Challenges of tribology in Space Mechanisms

Lionel GAILLARD

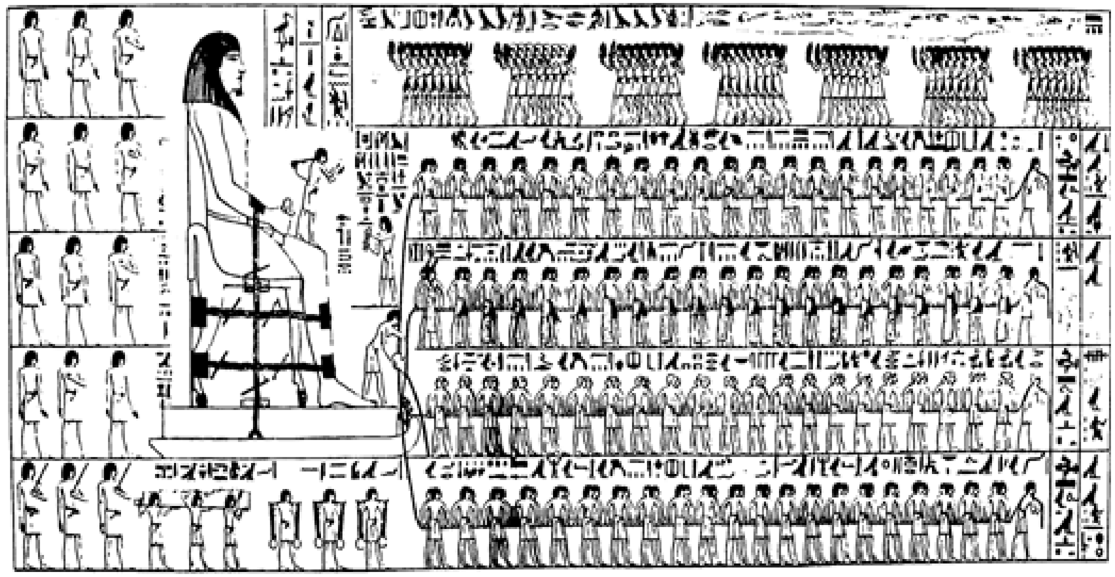
Head of the Mechanisms Section @ ESA/ESTEC

KIVI 03/11/2016

What is Tribology?

- Tribology = Tribos (to rub) + logos (study of)
- (*Jost Committee Report, a definition in 1966*) 'The science and technology of interactive surfaces in relative motion and related subjects and practices'
- But Tribology didn't start in 1966 - it's been around for ages...

Transporting an Egyptian Colossus c.1900 BC



Colossus weighs ~ 6 x 10^5N

172 slaves

Each slave pulls with ~800N

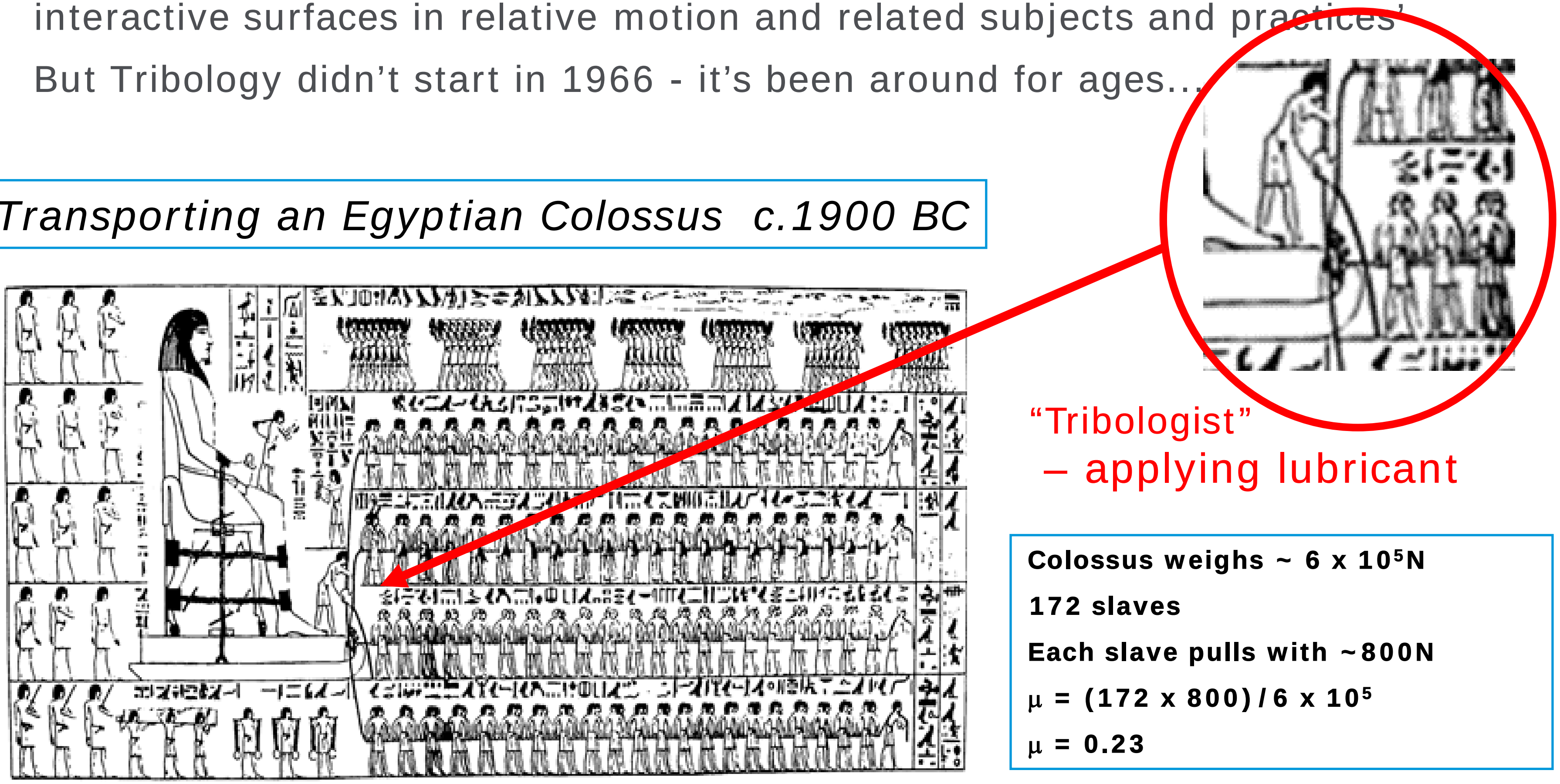
μ = (172 x 800) / 6 x 10^5

μ = 0.23

What is Tribology?

- Tribology = Tribos (to rub) + logos (study of)
- (*Jost Committee Report, a definition in 1966*) ‘The science and technology of interactive surfaces in relative motion and related subjects and practices’
- But Tribology didn’t start in 1966 - it’s been around for ages…

Transporting an Egyptian Colossus c.1900 BC



“Tribologist” – applying lubricant

Colossus weighs ~ 6 x 10⁵N

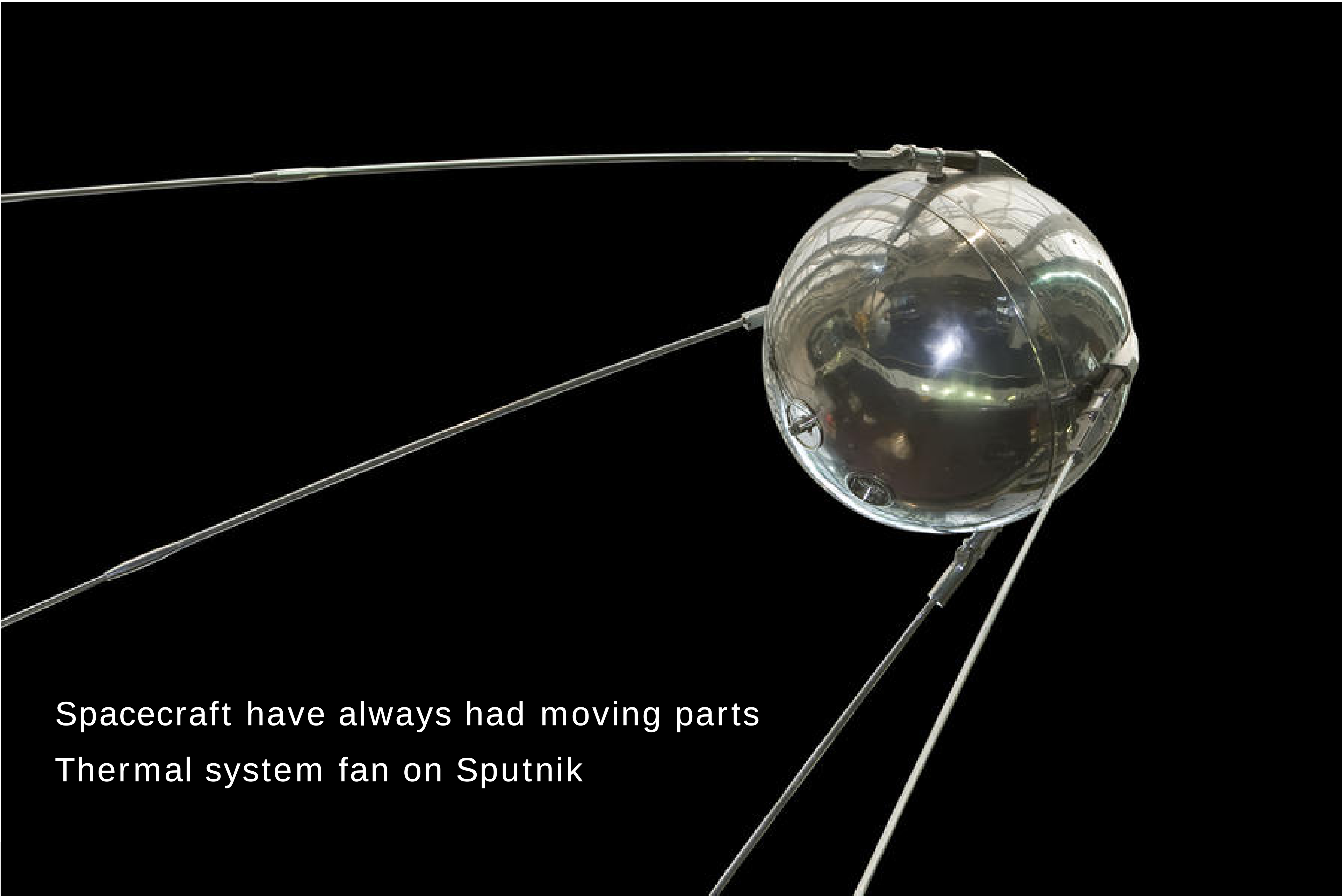
172 slaves

Each slave pulls with ~800N

$\mu = (172 \times 800) / 6 \times 10^5$

$\mu = 0.23$

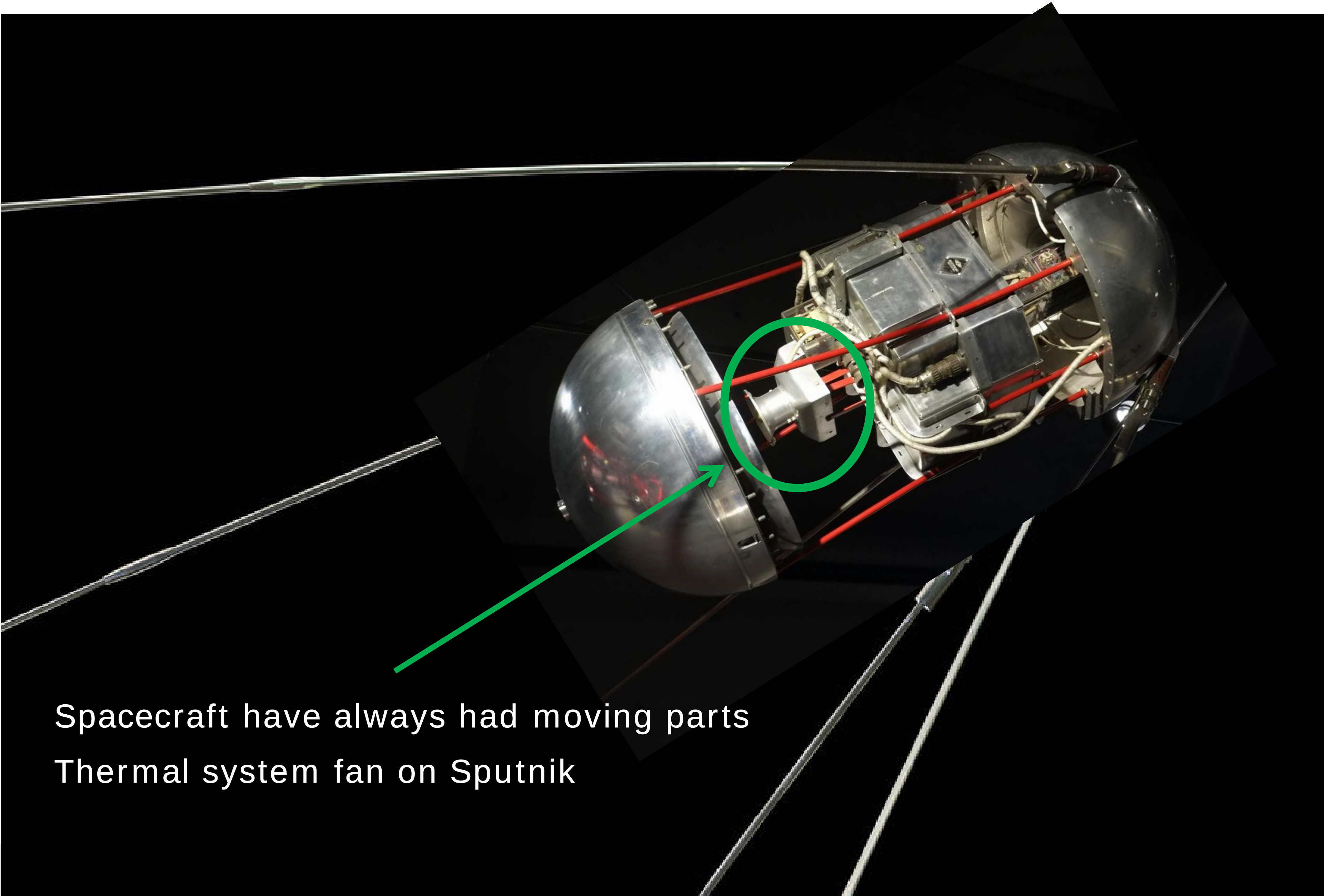
Mechanisms on Spacecraft



Spacecraft have always had moving parts

Thermal system fan on Sputnik

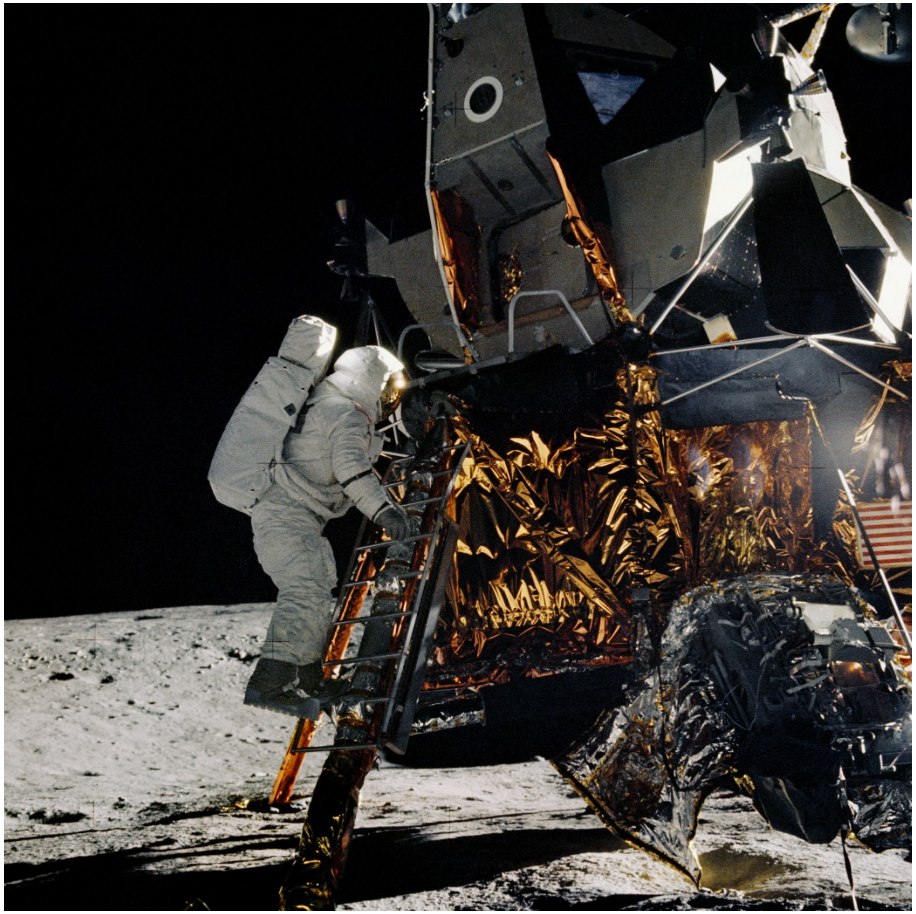
Mechanisms on Spacecraft



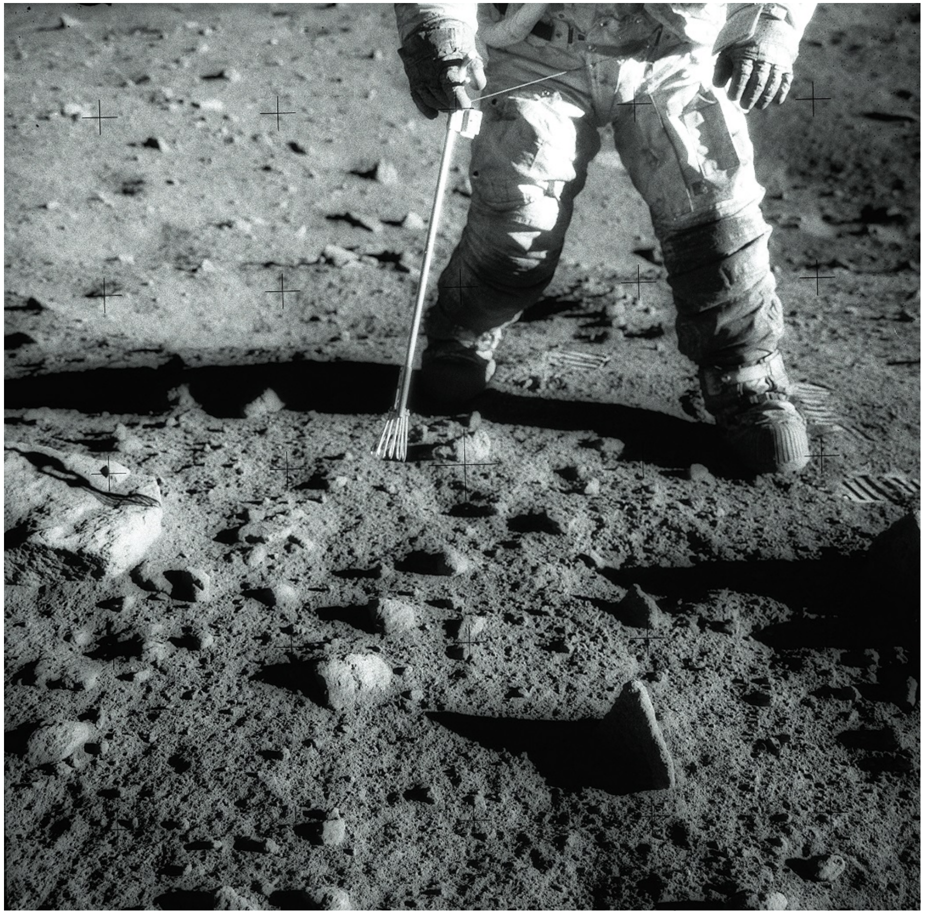
Spacecraft have always had moving parts

Thermal system fan on Sputnik

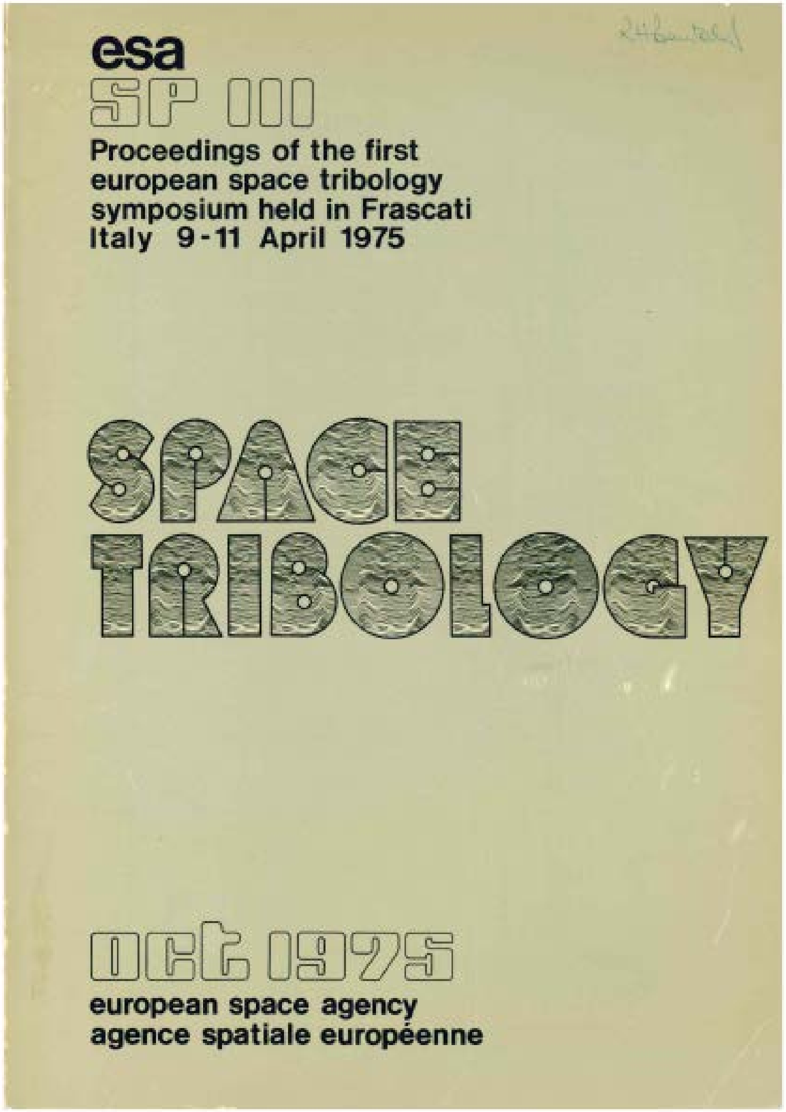
Apollo Program (1961-72)

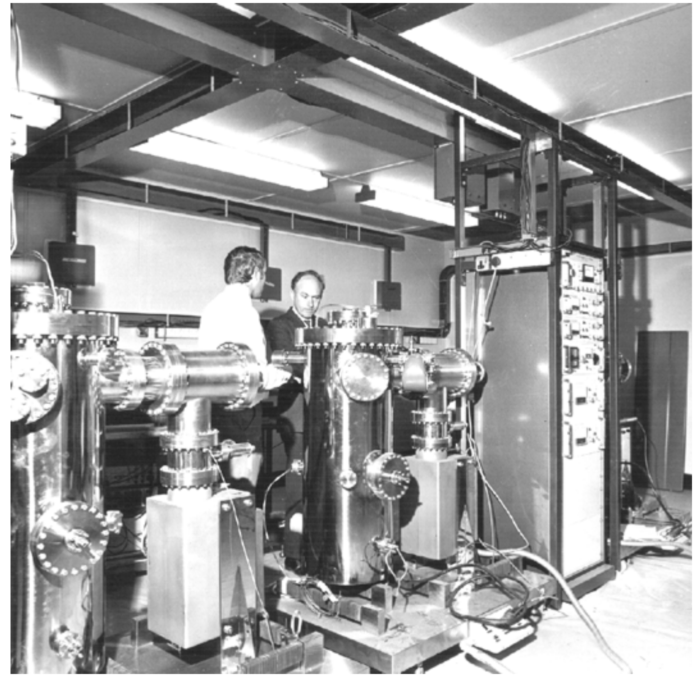


- Moon dust highly abrasive
- Affected seals, optical surfaces and interlocking components



Tribology in Europe ... ESA and ESTL

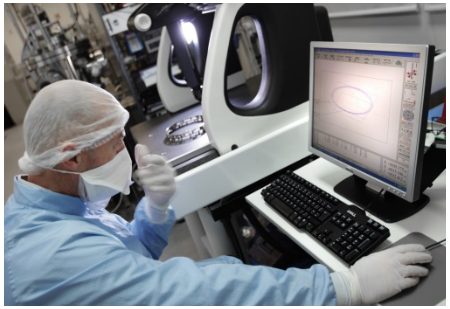


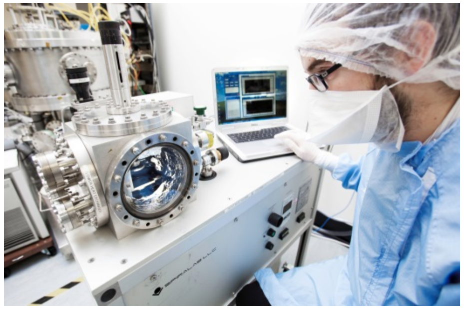


European Space Tribology Laboratory (ESTL)
Was established in 1972 and still active today

<u>Fundamental objective :</u>
"*to increase the efficiency and reliability of spacecraft through the application of good tribology*"

European Space Tribology Laboratory (ESTL)

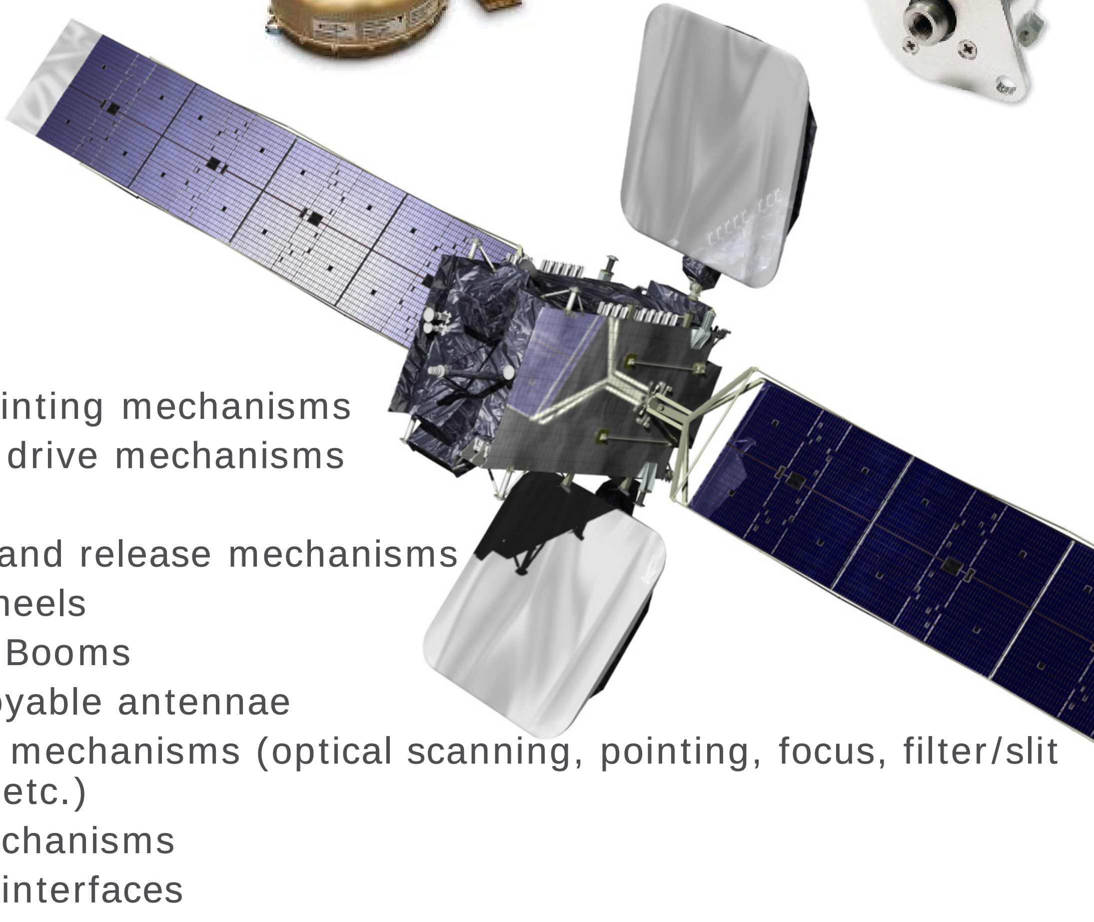




Mechanisms on today Spacecraft





- Antenna pointing mechanisms
- Solar array drive mechanisms
- Hinges
- Hold down and release mechanisms
- Reaction wheels
- Deployable Booms
- Large deployable antennae
- Instrument mechanisms (optical scanning, pointing, focus, filter/slit positioning etc.)
- De-spin mechanisms
- Separation interfaces
- ...& many more!

Mechanisms on Spacecraft variety

A wide range of applications and life-times:

1 shot → ~10,000,000,000 revs

(>15 years)

All rely on a knowledge of friction and wear within the system and understanding of expected lifetime under the required operating conditions.

Where Spacecraft Mechanisms operate

On Ground:

Manufacturing/Assembling (cleanroom environment)

Extensive testing (includes thermal vacuum and simulated launch)

Transportation (controlled temperature and humidity)

Storage (months to decades)

Integration at launch site (cleanroom)

Planetary protection (biologically clean for planetary missions)

Then:

Launch (high levels of vibration and shocks, Pressure decrease)

Finally:

Vacuum (~10^{-7} to 10^{-13} mbar)

Atomic Oxygen

Reactive environments (planetary missions may experience CO_2, H_2, traces of CH_4)

Temperature extremes (and high thermal gradients)

Radiation

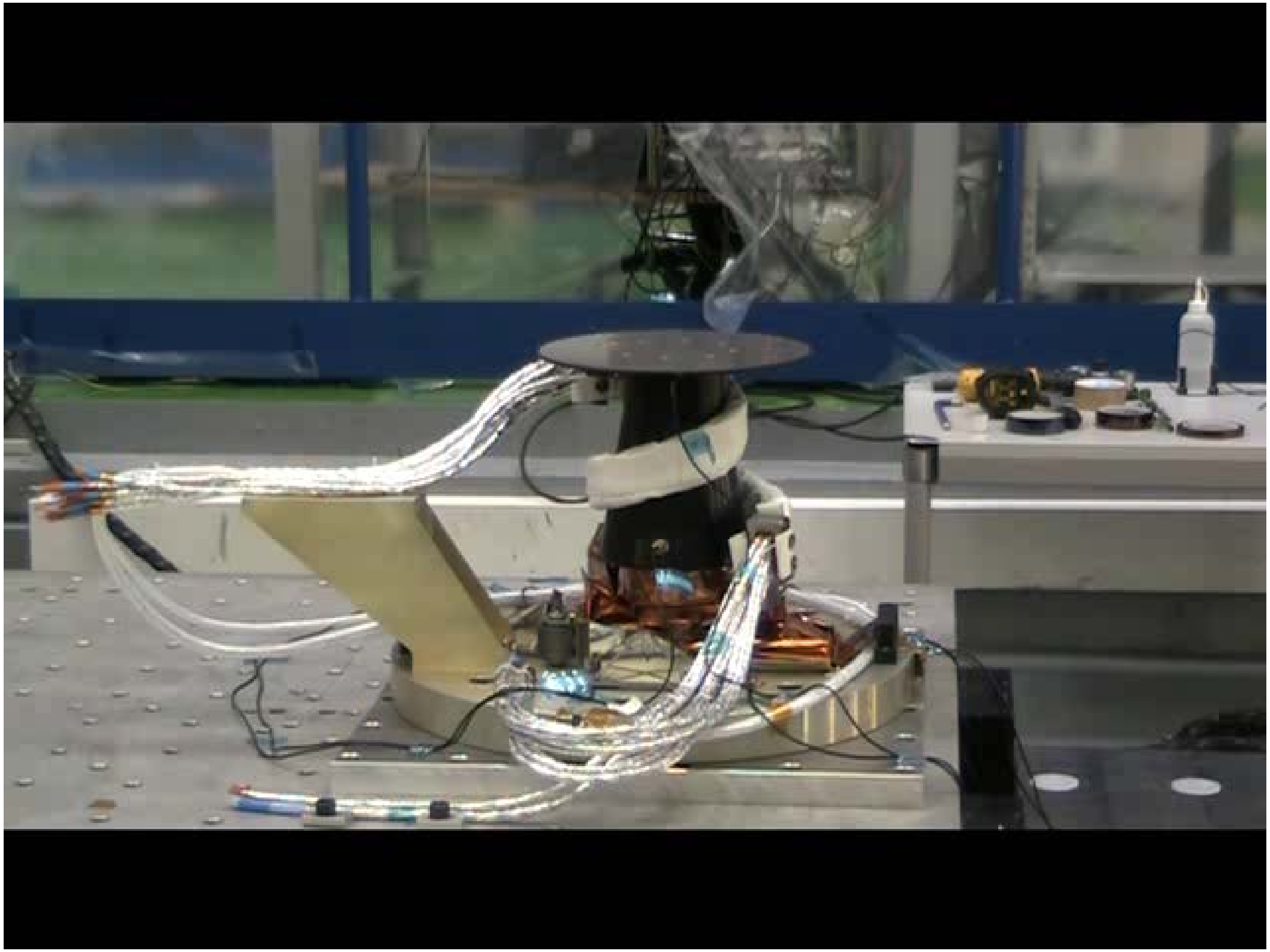
Prolonged Stasis (long inactivity, followed by “must work” moment)

Micro-meteorite impacts …

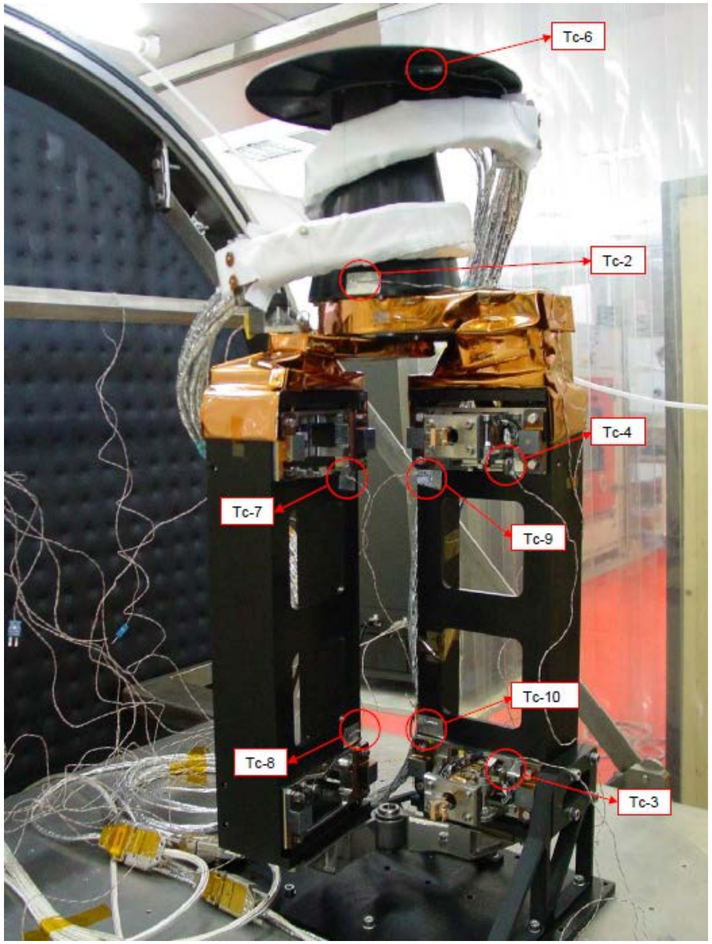
Example of mechanisms operation in space

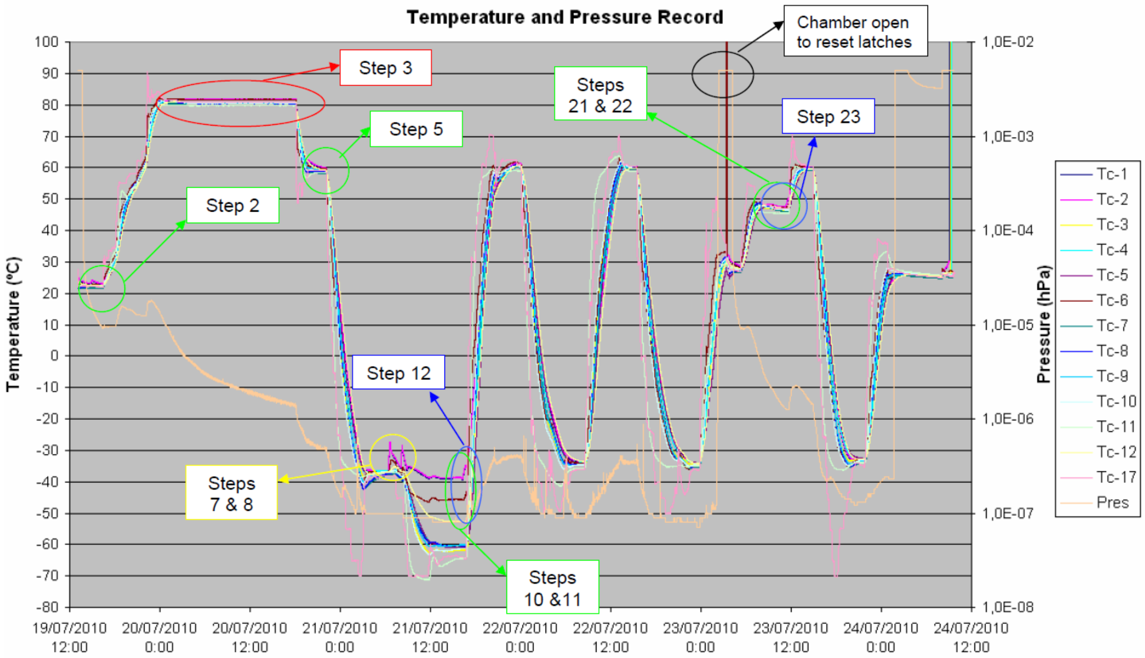
Mechanisms test on ground

Vibration test on ground, example

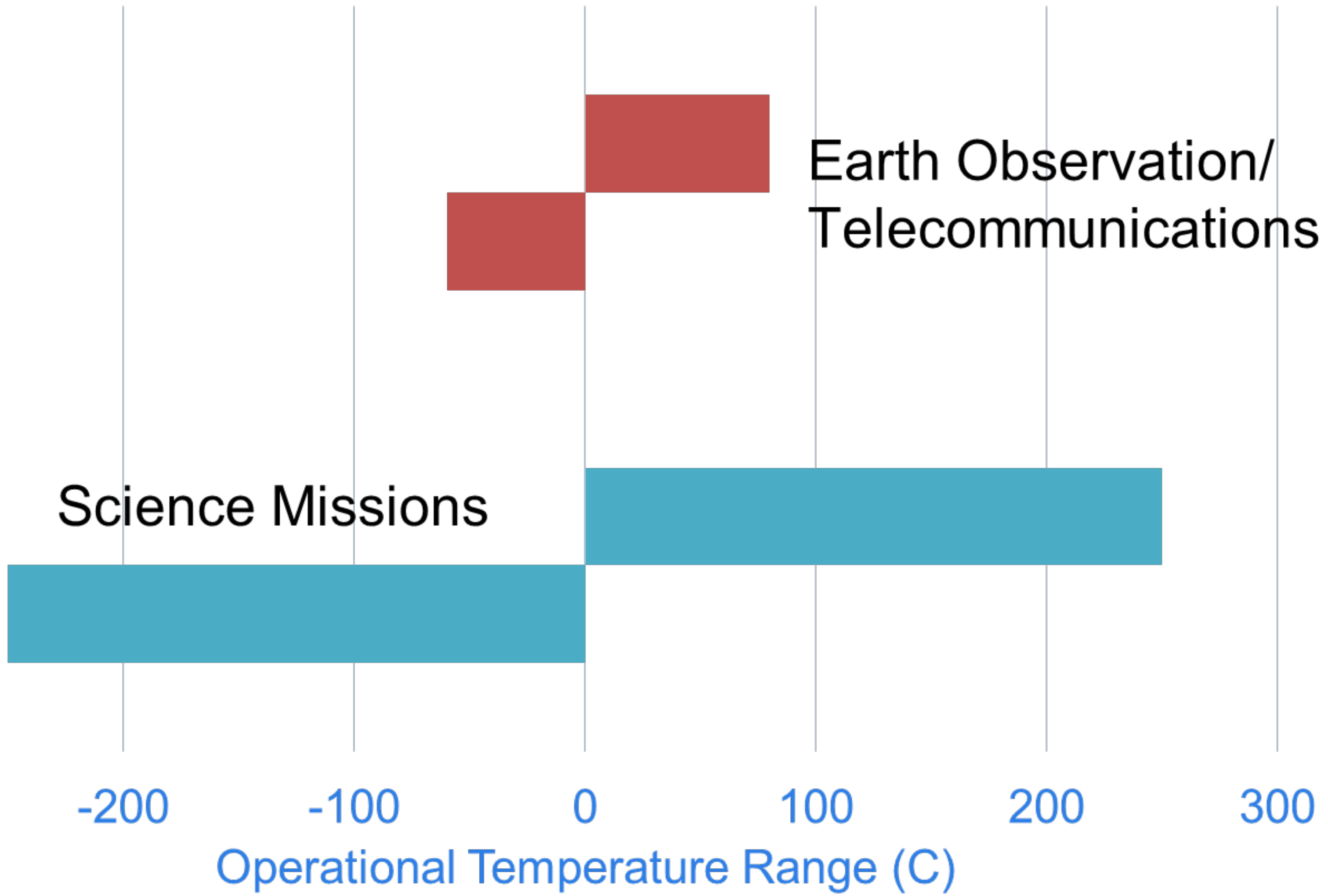


Thermal Vacuum





Typical Temperature ranges



Lubrication – On Earth

Definition:

'Apply a substance such as oil or grease to (an engine or component) so as to minimize friction and allow smooth movement'

(Oxford English Dictionary)

…Better Definition (permits solids):

'*The separation or protection of surfaces in relative motion, in order to reduce friction and wear*' or better control it (less variation)

BUT

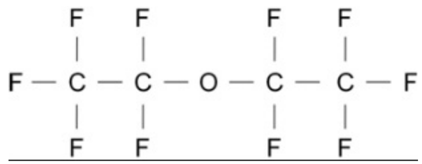
Conventional oils (and greases) would evaporate within seconds in the vacuum of space leaving a dry unlubricated mechanism and producing gross contamination of their surroundings.

So what CAN we use in space?

Fluid Lubricants (oil or grease) for Space

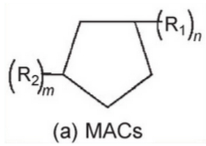
Multiply-Alkylated Cyclopentanes (MACs) or PerFluoroPolyEther (PFPE)

- Synthetic, long chain, chemically stable and inert oils, e.g. MACs and PFPEs (and greases derived from them, often thickened by PTFE).
- VERY low volatility
- Stability to shear and extreme pressures
- Typical Temperature
  - Minimum >~-60°C
  - Maximum ~ +80 to +100°C
- **BUT**
- Increasing viscosity when cold and evaporation limits high temperature



part of a linear **PFPE** molecule in simplified form

- Very very low volatility
- Long life in vacuum

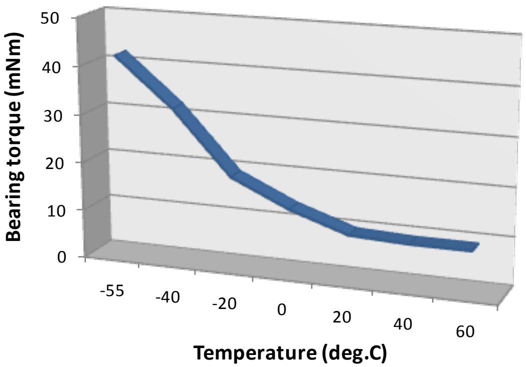


where R_1 and R_2 are hydrocarbyl groups

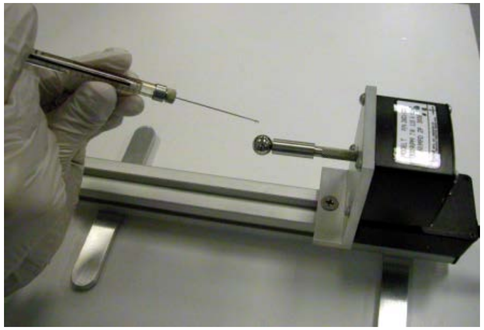
- Very low volatility
- Very Long life in vacuum

Benefits:

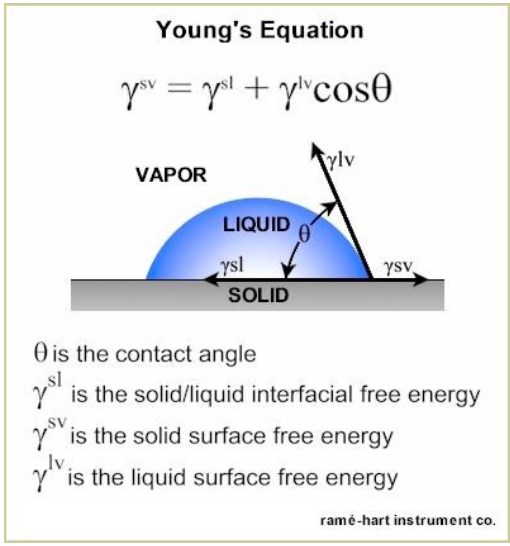
- High thermal conductance
- Super smooth operation (low torque noise)

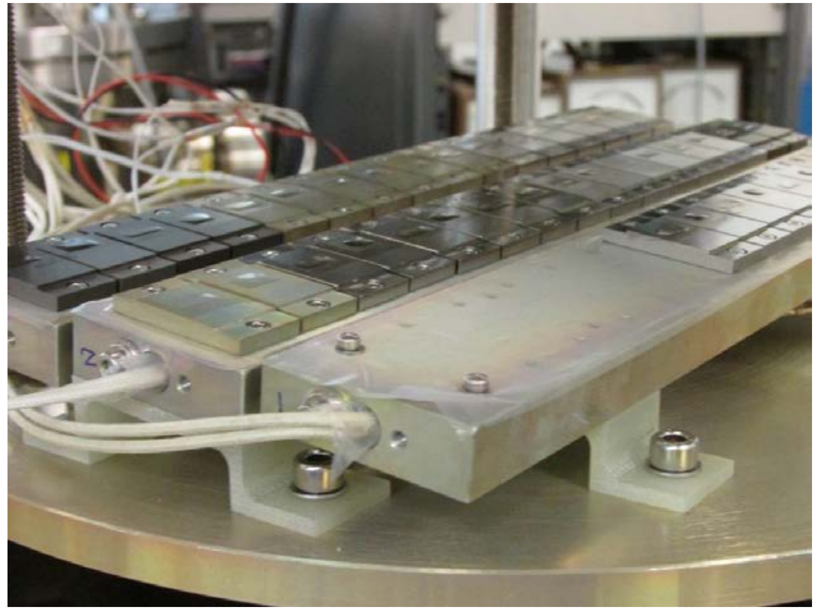


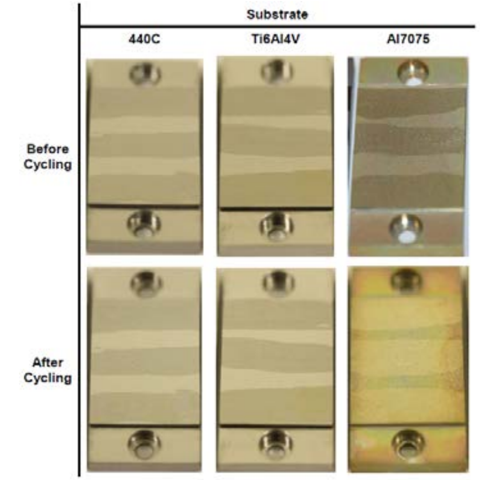
PFPE Oil (Z25)



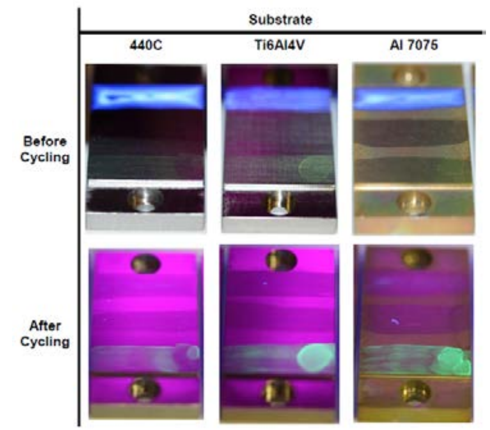
Anti-Creep Barriers are needed with Fluid lubricant

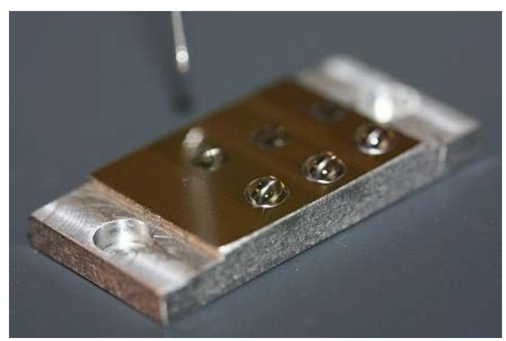






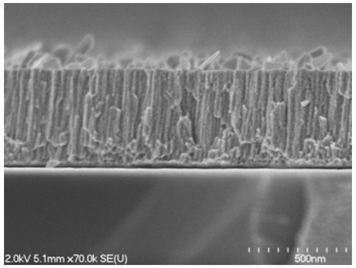
Under UV light



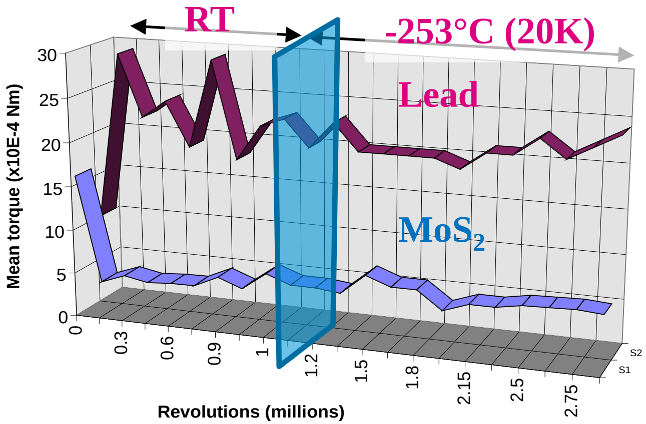


Solid Lubricants for Space

- Low shear strength metals
  (e.g. lead, silver)
- or lamellar solids
  (e.g. MoS_2, WS_2).
- low-shear strength Polymer
  (PTFE, polyimide)



- Negligible volatility
- Can be insensitive to temperature
- Stable, but generally lower lifetime and more “noisy” than fluids.
- Permissible Temperatures
  - Minimum >~ -270°C
  - Maximum ~ >+300°C



- **BUT**
  - Adhesion, thickness, life and replenishment may be issues
  - Operation in air may be forbidden or very severely restricted.

Benefits:

- Accelerated testing feasible
- Some are electrically conducting

Solid or Liquid Lubricant? That is the (first) question !

Conditions when only dry (solid) lubricants should be used:

- Temperature extreme (high or low)
- Contamination risk to other parts of spacecraft (evaporation or creep)

Conditions when only fluid lubricants should be used:

- Very long life required
- Significant running in air required (ground testing)

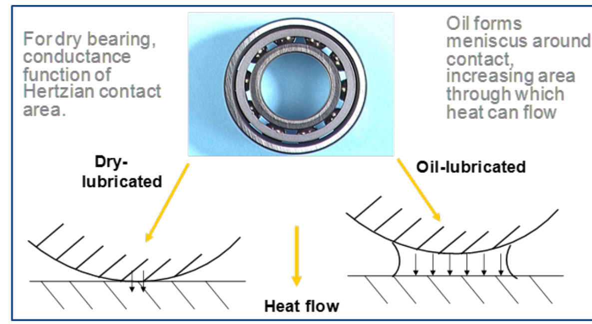
Other criteria:

- High thermal conductance
- Low torque noise

} Fluid lubricant

- Accelerated testing needed
- Low electrical resistance

} Solid lubricant



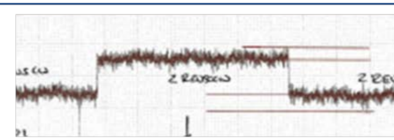
Monolayer formation time:

Oils - typical for best space oils:

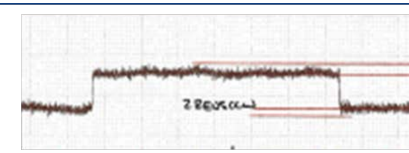
3 years at 0°C

3 hrs at 100°C

Lead ~30,000 years at 100°C



Torque trace from lead-lubricated bearings



Torque trace from oil-lubricated bearings

Some Practical Lubricant Problems

- Solution has to be effective in vacuum and at extreme temperatures
- It has to work in space and on ground, if possible
- Need to consider lubrication in early stages of design. (Impact on motors size; etc…)
- Limited range of lubricants available (two base oils, then a couple of solid)
- Re-lubrication in space is not normally an option
- Qualification or acceptance of new lubricant solutions or other new surface treatments is a long process.

- **What flies may often be a compromise**
  – the perfect "one fit all" lubricant for space does not exist…
  therefore extensive testing and experience is needed for the lubricant selection and optimisation for each new application.

Test Level Hierarchy

- **Tribometer Level** : basic friction & wear for materials and coatings, thin film durability, relative performance of candidate lubricants in idealised but controlled conditions (Mainly Pin-on-Disc and spiral Orbit tribometer)

- **Component Level** : e.g. Ball bearing, gears, etc .. - assessment & validation of torque, life, efficiency, adhesion etc. of individual components. Gives increased confidence but may be difficult to "condition" test item in isolation – so how representative is the test?

- **Mechanism Level** : only valid way of qualifying/accepting a mechanism lubrication solution, but little information on individual component performance

Pin-On-Disk Tribometer

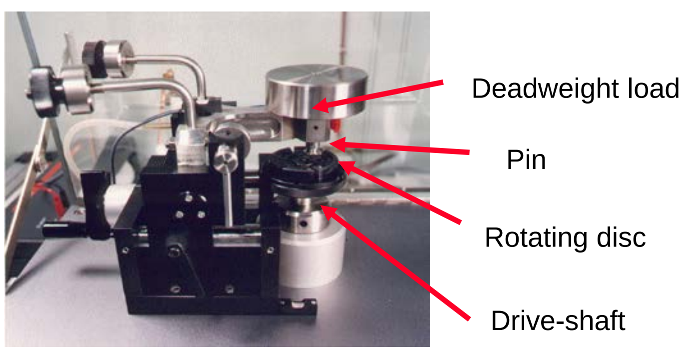
Vacuum (2) and non-vacuum (2) sliding tribometers

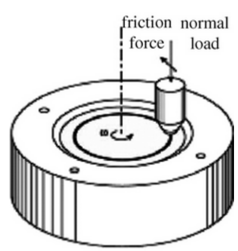
- Fully controllable (unidirectional / reciprocating)

Uses / recent studies:

- Investigation into the impact of surface treatment on the performance of thin solid lubricating films
- Characterisation of lubricant-free material pairings
- Development of improved lubricants

- Load: 10 - 25N
- Various pin diameters (stresses)
- Various pin/flat materials
- Speed: 0.1-500rpm
- Sliding Speed: ~1e-4 to 1m/s
- -100 to 200°C
- Cover gas to high vacuum



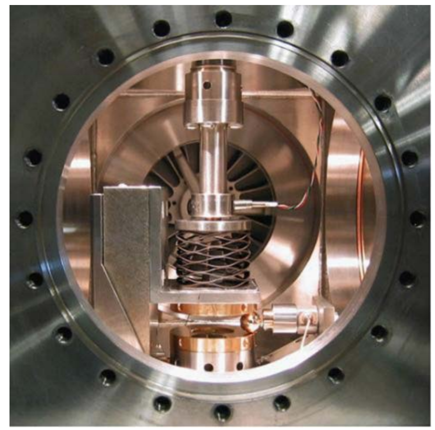


pin-on-disc apparatus

Spiral Orbit Tribometer

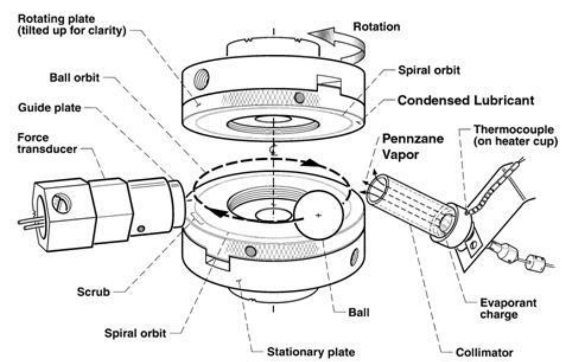
Unique facility – only machine outside of NASA

Rolling tribometer, more representative kinematics of a angular contact bearing



- Load: 10-225N
- Peak Hertz stress: 0.3 to 3GPa
- Ball diameter: 3.175 - 12.7 mm
- Speed: 1-200rpm
- Ambient to 100°C
- Various atmospheres including vacuum to ~10^{-8} mbar

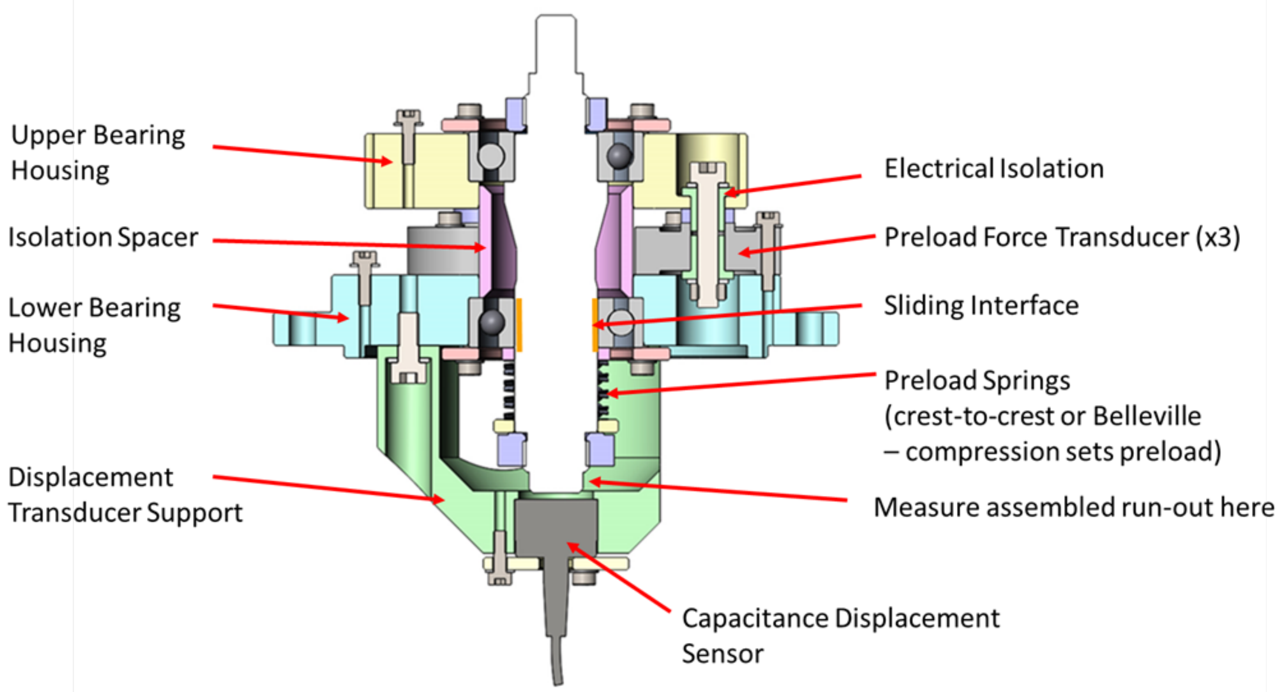
- Uses / recent studies:
  - Evaluation and comparison of fluid lubrication (PFPE, MAC, ionic)
  - In-situ analysis of fluid degradation behaviour (using mass spec.)
  - Characterisation of lead replacements for thin film solid lubrication
  - Study of transfer film lubrication, ACE etc.



Advanced Bearing Test Rig (In Commissioning)

Background:

Polder, EarthCARE, and some wheel programmes highlighted a lack understanding of fluid or transfer film health /formation at bearing level.



- Measured parameters
  - Torque , axial shaft displacement (capacitative measurement of lubricant film thickness <10nm resolution), preload, film thickness (electrical resistance), temperature

Gear Testing – Unit Level (1/2)

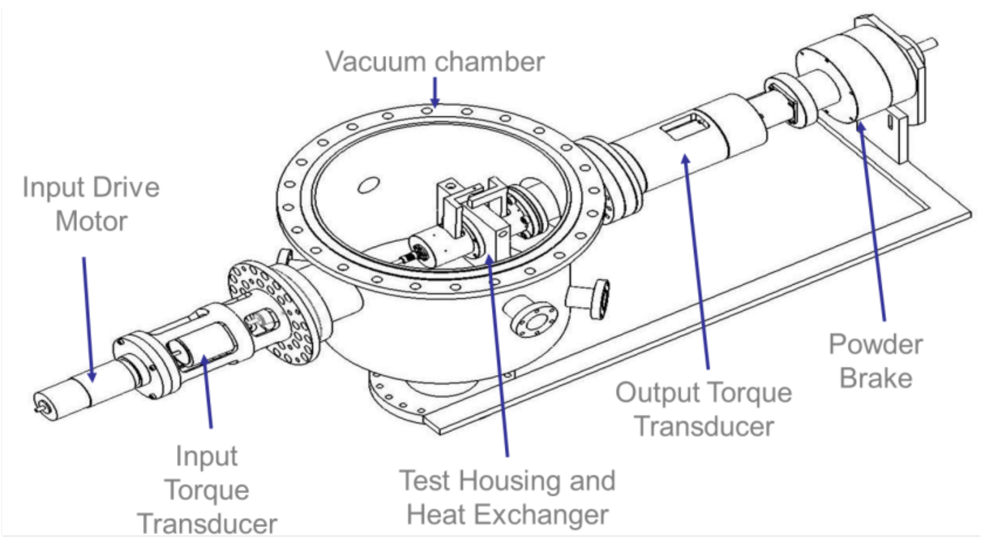
Torque to 400Nm (most recent tests around 4-30Nm)

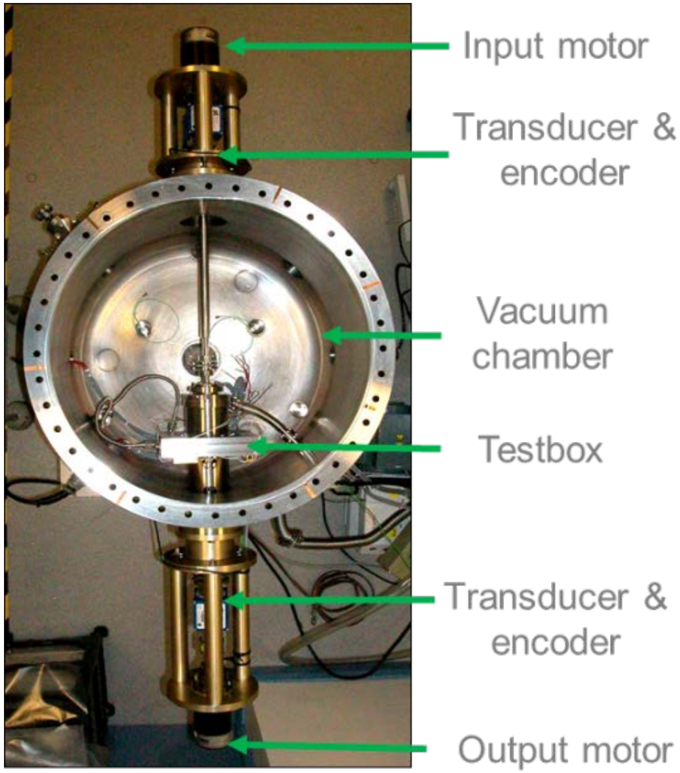
Temperature: -40/+90°C (typ.)

Speed: 0.1-500rpm at input (typically 50rpm)

Environment: Cover gas to high vacuum

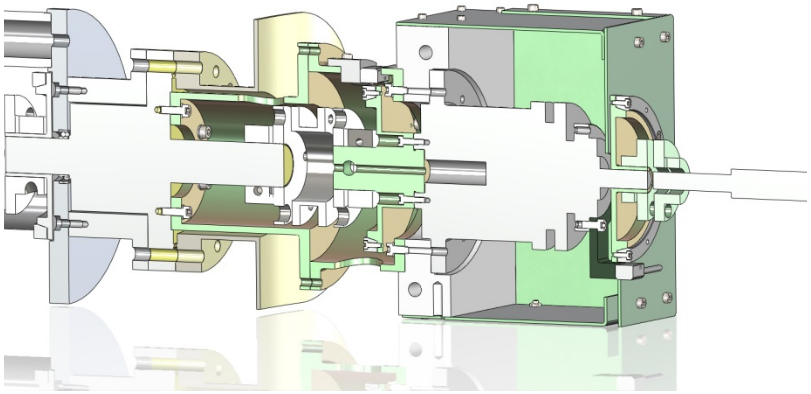
- Break-out torque , efficiency ,hysteresis, lost motion (backlash), torsional stiffness, no-load back-driving torque

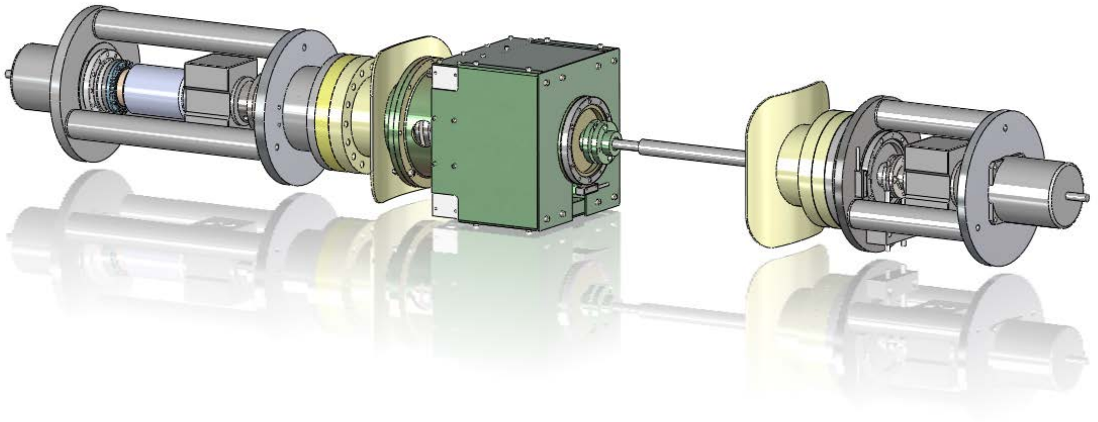




Gear Testing – Unit Level (2/2)

- Programme Findings:
- Efficiency, speed and output torque behaviours PFPE/MAC
- Maplub PF100a and SH050a – flex-spline wave generator interface
- Life limit by oil LOSS from FS/WG interface
- Re-lubrication after run-in for maximum life (17 million i/p / 106250 o/p)
- ARTES 5.1 (HFUC7) – Maplub 100b/Nye 2001a - suspended



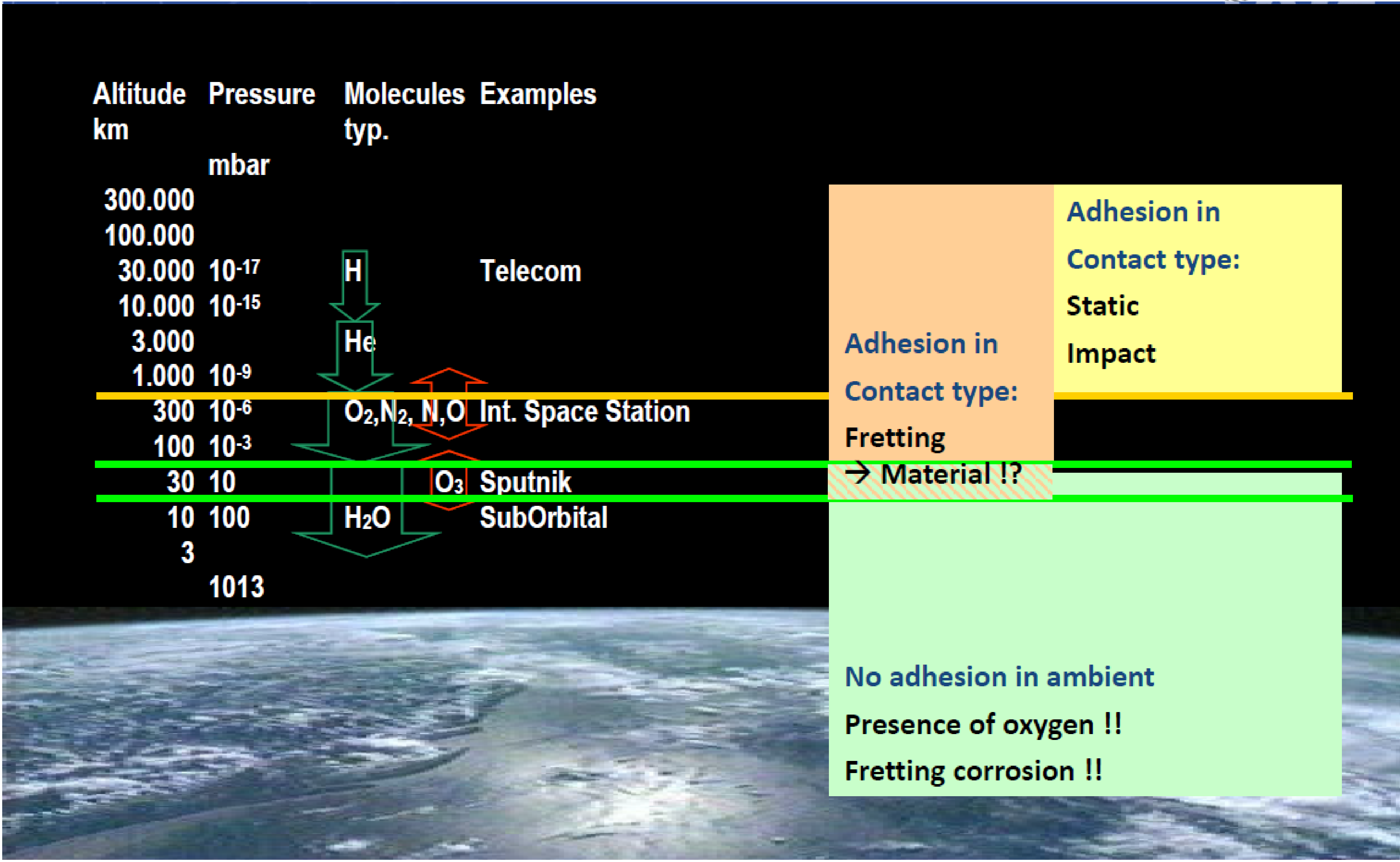


- 2015 HD in small angle oscillatory motion – proof of facility and lifetest (100k oscillations of ±0.0025°)

Coating Facilities

- 2 Unbalanced magnetron sputtering (PVD) facilities (CF4 &CF5)
- Validated Space Processes for PVD – MoS2, Lead, Silver
- Films typically 0.2-0.5µm on bearings, up to 1µm for other components
- Thinner films for industrial applications
- Future
  - Enhanced MoS_2
  - Lead Replacement
  - In-process RGA to support product development/quality monitoring
  - Higher and more automated bearing run-in capacity

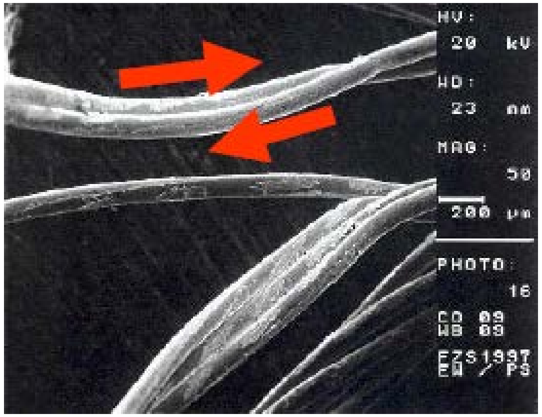
Cold-Welding (also called galling ...)

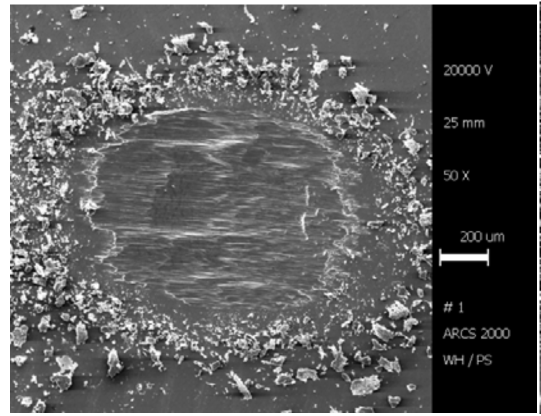


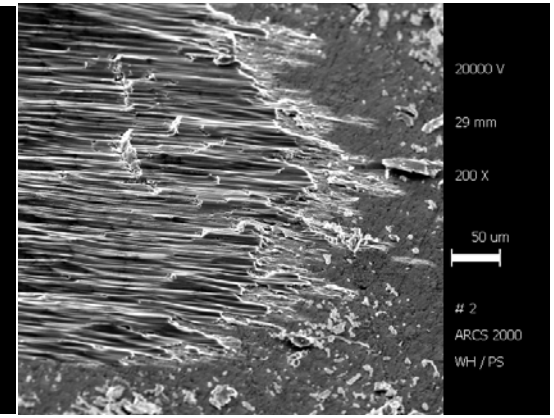
Cold-Welding

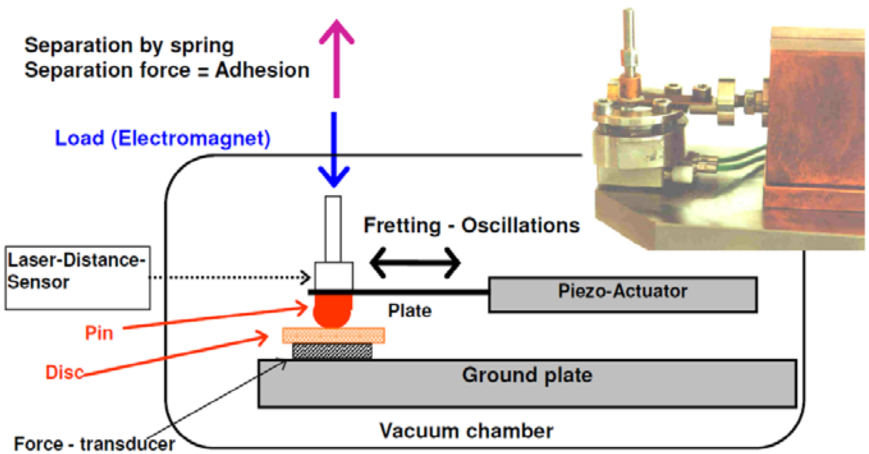
Vacuum level	Effect on surface	Adhesion likely in contact types:
High vacuum l Less than 10^{-8}mbar l Contamination time 100 sec	→ Surfaces will not be re-covered → Destruction of surface layers result in clean surfaces → Adhesion very likely !!!	Static, Impact, Fretting
Low vacuum l 10^{-3} to 10^{-6} mbar l Contamination time < 1sec	→ Surfaces may become clean, e.g. under fretting → Adhesion under certain criteria possible, e.g. fretting !!	(Impact) Fretting
Air (oxygen) l Pressure > 0,1 mbar l Contamination time < 0,00001 sec	→ Surfaces covered → Metal-atoms of two bodies cannot come close enough → No adhesion	**Exception:** Tightening of stainless steel screws

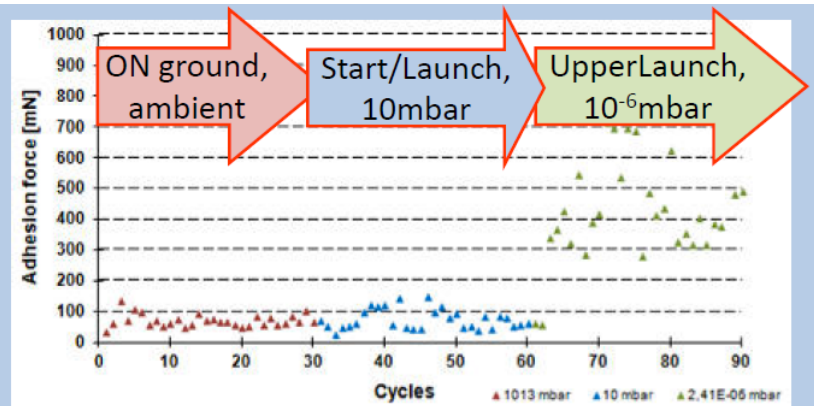
Cold-Welding











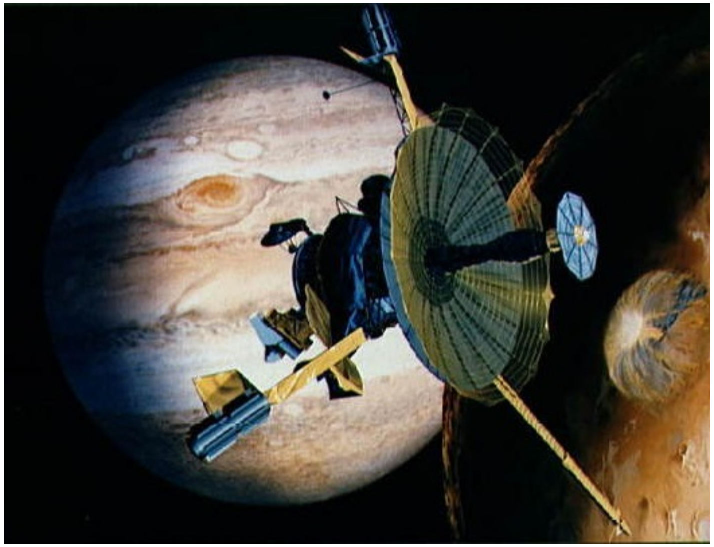
No adhesion in low vacuum (blue) after shaking in air (creation of oxidative surface layer on blank Ti6Al4V)

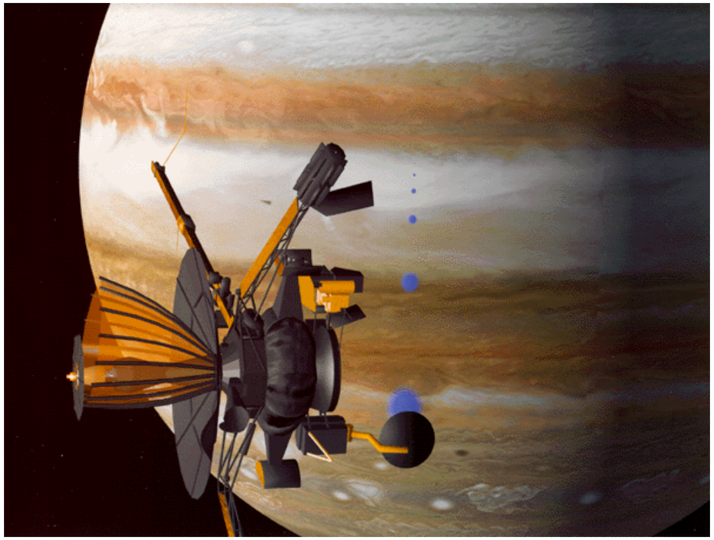
Importance of Engineering for All Mission Phases

- Galileo Mission (US)

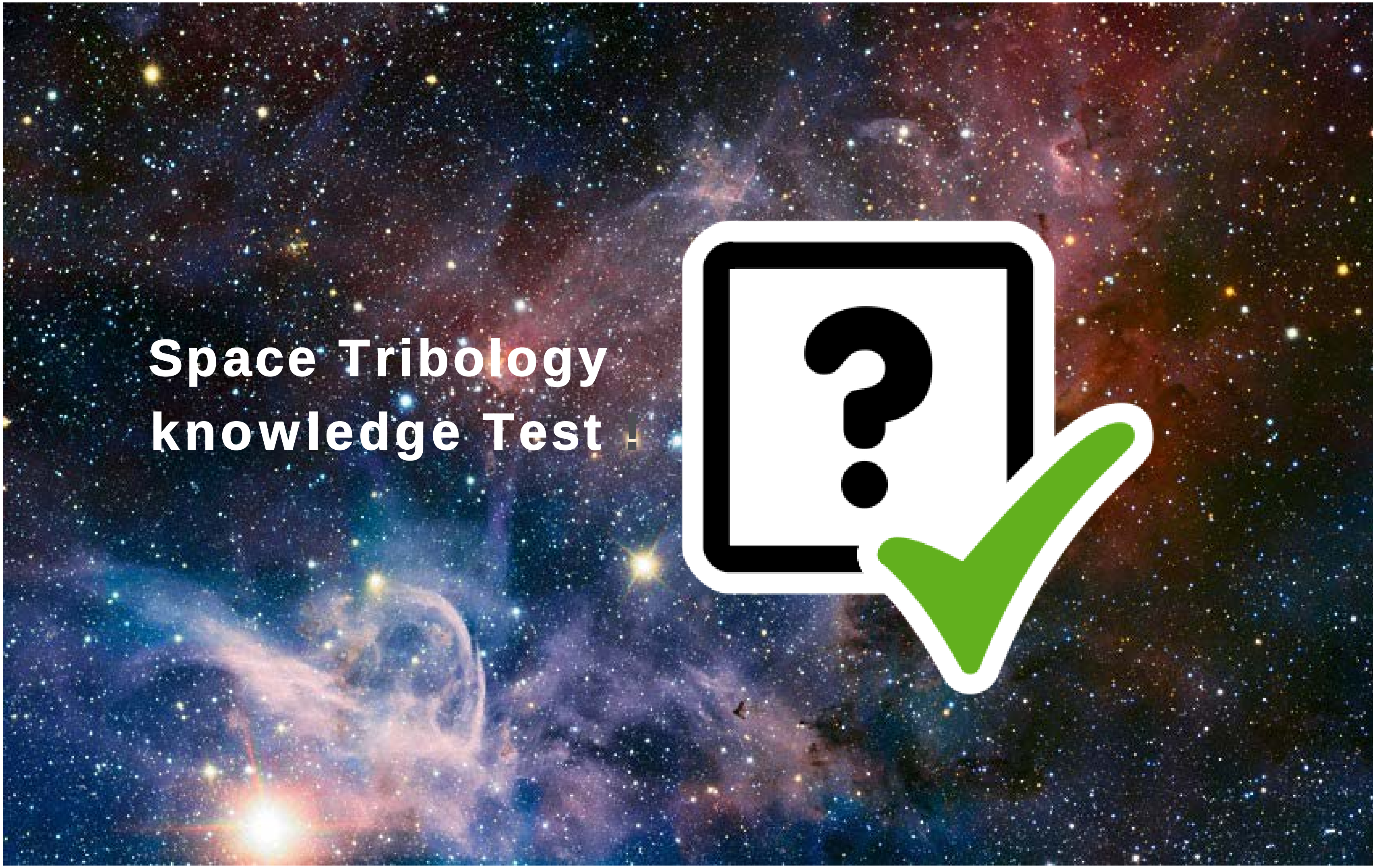
- Launched Oct 18th 1989 on STS34
- Jovian orbit insertion Dec. 1995
- $1.4 billion mission cost

Galileo Mission – Mechanism Failure

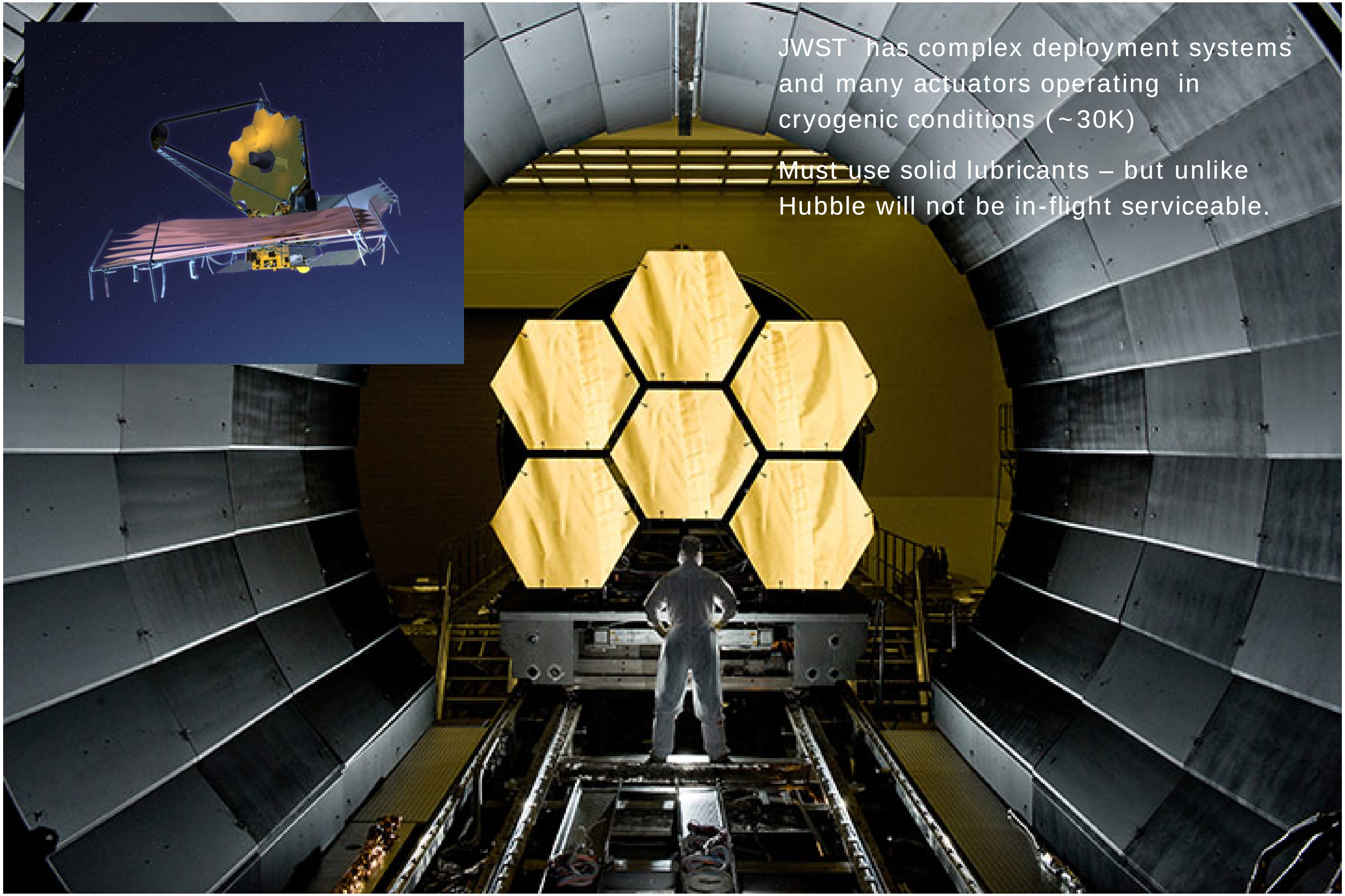




- High gain antenna failed to open
- Loss of 70% of its science data
- Reason:
  - MoS2 lubricant coating on antenna mesh wore away during long over-land journeys on ground.
  - Also spent 4.5 years in storage following Challenger disaster
  - Fretting and adhesion after transportation


Space Tribology
knowledge Test !

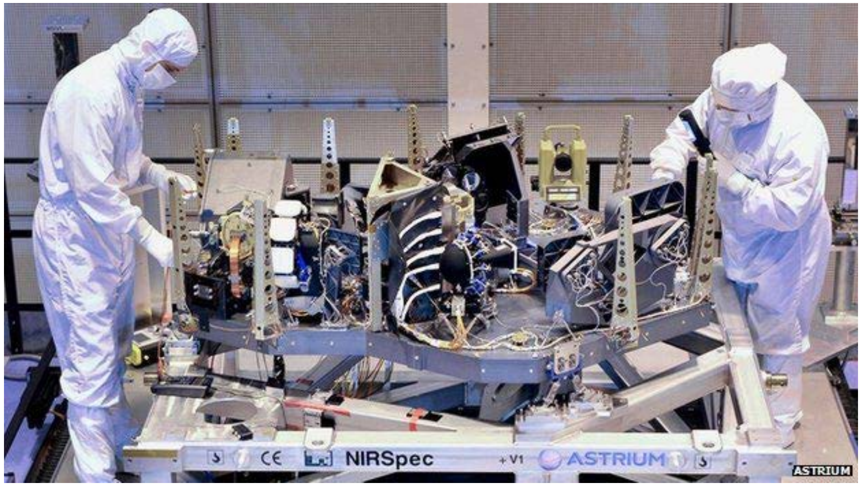
Solid lubrication (30K)

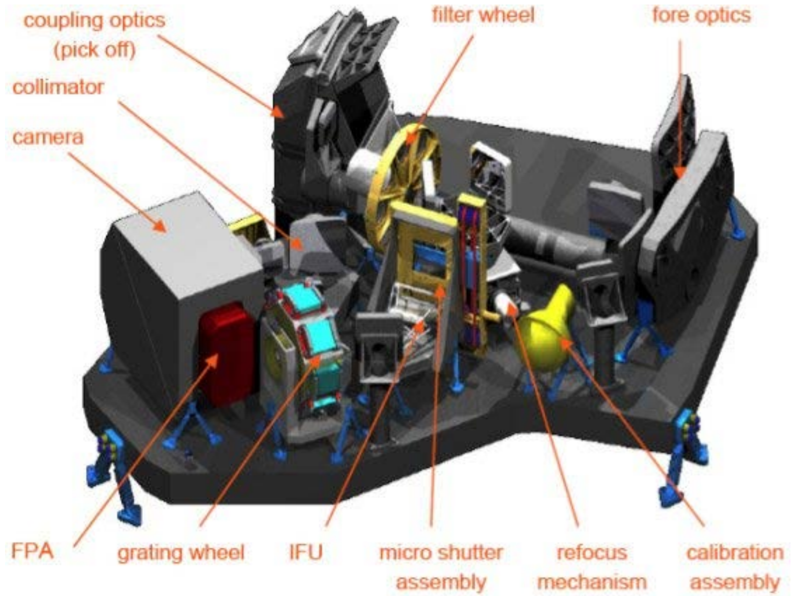


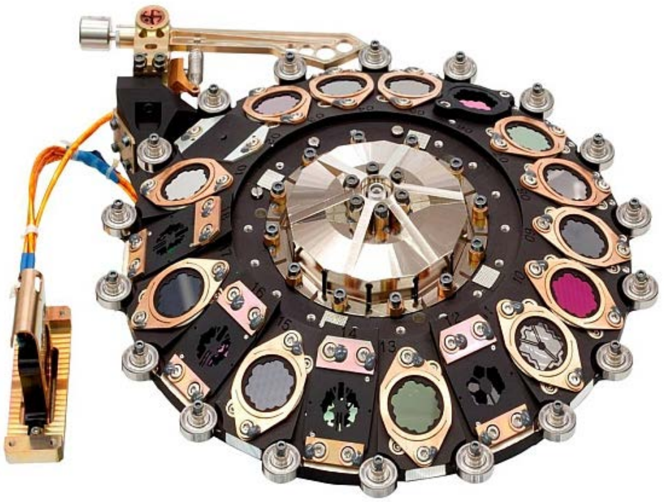
JWST has complex deployment systems and many actuators operating in cryogenic conditions (~30K)

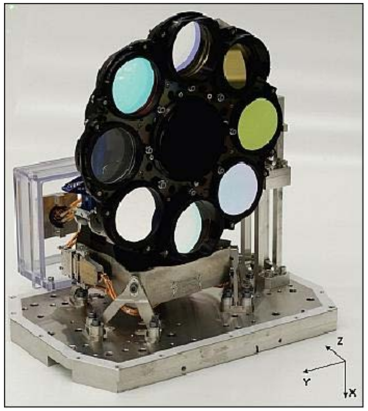
Must use solid lubricants – but unlike Hubble will not be in-flight serviceable.

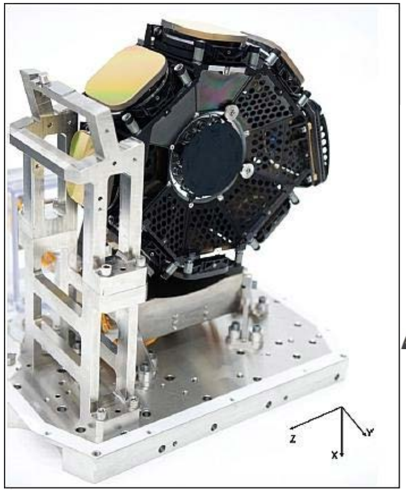
Solid lubrication (4K and 20K)



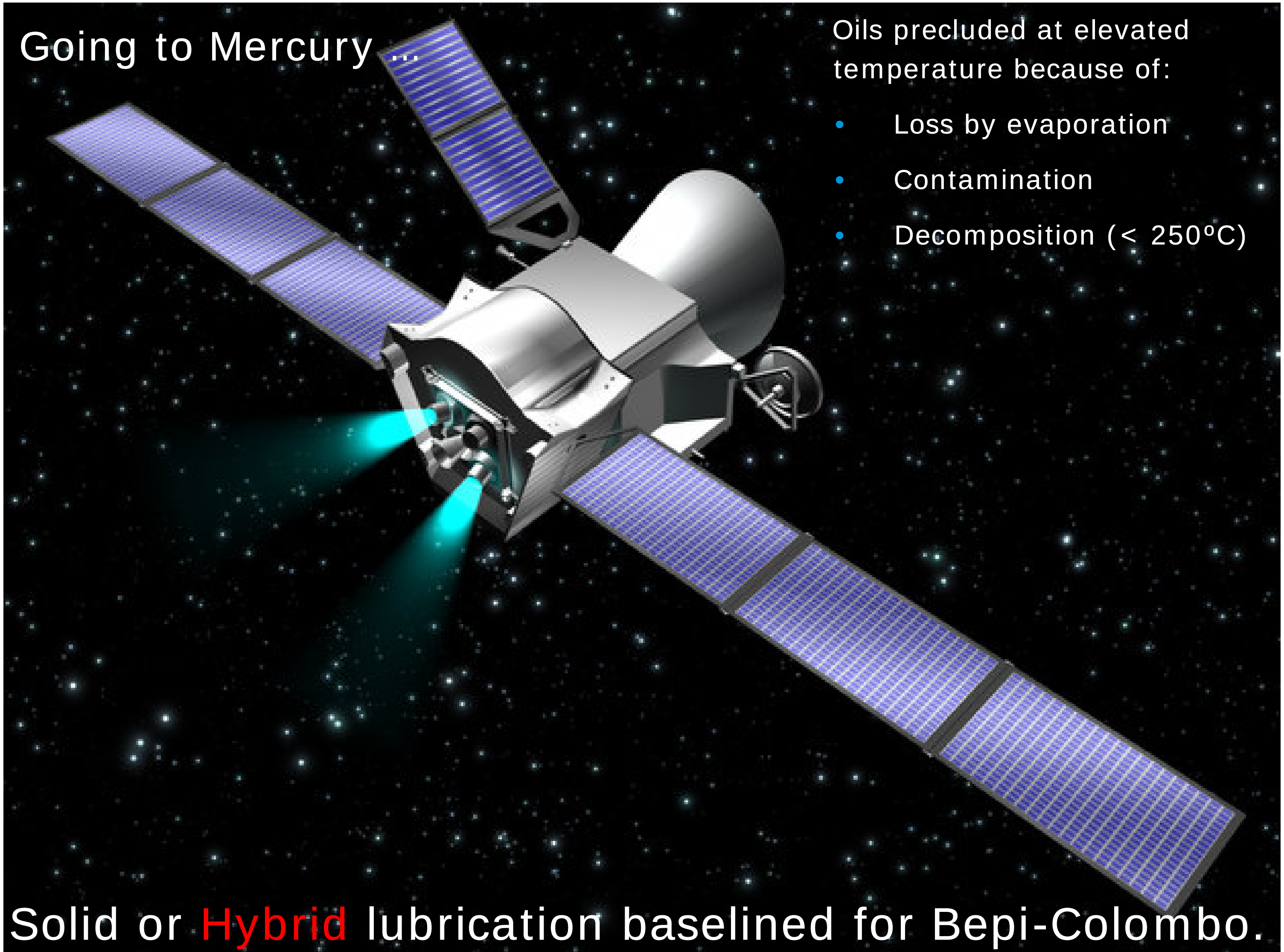








Solid lubrication >> 100ºC

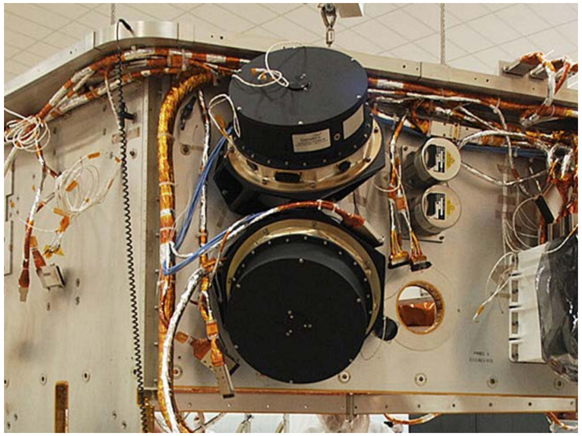


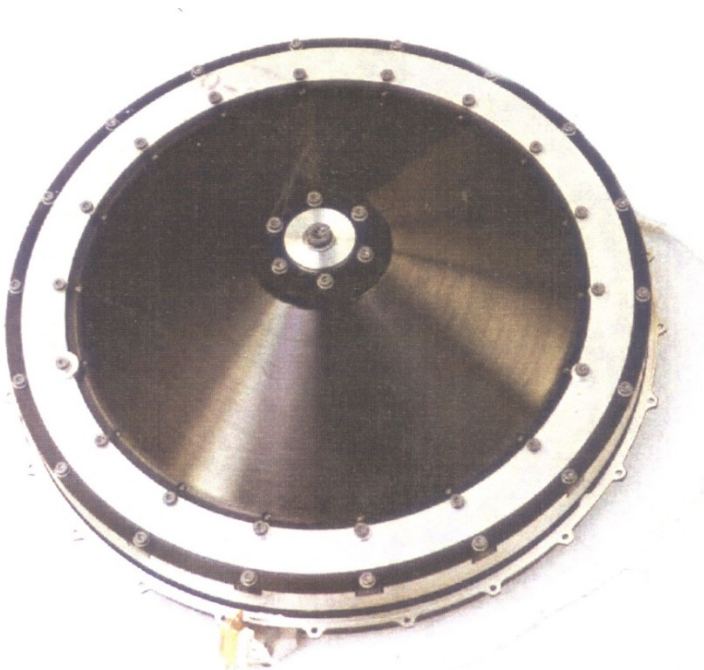
… for highest duty applications

Limit of life for solid lubricated bearings is ~1000 million revs.

Oils in hydrodynamic lubrication mode can last considerably longer e.g. momentum wheels

Important to maintain oil where required… and understand bearing stability





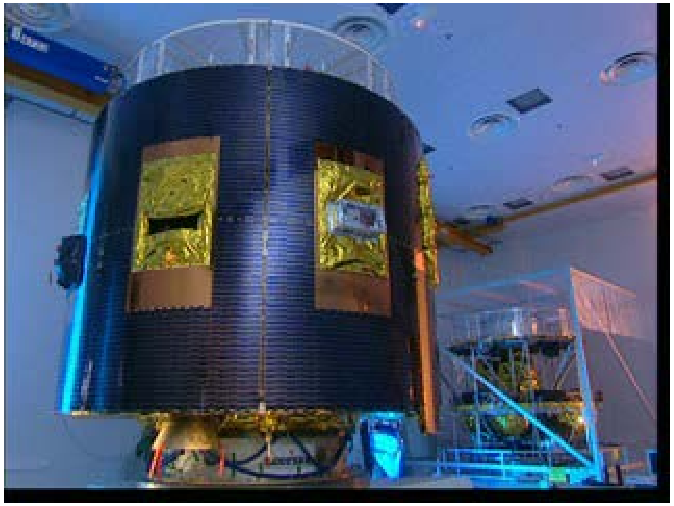
ENVISAT – One spacecraft – many lubricant solutions

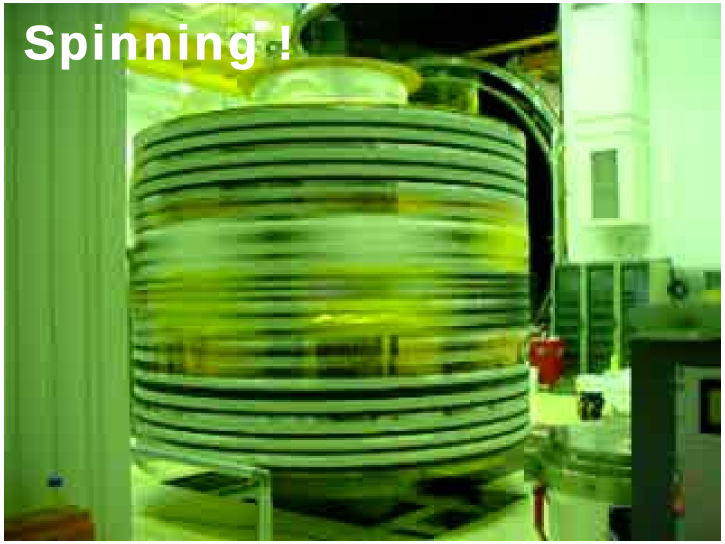
Typical of many spacecraft – lubricants selected to be optimal for the specific requirements of each instrument – meaning:

- Instruments:
  - Lead, MoS_2, self-lubricating bearings, hybrid lubrication (lead and grease), grease alone.
- Reaction Wheels:
  - Oil

MSG – GERB Example

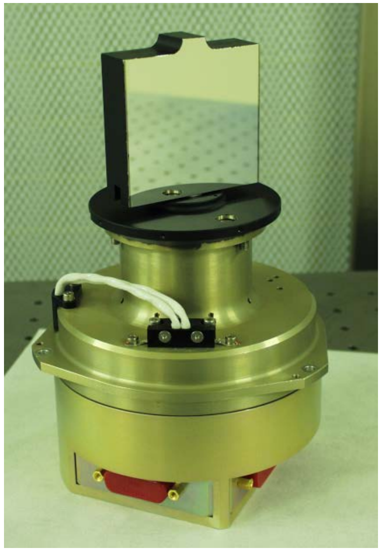
- MSG-1,2 and 3 in GEO Orbit
- Spin stabilised 100rpm
- GERB Instrument – Geostationary Earth Radiation Budget
- Solid lubrication strongly preferred

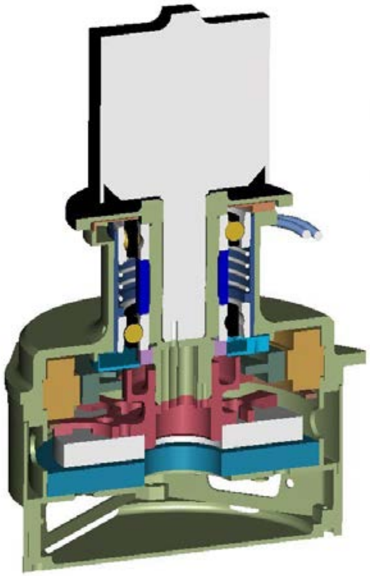


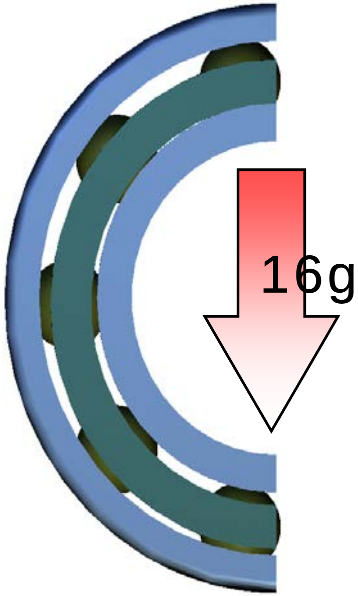


MSG – GERB Example

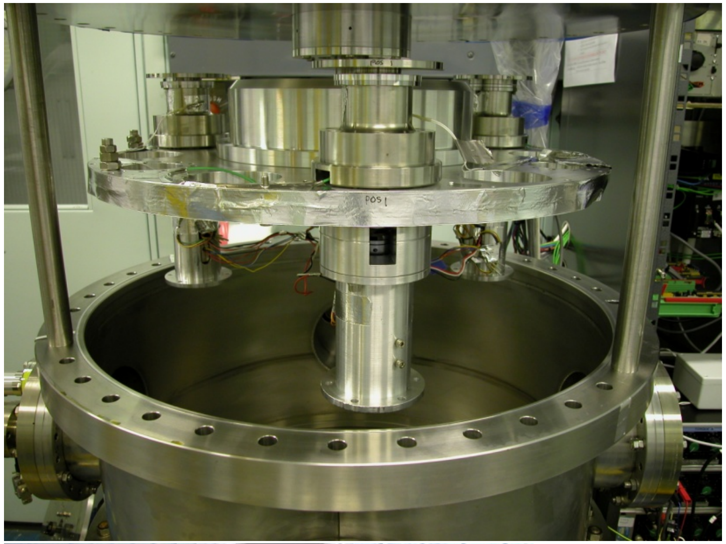
- Spring preloaded bearing pair
- 16g continuous radial acceleration due to position on spacecraft
- Operational requirement 230 million revs







MSG – GERB Example

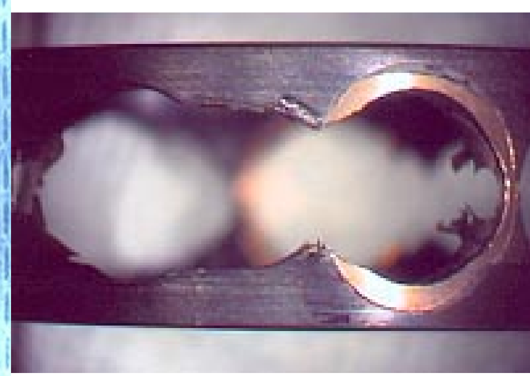


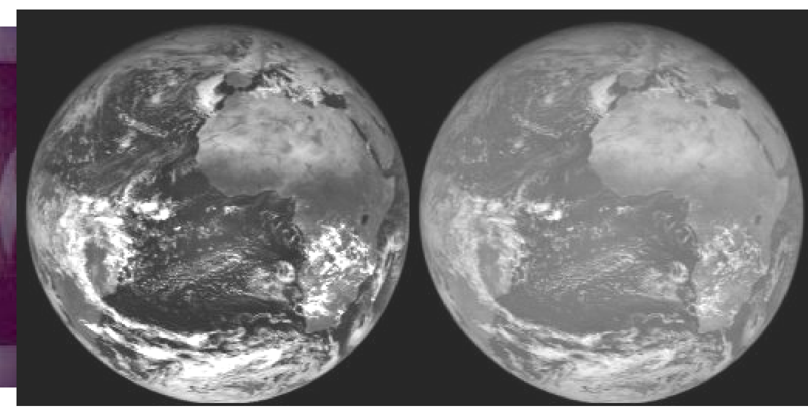
Various concepts trialled

Life-test Under 16g on centrifuge

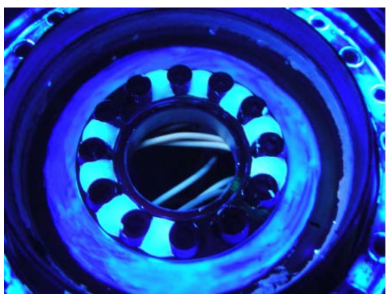
Design modified to include “Debris traps”

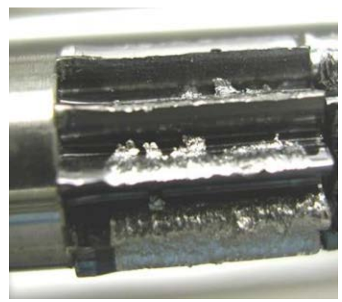
Three major iterations of design before a successful design was achieved.

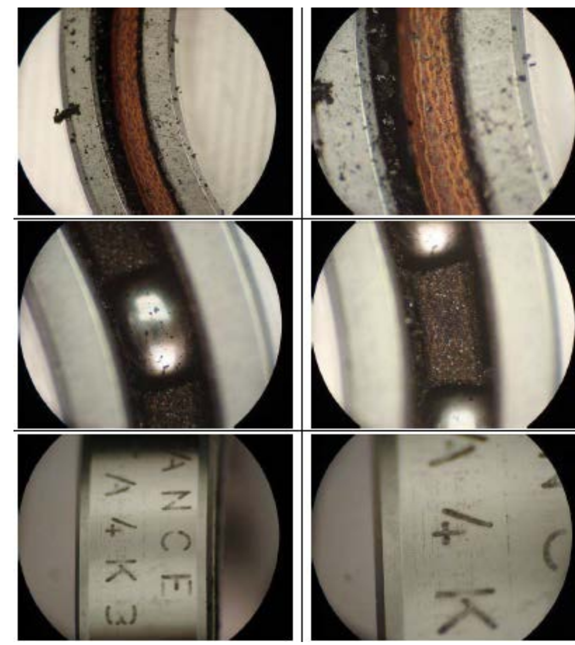


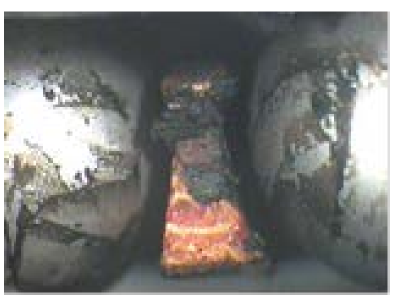


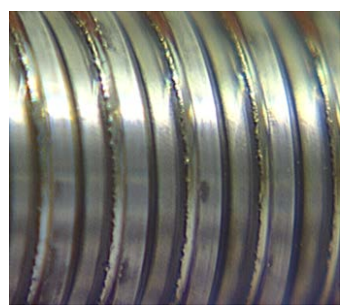
Inspection after Life Test











Now Under Developments

- Solid coating improvement (MoS_2 process)
  - Longer life, fewer operational constraints
- New European Self-lubricating cage materials
  - Lower cost, long life
- New European MAC type of Oil
- Ionic Fluids (a new class of fluid lubricants?)
  - Lower volatility and greater resistance to degradation then PFPEs
- REACH (Registration, Evaluation and Authorisation of Chemicals)
  - Replacement of established lubricants (Lead), solvents and other materials

Foreseen Developments

- Long-term storage
  - Understanding of issues for spacecraft batch assembly, or “in orbit storage” for demisable spacecraft

- European anti-creep barrier

- Re-usable turbomachinery and its implication at tribology levels

- Quest for the Magic Lubricant ???

- No lubricant (magnetic bearings and magnetic gears …)

In summary ….

- Good application of tribology is critical to successful space missions
- Tribological systems are complex and varied
- It is difficult to predict tribology by "model"; test highly recommended !
- And … There is still a lot to be done !!!


Thank You for Your Attention