ECSS E-31 Thermal Control General Requirements Training Course

Presented by

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Thermal Control Section, TEC-MTT
ESA-ESTEC
May 10th 2023

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Outline

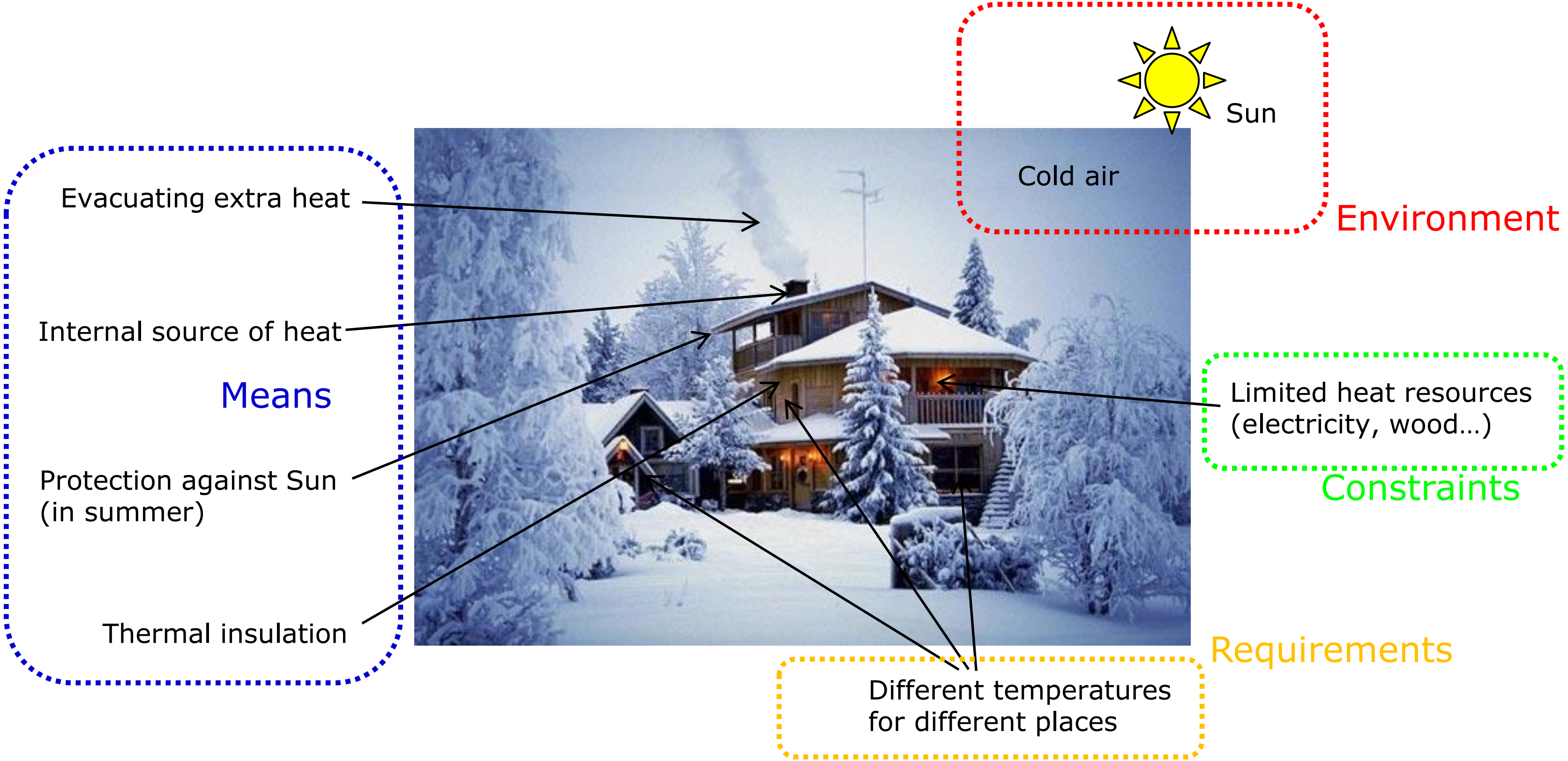
1. **Introduction to Thermal Engineering**
2. **Thermal Standards – Overview**
3. **Mission Specific Requirements**
    1. **Launch to Landing**
    2. **Thermal Space Environment**
4. **Performance Specific Requirements**
5. **Requirement towards other subsystems & Design Requirements**
    1. **Requirements towards other subsystems**
    2. **Thermal design requirements**
    3. **Thermal control means**
6. **Verification**
    1. **Thermal Model and Analysis**
    2. **Thermal Tests**

Objectives of this lecture

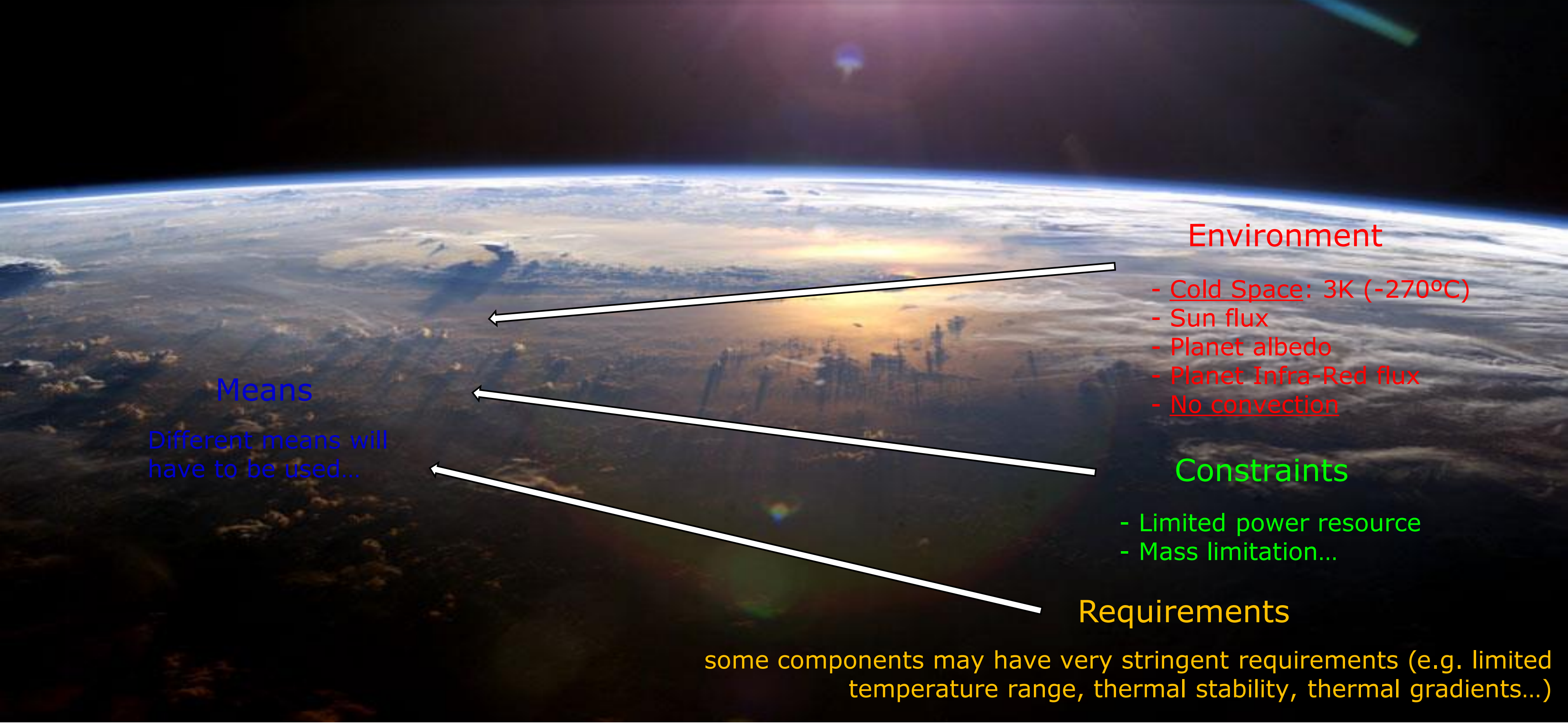
- Be able to answer the following questions:
  - What are the main thermal design drivers?
  - Which are the basic thermal control means?
  - What are the interactions between the thermal design and other sub-systems?
  - How to analyze the complex thermal interactions in a spacecraft?
  - What are the different test requiring thermal engineering support?
  - Why are thermal balance tests paramount for the thermal engineer?
  - What does the thermal ECSS provide and what not?
  - How to use the available standard(s) to support thermal control, design, analysis and test

1. Introduction to Thermal Engineering

1. Introduction to Thermal Engineering:
Why do we need thermal control ? (1/2)



1. Introduction to Thermal Engineering: Why do we need thermal control ? (1/2)



1. Introduction to Thermal Engineering:
What are the objectives and the tasks ?

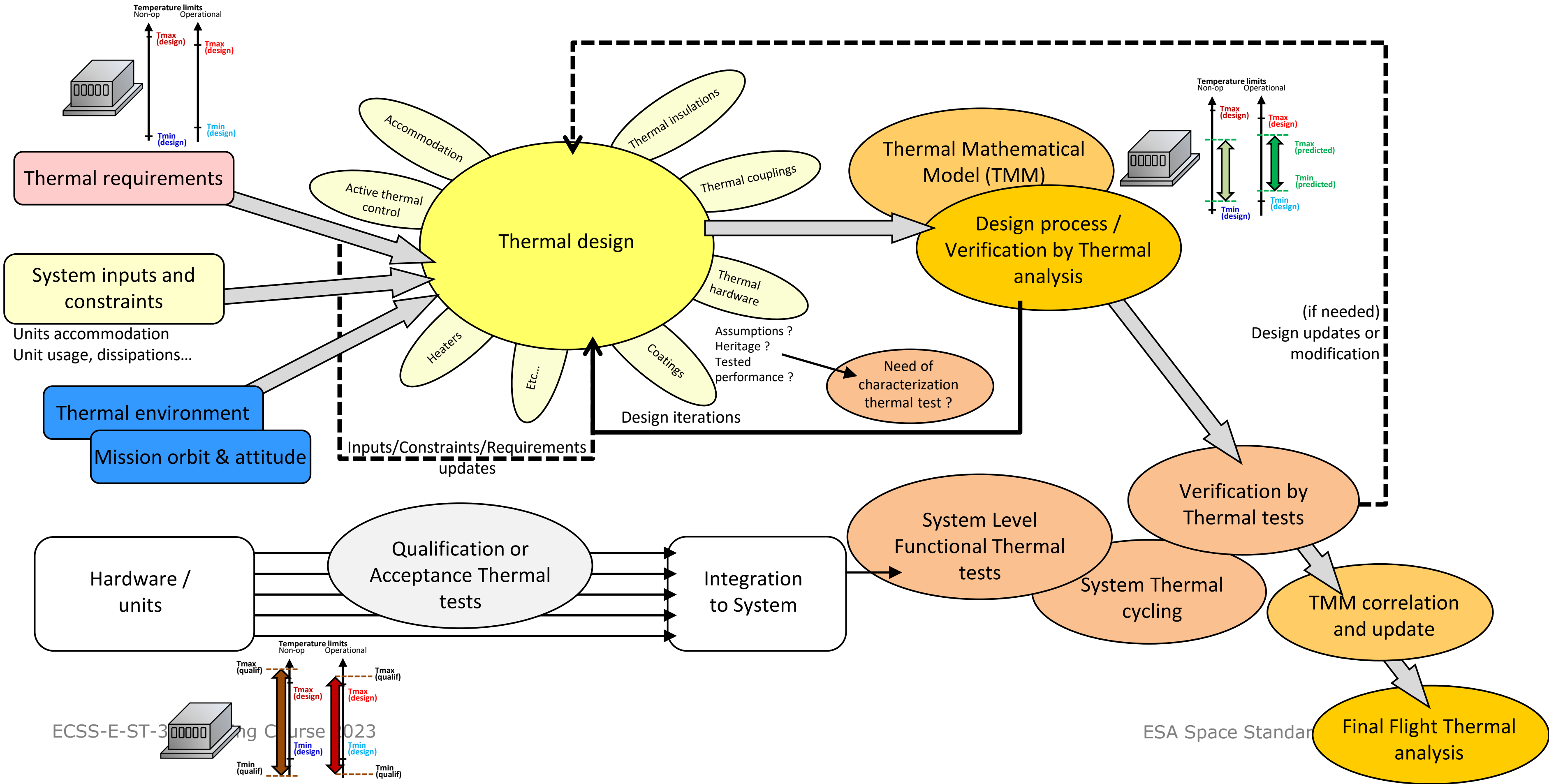
<u>Objectives:</u>

- Control temperatures
- Control temperature gradients
- Control temperature stability
- Manage heat fluxes

<u>Tasks:</u>

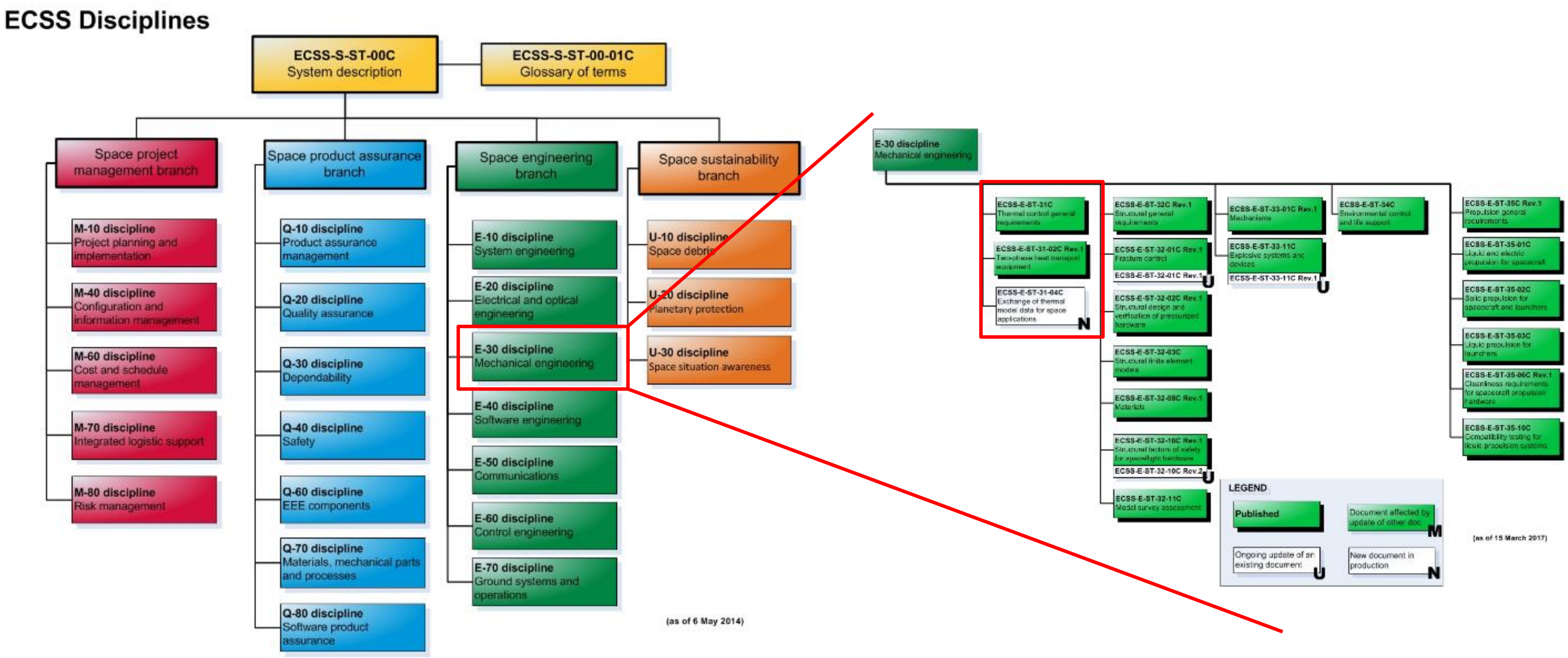
- Thermal Design
- Thermal Analysis
- Thermal Test

1. Introduction to Thermal Engineering:
Thermal engineering in a nutshell



2. Thermal Standards - Overview

2. Thermal standard overview:
Thermal standard in the ECSS tree



ECSS Documents for Thermal Engineering

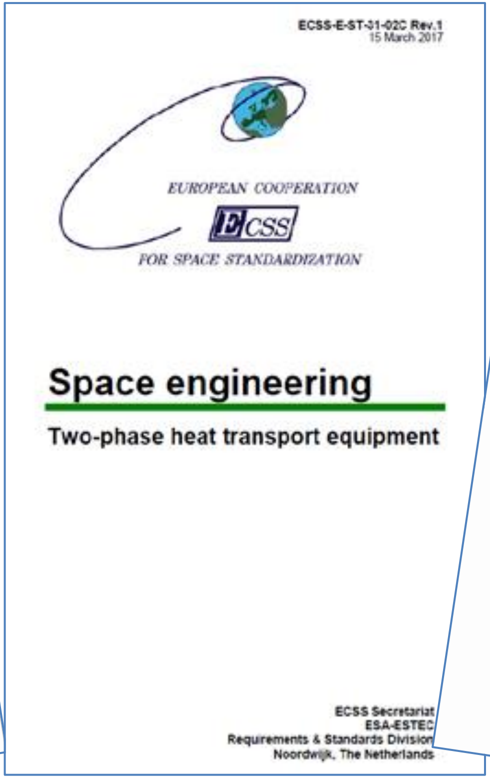
ECSS-E-ST-31C
15 November 2008

EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION

Space engineering

Thermal control general requirements

ECSS Secretariat
ESA-ESTEC
Requirements & Standards Division
Noordwijk, The Netherlands



ECSS-E-ST-31-02C Rev.1
15 March 2017

EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION

Space engineering

Two-phase heat transport equipment

ECSS Secretariat
ESA-ESTEC
Requirements & Standards Division
Noordwijk, The Netherlands

ECSS-E-ST-31-04C
1 February 2018

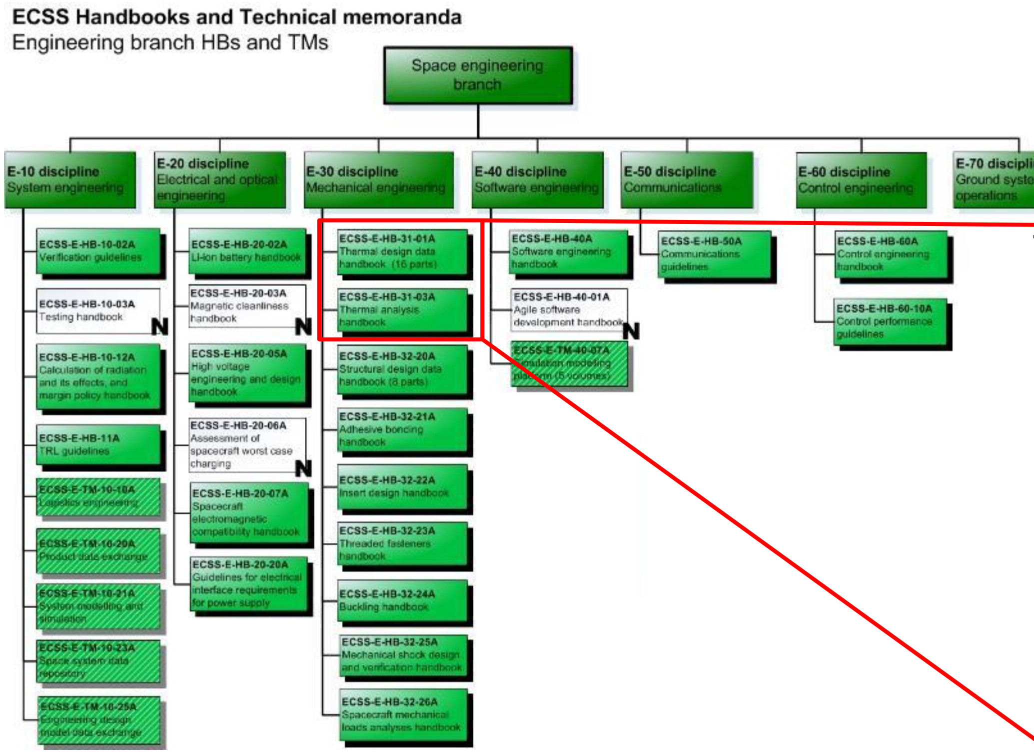
EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION

Space engineering

Exchange of thermal analysis data

ECSS Secretariat
ESA-ESTEC
Requirements & Standards Division
Noordwijk, The Netherlands

2. Thermal standard overview: Thermal handbooks



Thermal handbooks:

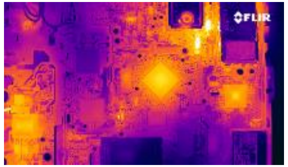
- ECSS-E-HB-31-01A - Thermal Design Handbook
  - Part 1 Thermal design handbook – Part 1: View factors
  - Part 2 Thermal design handbook – Part 2: Holes, Grooves and Cavities
  - Part 3 Thermal design handbook – Part 3: Spacecraft Surface Temperature
  - Part 4 Thermal design handbook – Part 4: Conductive Heat Transfer
  - Part 5 Thermal design handbook – Part 5: Structural Materials: Metallic and Composite
  - Part 6 Thermal design handbook – Part 6: Thermal Control Surfaces
  - Part 7 Thermal design handbook – Part 7: Insulations
  - Part 8 Thermal design handbook – Part 8: Heat Pipes
  - Part 9 Thermal design handbook – Part 9: Radiators
  - Part 10 Thermal design handbook – Part 10: Phase – Change Capacitors
  - Part 11 Thermal design handbook – Part 11: Electrical Heating
  - Part 12 Thermal design handbook – Part 12: Louvers
  - Part 13 Thermal design handbook – Part 13: Fluid Loops
  - Part 14 Thermal design handbook – Part 14: Cryogenic Cooling
  - Part 15 Thermal design handbook – Part 15: Existing Satellites
  - Part 16 Thermal design handbook – Part 16: Thermal Protection System
- ECSS-E-HB-31-03A - Thermal Analysis Handbook

2. Thermal standard overview:
Scope of the thermal ECSS

Thermal control general requirements (ECSS-E-ST-031C)

- The standard:
  - contains requirements for the definition, analysis, design, manufacture, verification and in-service operation of thermal control subsystems of spacecraft and other space products.
  - is applicable to the complete temperature scale, unless stated otherwise.
  - is applicable to all flight hardware of space projects, including spacecraft and launchers.
  - may be tailored (in conformance with ECSS-S-ST-00)

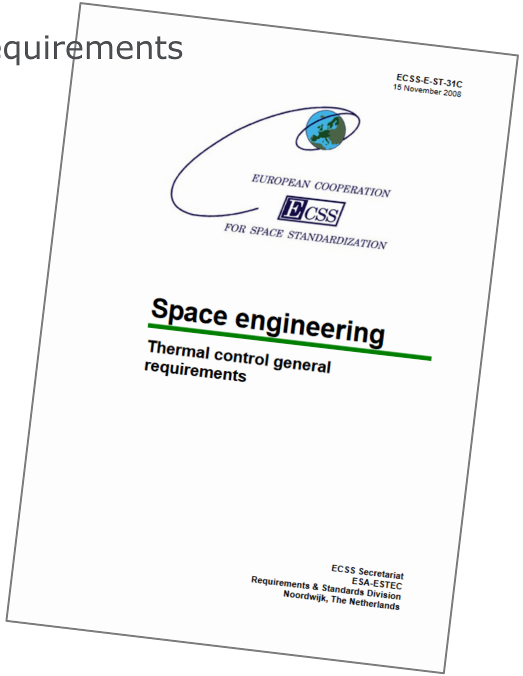
- Temperature scale is divided into:
  - Cryogenic temperature range (<200 K i.e. -73°C),
  - Conventional temperature range (200 to 470 K i.e. -73°C to ≈200°C),
  - High temperature range (>470 K i.e. >200°C).



2. Thermal standard overview:
Thermal ECSS disclaimer

- ECSS-E-ST-31C Space Engineering Thermal control general requirements
  - is not a design guide!
  - It is not telling you how things have to be done.
  - It is a reference to remind you what should be done.

- Thermal Engineering is
  - A system task -> interaction with almost all subsystems
  - Differs for every mission



2. Thermal standard overview:
Thermal ECSS structure

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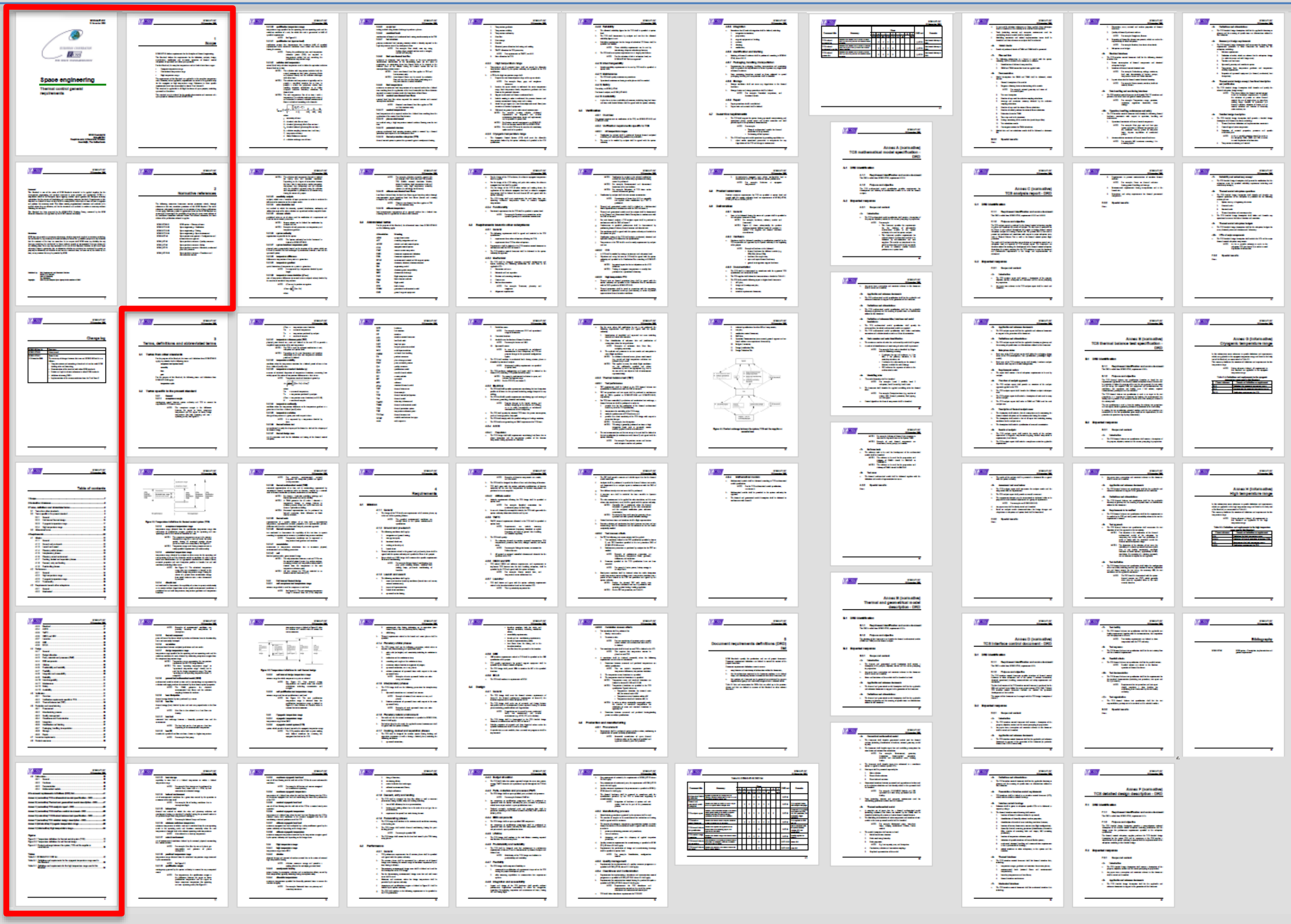
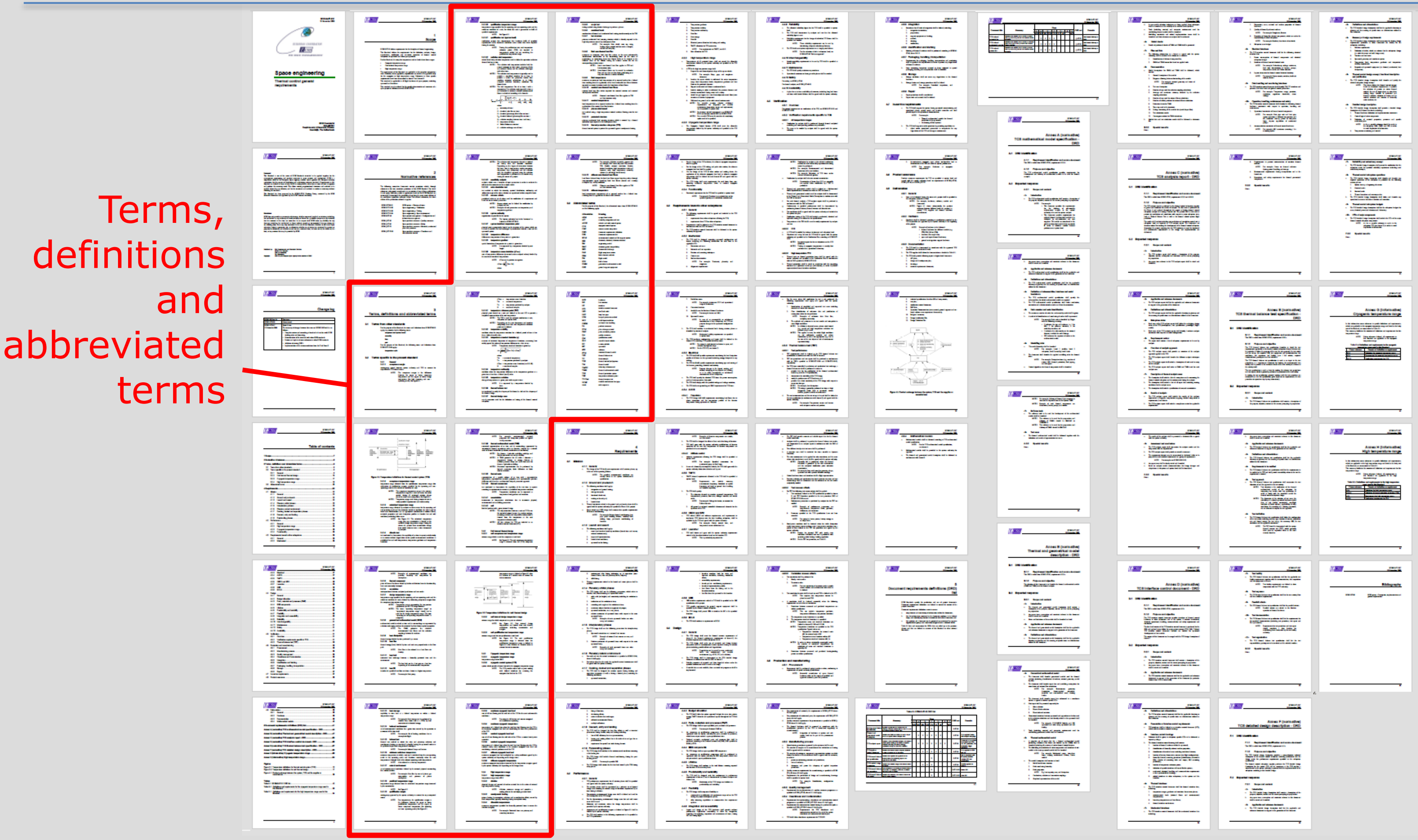
2. Thermal standard overview:
Thermal ECSS structure

Introduction

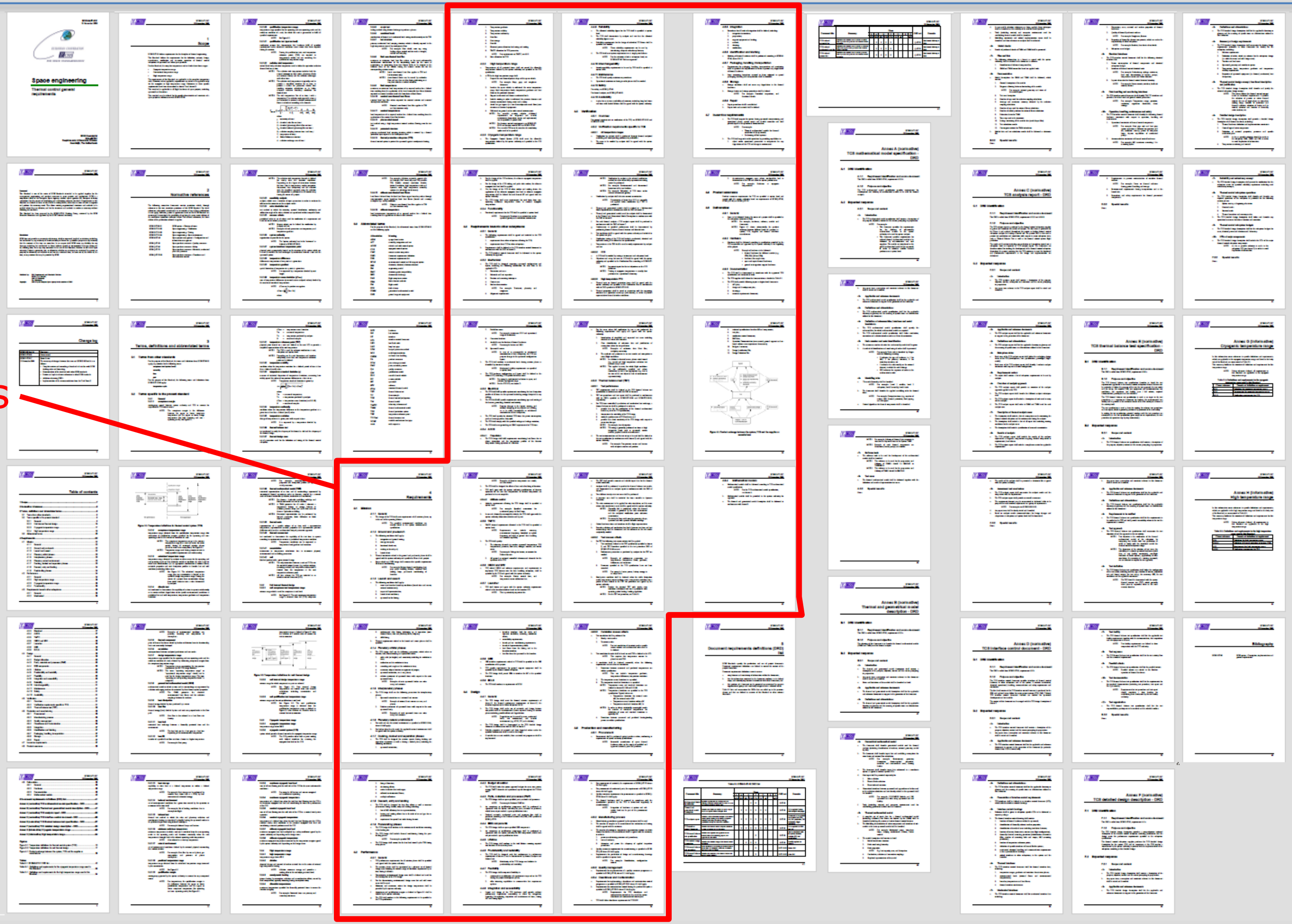


2. Thermal standard overview:
Thermal ECSS structure



2. Thermal standard overview:
Thermal ECSS structure

Requirements



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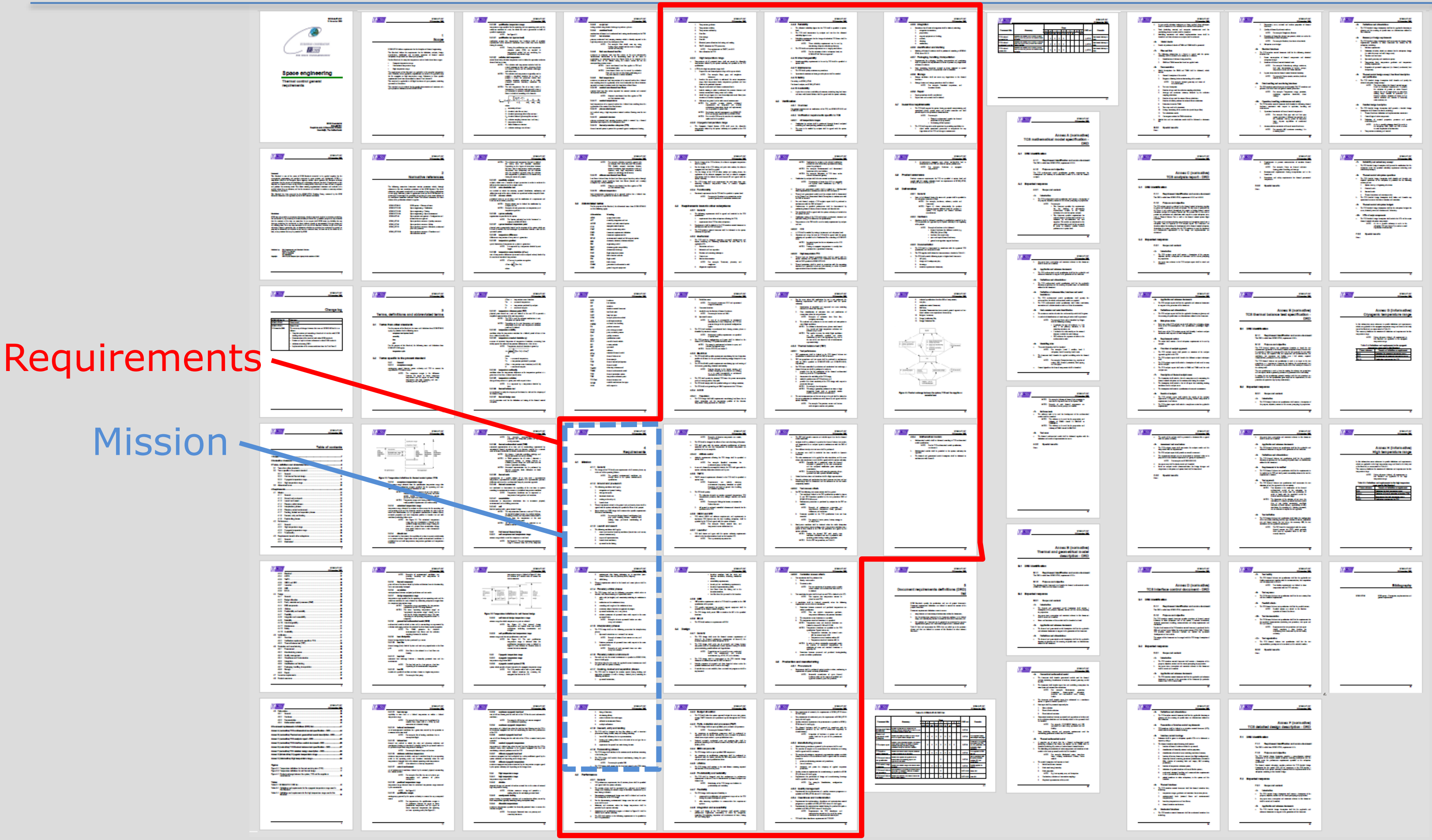
Thermal ECSS structure



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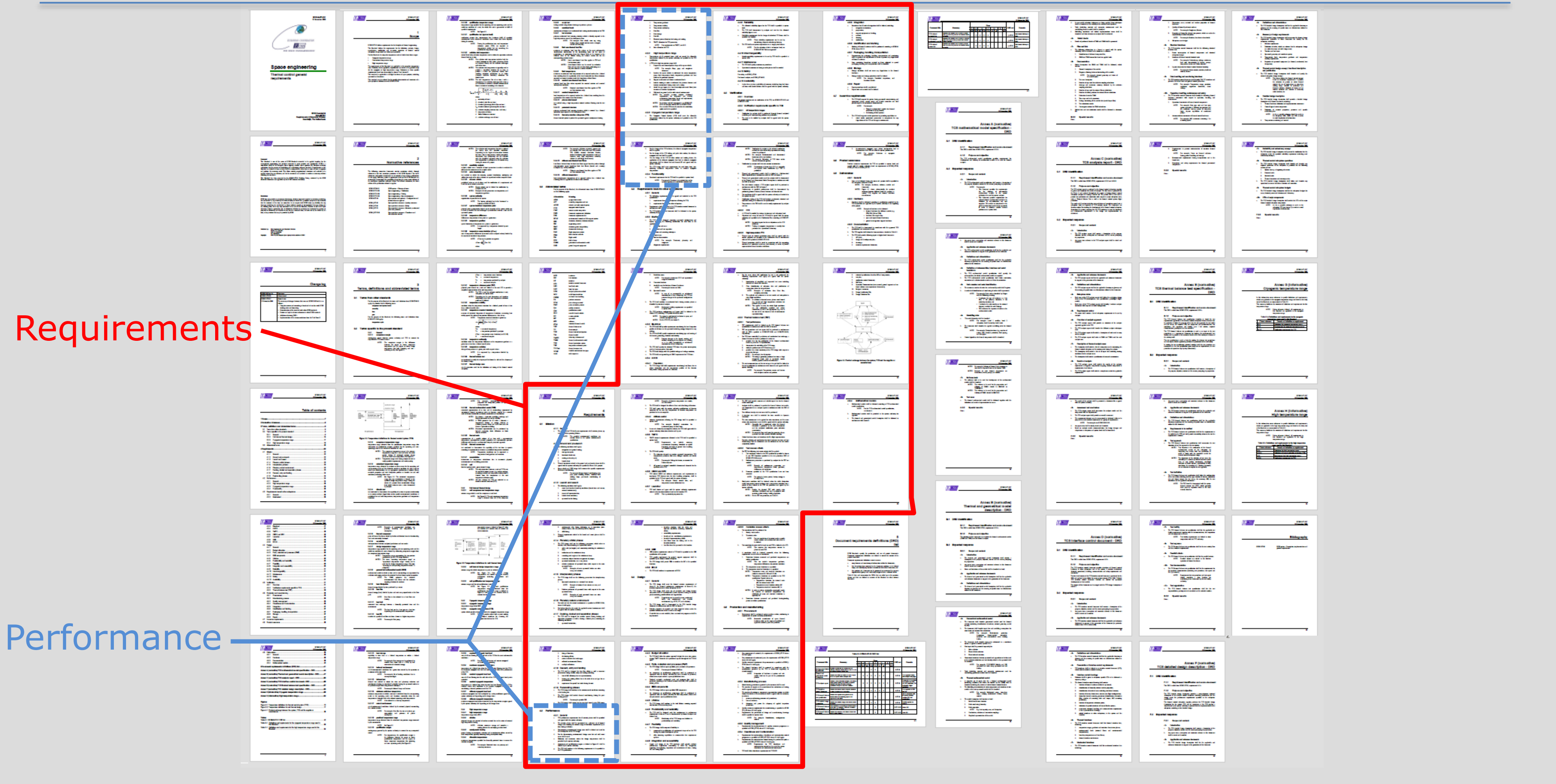
Thermal ECSS structure



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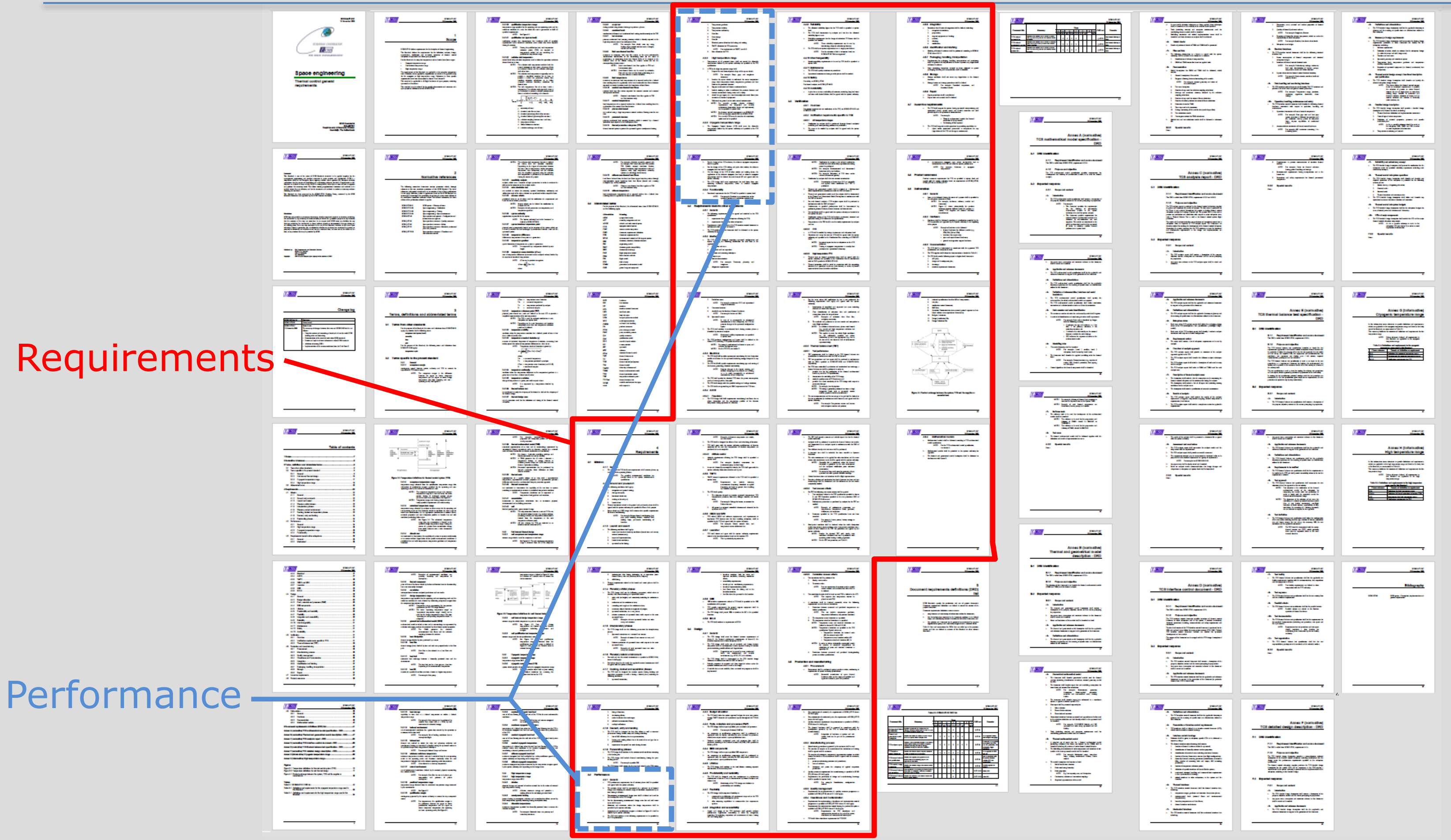
Thermal ECSS structure



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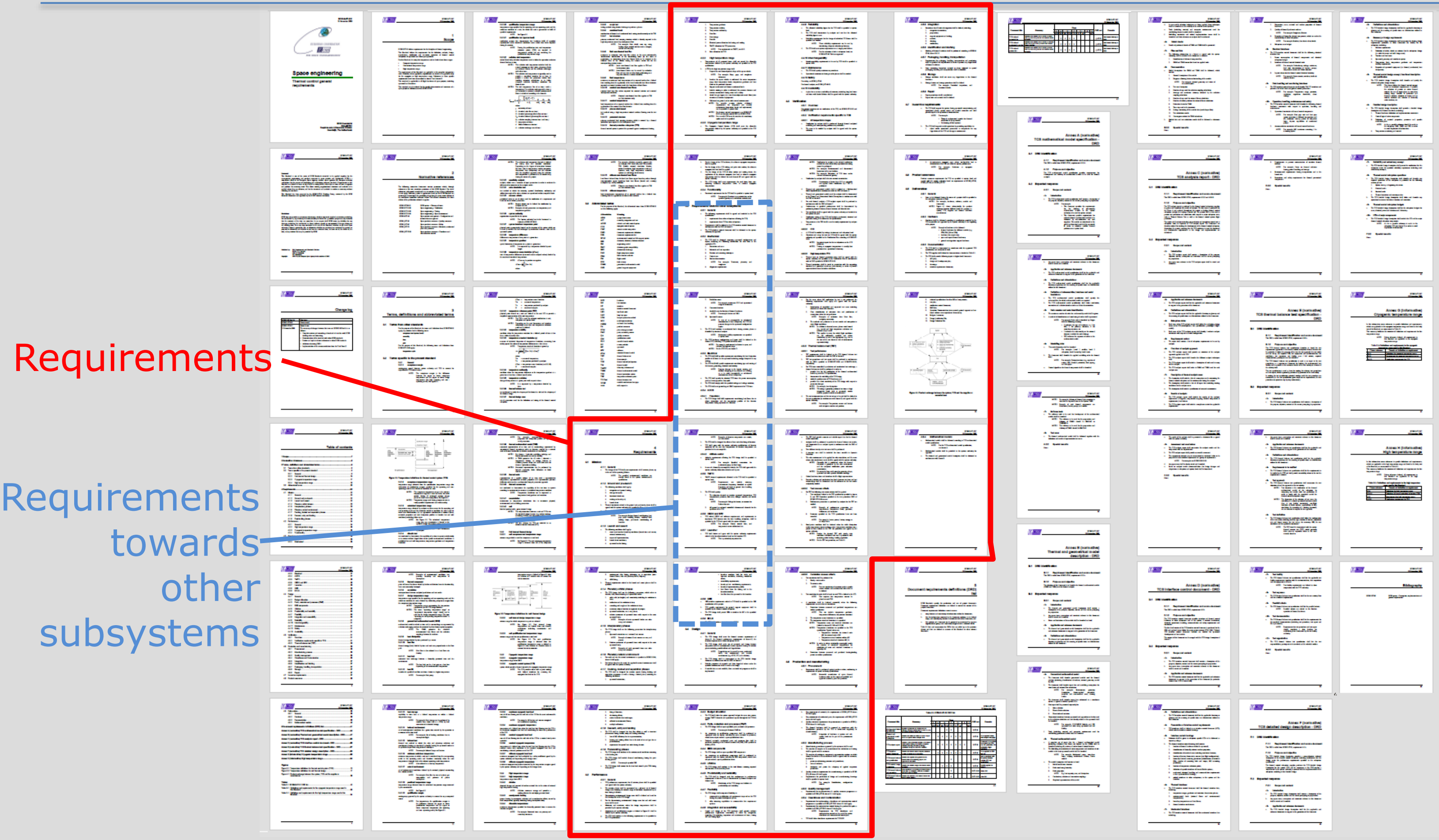
Thermal ECSS structure



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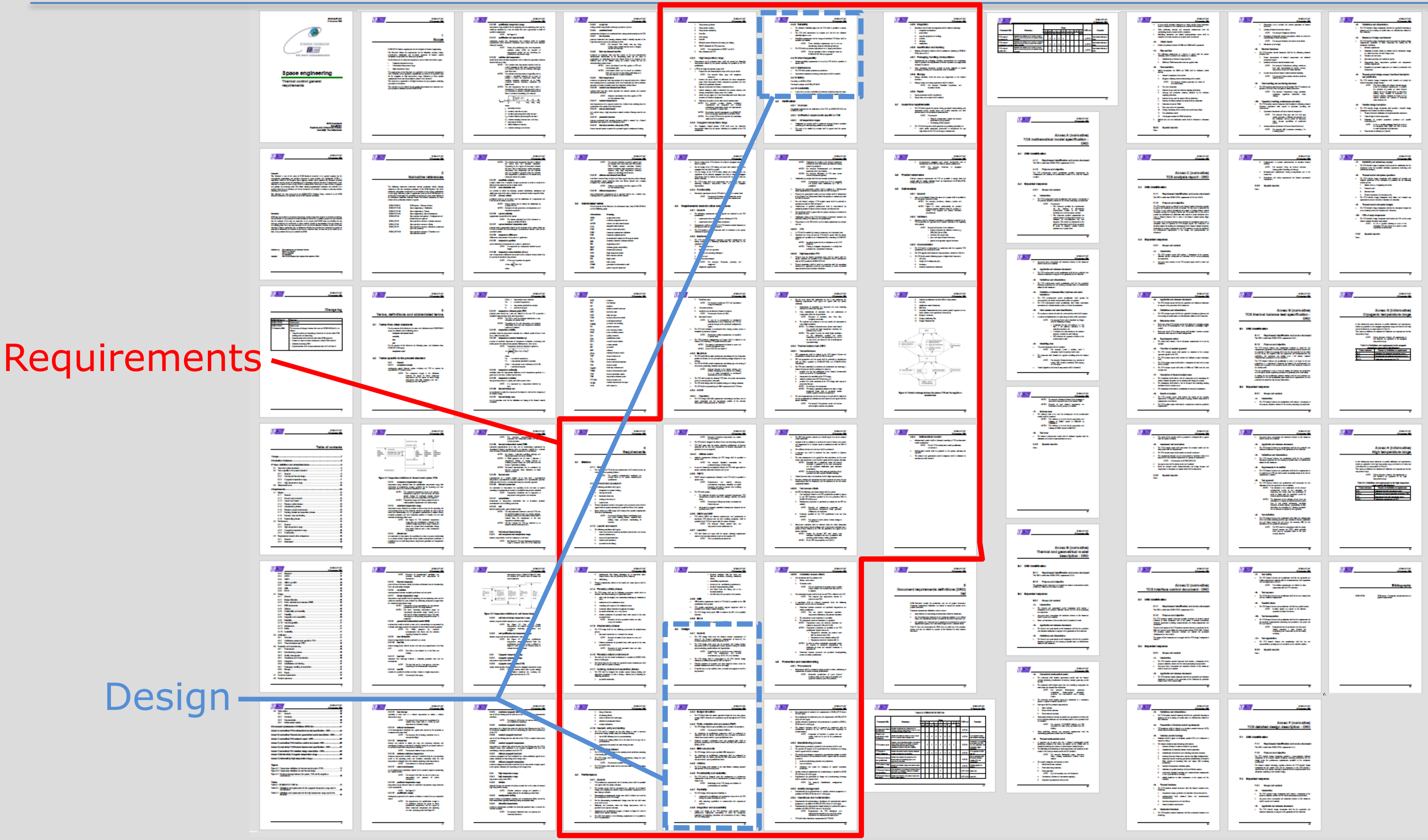
Thermal ECSS structure



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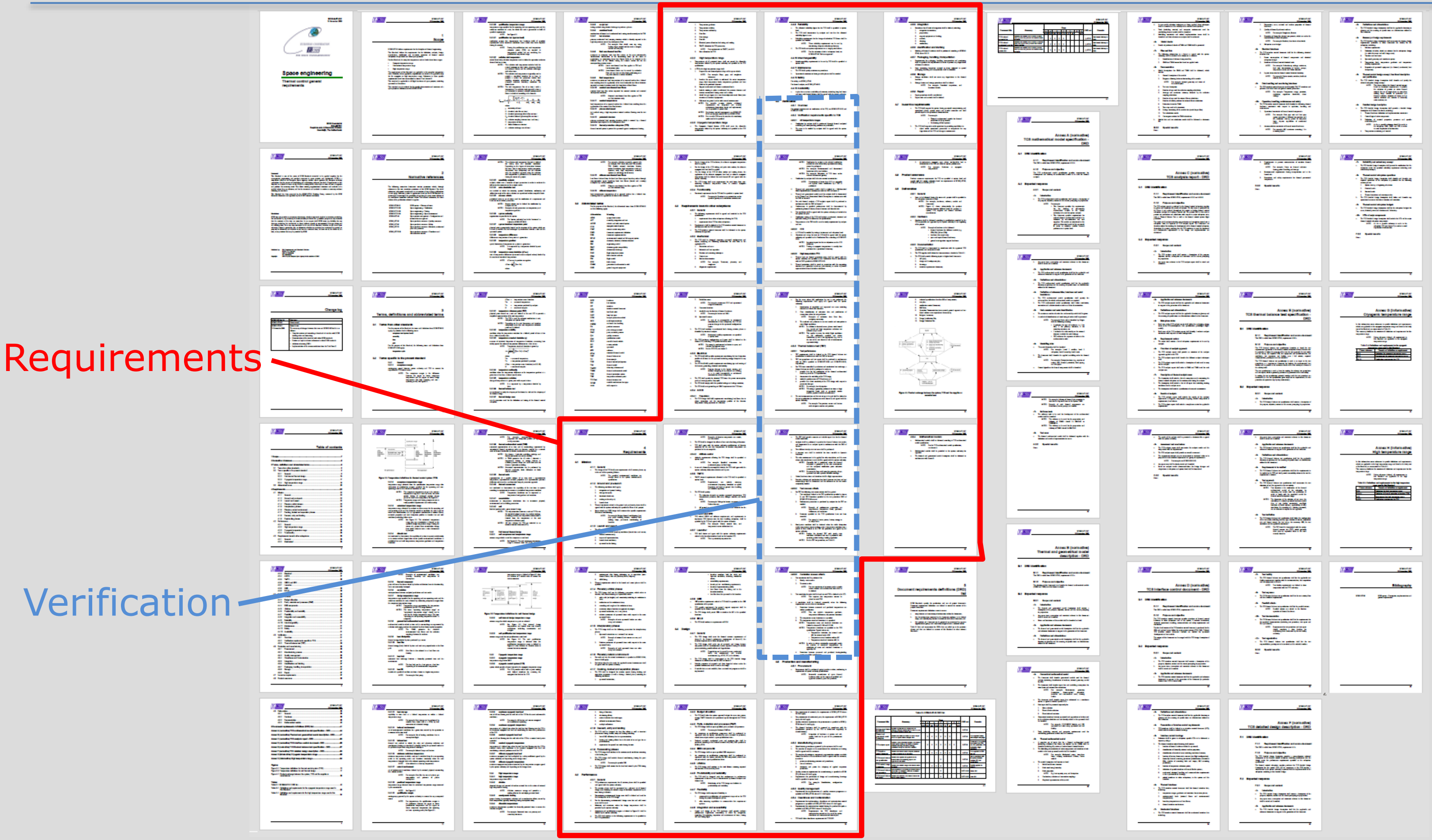
Thermal ECSS structure



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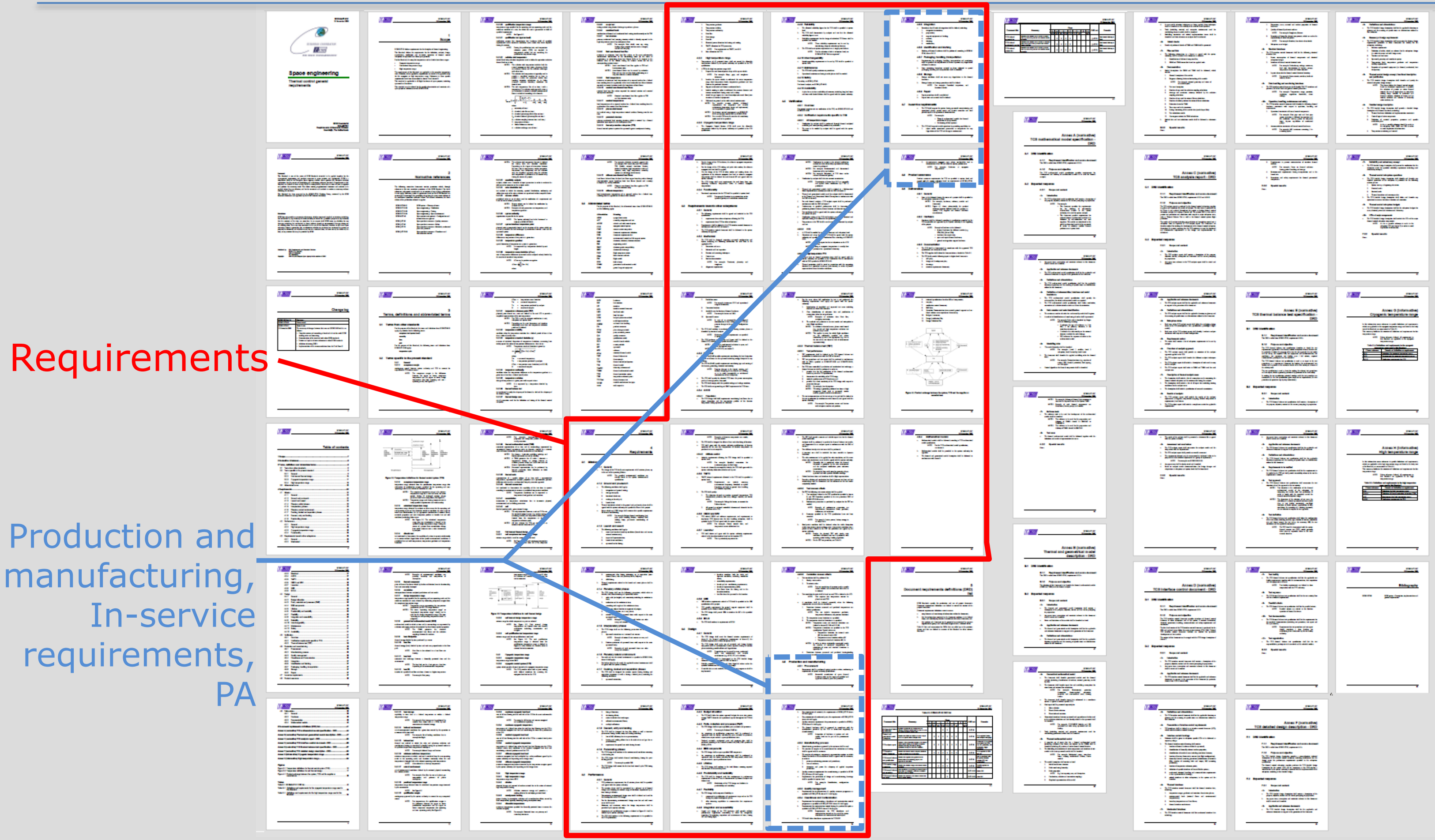
Thermal ECSS structure



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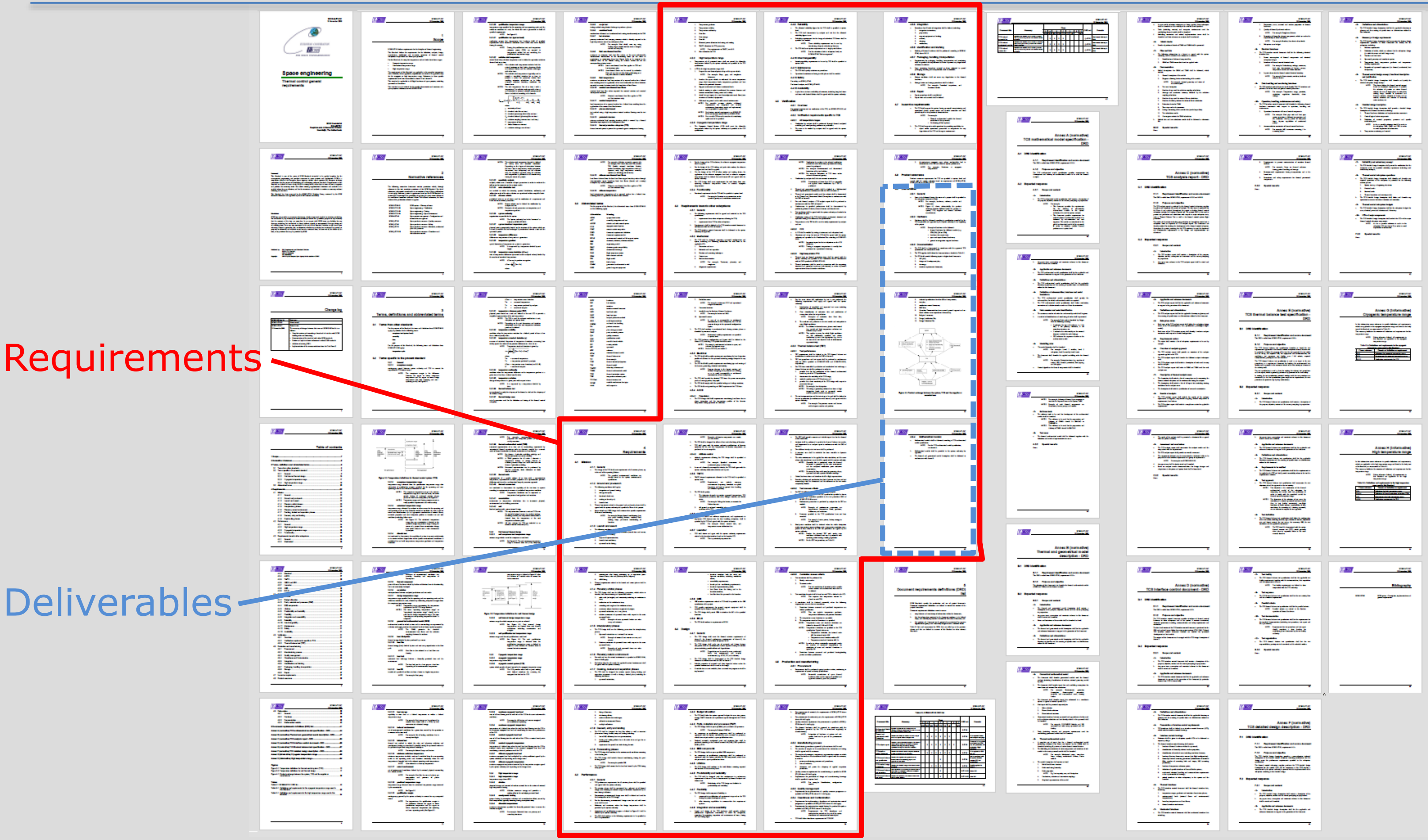
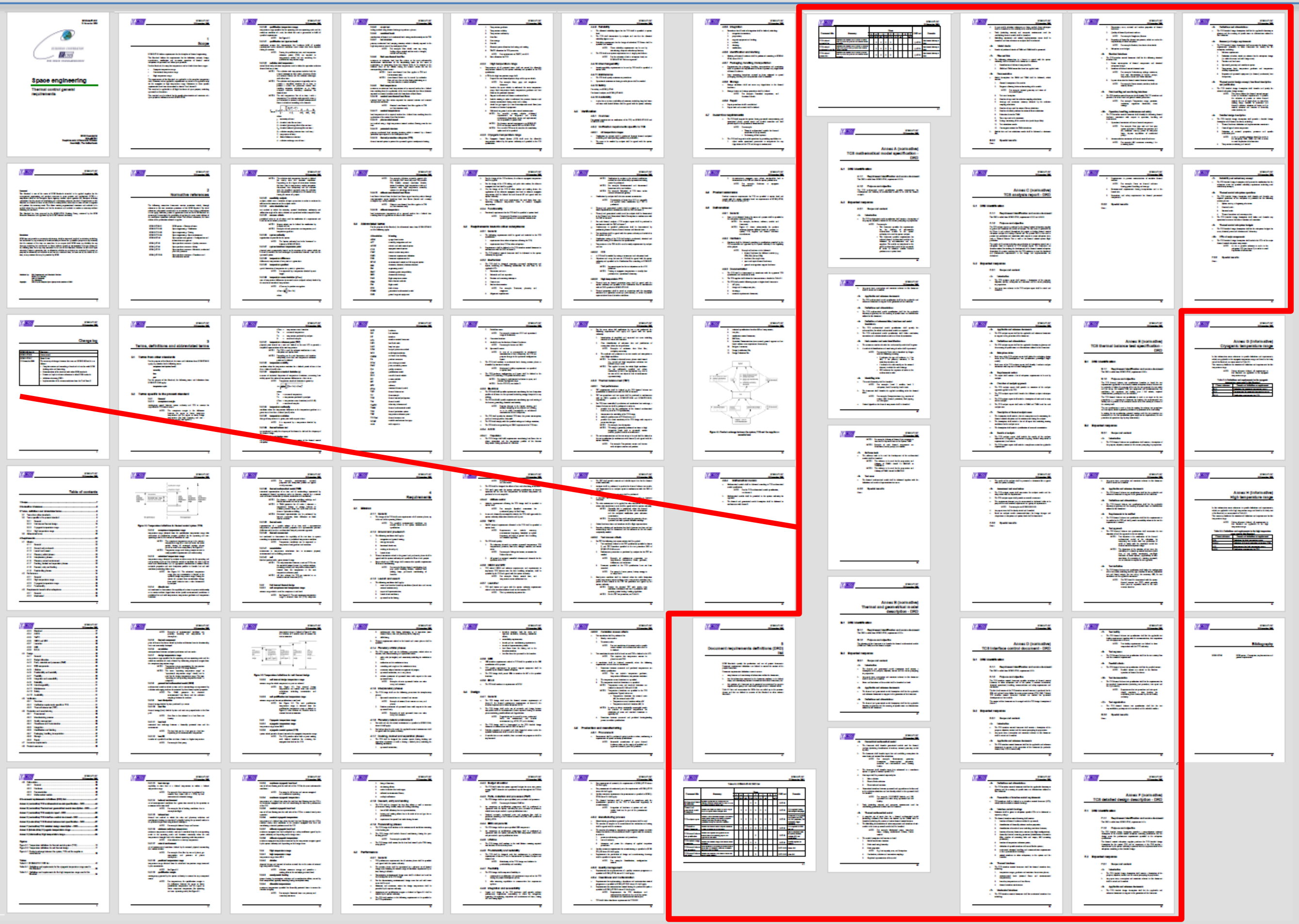
Thermal ECSS structure

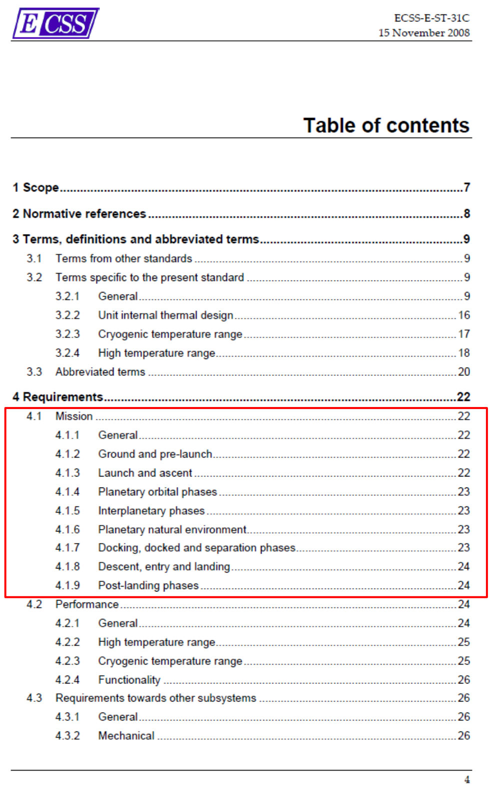


2. Thermal standard overview:
Thermal ECSS structure

Document requirements definitions



3. Mission specific requirements

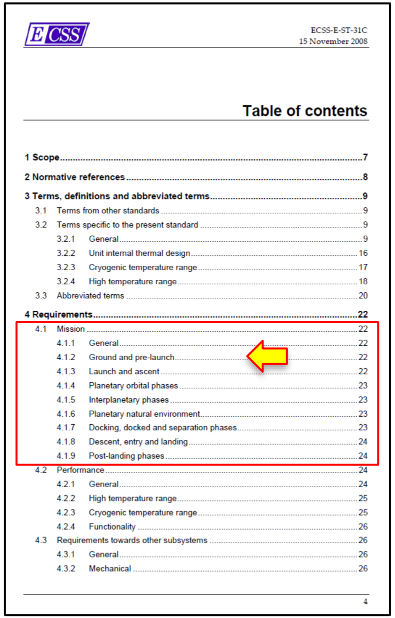


3. Mission requirements: Ground and pre-launch

ECSS-E-ST-031C: Clause 4.1.2: Ground and pre-launch

- integration and ground testing
- storage, transport
- functional check-out
- waiting on launch pad
- launch abort

⇨ implications for batteries, heat pipes, auxiliary fluid loop, RHUs, etc.


ECSS-E-ST-31C
15 November 2008

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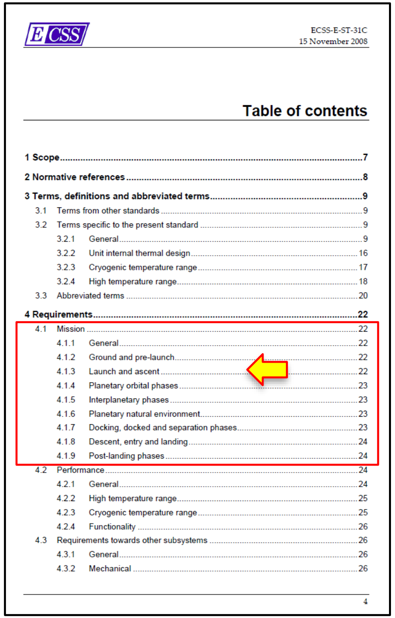
3. Mission requirements: Launch and ascent

ECSS-E-ST-031C: Clause 4.1.3: Launch and ascent

- worst case launcher boundary conditions (launch time and season; external environment)
- depressurization
- launch abort
- spacecraft under fairing
- environment after fairing jettisoning up to separation (aero-thermal fluxes, solar and planetary fluxes, eclipses)
- ABM firing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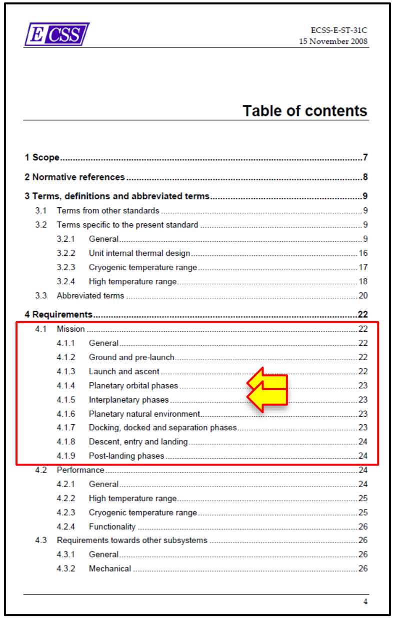
3. Mission requirements: Planetary orbital & interplanetary phases

ECSS-E-ST-031C: Clause 4.1.4: Planetary orbital phases

- orbit radii (or heights) and eccentricity including its evolution in time
- inclination and its evolution in time
- ascending node angle and its evolution in time
- maximum eclipse duration or argument of perigee
- spacecraft orientation, w.r.t. sun, planet
- relative movement of spacecraft items with respect to the main spacecraft body

ECSS-E-ST-031C: Clause 4.1.5: Interplanetary phases

- Spacecraft orientation w.r.t. external heat sources
- Relative movement of spacecraft items with respect to the main spacecraft body.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Detour 1 - Thermal implications of the space environment

a. Space thermal environment

esa

Cold Space

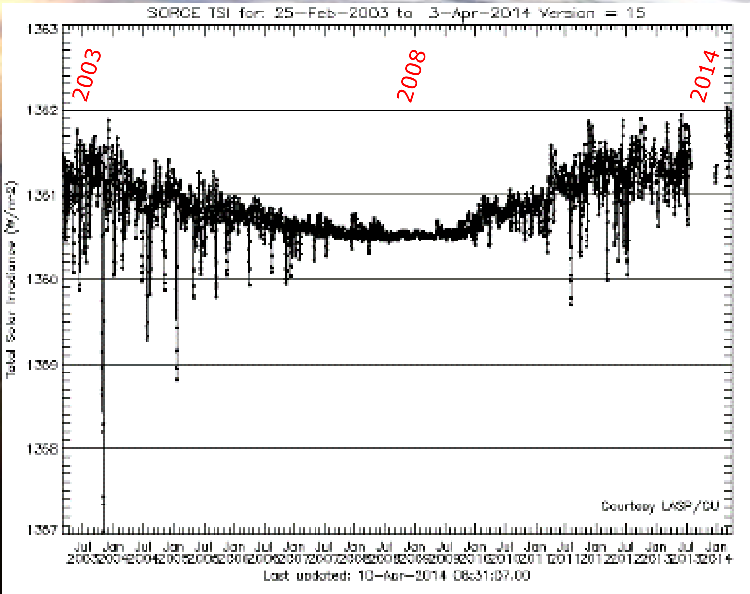
Ultra-high vacuum < 10^{-9} mbar

Cold Space can generally be considered as a Black Body at 3 K (-270°C)

Step 5: Space thermal environment: Sun

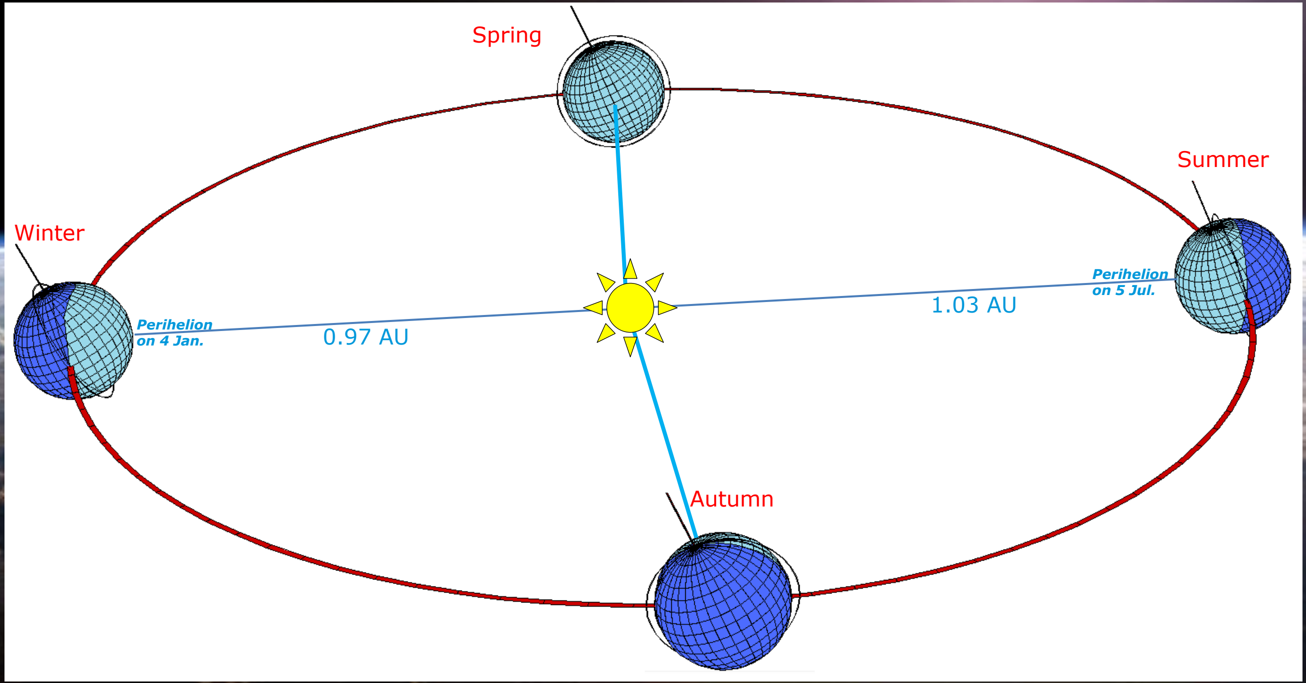
Sun flux

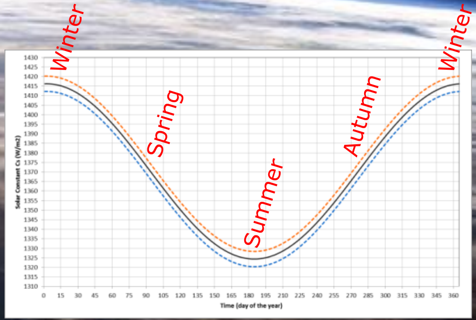
For Earth orbit spacecrafts, the received Sun flux is around 1361 W/m^2 (max 1419 W/m^2 in Winter, min 1321 W/m^2 in Summer)



Solar constant variation over years (at 1 AU)

Step 5: Space thermal environment: Sun





Solar flux variation over one year on Earth (due to Sun-Earth distance variation)

Step 5: Space thermal environment: Earth

Cold Space

Sun flux

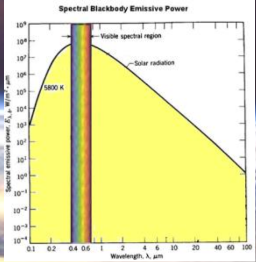
The Earth can be considered as a Black Body at 254 K (with local variations)

$$Q_E = (4\,\pi\,R_E^2)\,\sigma\,T_E^4$$

Average Earth IR flux: ≈ 240W/m²

Average Earth black body temperature @ 254 K

Albedo flux



Solar flux (and albedo flux) radiation spectrum

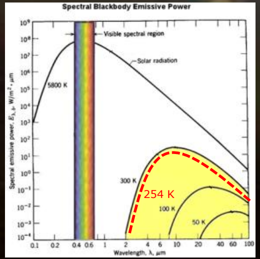
The Earth average albedo coefficient is about 0.3 (with local variations)

ECSS-E-ST-031C: Clause 4.1.6: Planetary natural environment

- For earth and sun the natural environment as specified in ECSS-E-10-04, clause 6 shall apply.

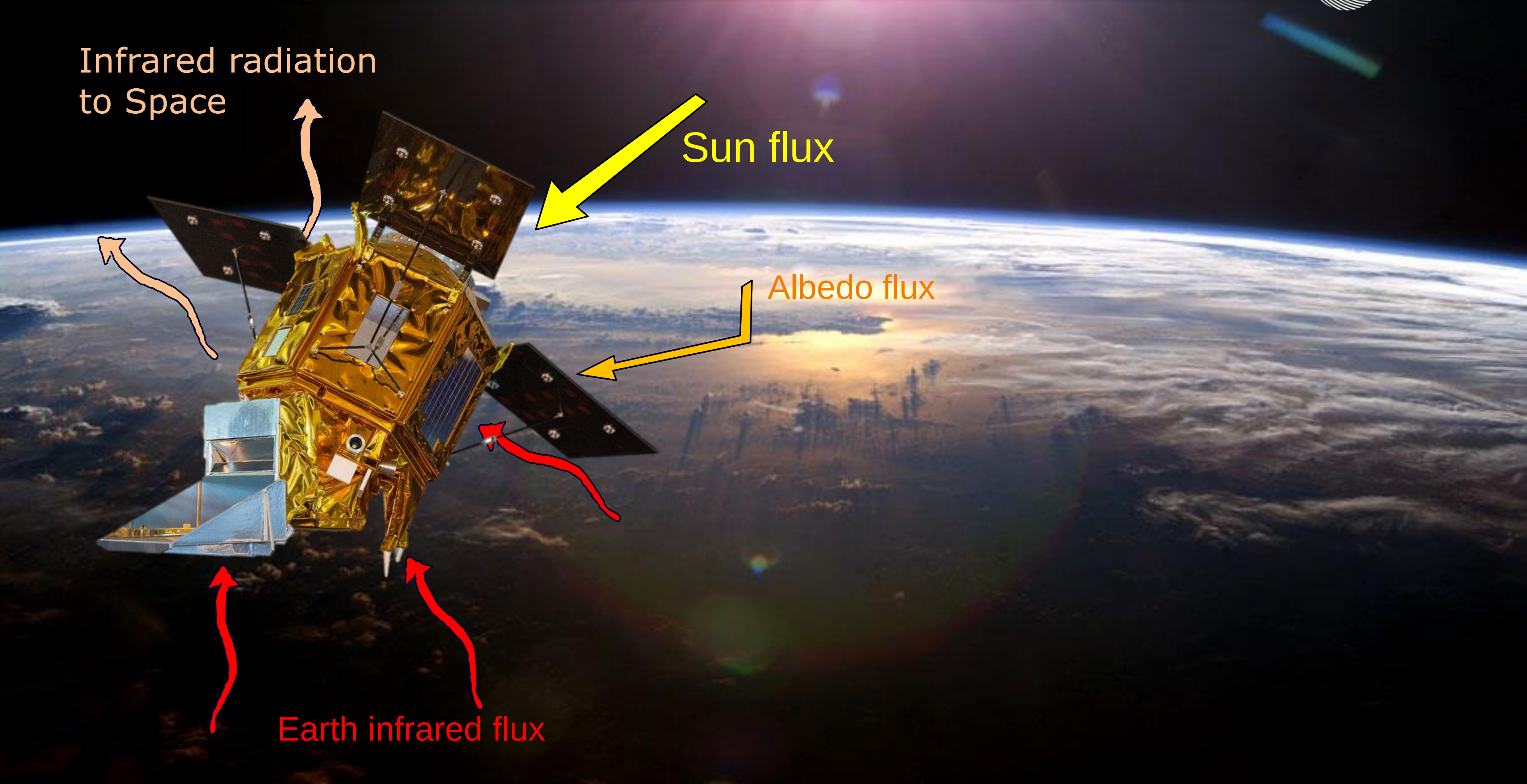
- For bodies other than the earth, the applicable natural environment shall be agreed with the system authority.

Earth infrared flux

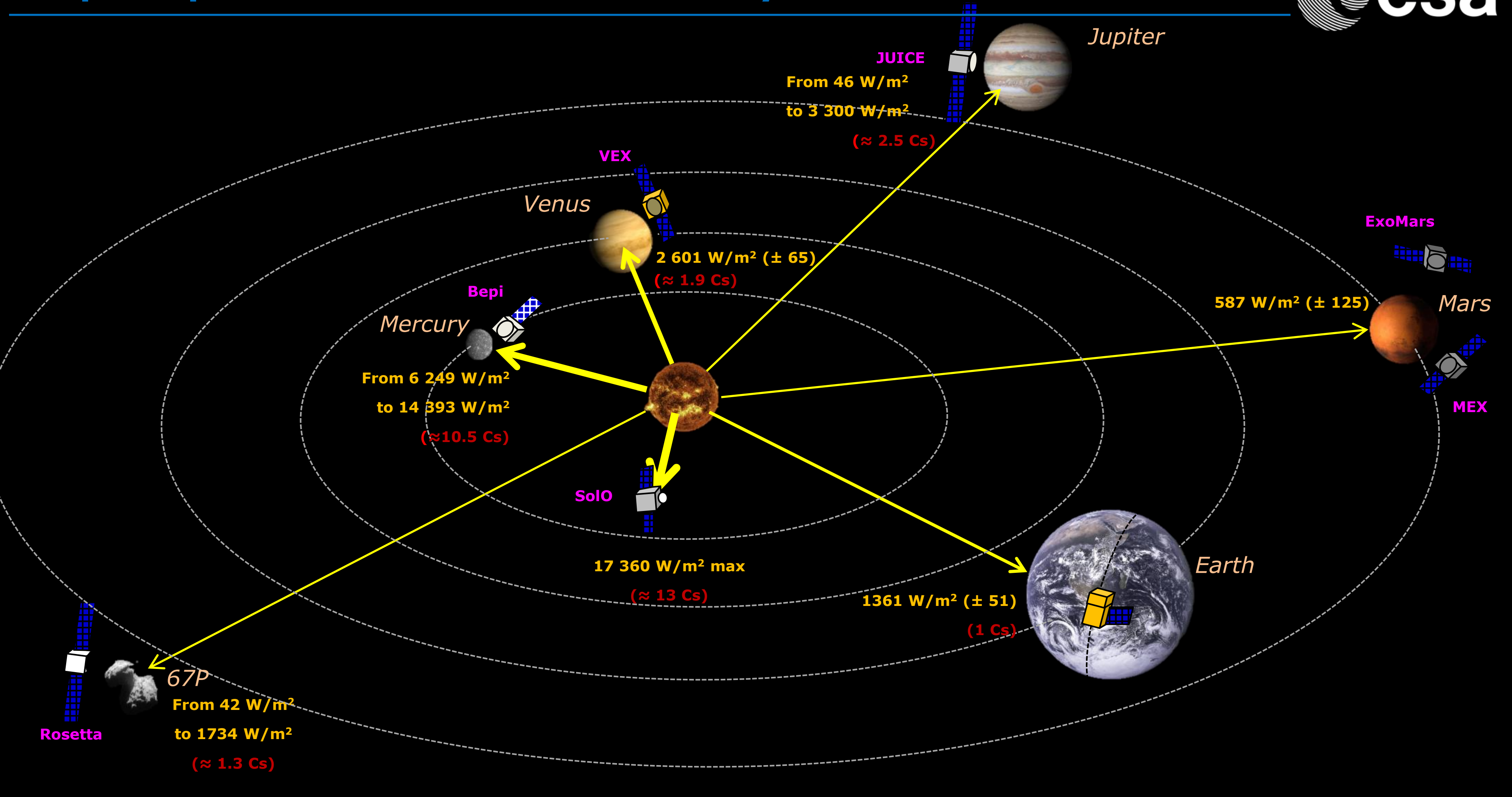


Black body @ 254 K radiation spectrum

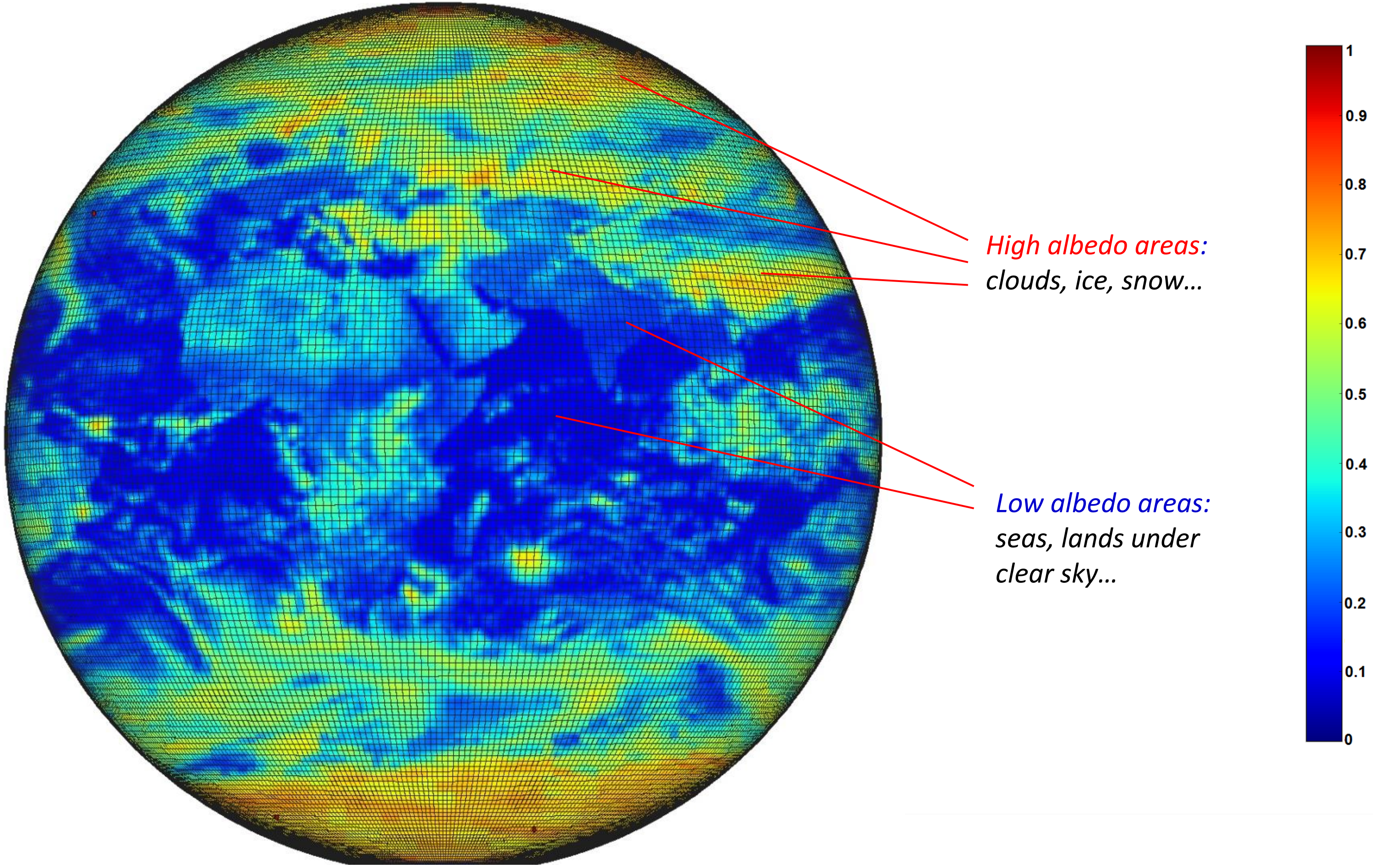
Step 5: Space thermal environment: Earth



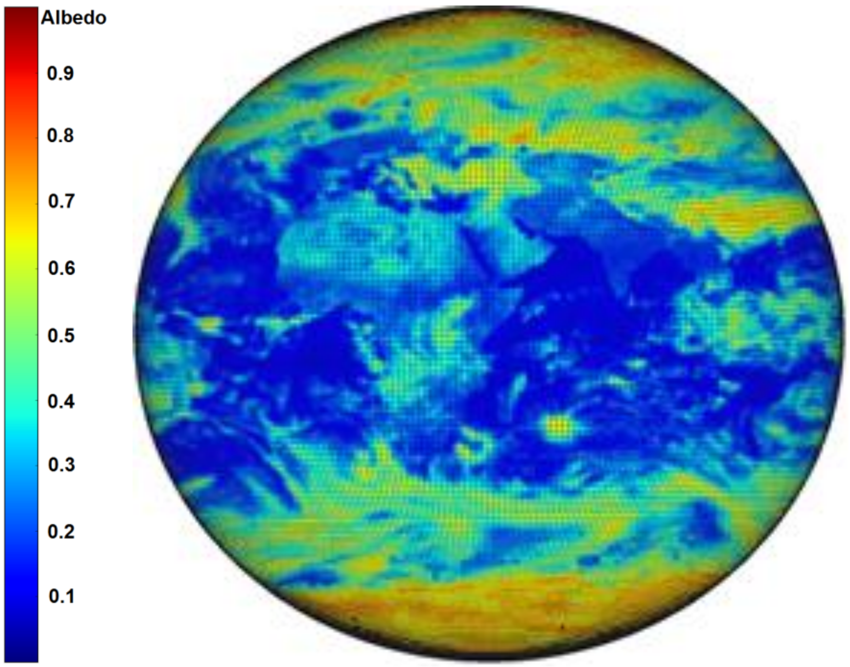
Step 5: Space thermal environment: beyond Earth orbit…

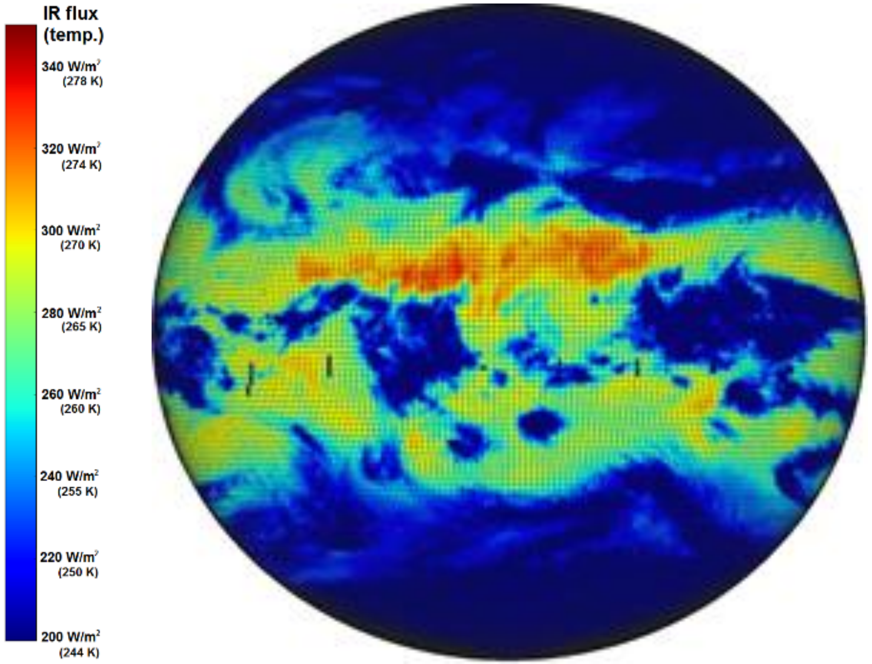


Space thermal environment: Planet albedo



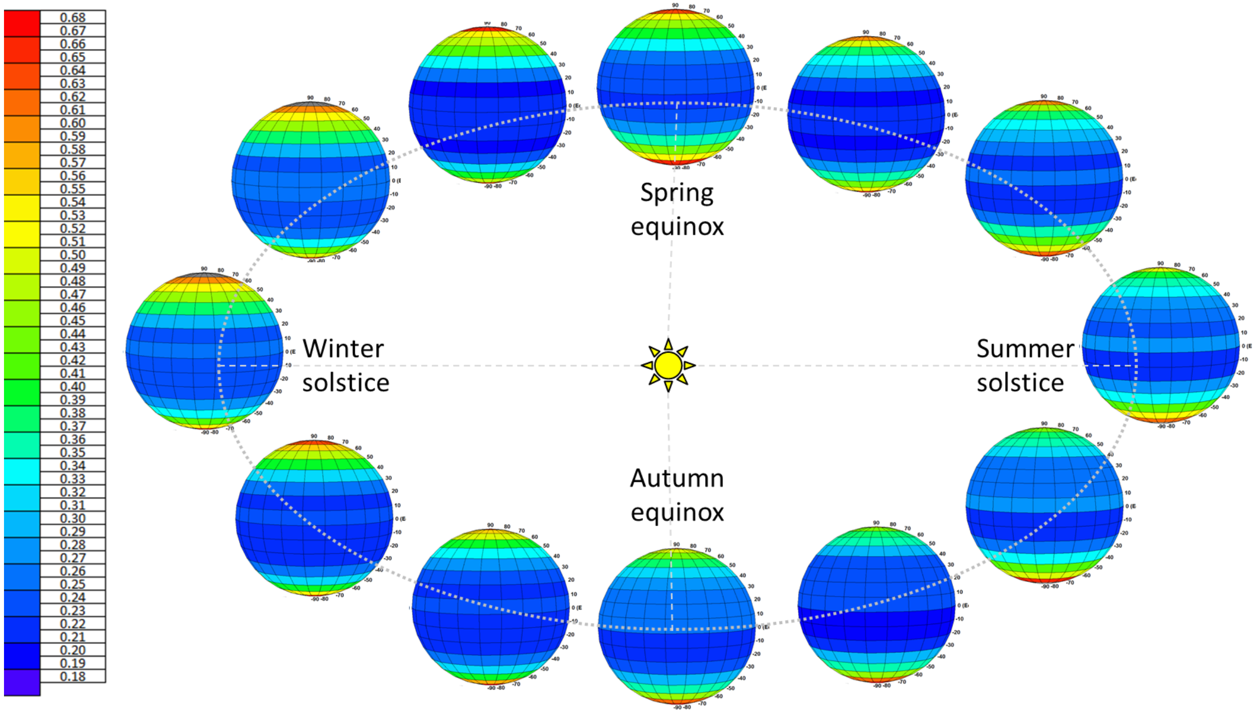
Space thermal environment: albedo and Infrared flux



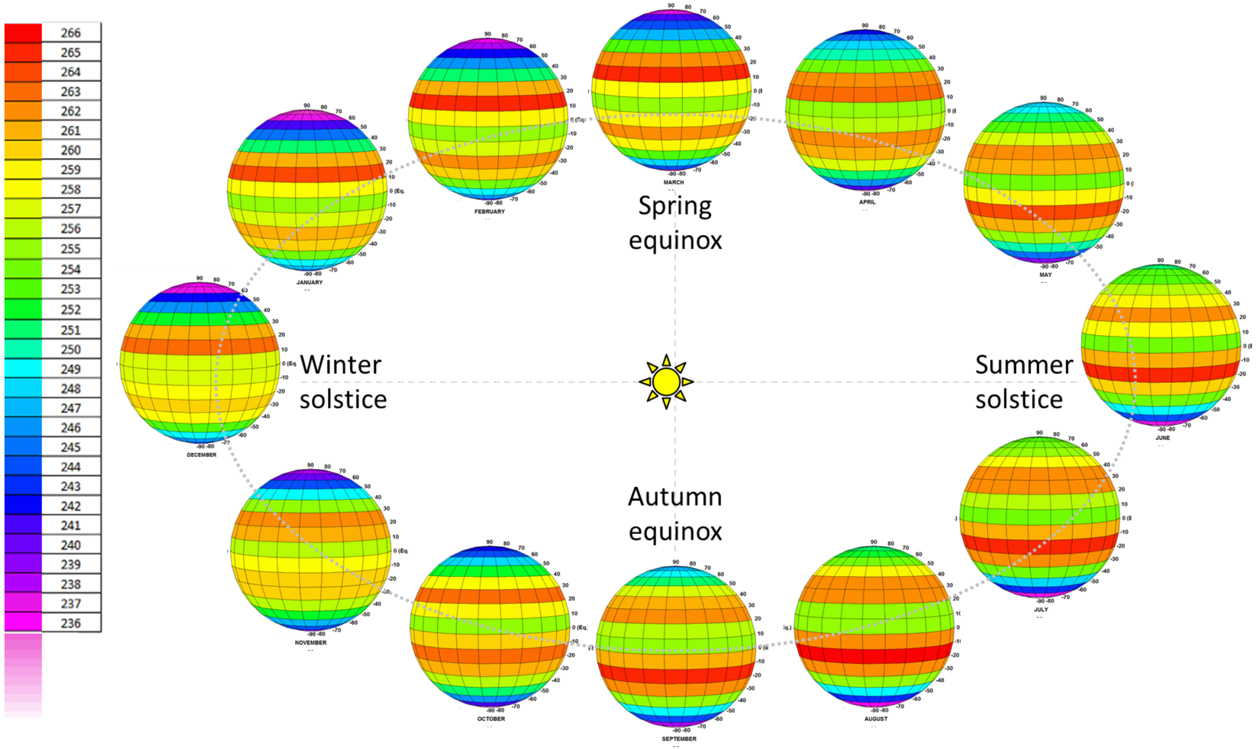


- *http://ceres.larc.nasa.gov/ "Cloud and the Earth's Radiant Energy System (CERES)"*
- *ICES-2017-142: Using Real Earth Albedo and Earth IR Flux for Spacecraft Thermal Analysis, R. Peyrou-Lauga, ESA*

Seasonal variation of Earth albedo

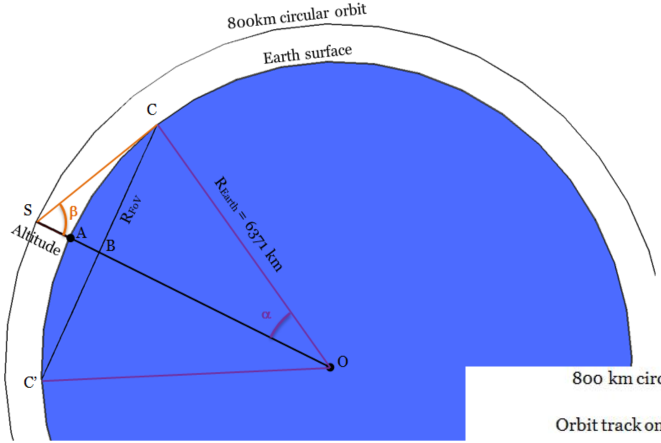


Seasonal variation of Earth temperature

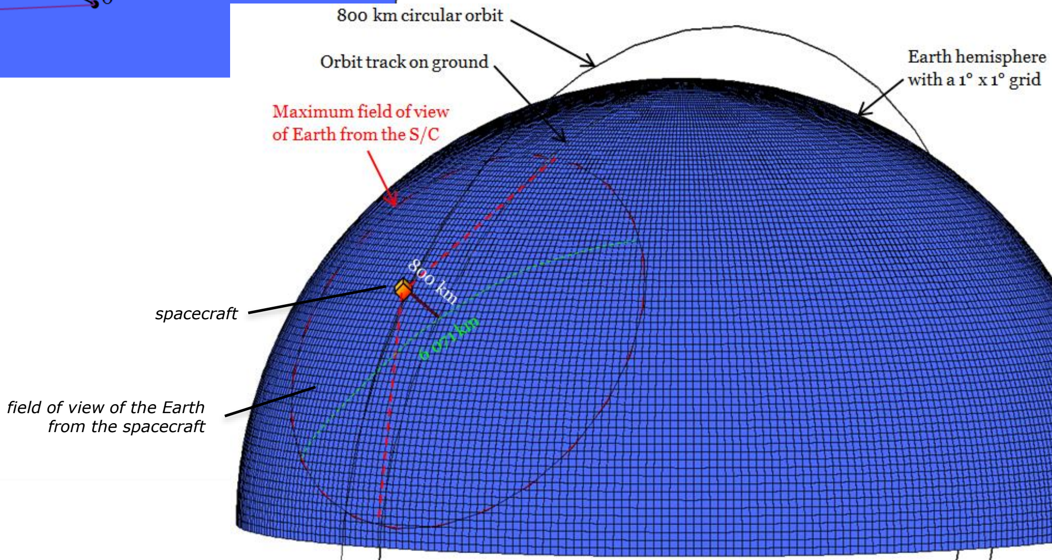


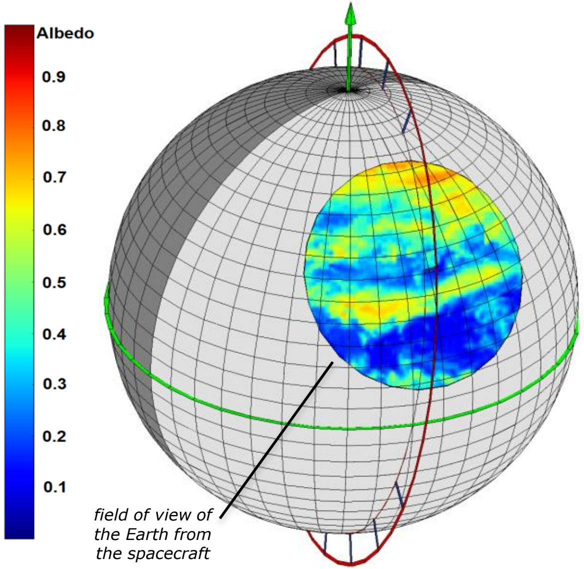
Space thermal environment: Planet flux

What's the Earth field of view from orbit ?



night





Example of real albedo as viewed from a spacecraft in low Earth

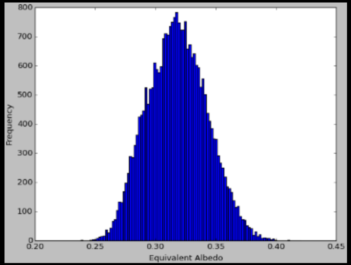
Space thermal environment: Earth environment typical values

Statistical distribution of average orbital albedo and Earth temperature over an orbit for several LEO orbits:

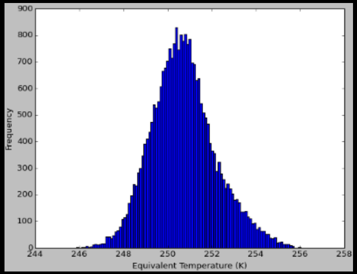
Albedo

Earth temperature

Sun-synchronous orbit
Inclination 98.6º
800 km, LTAN 22:00

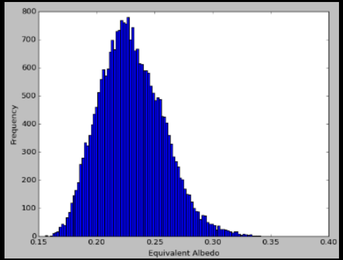


Range: **0.25 - 0.40**
Mean: 0.31

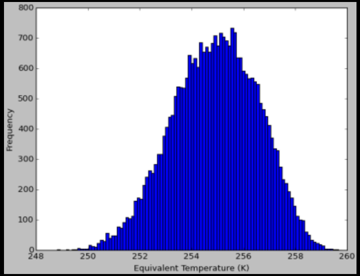


Range: **246–256 K**
Mean: 250 K

ISS orbit
Inclination 51.6º
400 km

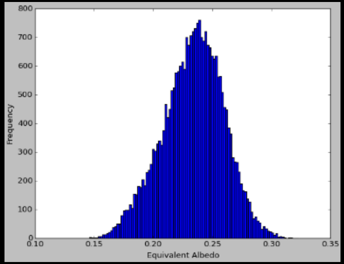


Range: **0.16 - 0.34**
Mean: 0.23

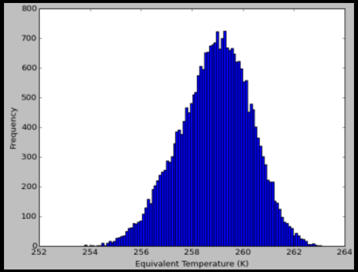


Range: **250–260 K**
Mean: 255 K

Equatorial orbit
Inclination 6º
800 km



Range: **0.15 - 0.31**
Mean: 0.24



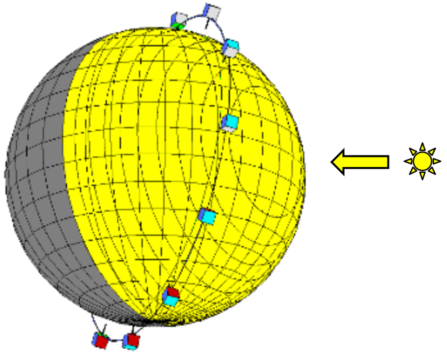
Range: **253–260 K**
Mean: 259 K

Detour 1 - Thermal implications of the space environment

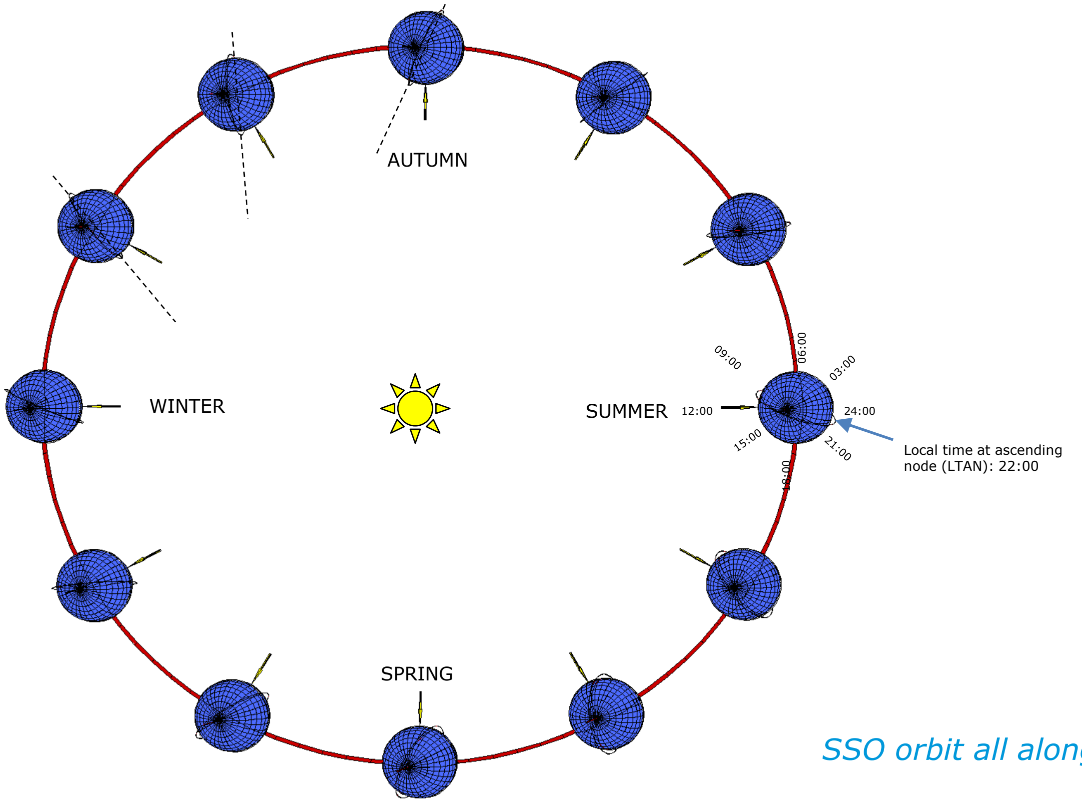
b. Thermal implications of typical orbits

Space Environment – Sun synchronous orbit (SSO)

- Nearly polar orbit.
- The satellite passes over any given point of the planet's surface at the same local mean solar time.



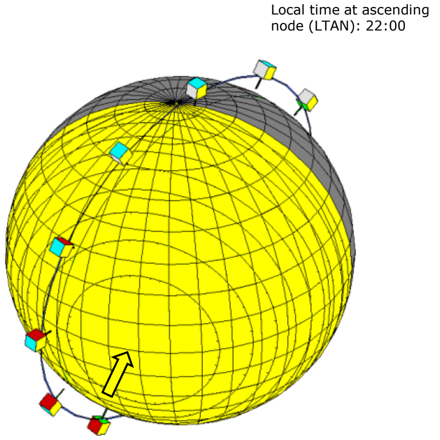
SSO orbit



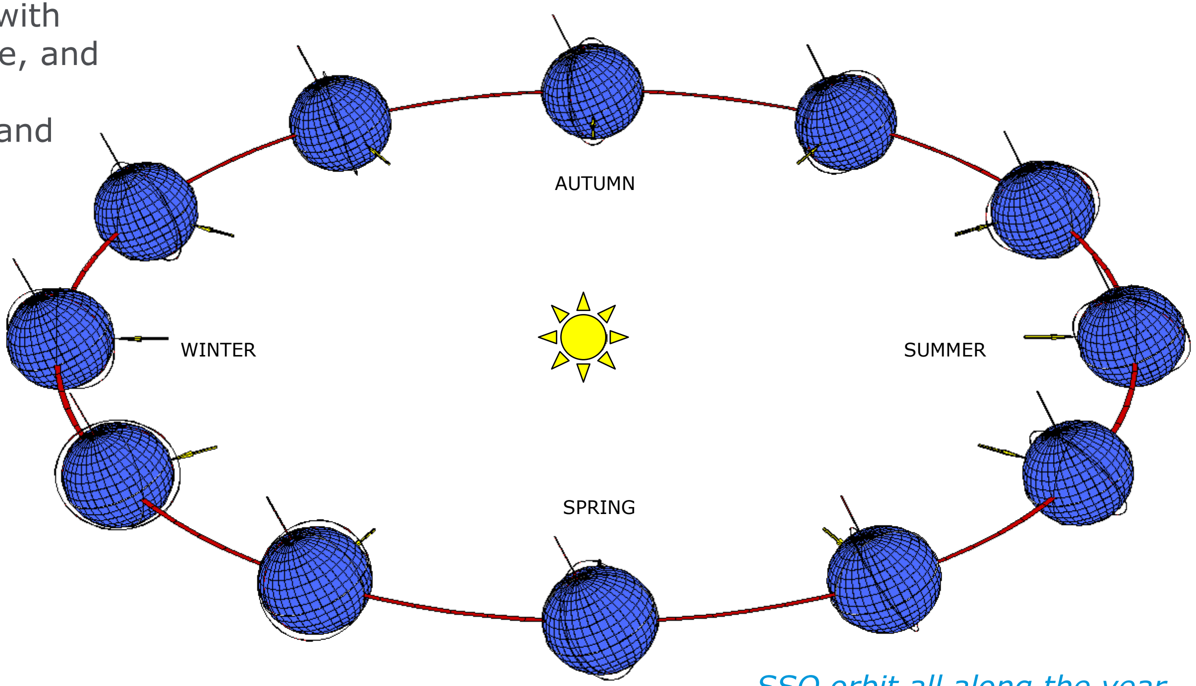
SSO orbit all along the year

Space Environment – SSO

- Typical sun-synchronous orbits are about 600–800 km in altitude, with periods in the 96-100-min range, and inclinations of around 98° (0° represents an equatorial orbit, and 90° represents a polar orbit).



SSO orbit



SSO orbit all along the year

Space Environment – SSO

Examples of satellite in SSO orbit

MetOp

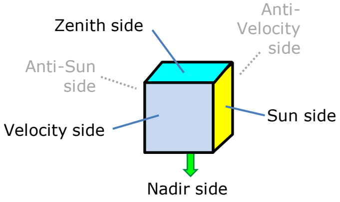
EnviSat

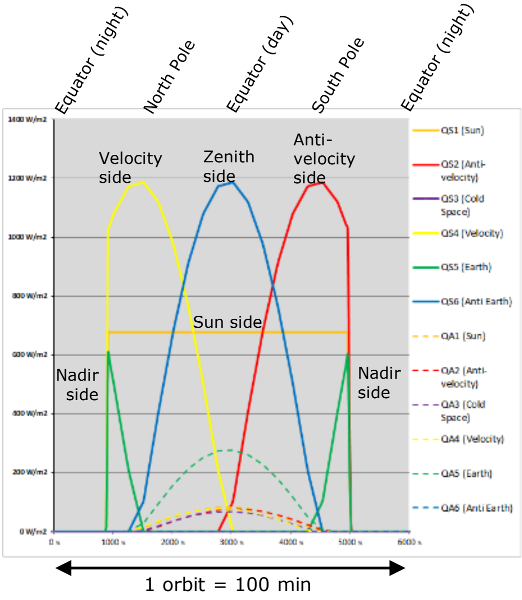
Sentinel 2

Sentinel 3

Earth-CARE

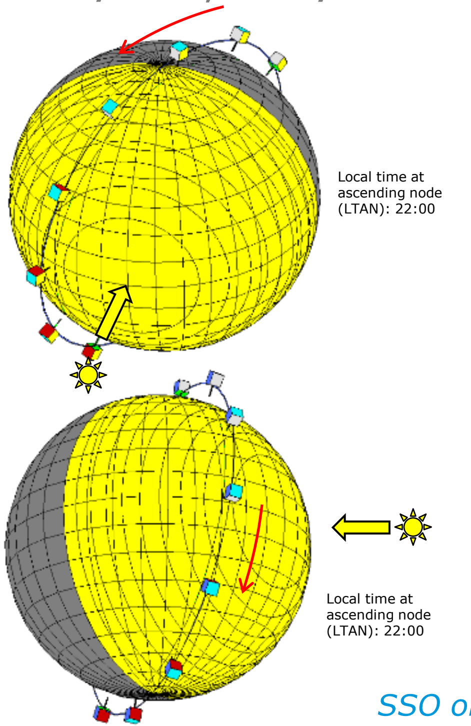
Fixed attitude:





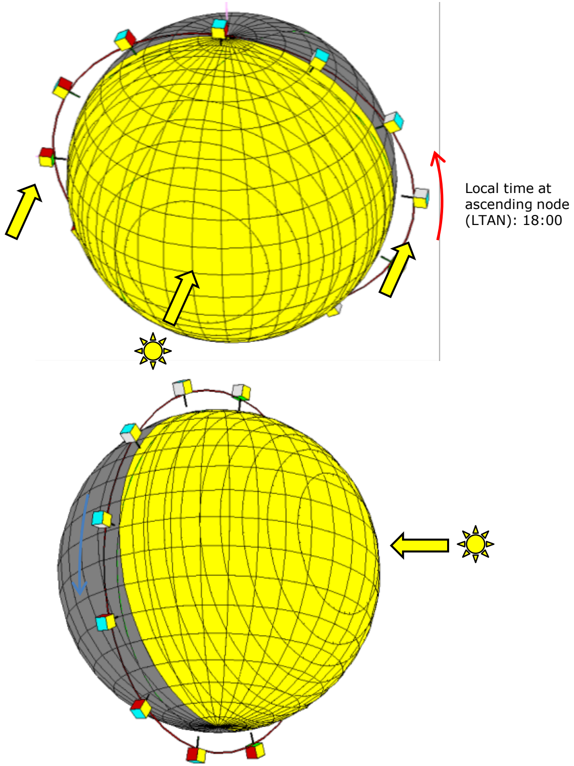
Received external flux on each side:

Typical LTAN around 22:00/10:00, 21:00/09:00



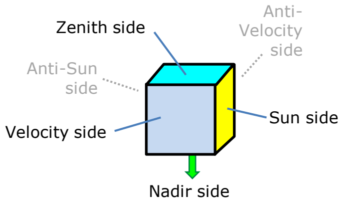
SSO orbit

Space Environment – SSO – Dawn/Dusk



Dusk/Dawn SSO orbit

Fixed attitude:

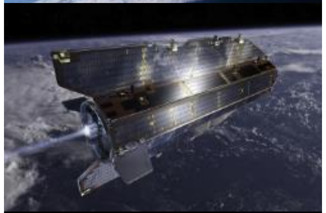


Dusk/dawn or Dawn/dusk orbits LTAN: 06:00 or 18:00

Sentinel 1

Aeolus

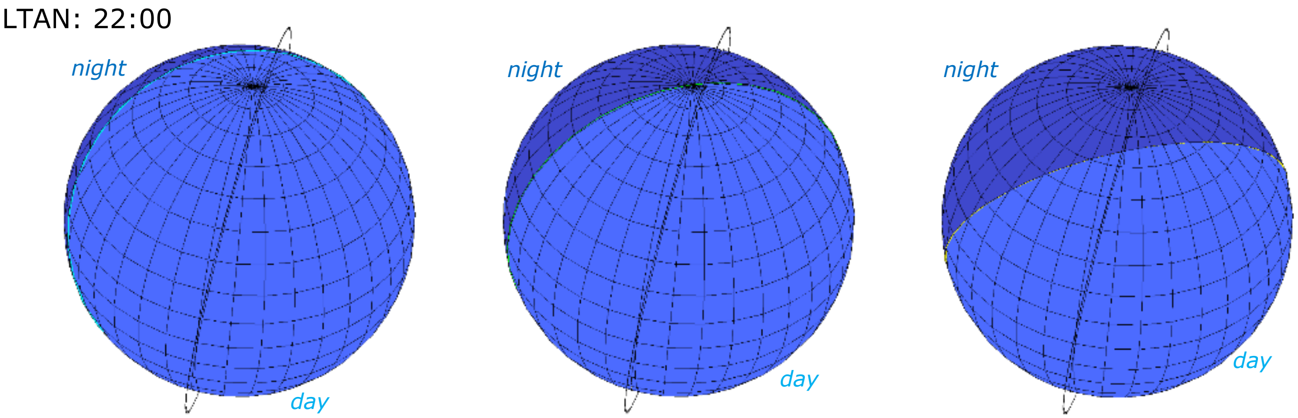
GOCE



SMOS

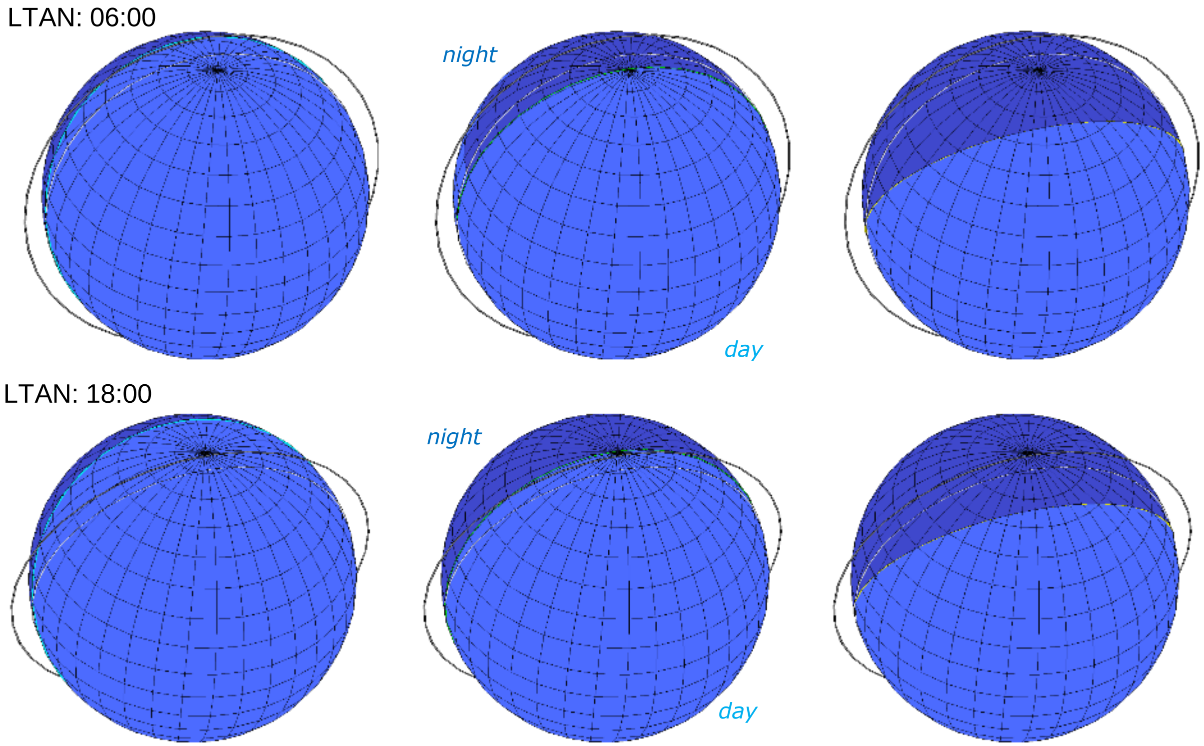
Examples of satellite in Dusk/Dawn SSO orbit

Space Environment – SSO – Seasonal Variations



SSO orbit (LTAN : 22:00) at 3 moments in the year

Space Environment – SSO – Seasonal Variations



2 different SSO orbits at 3 moments in the year

End of detour 1

Outline

3. Mission requirements:
Docking, docked and separation phases

ECSS-E-ST-031C: Clause 4.1.7: Docking, docked and separation phases

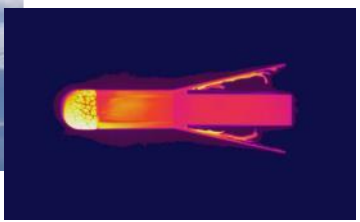



- spacecraft orientation
- firing of thrusters
- shadowing effects
- mutual radiative heat exchanges
- reflected environmental fluxes
- multiple reflections

3. Mission requirements:
Descent, entry and landing

ECSS-E-ST-031C: Clause 4.1.8: Descent, entry and landing

- Loss of multi-layer insulation (MLI) efficiency due to re-pressurization
- Heating and cooling effects due to the inlet of air and gas for repressurization
- Requirement for special heat sinks during descent

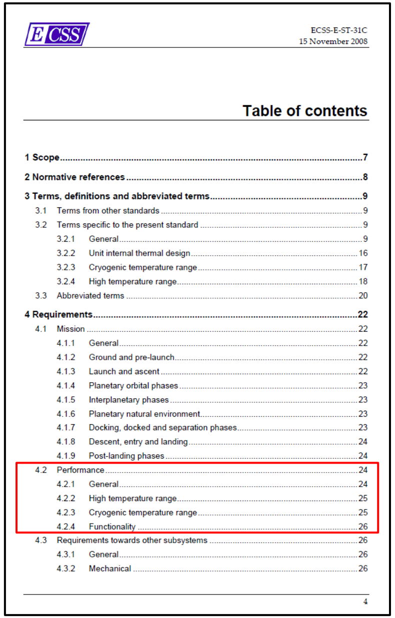


3. Mission requirements: Post-landing phases

ECSS-E-ST-031C: Clause 4.1.9: Post-landing phases

- The TCS design shall conform to the environmental conditions occurring at the landing site.
- The TCS design shall include thermal conditioning during the postlanding phases.
- The TCS design shall account for the heat load stored by the TPS during entry phases.

4. Performance specific requirements


ECSS-E-ST-31C
15 November 2008

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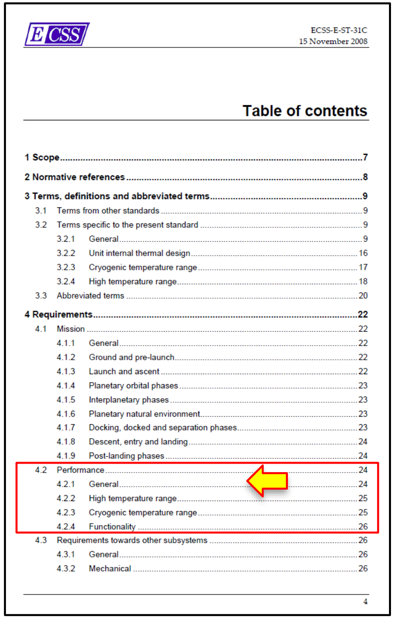
Thermal performance

ECSS-E-ST-031C: Clause 4.2.1 General:

- Thermal Control Specification necessary
  - System Authority to provide design temperatures
  - Acceptance and qualification margins

- Thermal design cases enveloping all conditions
  - Worst hot case
  - Worst cold case
  - Begin of life and End of life conditions
  - Lifetime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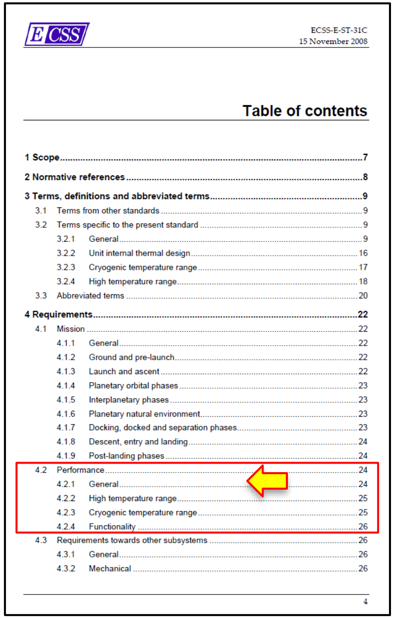
4. Performance specific requirements
Thermal performance

ECSS-E-ST-031C: Clause 4.2.2: Thermal Control Subsystem (TCS) Performance:

- The TCS shall conform to the following requirements to be specified in the TCS specification:
  - Temperature gradients
  - Temperature stability
  - Temperature uniformity
  - Heat flux
  - Heat storage
  - Heat lift
  - Electrical power allocation for heating and cooling
  - TM/TC allocation for TCS parameter
  - Mass allocation for TCS

- Tailoring and translation into specific project requirements is necessary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(Short) detour 2 - Terms, definitions and abbreviated terms

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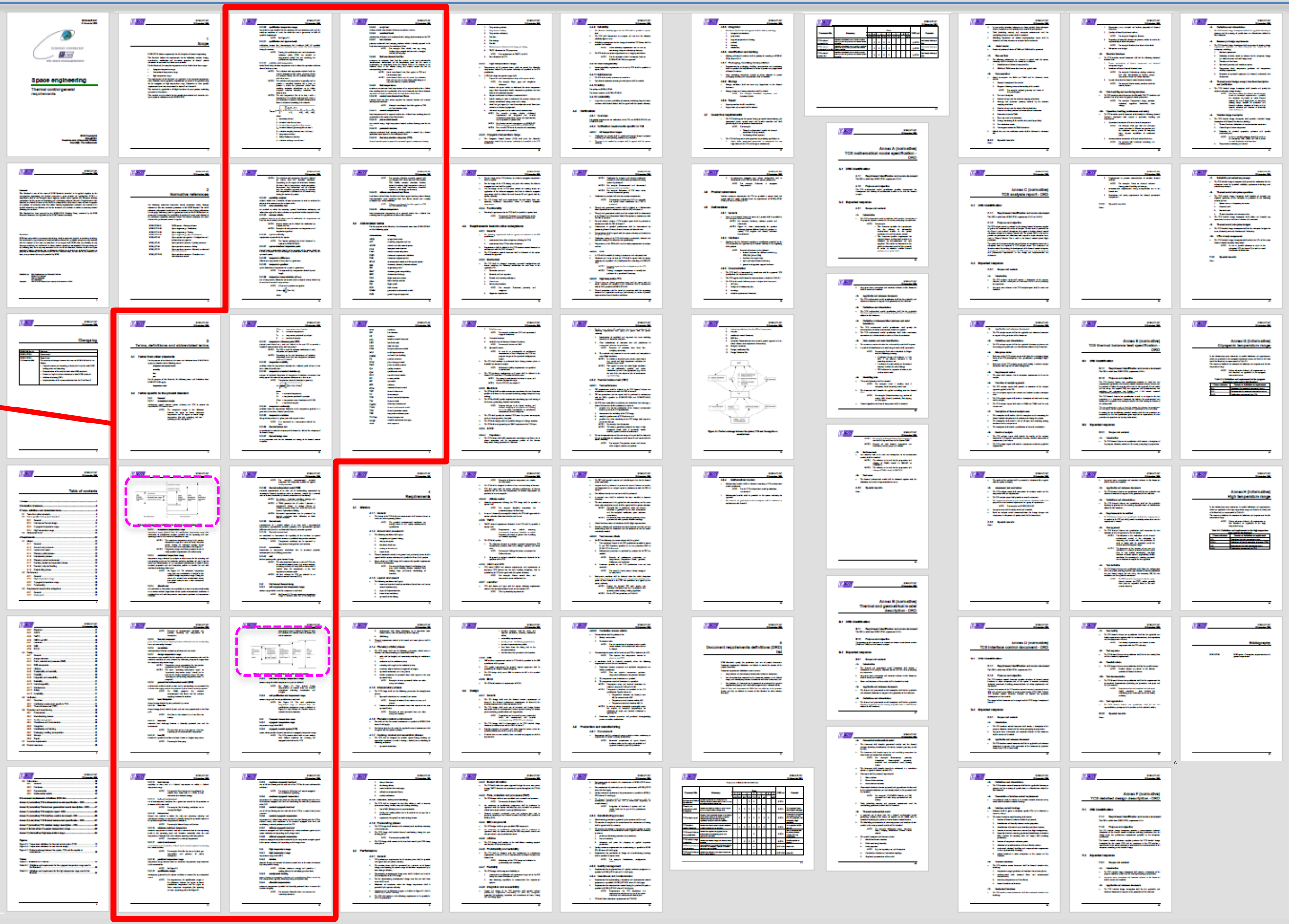
2. Thermal standard overview:
Thermal ECSS structure

Terms, definitions and abbreviated terms



Detour 2 - Terms, definitions and abbreviated terms
Heat flux, Temperature gradient, temperature stability

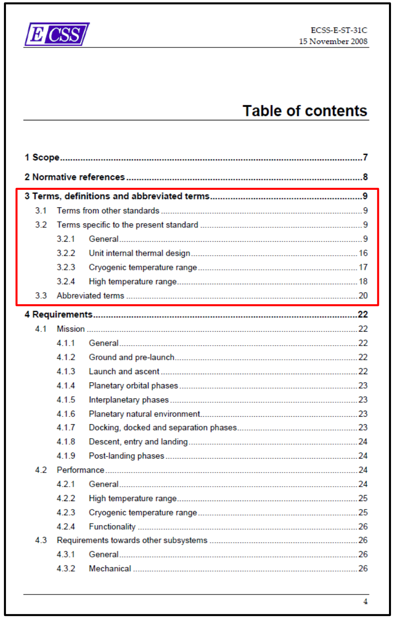
ECSS-E-ST-031C: Chapter 3: Terms, definitions and abbreviated terms

<u>Examples:</u>

- Heat flux (clause 3.2.1.10)
  - thermal energy (heat) divided by time and unit area perpendicular to the flow path

  NOTE Heat flux is also referred to as heat flow rate density.

- Temperature gradient (clause 3.2.1.29)
  - spatial derivation of temperature in a point at a given time
- Temperature stability (clause 3.2.1.32)
  - condition when the temperature variation for a defined period of time is less than a defined (small) value



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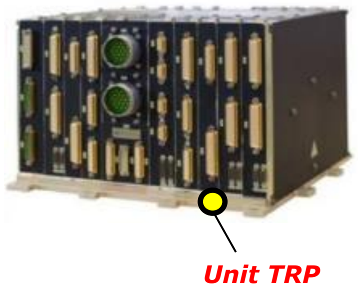
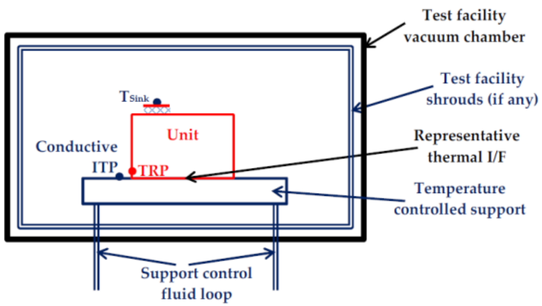
Detour 2 - Terms, definitions and abbreviated terms
TRP - Temperature Reference Point

TRP: Temperature Reference Point *(Clause 3.2.1.31)*

- physical point located on a unit and defined in the unit ICD to provide a simplified representation of the unit temperature
  - NOTE 1 The TRP is used for coherent verification at unit, subsystem and system level.
  - NOTE 2 Depending on the unit dimensions and interface complexity, more than one temperature reference point can be defined.
- **TRP location & usage**
  - easily accessible on the unit close to the S/C structure
  - equipped with a flight temperature sensor (e.g. on the baseplate)
  - ‘thermal interface’ point between two different entities
  - drives the temperature of the rest of the unit on all levels
  - ‘representative’ of the average temperature of the whole unit





Detour 2 - Terms, definitions and abbreviated terms
Temperature ranges

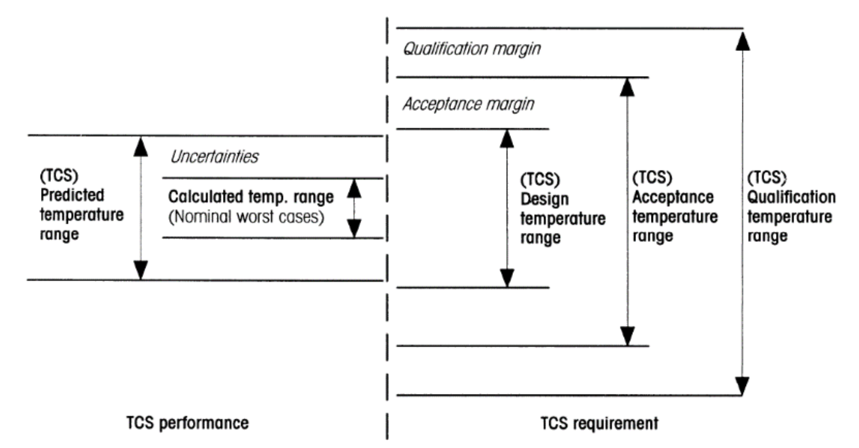
ECSS-E-ST-31C: Clause 3.2; Figure 3-1

Design temperature range (clause 3.2.1.7)

- temperature range specified for the operating and non-operating mode and the switch-on condition of a unit, obtained by subtracting acceptance margins from the acceptance temperature range

NOTE 1 Temperature range representing the temperature requirement for the TCS design activities.

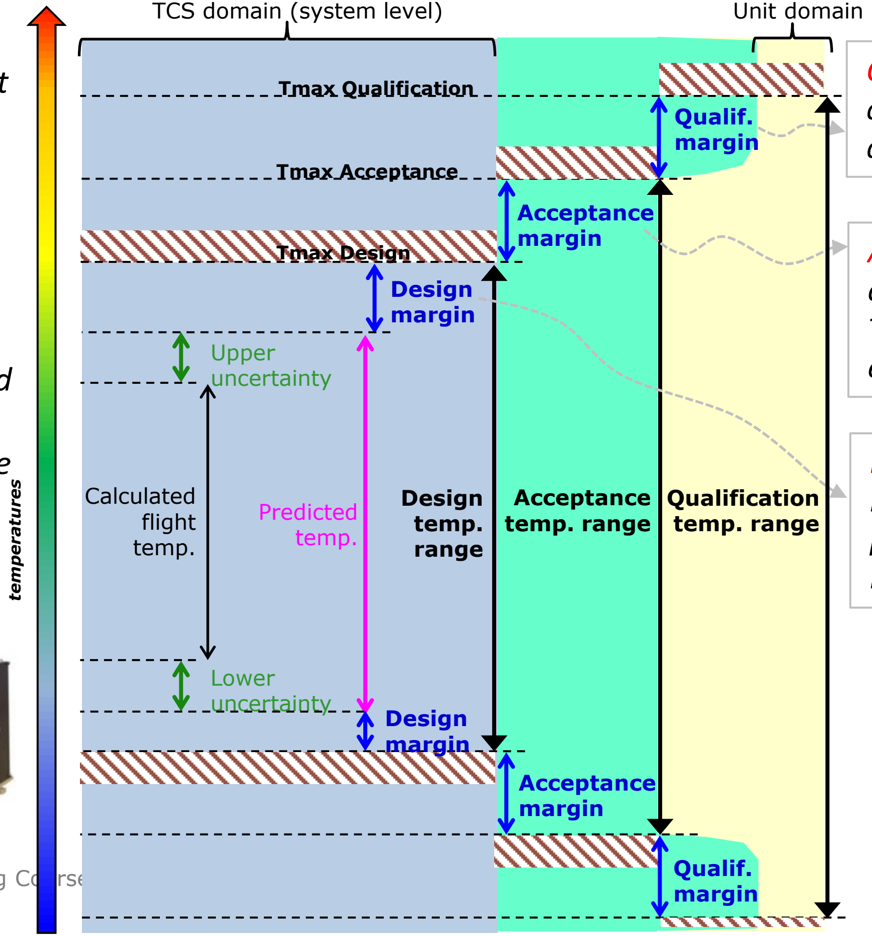
NOTE 2 The terms "operating temperature range" or "operational temperature range" should not be used for the design temperature range. The term "operating or non-operating temperature limits" is acceptable.



Detour 2 - Terms, definitions and abbreviated terms
Temperature ranges

- *We're talking about here Unit Temperature Reference Point (TRP)*

- *Temperature ranges are defined for both*
  - ☞ *operational mode*
  - ☞ *non-op. mode*



Qualification margin = *contingency approved by the system authority to account for any unexpected events*

ECSS-E-ST-10-03C (Jun. 2012)

Acceptance margin = *contingency agreed between system authority and TCS to account for unpredictable TCS-related events*

ECSS-E-ST-10-03C (Jun. 2012)

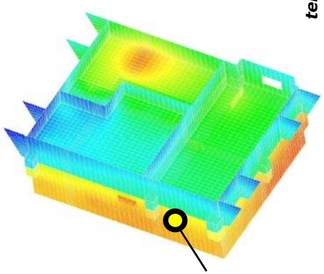
Design margin: *Remaining delta T between design limit and prediction. Not formally defined in the ECSS. No value imposed ⇨ can be equal to 0*

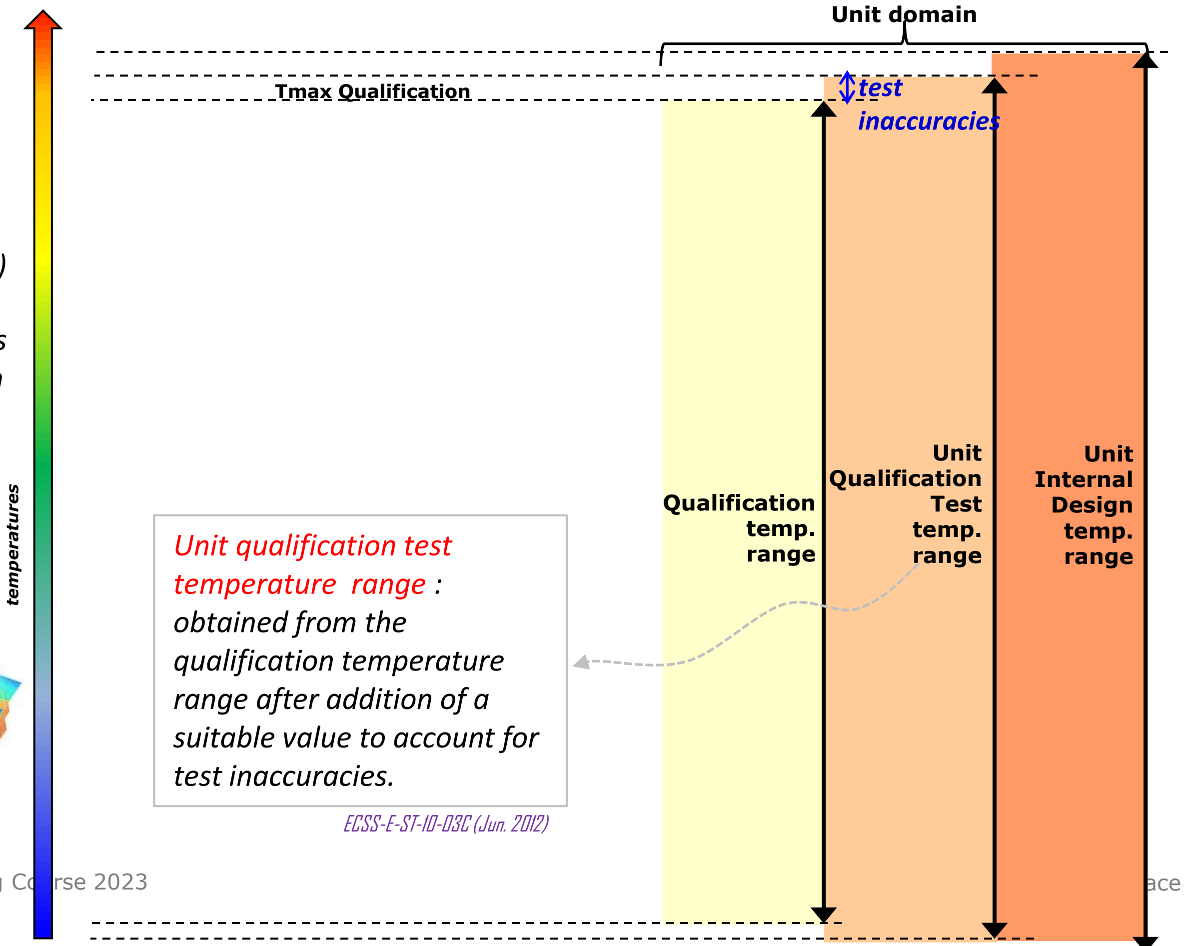
ECSS-E-ST-10-03C (Jun. 2012)

Detour 2 - Terms, definitions and abbreviated terms
Temperature ranges

- *We’ re talking about here Unit Temperature Reference Point (TRP)*

- *Temperature ranges are defined for both*
  - ☞ *operational mode*
  - ☞ *non-op. mode*



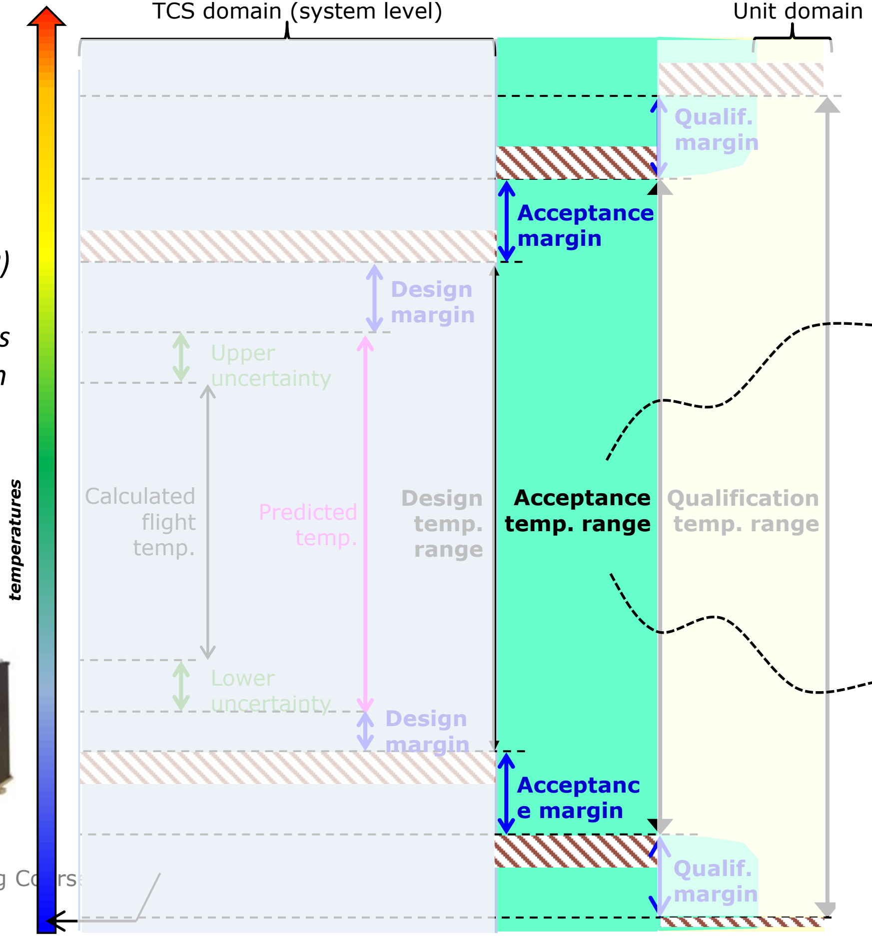


Unit qualification test temperature range : *obtained from the qualification temperature range after addition of a suitable value to account for test inaccuracies.*

ECSS-E-ST-10-03C (Jun. 2012)

Detour 2 - Terms, definitions and abbreviated terms
Temperature ranges

- *We' re talking about here Unit Temperature Reference Point (TRP)*
- *Temperature ranges are defined for both*
  - *operational mode*
  - *non-op. mode*



The acceptance temperature range is the extreme temperature range that a unit can reach, but never exceed, during all envisaged mission phases.

ECSS-E-ST-10-03C (Jun. 2012)

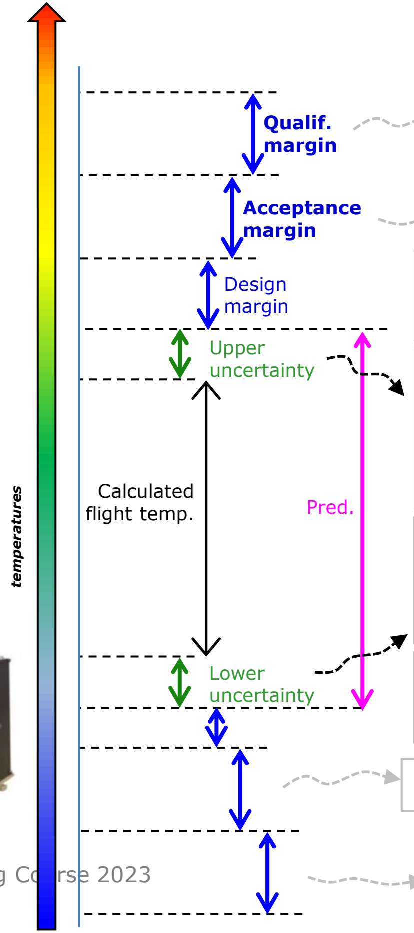
Acceptance temperature range used during acceptance tests to verify specified requirements and workmanship.

ECSS-E-ST-10-03C (Jun. 2012)

Detour 2 - Terms, definitions and abbreviated terms
Temperature ranges

- Margins are usually imposed at project level

- During the course of a project these uncertainties change from initial estimates into a value determined by analysis.



Usually 5°C imposed

Usually 5°C imposed

Uncertainty analysis are performed to support thermal analysis, and usually encompass random and more systematic errors.

- The random errors are coming from the variation of statistically independent parameters. The root-sum-square of each individual error is added. Each error is expressed in terms of temperature variation (ΔT) obtained from the variation of the parameters (Δp) in the mathematical model.

- The systematic errors are coming from the variation of statistically dependent parameters. They are linearly added. In general, the systematic errors are estimated from past experience and/or from test results.

In the absence of any uncertainty analysis performed at unit level, an initial uncertainty of 10°C is usually recommended.

Usually 5°C imposed

Usually 5°C imposed

5. Requirement towards other subsystems

& Design

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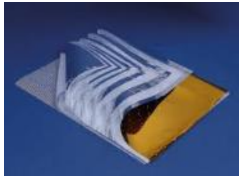
5. Performance specific requirements
Thermal Control Means - Passive

Surface coatings


Thermal Fillers, Washers

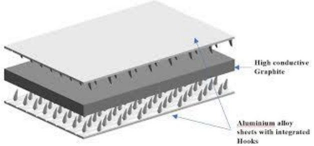

Thermal Straps


Multi-Layer Insulation (MLI)

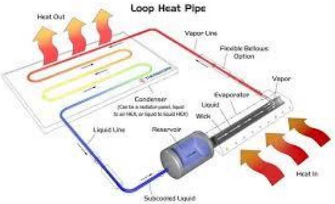
Second Surface Mirror (SSM) & Optical Solar Reflector (OSR)

Doubler

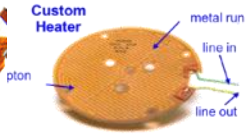
Heat pipes


Loop heat pipes



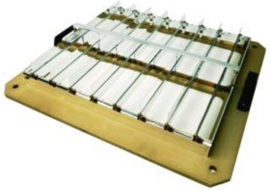
Thermal Control Means – Active

Heaters

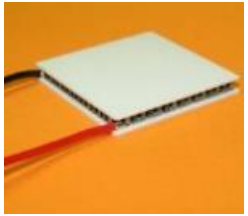


Thermostats

Louvers



Thermo-electric coolers



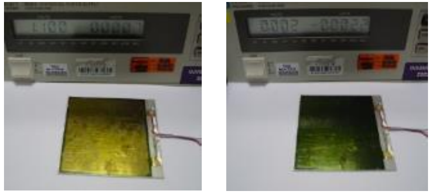
Thermistors
(PT100, PT1000, 15kOhm)

Cryo coolers
(Stirling / Joule-Thompson)

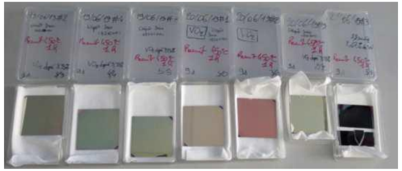
Fluid Loops
(mechanically / electrically pumped)

Thermal Control Means - Further

Electrochromics



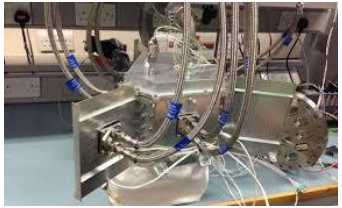
Thermochromics



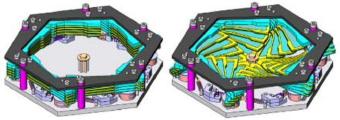
Phase Change Material

Radiotopic heater units (RHU)

Radiotopic thermal generator (RTG)



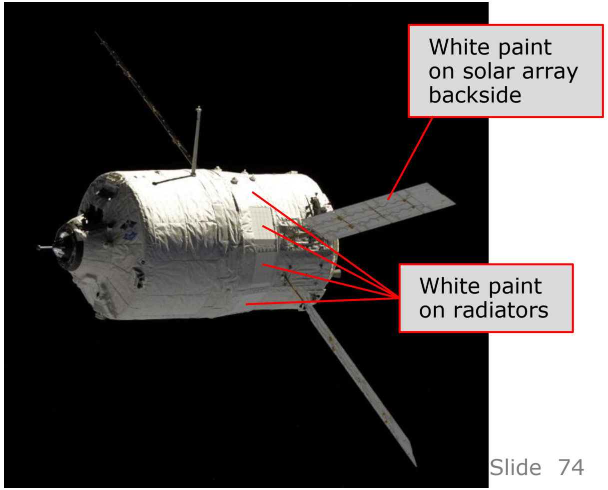
Microlouvers



Self regulating heaters

Passive Means - Surface Coatings

- Thermal control paints
  - Black & white
- Coatings (on metals)
  - Oxidation protection
  - Electrical discharge protection
  - Conformal coatings
- Untreated surface
  - Polymers
  - composites
  - Ceramics
- …



5. Performance specific requirements

Material factors – degradation / ageing

Clause 4.4.1: Design - General

b. The TCS design shall make use of materials and design features **compatible with the environmental** factors expected during all mission phases including possible effects and degradations.

NOTE Degradation can be caused by wear, mechanical loads, test environment, and in-orbit environment (e.g. ATOX, UV, and radiation).

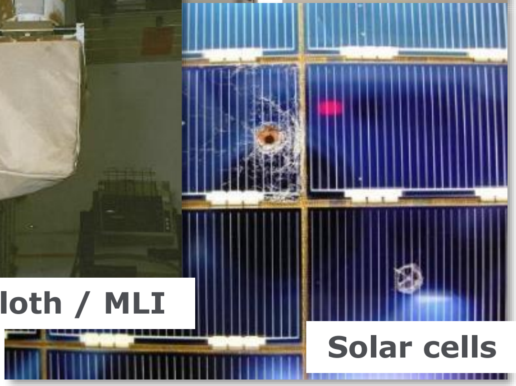
b. The TCS design shall be documented in the TCS detailed design document in conformance with the DRD of Annex F.

c. Reliable properties of materials and their degraded values under the specified environment shall be used in the design.

d. If suitable data are not available, then a material test programme shall be implemented.

White paints and ceramics

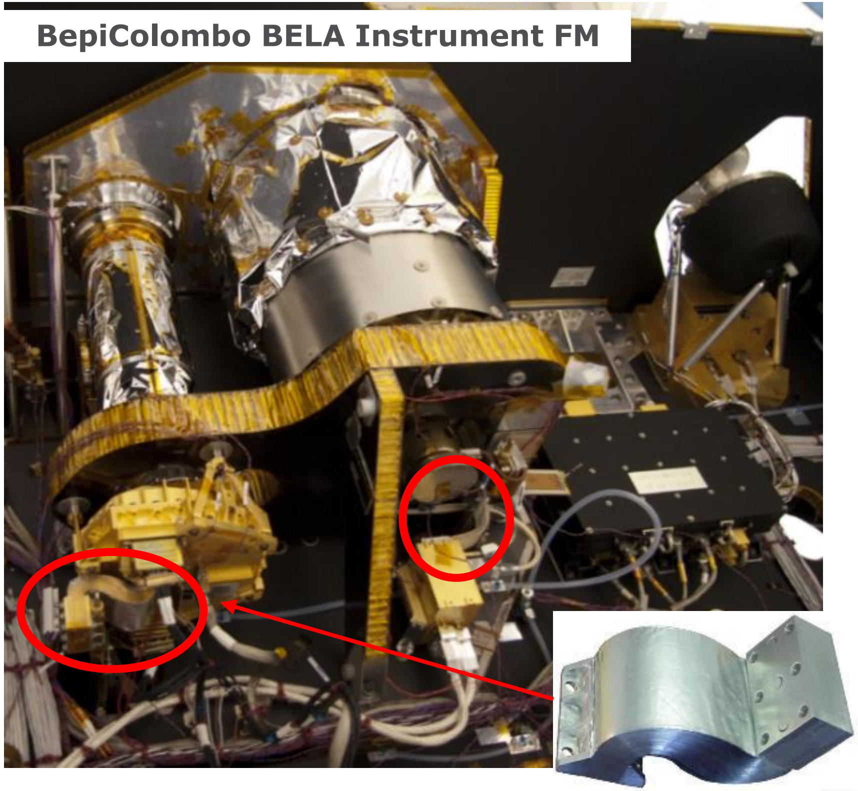
Beta cloth / MLI



Solar cells

5. *Performance specific requirements*

Passive Means – Thermal Strap

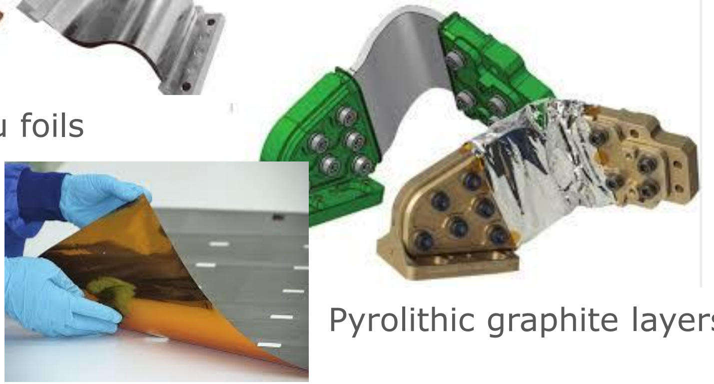


Various thermal Straps

Copper braids

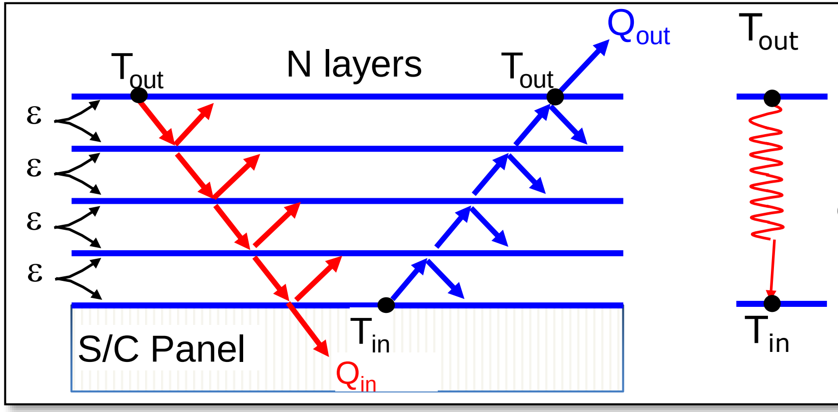
Graphite braids

Copper & alu foils



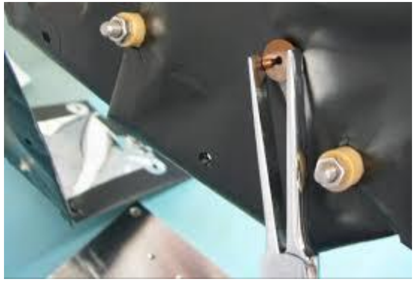
Pyrolithic graphite layers

5. Performance specific requirements
Passive Means – MLI



THEORY for N Layers

$$Q_{in/out} = \frac{\varepsilon}{N}\sigma\left(T_{hot}^4 - T_{cold}^4\right)$$

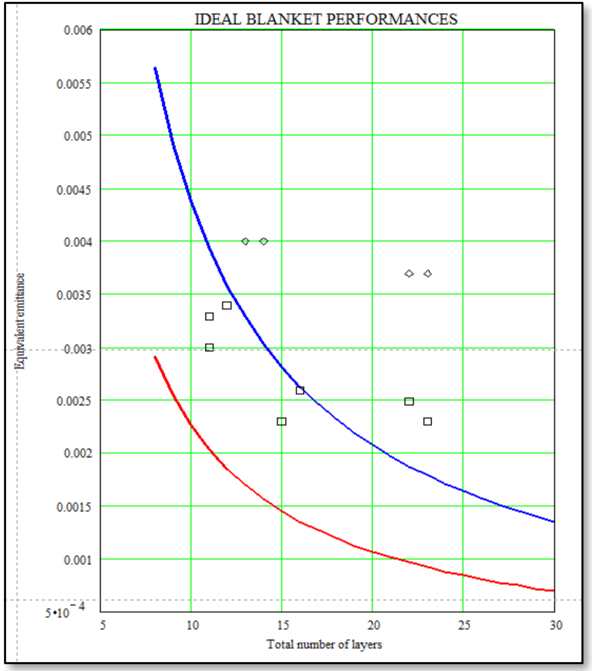


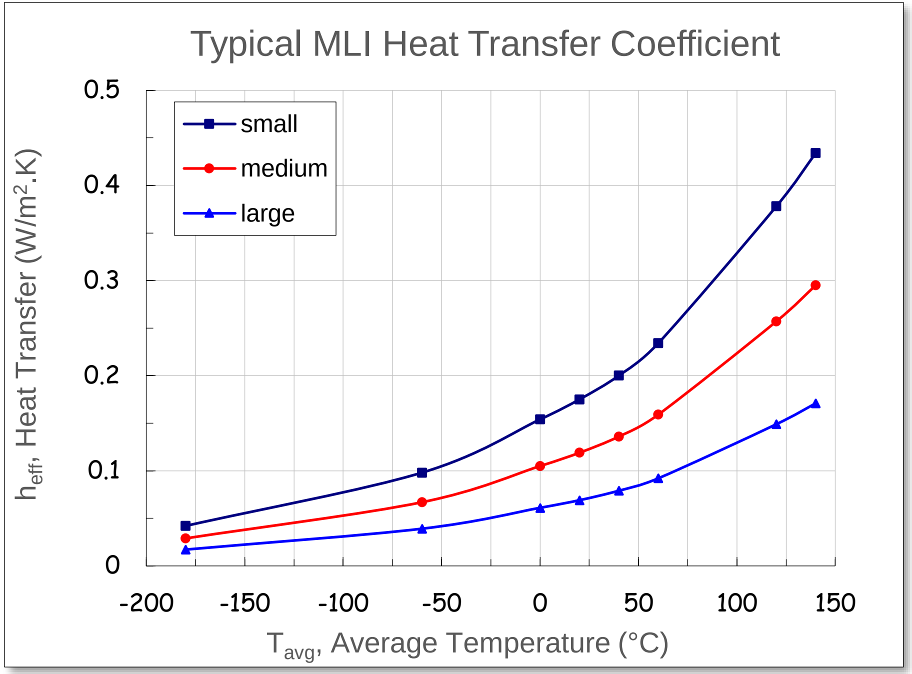
- Theory $N = 12$ layers of Mylar (ε=0.05) gives $\frac{\varepsilon}{N} = 0.004$
- Lab. measurement gives similar results <u>but correlated value</u> $\frac{\varepsilon}{N} =$ $0.01 \ldots 0.03$
- Specific mass: 250…500 g/m² with grounding wires for 12...22 layers
  - depends on the type of material Mylar, Kapton, Dacron net… and layup
  - Bepi-Colombo up to 2.2 kg/m² with up-to 4 blankets stacked

Passive Means – MLI efficiency

Styrofoam@air $k@20°C = 0.027\,W/mK$

MLI $k = h \cdot t = 0.12\frac{W}{m^2K} \cdot 1\,cm = 0.0012\,W/mK$





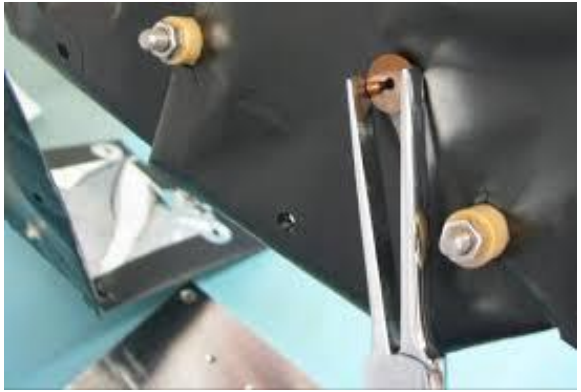
Parts, materials and processes (PMP)

Clause 4.4.3: Parts, materials and processes (PMP)

a. The TCS design shall use space qualified parts, materials and processes.

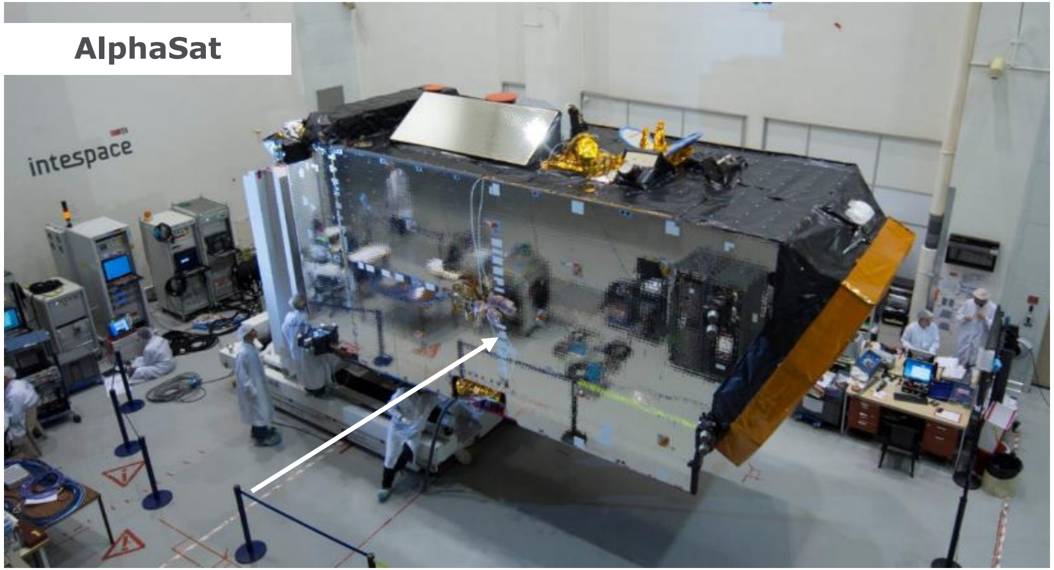
b. An acceptance or qualification programme shall be performed for PMP if not available.

c. Declared materials, mechanical parts and processes lists (DMPM) shall be produced according to the Declared material list (DML).



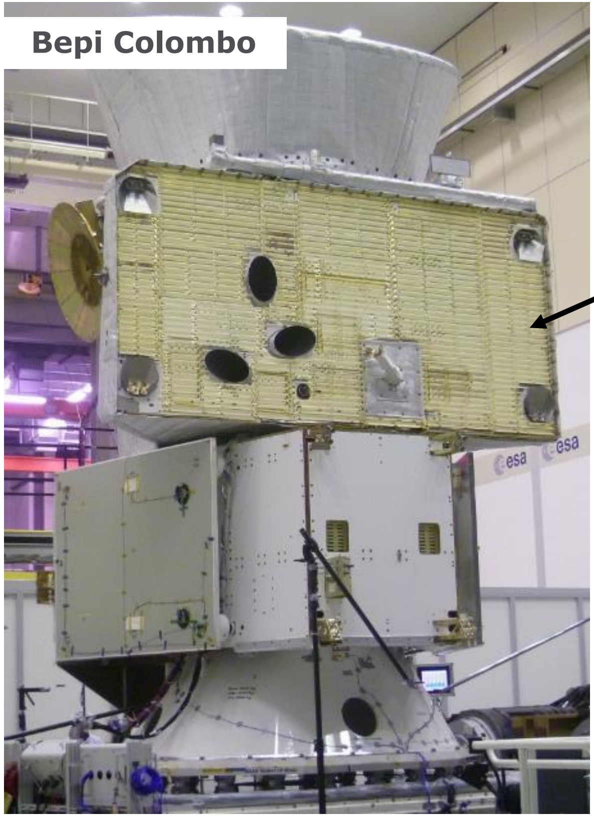
Passive Means – Radiators

Small GEO OSR radiators cover the maximum available surface on North and South sides.



AlphaSat OSR radiators cover the maximum available surface on North and South sides to radiate more than 10 kW of dissipation. The smaller radiator, on Nadir side cools down the Laser Communication Terminal.

5. Performance specific requirements
Passive Means – Radiators



Bepi Colombo OSR radiator are equipped with Planet Infrared flux deflective blades

5. Performance specific requirements
Flexibility

Clause 4.4.7 Flexibility

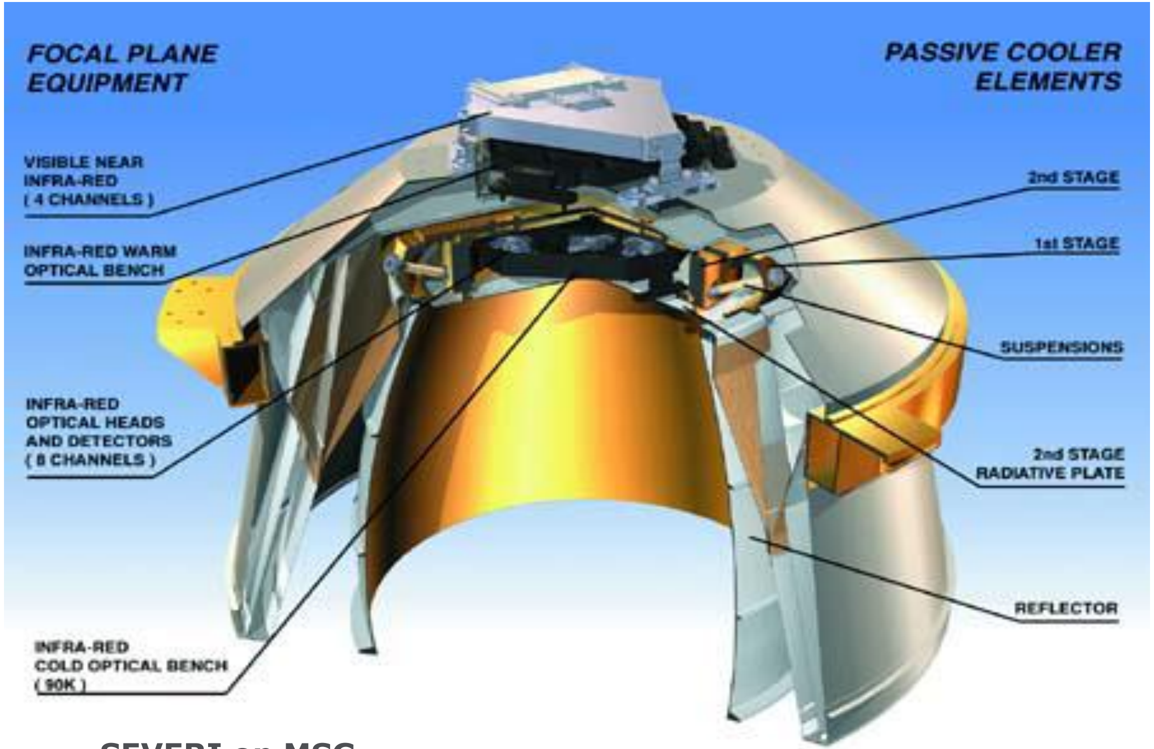
a. The TCS design shall incorporate flexibility to

   1. accommodate modifications of requirements imposed on the TCS during the project development phase;

   2. offer trimming capabilities to accommodate late requirement updates.

METOP-C

5. Performance specific requirements
Passive Means – Multi-stage Radiators

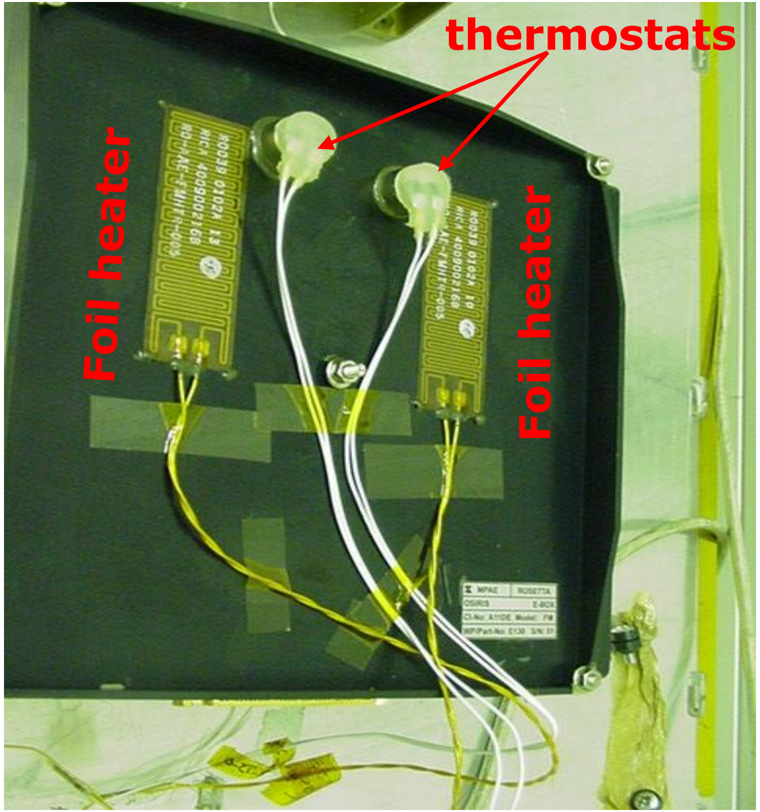


SEVERI on MSG

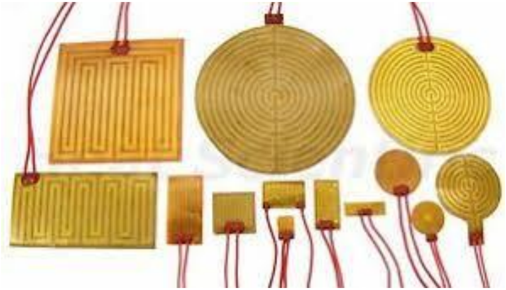
Passive Means – Dewar

- HERSCHEL Characteristics
  - 2367 l of superfluid Helium at 1.6 K
  - Heat budget of He Tank: 56 mW = 2.5 mg/s
  - Lifetime 3.5 years
  - Cryostat passively cooled to about 75 K
  - Telescope passively cooled to 90 K
  - Cryo-harness: 5000 links 300 K & 4 K, in 3 sections (steel & brass)
  - Further cooling to 0.3 K inside instruments

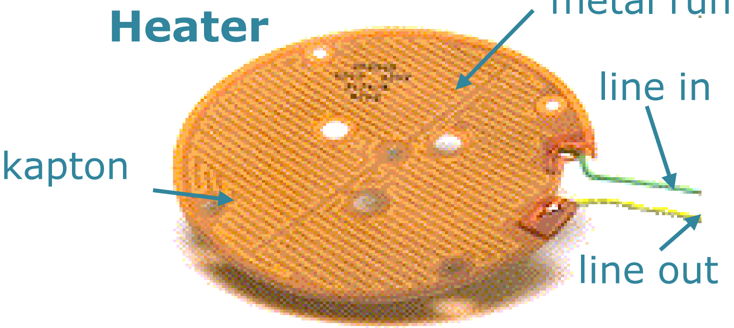
Active Means – Heater + Thermostat



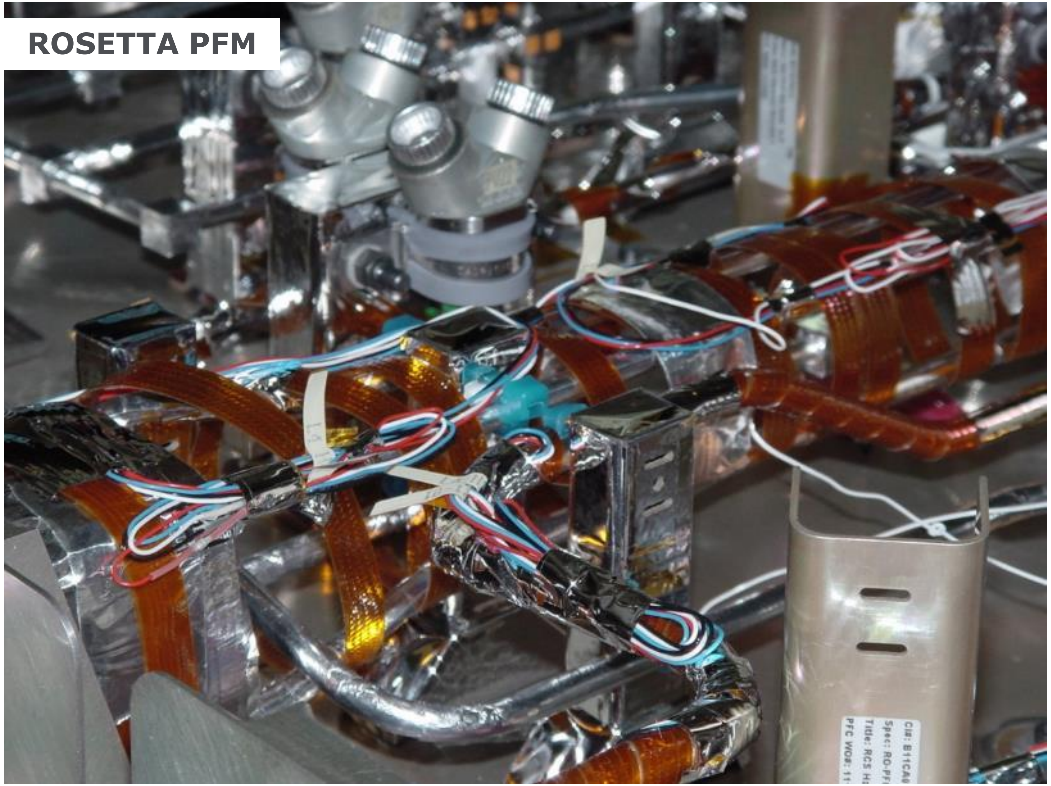
Ribbon heater

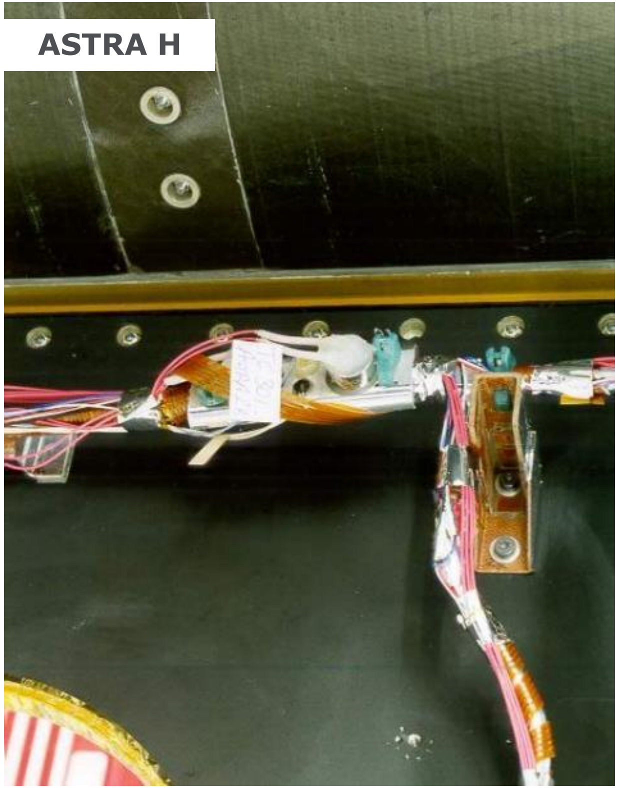


Custom Heater



5. Performance specific requirements
Active Means – Heaters + Thermostat





5. Performance specific requirements
EEE components & electrical

Clause 4.3.3 (Requirements towards other subsystems)

a. Heat dissipation (including cabling)

b. Routing of the harness, grounding, electrical conductivity.

c. Power consumption, peak and average power, duty cycle

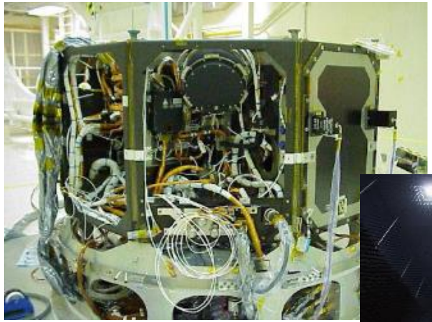
d. Comply with the specified voltage and voltage variation.

e. Grounding and EMC requirements for TCS items.

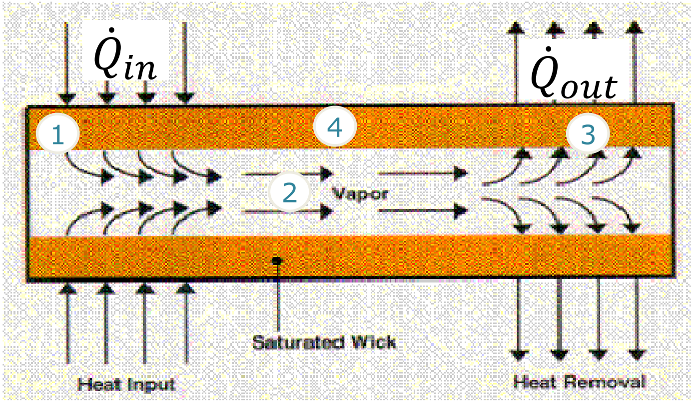
4.4.4 EEE components (Thermal Design)

a. Use space qualified EEE components.

b. An acceptance or qualification programme for new EEE components



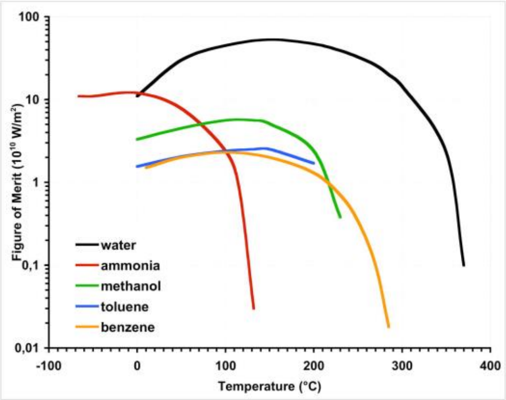
Active Means – Heat-Pipes



Working principle:

1. Vaporization in the evaporator;
2. Vapor flow in the core region of the container;
3. Condensation in the condenser, and
4. Liquid return to the evaporator by capillary action in the wick.

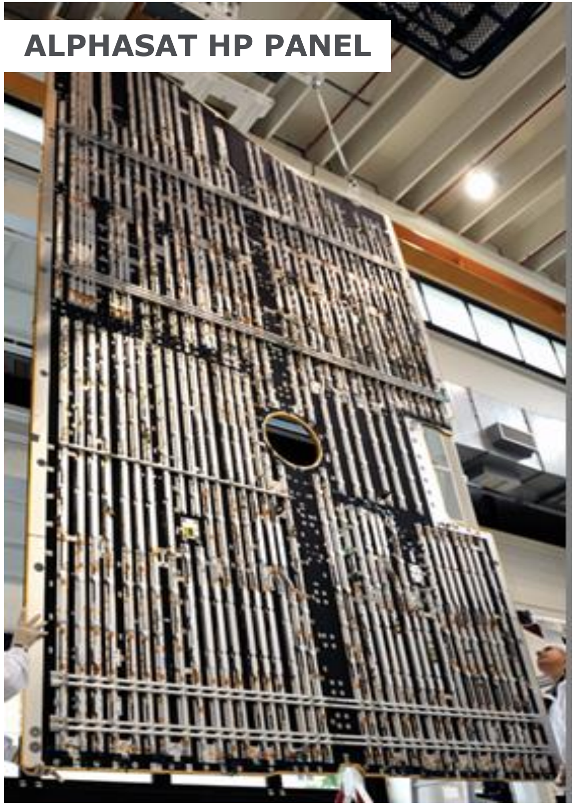
Figure of merit of heat pipes



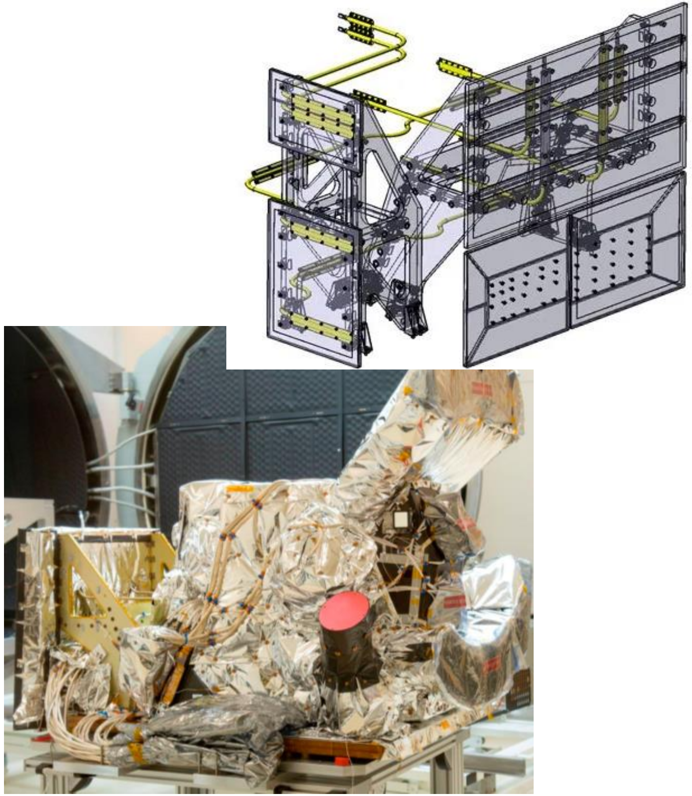
ECSS-E-ST-31-02C Rev1

- capillary induced fluid flow, *instead* of gravitational or mechanical work

5. Performance specific requirements
Active Means – Heat-Pipe Examples



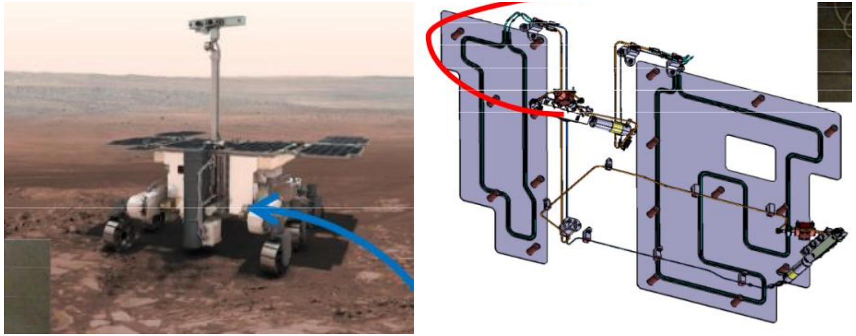
Sentinel 3 SLSTR Linking HP



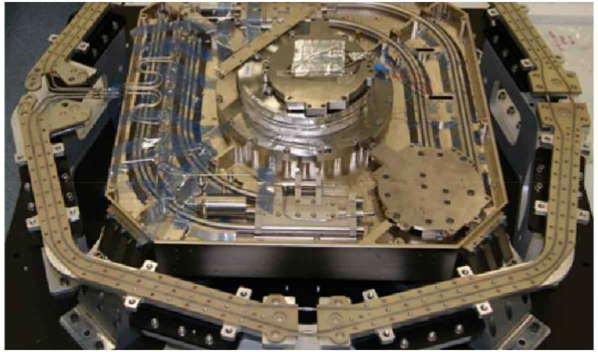
5. *Performance specific requirements*

Active Means – Loop Heat-Pipe Examples

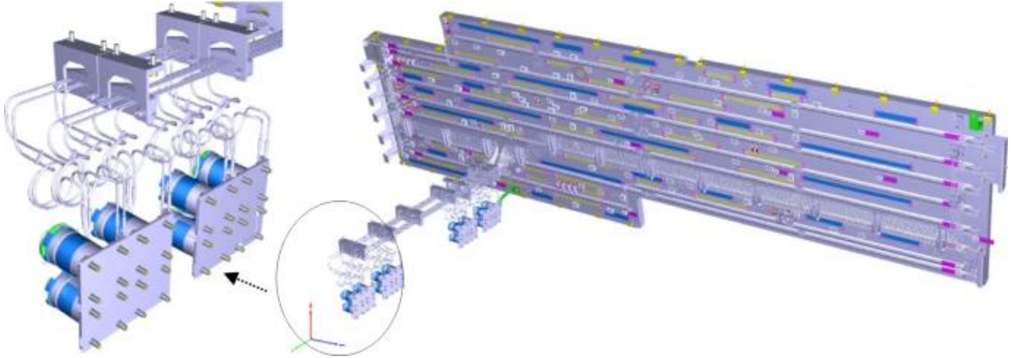
Exomars Rover Loop Heat Pipes Heat Switch



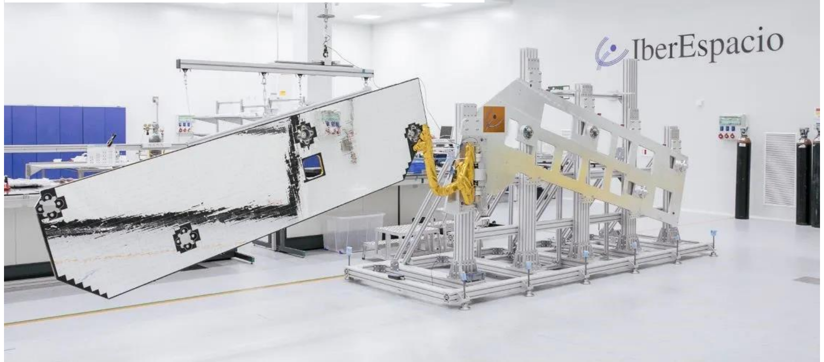
Sentinel 1 Laser Communication Terminal LHPs



EARTHCARE ATLID Mini-LHPs



Deployable Radiator using Loop Heat Pipes

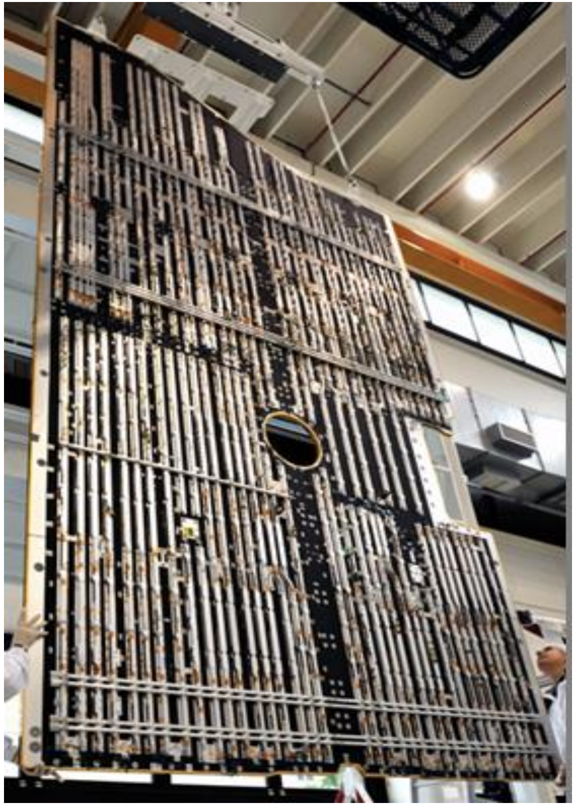


Predictability and testability

Clause 4.4.6 Predictability and testability

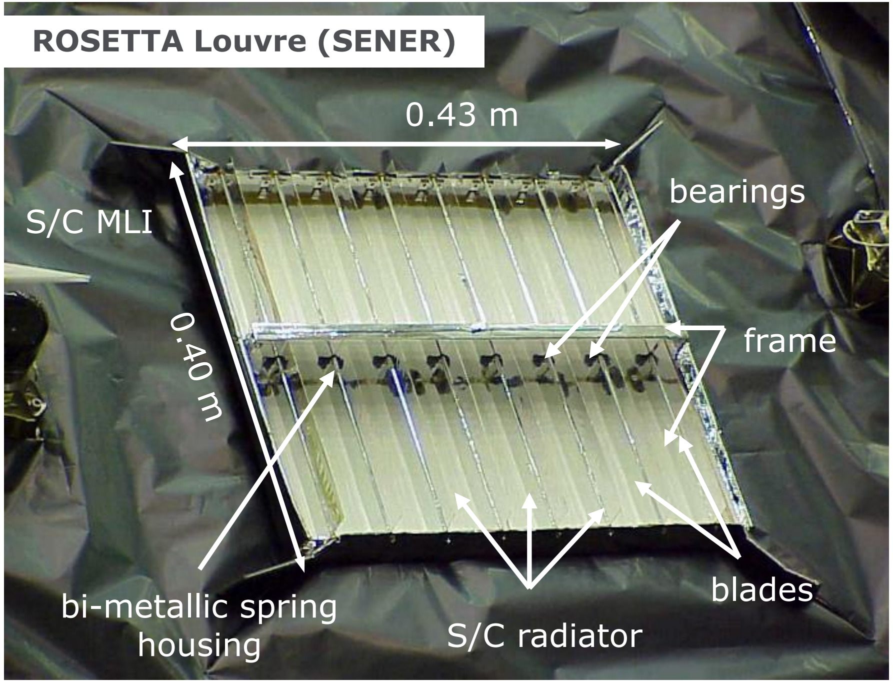
a. The TCS shall be designed such that conformance to performance requirements of clause 4.2 can be demonstrated by thermal analyses and thermal test.

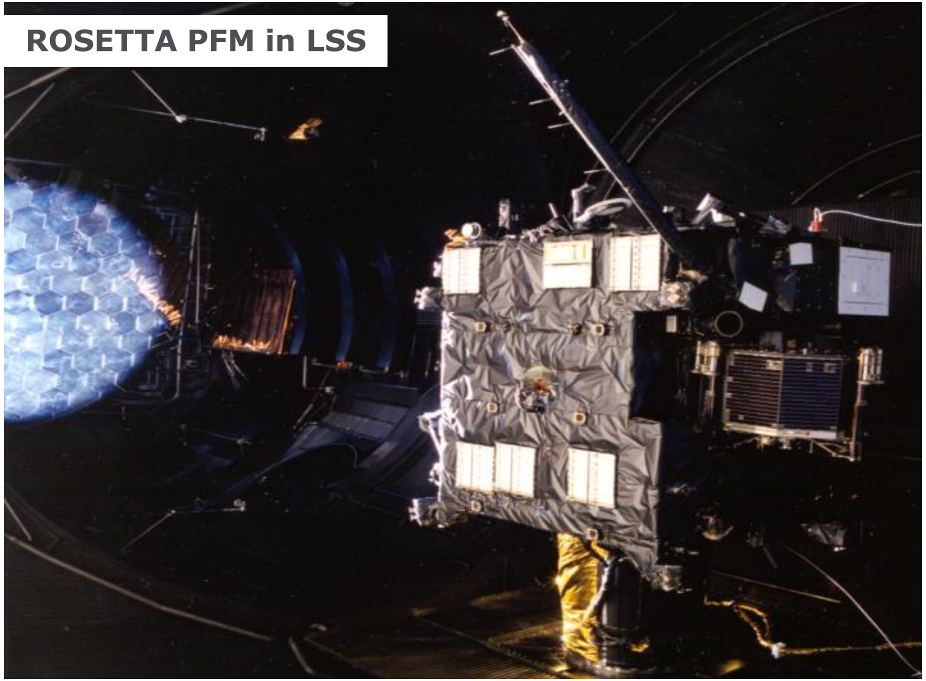
NOTE Modularity of the TCS design can facilitate its predictability and testability.



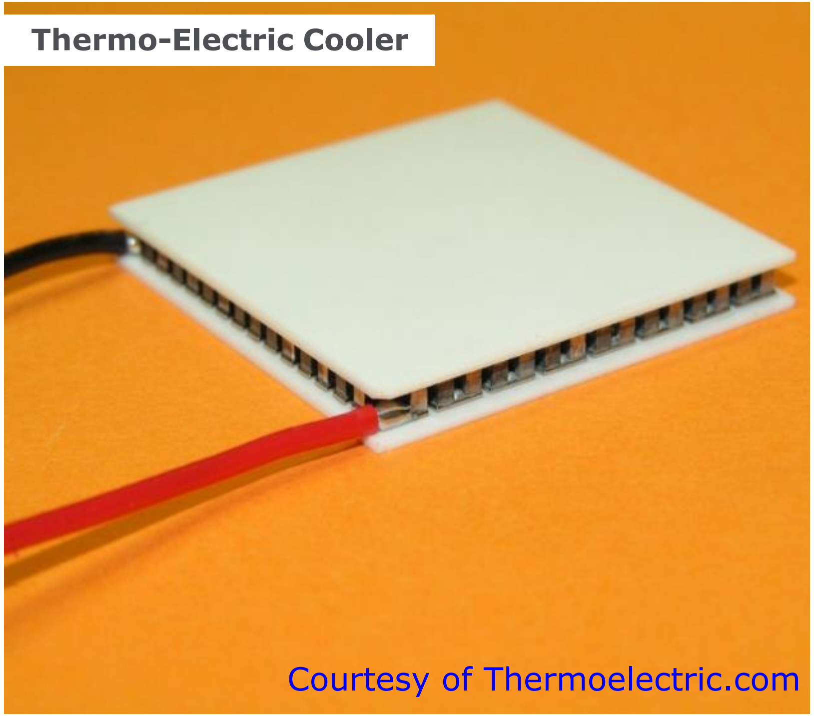
5. Performance specific requirements

Active Means – Louvres





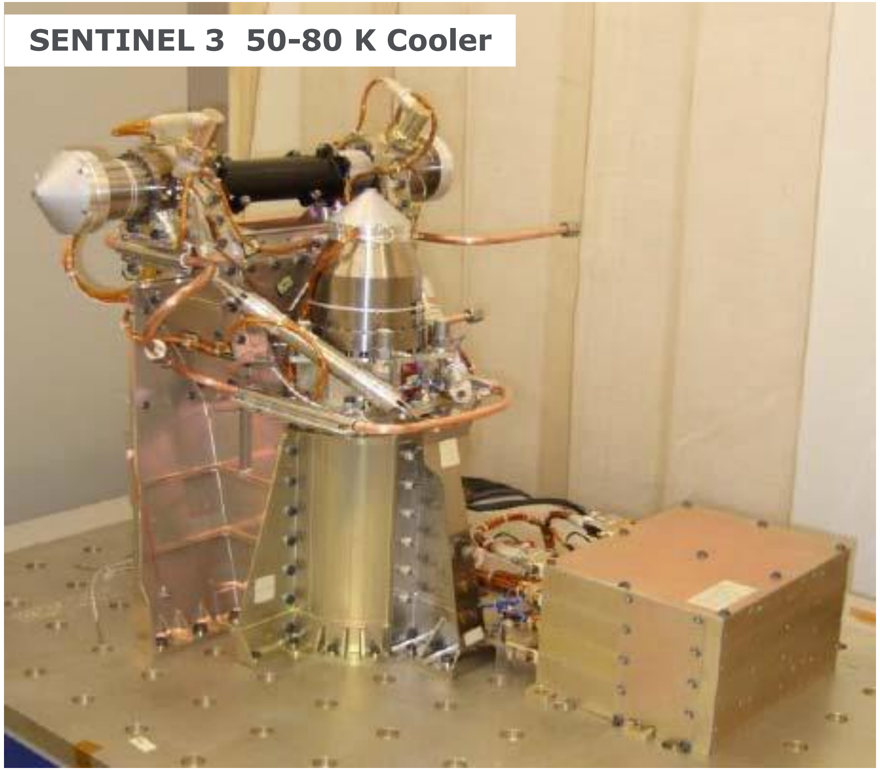
5. Performance specific requirements
Active Means – Coolers



- Max ΔT @0 W ~40°C (1 stage)
- Max ΔT @0 W ~70°C (multi stage)
- typical COP 0.30-0.70

- COP = coefficient of performance $Q_C/_{I \cdot V}$
- I = current
- V = voltage
- Q_C=cooling power

Active Means – Stirling Coolers

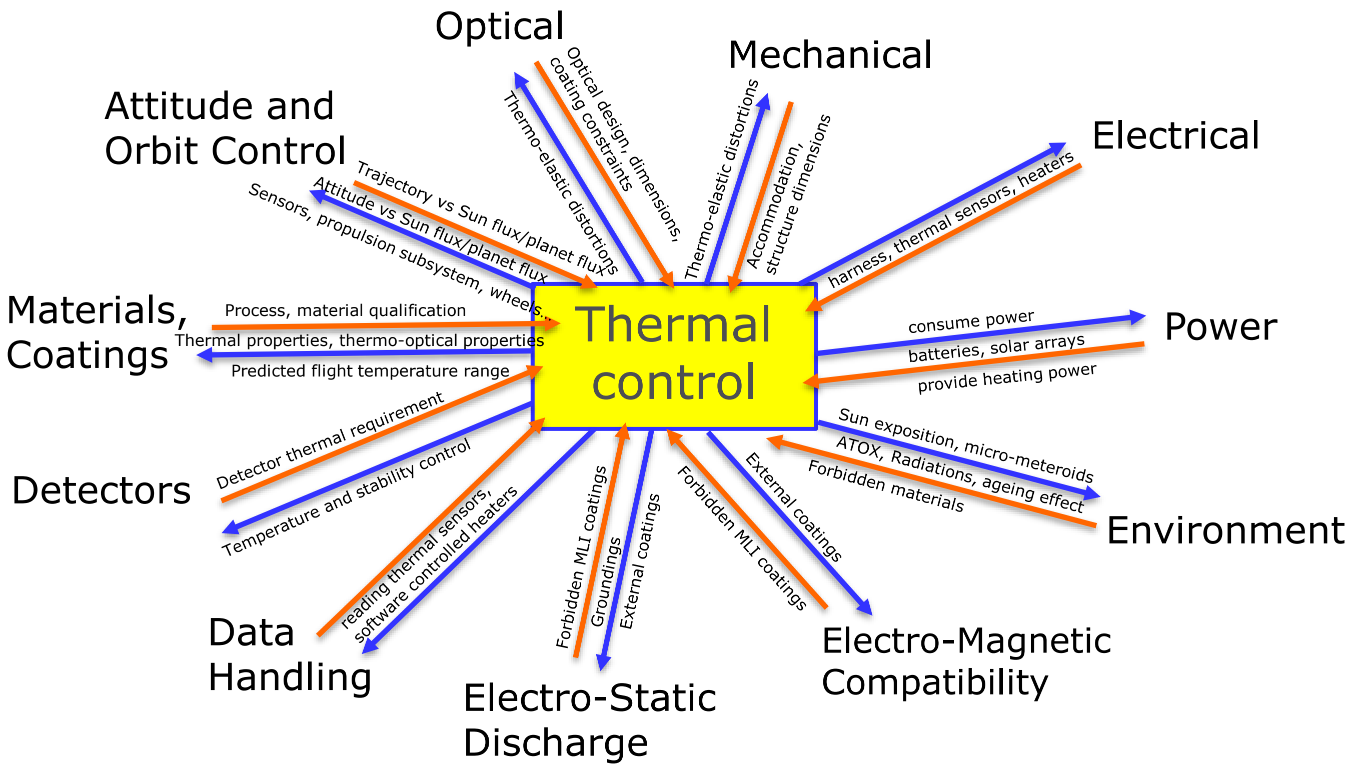


- Heat lift 1.5 W @80K
- Input power 52 W

Outline

✓

Requirement towards other subsystems



As a discipline, Thermal is close to System. Thermal has interface with almost all other domains, but without the need to know everything in great details.

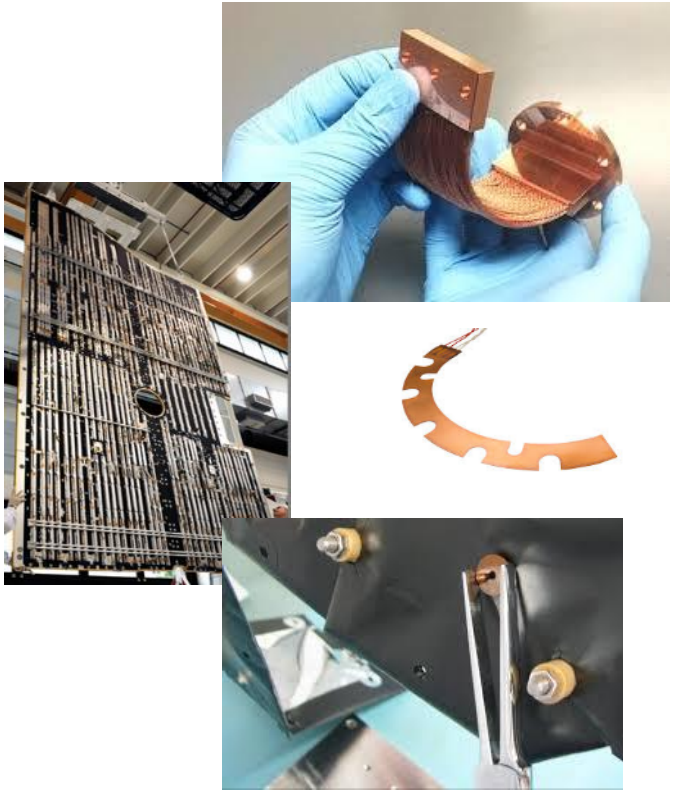
5. Performance specific requirements

Requirements towards other subsystems - Mechanical

Clause 4.3.2:

a. The TCS shall be designed respecting spacecraft configuration and layout, including the following information for each item in the applicable ICD

1. Dimension and mass
2. Materials and heat capacities
3. Fixation and mounting techniques
4. Contact area
5. Surface characteristics
6. Alignment requirements
7. Forbidden zones
8. Connector locations
9. Available area for fixation of thermal hardware
10. Spacecraft harness.



5. Performance specific requirements

Requirements towards other subsystems - AOCS

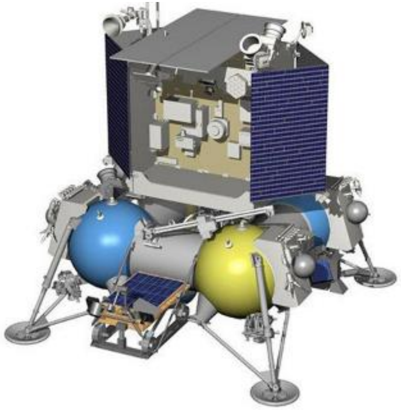
4.3.4.1 Propulsion

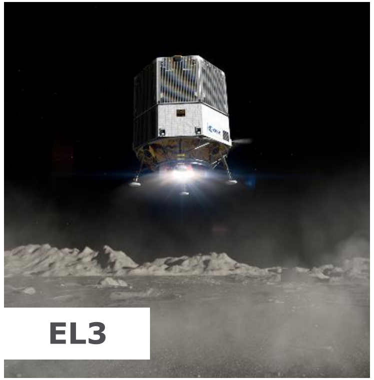
a. The TCS design shall fulfil requirements considering heat fluxes due to plume interaction and the temperature profiles of the thruster components during operation of a thrusters

b. The TCS shall be designed for effects of heat soak after firing of thrusters.

c. TCS shall agree with the system authority modifications of thruster operation for the case that temperatures of thruster components are predicted to be not acceptable.

Luna-27 lander





EL3

Falcon Heavy - boosters

Requirements towards other subsystems - AOCS

4.3.4.2 Attitude control

a. Attitude requirements affecting the TCS design shall be specified at system level.

NOTE For example: Specified momentum for mechanical pumps in fluid loops.

b. In case of a thermally unacceptable attitude, the TCS shall agree with the system authority alternative attitudes and lay out.

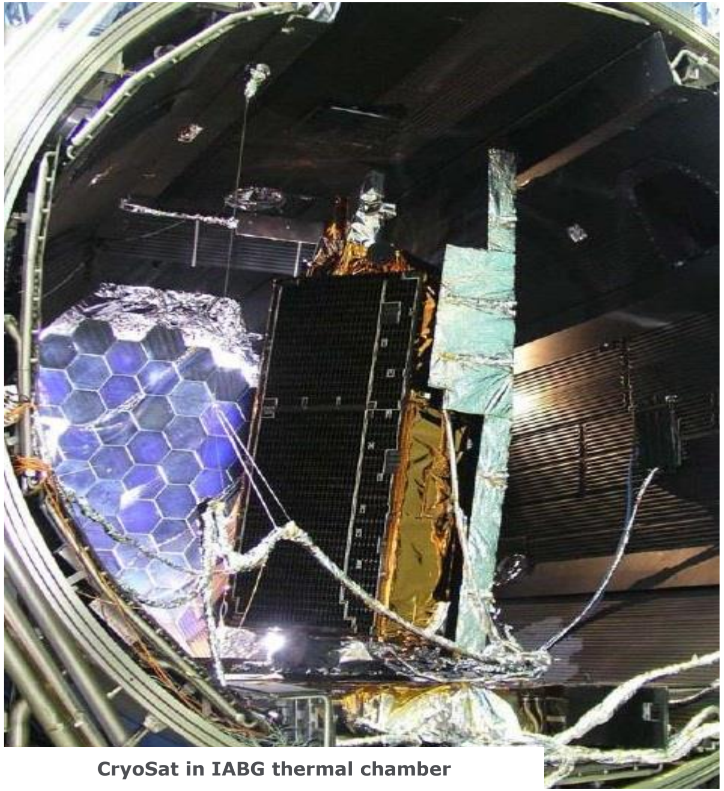
Requirements towards other subsystems - GSE

4.3.8 GSE

a. GSE interface requirements related to TCS shall be specified in the GSE specification of the project.

b. TCS specific requirements for ground support equipment shall be specified by the thermal control subsystem.

c. The TCS design shall permit GSEs to interface the S/C at the specified locations.



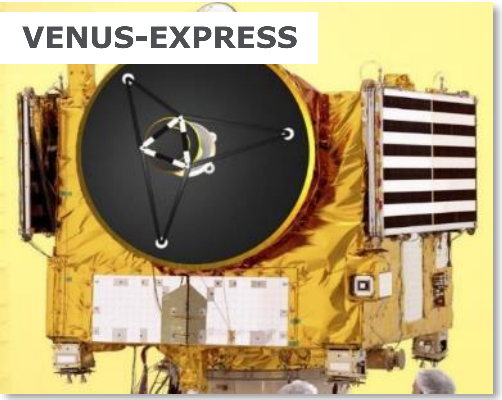
CryoSat in IABG thermal chamber

Outline

1. Introduction to Thermal Engineering
2. Thermal Standards – Overview
3. Mission Specific Requirements
    1. Launch to Landing
    2. Thermal Space Environment
4. Performance Specific Requirements
5. Requirement towards other subsystems & Design Requirements
    1. Thermal control means
    2. Requirements towards other subsystems
    3. **Thermal design requirements**
6. Verification
    1. Thermal Model and Analysis
    2. Thermal Tests

Thermal Design – Activities

- **Define optical surface properties**
  - Paints,
  - Coatings
- **Define insulation means**
  - MLI, or other insulation (foams)
  - washers, stand-offs, etc.
- **Design heat transport/spreading systems**
  - doubler
  - fluid loop
  - heat-pipes, etc.
- **Define temperature regulation principle and control algorithm**
  - number and position + power/profile of heaters
  - number and position of flight sensors (thermostats, thermistors, etc.)
- **Establish the budgets**
  - temperature, heater and power



Thermal Design – Activities

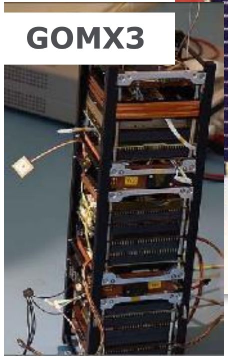
- **Distribution of dissipative units**
  - preferably directly behind a radiator
  - group unit with similar temperature requirements
  - but distribute units to avoid hot spots
  - maximize radiative exchange inside cavities to minimize temperature gradient
- **Position and dimension of radiators**
  - on faces not exposed to the Sun or high intensity heat sources
  - with maximum view factor to deep space
  - far from contamination sources (thruster, venting holes, apertures)
  - radiator must have a trimming capability in area to cope with power increase and adjustment after satellite TBTV test

Typical Thermal Designs – Non-Insulated Design

- **Non-insulated design is possible**
  - when internal dissipation is small compared to the environmental heat loads

- **Characteristics**
  - no/little insulation with MLI, units in the middle of the body
  - external faces receive environmental fluxes
  - design relies on internal mass $(m \cdot c_p)$ of units and decoupling from external faces
  - more temperature variation than insulated design

- Examples PROBA1, P2, Cubesat

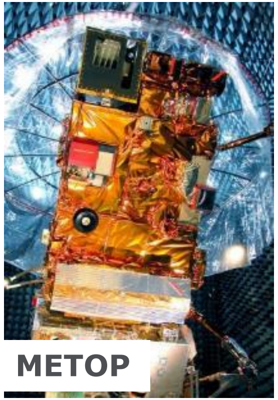


Typical Thermal Designs – Radiative Design

- **Radiative design is possible**
  - when internal dissipation is higher w.r.t. environmental heat loads

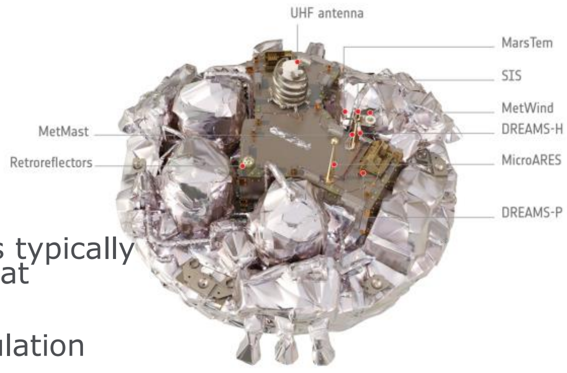
- **Characteristics**
  - S/C body protected by MLI from undesirable environmental fluxes
  - design relies on radiative surfaces placed everywhere at preferred locations that radiate to deep space => RADIATORS
  - control of attitude to avoid as much as possible heat loads on radiators
  - less temperature variation than “bulk” design

- **Examples**: ***most*** of the existing satellites:
  - Scientific XMM, HUYGENS, BepiColombo MPO, ROSETTA
  - Telecoms ALPHASAT, ASTRA 1K

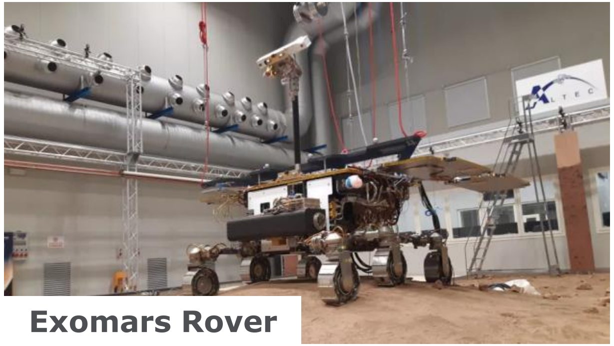


5. Performance specific requirements
Typical Thermal Designs – Convective Environment Design

- **Convective design is possible**
  - Fluid loops and Forced Air convective heat transfer is possible
  - Surface Missions with atmosphere allowing natural convection and wind
- **Characteristics**
  - Fins to increase the surface area with gas and fluid flow using pumps or fans typically used on Crew missions for internal pressurized compartment or fluid loop heat exchangers
  - Surface missions, as Mars, insulated design with heat switch using thick insulation with a minimum of 3cm
  - Mars and Moon Mission using Warm Compartment to use waste heat to survive and to increase thermal capacity to extend further in the night
  - Highly insulated design may cause issue during the Cruise phase when incapsulated
  - RHU can be used to help surviving the night and Dust storm season
- **Examples**: ***most*** of the existing satellites:
  - Crewed Shuttle, ISS payloads, and Gateway
  - Surface Exomars



Exomars Schiaparelli



Exomars Rover

6. Verification

Table of contents

Verification requirements specific to TCS

4.5.2.1 All temperature ranges

a. Verification by analysis shall be performed through thermal analytical modelling and corresponding performance predictions.

b. The cases to be verified by analysis shall be agreed with the system authority.

NOTE 1 Verification by analysis is the selected verification method for cases where fully representative testing cannot be performed.

NOTE 2 For example: Environmental and dimensional limitations of the test facilities.

NOTE 3 For example: Behaviour of TCS items under reduced or increased gravity.

LSS = Large Space Simulator @ ESTEC

Verification requirements specific to TCS

4.5.2.1 All temperature ranges (cont'd)

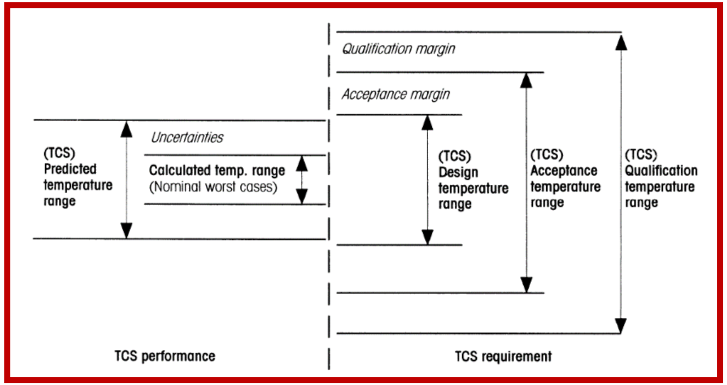
c. Verification by analysis shall take into account uncertainties.

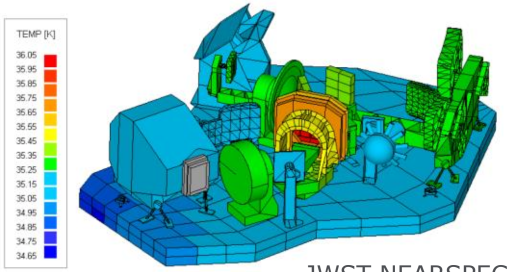
NOTE Uncertainties of lower than 10 K are generally not applied before verification by a TBT is performed.

d. Thermal and geometrical models shall be defined in a Mathematical Model Specification in conformance with the DRD of Annex A.

e. Thermal and geometrical models used for analysis shall be documented in the Thermal and Geometrical Model Description in conformance with the DRD of Annex B.

f. For each thermal analysis a TCS analysis report shall be produced in conformance with the DRD of Annex C.





JWST NEARSPEC

Detour 3 – Thermal Modelling & Analysis

Detour 3
Thermal Models – Overview

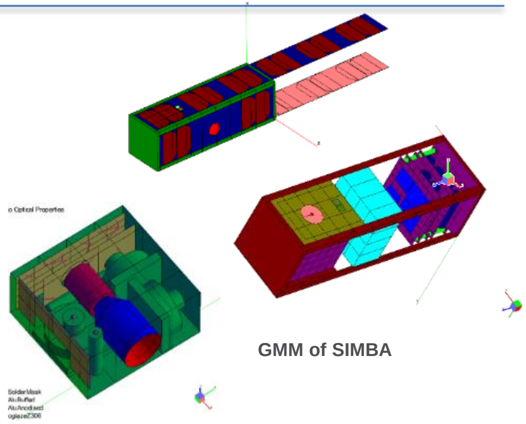
- Mathematical representation of the satellite and its environment by:
  - a geometry of the problem with S/C, planet…

    Geometrical mathematical model (GMM)

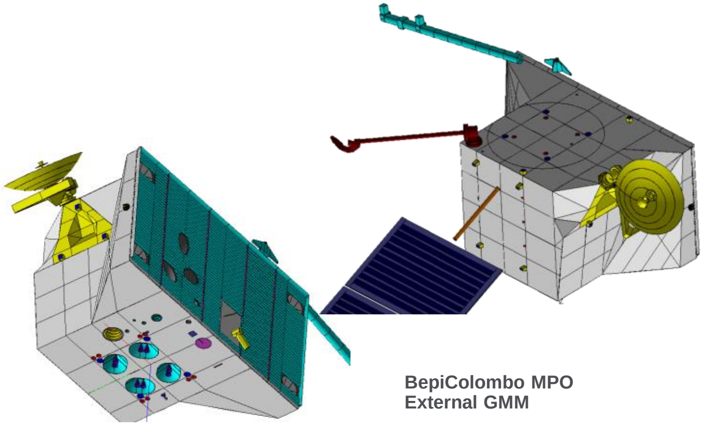
  - a network of nodes, couplings, heat sources

    Thermal mathematical model (TMM)

- Thermal models are used during the thermal analyses:
  - by iteration of different design solutions or configurations
  - it avoids unnecessary and expensive hardware test



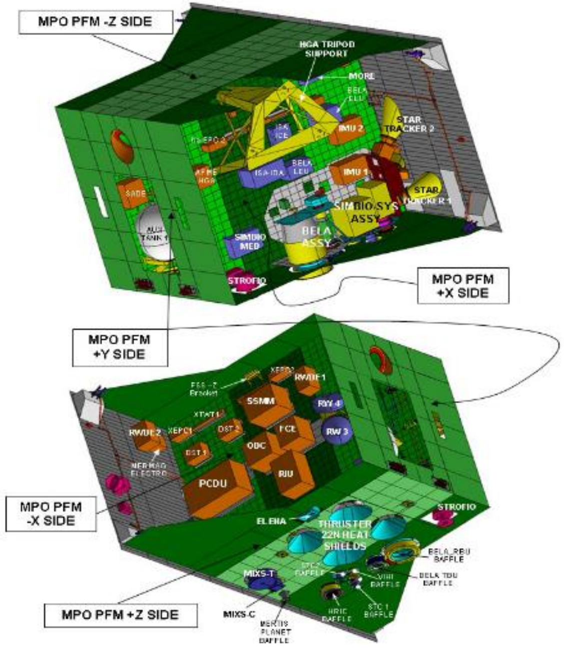
GMM of SIMBA



BepiColombo MPO
External GMM

Detour 3
Geometrical Mathematical Model (GMM)

- **Geometric representation of S/C**
  - by basic surfaces (rectangle, triangle, disk, cylinder…)
  - with relevant thermo-optical properties solar absorptivity α, infrared emissivity ε ; ageing properties: Begin-of-life (BOL) and end-of-life (EOL)
  - in relevant orbits (transfer, operational; single or chained)
  - for various attitudes w.r.t. Sun, planet, etc.
- **Model granularity**
  - "As detailed as necessary, as simple as possible"
  - local model detailed enough to assess critical elements (sensitive components, high power density)
- **GMM is used to calculate**
  - radiative couplings, view factors $F_{1 \to 2}$
  - environmental heat loads Q_S, Q_A, Q_E

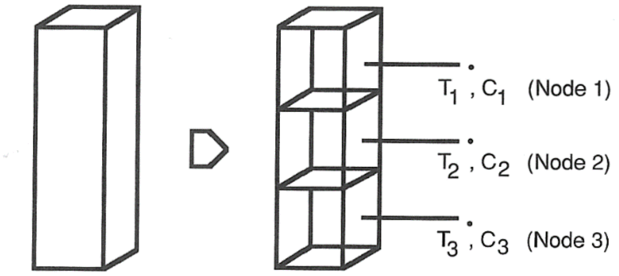


Detour 3

Thermal Mathematical Model (TMM)

- **Mathematical representation of the S/C**
  - Discretization of structural parts (lumped nodes)
  - Accounting for mechanisms & structural parts
  - Electronic components and heat dissipation
  - Use relevant material properties
    - heat capacity, density, thermal conductivity,
    - heat transfer coefficient, contact conductance,
    - Ablation, phase change, …
  - Use of control laws of heater/unit dissipation, mechanism positions if any
  - Represent operational modes

-> in a set of differential equations



$$C_i \frac{dT}{dt} = \sum_{i \neq j} G_{ij} \left(T_j - T_i\right) + \sum_{i \neq j} R_{ij} \left(T_j^4 - T_i^4\right) + Q_i$$

$$G_{ij} = \frac{\lambda \cdot A_{ij}}{l_{ij}}$$

$$R_{ij} = A_i \cdot F_{ij} \cdot \varepsilon_i \cdot \alpha_j$$

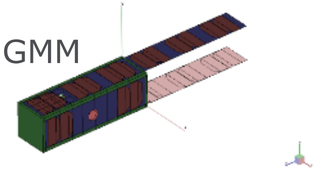
- All GMM nodes are represented in the TMM – vice versa not all TMM nodes are represented in the GMM
- **All G/TMM must be correlated to some extent against test data**

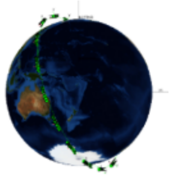
Detour 3
Thermal Analyses – Worst Cases

- **Definition of extreme cases**
  - **Hot case**
    - End-of-Life (degraded) thermo-optical properties
    - winter solstice when solar intensity is maximum
    - maximum internal heat dissipation
  - **Cold case**
    - Beginning-of-Life thermo-optical properties
    - Summer solstice
    - Minimum internal heat dissipation

Orbit / Mission dependent
- Worst case may occur at another time
- During a long eclipse

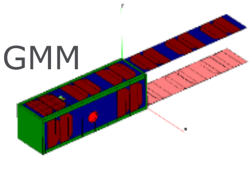
GMM

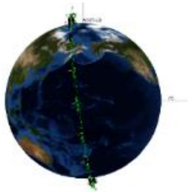




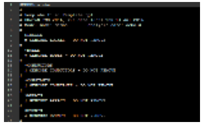
TMM

GMM



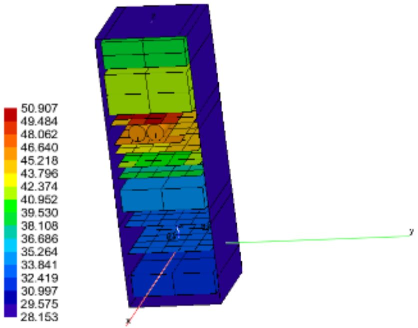


TMM

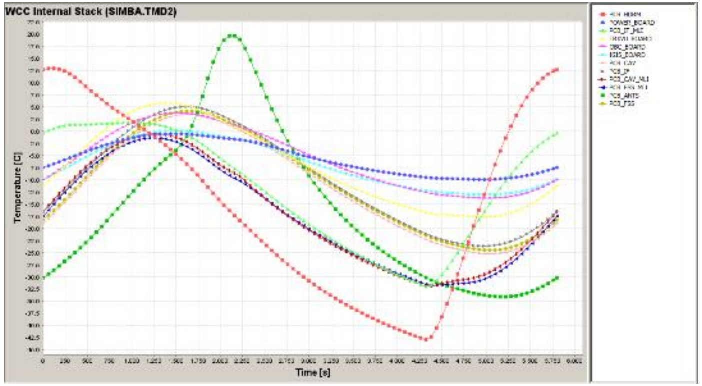


Thermal Analyses – Results

- **Calculation of temperature field and heat flows**
  - for each mission phase
  - in steady-state: operational orbit for extreme cases
  - in transient
    - for launch and transfer orbit
    - cyclic temperature evolution along orbit
    - failure cases (loss of attitude, loss of heat-pipe …)



- **Evaluation of the TCS performances**
  - temperatures, gradient
  - radiator dimension, absorptivity emissivity
  - heater power & duty cycle
  - heat flow (Q) distribution and balance
  - transient fluctuation, evolution of T and Q



Detour 3
Conductive heat transfer - basics

Conductive heat transfer

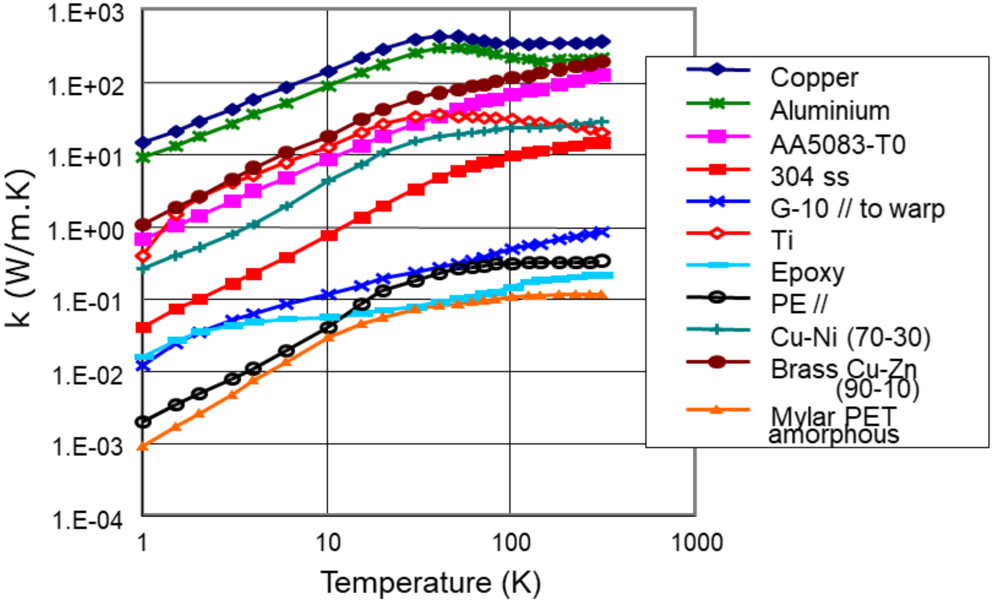
a. propagation of energy from particle to particle

b. in solid, liquid or gaseous matter, homogeneous or not

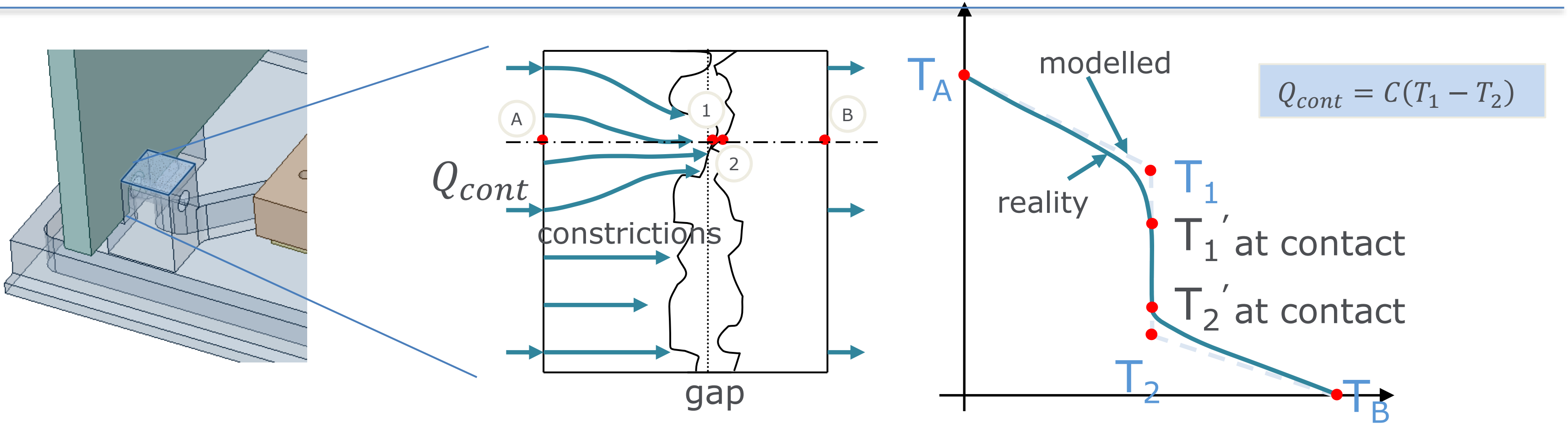
Fouriers law

$$\dot{q}_{cond} = -\frac{\lambda_x}{x}(T_2 - T_1)$$

Thermal conductivity vs. temperature



Contact Conductance



Interface between two bodies:

- all mechanical fastening: screws, bolts, potted inserts
- difficult to evaluate even through test
  - gap
  - micro-constrictions

Interstitial space:

- gas filled: air (on ground), N_2 , CO_2 (on Mars)…
- vacuum: environmental thermal test / space
- Glue or interface filler: e.g. graphite or boron nitride

Difficult to characterise:

- not always reproducible
- Its value depends on:
  - materials in contact, mechanical forces (area, rigidity…)
  - interstitial gas
  - contact surface quality: roughness and planarity
  - temperature

Radiative Heat Transfer – Basics

$$E_{\lambda,T} = \frac{2\pi hc^2}{\lambda^5\left(e^{\frac{hc}{k_B\lambda T}}-1\right)}$$

Planck's law

hemispherical **spectral** emissive power [W/m²/µm]

$$E_{bb,T} = \int_0^\infty E_{\lambda,T}\,d\lambda = \sigma T^4$$

Stefan – Boltzmanns law

hemispherical **total** emissive power [W/m²]

$$\lambda_{\max} = \frac{2\pi hc^2}{T} \approx \frac{2898}{T}$$

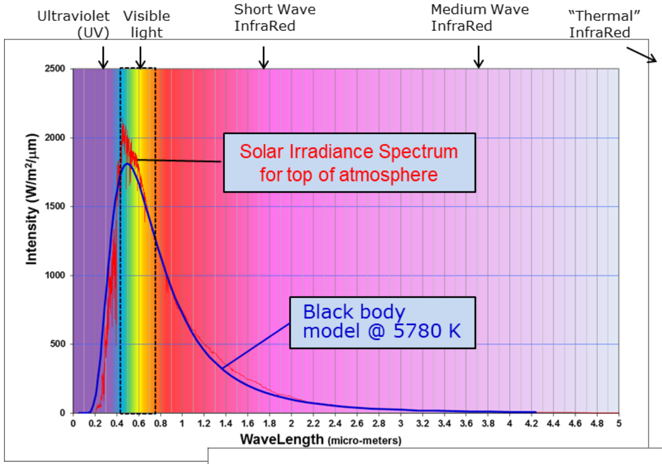
Wien's Displacement law

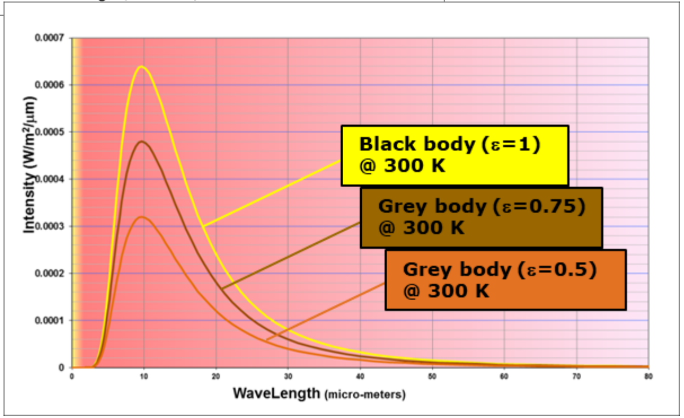
Wavelength of maximum emission [µm]

Black Body

$$\alpha(\theta,\lambda) = \alpha = 1$$

$$\varepsilon(\theta,\lambda) = \varepsilon = 1$$





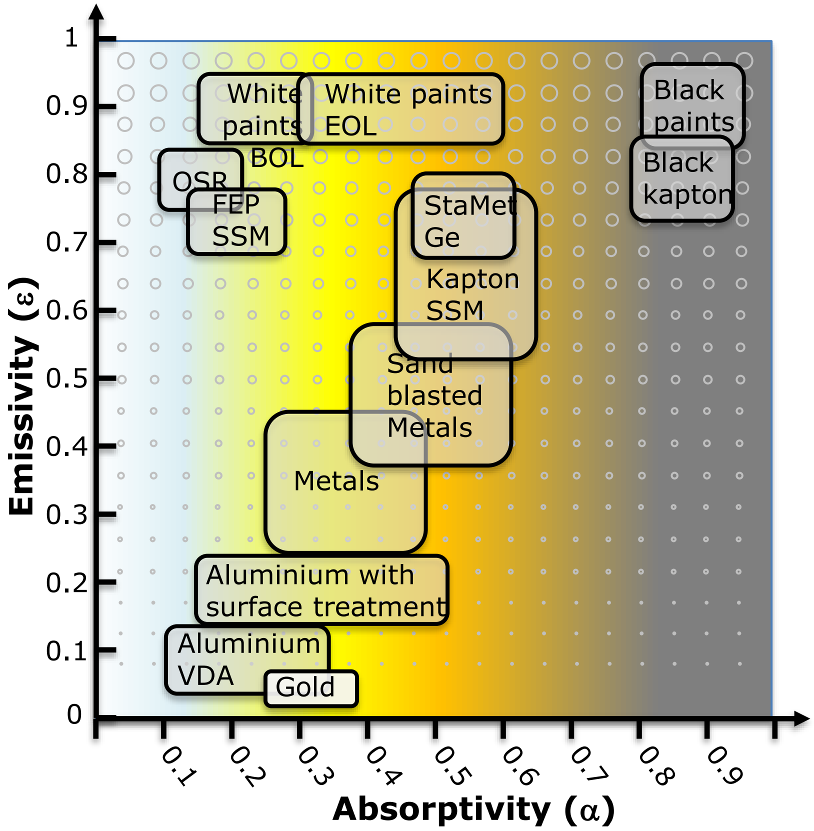
Detour 3

Optical Surface Properties

Finish	α_s	ε_{IR}	$\alpha_S/\varepsilon_{IR}$
Vapour deposited (VD) Au	0.23	0.03	9.20
VD Al (VDA)	0.15	0.05	3.00
Black paint	0.94	0.81	1.16
White paint	0.2	0.88	0.23
Second surface mirror (SSM) (Ag 2 mils)	0.10	0.60	0.17
Optical surface mirror (OSR)	0.09	0.82	0.11
Typical for CubeSats (examples)			
Black Anodization	0.86	0.86	1.00
Alodine (bare)	0.37	0.06	6.17
Alodine (sandblasted)	0.46	0.25	1.84

- **Values to be treated with care!!!**
  - dependence on substrate, application process, post-processing, thickness, temperature range …
  - angle of incident …

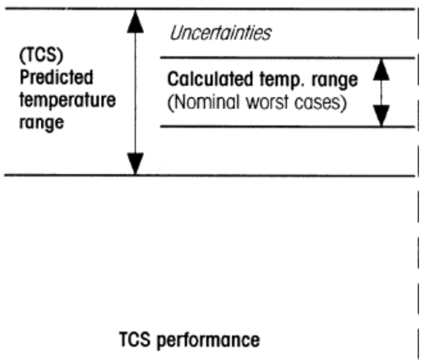
In doubt? –> Measure!



Detour 3
Thermal Analysis – Uncertainties vs. Margins

!!

- **Uncertainties in thermal modeling:**
  - Numerical uncertainties
  - ‘Physical’ uncertainties
    - material properties (anisotropy, batch differences)
    - optical surface properties (literature vs. real values; wavelength dep opacity)
    - contact uncertainties (surface roughness, pressure, interstitial medi
    - geometrical uncertainties (simplified geometry, no harness, etc.)
    - control uncertainties (thermostat switching, PID settings, etc.)
  - Model uncertainties are the responsibility of the thermal analyst
  - Model uncertainties can be reduced through test and sensitivity a values: +/- 15 K @ Phase 0/A, +/- 10 K @ Phase B/C.



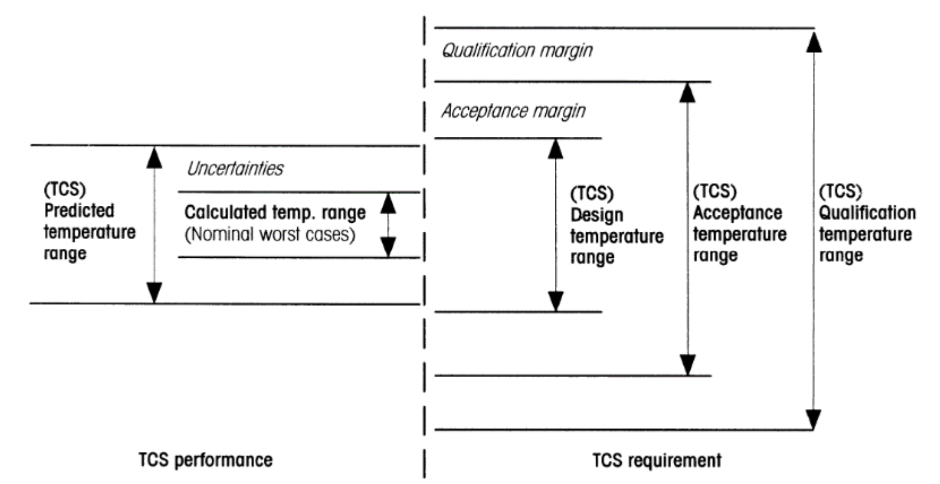
- **All results (calculated temperature) produced with computer models have uncertainties (predicated temperatures) – as each measurement has a measurement uncertainty.**

Detour 3
Thermal Analysis – Uncertainties vs. Margins

- **Uncertainties:**
  - Modeling Uncertainties
    - Geometry -> simplifications (holes, bolts, harness), …
    - Material properties -> bulk, anisotropy, …
    - Optical surface properties -> substrate, literature data, wavelength, opacity, specularity, …
    - Conductive interfaces -> geometry, contact conductance, …
  - Numerical Uncertainties

- **Margins:**
  - Design Margin : project specific
  - Acceptance Margin : typical ±5K
  - Qualification Margin : typical ±5K

Uncertainty ≠ Margin
- **Uncertainty is inherent to model**
- **Margin is systematic "safety"**



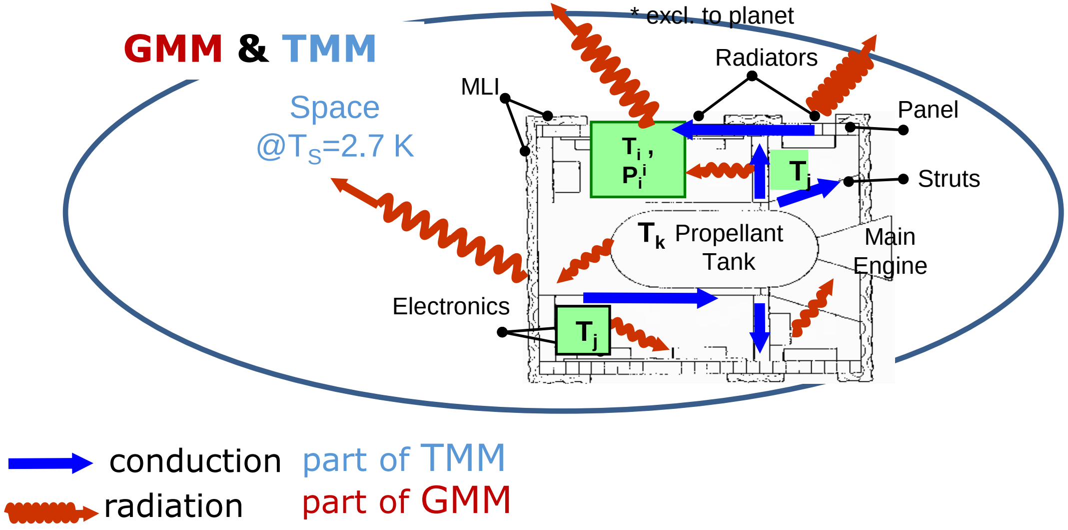
Thermal Models – Energy Balance Equation

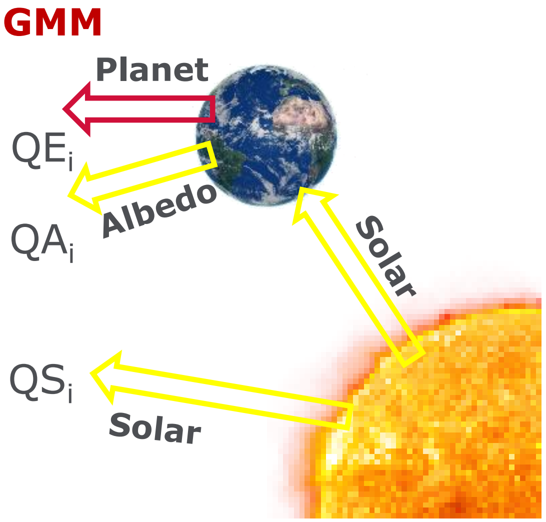
ENERGY CONSERVATION written at EACH thermal node i

stored energy		conducted* flux		radiated* flux		fluid flow (not visualised)		external loads		internal loads
$m_i\, C_i\, \frac{dT_i}{dt}$	$=$	$\sum_j G_{ij}\,(T_j - T_i)$	$+$	$\sum_j R_{ji}\,(T_j^4 - T_i^4)$	$+$	$\sum_j F_{ji}\,(T_j - T_i)$	$+$	$QE_i + QA_i + QS_i$	$+$	P_i^i

* Or convective

* incl. to space
* excl. to planet





Verification cont'd

ECSS

ECSS-E-ST-31C
15 November 2008

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ECSS

Verification requirements specific to TCS

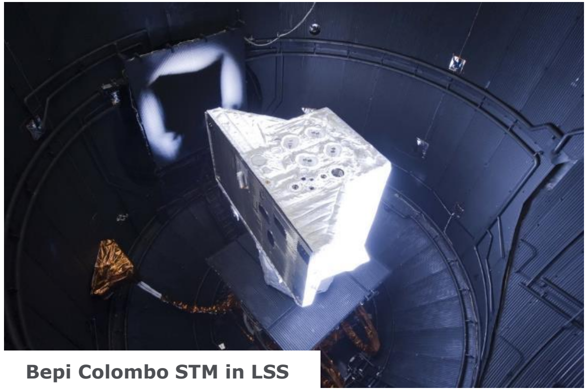
4.5.2.1 All temperature ranges (cont'd)

g. Conformance to specified performance shall be demonstrated by performing **thermal balance**, thermal vacuum and climatic tests.

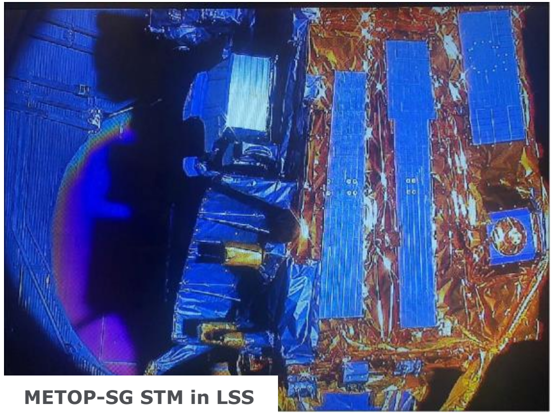
h. Test conditions shall be agreed with the system authority and included in the system test plan.

i. Verification testing of the TCS shall include, mechanical, electrical and hydraulic testing to be defined in test specifications.

j. Temperatures at the TRP shall be used to verify requirements by analysis and test.

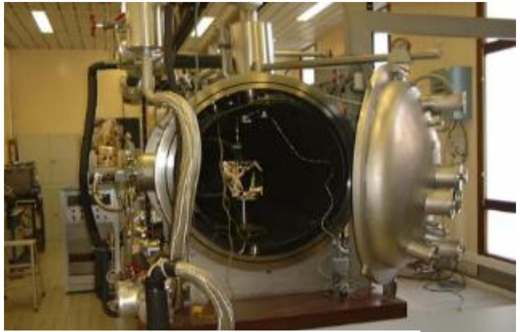


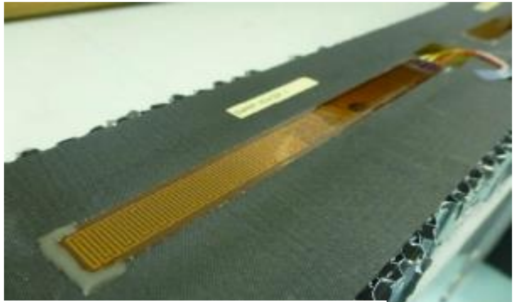
Bepi Colombo STM in LSS



METOP-SG STM in LSS

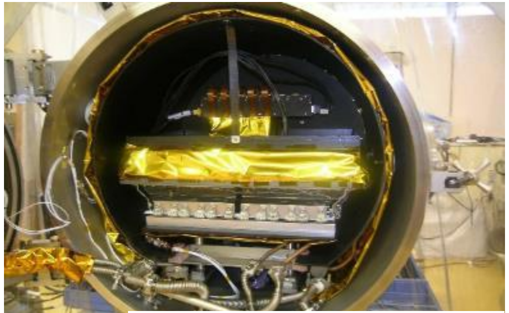
Thermal tests on different levels / items


MLI characterisation test (Herschel)


Heater qualification (SWARM)


AlphaSat thermal test


Magnetorquer qualification test (SWARM)


FPA thermal test (GAIA)

(System) Thermal tests overview

- **Thermal Vacuum Test**

  System level test under vacuum conditions at minimum and maximum - to be expected - temperatures.

- **Thermal Cycle Test**

  Product assurance (PA) test under ambient pressure or vacuum to acceptance (FM) or qualification (QM/PFM) temperature range.

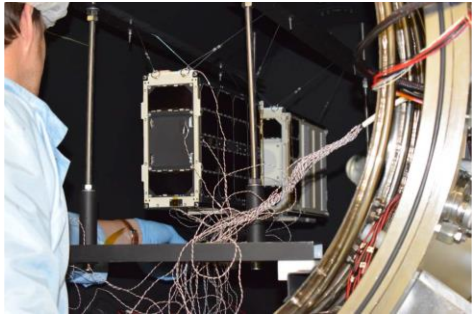
- **Thermal Balance Test**

  Thermal model correlation and thermal design verification

  -> the thermal test

  -> Often these tests are combined

SWARM in IABG 6m thermal chamber



GOMX4A&B in ESTEC MSL LAVAF

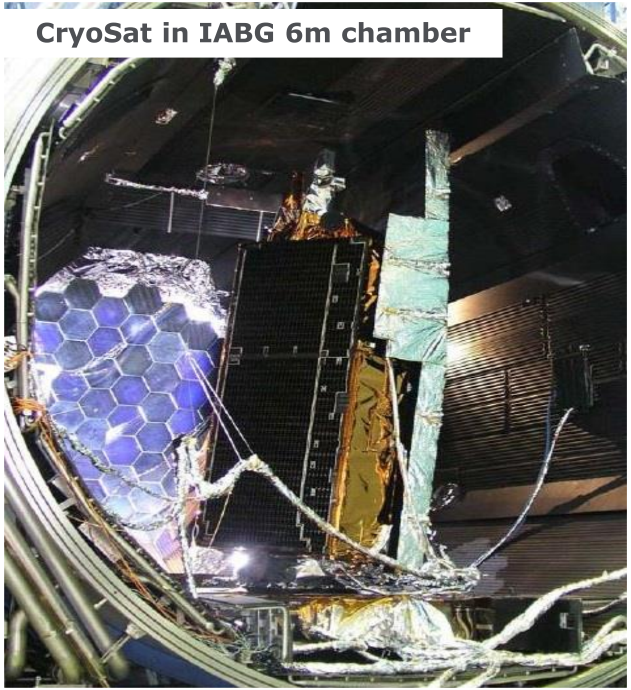
Thermal Vacuum (TVac) Test

Thermal Vacuum Test, also called System Functional Tests (SFT)

Its objective is to demonstrate the **system** ability to fulfil all functional requirements in flight like conditions, i.e. extreme temperatures (over the flight predicted temperature but within the allowed temperature limit) and vacuum.

- All the units must be tested in (individually defined) extreme temperature ranges
- To achieve these objectives, different test means can be used: Flight heaters, test heaters, infrared lamps, Sun simulator, thermal panels / shrouds

-> Temperature limits are more important than flight representativeness

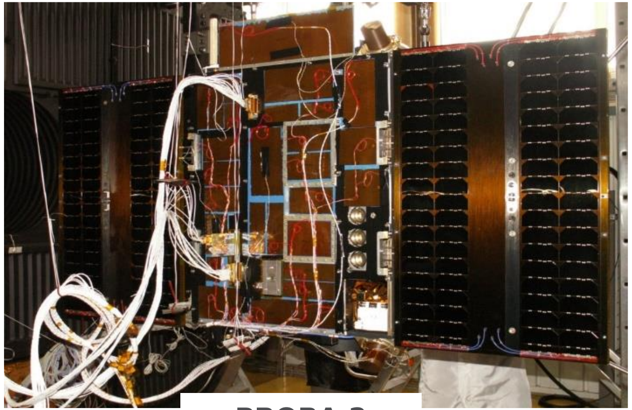


Thermal Cycle (TC) Test

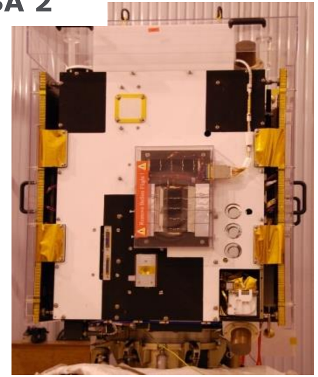
The thermal cycle test

is part of the thermal vacuum test, i.e. has the same main objectives plus: Verify the test item design w.r.t. mechanical stress and workmanship errors.

- for most satellite PFM and CubeSats
  - 1 cycle in non-operational temperature range
  - 3 cycles in operational temperature range
  - Dwell phase at plateaus (2 hours)
  - Stabilization criterion <1K/h
  - Temperature rate of change <20 K/min
- For QMs and subsystem or unit level testing 8 cycles
- Temperatures depend on approach and model (acceptance vs. qualification); result from thermal analysis



PROBA 2



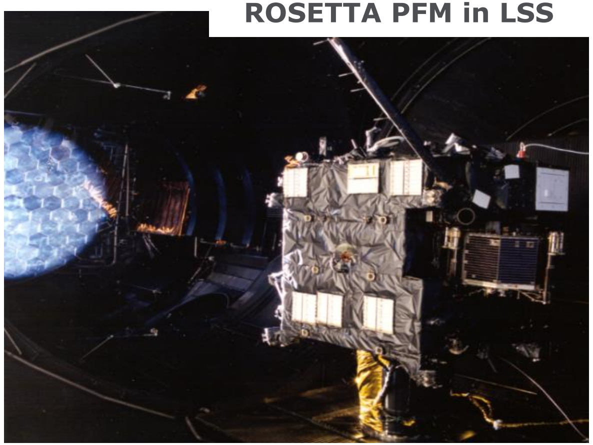
Thermal Balance (TBal) Test

Thermal Balance Test

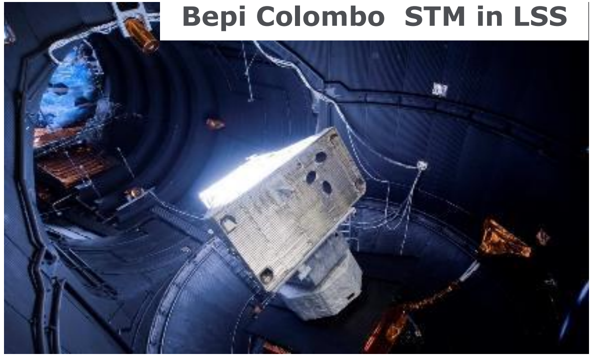
Provides a set of temperature data to correlate the thermal mathematical model and to verify the thermal control subsystem (TCS) design.

- Representativeness of flight thermal conditions
  - environmental worst case conditions (2 to 3 TBal phases)
  - unit dissipations
- Stabilization of temperatures; typical criteria <0.5K/5h for model correlation
- Verifies functionality and performance TCS

ROSETTA PFM in LSS



Bepi Colombo STM in LSS



TBT - ECSS-E-ST-031C

4.5.3.1: TBT test performance

- Need of test specification, procedures, test report and test predictions
- Purpose of TBT to verify
  - Thermal mathematical model
  - Suitability of TCS design
  - Performance of TCS hardware
  - Sensitivity of TCS with respect to parameter changes
- Two different steady-state test cases + transient case
- Solar simulation, when behaviour is governed by solar environment
- Critical hardware flight representative
- Reduction and determination of parasitic heat loads (for correlation)

METOP-SG STM in LSS

CRFP panel with inserts

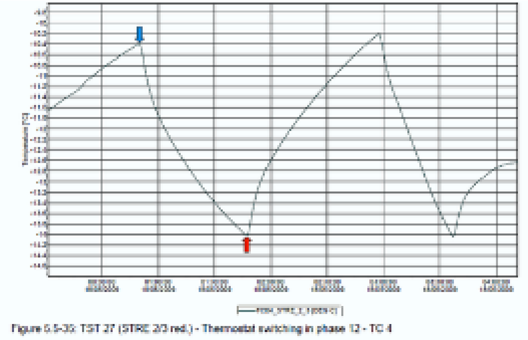
TBT - Thermal Control Verification

CryoSat 2

Thermal balance tests are the unique opportunity to **Validate the Thermal Control Subsystem** (TCS):

- Heating lines verification (switch on/ switch off); appropriate sizing
- Thermostats, thermistors, etc. verification
- Optical surface behavior verification (mainly IR but including solar simulator if necessary)
- Radiator sizing
- heat pipe operation

Example : **CRYOSAT 2** thermostat switch on/ switch off thresholds validation



A thermostat

Requires:

- Representative environmental conditions
- Representative internal dissipation
- Stabilized (or 'balanced') thermal conditions (stable dissipation, heat fluxes and temperatures)
- Accurate knowledge of conditions (calibration of temperature sensors, dissipations, etc.)

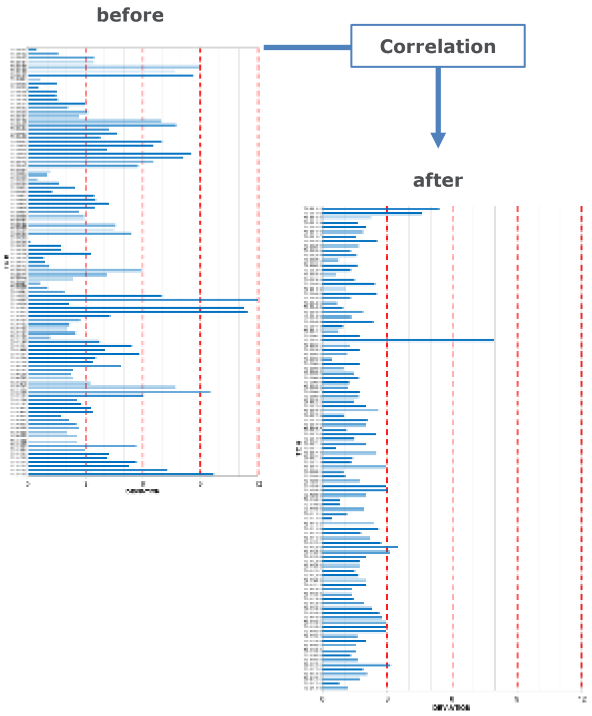
TBT - ECSS-E-ST-031C

TBT test success criteria (clause 4.5.3.2)

- Steady-state conditions, when temperature sensor readings meet predefined temperature variation over a predefined time period (stabilization criteria e.g. <0.5°C/5h)

TBT correlation success criteria (clause 4.5.3.3)

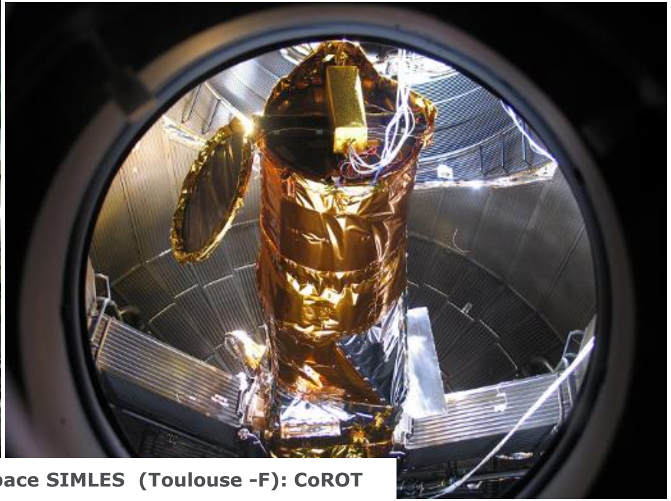
- Test correlation for steady-state and transient modes based for units on unit temperature reference points (TRP)
- Test correlation successful
  - Deviations between measured and predicted temperatures are as specified (typical for internal units <5K, for external units <10K)
  - Temperature mean deviation as specified (typical within ±2K)
  - Temperature standard deviation as specified (typical <3K, 1σ)
  - Deviations between measured and predicted heating / cooling power within specification



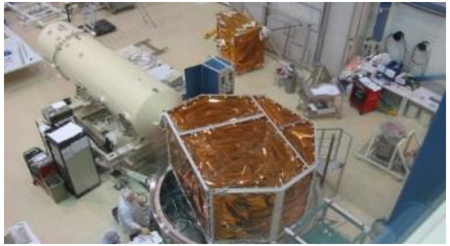
Space Thermal Environment – Thermal Shrouds

Thermal vacuum testing implies the use of **radiative thermal shrouds**

- They can be already existing in the vacuum chamber or,
- be manufactured especially for the test.

Intespace SIMLES (Toulouse -F): CoROT

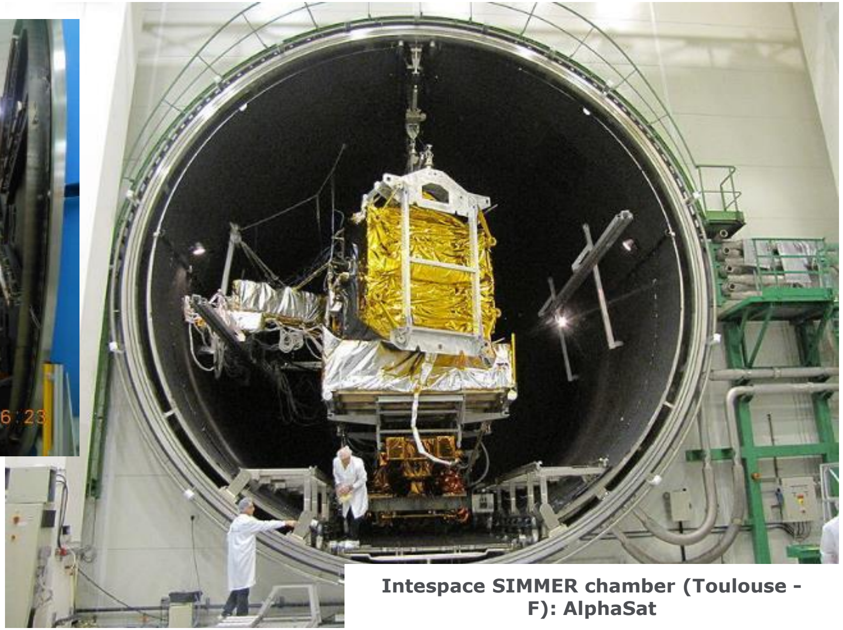



CSL (Liège-B): Thermal shrouds for CoROT Instrument Thermal Test

Space Thermal Environment–Thermal Shrouds

IABG (Ottobrunn - D): Sentinel 2A

TAS-I (Roma - I): Sentinel 1A



Intespace SIMMER chamber (Toulouse - F): AlphaSat

Thermal shroud temperature and emissivity:
It depends of the test item temperature…

$$Q = \sigma V_f A \varepsilon_{eq} (T_{rad}^4 - T_{env}^4)$$

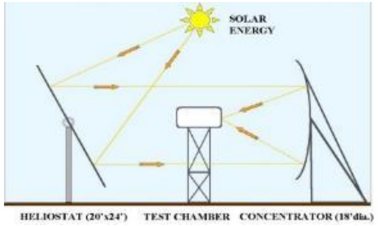
- Black painted (ε=0.8) Liquid N_2 (⇨ -196°C / 77 K) cooled thermal shrouds are suitable for most Spacecraft / Instruments test.
- Helium (⇨ ~ 10 to 50 K) is adequate for passive cryogenics Spacecraft / Instruments.
- Specific highly emissive shrouds (ε=0.8) may be required for extreme low temperature Spacecraft / Instruments.

Space Thermal Environment – Solar Flux

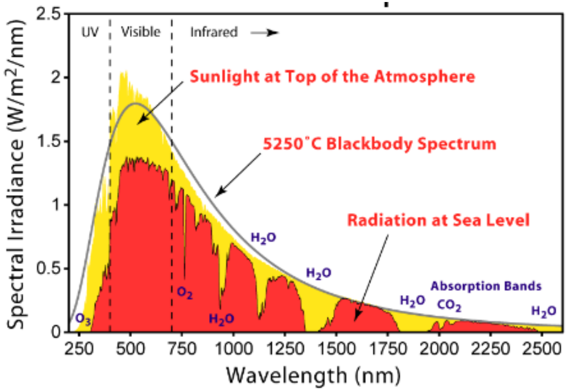
- Real Sun flux may be used for small test item which require high density solar flux for short durations

DLR Solar furnace facility (Köln – D)

NASA Marshall Space Flight Center (MSFC) Solar Furnace Facility

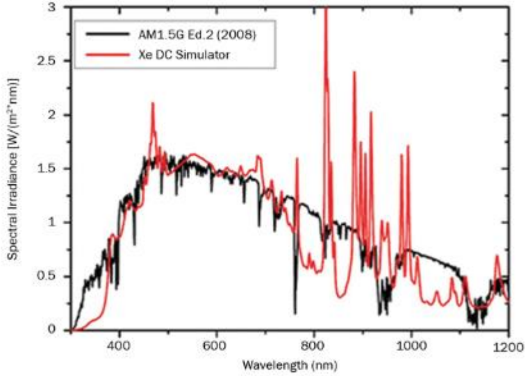


Solar radiation spectrum



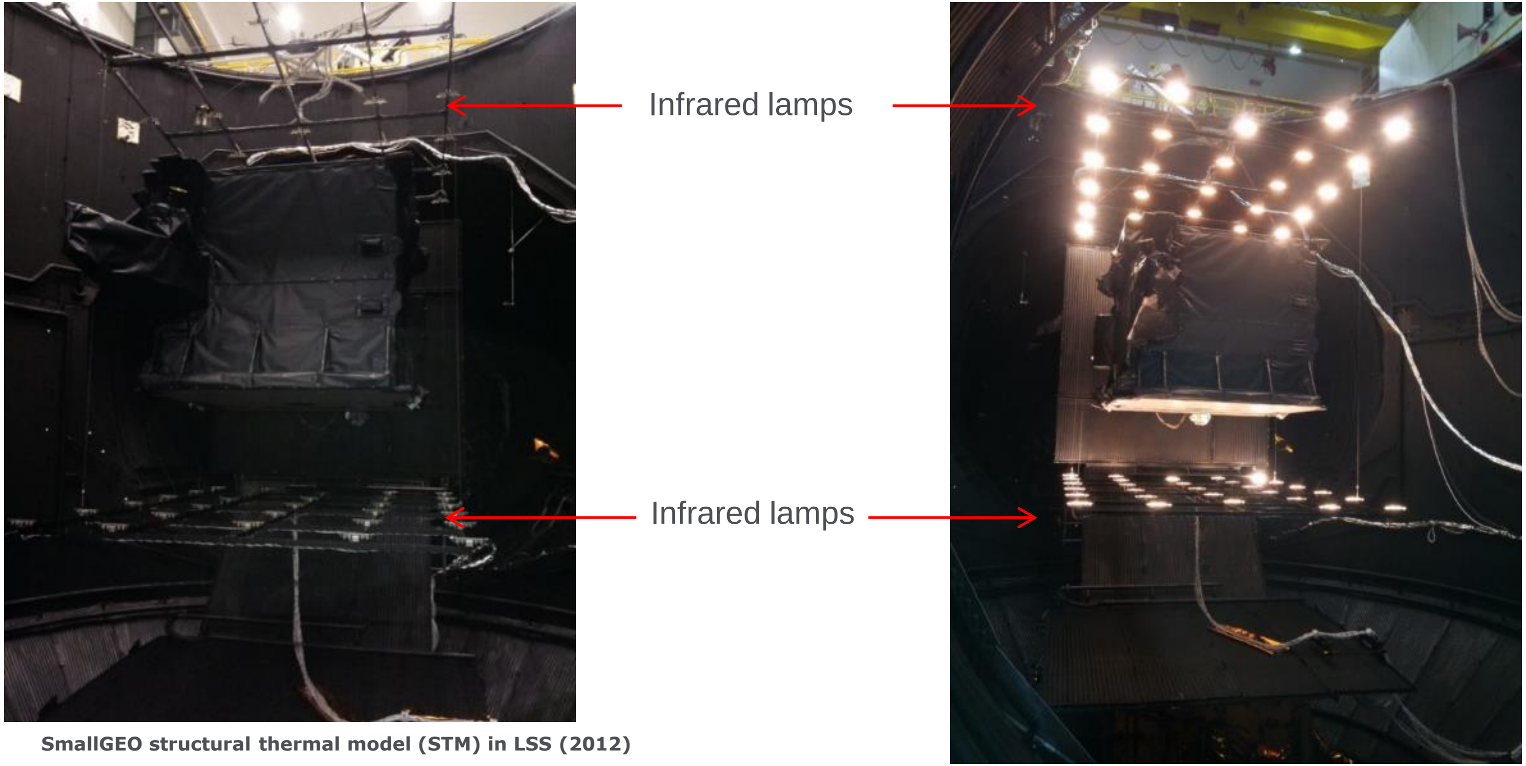
Space Thermal Environment – Sun Simulator

ESTEC LSS (Noordwijk - NL): GOCE



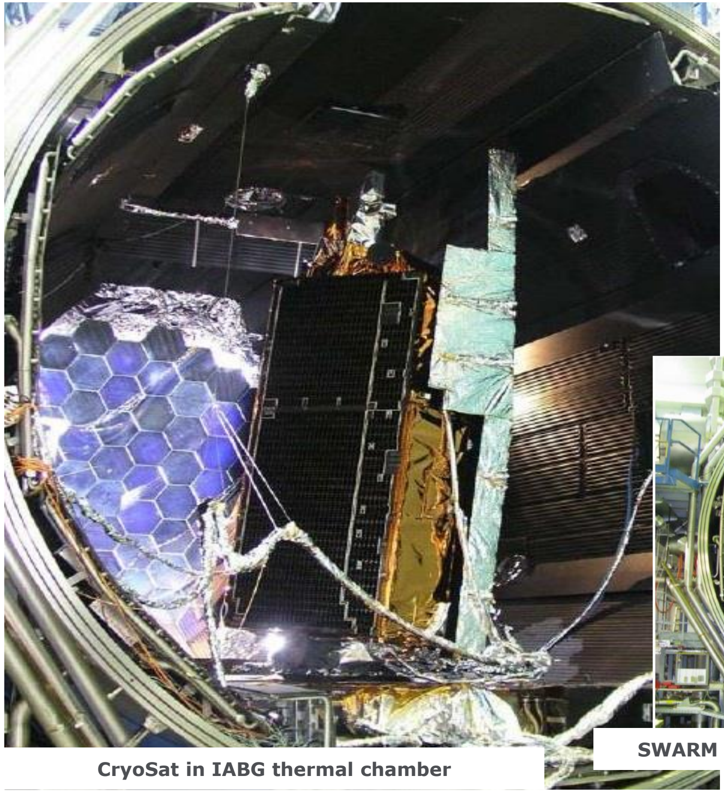
Solar radiation spectrum + Xenon Sun simulator radiation spectrum

Space Thermal Environment – Infrared Lamps

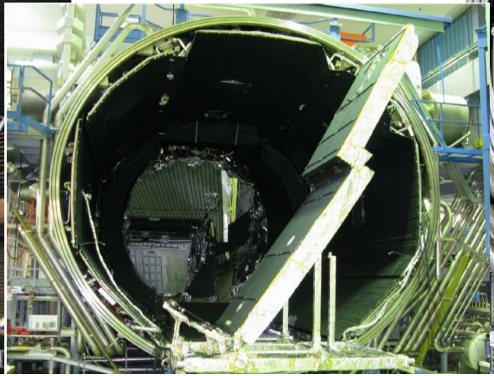


SmallGEO structural thermal model (STM) in LSS (2012)

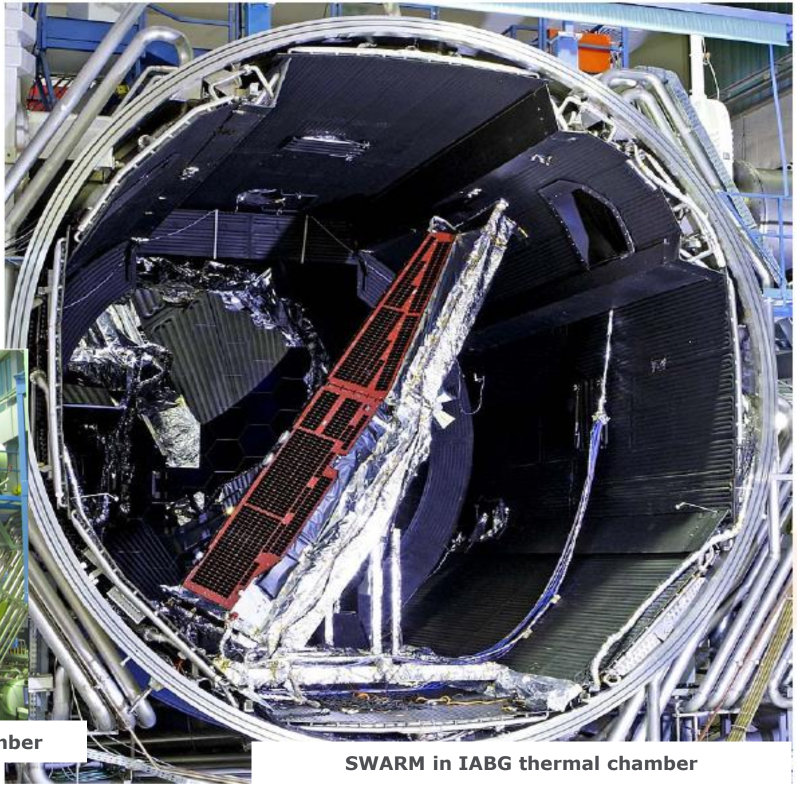
Space Thermal Environment – Thermal Panels



CryoSat in IABG thermal chamber

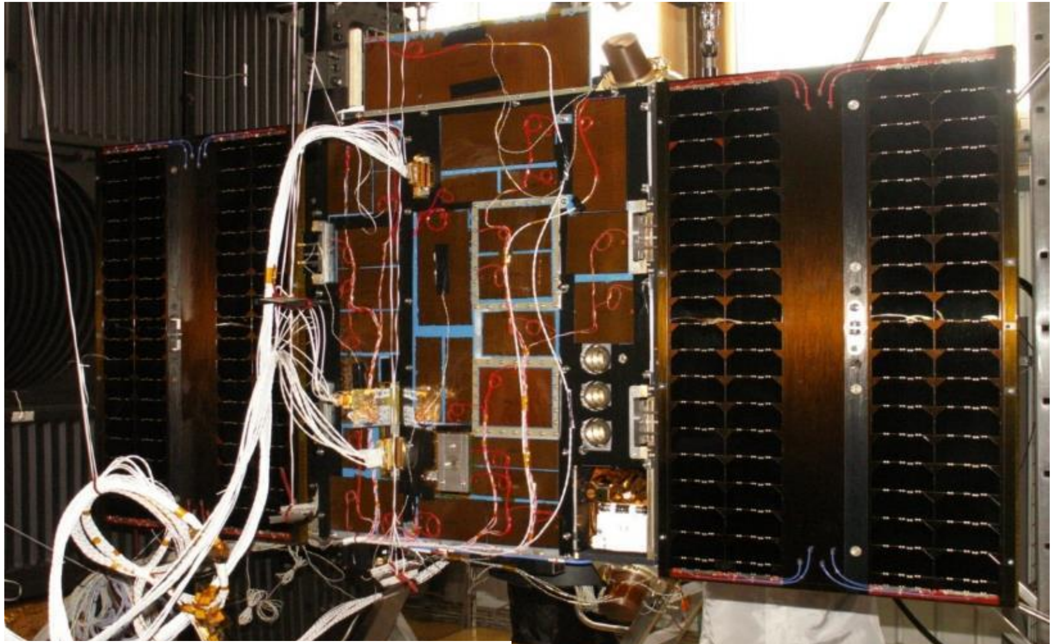


SWARM thermal panels in IABG thermal chamber

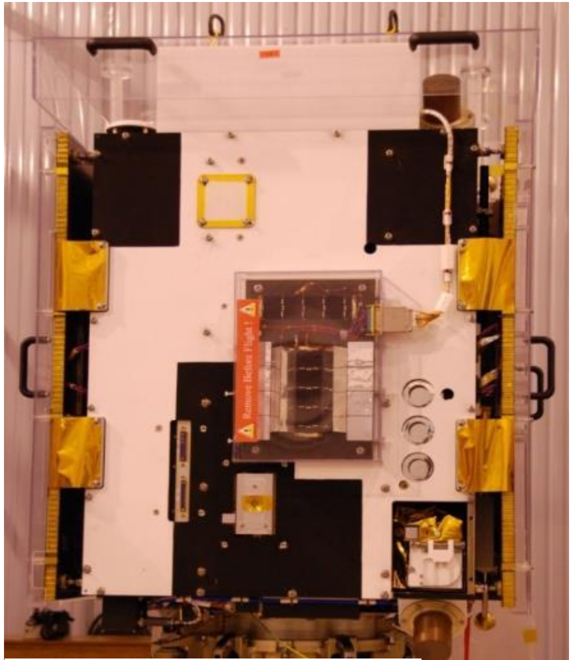


SWARM in IABG thermal chamber

Space Thermal Environment – Test Heaters



PROBA 2 in TV Test configuration



PROBA 2 in Flight configuration

Remaining Aspects

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Remaining Aspects

Production and manufacturing (clause 4.6)

- Procurement
- Manufacturing
- Quality management
- Cleanliness & Contamination
- Integration
- Identification and Marking
- Packaging, handling, transportation
- Storage
- Repair

In-service requirements (clause 4.7)

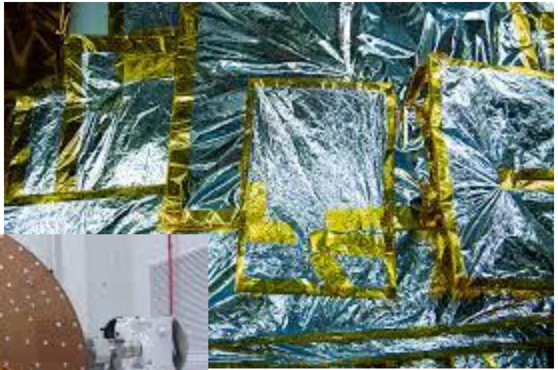
- Spacecraft commissioning, in-orbit anomalies

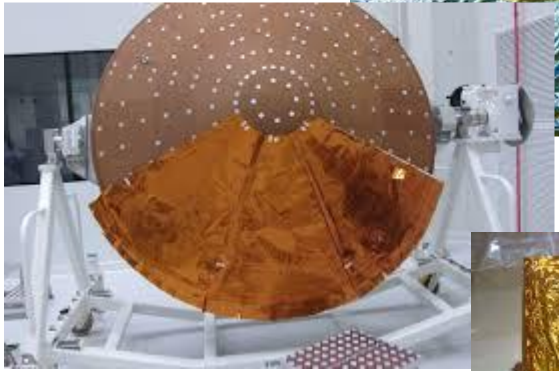
Product assurance (clause 4.8)

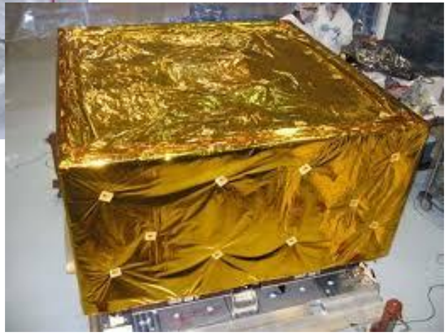
- Reference to dedicated PA ECSS

Deliverables (clause 4.9)

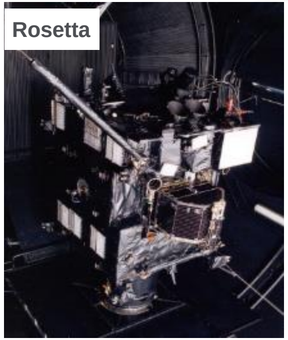
- Hardware, Documentation and mathematical models







Acknowledgments



These slides are based on lectures prepared by my colleagues in TEC-MTT:

- *Philipp Hager, Philippe Poinas, Romain Peyrou-Lauga*

List of acronyms

- ATOX Atomic Oxygen
- BOL Begin-of-Life
- COP Coefficient of performance
- DML Declared material list
- DMPM Declared materials, mechanical parts, and processes list
- EEE Electronic, Electrical and Electro-mechanical parts
- EMC Electromagnetic Compatibility
- EOL End-of-Life
- GEO Geostationary Orbit
- GMM Geometrical Mathematical Model
- GSE Ground Support Equipment
- ICD Interface Control Document
- LEO Low Earth Orbit
- LTAN Local Time of the Ascending Node
- MLI Multi-Layer Insulation
- OSR Optical Solar Reflector
- RHU Radioisotopic heater unit
- RTG Radioisotopic thermal generator
- PMP Parts, materials and processes
- S/C Spacecraft
- SFT System Functional Test
- SSM Second Surface Mirror
- SSO Sun synchronous orbit
- TBal test Thermal Balance Test
- TVac test Thermal Vacuum Test
- TMM Thermal Mathematical Model
- TCS Thermal Control Subsystem
- TRP Temperature Reference Point

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