Introduction to *Spacecraft Mechanisms:*

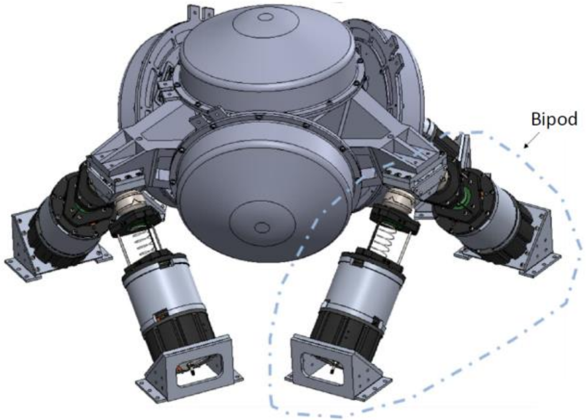
ECSS-E-ST-33-01C

Geert Smet

25/10/2023

Trainer

- Geert Smet
  - Microvibration expert, particularly isolation systems and reaction wheels
  - SADM focal point
  - CleanSpace focal point
  - Almost as fast as Eliud Kipchoge



Content

Terms and Definitions

→ What is a mechanism? Which disciplines are involved?

Scope

→ When is the standard applicable? How to use it?

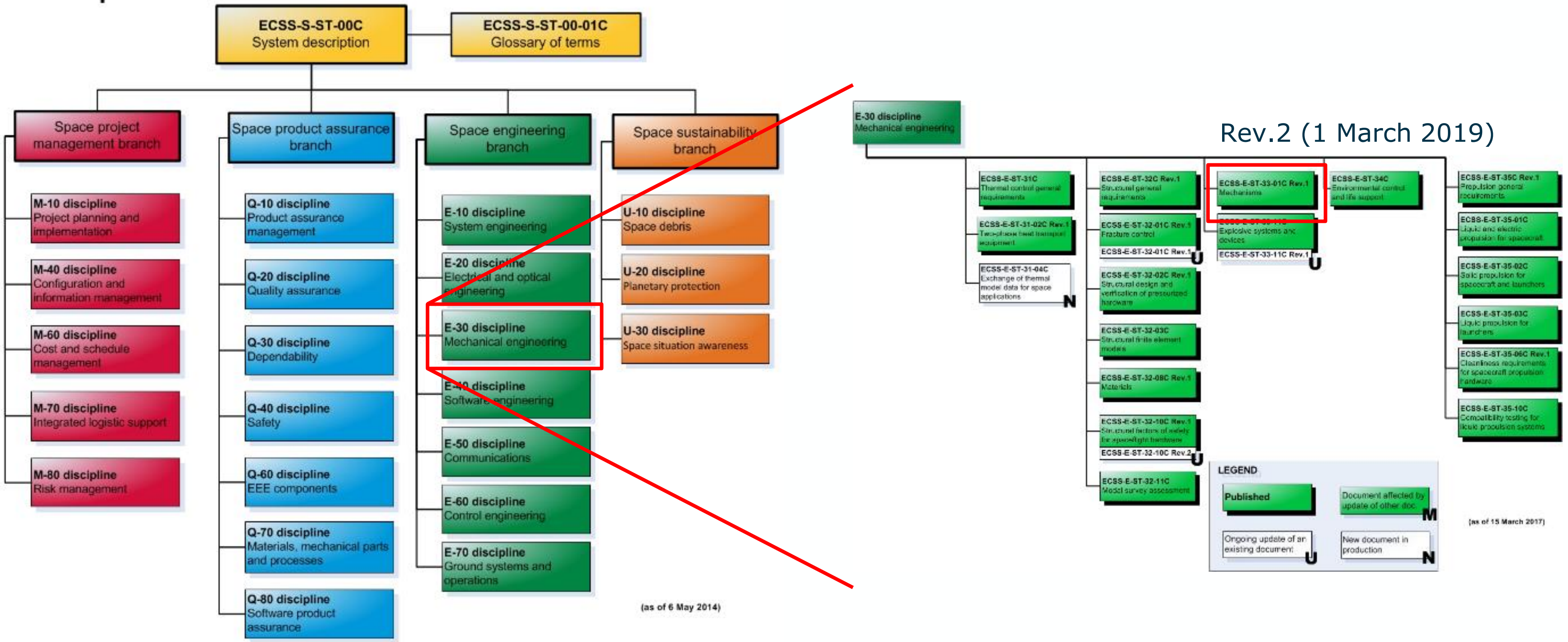
Requirements

→ Design (dimensioning, material selection, etc.)

→ Verification (analysis and test)

Where to find our standards?

ECSS Disciplines

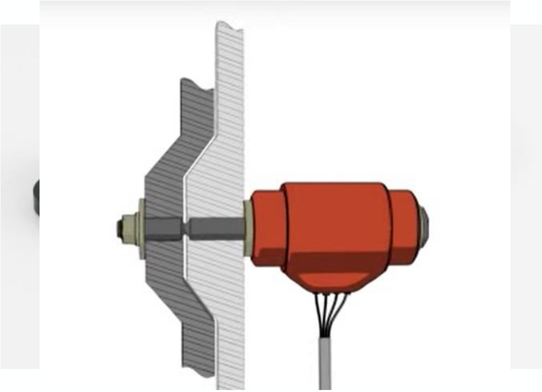


Spacecraft Mechanisms

"Assembly of components that are linked together to intentionally **enable a relative motion**."

Spacecraft Mechanisms

Actuators	e.g. electric motor, spring, SMA, voice coil, piezo-electric, etc.
Transmission	e.g. shafts, couplings, gears, etc.
Bearings	e.g. ball bearings, journal bearings, etc.
Sensors	e.g. optical, magnetic, mechanical, etc.
Controller	open / closed loop, uncontrolled



tribology

discipline that deals with the design, friction, wear and lubrication of interacting surfaces in relative motion to each other

lubrication

use of specific material surface properties or an applied material between two contacting or moving surfaces in order to reduce friction, wear or adhesion

ECSS-E-ST-33-01C Rev.2

…specifies the **requirements** applicable to the

- concept definition
- development
- design
- production
- verification
- in-orbit operation

of space mechanisms on spacecraft and payloads

in order to **meet the mission performance requirements**.

Normative references

ECSS-S-ST-00-01	ECSS system — Glossary of terms
ECSS-E-ST-10-02	Space engineering – Verification
ECSS-E-ST-20	Space engineering – Electrical and electronic
ECSS-E-ST-20-06	Space engineering – Spacecraft charging
ECSS-E-ST-20-07	Space engineering – Electromagnetic compatibility
ECSS-E-ST-31	Space engineering – Thermal control general requirements
ECSS-E-ST-32	Space engineering – Structural
ECSS-E-ST-32-01	Space engineering – Fracture control
ECSS-E-ST-32-10	Space engineering – Structural factors of safety for spaceflight hardware
ECSS-E-ST-33-11	Space engineering – Explosive systems and devices
ECSS-Q-ST-30	Space product assurance - Dependability
ECSS-Q-ST-40	Space product assurance – Safety
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
ISO 76 (2006)	Rolling bearings – Static load rating
ISO 128 (1996)	Technical drawings
ISO 677 (1976)	Straight bevel gears for general engineering and for

General Requirements: Units

All units to be used: SI

E.g. kinematic viscosity

= [St] Stokes

= 10^{-4} $m^2 \cdot s^{-1}$

Remember the Mars Climate Orbiter incident from 1999?

General Requirements: Maintainability

→ Mechanisms shall be designed to be **maintenance free**

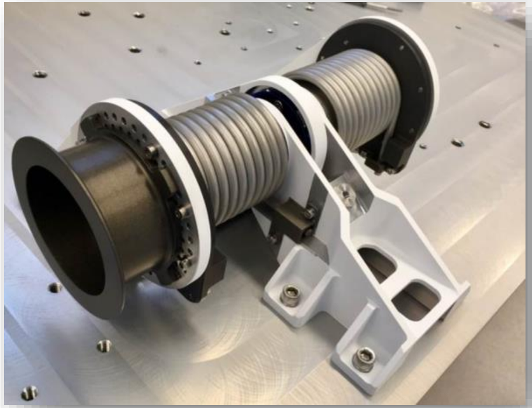
→ If maintenance is required, it shall be **approved** by the customer and **procedures** shall be provided

General Requirements: Redundancy

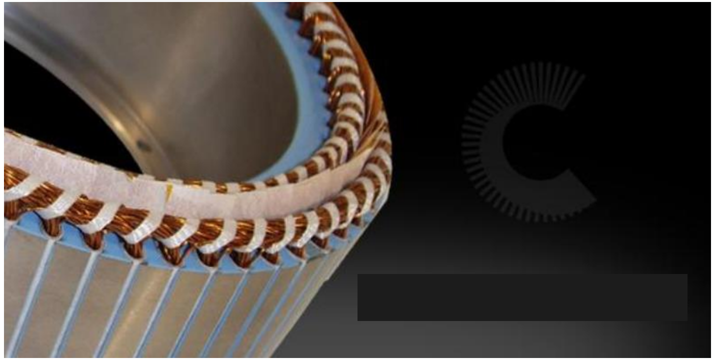
- single point failure modes shall be identified

- single points of failure should be eliminated by **redundant components**

- **active elements** of mechanisms shall be redundant, such as sensors, motor windings, brushes, actuators, switches and electronics



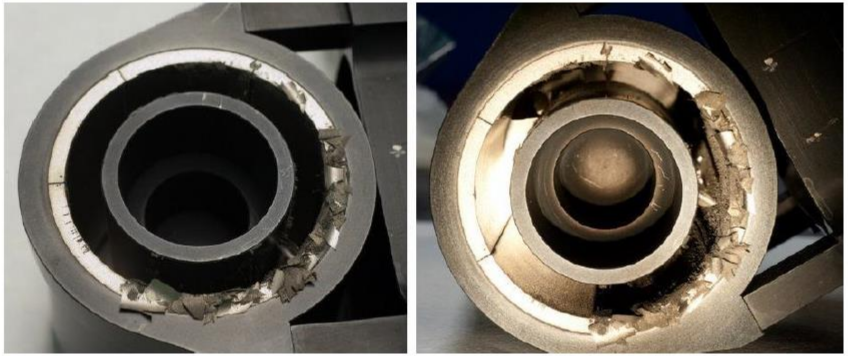
Courtesy of Sener (PL)



http://www.componeticsinc.com/

Mission Environment

The mechanism engineering shall consider **every mission phase** identified for the specific space programme, i.e.:



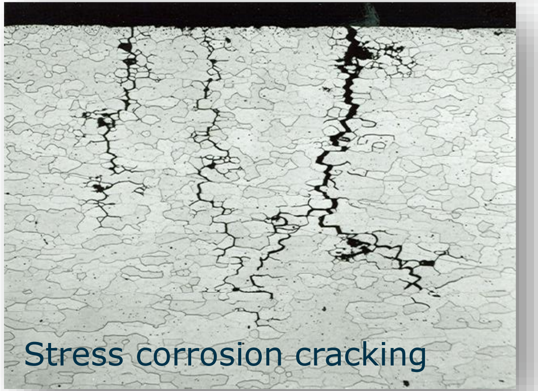
IASI Voice coil actuator stator,
VACODYM 383 HR (VAC) magnets with Nickel coating

- → Assembly and integration (humidity, oxygen)
- → Testing (1 g environment, additional resistive loads)
- → Storage (long term effects)
- → Handling and shipment (loads, accessibility)
- → Launch (mechanical loads)
- → In-orbit operation / hibernation (operational loads, thermal, radiation, EMC, life, etc.)
- → End of life / satellite disposal (Design for Demise)

Material selection

… shall be performed in conformance with **ECSS-Q-ST-70 (Materials)**:

- → Corrosion
- → **Galvanic corrosion (→ dissimilar metals)**
- → **Stress corrosion cracking (e.g. 440C, Cronidur X30)**
- → Fungus protection
- → Flammable, toxic and unstable materials
- → Induced emissions (stray light protection)
- → Radiation
- → Atomic oxygen
- → Fluid compatibility



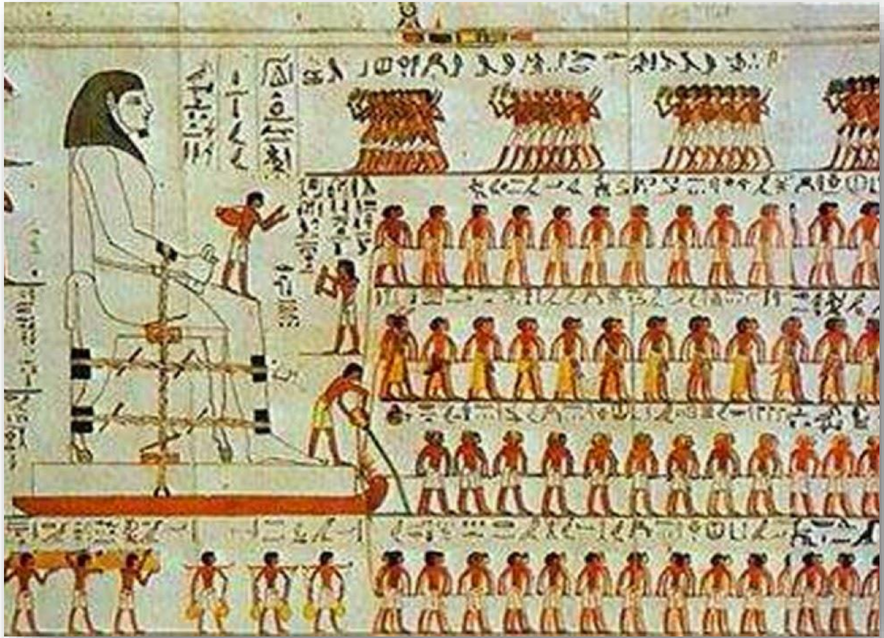
Design Requirements: Tribology

Mechanisms shall:

- ➢ be designed with a **lubrication function** between surfaces
  - → Reduce friction and wear
  - → Increase lifetime

- ➢ use only lubricants **qualified for the mission**
  - → Temperatures, ambient pressure, contact pressure, number of cycles, lifetime, relative velocity etc.

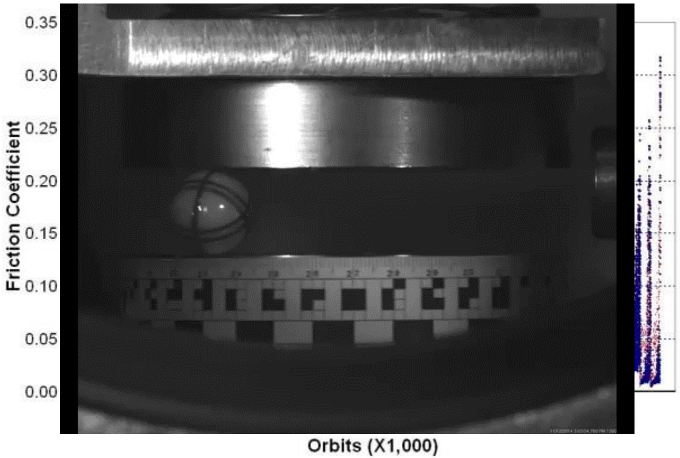
https://www.esmats.eu/esmatspapers/pastpapers/pdfs/2023/kent.pdf

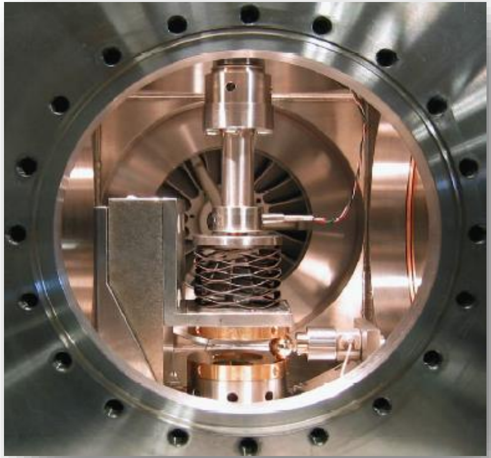


Design Requirements: Tribology (cont’d)

Qualification of lubricant via:

- → Heritage or dedicated lifetest (see slides 51 ff.)
- → Component level: bearing / gear test rigs, Pin on disc (POD), Spiral orbit tribometer (SOT)





SOT device by ESTL

European Space Tribology Laboratory (ESTL):

- → operates test facilities
- → has data base on qualified lubricants
- → provides consultancy (Minor consultancy is free, paid by ESA)

www.esrtechnology.com

Design Requirements: Dry Lubrication

... preferred for operation in **high temperature**, at **low speeds**, **low number of operational cycles**, when **cleanliness** is an issue (e.g. optical payloads have problems with condensation)

... applied through processes such as sputtering, vapor deposition etc.

... e.g. MoS_2, WS_2, graphite, PTFE, lead, gold

→ Samples of representative material […] shall be co-deposited in each process with the flight components so that verification checks can be performed;

→ The thickness and adhesion of the lubricant on samples shall be verified;

Design Requirements: Fluid Lubrication

... for **high speed**, **low friction** and **high number of operational cycles**

... wide range of space qualified hydrocarbon and synthetic oils

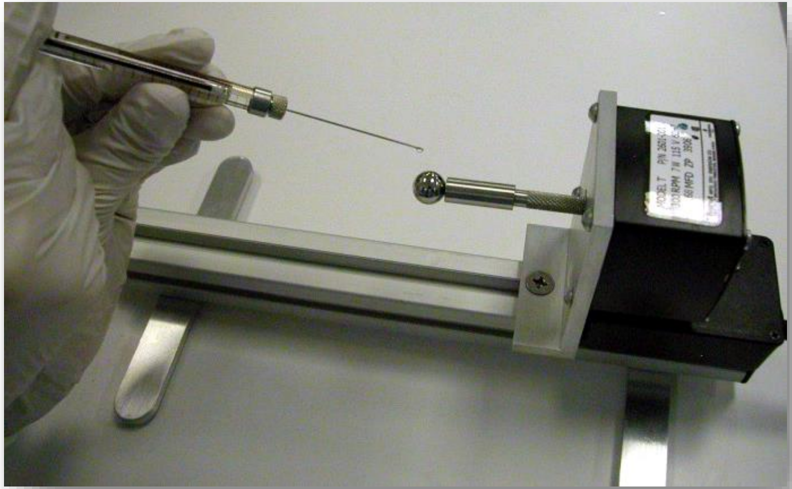
→ The **quantity** of lubricant used shall be determined.

→ Oil loss mechanisms: **Outgassing**, **creep** and absorption shall be taken into account (including **ground effects**, i.e. gravity)

→ Oil budget needs to be established

→ For rules on outgassing (total / relative mass loss, collected volatile condensable materials):

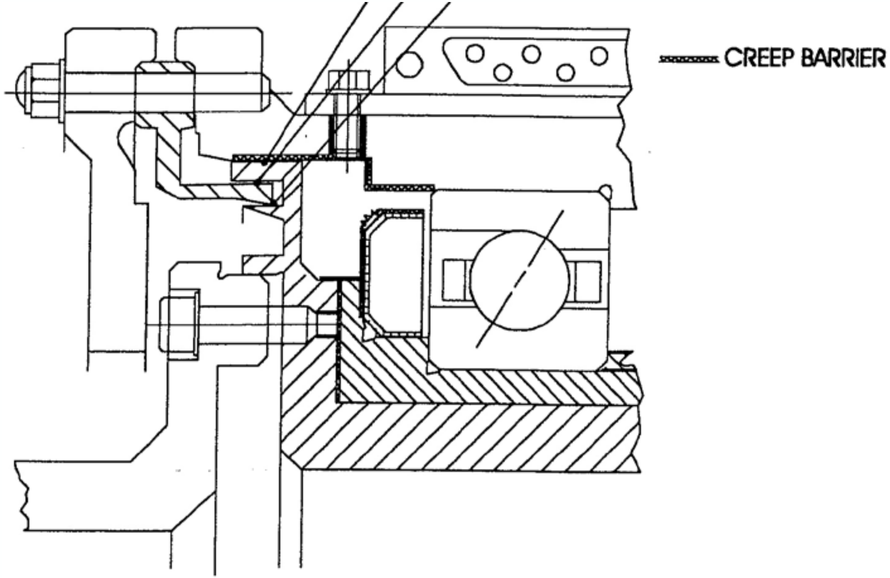
→ **ECSS-Q-ST-70-02**



Courtesy of ESTL

Design Requirements: Anti-creep barriers

- **avoid migration** of fluid lubricants to the internal/external sensitive equipment;
- causes a **change of the lubricant amount** on the parts to be lubricated;
- **integrity** of the anti-creep barrier shall be verifiable by indicators.



Design Requirements: bearing preload

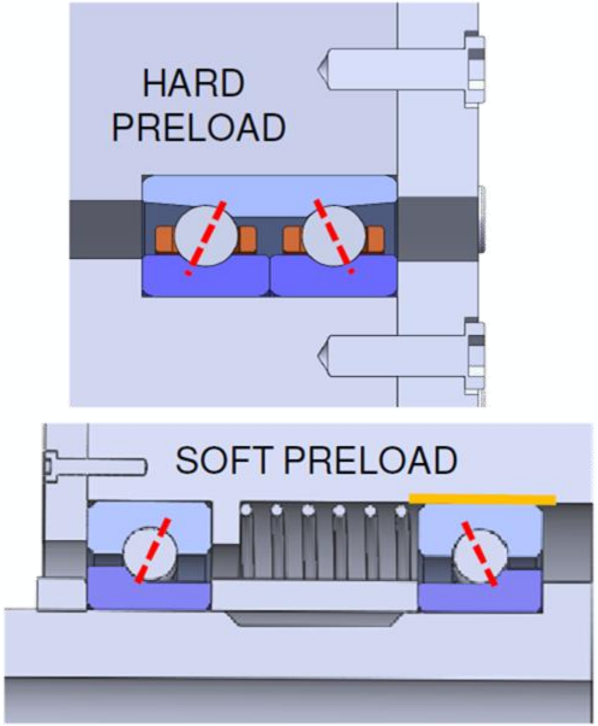
→ Ball bearings shall be preloaded to **withstand mechanical environment**;

→ Preload **calculation** shall be made available

→ Preloading should be applied by **solid or flexible** preload;

→ Preload **should be measured** after assembly;

→ preload should be confirmed **after running-in**;



Design Requirements: structural dimensioning

Mechanisms shall be designed with a **positive margin of safety** against yielding and against ultimate under all environmental conditions and operational load conditions

→ **ECSS-E-ST-32** (structures):

4.5.16 Margin of safety (MOS)

a. Margins of safety (MOS) shall be calculated by the following formula:

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

NOTE Loads can be replaced by stresses if the load- stress relationship is linear.

→ **ECSS-E-ST-32-10** (factors of safety):

$$FOS_Y = 1.1$$

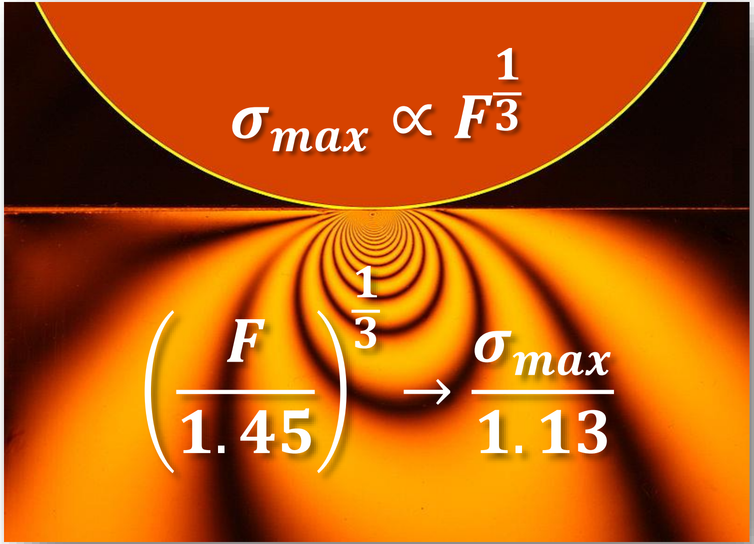
$$FOS_U = 1.25$$

(typical values)

Design Requirements: ball bearings

→ shall be sized with respect to the maximum allowable **peak hertzian contact stress**;

→ For the evaluation of the peak hertzian contact stress, a minimum **factor of 1.45** shall be applied to the design limit load;



According to **ISO76** (static load rating):

→ axial / radial static load capacity ≙ load producing a maximum contact stress of

4200 MPa (for hardened steels, e.g. SAE 52100)

4000 MPa (for stainless steels, e.g. 440C)

Design Requirements: motorisation

Actuators shall be sized to provide ***torques*** / ***forces*** in conformance with:

$$T_{min} = 2 \cdot (1.1 \cdot I + 1.2 \cdot S + 1.5 \cdot H_M + 3 \cdot F_R + 3 \cdot H_Y + 3 \cdot H_A + 3 \cdot H_D) + 1.25 \cdot T_D + T_L$$

$$T_{min} \geq 2 \cdot \sum_i \left(k_i \cdot T_{res,i}\right) + T_L + 1.25 \cdot T_D$$

- throughout the operational **lifetime** (ageing, lubricant degradation, creep, etc.)
- over the full **range of travel**
- worst case **environmental and operational conditions** (temperatures, mechanical loads)

Design Requirements: motorisation (cont'd)

Actuators shall be sized to provide ***torques*** / ***forces*** in conformance with:

$$T_{min} = 2 \cdot (1.1 \cdot I + 1.2 \cdot S + 1.5 \cdot H_M + 3 \cdot F_R + 3 \cdot H_Y + 3 \cdot H_A + 3 \cdot H_D) + 1.25 \cdot T_D + T_L$$

$$T_{min} \geq 2 \cdot \sum_i \left(k_i \cdot T_{res,i}\right) + T_L + 1.25 \cdot T_D$$

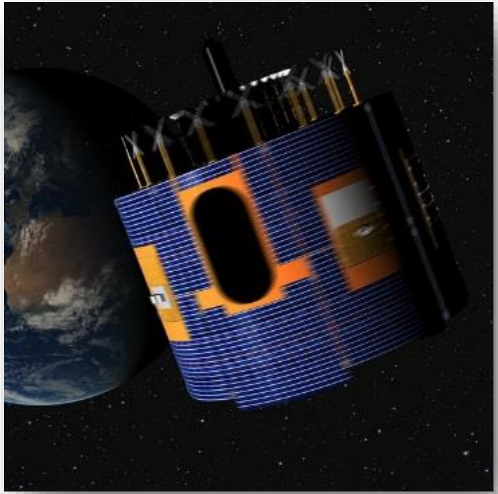
T_L: Deliverable **output torque of the mechanism** when specified by customer

T_D: **inertial resistance torque** caused by the worst-case acceleration function specified by the customer (i.e. customer specifies a motion rather than a torque)

Design Requirements: motorisation (cont'd)

Minimum uncertainty factors for **loss terms:**

Resistive force or torque contributor	Symbol	Theoretical Factor	Measured Factor
Inertia	I	1,1	1,1
Spring	S	1,2	1,1
Magnetic effects	H_M	1,5	1,1
Friction	F_R	3	1,5
Hysteresis	H_Y	3	1,5
Others (e.g. Harness)	H_A	3	1,5
Adhesion	H_D	3	3



→ **I ≠ T_D**, but resistive inertia load due to acceleration of mechanism itself (e.g. spinning spacecraft!)

→ **S ≠ actuation torque**, but resistive spring load (e.g. latch)

Design Requirements: motorisation (cont'd)

If actuation force / torque is supplied by a spring:

→ springs shall be redundant (e.g. 1:2 or 2:3 redundancy)

→ actuation torque / force shall be multiplied by an uncertainty **factor of 0.8** (→ only if ageing measurements are not available)

If actuation force / torque is supplied by an electric motor:

→ Worst case actuation torque / force shall be **measured at operating conditions** (i.e. at representative temperatures, pressures, speeds, loads etc.)

→ Assess the failure case with short circuited redundant motor windings

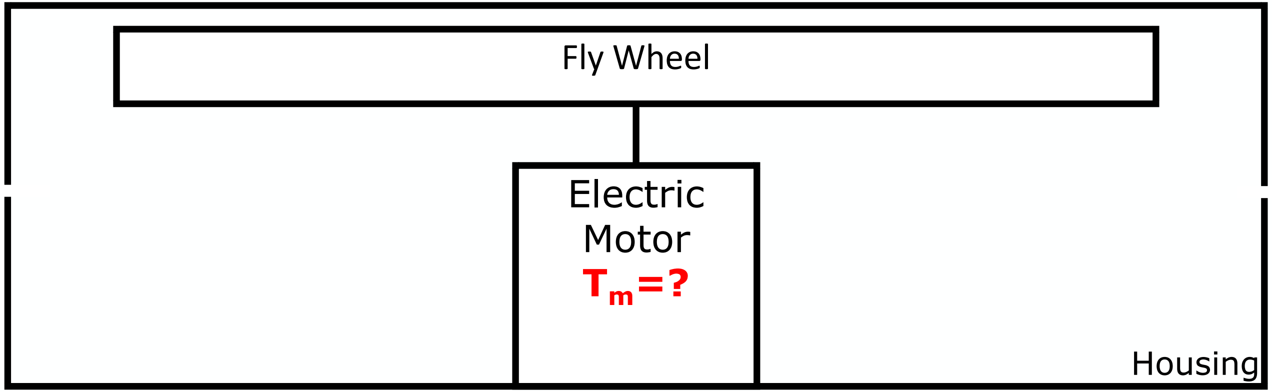
Actuation forces / torques supplied by **devices whose primary function is not to provide actuation** (e.g. harness) shall not be taken into account

Exercise: Motorisation I
reaction wheel

$$T_{min} \geq 2 \cdot \sum_i \left(k_i \cdot T_{res,i}\right) + T_L + 1.25 \cdot T_D$$

$T_{reaction}$ = 0.10 Nm from customer spec
$T_{friction}$ = 0.01 Nm from data sheet
$T_{magnetic}$ = 0.01 Nm from analysis
$T_{Windage}$ = 0.02 Nm from experience

$$T_m = 2 \cdot \left(1.5 \cdot T_{friction} + 1.5 \cdot T_{magnetic} + 3 \cdot T_{windage}\right) + T_{reaction} = 0.295 Nm$$

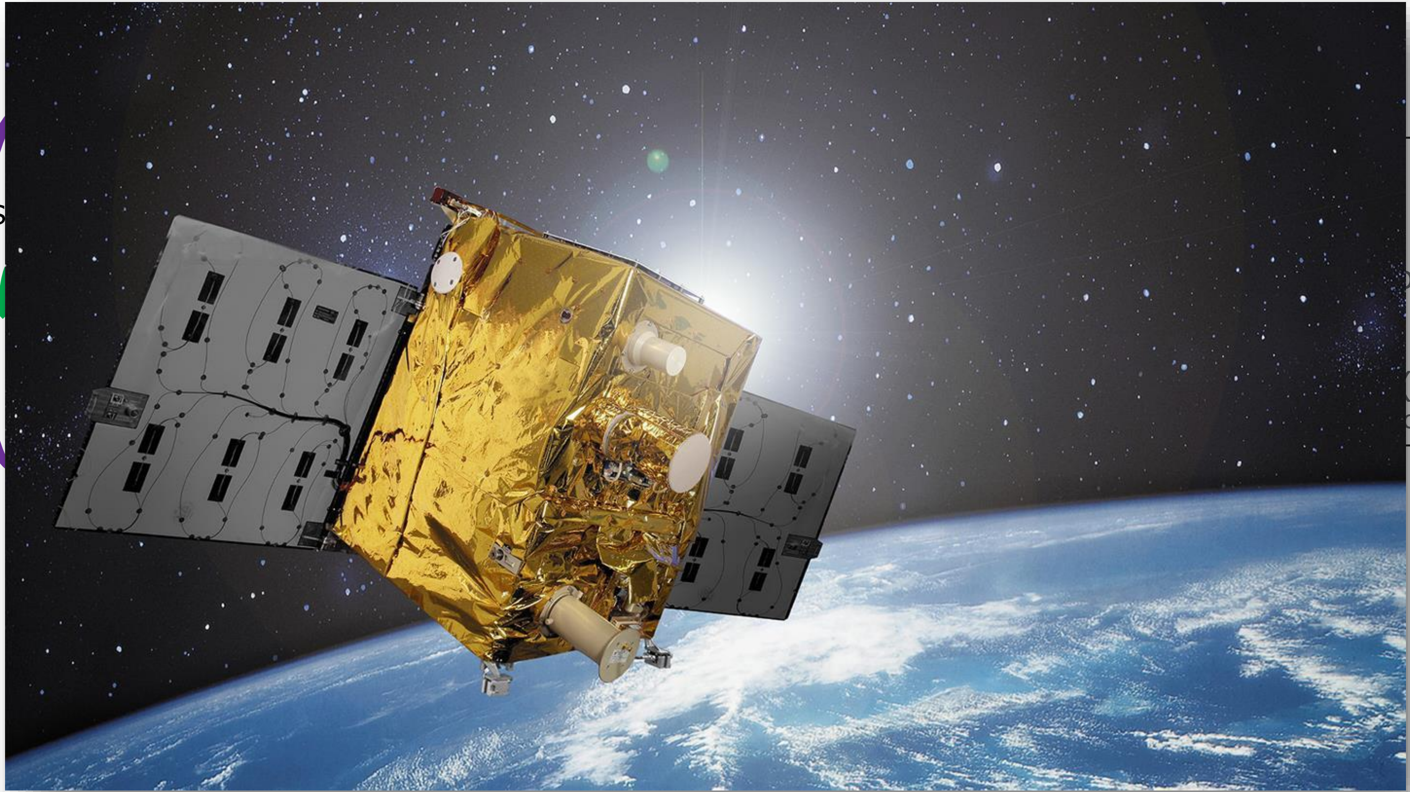


Exercise: Motorisation II

Spring driven deployment mechanism

Harness

S



om Z = 1.5 m

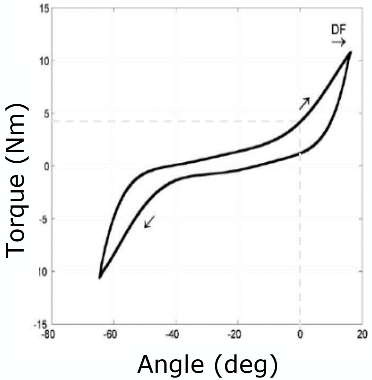
(any axis)

celerations)

Exercise: Motorisation II
Spring driven deployment mechanism

Example Budget:

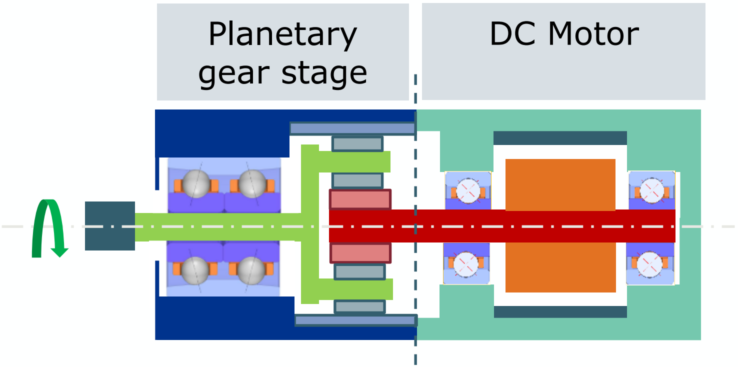
Contributor Description	Contributor Origin	Values	Units	ECSS Factor	Factored Contribution	Reference
Inertia	I	1.5	Nm	1.1	1.65	*Derived from requirements R2, R3 & R4.*
Bearing Friction	Friction (FR)	0.1	Nm	1.5	0.15	*Tested at bearing level. Report xxx.*
Damper	Friction (FR)	0.2	Nm	1.5	0.3	*Tested at damper level. Report xxx.*
Latch	Friction (FR)	0.1	Nm	3	0.3	*Predicted by analysis. Report xxx.*
Harness	Other (HA)	4	Nm	1.5	6	*Tested on Harness EM. Report xxx.*
	Magnetic effects	n/a	n/a	n/a	n/a	n/a
	Hysteresis	n/a	n/a	n/a	n/a	n/a
	Adhesion	n/a	n/a	n/a	n/a	n/a
	Dynamic Acceleration	n/a	n/a	n/a	n/a	n/a
Total Resistance		**5.9**	**Nm**		**8.4**	
Torque including motorisation factor				2	16.8	
Min required torque per spring	Spring		**Nm**	0.8	**21**	



e.g. Harness resistance data

Exercise: Motorisation III

DC motor with reduction stage



Example Relevant Requirements:

R1. Output Torque = 0.2 Nm

R2. Max commanded speed = 1.5 rads/s

R3. Max command current = 2 A

R4. Max command voltage = 24 V

R5. Temperature range = -20 °C to 30 °C

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

Exercise: Motorisation III

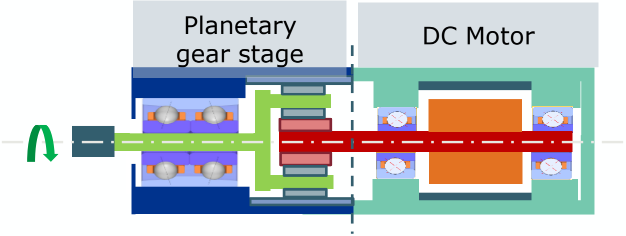
DC motor with reduction stage

Budget for cold case @ -20 °C Gear ratio : 8

Contributor Description	Contributor Origin	Units	Unfactored value at output	ECSS Uncertainty Factors	Factored Contribution @ Output	Factored Contribution @ Motor	Reference
Deliverable Output Torque	(T_L)	Nm	0.20	1.0	0.20	0.025	*Derived from requirement R1*
Gearbox output bearings	Friction (FR)	Nm	0.080	1.5	0.12	0.015	*Tested at bearing level. Report xxx.*
Planetary gear stage 1 (based on efficiency)	Friction (FR)	Nm	0.040	1.5	0.06	0.0075	*Tested at gear level. Report xxx.*
Motor Bearings Uncertainty	Friction (FR)	Nm	-	1.5-1=0.5	0.04	0.005	*Tested at bearing level. Report xxx.*
Total Resistance		Nm	0.200		0.22	0.028	
Motorisation factor			2		2	2	
Total incl. Motorisation factor		Nm	0.400		0.44	0.055	
Gearbox inertia	Inertial resistance (Td)	Nm	2.458E-04	1.25	3.07E-04	3.84E-05	*Actuator design report xxx.*
Min required torque	**0.055**	**Nm**					

This is a "black box" motor case needing caution

The budget is calculated from output to input to ensure the consequence of output uncertainty is reflected on gears



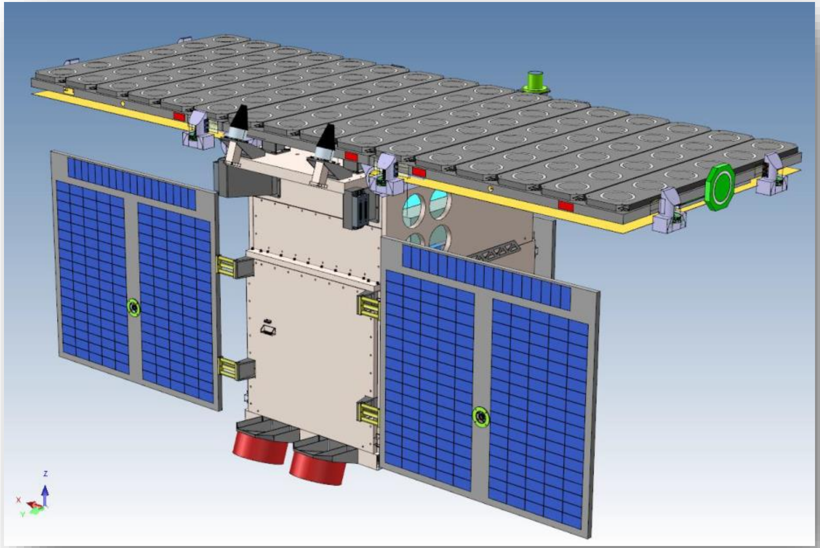
Design Requirements: end stops

For mechanisms with restricted travel or rotation:

→ Use of regular or emergency mechanical end stops (i.e. don't rely on actuator function, e.g. by electric motor)

→ deployment indicators shall not be used as mechanical end stops

→ Requirements on separable contact surfaces do apply (see next slide)



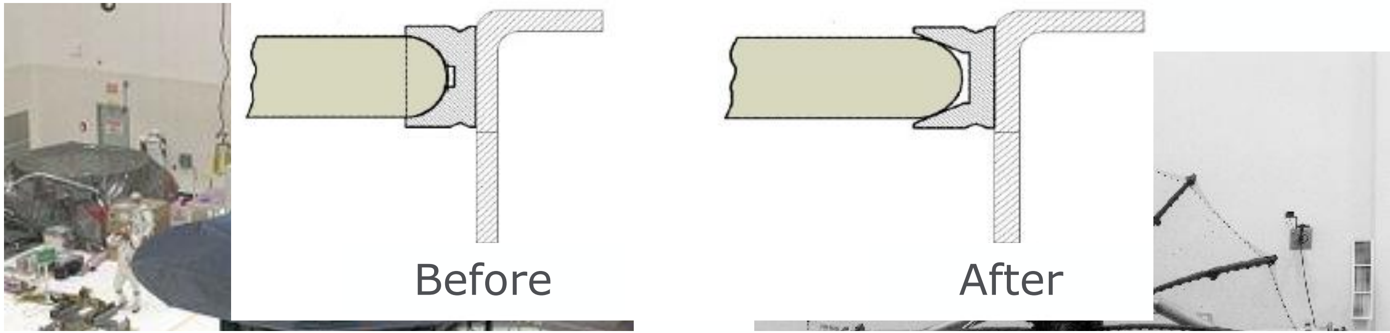
Courtesy of Qinetiq Space N.V.

Design Requirements: separable contact surfaces

(other than gears, balls and journal bearings)

- maintain **adhesion forces** below the specified limits
- contact between the mating surfaces **shall be characterized**
  - → surface roughness, hardness, contact geometry
- the **peak hertzian contact stress** shall be verified to be below 93 % of the yield limit of the weakest material
- avoid potential contact surface **property changes**
- for metallic surfaces (→ risk of **cold welding**!):
  - → minimum **hardness** of 500HV
  - → use of **dissimilar metal** (conflict with galvanic corrosion constraints)
  - → use of lubricant / dissimilar coatings

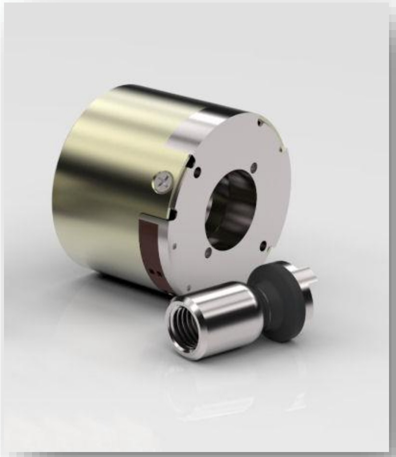
Example: NASA’s Galileo High Gain Antenna



- → Introduction of a “minor” design change
- → Significant increase in hertzian contact pressure (in particular during launch vibrations)
- → Lubrication breakdown
- → Relative motion in vacuum leading to cold welding between pin and socket
- → Partial deployment failure
- → Significantly reduced down-link rate

Design Requirements: Threaded parts

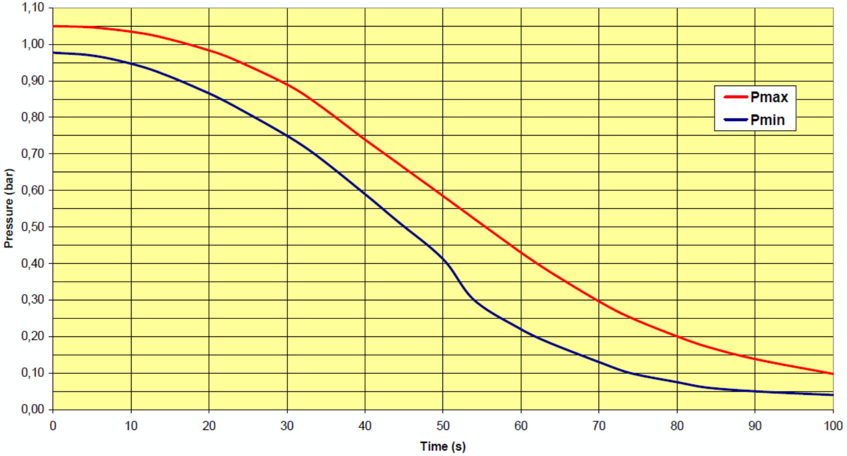
- Use of materials not susceptible to **stress corrosion cracking**
  - → Material selection according to ECSS-Q-ST-70-36C
- shall be designed to be **fail-safe** **≠ safe life**
  - → **Fracture control** requirements in ECSS-E-ST-32-01C Rev.1
- **preload** shall be justified taking into account **scattering** of all parameters
  - → e.g. manufacturing, lubrication and tightening tolerances



http://www.neaelectronics.com/

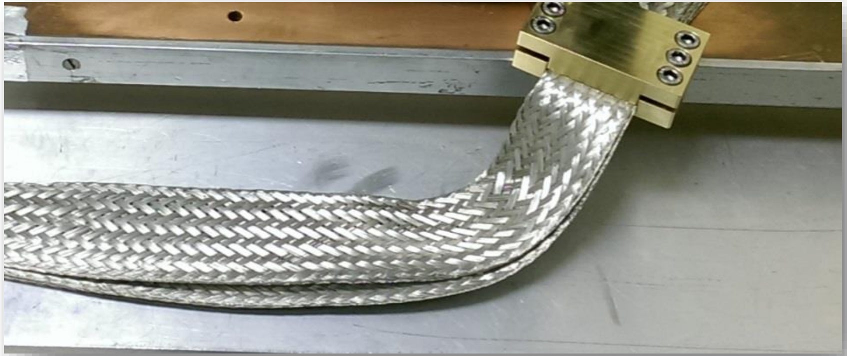
Design Requirements: Venting

- all closed cavities shall be provided with a **venting hole**
- **prevent particles contamination** of bearings, optics and external sensitive components
  - → e.g. by means of filters
- **compatibility of the lubricant** with the other spacecraft materials



Design Requirements: Grounding

- Each mechanism shall be **electrically bonded** to the spacecraft structure
- a ground **bonding strap** shall be used between the mechanism housing and the mounting ground plane
- the **length-to-width ratio** of the bonding strap should be smaller than four
- **DC resistance** shall be less than 10 mΩ.



Design Requirements: Others

Other design requirements, regarding:

- Open and closed loop **control systems** (e.g. gain and phase margins)
- Electrical **insulation**
- **Strain** on wires
- Mechanical **clearances** (e.g. MLI support locations)
- Marking and **labelling**
- Flushing and **purging**
- Thermal control (shall be **passive**!)
- **Magnetic cleanliness / EMC**

Verification Requirements: General

Verification process in conformance with

ECSS-E-ST-10-02 (Verification)

Review of design, Inspection, Measurement, **Analysis**, **Test**

→ Verification matrix shall be established

Verification by analysis

… shall cover extreme conditions

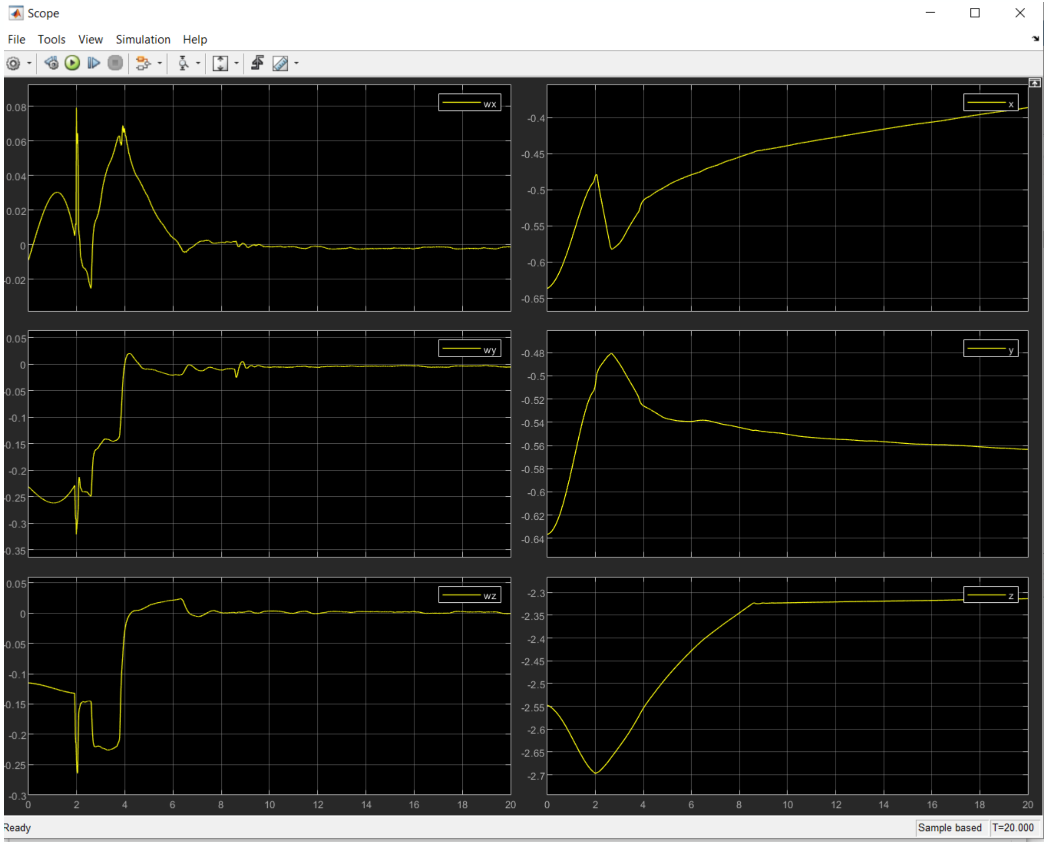
- In flight
- On ground

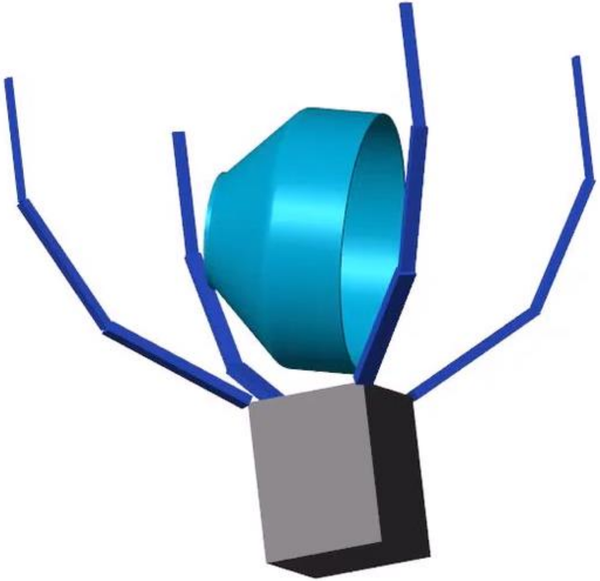
- ❑ Thermal analysis
- ❑ Structural analysis
- ❑ Preload budget
- ❑ Functional performance analysis
- ❑ Hertzian contact analysis
- ❑ Functional dimensioning analysis
- ❑ Reliability analysis, FMECA
- ❑ Gear analysis
- ❑ Shock generation and susceptibility
- ❑ Disturbance generation and susceptibility
- ❑ Analysis of control systems
- ❑ Lubrication analysis
- ❑ Lifetime analysis
- ❑ Hygroscopic effect analysis
- ❑ Magnetic and electromagnetic analysis
- ❑ Radiation analysis
- ❑ Electrical analysis

Functional performance analysis

- Analytical / numerical model based using, e.g.
  - MS Excel, hand calculation
  - Matlab / Simulink
  - Multi-body simulation tools: Simscape, MSC Adams, Dcap, …
  - Many more suitable tools
- Verify actuator design / sizing, performance, load generation, motion profile, etc.
- Sensitivity analysis, analyze failure cases
- For deployables / complex robotics systems: main verification technique
- always requires correlation with hardware test data

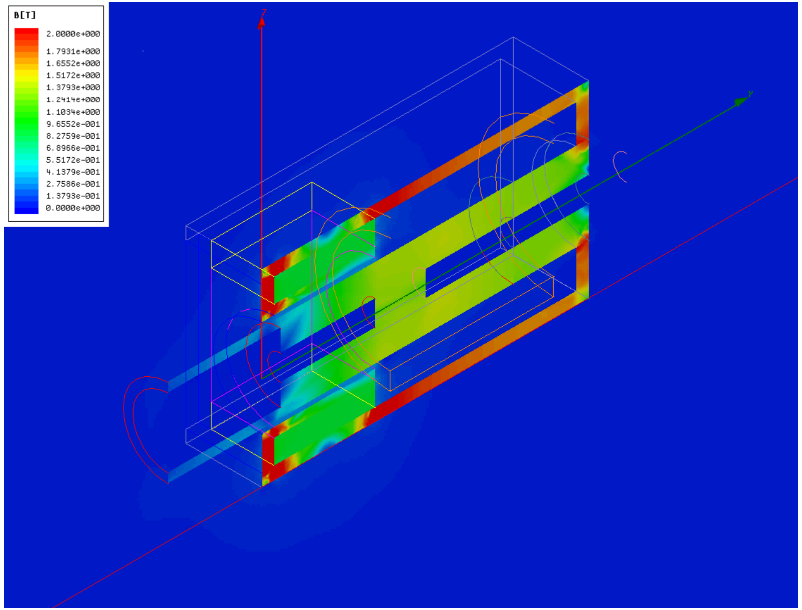
Functional performance analysis (example)

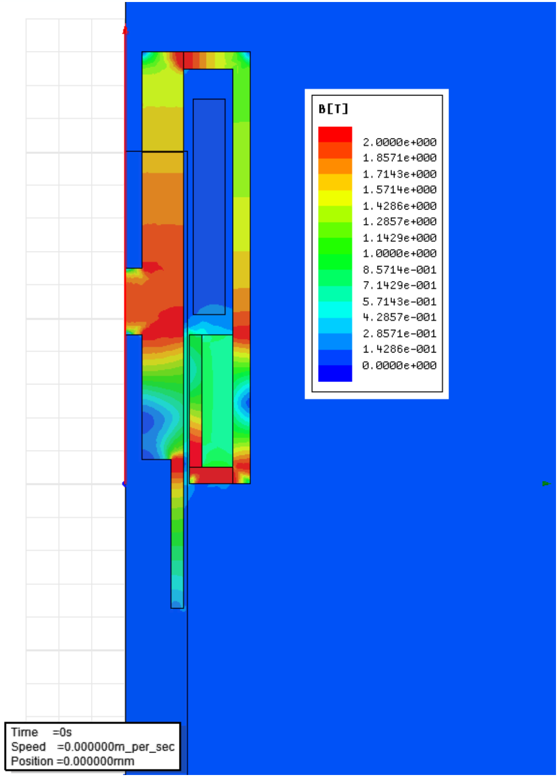




Magnetic and electromagnetic analysis

Example: Polarised Solenoid (Pin Puller)





Ball bearing analysis

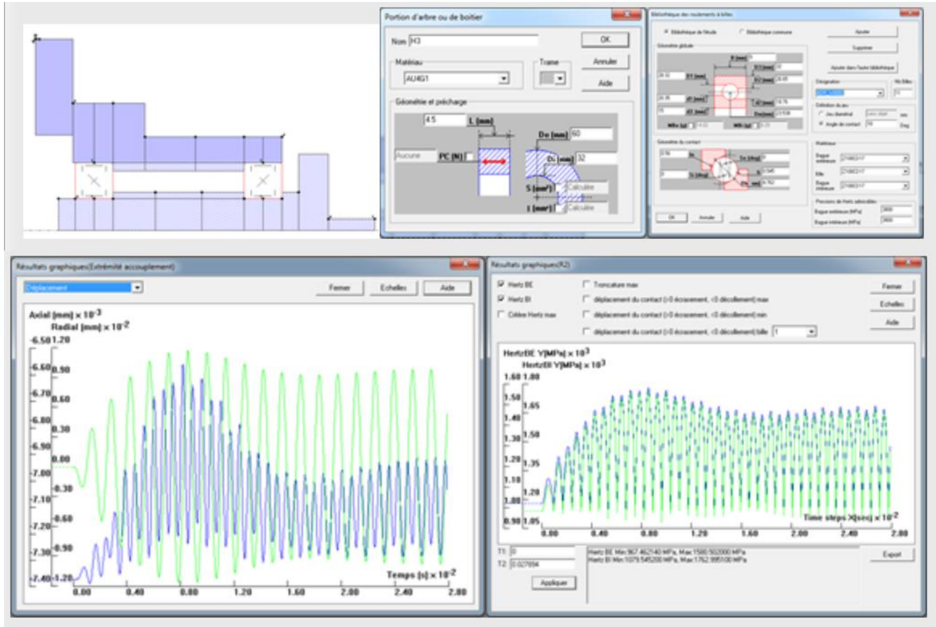
- Analysis of the **predicted hertzian contact stress** to verify the compliance with the material allowable

- Analysis to verify **sizing of ball bearings** in conformance with the allowable peak hertzian contact stress

  → Ball bearing analysis tools: CABARET, RBSDyn, KISSsoft, ORBIN

  → Also for separable contact surfaces, gears, end stops

RBSDYN by CNES



source: https://logiciels.cnes.fr/en/node/56?type=desc

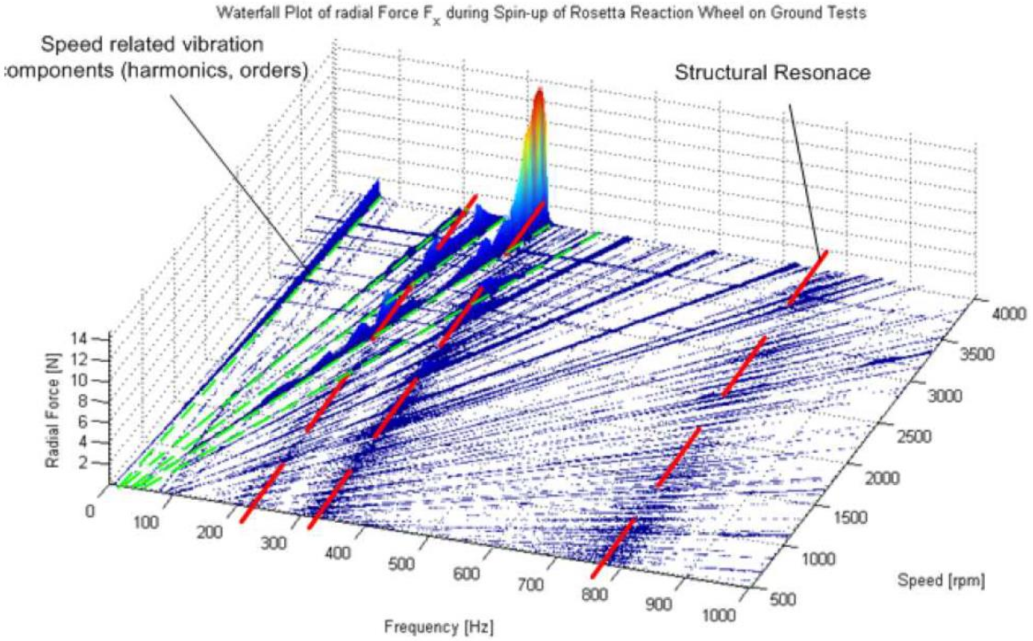
Disturbance generation

Example: Microvibration generation of reaction wheels

- Bearing geometry
- Unbalance
- Structural resonances (e.g. FEM model)
- Control frequencies
- Rotor dynamics

$$FTF = \frac{f_r}{2} \cdot \left(1 - \frac{d}{D} \cdot \cos\alpha\right)$$

e.g. Fundamental train frequency



Lubrication analysis

Analysis of quantity of liquid lubrication based on

- partial / ambient pressure
- temperature
- design of labyrinth seal

$$\frac{dm}{dt} = (p_v - p_p)\sqrt{\frac{M}{2 \cdot \pi \cdot R \cdot T}}$$

e.g. Langmuir equation to analyse oil loss by evaporation

$$\frac{dm}{dt} = \frac{(p_i - p_o) \cdot d \cdot b \cdot v}{(4 + \frac{1.5}{b})}$$

e.g. mass flow over labyrinth seal according to Space Tribology Handbook (ESTL)

Potential Oil Loss Mechanisms:

Creep, centrifugal forces, evaporation, absorption by porous materials

Verification by test

- The tests to be performed shall be
  - Defined in a test plan
  - Agreed by the customer
- conformance to ECSS and mechanisms specification
- conformance to functional dimensioning
- performance in launch and operation configuration
- thermal verification
- structural verification
- characterize the dynamic behavior

- Characterisation testing
- Qualification testing
- Acceptance testing

Characterisation testing

- Breadboard model testing during **Phase A or B**
- Gain confidence in technology (no flight representative hardware)
  - Functional performance test
  - Vibration and thermal tests
  - Tribological lifetime test on critical items

    (Example: usage of certain lubricant in bearing / gear test rig)

→ **No formal qualification!**

Table 5-1: Space segment equipment - Qualification test baseline

Test	Reference clause	Ref. to Level & Duration	Applicability versus types of space segment equipment												Application notes
			a	b	c	d	e	f	g	h	i	j	k	l	
General															
Functional and performance (FFT/RFT)	5.5.1.1		R	R	R	R	R	R	R	R	R	R	R	R	For k (solar array), the deployment test is mandatory before and after the environmental tests (manual deployment before the environmental tests).
Humidity	5.5.1.2		X	X	X	X	X	X	X	X	X	X	-	X	For k (solar array) and l (solar panel), see ECSS-E-ST-20-08.
Life	5.5.1.3	See Table 5-2 No 1	X	X	R	R	X	X	R	X	X	R	-	-	To be performed on dedicated model. For l (solar panels), the life tests are covered by the ECSS-E-ST-20-08.
Burn-in	5.5.1.4		X	-	-	X	-	-	X	-	-	-	-	-	The test is performed in parallel with other funct. & environm. tests.
Mechanical															
Physical properties	5.5.2.1		R	R	R	R	R	R	R	R	R	R	R	R	Upon agreement with customer the CoG and MoI is not measured by test but calculated.
Static load	5.5.2.2	See Table 5-2 No 2	X	X	X	X	X	X	X	X	X	X	X	-	One of the three types of test is performed if not covered by the sinusoidal vibration test.
Spin	5.5.2.2	See Table 5-2 No 3	X	X	X	X	X	X	X	X	X	X	X	-	
Transient	5.5.2.2	See Table 5-2 No 4	X	X	X	X	X	X	X	X	X	X	X	-	
Random vibration	5.5.2.3	See Table 5-2 No 5	R	X	R	R	R	R	R	R	X	X	X	-	For k (solar array), the random vibration test should be added to acoustic test for fixed solar array mounted directly to the spacecraft side wall (without offset bracket). For b (antennas), i (optical), j (mechanism), random vibration or, acoustic or both tests are selected depending on the type, size and location of the space segment equipment.
Acoustic	5.5.2.4	See Table 5-2 No 6	-	X	-	-	-	-	-	-	X	X	R	-	
Sinusoidal vibration	5.5.2.5	See Table 5-2 No 7	R	R	R	R	R	R	R	R	R	R	R	-	
Shock	5.5.2.6	See Table 5-2 No 8	R	X	R	R	R	X	R	X	R	R	-	-	If it is demonstrated that the susceptibility to shock of the space segment equipment is above the shock environment, the test needs not to be performed. For k (solar array) shock qualification is performed at components level and confirmed during the deployment test.
Micro-vibration generated environment	5.5.2.7		X	X	-	X	X	-	X	-	-	X	-	-	Test to be performed only if need is identified by analysis.
Micro-vibration susceptibility	5.5.2.8	See Table 5-2 No 9	X	-	-	-	-	-	-	-	X	X	-	-	Test to be performed only if need is identified by analysis.
Structural integrity															
Leak	5.5.3.1	See Table 5-2 No 10	X	-	R	R	R	R	X	X	-	-	-	-	Leak and pressure tests may be combined.

Life test model

Flight representativeness regards:

- *Design (dimensions, tolerances, surface properties)*
- *Part quality*
- *Materials*
- *Processes*
- *Pre-conditioning (accept. test, run-in)*
- *Operation (e.g. speed profile, control, duration)*

→ The life test model shall be equal to the FM**, but shall not be the FM**

→ Best practice: **life qualification on the QM**

Lifetime related effects / failure modes

cycle dependent

Time dependent

- **Wear out**
- **Accumulation of wear**
- **Pitting**
- **Fretting**
- **Material fatigue**
- **Settling**
- **Defect propagation**
- **Lubricant deterioration**
  (e.g. oil separation, chemical reaction)
- **Oil loss**
  (e.g. migration, evaporation, absorption, diffusion)
- **Creep**

- **radiation effects**
- **thermal effects**
- **electromigration**
- **storage effects**

not addressed by ECSS-E-ST-33-01C

Pre-conditioning

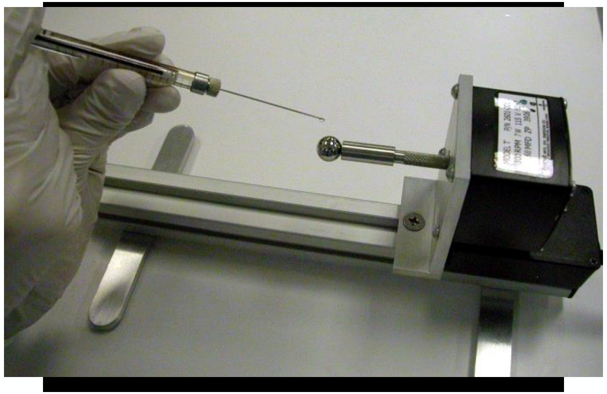
1. **Flight-representative assembly and integration**

   e.g. pre-loading, lubricant quantity and application process etc.

2. **Run-in and thermal settling (cycling)**

3. **Vibration testing**

   (ECSS-E-ST-33-01C, para. 4.8.3.3.11 b)



$$1 \times qual.\,test + n \times (accept.)\;test$$

Including sub-system and system level tests!

Life test duration

" […] shall be verified using the factored sum of the predicted nominal ground test cycles […] and the in-orbit o

able 4-4: Life test duration factors

	Number of expected cycles	Factor
	1 to 1 000 cycles	4
s to	1 001 to 100 000 cycles	2
	> 100 000 cycles	1,25
	1 to 10 cycles	10
	11 to 1 000 cycles	4
	1 001 to 100 000 cycles	2
	> 100 000 cycles	1,25

	e.g. SA deployment	e.g. SADM
No. of in-orbit cycles	1	29219
on-ground	2	320
lifetest	$1 \times 10 + 10 = 20$	$10 \cdot 10 + 990 \cdot 4 + 28219 \cdot 2 + 10 \cdot 10 + 320 \cdot 4 = 61878$

Accelerated life testing

- Acceleration: Increasing the rate of ageing by increasing st… …ctors
  by a known amount!

  - Example: compr…
    (with long peri…
    pointing, sc…

Stress factors

temperature

contact stress

current density

temperature cycles

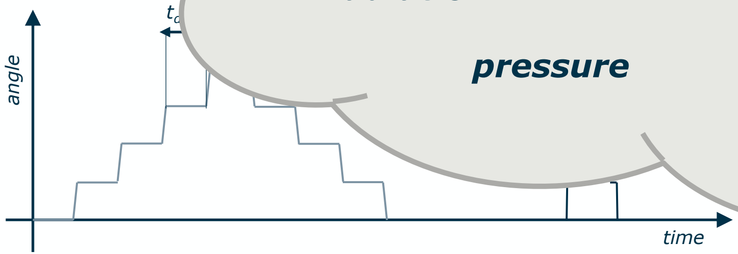
speed

radiation

voltage

pressure

operational frequency

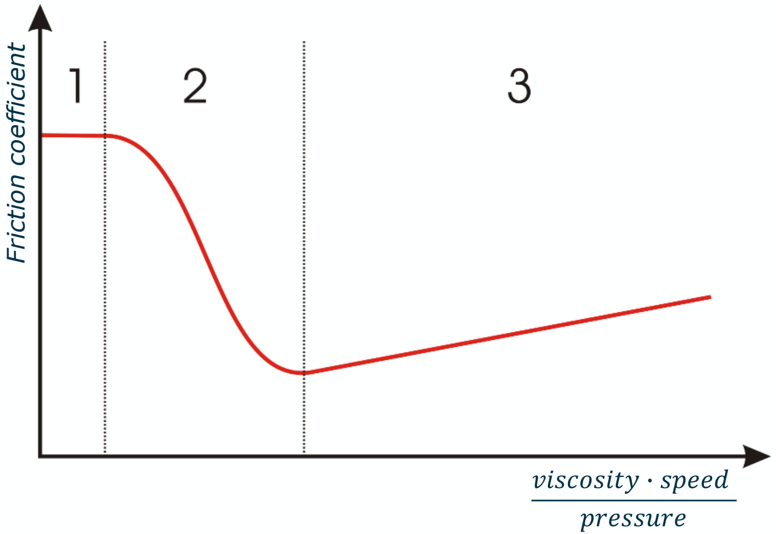


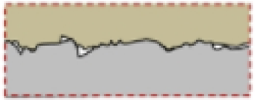
…tional level

… effects & …e modes …re the same

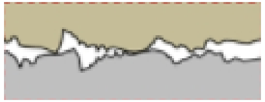
nominal operational level

Stribeck – introduction into lubrication regimes

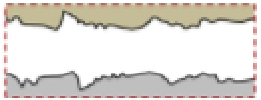




boundary lubrication
continuous asperity contact
high friction and wear rate



mixed lubrication
some asperity contact
fluid film carries load



hydrodynamic lubrication
no metal-to-metal contact
viscous friction

Stribe…

From [9] for elliptical contacts:

$$U = \eta_0 * \frac{v}{E' R_x}$$

$$G = E\alpha$$

$$W = \frac{F}{E' R_x^2}$$

$$k = \frac{a}{b}\ (ellipticity\ parameter)$$

$$\eta_0 = Base\ viscosity\ of\ lubricant$$

$$E' = reduced\ elatsic\ modulus$$

$$F = elliptic\ integral\ (= 1.5277 + 0.60.23 \ln(R_x/R_y))$$

$$\alpha = Lubricant\ pressure - viscosity\ coefficient$$

$$a, b = Hertzian\ contact\ semi - mino\ and\ semi - major\ dimensions$$

The λ-ra…

With

λ >10 :

10> *λ* ≥3:

0.8< *λ* <3

λ ≤0.8:

Conclusion on accelerated life testing

- **General**
  - *Life test as much as possible flight representative*
  - *Every deviation from flight condition to be carefully assessed*

- **Accelerated testing**
  - *Numerous ageing effects and failure modes*
  - *Stress factors contribute differently*
  - *Ageing effects shall remain representative*
  - *Acceleration by increased*
    - *Frequency of operation: OK (unless very long standstill)*
    - *Temperature: NOK*
    - *Speed: OK for fluid and dry lube; NOK for greases*
    - *Other stress factors: check case-by-case*

Qualification testing success criteria

Disassembly and visual inspection of tribological parts:

- No direct contact between metallic parts
- Surface properties of contact surfaces not modified beyond specified limits
- No chemical deterioration beyond the specified limits of fluid lubricants
- Amount and size of wear acceptable (performance, contamination)
- Resistive torques according to 4.7.5.3. (motorization)
- Less than 50% degradation of resistive torques / forces
- Performance according to spec

Acceptance testing

- Tests to confirm that flight hardware free from manufacturing defects;
- Test content according to ECSS-E-ST-10-03C, table 5-3;
- Vibration levels and thermal loads which are higher than expected in flight but less than qualification
- Refurbishment should not be performed after successful acceptance testing

Thank you for your attention!

Contact: geert.smet@esa.int

ESA Mechanisms team today

22 FTE (15 Staffs / 7 Contractors) + 1 integrated support

1 YGT, 1 trainee

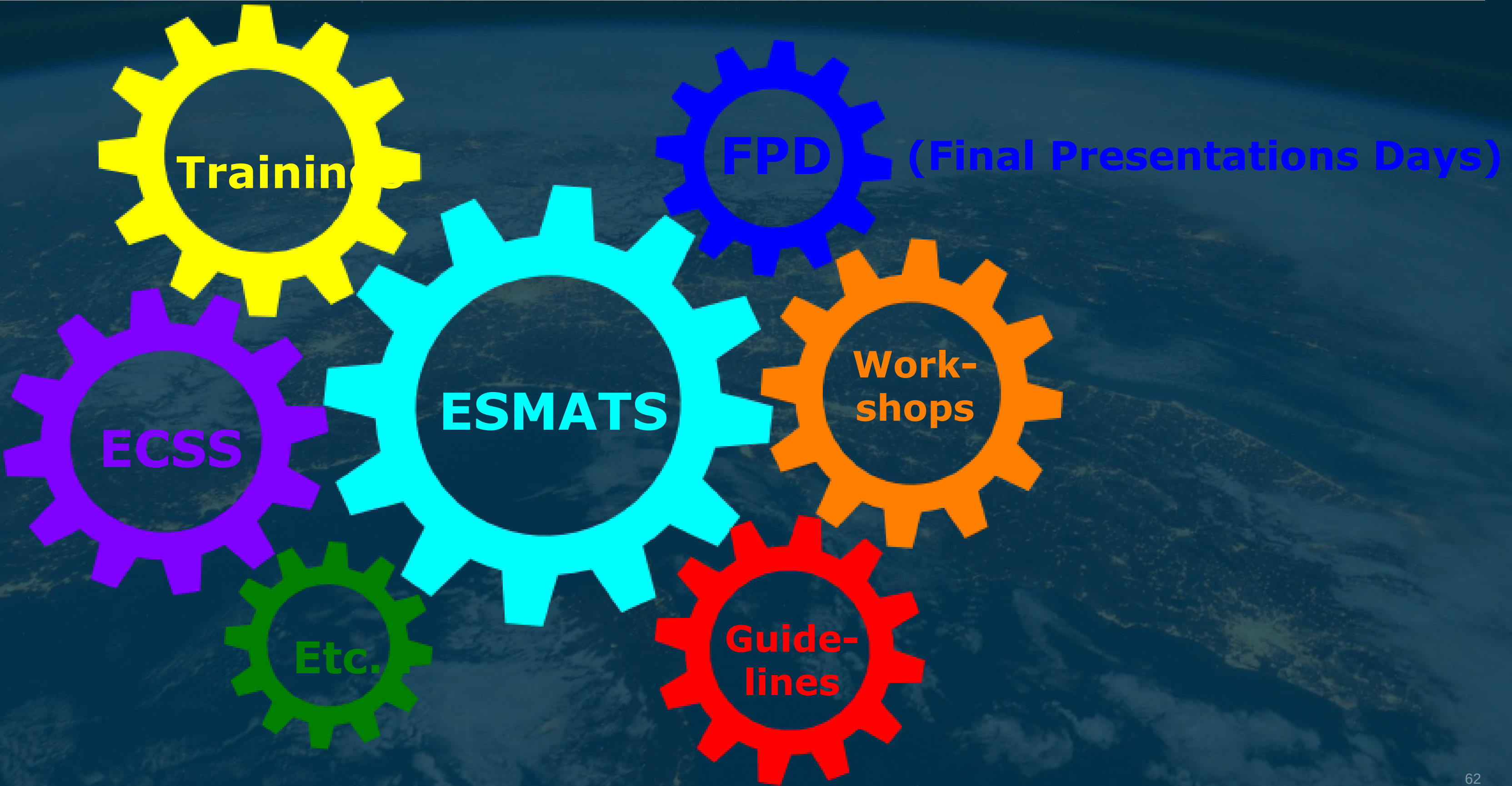
10 different nationalities…

Integrate
d support

YGT

Trainee

Ex-
Mechanisms
members


Trainin
FPD
(Final Presentations Days)
ESMATS
ECSS
Work-
shops
Etc.
Guide-
lines

15th ESA Space Mechanisms Workshop !

2009 – WS#1 - Hold-Down and Release Mechanisms
2010 – WS#2 - Multi-Body simulation
2011 – WS#3 - Pyrotechnics
2012 – WS#4 - Tribology
2013 – WS#5 - Electromagnetic devices
2014 – WS#6 - Micro-vibrations
2015 – WS#7 - Ball-bearings
2016 – WS#8 - Gear technology
2017 – WS#9 - Workshop on Mechanisms Testing and Health Monitoring
2018 – WS#10 - Optical Mechanisms
2019 – WS#11 - Space Mechanisms Legacy from New ESA players
2020 – WS#12 - Pyrotechnics and Ball Bearing software (2 workshops in parallel)
2021 – WS#13 - Position Sensors
2022 – WS#14 - Mechanisms Microvibrations
2023 – WS#15 - Mechanisms for CubeSats and MicroSats
2024 – WS#16 – CleanSpace 11PM&12AM/03/2024

(Participation limited to ESA member states and cooperating states)

Space Mechanisms R&D Final Presentations Days ?...

A final presentation is mandatory/requested at the end of any ESA R&D contracts

Instead of organising a final presentation at the end of each R&D contract, we proposed since more than 25 years to :

- Merge all final presentations in to a single event, to share more detailed information in front of a bigger audience / Space mechanisms community
- Promote your latest R&D to potential customer
- Promote Networking
- Stimulate Ideas / Partnership for future R&D

Next event planned 12PM&13/03/2024

(Participation limited to ESA member states and cooperating states)

6 Active Harmonisation Dossiers

- AOCS Sensors and Actuators (Reaction Wheels & CMG's)
- Actuators Building Blocks for Mechanisms (Covering now Electric motors, actuators, gears (as before) and position sensors)
- Electric Propulsion Pointing Mechanisms (EPPM)
- Hold Down, Release, Separation and Deployment System
- Pyrotechnics Devices
- Solar Array Drive Mechanisms (SADM)
- Deployable Booms (*now on hold*)

→ Toward harmonised Roadmaps between you and us

(Participation limited to ESA member states and cooperating states)

Some of our Guidelines / Handbooks :

Already released:

- Electric Motors For Space Applications Handbook
- Ball-bearing design assembly and preloading operations
- Accelerated testing of liquid Lubricated Mechanisms
- Sizing of an actuator with a gearbox in the drive unit
- Consideration for Long Term Storage of Mechanisms
- Space mechanisms Micro-Vibration Handbook
- Gear handbook Part 1 (Harmonic Drives)
- Pyrotechnics handbook Part 1 (Pyrotechnics devices)

More to come: (feel free to propose new ones)

- Gears handbook Part 2 (Spur gears)
- Pyrotechnics Part 2 (Lessons learned)
- CuBeSat mechanisms Guideline

(Participation limited to ESA member states and cooperating states)

www.esmats.eu

ESMATS 2023 | OVERVIEW ▾ | AGENDA | TRAINING COURSES ▾ | ASTRONIKA | SPONSORS ▾ | EXHIBITORS | ABOUT ESMATS | AMS 2024

EPFL

SPACE INNOVATION

almatech

csem

esmats 2025

24th – 26th September 2025
Lausanne Switzerland

École
polytechnique
fédérale
de Lausanne

20th ESMATS 2023 related courses schedule

Mpnday 11/09/23, Tuesday 12/09/23	Cabaret Ball-Bearing Simulation Software Tutorial Course (from ESR Technology)	OnLine
…		
Saturday 16/09/23		
Sunday 17/09/23		
Monday 18/09/23, Tuesday 19/09/23	ESTL - Space Tribology Course (from ESR Technology) Compliant Mechanisms Design Course (from CSEM) Fundamentals of Space Vehicle Mechanisms (from Launchspace) Advanced Mechanisms Design Course (from ESA mechanisms team)	In-situ, Warsaw
Wednesday 20/09/23, Thursday 21/09/23, Friday 22/09/23	ESMATS 2023	In-situ, Warsaw

Advanced Mechanisms Design course (from the ESA team)

- **AGENDA in 2021**
  Gear technology for Space Application
- Long term storage of Space mechanisms, Considerations for Tribological Components and Magnets
- Ball Bearing Technology - Part 1: "Draw me a bearing and justify its performances"
- Model philosophy and test including Logic development
- Electrical Motors for space applications
- Bushings
- Hardware Post-Test Inspection; Pass/Fail Criteria
- Position Sensors for Space mechanisms
- Life Testing of Spacecraft Mechanisms
- Design for Demise (D4D) for Space Mechanisms
- A Mechanisms Perspective on Microvibration
- Motorisation Margins
- Space Mechanisms System Engineering
- Reliability/statistics on mechanisms
- Vibration Tests of Mechanisms
- Pyrotechnics Shock Assessment for Mechanisms
- Errors Analysis for Accurate Positioning
- Advanced Dynamics Simulations for Space Mechanisms
- Ball Bearing Technology - Part 2: Advanced Considerations
- Appendages design and verification
- Piezo actuators
- Hold-down and release mechanisms, Design, Analysis and Test considerations
- Closed Loop Control

Prevention of potential problems!

Following on from the successful AMDC at previous ESMATS in 2017, 2019 and 2021 (on-line),
ESA Mechanisms Section is proud to announce their updated training course on ‘Advanced Mechanisms Design’
This course will give some practical information for understanding, in greater detail, the main specificities of these technologies, in order to help the designers to be aware of the potential pitfalls when designing Space mechanisms.
Rather than giving some closed solutions to a particular problem, this course will provide proper technical understanding of several important mechanisms fields, such that preventive actions can be put in place before a problem occur, and would need expansive and time demanding action to solve the encountered problem in a curative way.

Agenda

2023	Start Time	End Tme		AMDC Training course topics	Presenters	Time
Day 1	9:00	9:15		Course package delivery and in-situ registration		15 min
	9:15	9:30	0	Welcome and Introduction	Lionel	15 min
	9:30	10:10	1	Space Mechanisms System Engineering (and how to win a contract)	Manfred	40 min
	10:10	10:10	2	New ECSS presentation	only slides (Florian)	0 min
	10:10	10:35	3	Model philosophy and test including Logic development	Ewelina	25 min
	10:35	10:50		PAUSE		15 min
	10:50	11:55	4	Ball Bearing Technology - Part 1: Bearings Technology for Space Application Overview of space bearing solutions for guiding function in rotation, with contact. Specific insight in ball bearings.	Alain	65 min
	11:55	12:30	5	Ball Bearing Technology - Part 2: Advanced Considerations	René	35 min
	12:30	13:15	6	Position Sensors for Space mechanisms	Fernando	45 min
	13:15	14:15		Lunch breack		60 min
	14:15	15:20	7	Gear technology for Space Applications	Adam	65 min
	15:20	16:20	8	Electrical Motors for space applications (Part1)	Claudia	60 min
	16:20	16:35		PAUSE		15 min
	16:35	17:35	9	Electrical Motors for space applications (Part2)	Cristina	60 min
	17:35	17:55	10	Piezo actuators	Ronan	20 min
	17:55	18:15	11	Smart Material Overview	Kobyé	20 min
Day 2	9:00	10:05	12	Motorisation Margins	Joe	65 min
	10:05	10:55	13	Errors Analysis for Accurate Positioning	Paolo	50 min
	10:55	11:10		PAUSE		15 min
	11:10	11:30	14	Vibration Tests of Mechanisms	Ewelina	20 min
	11:30	11:50	15	Pyrotechnics Shock Assessment for Mechanisms	Massimo	20 min
	11:50	12:35	16	Hold-down and release mechanisms, Design, Analysis and Test considerations	Sandro	45 min
	12:35	13:00	17	Appendages design and verification	Ronan	25 min
	13:00	14:00		Lunch breack		60 min
	14:00	14:30	18	Life Testing of Spacecraft Mechanisms	Asier	30 min
	14:30	15:00	19	Hardware Post-Test Inspection; Pass/Fail Criteria	Asier	30 min
	15:00	15:00	20	Advanced Dynamics Simulation for Space Mechanisms	Only Slides (Philipp)	0 min
	15:00	16:10	21	A Mechanisms Perspective on Microvibration	Geert & Sandro	70 min
	16:10	16:25		PAUSE		15 min
	16:25	16:50	22	Reliability/statistics on mechanisms	Massimo	25 min
	16:50	17:05	23	Long term storage of Space mechanisms, Considerations for Tribological Components and Magnets	Adam	15 min
	17:05	17:25	24	Design for Demise (D4D) for Space Mechanisms	Geert	20 min
	17:25	17:55	25	Closed Loop Control	Stefan	30 min
	17:55	18:15		SURVEY completion, Certificate delivery, Control loop Demo	All participants	20 min

Space Tribology Course (STC) - from ESTL

ESTL
Keeping Space Moving

The course will cover the following subjects:

Fundamentals of Tribology – in which tribological concepts are introduced and the special considerations for space and vacuum tribology highlighted.
Tribo-component Design and Performance – in which an overview of the different types,
characteristics and performances of tribo-components (ball bearings, gears, plain and ball/rollerscrews, etc.) used in spacecraft applications is provided. This includes a detailed presentation of considerations for design, selection and load capacity verification of ball bearings for space applications.
Materials for Tribo-Contacts – in which an overview of the main categories of materials and their use in spacecraft tribo-components and surfaces is presented.
Lubrication of Spacecraft Components – in which the application-driven considerations
for selection of fluid or dry (solid) lubricants for tribo-components and surfaces are provided.
This part includes the considerations and typical performances of dry (solid) and fluid lubricants,
respectively. Some practical issues concerning application, handling and preloading of ball bearings and testing of mechanisms where tribological performance is critical are also presented.
Lessons Learned – presenting a selection of the (sometimes painful!) lessons learned on various
programmes. The course is presented by experienced staff from ESTL with over 50+ combined years
of space tribological experience and will be valuable both for younger engineers entering the industry and for the more experienced who may wish to refresh or challenge their tribological understanding.

Compliant Mechanisms Design Course – from CSEM

The course will cover the following subjects:

Introduction to compliant mechanisms
Presentation of space applications using compliant mechanisms
Design principles
Finite Element Modeling guidelines
Material and lifetime aspects
Manufacturing guidelines, including recent additive manufacturing advances
Failure modes and preventions
Integration and testing guidelines
Sensor and actuator selection and integration
Control aspects

Compliant Mechanisms (CM) are proposed to achieve macroscopic linear and rotary motion without friction, wear, backlash, and with extremely high fatigue performance thanks to the elastic deformation of flexible structures.
They are used in harsh environments such as vacuum, cryogenic and space where friction is to be avoided while high-precision and a high lifetime are required.
While the potential of CM in space has already been proven over many years, their development can still be challenging. This course will address the complete development aspects for compliant mechanisms, comprising of design and analysis, manufacturing, assembly and testing. The recent advances on CM brought by additive manufacturing will also be presented.

This course is intended for engineers involved in the design, manufacturing and testing, for managers and anyone else interested in having a practical knowledge of the advantages and challenges of compliant mechanisms. This course will give some practical information for understanding, in greater detail, the main specificities of these technologies,

Fundamentals of Space Vehicle Mechanisms – From LaunchSpace

This course is at the right level for someone:

- With less than 15 years of experience with space mechanisms
- Who is responsible for the design of aerospace mechanisms
- Tasked with analysis activities in thermal or structural elements of mechanisms
- With responsibility for developing drive electronics for mechanisms or
- Tasked with systems work related to implementing mechanisms

Course topics include:

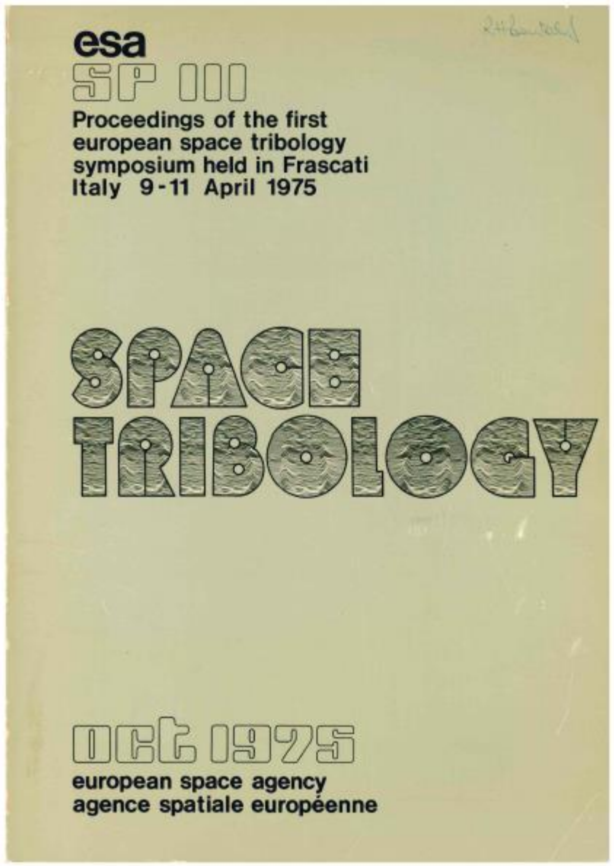
- Mechanisms used in space vehicle
- Pointing subsystems, motors and feedback devices
- Bearings, gears and lubrication fundamentals
- Release and deployment systems
- Power transfer and slip rings
- Mechanisms analysis
- Critical materials for mechanisms
- Spacecraft – mechanism interfaces and sources of mechanism requirements

Fundamentals of Space Vehicle Mechanisms is a special edition of the internationally popular course on this topic. The instructor, Bill Purdy, explores the technologies required for successful space mechanisms design and offers a detailed look at many of the key components common to most mechanisms. The materials necessary to achieve high performance are discussed. Examples of the many types of mechanisms are included for illustration. In addition, mechanisms' relationships and interfaces with other vehicle systems are explored. The course includes design and analysis examples to demonstrate principles involved in understanding how mechanisms should work and how design margins should be evaluated during the evolution of a programme.

If you want to pick the right type of motor for your application, lubrication for your application or angular measurement device for your application, then this is the right course. You will learn the fundamentals of space mechanisms from a leading mechanisms expert. A unique benefit is the instructor's sharing of his experience and lessons learned.

External Laboratory

External Laboratory

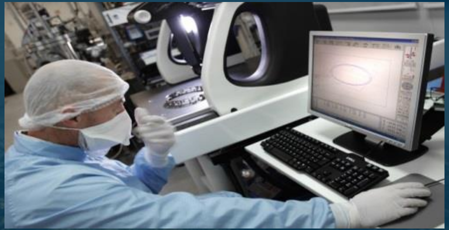


European Space Tribology Laboratory (ESTL)
Was established in 1972 … and still rocking !

Fundamental objective :
"to increase the efficiency and reliability of spacecraft through the application of good tribology"

-> Minor consultancy
-> Major consultancy

European Space Tribology Laboratory (ESTL) in UK



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COLD WELDING DATABASE

Based on the result of "General Validation Studies" a data base was initiated:

- Comparable due to test parameters related to material properties
- It covers the contact modes " impact" and "fretting"
- A summary table shows available material combinations
- For each tests a detailed data sheet is available
- The summary table shows a "calissification" related to the severity of adhesion

http://coldweld.aac-research.at/

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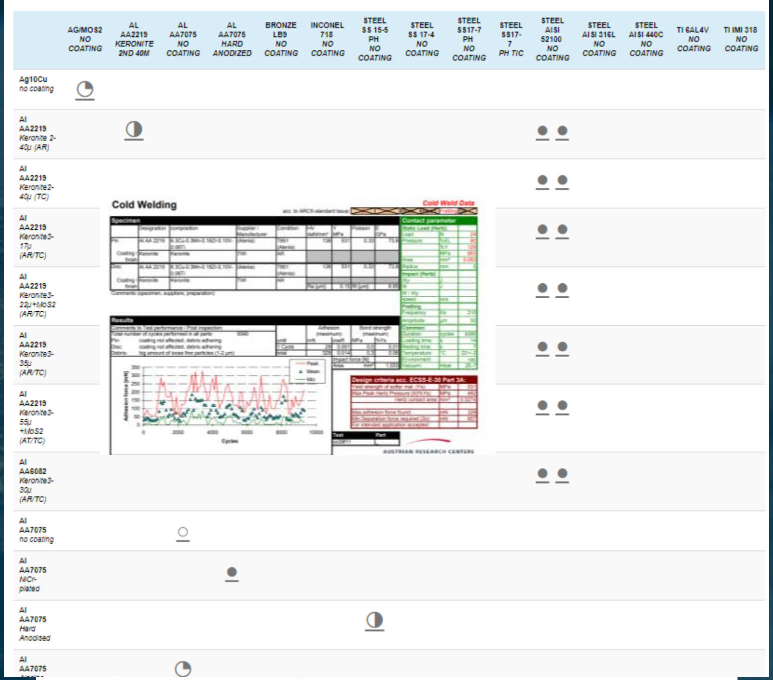

- The summary tables are based on following classification:

Symbol	Adhesion force [mN] lower imit	Adhesion force [mN] upper limit	Comment to adhesion
●	0	200	No or negligible adhesion, noise of test
◑	201	500	Small measureable adhesion
◔	501	5000	Strong adhesion
○	5001	higher	Severe adhesion