometry can be achieved, topology optimization, no assembly (geometry complexity ≠ manufacturing complexity)
    - ***Drawback:*** post-processing required, complex product assurance
- **Assembly of parts** (always critical processes requiring qualified personal)
  - **Welding**:
    - Metallurgical transformation with the creation of lower strength area
    - Risk of corrosion
    - Incompatible materials (e.g. Al-Li)
  - **Riveting**
    - Highly elaborated and well-known technology (aerospace).
    - Highly dependent on qualified personal
    - Risk of stress corrosion cracking. Surface finish and cleanliness are key
  - **Gluing**
    - Highly dependent on surface finish (cleanliness, presence of a potential primer, surface roughness, …)
    - Selection of the glues with respect to the use
    - Risks during operations: aging under radiations, thermal degradation, softening (e.g. glass transition temperature, chemical modifications …) …

Source: RUAG Group

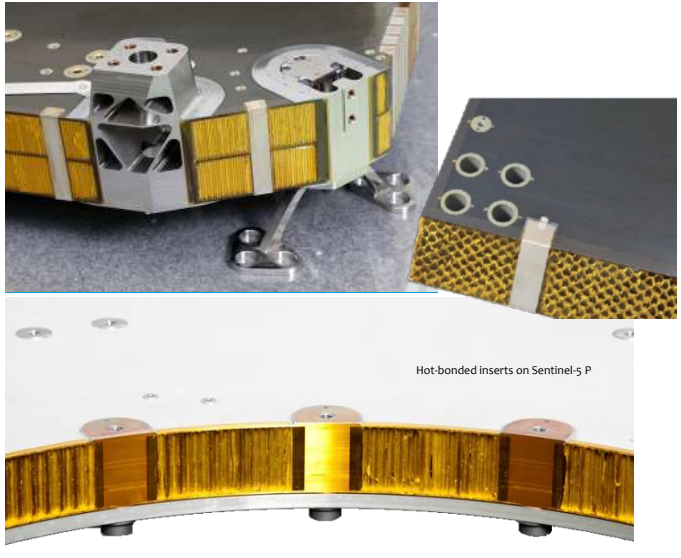


Source: ESA–G. Porter

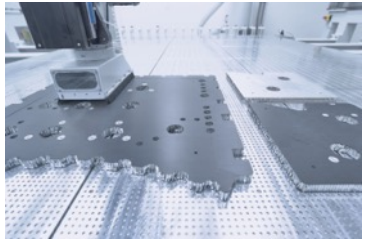
Assembly of structures

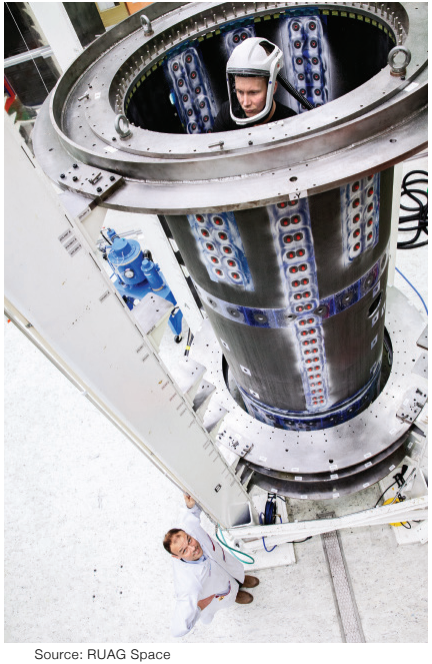

©Airbus

- Example of assembly
  - Inserts and threaded inserts glued into a CFRP honeycomb structure



Source: APCO Technologies




Source: RUAG Space

Space Mechanism & Structure Standards

- **European Cooperation for Space Standardization (ECSS)** https://ecss.nl
  - **ECSS-E-ST-33-01C** - Space engineering: **Mechanisms**
  - **ECSS-E-ST-32C** - Space engineering: **Structural general requirements**
  - ECSS-E-ST-10-03C - Space engineering: **Testing**
  - ECSS-Q-ST-70 - Space product assurance: **material, mechanical part and process**
    - ECSS-Q-ST-70-36 - Space product assurance: Material selection for controlling stress corrosion cracking
    - ECSS-Q-ST-70-37 - Space product assurance: Determination of the susceptibility of metals to stress corrosion cracking
    - ECSS-Q-ST-70-71 - Space product assurance: Data for selection of space materials and processes
  - …
- **Others (NASA, MIL, …)**

+ various handbooks (ECSS, NASA, …)

Testing

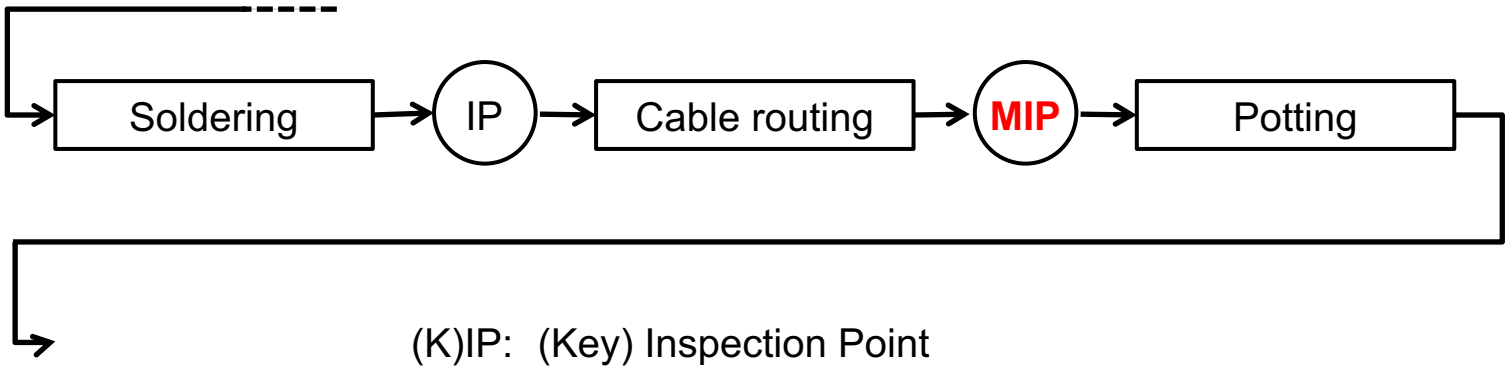
- Functions
- Interfaces
- Vibration
- Shocks
- Thermal vacuum
- Lifetime

©Melissa & Doug

Model and MAIT Philosophy

- **BBM, EM, STM, QM, EQM, PFM, FM ...**
  - **Early stage fit and functions: concepts, principle of operations, cable routing, ...**

- **MAIT Plan, Sequence of Integration**
  Manufacturing, **A**ssembly, **I**ntegration and **T**esting



(K)IP: (Key) Inspection Point

MIP: **Mandatory Inspection Point** (ECSS-Q-ST-20C)

Dependability … Reliability, Safety

- **Redundancy most of the time impossible to implement**
  - **Fail-Safe**
  - **Single Point of Failure**

- **Failure mode, effects and criticality analysis (FMECA) -** *ECSS-Q-ST-30-02C*

- **Safety (manned flight, ground equipment, launch vehicles, …)**
  - **Hazard scenario,**
  - **Likelihood,**
  - **Severity.**

  } ⇒ **Magnitude of safety risk**

Conclusion

- **Mechanisms are never perfect**
  - Dimensions, mass
  - Stiffness
  - Non-linearities, backlash
  - Tribology, Wear
  - Microvibrations
  - Reproducibility
- **Mechanisms are potentially single point of failure (SPF)**
- **Complexity = Risk**
- **Challenges of structures**
  - Strength
  - Deformations, including thermo-elastic deformations
  - Mass
  - Assembly

☞ **Test, test, test …**