Spacecraft Thermal Control

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My background

Graduated in 2009, M.Sc. Thesis OUFTI-1 Thermal design

2009-2011: Thermal/mechanical engineer @CSL

- vibration testing, Solar Orbiter EUI/Sun Sensor, terrestrial solar concentrator

2011-2012: YGT @ ESTEC (Advanced Concepts Team)

- Space solar power

2012: ISU SSP @ Florida Tech/NASA KSC

- Space debris

2013-2016: PhD @ ULg S3L / CSL

- Space Thermal Analysis through Reduced Finite Element Modelling

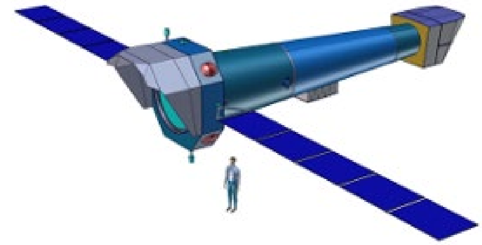
2017: Thermo-mech engineer & Project Manager @ CSL

Thermal control, a mission driver?

ISO (1995-1998†)

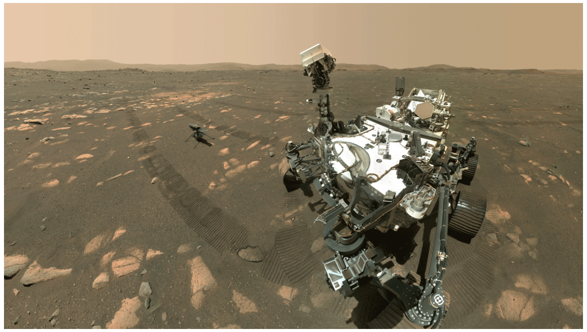
Solar Orbiter (2020)

Athena
(2035)



JWST
(2021)

Planck & Herschel
(2009-2013†) (2009-2013†)



MSL/Curiosity (2011)
Mars2020/Perseverance (2020)

Hubble
(1990)

?
→

S/C thermal design workflow

Scientific/Mission objectives

⬇

Mission parameters & technical requirements

(Orbit, attitude,…) & (Power, temperatures, gradients, stability)

⬇

Thermal control methods & Mathematical modeling

(active vs. passive control) & (worst case approach,…)

⬇

Testing

(thermal balance, thermal cycling, solar simulator,…)

How is it done on Earth?

Objective: computing power

Technical parameter & requirements:

- Intel® Core™ i9-9980XE: TDP (Thermal Design Power) of 165W
- Max junction (die) temperature: 84°C

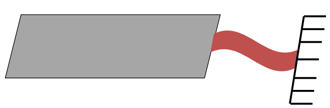
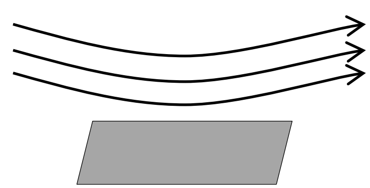
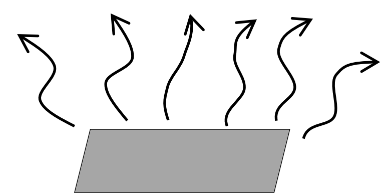
Thermal control system:

- Porous heat-pipe
- Air-cooled radiator (fan)

First,…

Some theoretical background

3 → 2 heat transfer mechanisms!

	Conduction	~~**Convection**~~	**Radiation**
Material parameters	Thermal conductivity	Convective heat transfer coefficient, fluid properties	Thermo-optical properties
Geometric parameter	Cross section, length	Surface area	Surface area, view-factor
Distance	low	medium	∞
2 nodes equation	$Q = k\frac{S}{L}(T_2 - T_1)$	$Q = hA(T_2 - T_1)$	$Q = GR\sigma(T_2^4 - T_1^4)$
Example: 100 x 100 mm² $Q = 10\ \mathrm{W}$ $T_{env} = 20\ °\mathrm{C}$	Copper strap, $k = 390\ \mathrm{W/mK}$ $S = 50\ \mathrm{mm}^2$ $L = 100\ \mathrm{mm}$  $T = 71°\mathrm{C}$	Wind speed: 1m/s $h{\sim}50\ W/m^2K$  $T = 40°\mathrm{C}$	view factor: 1 Emittance: 1  $T = 125°\mathrm{C}$

Conductive heat transfer

Material property: thermal conductivity k [W/mK]

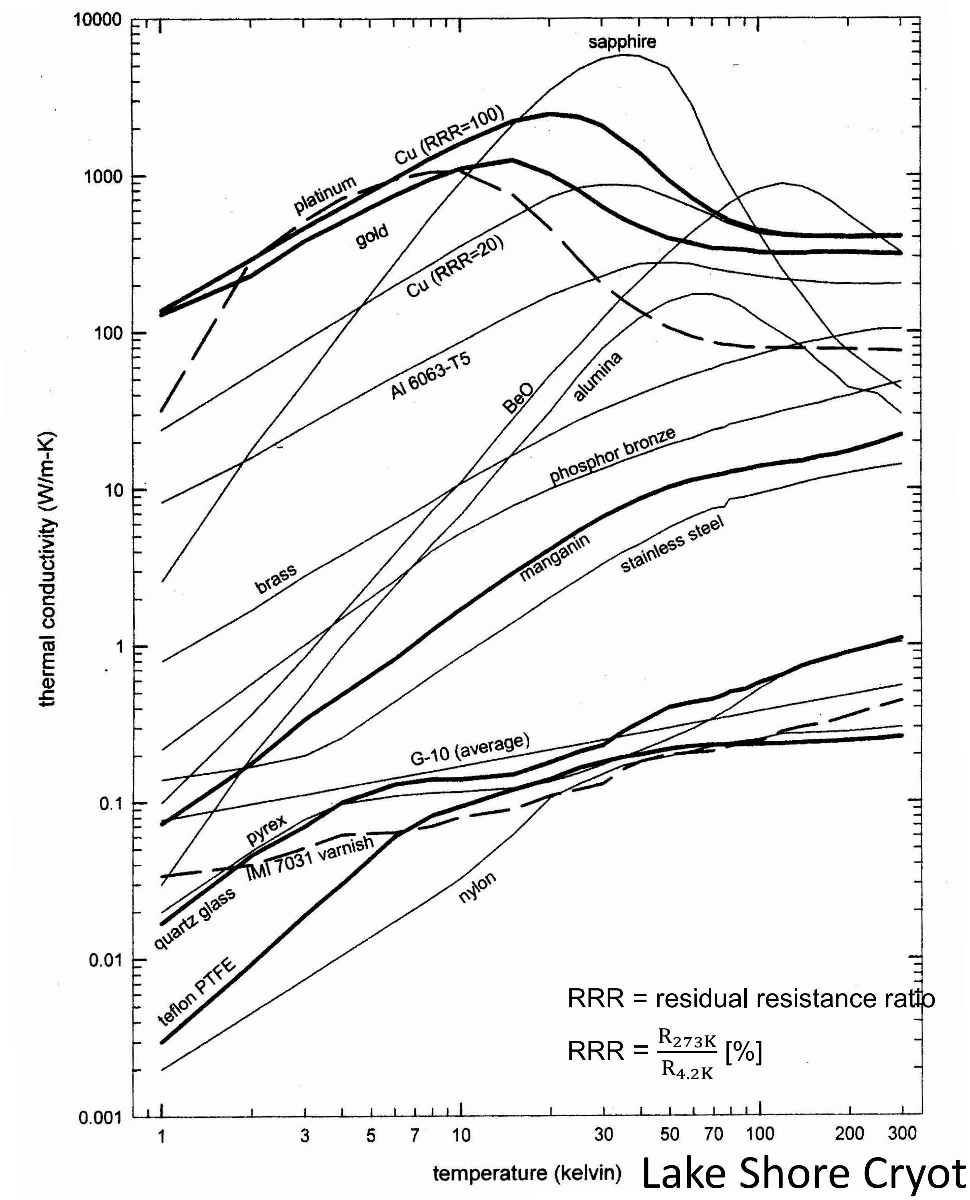
Mechanism:

- through electrons: mostly in electrical conductors
    - ex: Aluminium, (~150-200 W/mK @ 300K), Copper (~390 W/mK @ 300K)
    - relationship between electrical and thermal conductivity: Wiedemann–Franz law

$$\frac{k}{\sigma} = LT$$

- through phonons (lattice vibrations): mostly in electrical insulators
    - ex: Aluminium Nitride (AlN 180 W/mK @ 300K), Silicon Carbide (SiC, ~120 W/mK @ 300K)

Thermal conductivity varies with T!

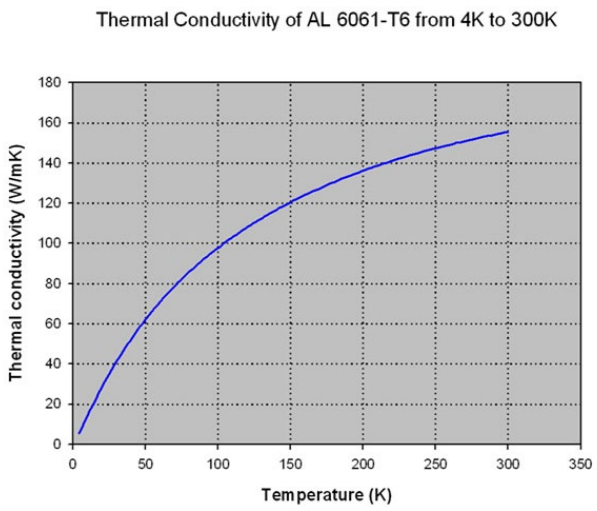


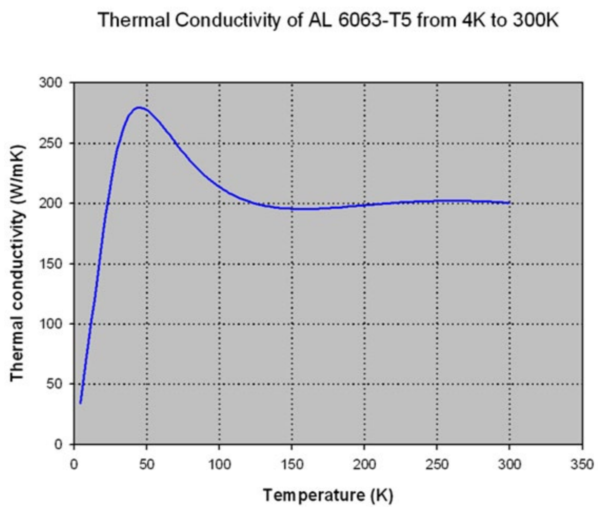
RRR = residual resistance ratio

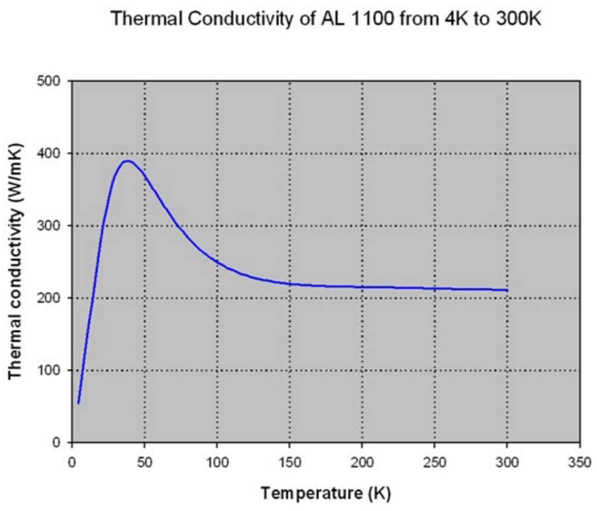
$$RRR = \frac{R_{273K}}{R_{4.2K}} [\%]$$

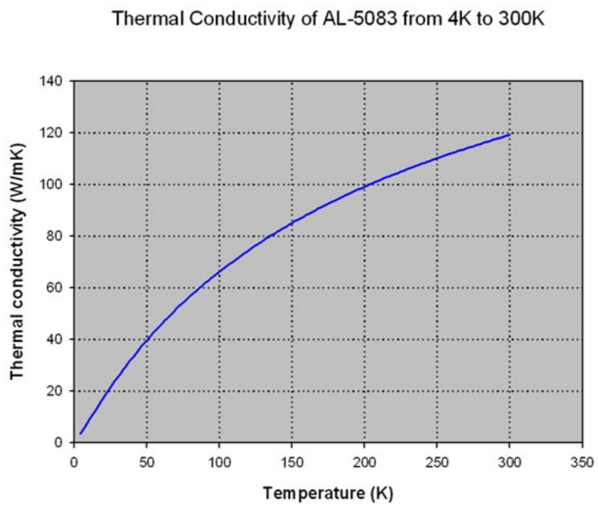
Lake Shore Cryotronics, Inc.

The exact alloy please!









Radiative heat transfer

Material property: surface thermo-optical properties

Mechanism: photons emission and absorption

Every medium continuously emits electromagnetic radiation into all directions at a rate depending on the local temperature and on the properties of the material.

Photon's energy:

$$\varepsilon = \frac{hc_0}{\lambda n}$$

Integrating Planck's Law

Planck's law (1901): black body-emissive power

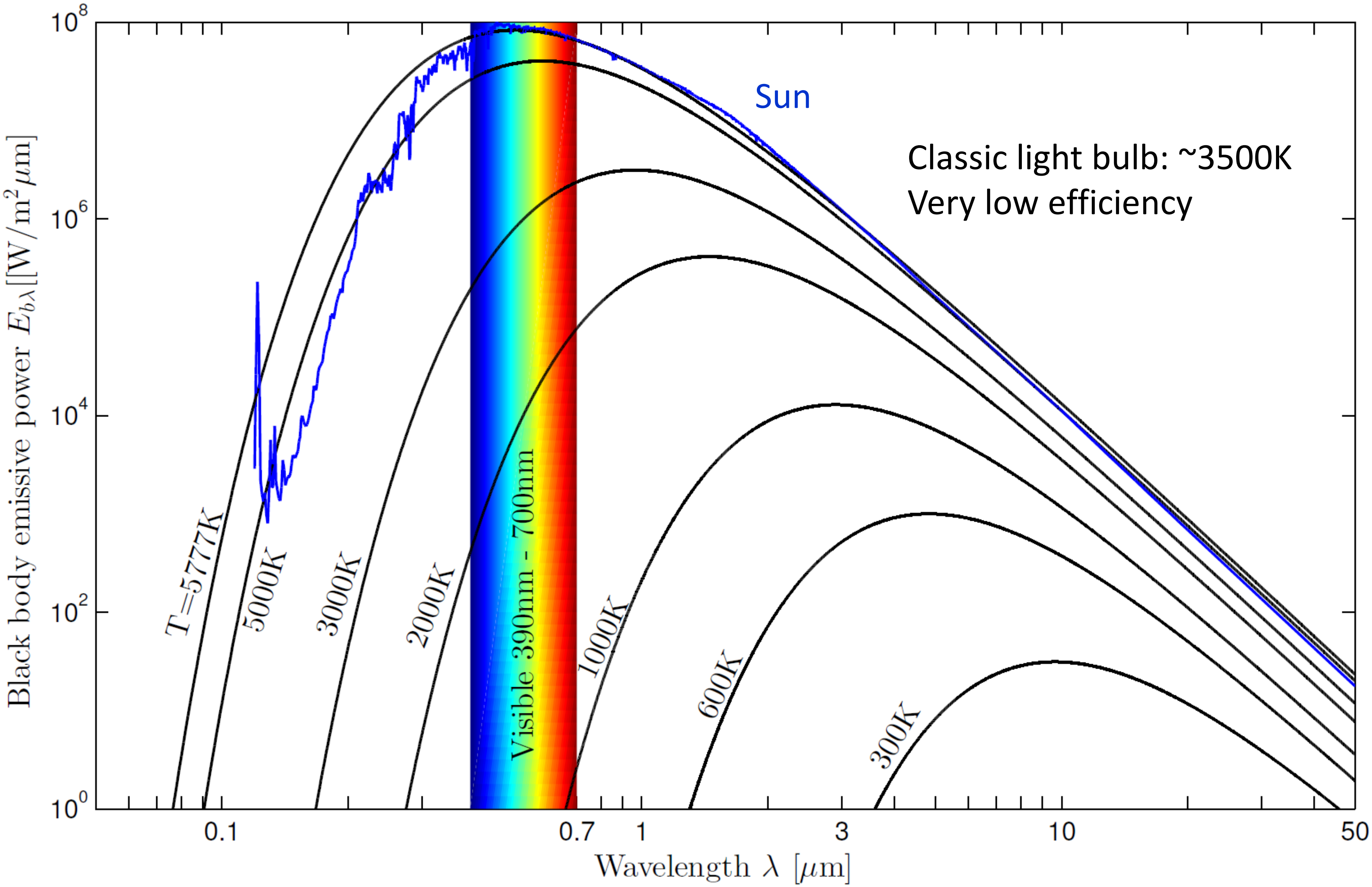
$$E_{b\lambda} = \frac{2\pi h c_0^2}{n^2 \lambda^5 \left(e^{\frac{h c_0}{n \lambda k T}} - 1\right)}$$

$$E_b = \int_0^\infty E_{b\lambda} d\lambda = \int_0^\infty \frac{2\pi h c_0^2}{n^2 \lambda^5 \left(e^{\frac{h c_0}{n \lambda k T}} - 1\right)} d\lambda = n^2 \boxed{\frac{2\pi^5 k^4}{15 h^3 c_0^2}} T^4$$

$$E_b = n^2 \sigma T^4$$

σ = Stefan Boltzmann's constant $= 5.67\ 10^{-8}\ W/m^2K^4$

Thermal spectrum



Thermo-optical properties

$$\text{reflectance } \rho \equiv \frac{\text{reflected part of incoming radiation}}{\text{total incoming radiation}}$$

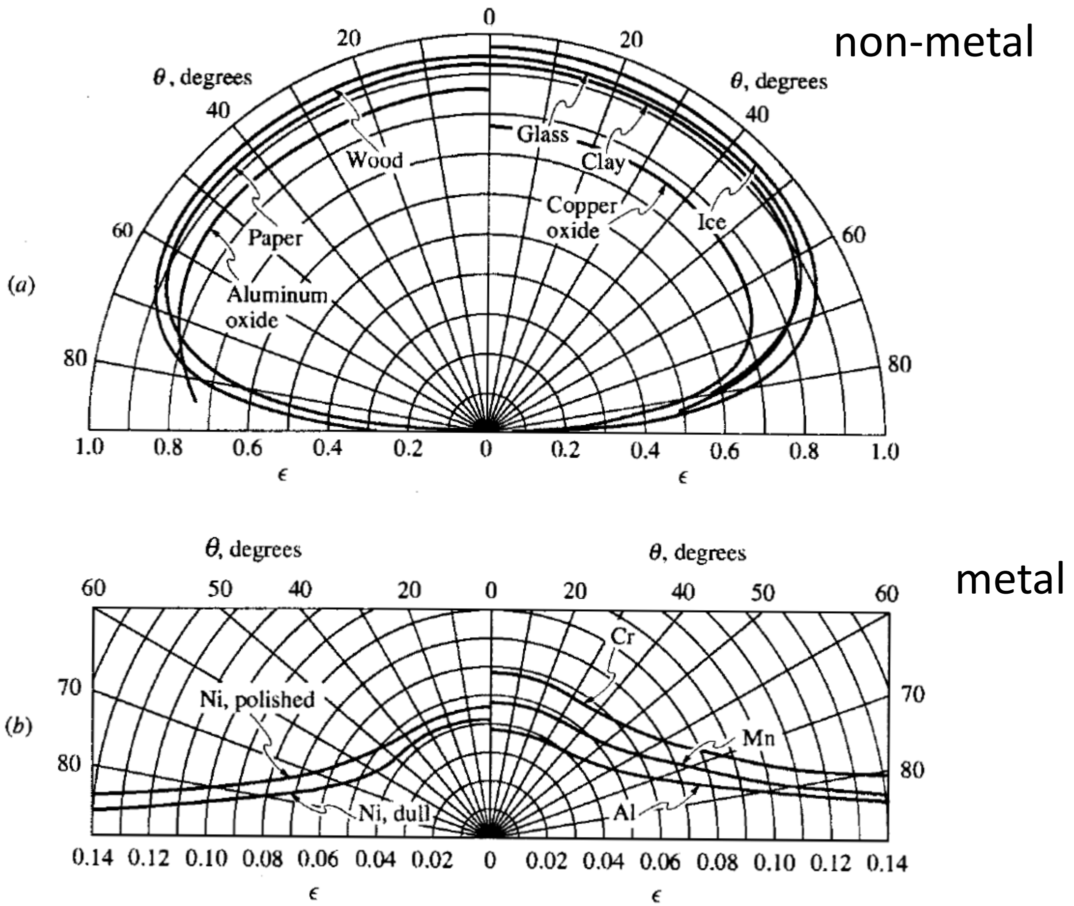
$$absorptance\ \alpha \equiv \frac{\text{absorbed part of incoming radiation}}{\text{total incoming radiation}}$$

$$transmittance\ \tau \equiv \frac{\text{transmitted part of incoming radiation}}{\text{total incoming radiation}}$$

$$emittance\ \epsilon \equiv \frac{\text{energy emitted from a surface}}{\text{energy emitted by an ideal black surface at the same temperature}}$$

Black body = body that absorbs all incident radiation regardless of direction or wavelength

Thermo-optical properties depend on direction

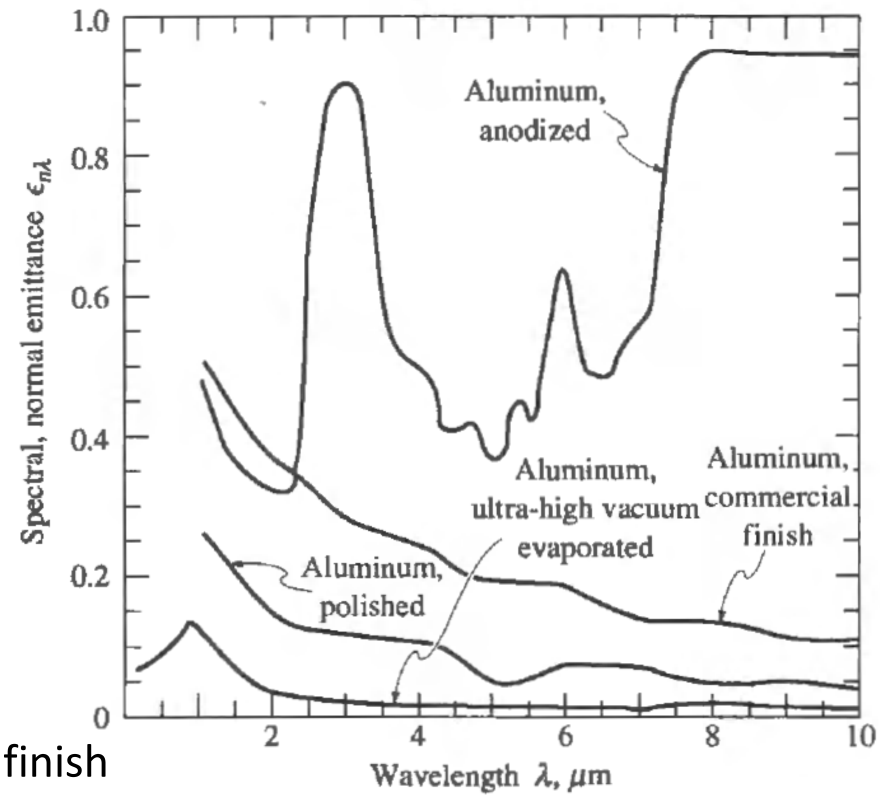


Emittance usually higher and smoother for non metals

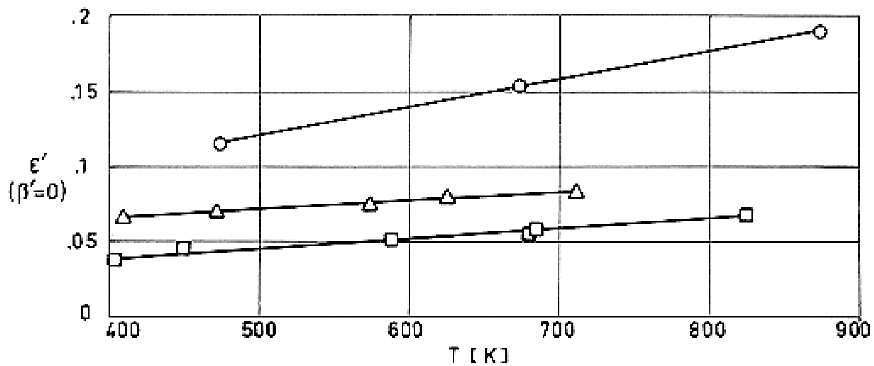
Emittance of metals usually high at grazing angles before dropping back to zero (not shown)

But also on wavelength, T°, surface finish

wavelength



Temperature & surface finish



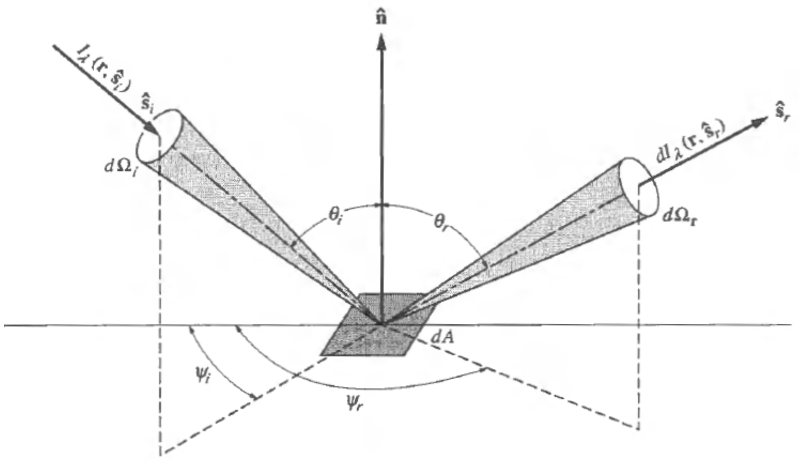
Key	Description
○	Cleaned, polished, and oxidized.
□	Pure. Highly polished.
△	Pure. Rolled, as received.

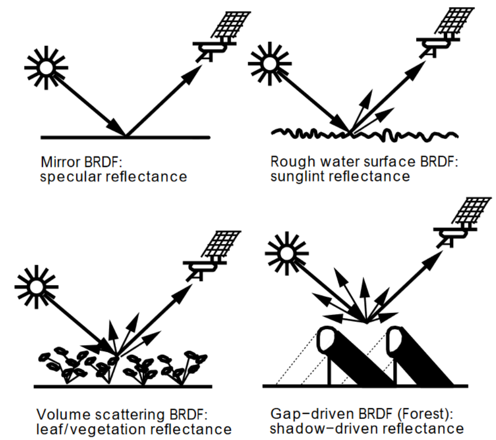
What's a BSDF?

BSDF = Bidirectional scattering distribution function

The reflectance/transmittance depends incident and reflected directions

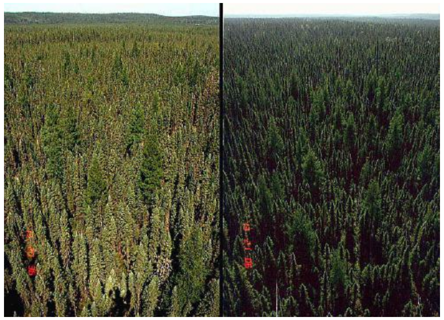
$$\tau''_\lambda \text{ or } \rho''_\lambda(T, \lambda, \theta_i, \psi_i, \theta_r, \psi_r)$$



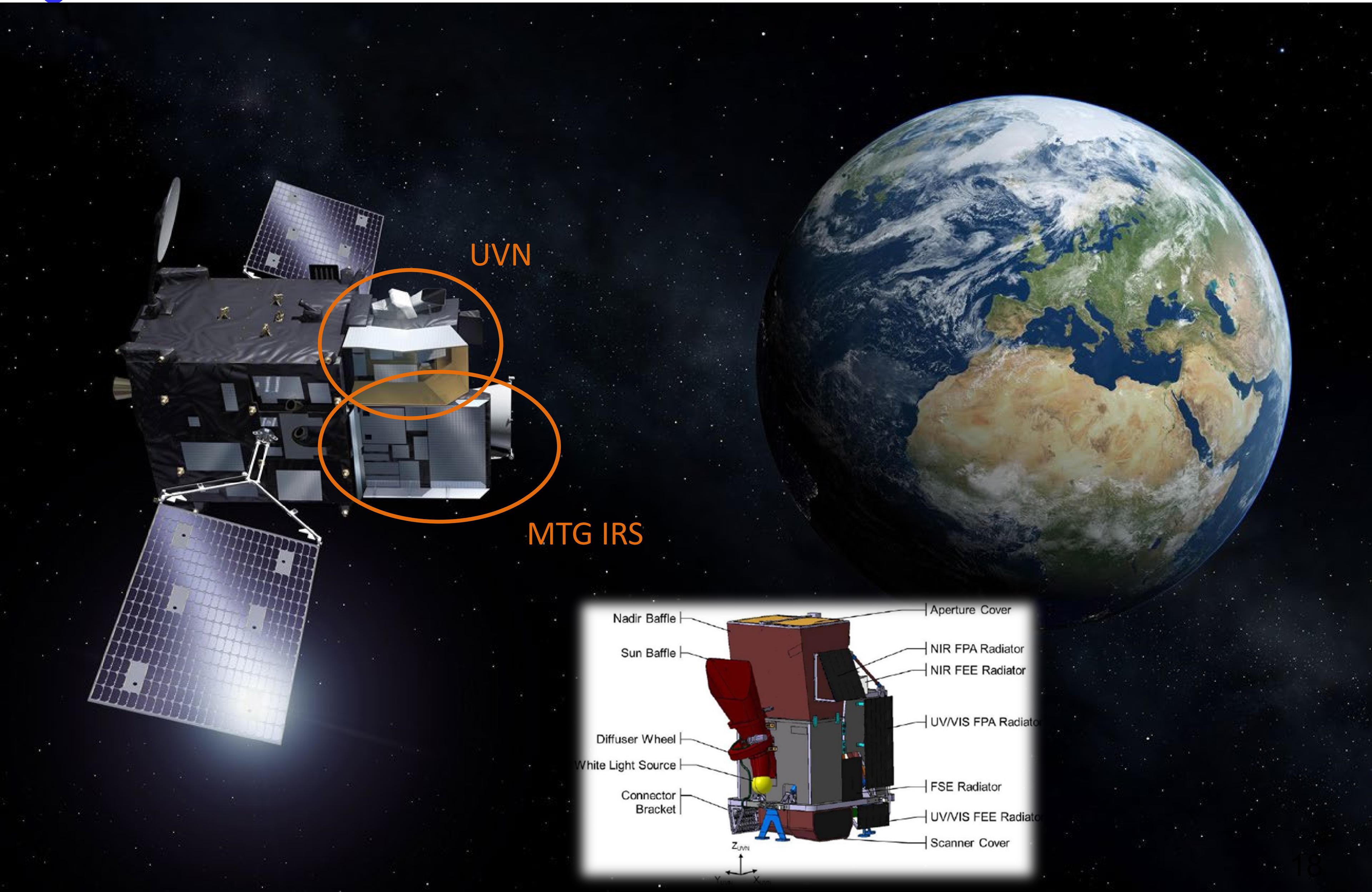


Widely used to analyze data from Earth observation satellites:

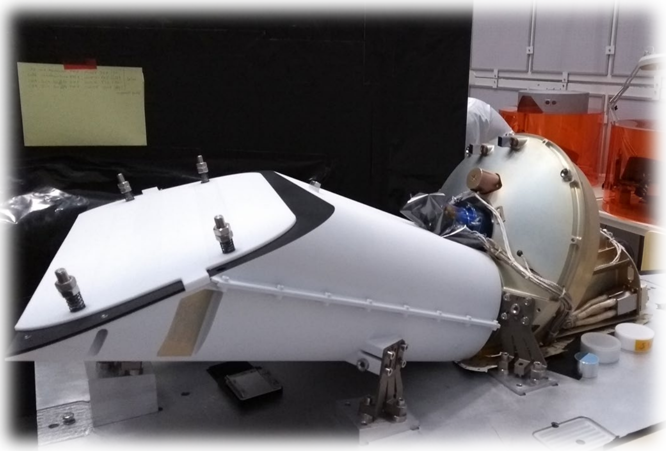
BRDF of plants canopy

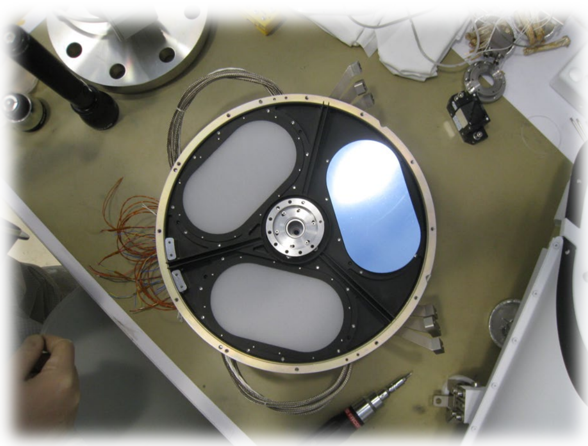


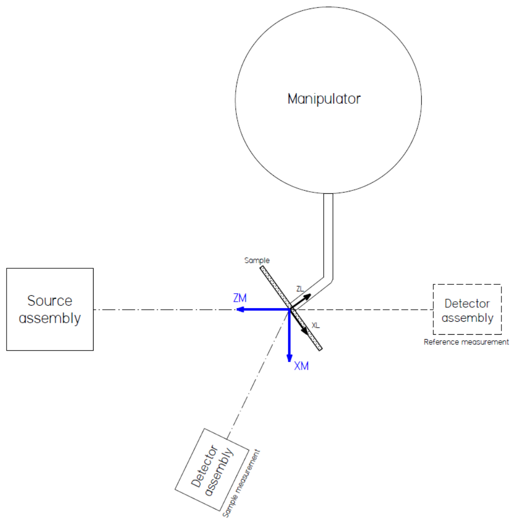
BTDF on Sentinel 4 - UVN

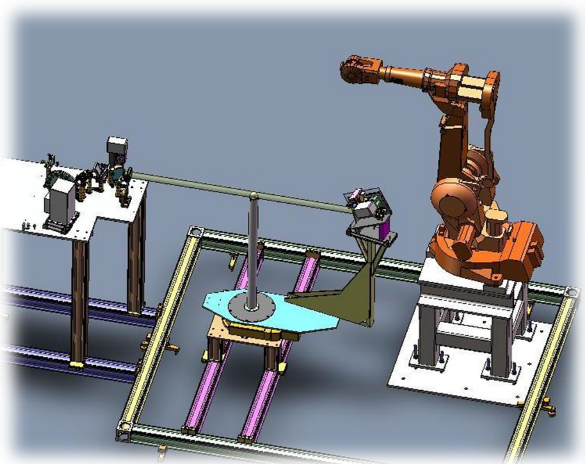


BSDF used for in-flight calibration

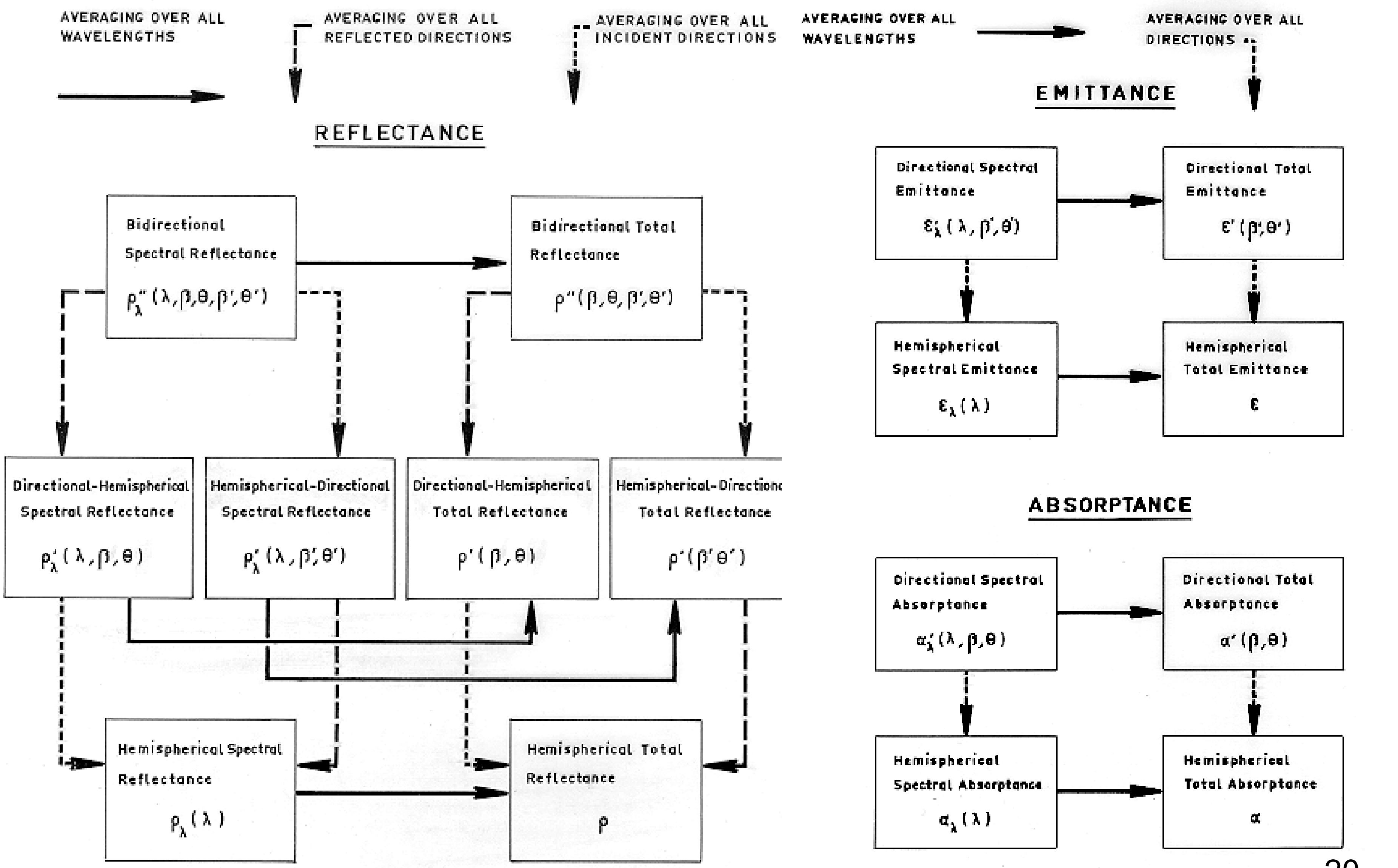








Spectral, directional → total, hemispherical



Conservation of energy & Kirchhoff's Law (1860)

The energy incoming a surface must either be absorbed, reflected or transmitted:

$$\alpha'_\lambda(T,\lambda,\theta,\phi) + \rho'_\lambda(T,\lambda,\theta,\phi) + \tau'_\lambda(T,\lambda,\theta,\phi) = 1$$

Kirchhoff's law:

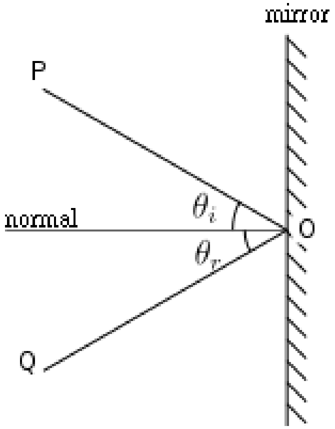
$$\alpha'_\lambda(T,\lambda,\theta,\phi) = \epsilon'_\lambda(T,\lambda,\theta,\phi)$$

Diffuse and specular surfaces

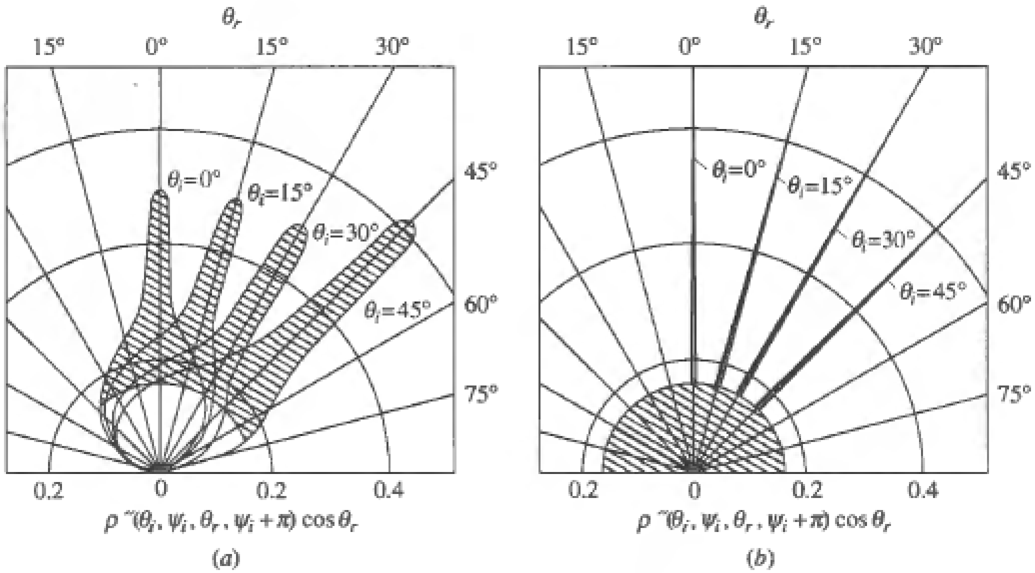
Measuring spectral, directional quantities is difficult

Simplification: assume that the surface has two components:

- specular: Snell's Law
- diffuse: independent of the direction



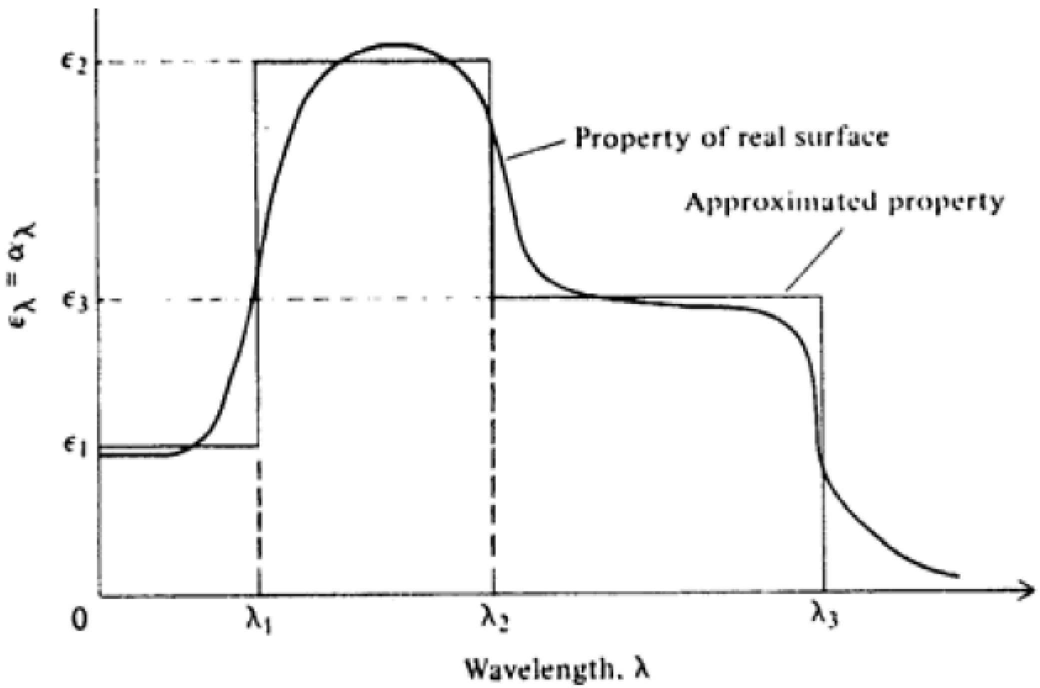
$$\rho = \rho_s + \rho_d$$



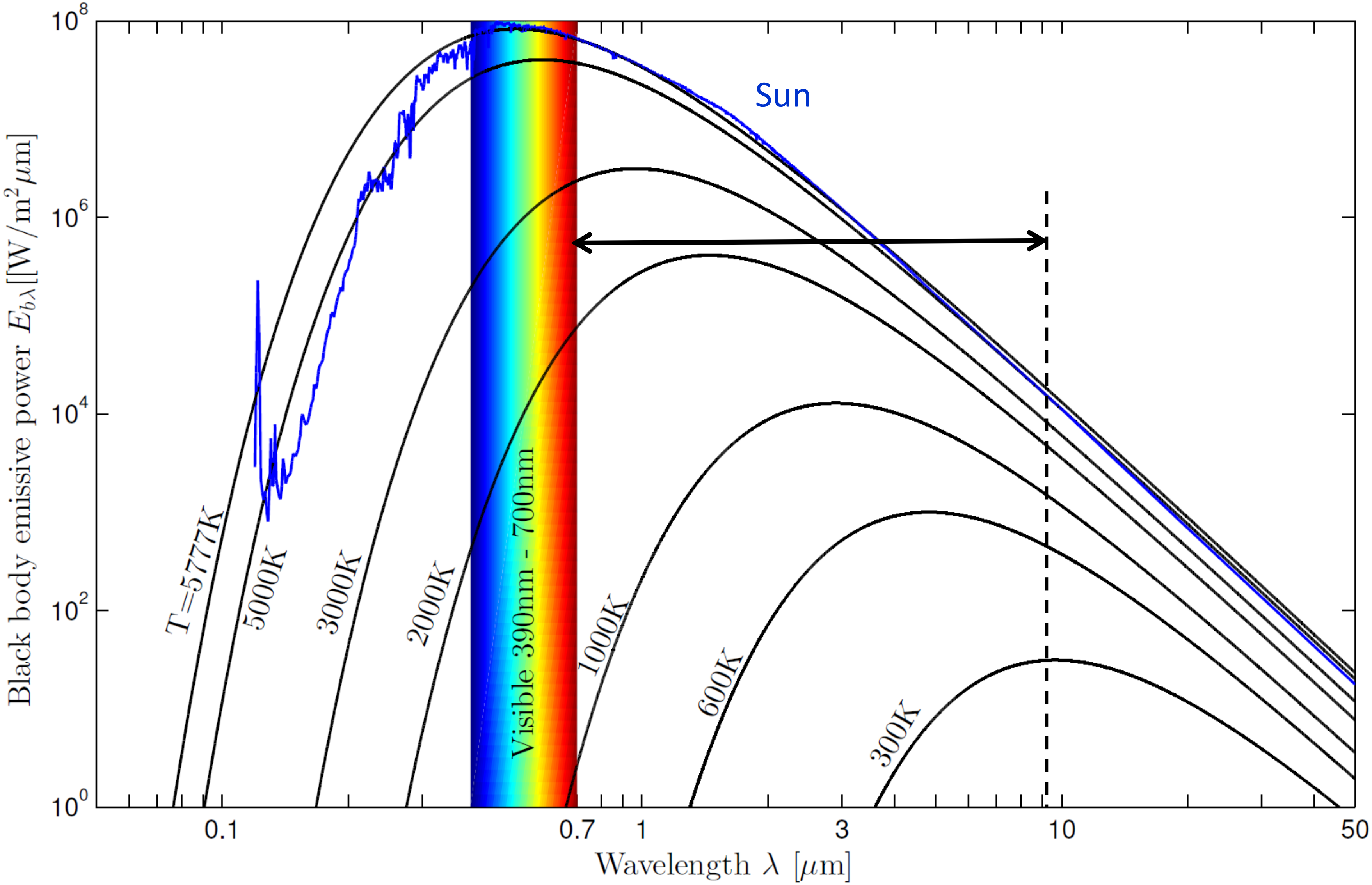
Grey surface assumptions

α and ϵ are independent of the wavelength

What is usually done is a semi-grey approximation:



Thermal spectrum



S/C thermal engineer convention

Dissociate two spectral ranges:

- "visible": 250-4000 nm, 99% of Sun's emissive power
- Infrared: 4-40μm, 95% of 300K black body emissive power

$$\alpha(T, \lambda, \theta, \phi) = \alpha'_{\lambda,\text{visible}}(T, \lambda, \theta, \phi) = \epsilon'_{\lambda,\text{visible}}(T, \lambda, \theta, \phi)$$

$$\epsilon(T, \lambda, \theta, \phi) = \alpha'_{\lambda,\text{IR}}(T, \lambda, \theta, \phi) = \epsilon'_{\lambda,\text{IR}}(T, \lambda, \theta, \phi)$$

Kirchoff's & conservation of energy law in both spectral ranges:

$$\alpha_{VIS} + \rho_{VIS,s} + \rho_{VIS,d} + \tau_{VIS} = 1$$

$$\epsilon_{IR} + \rho_{IR,s} + \rho_{IR,d} + \tau_{IR} = 1$$

α / ϵ ECSS definition

ECSS = European Cooperation for Space Standardization

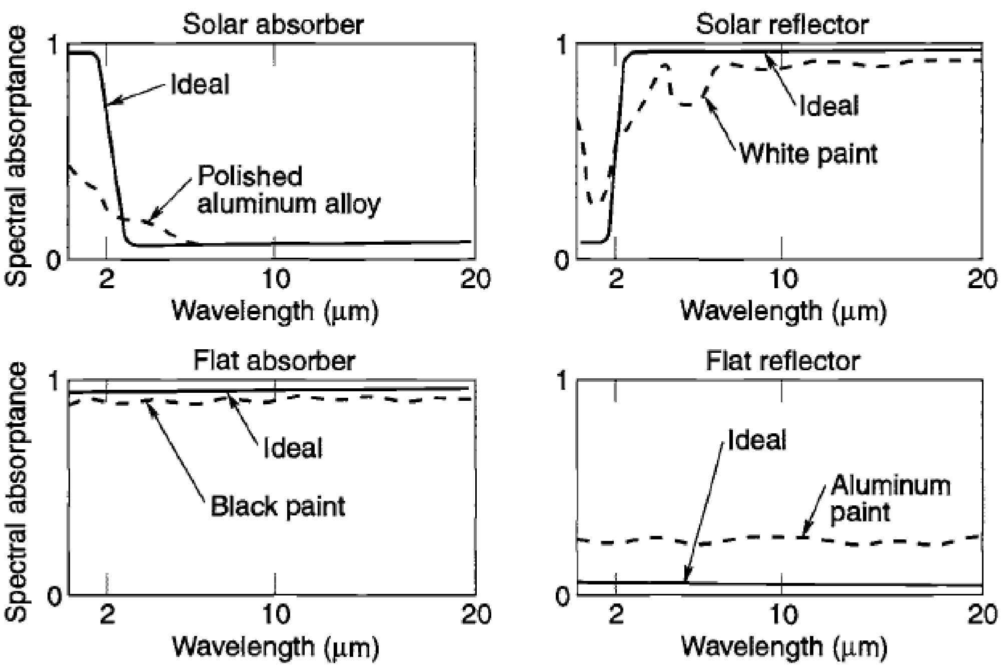
$$\alpha_{VIS} = \frac{\int_{\lambda_{1,vis}}^{\lambda_{2,vis}} \alpha_\lambda(\lambda) S(\lambda) d\lambda}{\int_{\lambda_{1,vis}}^{\lambda_{2,vis}} S(\lambda) d\lambda} \qquad \epsilon_{IR} = \frac{\int_{\lambda_{1,IR}}^{\lambda_{2,IR}} \epsilon_\lambda(\lambda) E_{b\lambda}(\lambda) d\lambda}{\int_{\lambda_{1,IR}}^{\lambda_{2,IR}} E_{b\lambda}(\lambda) d\lambda}$$

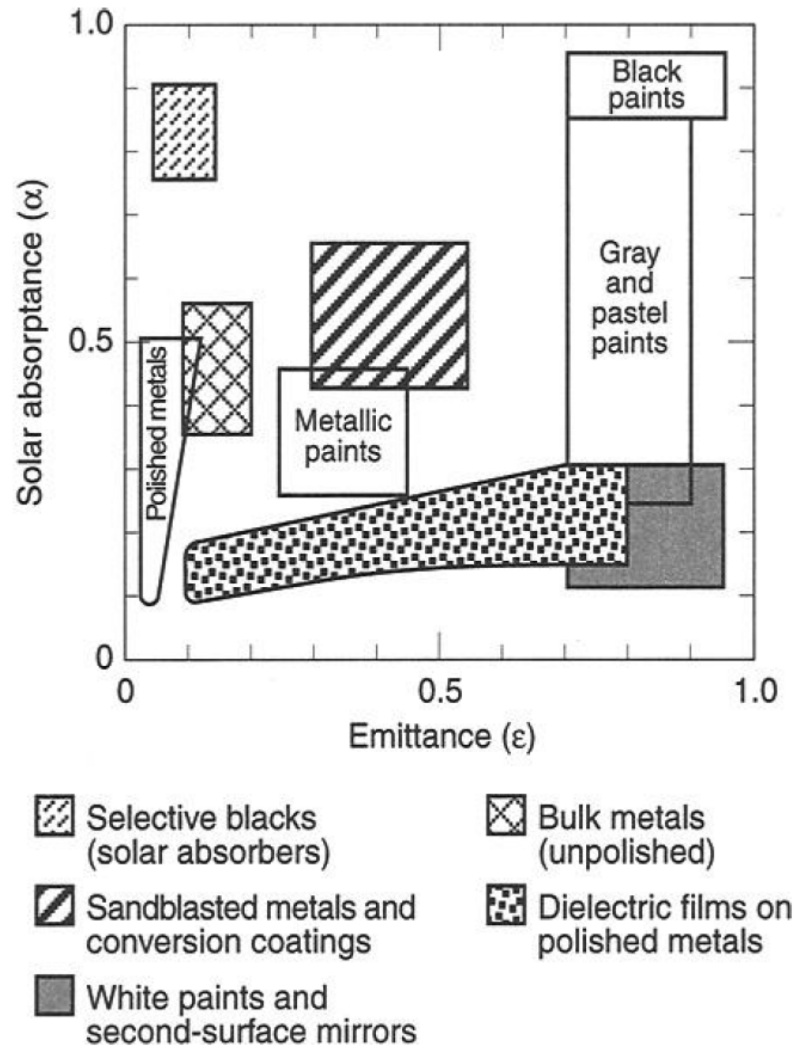
$S(\lambda)$ $[W/m^2\mu m]$: spectral solar irradiance, $[\lambda_{1,vis},\ \lambda_{2,vis}] = [0.25, 2.5]\mu m$

$E_{b\lambda}(\lambda)$ $[W/m^2\mu m]$: 300K BB emissive power, $[\lambda_{1,IR},\ \lambda_{2,IR}] = [3, 20]\mu m$

Attention if wide T° ranges (ex: $\epsilon \rightarrow \alpha$ at high T°)

Wide range of α / ϵ combinations



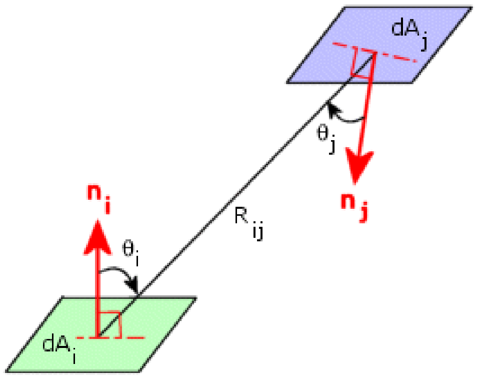


How to model radiative heat exchanges?

View factor: only geometry

$F_{ij} \equiv$ fraction of the diffuse energy leaving surface i that is directly intercepted by surface j

$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi r_{ij}^2} \chi_{ij} dA_j dA_i$$



Radiative exchange factor: geometry + surface properties

$B_{ij} \equiv$ fraction of the total energy emitted by surface i that is absorbed by surface j

either directly or after any number or type of reflections/transmissions

Question: can $B_{ij} \neq 0$ if $F_{ij} = 0$?

How to use F_{ij} or B_{ij}?

Heat exchange between two surfaces i and j:

$$Q_{ij} = GR_{ij}\sigma\left(T_i^4 - T_j^4\right)$$

$$GR_{ij} = \epsilon_i A_i B_{ij}$$

F_{ij} can be used directly with black-body surfaces (no reflections) $\alpha = \epsilon = 1$

and $B_{ij} = F_{ij}$.

If isothermal, diffuse, uniformly irradiated grey surfaces: Gebhart's method (1957):

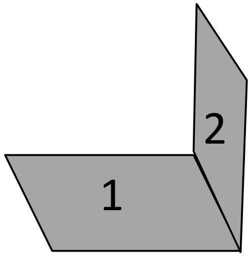
$$B_{ij} = F_{ij}\epsilon_j + \sum_{k=1}^{N} F_{ik}(1 - \epsilon_k)B_{kj}$$

Or in matrix form, with $\beta_{ij} = F_{ij}\epsilon_j$:

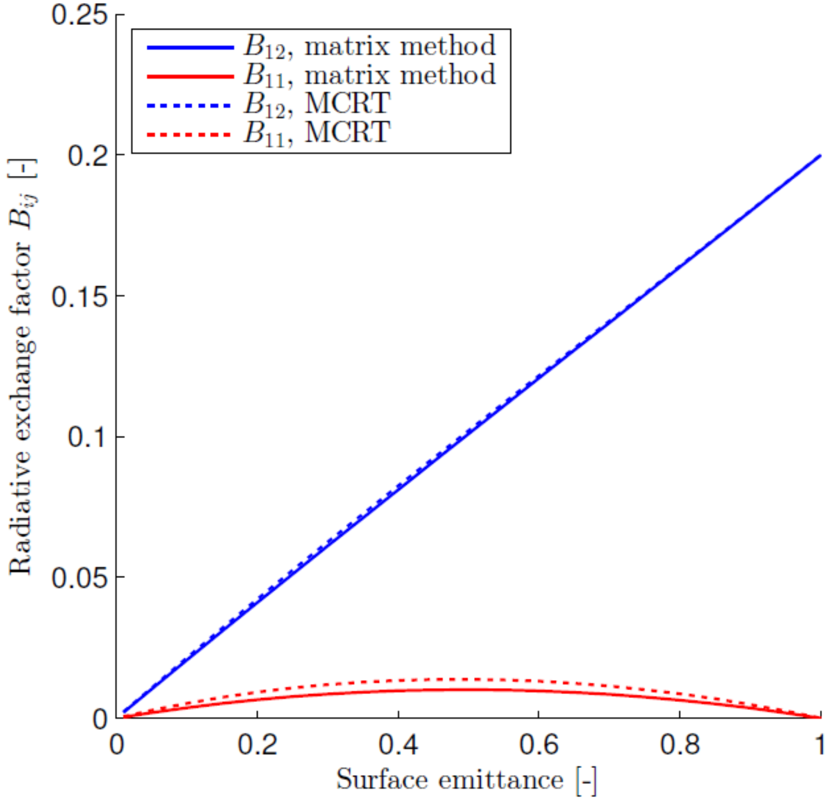
$$\boldsymbol{B} = (\boldsymbol{I} + \boldsymbol{\beta} - \boldsymbol{F})^{-1}\boldsymbol{\beta}$$

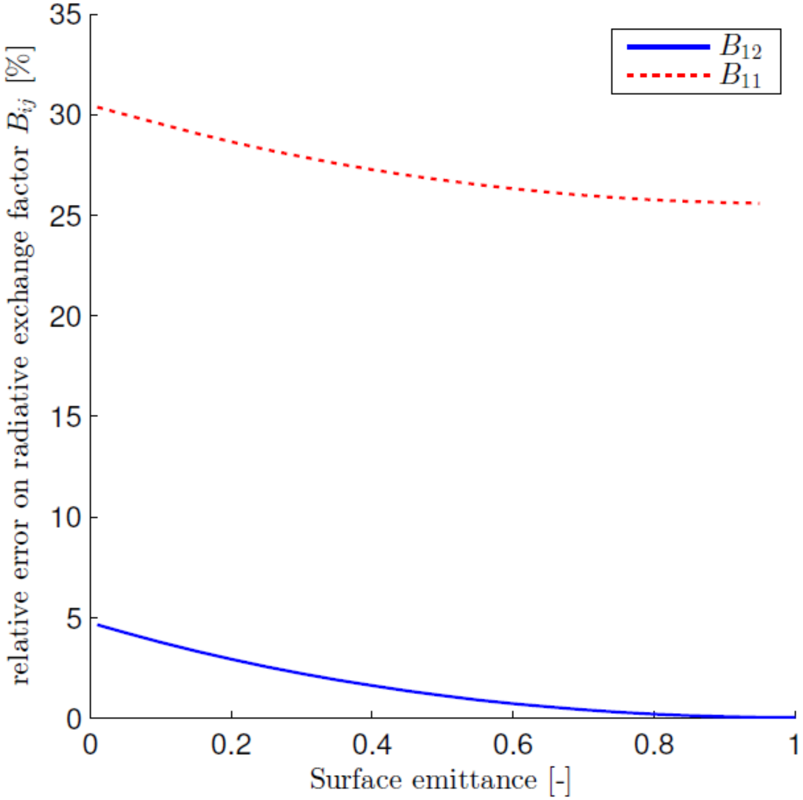
Analytical formulae rapidly not valid

Example: two perpendicular squares



$$F_{12} = 0.2$$





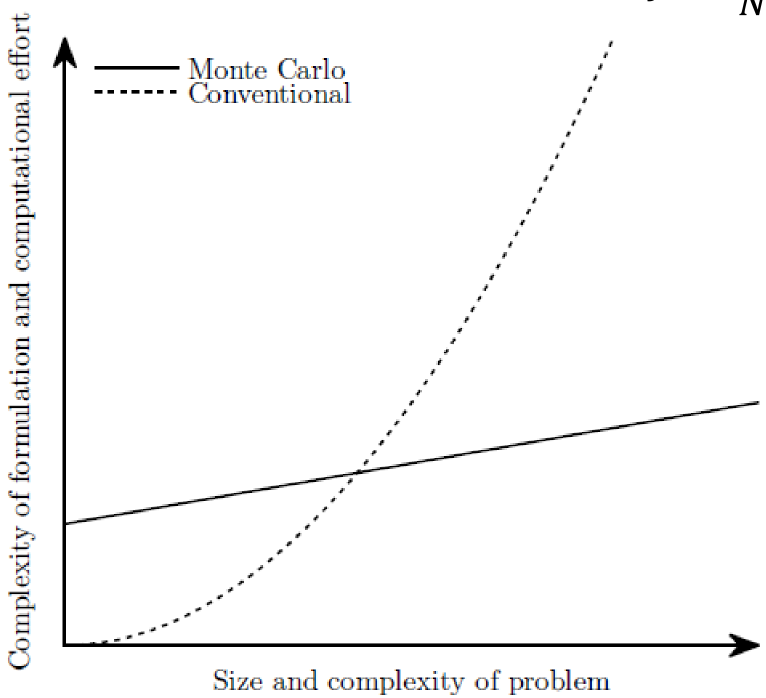
Why? not uniformly irradiated!

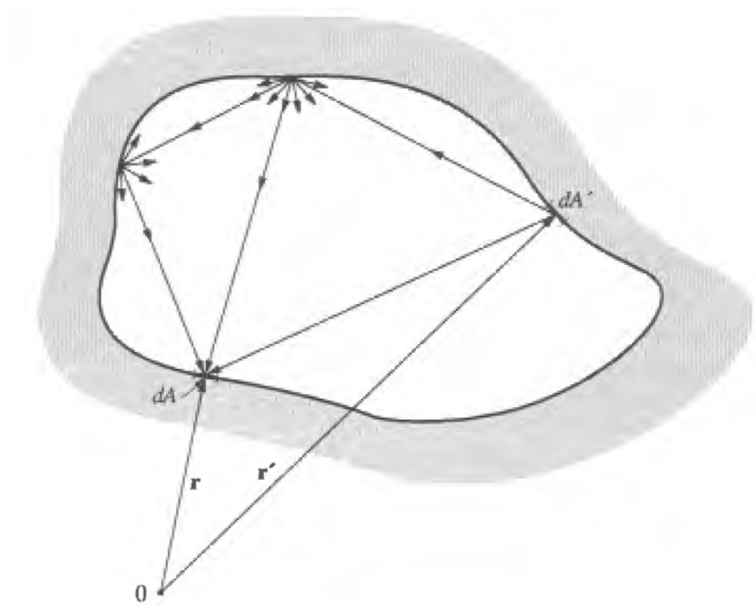
Need for general method to compute REFs

Monte Carlo ray-tracing:

Generate rays (bundles of photons) in many, random directions over surface i and count how many strike surface j

$$B_{ij} = \lim_{N_i \to \infty} \frac{N_{ij}}{N_i} \cong \left. \frac{N_{ij}}{N_i} \right|_{N_i \gg 1}$$





Ray-tracing used in many fields

Originates from nuclear research (40’s)

Extensively developed for computer graphics

In space engineering:

- Thermal radiation modelling
- Contamination modelling

That's it for the theory

S/C thermal design workflow

Scientific/Mission objectives

⬇

Mission parameters & technical requirements

(Orbit, attitude,…) & (Power, temperatures, gradients, stability)

⬇

Thermal control methods & Mathematical modeling

(active vs. passive control) & (worst case approach,…)

⬇

Testing

(thermal balance, thermal cycling, solar simulator,…)

The launch phase

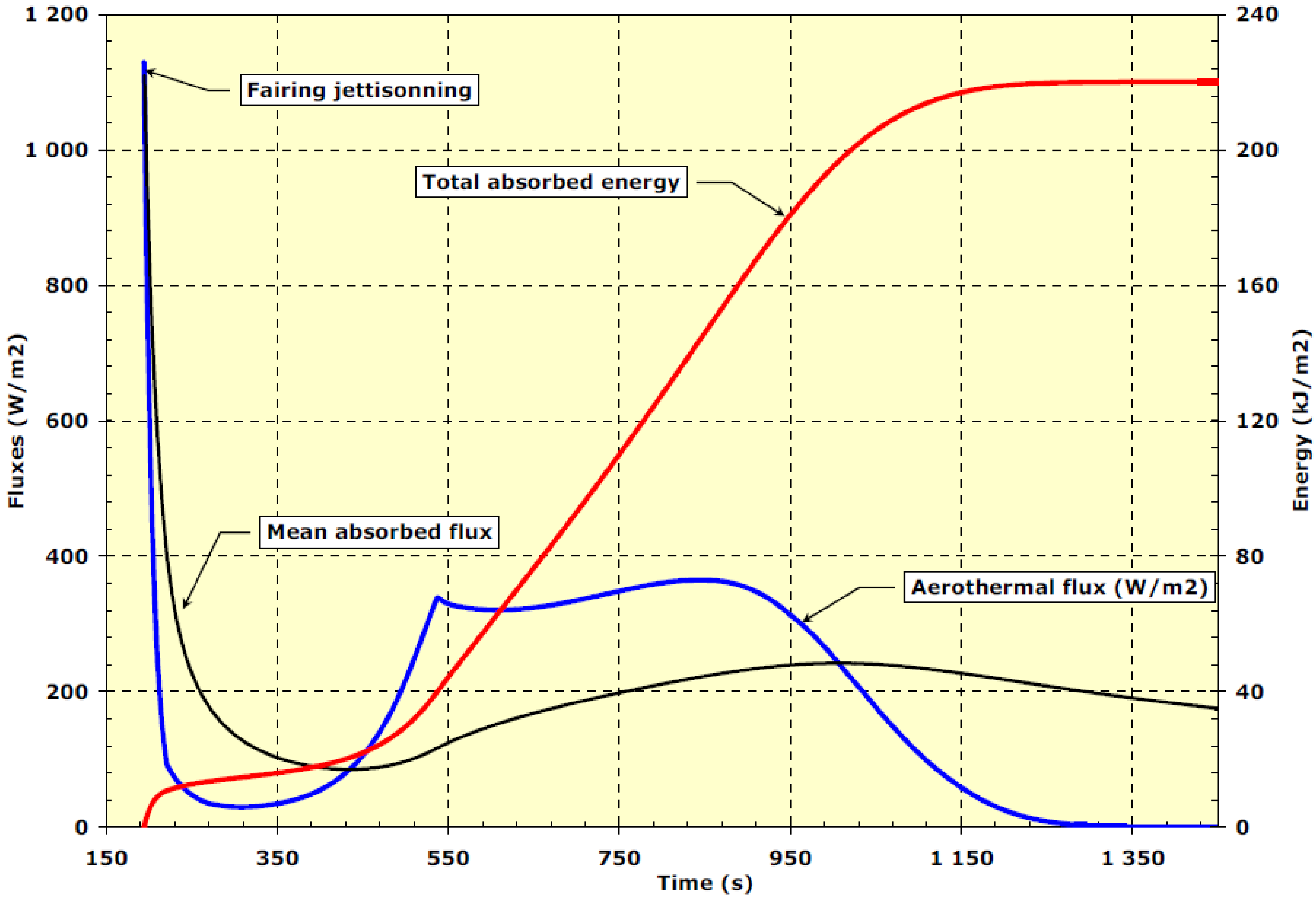
Before fairing jettisoning (~150km, ~3min): driven by fairing temperature

- <1000W/m^2 for Ariane 5 and Vega, <800W/m^2 for Soyouz (from CSG)
- As long as pressure inside the fairing > threshold: convective heat transfer

After fairing jettisoning:

- aero-thermal fluxes (+ also re-entry & aero-braking maneuvers)
- Heat fluxes generated from upper stages attitude thrusters

Ariane-5 profile



The space thermal environment…

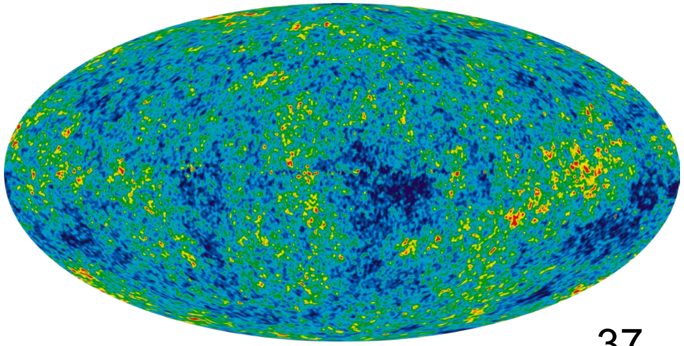
What is the temperature in space?

What are the different heat sources?

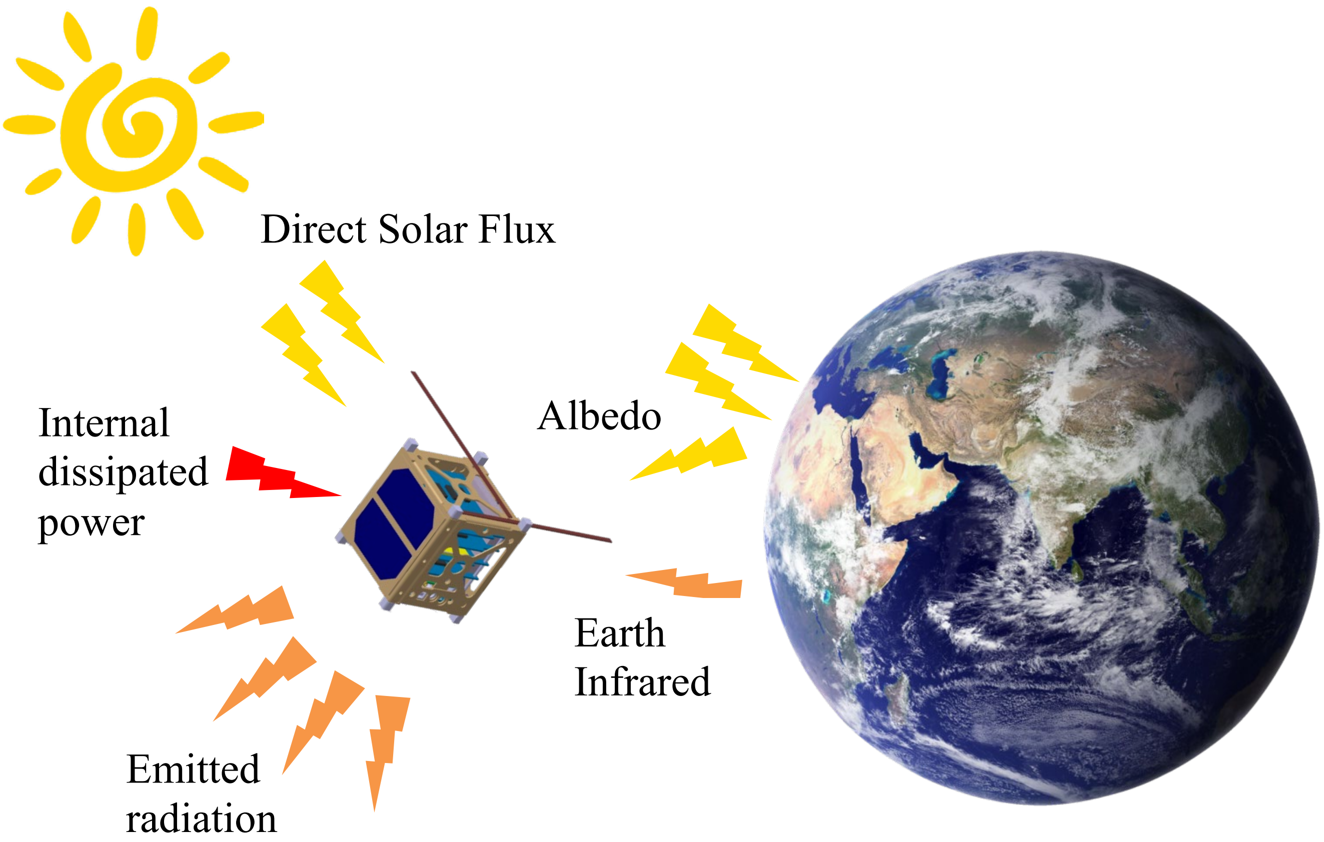
- Sun: 1367 W/m² (800-900 W/m² in Belgium for clear sky day in summer)
- Planetary IR (~200 W/m² in LEO, ~0 in GEO)
- Planetary albedo (~400 W/m² in LEO , ~0 in GEO)
- Internal dissipation (stored energy coming from RTGs, batteries,…)

Conservation of energy: where does the heat go?

- Deep space is the only heat sink @ 2.7K (cosmic microwave background = most perfect blackbody, discovered accidentally in 1964 and mapped by COBE, WMAP and Planck)



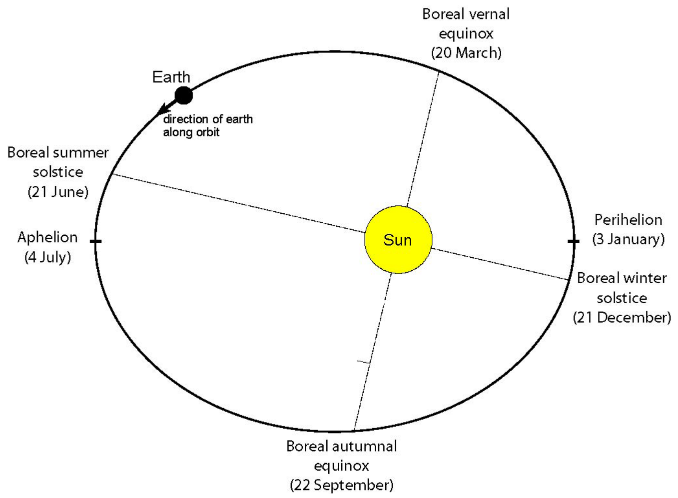
The space thermal environment…



Sun heat flux is higher in winter (northern hem.)

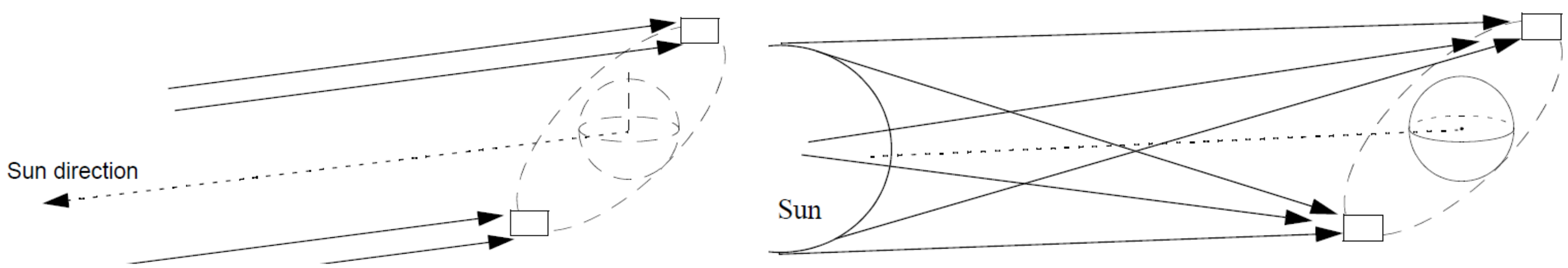
Earth's orbit around the sun is elliptic!

- 1414 W/m² in boreal winter (d_{Sun} = 0.98AU)
- 1322 W/m² in boreal summer (d_{Sun} = 1.01AU)



The Sun can be modeled as:

- an infinitely far source → parallel rays
- a finite source → divergence of Sun's ray taken into account



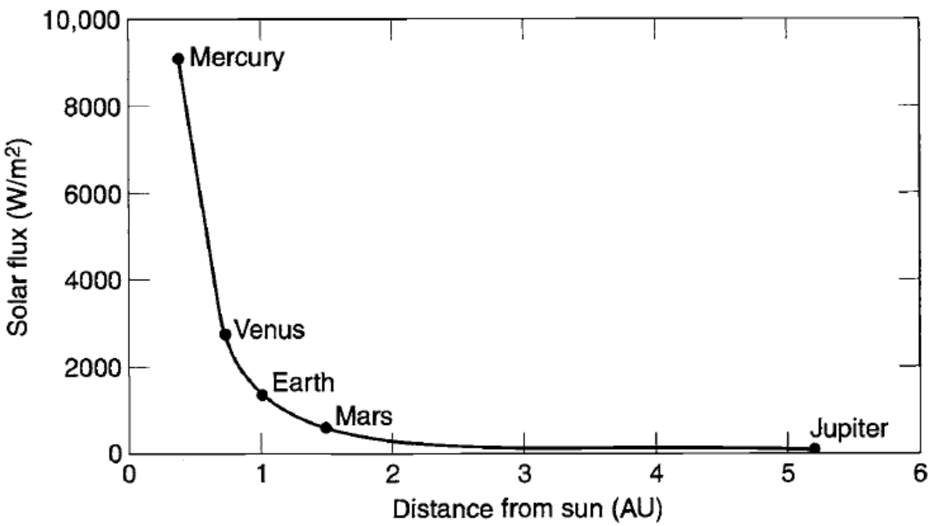
If you go for an interplanetary journey…

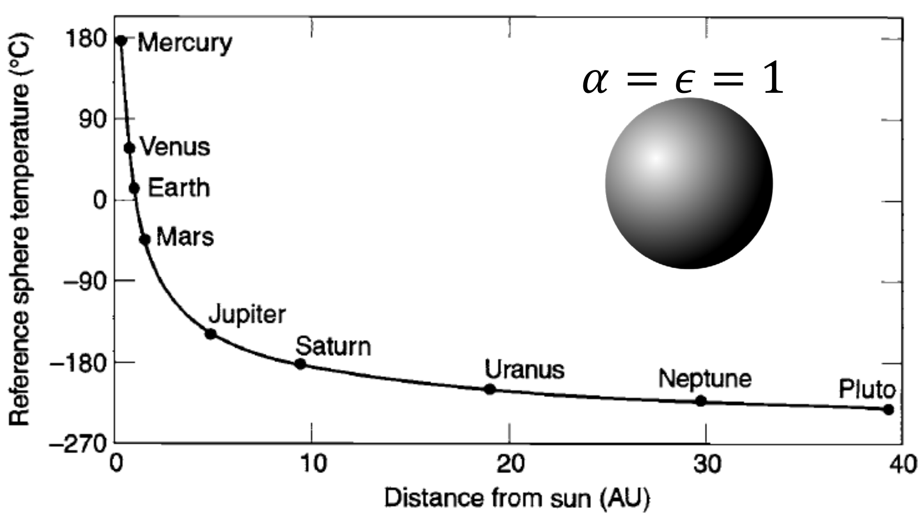
Solar flux increases as $1/d_{sun}^2$.

1367 W/m² annual average at Earth distance (1AU)

$$q_{Sun} = \frac{1367}{d_{[AU]}^2}$$

Solar Orbiter perihelion: 0.28AU → 17500 W/m²





Earth infrared radiation

Can be approximated from a balance equilibrium on annual average:

For a rapidly rotating planet (globally uniform temperature):

$$T = \sqrt[4]{\frac{q_{Sun}(1-a)}{4\epsilon\sigma}}$$

Where a is the albedo coefficient = average reflectivity = 0.3 for Earth, ϵ = planet emittance ~ 1

$$T_{Earth} \cong 255 \text{ K}$$

IR vary in function of

- cloud cover: IR ↘ as cloud cover ↗ since cloud tops are colder + block IR
- local Earth's surface temperature: higher in desert and tropical regions
- View factor with Earth (1/distance^2)

Earth infrared radiation computation

The incident planetary heat load can be computed as follows:

$$Q_{IR} = \sigma F_{i,Earth}\, T_{Earth}^4$$

With $F_{i,Earth}$ the view factor between the surface and the Earth. Earth IR can be reflected to other surfaces that have not a direct view with the Earth…

If necessary, temperature distribution of the planet surface can be taken into account

Albedo

Fraction of incident sunlight that is reflected by the planet

Highly variable, highest at sub-solar point

Decreases as $1/d^2$ (view factor with Earth), as S/C approaches terminator

Wide range:

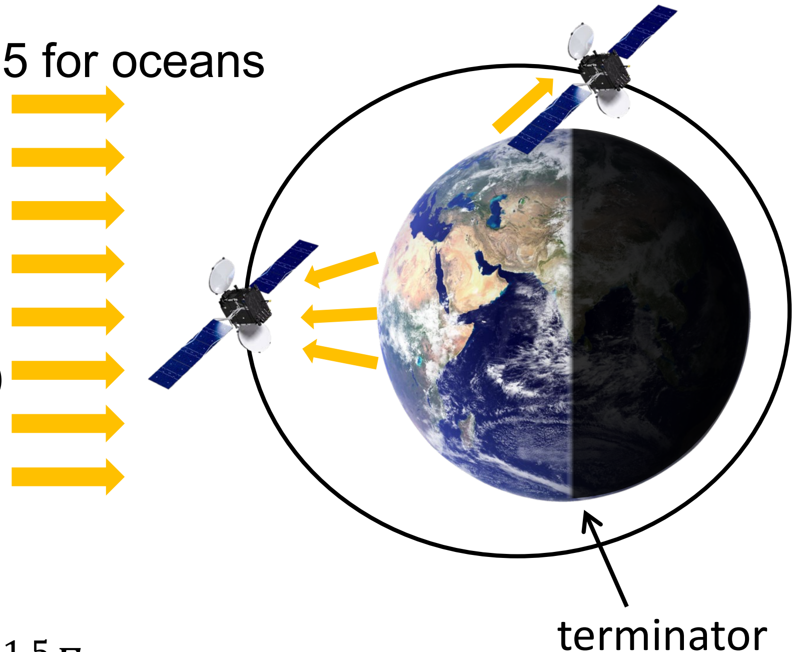
0.8-0.9 for snow, 0.4-0.8 for clouds, 0.05 for oceans

Averages:

Earth: ~0.33

Moon: ~0.07 (not as bright as it seems)

Mars: ~0.25



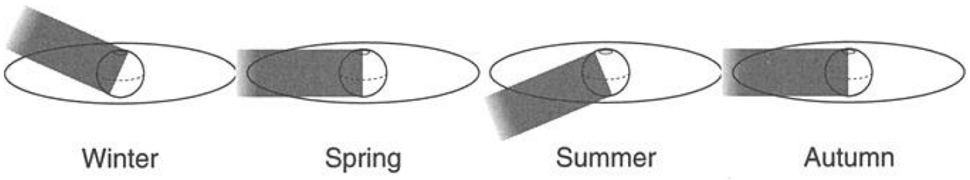
Simplified analytical formula:

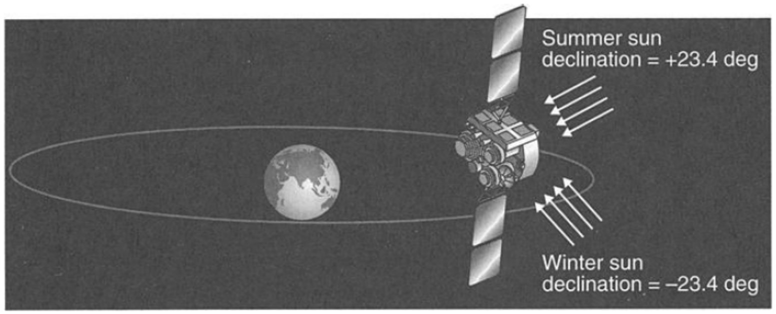
$$q_A = q_{Sun} a (\cos 0.9\theta)^{1.5} F_{i,Earth}$$

Mission parameters: the orbit

LEO: strong variation due to eclipses…

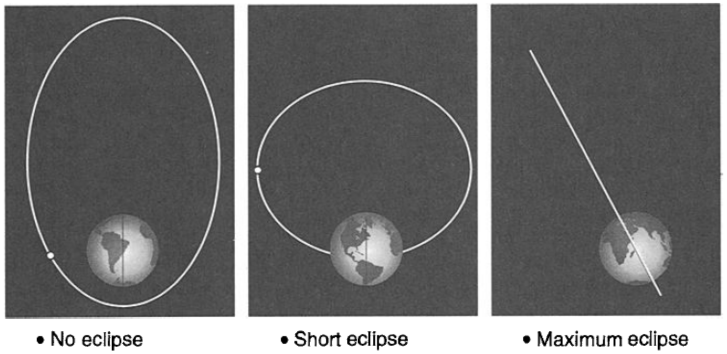
GEO: eclipses (max 72min) and only around equinoxes





HEO: strong Earth loads near perigee, more stable at apogee, eclipses duration from 0 → ~70min

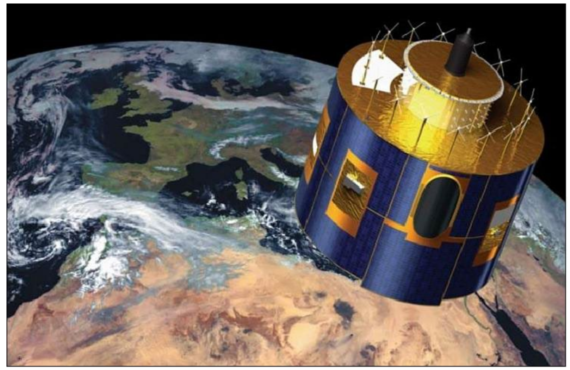
(XMM: 9000km x 114000km)



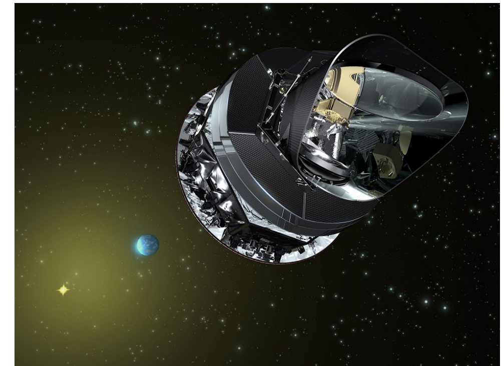
L1/L2 very stable thermal environment (Planck, Herschel, JWST, SOHO,…)

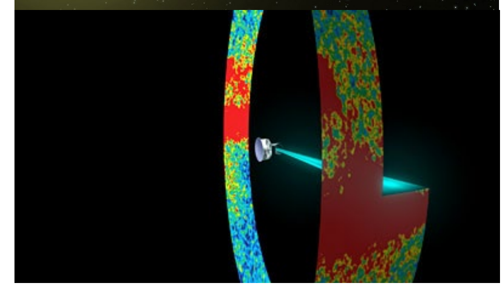
Mission parameters: the attitude

Spinning satellite:



100 rpm





1 rpm

3 axis stabilized:

SOHO

Artemis & OICETS

Juno

S/C thermal design workflow

Scientific/Mission objectives

⬇

Mission parameters & technical requirements

(Orbit, attitude,…) & (Power, temperatures, gradients, stability)

⬇

Thermal control methods & Mathematical modeling

(active vs. passive control) & (worst case approach,…)

⬇

Testing

(thermal balance, thermal cycling, solar simulator,…)

Testing, launch then end-of-life…

“*The PI* *shall* *ensure that the unit thermal design maintain all the internal parts within their allowed limits at any time of the mission, during the unit level acceptance tests, during the unit level qualification tests and during the ground satellite tests.*”

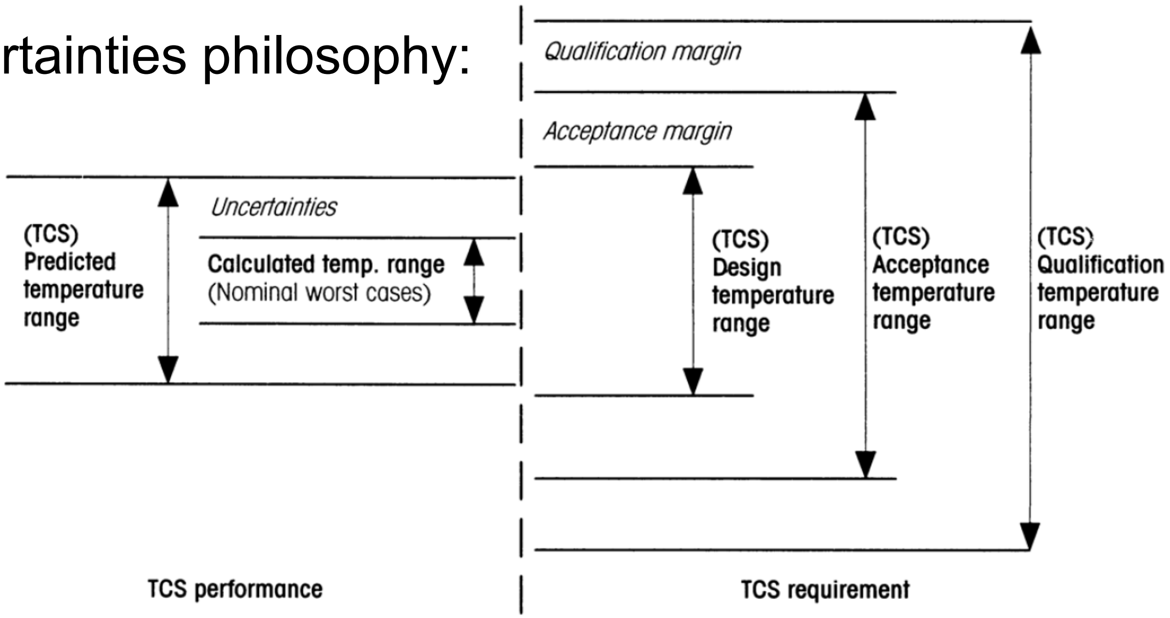
Requirement from Solar Orbiter Experiment interface Document, part A (EID-A)

Temperatures ranges

Each subsystem/part has its own temperature range:

	$T_{min,OP}$ [°C]	$T_{max,OP}$ [°C]
Electronics	-20	50
Batteries	-5	30
Solar Cells	-150	70
Detectors	-250	0
…		

Margin and uncertainties philosophy:

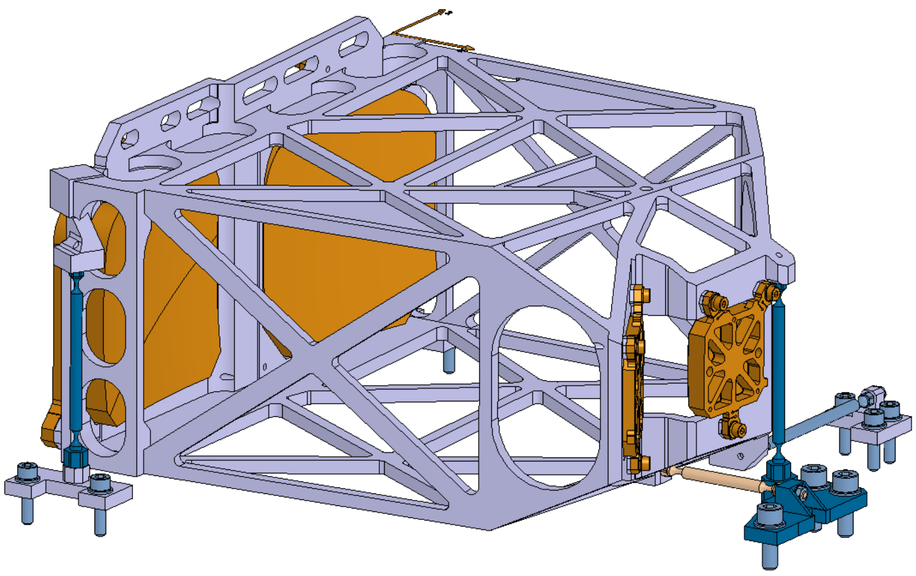


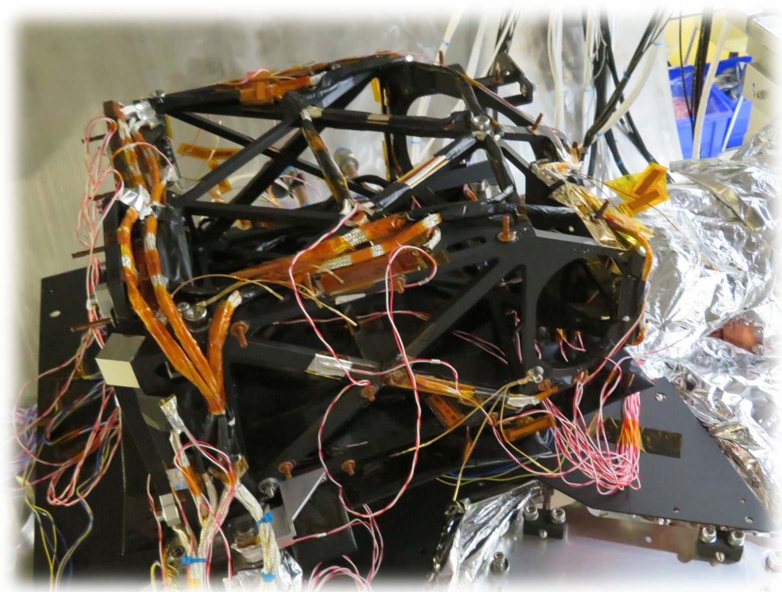
Temperature variations: in space and time

Usually comes from optical considerations and thermo-elastic deformations

Example: Back Telescope Assembly on MTG (Meteosat Third Generation)

all the mirrors remains at 0°C +/-0.5K during the operational phases and provide a temperature stability at least of 0.1K over a period of 15min on all the BTA mirrors



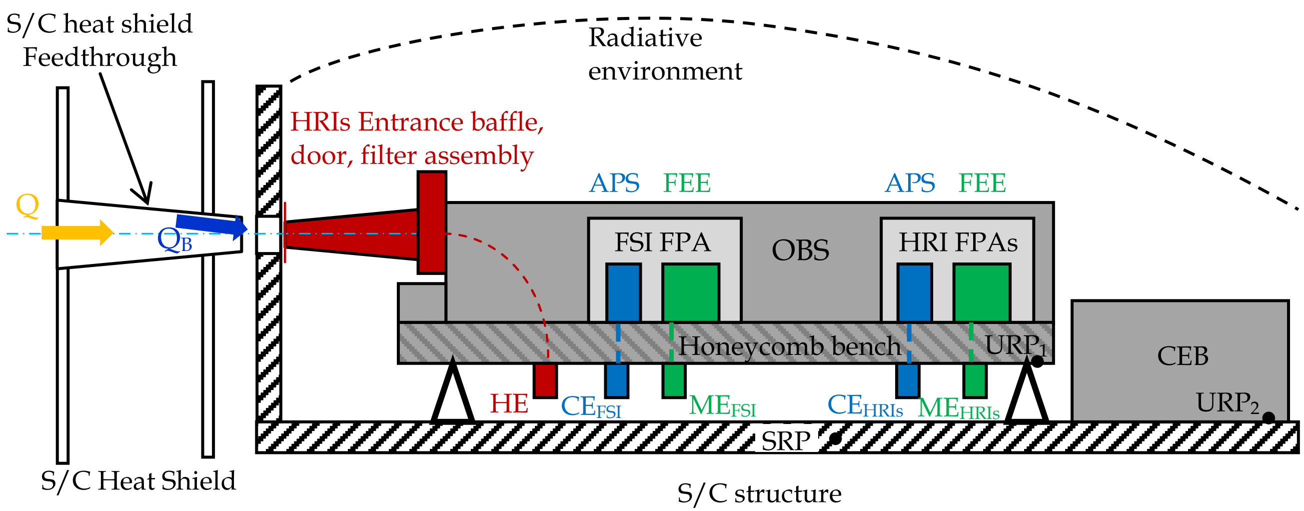


Payload interface heat loads

Thermal interfaces are defined between S/C and payloads

Example: EUI on Solar Orbiter

In practice: interface T° vary with heat load → iterative process



S/C thermal design workflow

Scientific/Mission objectives

⬇

Mission parameters & technical requirements

(Orbit, attitude,…) & (Power, temperatures, gradients, stability)

⬇

Thermal control methods & Mathematical modeling

(active vs. passive control) & (worst case approach,…)

⬇

Testing

(thermal balance, thermal cycling, solar simulator,…)

How to meet the requirements?

2 categories of thermal control methods:

Passive	**Radiation** - Coating - MLI blanket - radiator **Latent heat & ablation** - Thermal protection system - Phase change material	**Conduction** - Structural material - Doubler, filler - Washer, strap, bolt - foam
Active	**Heater** - Thermostat control - Electronic control - Ground control **Peltier element**	**Heat pipes** - fixed/variable conductance **Fluid loops** - mono/diphasic fluid **Louvers** **Coolers**

Conservation of energy is the key

All that is absorbed or generated is eventually stored as thermal energy then radiated to deep-space (IR + …):

$$Q_{in} - Q_{out} = C\frac{dT}{dt}$$

$$Q_{in} = Q_{int} + Q_{Sun} + Q_{Earth,IR} + Q_{albedo}$$

The harder it is for the heat to escape, the hotter…

Solar cells from thermal point of view

Just a delocalization (in space and time) of heat generation…

q_{SUN}

$Q_{inc} = Aq_{sun}$

$Q_{refl} = (1 - \alpha)Q_{inc}$

$Q_{abs} = \alpha Q_{inc}$

$Q_{ther,1}$

$Q_{elec} = \eta(T)Q_{inc}$

$Q_{ther,2}$

$$Q_{inc} = Q_{abs} + Q_{refl}$$

$$Q_{abs} = Q_{ther,1} + Q_{elec}$$

How to meet the requirements?

Passive	**Radiation** - Coating - MLI blanket - radiator **Latent heat & ablation** - Thermal protection system - Phase change material	**Conduction** - Structural material - Doubler, filler - Washer, strap, bolt - foam
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S/C external coatings drive their T°

Case of a sphere in sunlight, far from Earth, steady-state, no internal dissipation:

$$Q_{in} = \alpha q_{Sun} \pi r^2 \qquad Q_{out} = 4\pi r^2 \epsilon\sigma(T^4 - 2.7^4)$$

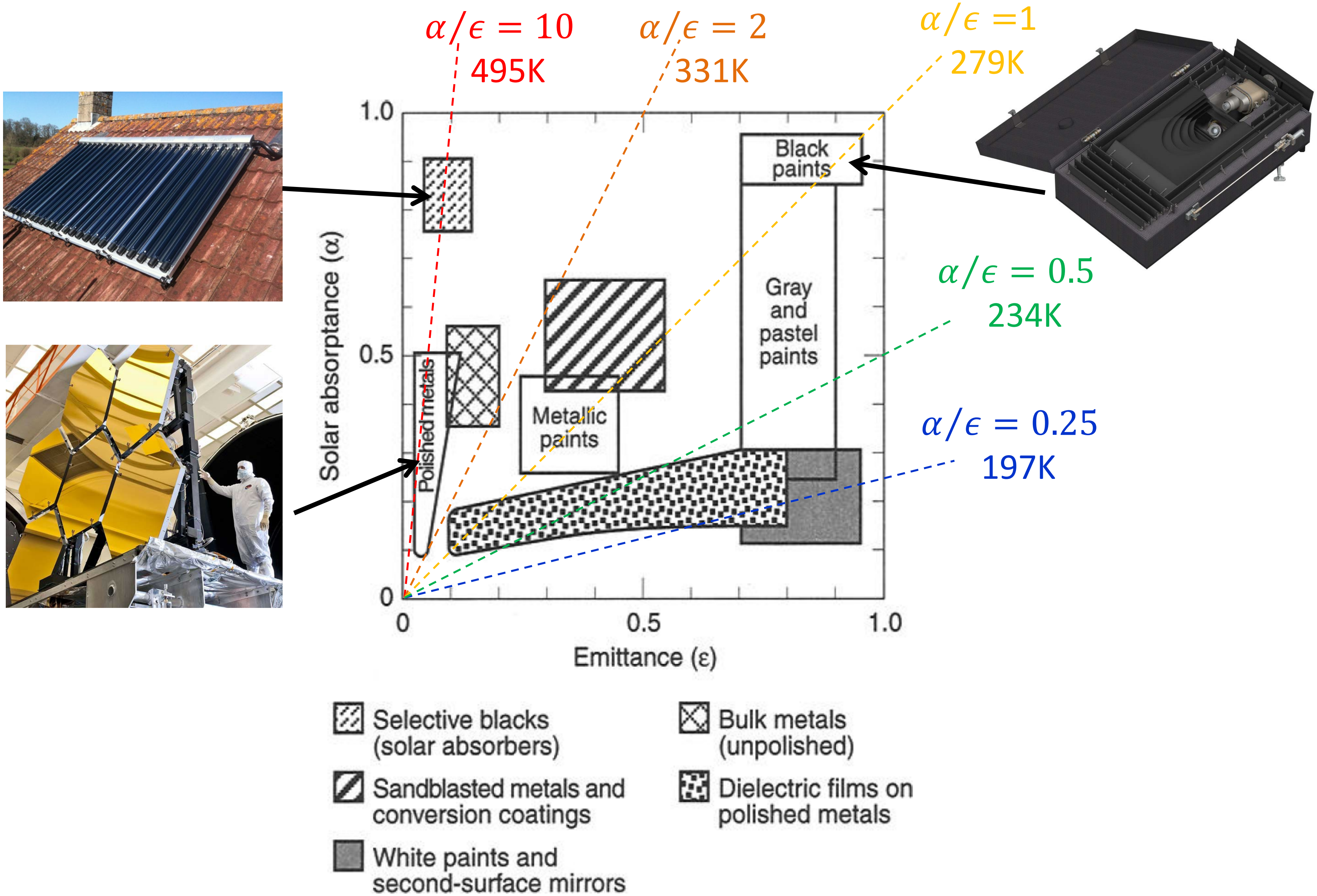
$$T[K] = \sqrt[4]{\frac{\alpha q_{Sun}}{4\epsilon\sigma} + 2.7^4}$$

Black-body ($\alpha = \epsilon = 1, \alpha/\epsilon = 1$): $T = 279\text{K}\ (6°\text{C})$

Polished gold ($\alpha = 0.3, \epsilon = 0.03, \alpha/\epsilon = 10$): $T = 495\text{K}\ (222°\text{C})$

White paint ($\alpha = 0.2, \epsilon = 0.85, \alpha/\epsilon = 0.24$): $T = 194\text{K}\ (-79°\text{C})$

A whole range of coatings



What are they used for?

Internally:

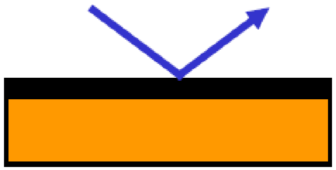
- to insulate sensitive subsystems: low ϵ
- to mitigate straylight (unwanted light → noise): high α and/or ϵ (depend on λ)
- to make the temperatures more uniform (electronics box): high ϵ
- …

Externally:

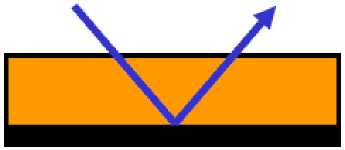
- to cool down a radiator: white paint if in sunlight, black paint otherwise
- to avoid temperature dropping: low ϵ (high α if in sunlight)
- …

First or second surface mirrors?

First surface mirror: low α, low ϵ



Second surface mirror (SSM) or OSR (optical solar reflector): low α, high ϵ



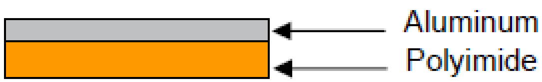
Typical substrate:

- PET (polyethylene terephthalate, polyester, Mylar)
- Polyimide (Kapton)
- FEP (Teflon)

Aluminized Kapton

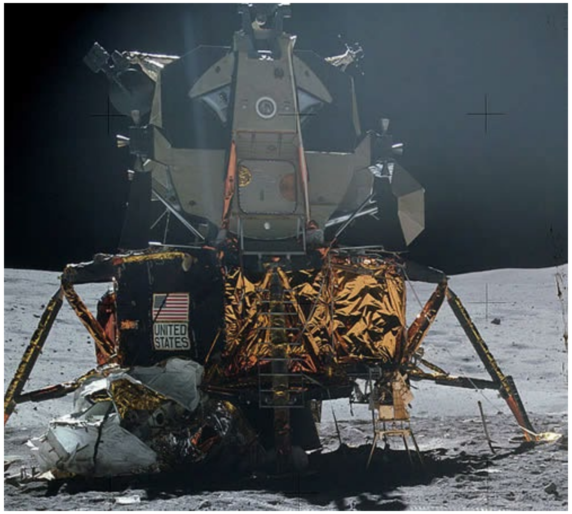
Typically used as MLI outer layer

Can be used as SSM or FSM



Parameter (independent of film thickness)	Specified Value
First surface solar absorptance (α)	$\leq$ 0.14
First surface hemispherical emittance (ε_H)	$\leq$ 0.035
First surface normal emittance (ε_N)	$\leq$ 0.035
Typical first surface α/ε	4 - 5
Aluminum surface resistivity	$\leq$1 Ω/square
Intermittent temperature range	-250° C to 400° C (-420° F to 750° F)
Continuous temperature range	-250° C to 290° C (-420° F to 550° F)

Thickness mil (μm)	Second Surface Mirror Properties			Typical Weight (g/m^2)
	α	εN	εH	
0.3 (8)	$\leq$ 0.35	$\geq$ 0.40	$\geq$ 0.40	11
0.5 (12.5)	$\leq$ 0.36	$\geq$ 0.50	$\geq$ 0.52	19
1.0 (25)	$\leq$ 0.39	$\geq$ 0.62	$\geq$ 0.64	36
2.0 (51)	$\leq$ 0.44	$\geq$ 0.71	$\geq$ 0.71	71
3.0 (76)	$\leq$ 0.46	$\geq$ 0.77	$\geq$ 0.77	109
5.0 (127)	$\leq$ 0.49	$\geq$ 0.81	$\geq$ 0.81	181



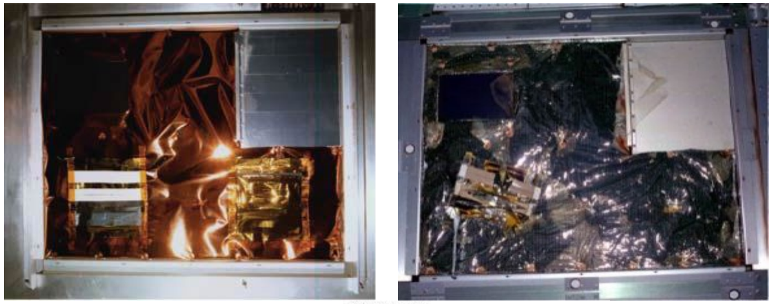
Space environment affects materials

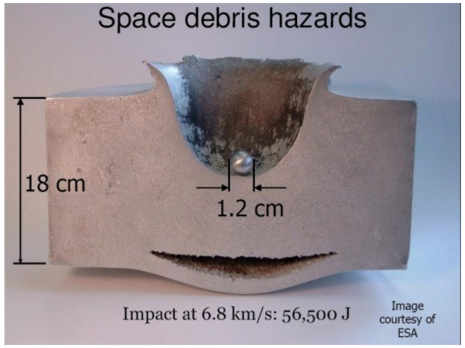
Degradation sources:

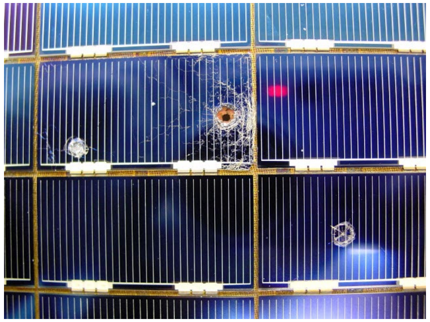
- UV radiation (not filtered by atmosphere)
- Charged particles
- Atomic oxygen
- High vacuum
- Contamination
- Micrometeoroids & debris
- Corrosion (launch site…)

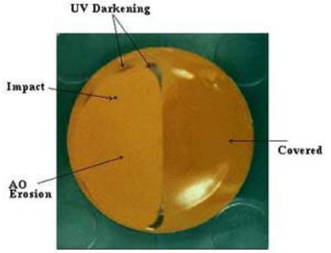
Long Duration Exposure Facility:
6yrs in LEO

Kapton before and after LDEF

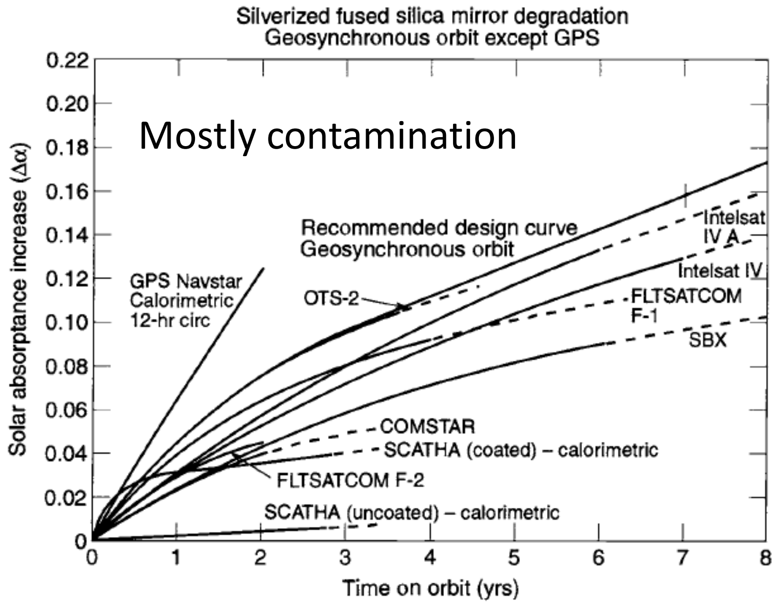




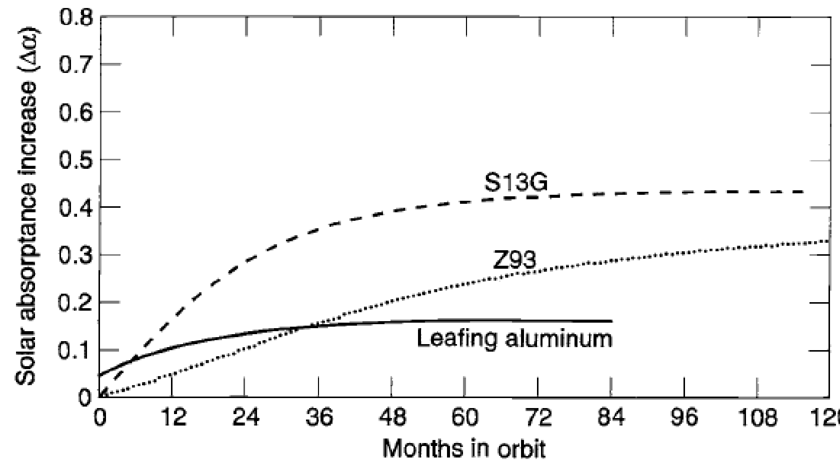




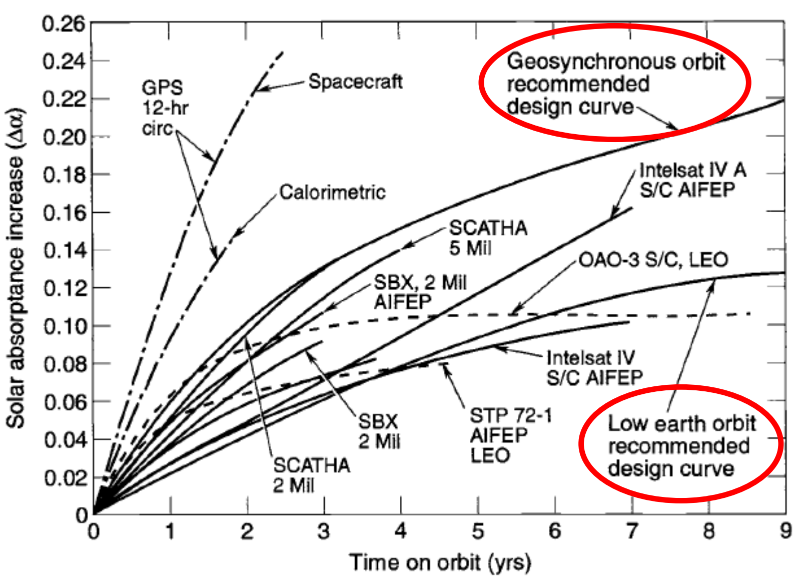
By how much? Mostly α



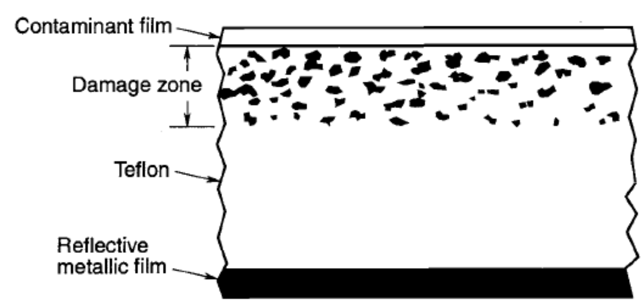
White paint is mostly affected by UV & charged particules



If affected by UV → higher degradation if closer to the Sun



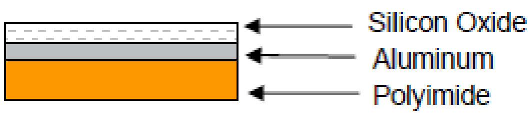
Metalized Teflon (Second surface mirror) degradation due to charged particles and contamination



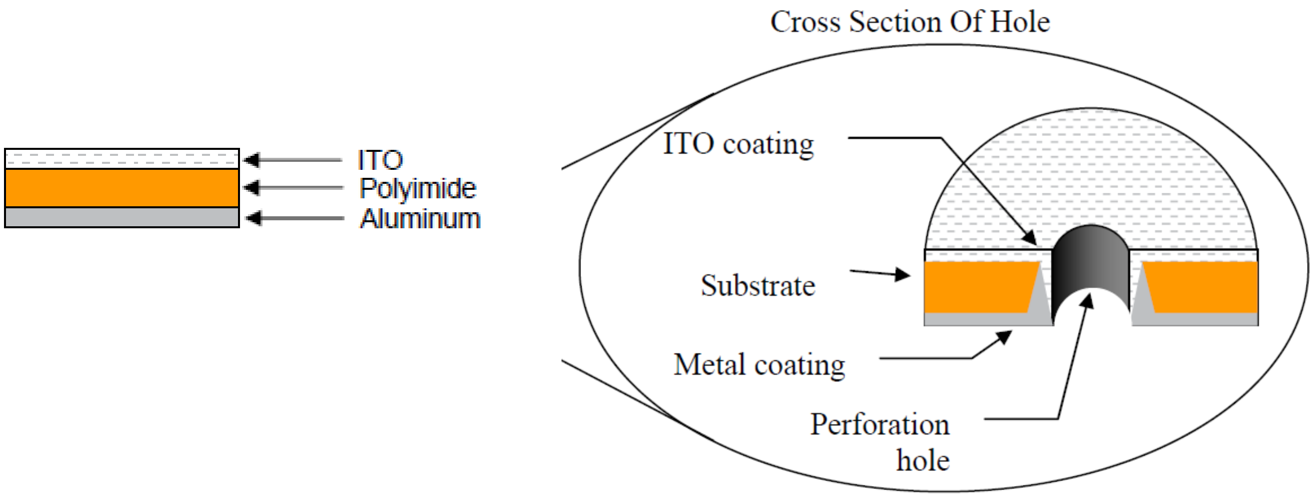
Coating overcoat…

Corrosion: use Gold (inert) instead of Aluminum

Atomic oxygen protection: Silicon oxide transparent (VIS) coating



Static charge control: Indium Tin Oxide (ITO) transparent (VIS) coating



How to meet the requirements?

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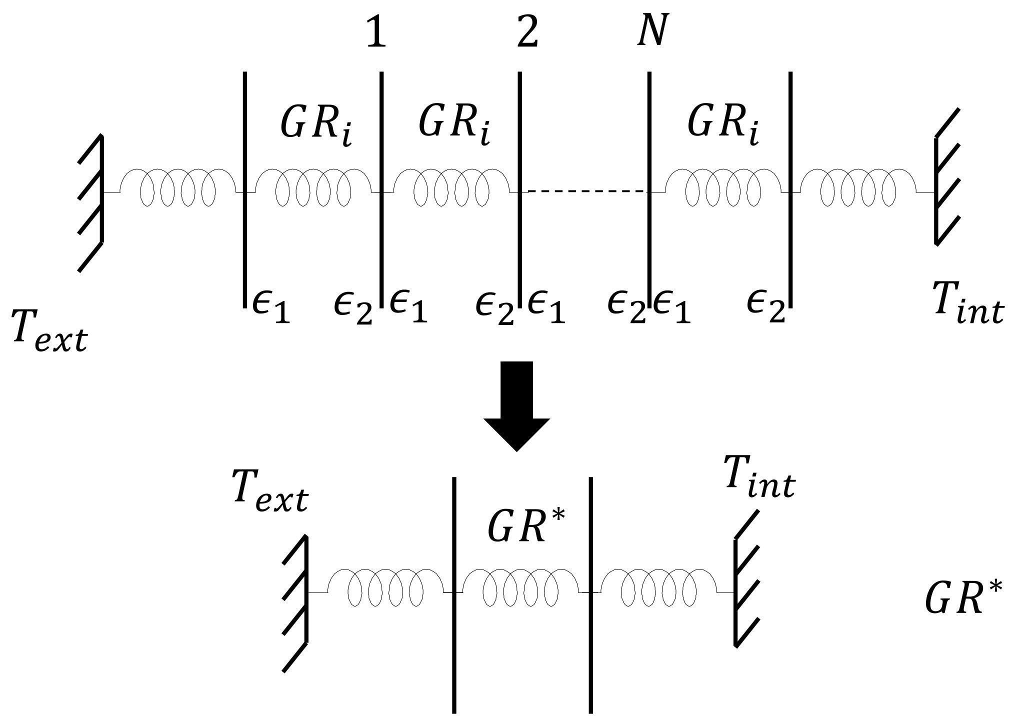
Spacecraft blanket: Multi-Layer Insulation

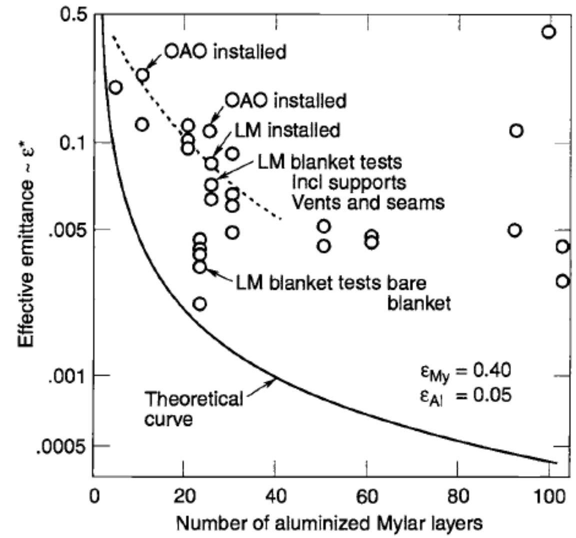


$$GR^* = A\epsilon^*$$

$$GR_i = \frac{1}{\frac{1-\epsilon_1}{A_1\epsilon_1} + \frac{1}{A_1 F_{12}} + \frac{1-\epsilon_2}{A_2\epsilon_2}} = \frac{A}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}$$

$$\boxed{\epsilon^* = \frac{1}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}\left(\frac{1}{N+1}\right)}$$

MLI: theory vs. practice

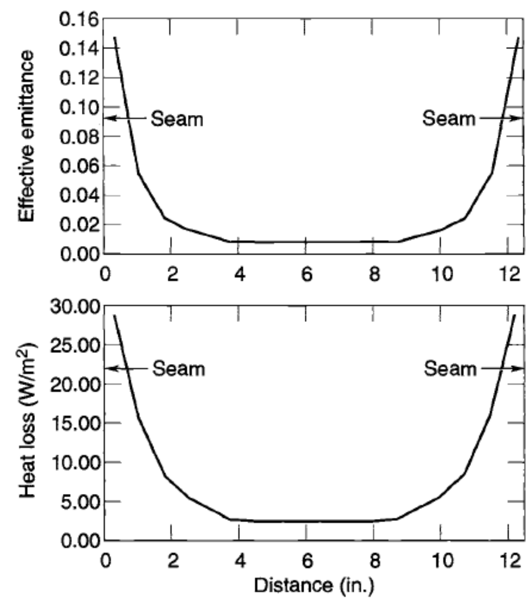


Contact between layers:

- crinkled, embossed layers
- Netting

Joints

Venting



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Radiator in everyday life?

No

More convection than radiation…

Yet, better to be painted…

Yes

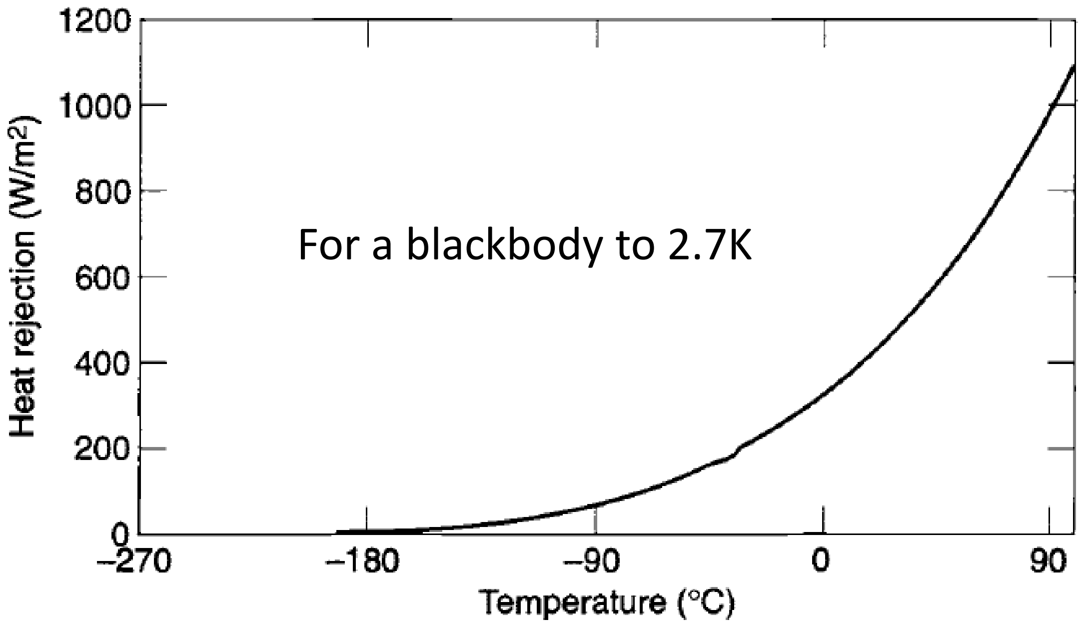
Radiating to deep space (2.7K)

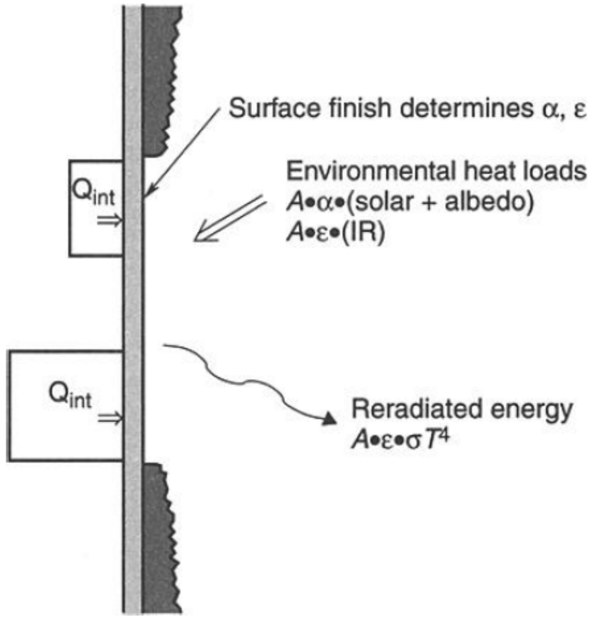
Typical use: cooling of a detector, cooling of electronics

Stood-off or part of the main structure

High emittance

High thermal conductivity (spread the heat to use the entire surface)





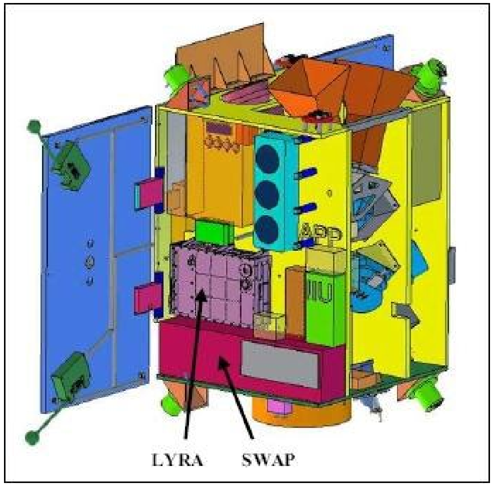
Other parts in the field of view

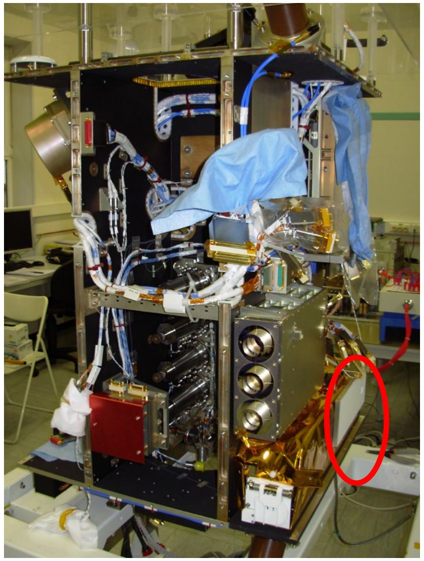
Sink temperature ≈ average of the radiative environment

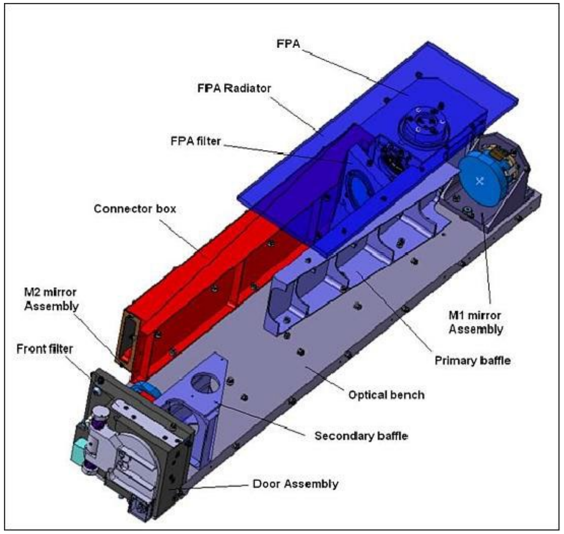
= radiative equilibrium temperature reached by the radiator when no heat load is applied (conductively decoupled)

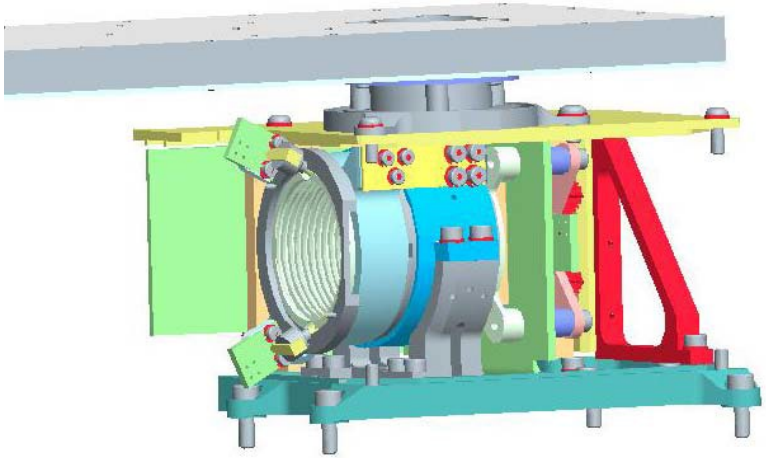
How to increase REF to deep space: IR mirrors

Example: SWAP (PROBA-2)



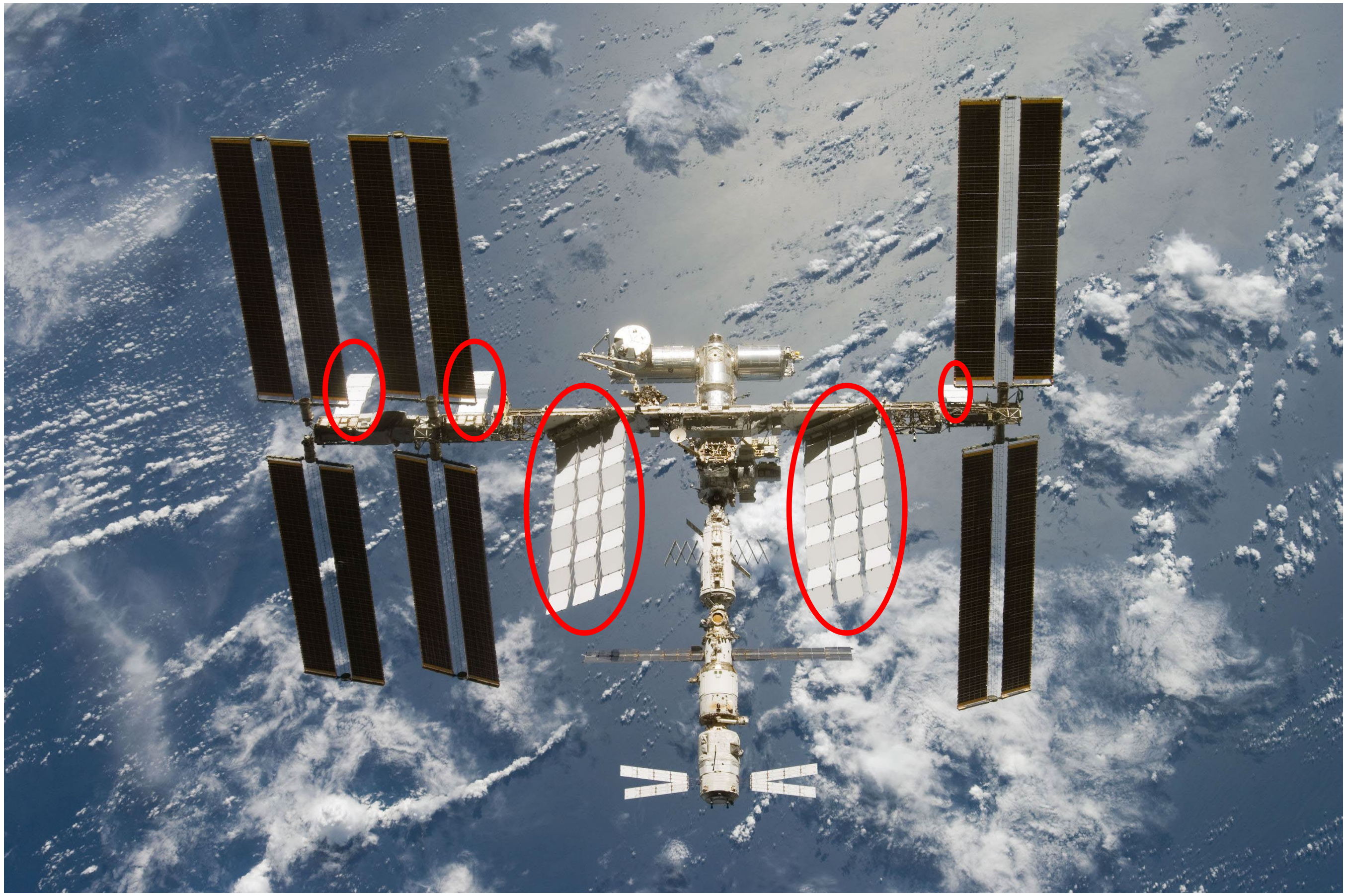






Example: ISS

Hint: perpendicular to solar arrays



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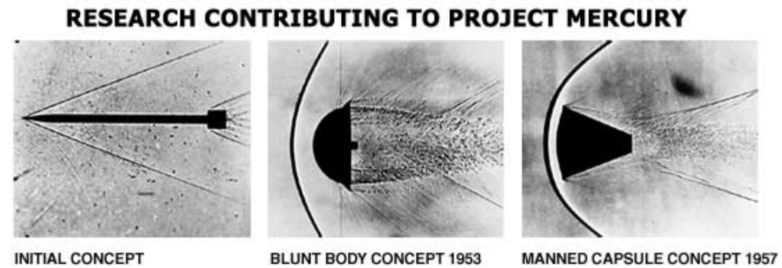
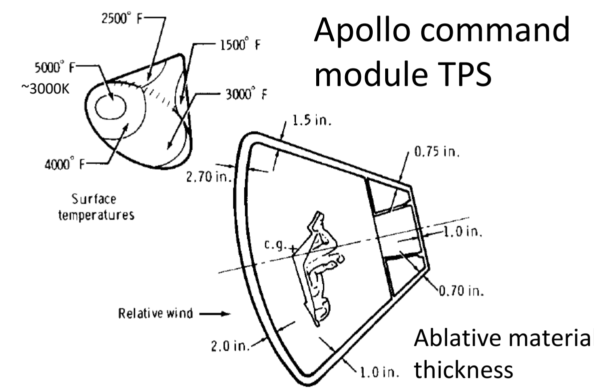
Thermal protection system = shield

TPS is the barrier that protects a spacecraft during atmospheric reentry.



First concept :

counter-intuitive discovery: the heat load is inversely proportional to the drag coefficient: bow shock wave moved forward along with hot gases.



Second concept: ablation

- lifts the hot shock layer gas away by production of gases
- heat absorbed by the ablative material: leaves S/C as the material ablates away
- the creation of a char layer: insulates + blocks radiated heat from the shock layer

Space Shuttle TPS

Reusable → non ablative, very light

> 20000 tiles checked and replaced if necessary

Columbia accident

How to meet the requirements?

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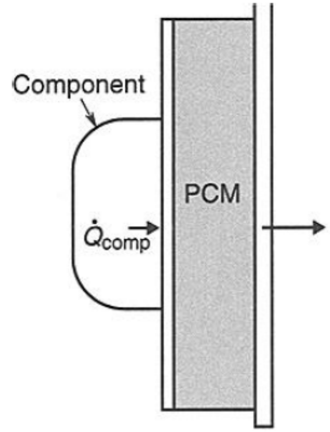
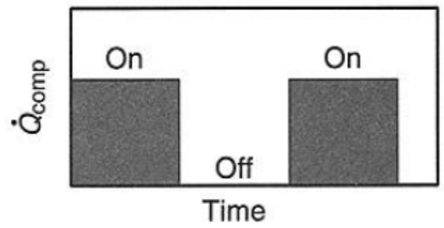
Damping based on latent heat…

Typically for cyclically operating components:

- Component ON: heat is stored in the PCM (fusion)
- Component OFF: heat is released to deep space to refreeze the PCM

→ Component operates at nearly constant temperature





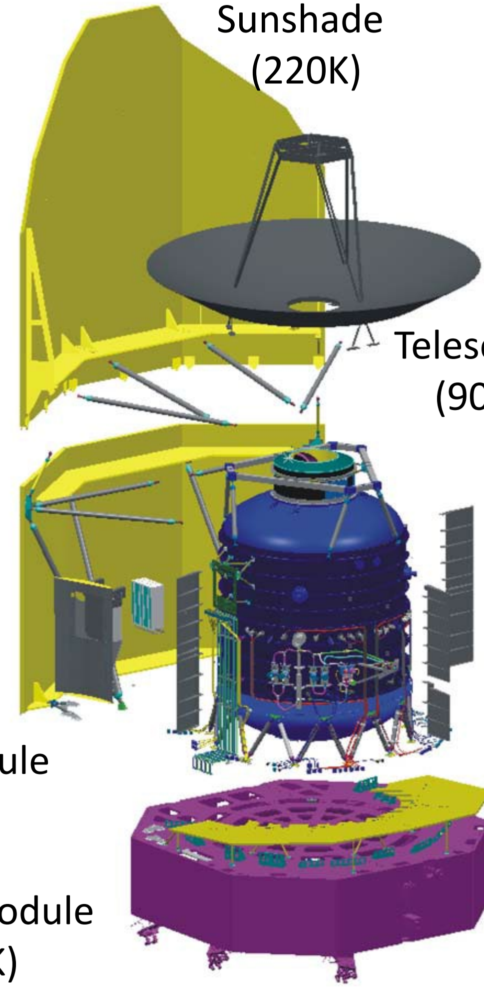
Satellite in LEO, landing vehicle on planet without atmosphere: cycling thermal environment

→ PCM used to damp the variations: in eclipse, releases the heat stored during sunlight

→ Studies by NASA for spacesuit gloves, eventually used in racing suits

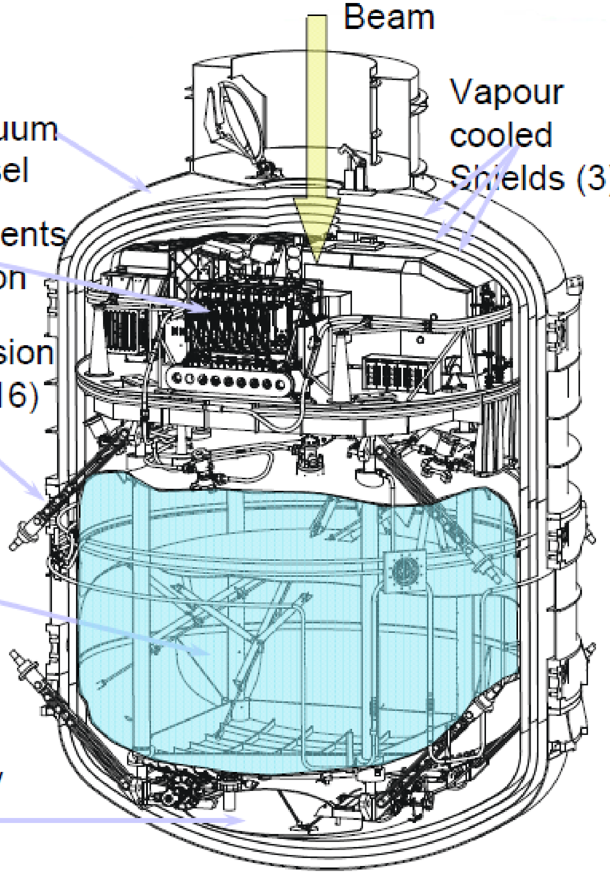
Another example: Herschel cryostat

- Works like human skin: evaporation
- Very slow evaporation (2.5mg/s=56mW) of superfluid He to precool detectors (1.6K & 0.3K)
- Superfluidity: a film around the entire reservoir
- Conditions the length of the mission



Herschel key figures:
3300kg, 7.5m x 4m, 2400L Helium

Herschel cryostat



How to meet the requirements?

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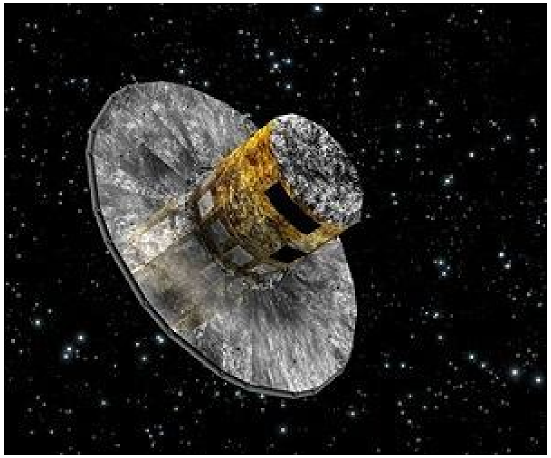
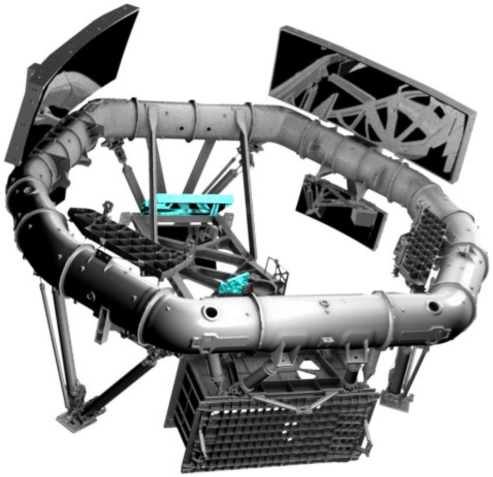
Active	**Heater** - Thermostat control - Electronic control - Ground control **Peltier element**	**Heat pipes** - fixed/variable conductance **Fluid loops** - mono/diphasic fluid **Louvers** **Coolers**

The structure plays an “active” role

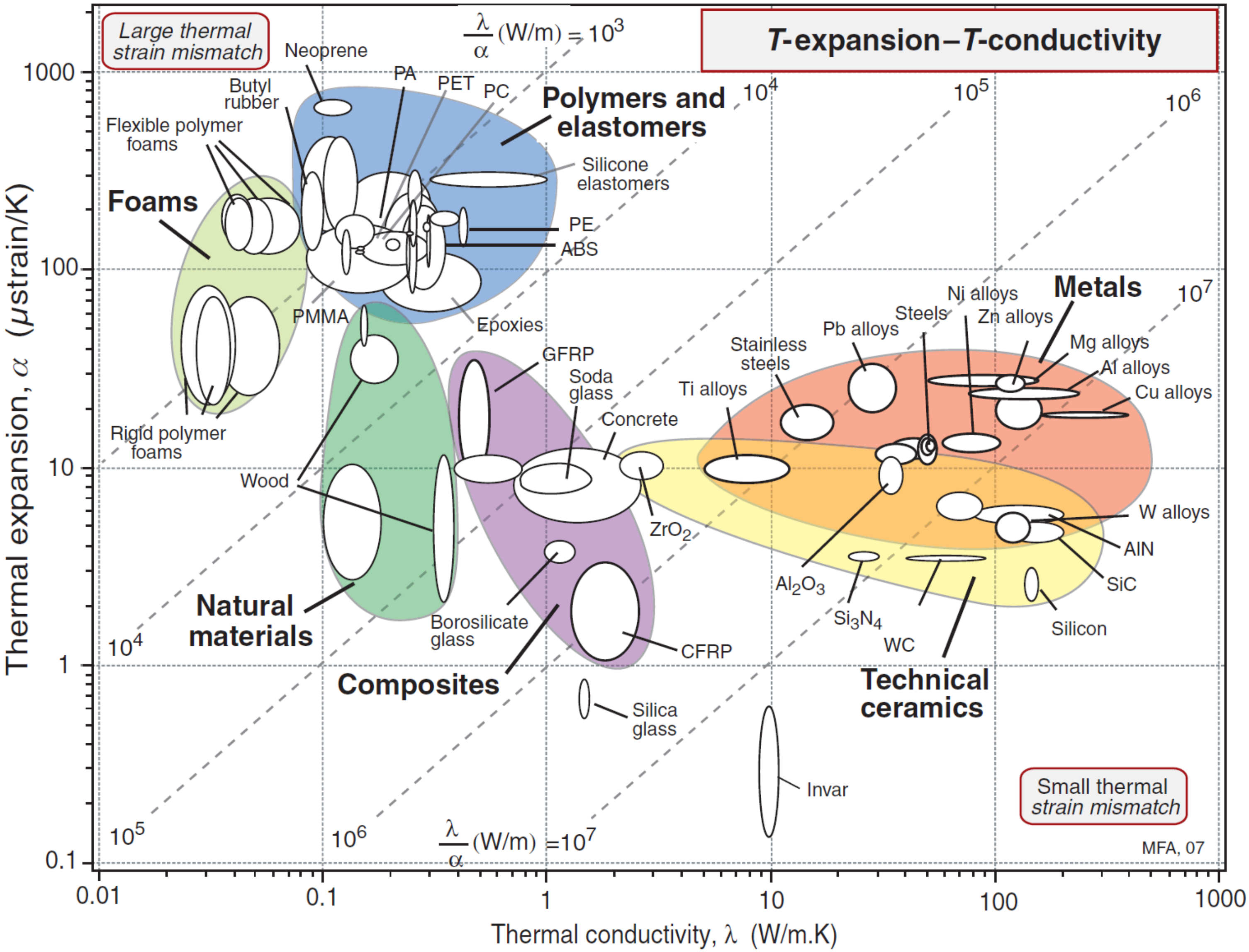
Choose the structure material to play both structural and thermal roles:

- Insulation
- Low coefficient of thermal expansion
- …





Coefficient of thermal expansion (CTE)



Materials - Engineering, Science, Processing and Design - M. Ashby, *et al*., (Elsevier, 2007)

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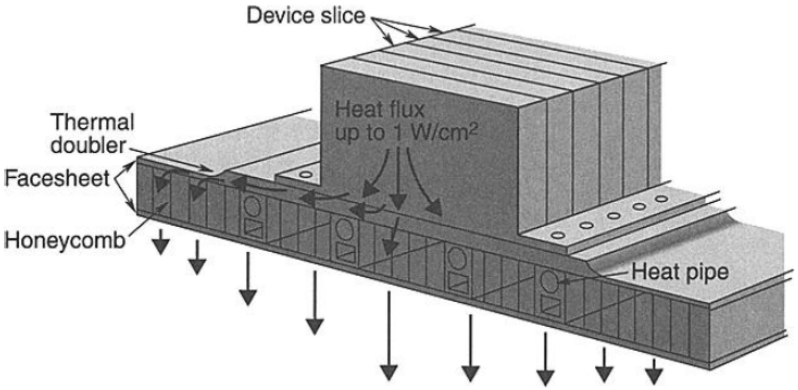
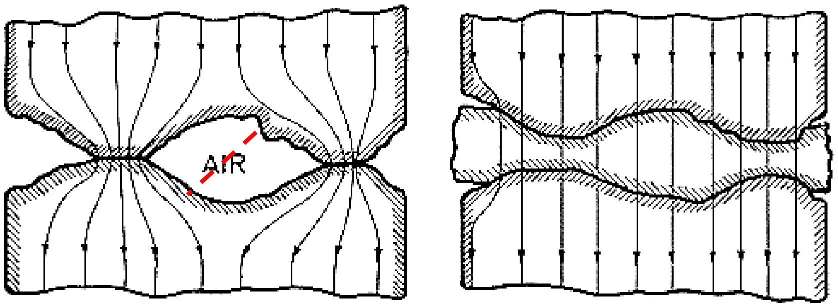
Mind the gap !

Unless a large force is applied, thermal contact is often negligible!

- Thermal doubler: spread the heat (large in-plane thermal conductivity)
- Thermal filler (gasket): fill the gap:

  usually soft material (Indium, CHO-THERM™, Sigraflex™)





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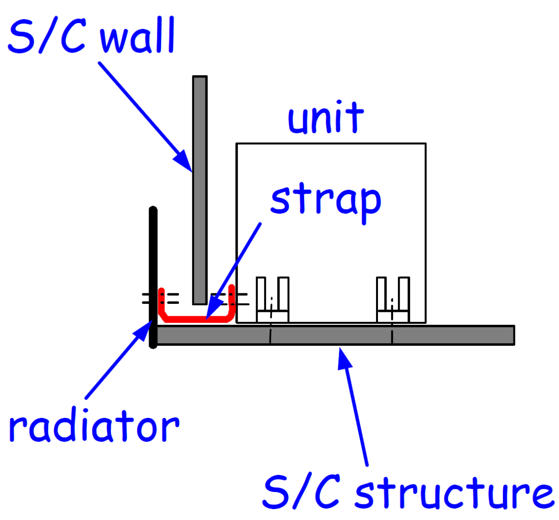
Thermal straps

Ensure conductive coupling between two parts

Sometimes important to decouple structurally while coupling thermally

→ Copper braids (heavy but thoroughly used in test setup)



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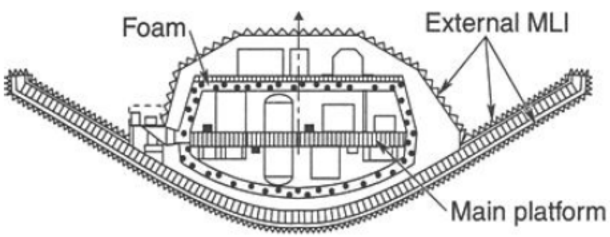
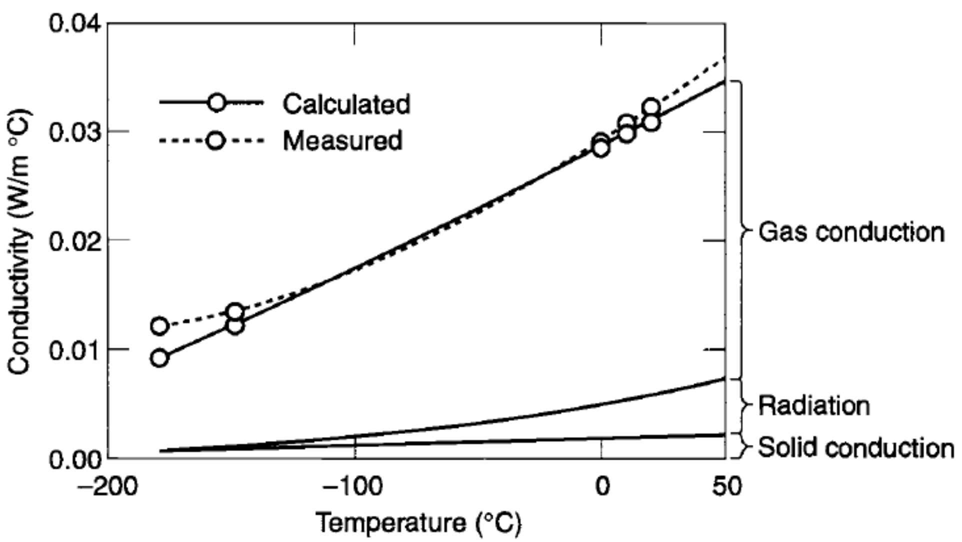
Foam: insulation under atmospheric cond.

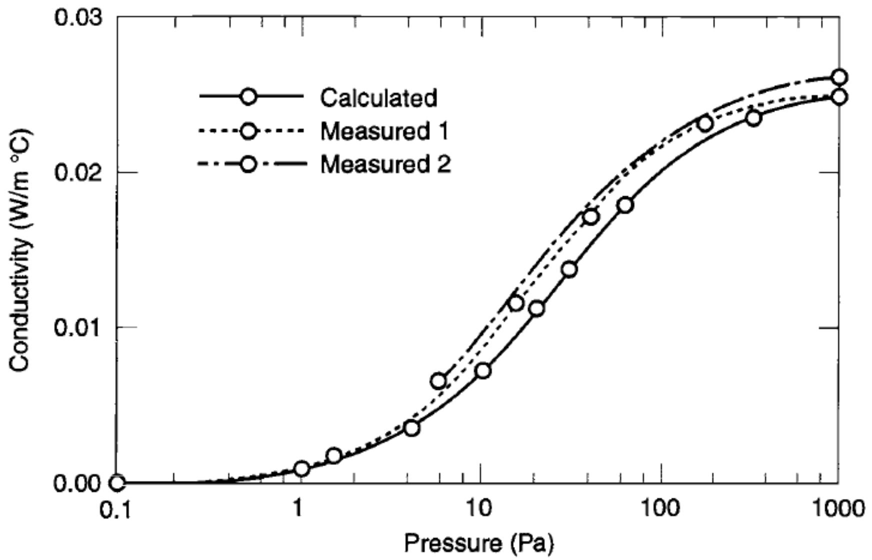
Open cells is preferable (less residual pressure)

Conduction, convection + radiation within cells



Foam used on Huygens probe





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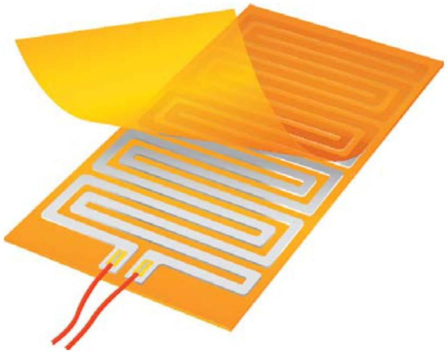
Heater: the most commonly used

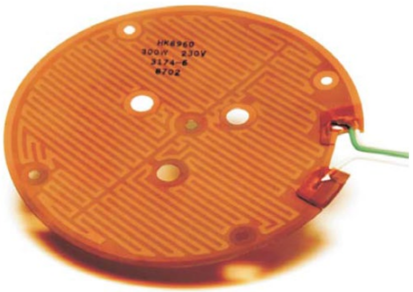
Goals:

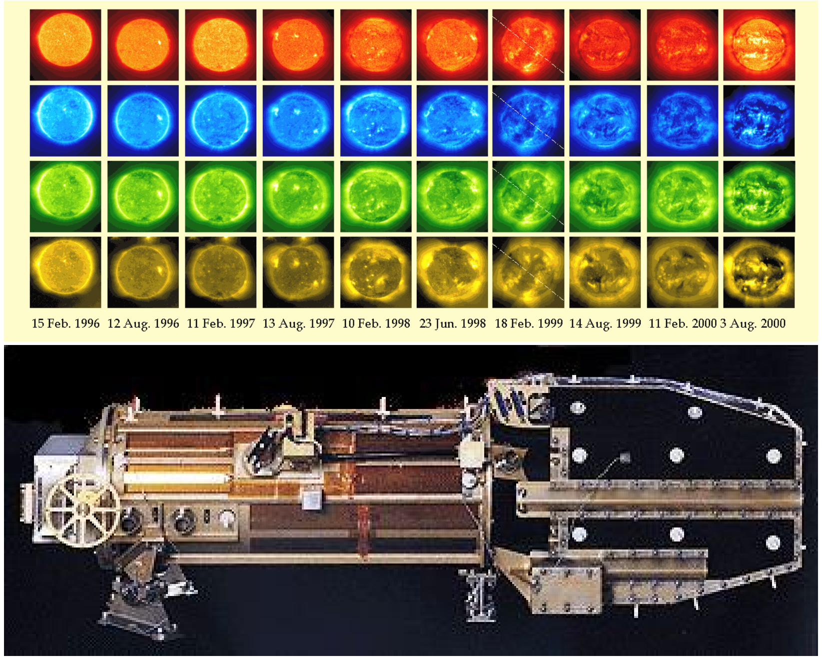
- replace heat dissipated by the unit when it is switched off
- warm up units prior to switch on
- control temperature gradient

OUFTI heater on the battery

Resistive wire embedded in Kapton







EIT on SOHO

How to meet the requirements?

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Peltier: the mirror of thermocouple

Also called TEC (Thermo-Electric Cooler)

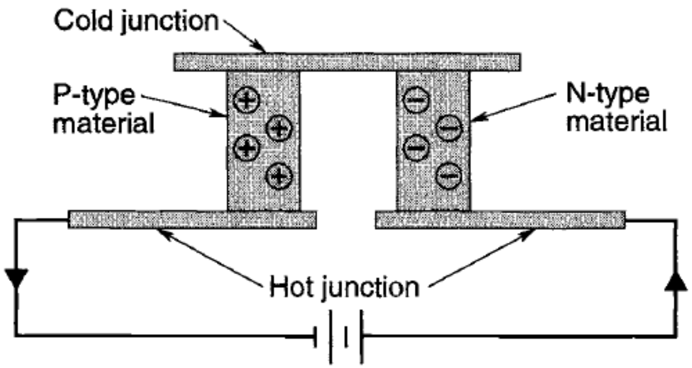
Inverse of the Seebeck effect (Thermo-electric effect)

Low efficiency but: compact, vibrationless, low mass, reliability

May be composed of stacked stages (pyramid, as the heat load increases)

Example: Hubble Space Telescope Imaging Spectrograph (STIS)

- Cold junction: -80°C
- Cooling power: 0.3W
- Rejected power: 17.7W
- Hot junction: 20°C



Another (future) example: CO2M FCU

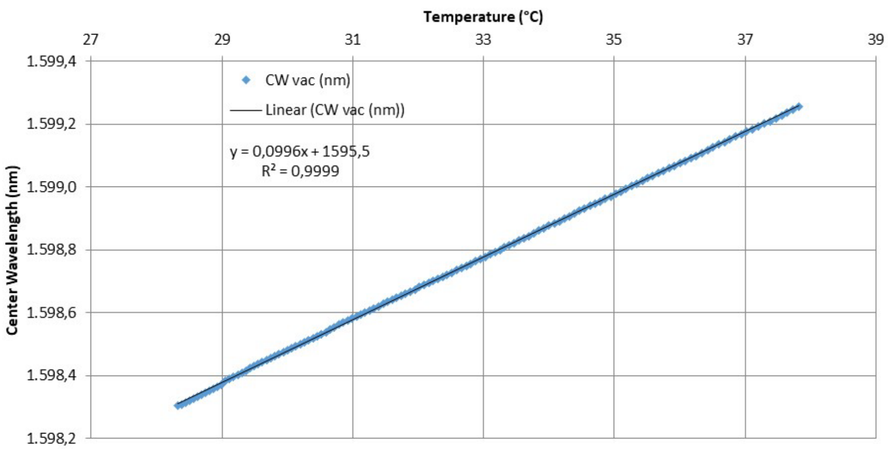
Copernicus Carbon Dioxide Monitoring mission, or CO2M

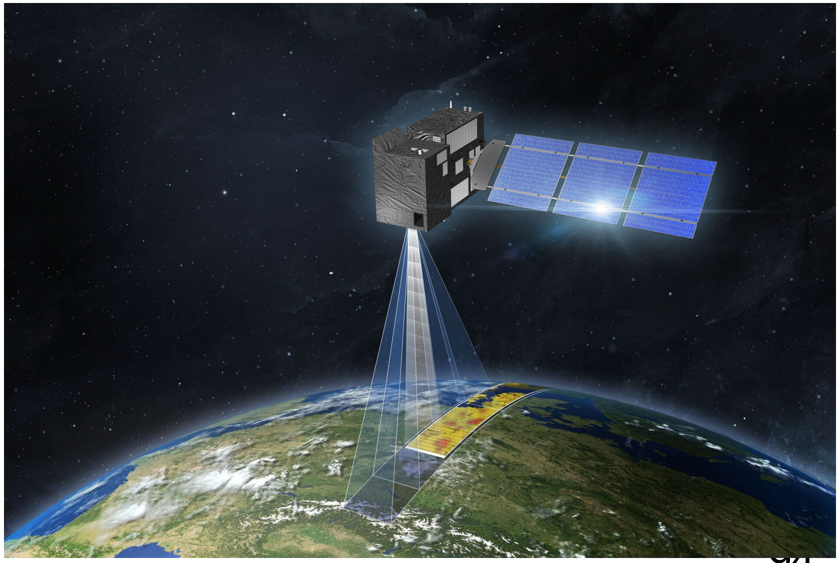
Flight Calibration Unit (FCU)

Laser diodes used for in-flight spectral calibration

→ wavelength regulation (pm) → temperature regulation

→ 2 TECs: 1 coarse & 1 fine





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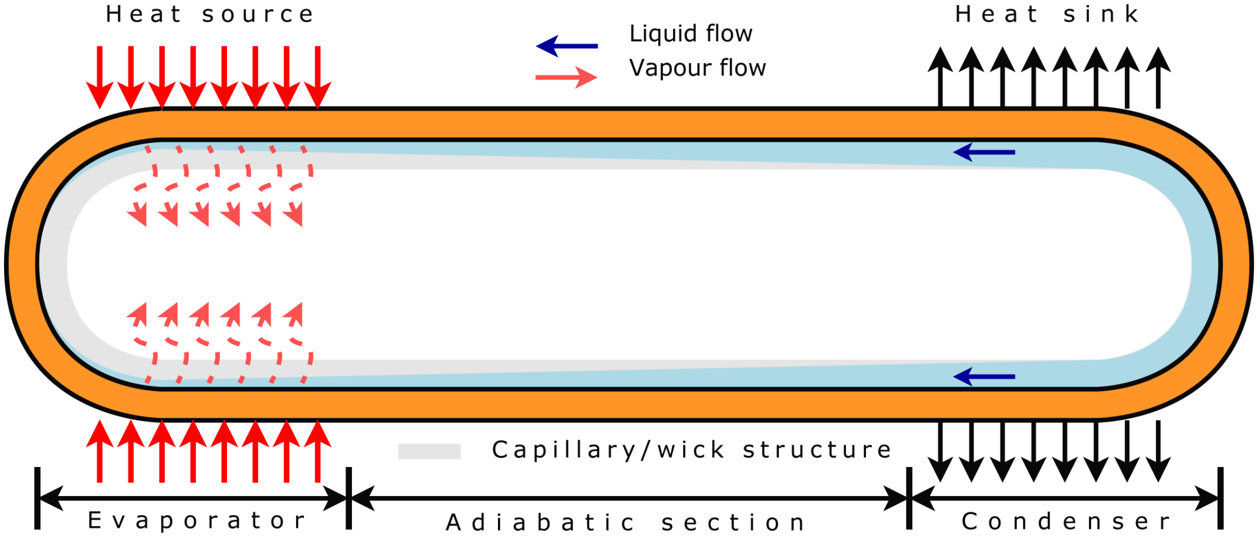
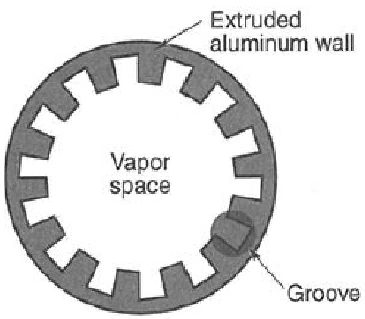
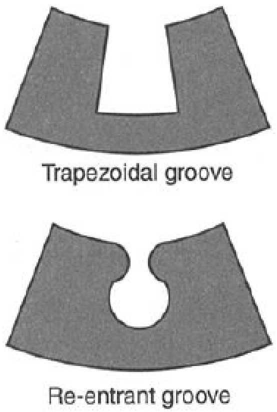
Heat pipe: evaporation + capillarity







Very low gradient

10mm Ø, 1m long heat pipe (50gr): 100W with less than 0.5K gradient

Same size copper: 3300K gradient & 700gr!

Main usage:

- Heat spreader (radiator,…)
- Heat transport over large distances

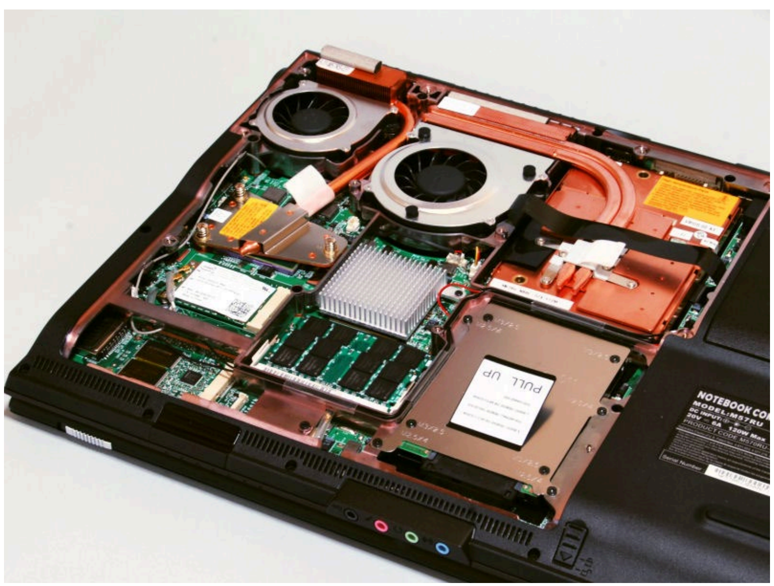
The fluid is such that its boiling point matches the controlled unit temperature range: at ambient T°, NH_3 and H_2O are most common

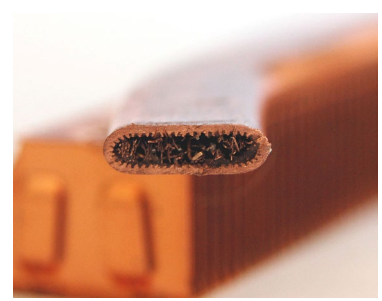
Length of condenser & evaporator are determinant

Gravity is important (capillarity forces > gravity) → impact testing

Heat pipes in your PC

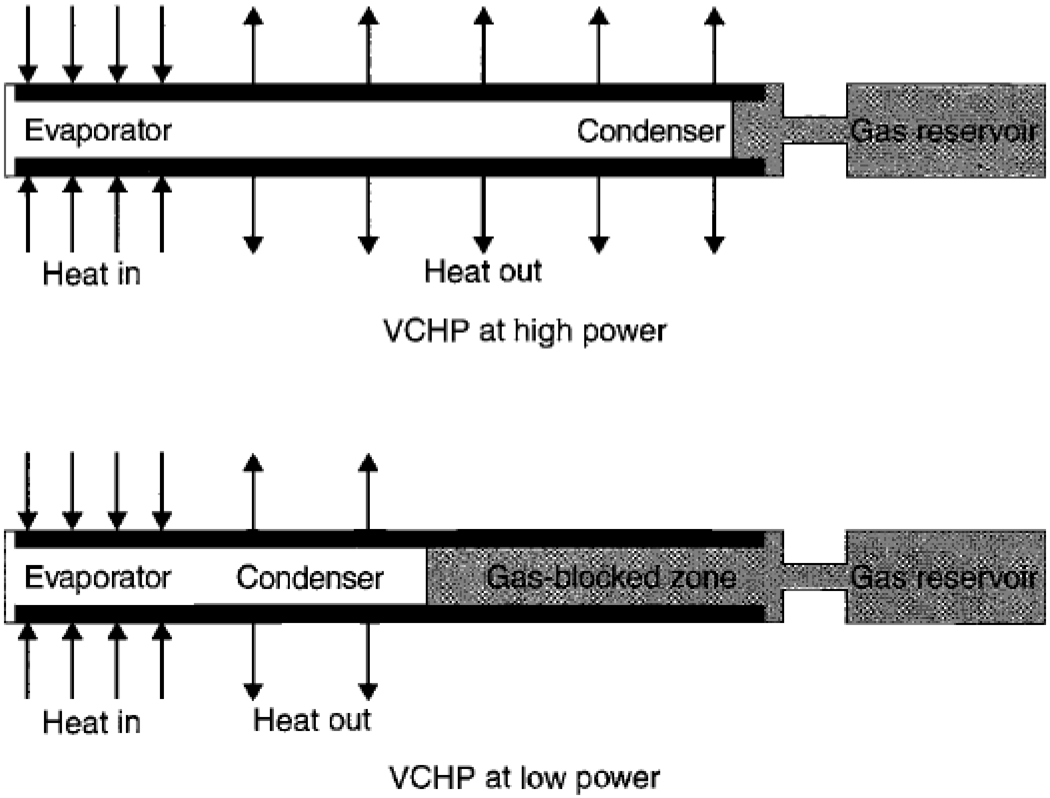
Porous wick





Variable conductance heat pipe

Inert gas varies the length of the condenser



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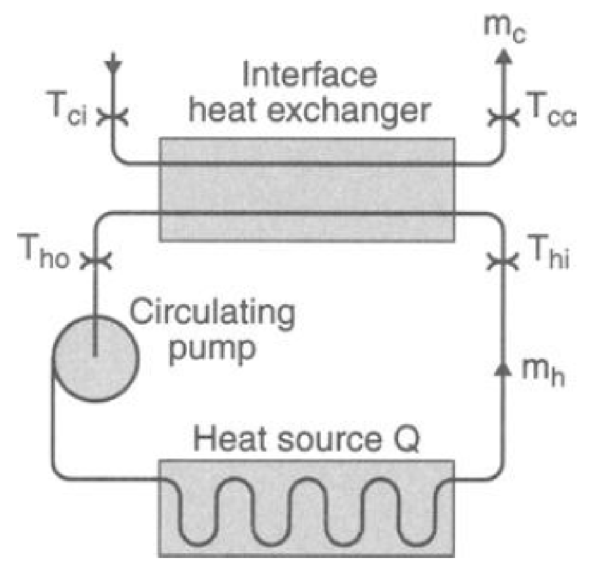
Pumped fluid loops: for large power

Forced liquid convective cooling

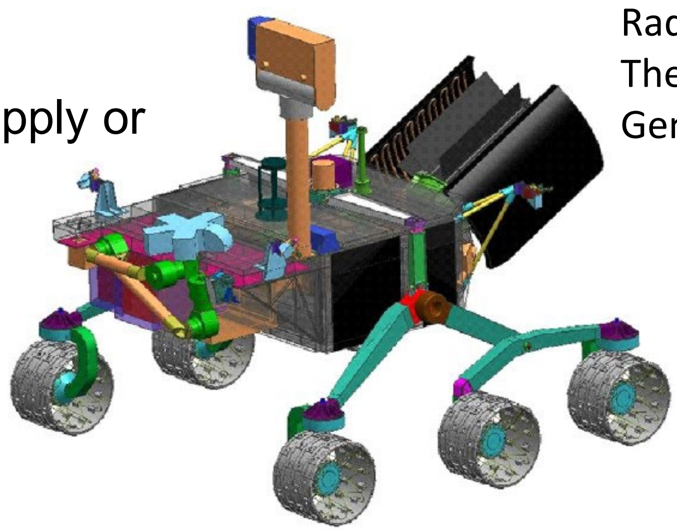
Single phase or biphasic

Used in Space Shuttle, MSL,…



MSL/Curiosity, Mars2020/Perseverance:

- 2000W wasted heat from RTG (~100W Electrical power for ~15years)
- Fluid loop as thermal bus to supply or pick-up heat from electronics



Radioisotope Thermoelectric Generator (RTG)

How to meet the requirements?

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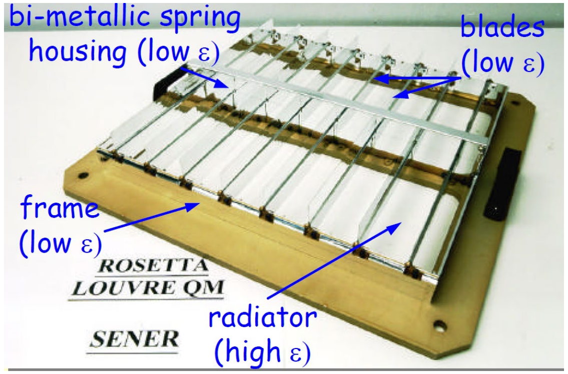
Louvers: like opening your window

Principle: exposing more or less area of a standard radiator to deep space



Variation of effective emittance (radiator: high ϵ, blades: low ϵ)

- Less variation than with a standard radiator
- Save heater power when unit switched off

How to meet the requirements?

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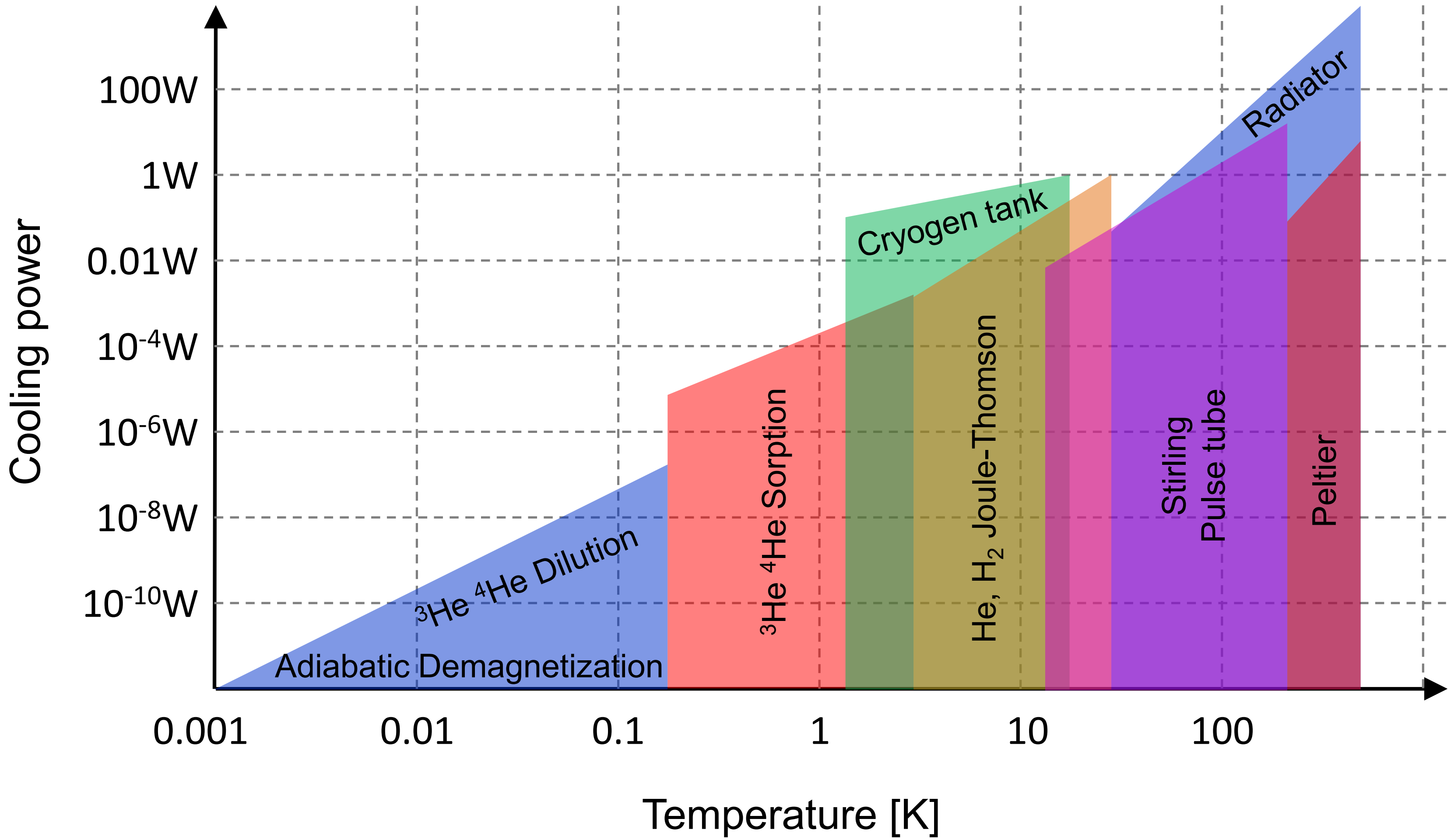
Different cooler types & operation ranges

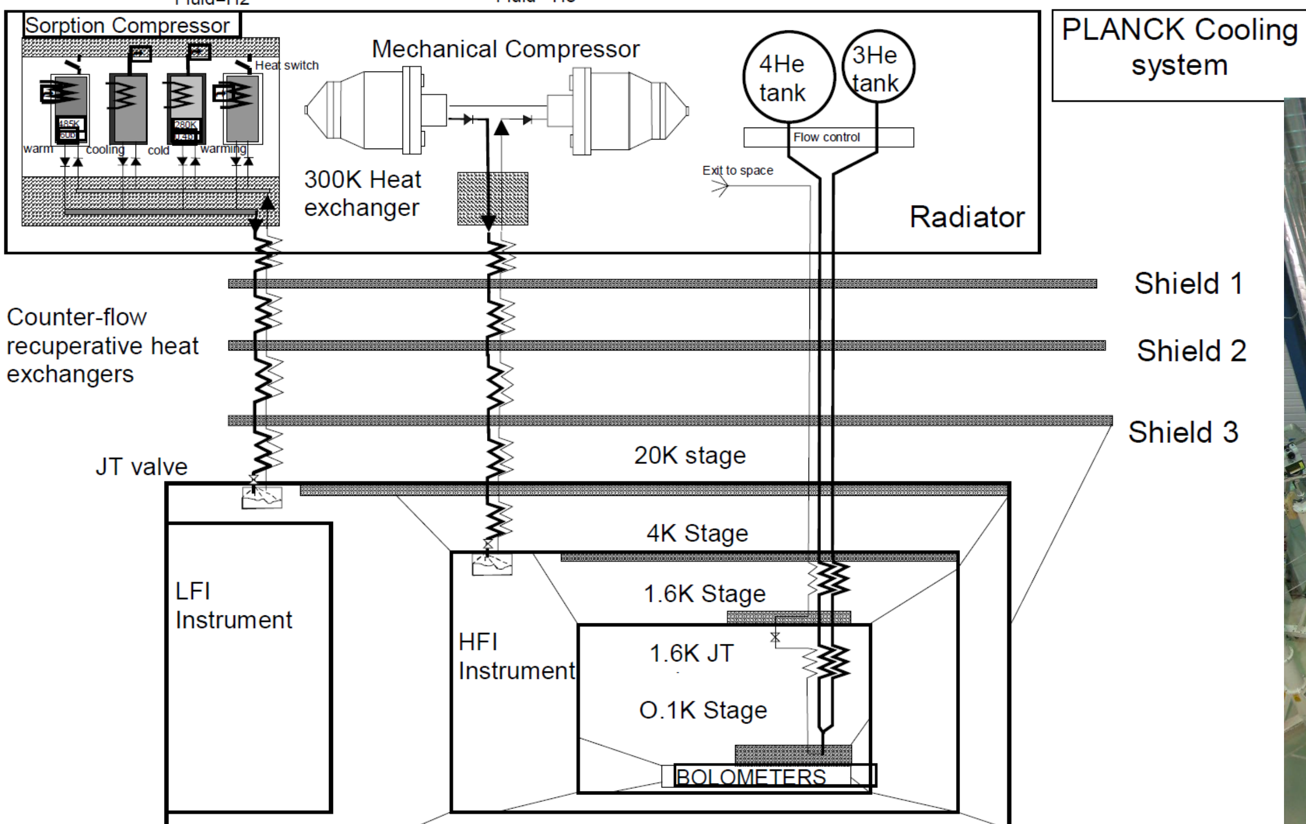


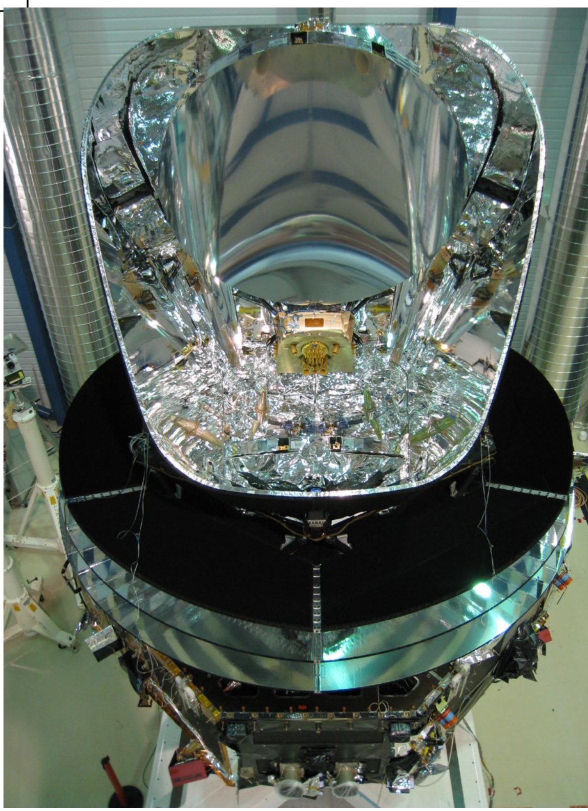
Planck cryogenic system

1W
20K Cooler
Fluid=H2

15mW
4K Cooler
Fluid =He

0.5mW → 1.6K (JT expansion stage)
0.2μW → 0.1K (^{4}He ^{3}He dilution)
Dilution cooler

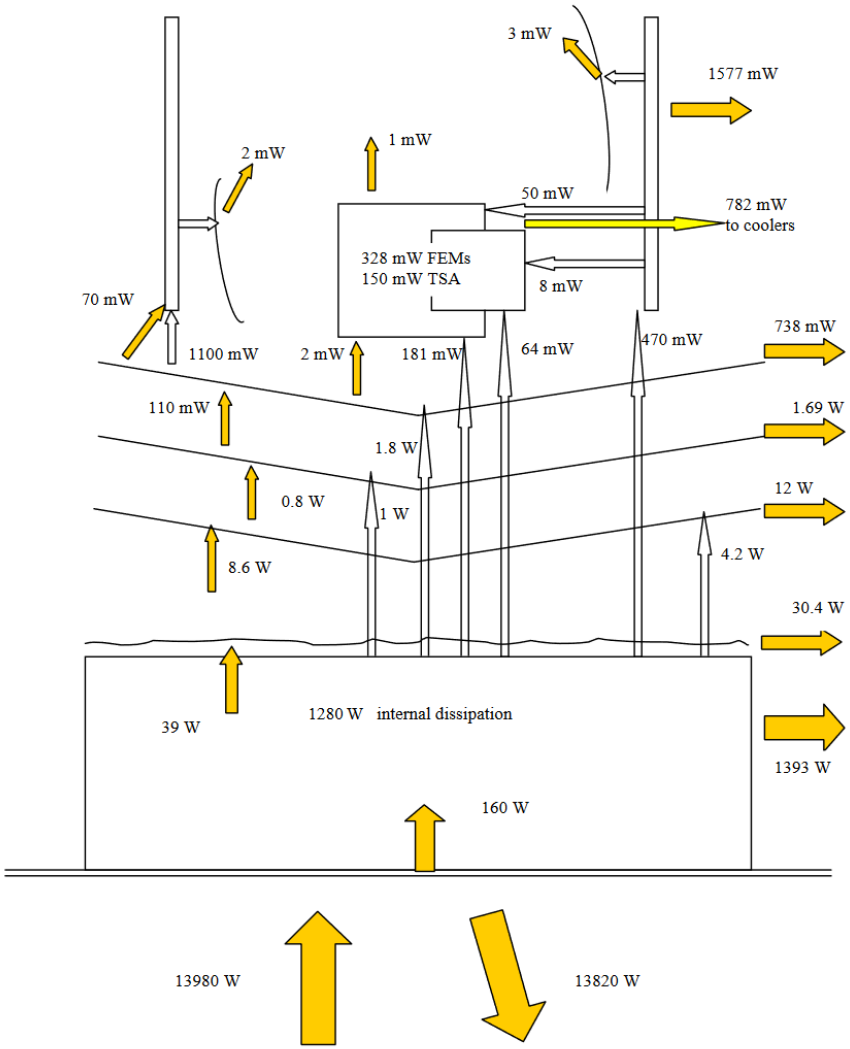




36000 litres of ^{4}He, and 12000 litres of ^{3}He, stored at 300bars (BOL)

Collaudin B, Passvogel T. The FIRST and Planck 'Carrier' missions. Description of the cryogenic systems. Cryogenics. 39. 1999. pp 157-165.

Planck heat flow



Planck Collaboration, Astronomy & Astrophysics manuscript no. Planck2011-1.3

S/C thermal design workflow

Scientific/Mission objectives

⬇

Mission parameters & technical requirements

(Orbit, attitude,…) & (Power, temperatures, gradients, stability)

⬇

Thermal control methods & Mathematical modeling

(active vs. passive control) & (worst case approach,…)

⬇

Testing

(thermal balance, thermal cycling, solar simulator,…)

Finite elements vs. Lumped parameter

Need to compute the radiative exchange factors (REFs) between all faces

→ computationally expensive: $N_{REFs} \propto N^2$ (non-sparse matrix)

→ computed with Monte Carlo ray-tracing

→ computed in visible, IR, at each orbital point + moving geometry

Temperature field smoother than stresses field: no need for mesh as fine as finite element mesh

Lumped parameter method (<1000s nodes) is traditionally used

But FEM is used for structural analyses → quid thermo-mechanical ?

The lumped parameter method

Based on finite difference, electrical network analogy

Isothermal nodes

Heat balance for each node of the model:

$$Q_{in} + \sum_j GR_{ij}\sigma\left(T_j^4 - T_i^4\right) + \sum_j GL_{ij}\left(T_j - T_i\right) = C_i \frac{dT_i}{dt}$$

- GR_{ij} = radiative coupling $[\mathrm{m}^2]$
- GL_{ij} = conductive (or convective) coupling $[\mathrm{W/K}]$
- C_i = nodal capacitance = $\rho_i c_i V_i$ $[\mathrm{J/K}]$

2 mathematical models

The geometrical mathematical model (GMM) used to compute:

- REFs
- Environmental heat fluxes: solar, albedo, IR

The GMM outputs are inputs to the thermal mathematical model (TMM):

- Defines the nodal properties (capacitance, dissipation)
- Defines the nodal conductive couplings (GLs)
- Additional user defined routines (coolers,…)

TMM solved based on previous equation

How to deal with wide range of parameters?

Uncertainties on many parameters, especially in early design phases:

internal dissipation, geometry, efficiency of MLI, degradation of coatings, contact conductance, material properties…

Worst case approach: 1 cold case + 1 hot case that encompass all cases

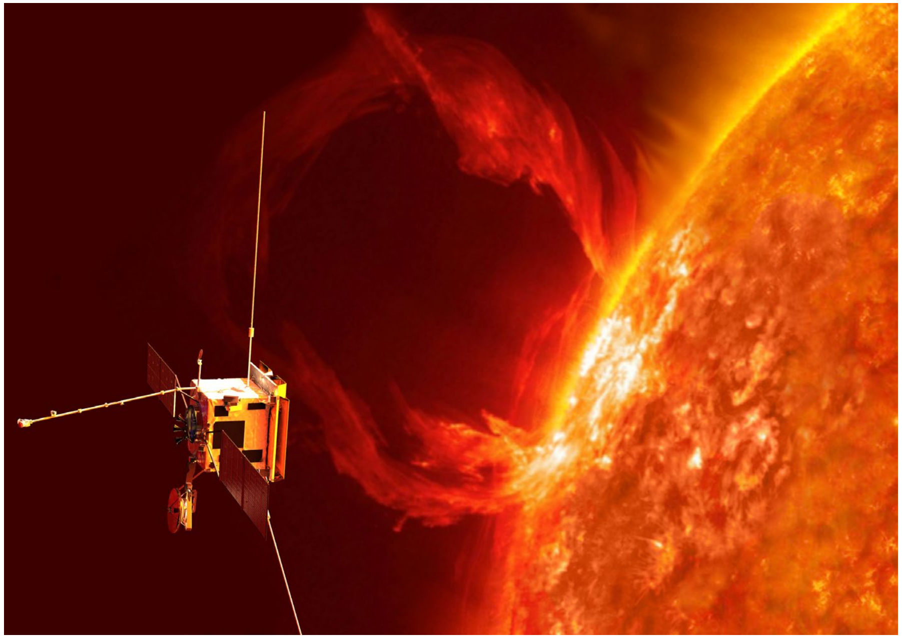
Hot (cold) cases is defined by taking all parameters giving the hottest (coldest) temperature.

Ex: hot case: winter solar constant, increased α, reduced ϵ, k, increased Q

Example: Solar Orbiter

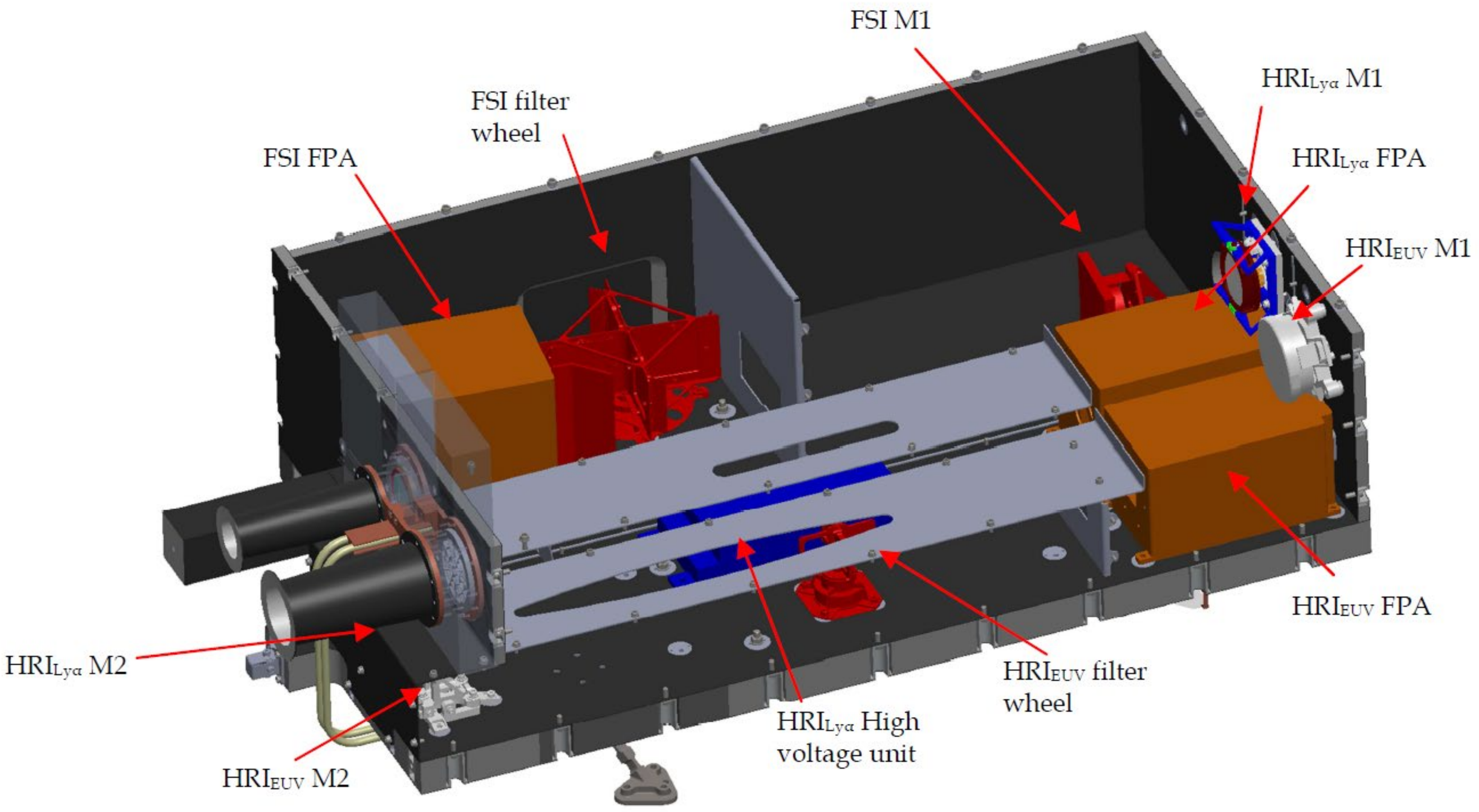
0.28 AU → 17500 W/m²

Heat shield protecting the internal instruments



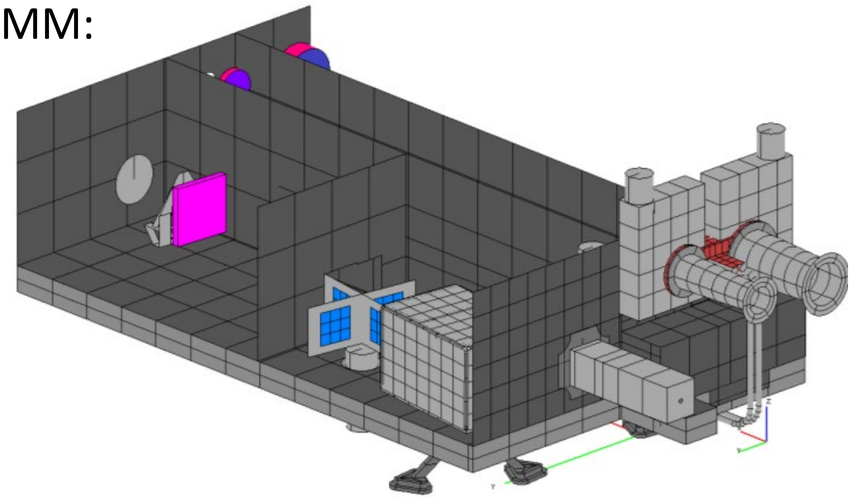
http://www.youtube.com/watch?v=LLMfGeIkA7E
https://www.youtube.com/watch?v=L00J3hZCdFs

Extreme UV Imager (EUI)

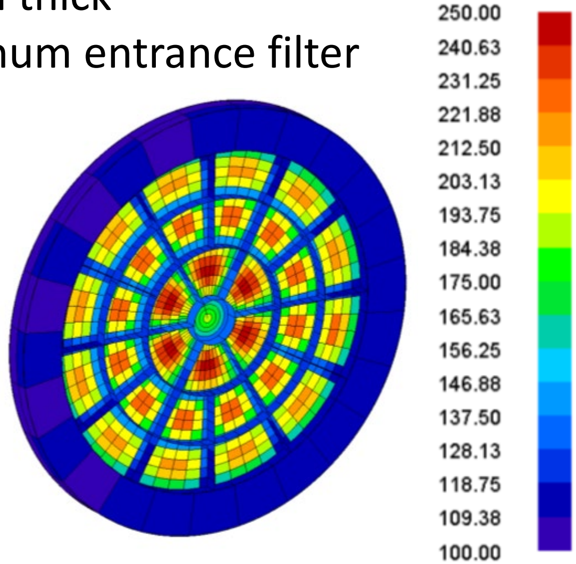


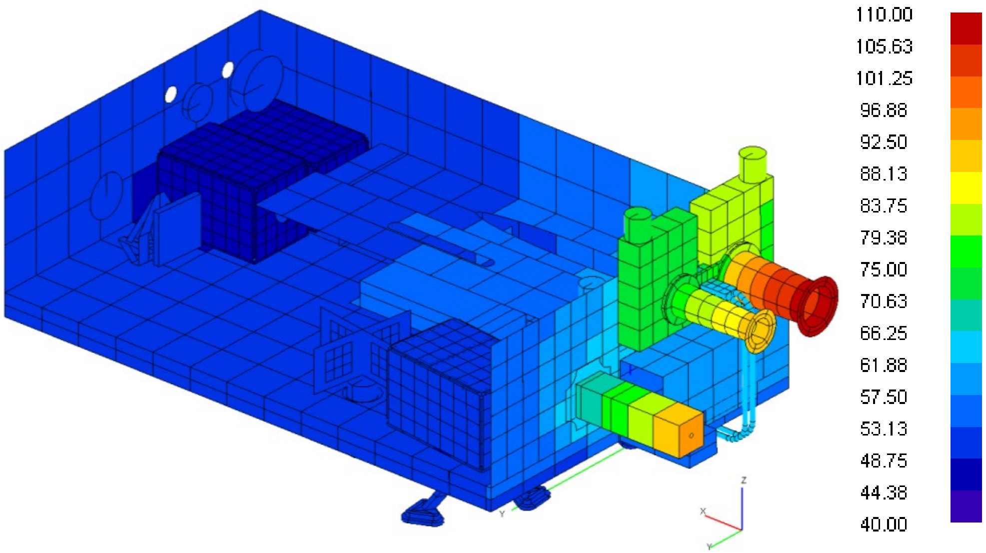
EUI thermal model

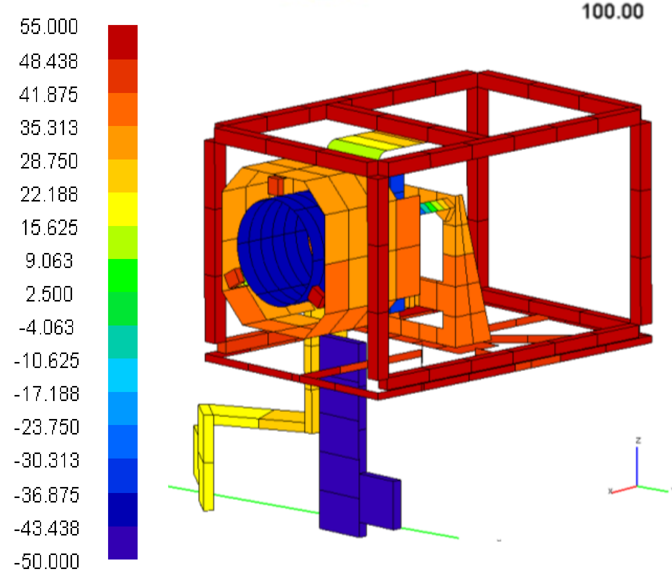
GMM:



150nm thick
Aluminum entrance filter







Knowing the heat path is important

More than just a temperature map!

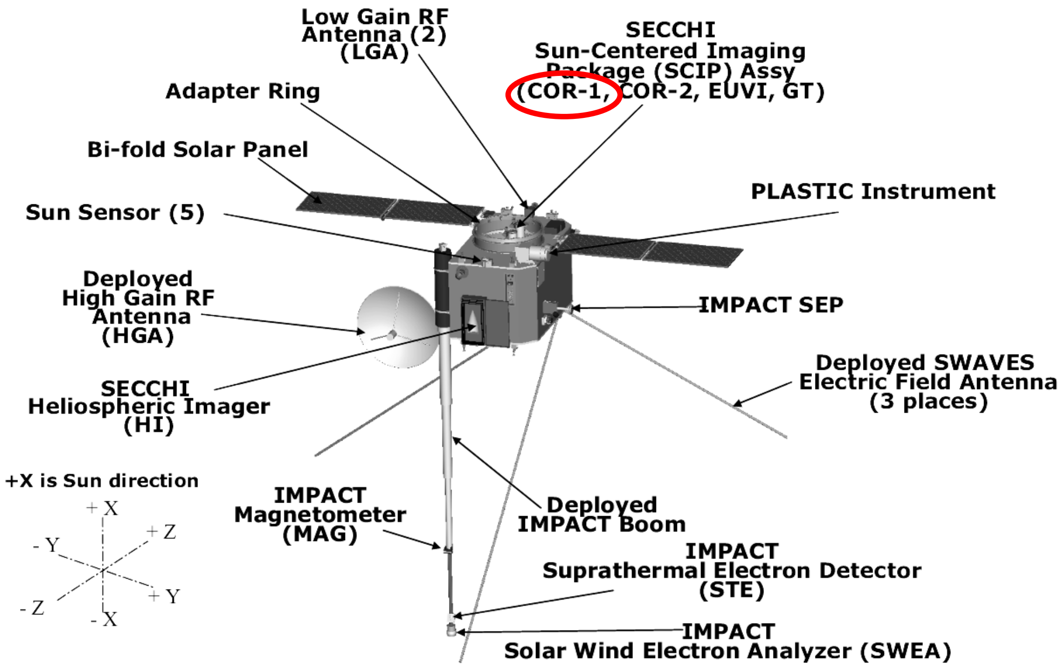
		QS [W]	QB [W]	QS+QB [W]		
HRI EUV	pupil	1.3	0.3	1.5	14.6 W VIS	15.8 W
	baffle	1.8	0.6	2.4	1.2 W IR	
	filter	7.0	0.0	7.0		
	door housing	4.6	0.3	4.9		
HRI Lya	pupil	0.8	0.2	1.0	6.2 W VIS	7.0 W
	baffle	0.6	0.4	1.0	0.8 W IR	
	filter	3.2	0.1	3.3		
	door housing	1.6	0.1	1.7		
FSI	pupil	0.5	0.9	1.5	0.7 W VIS	1.8 W
	baffle	0.0	0.1	0.1	1.1 W IR	
	filter	0.1	0.0	0.1		
	door housing	0.1	0.0	0.1		
Stru (goggles) & MLI		0.4	0.3	0.7		0.7 W
Total		21.9 W +	3.4 W =	25.3 W		

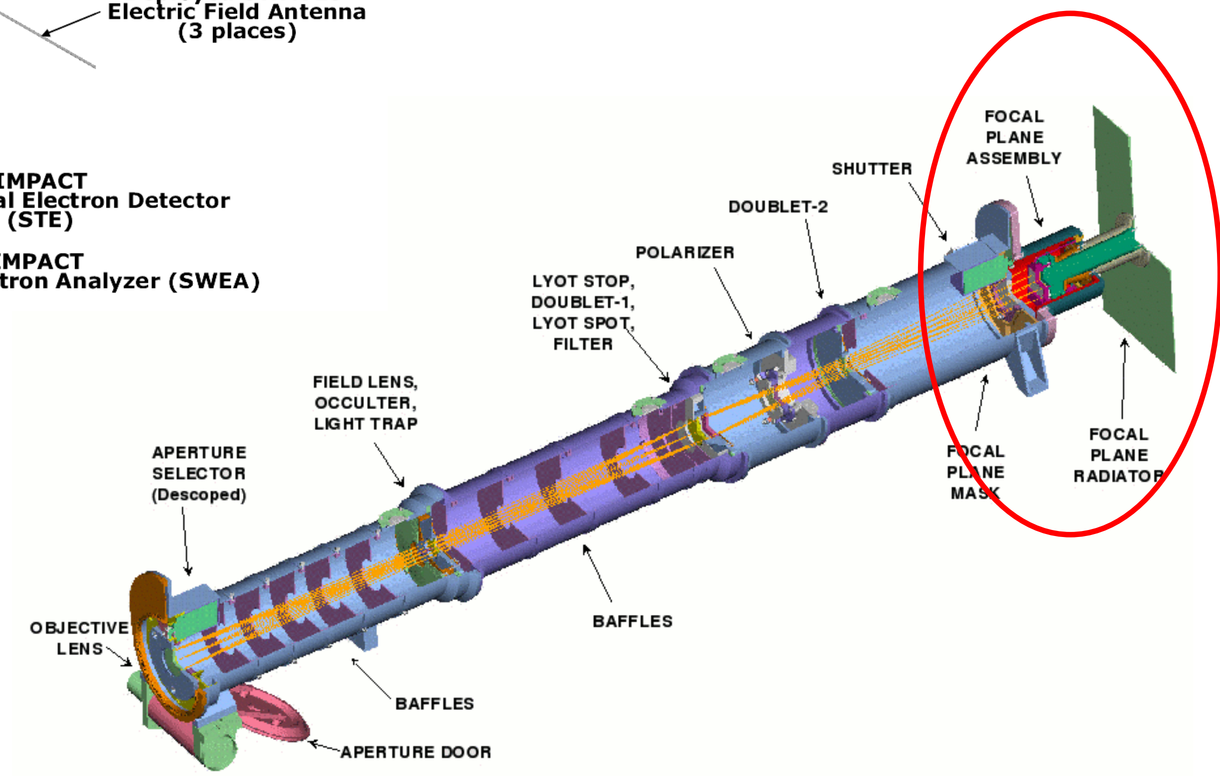
QS+QB 25.3 W → Q TOT 34.8 W ← QI 9.5 W

		Q [W]
Q_{SRP} = 0.1 W		0.10
Q_R = 7.7 W	FPAs CE & ME	-0.71
	Stru	3.20
	MLI	0.33
	EUV	2.73
	Lya	1.56
	FSI	0.61
$Q_{CE,HRIs}$ = 5.7 W	EUV FPA	2.36
	Lya FPA	2.84
	S/C, Stru	0.54
$Q_{CE,FSI}$ = 3.4 W	FSI FPA	3.08
	S/C, Stru	0.29
$Q_{ME,HRIs}$ = 2.8 W	EUV FPA	1.19
	Lya FPA	1.22
	S/C, Stru	0.38
$Q_{ME,FSI}$ = 1.4 W	FSI FPA	1.29
	S/C, Stru	0.12
Q_{HE} = 13.6 W	Heat pipe	13.61

Example: SECCHI COR-1 (STEREO)

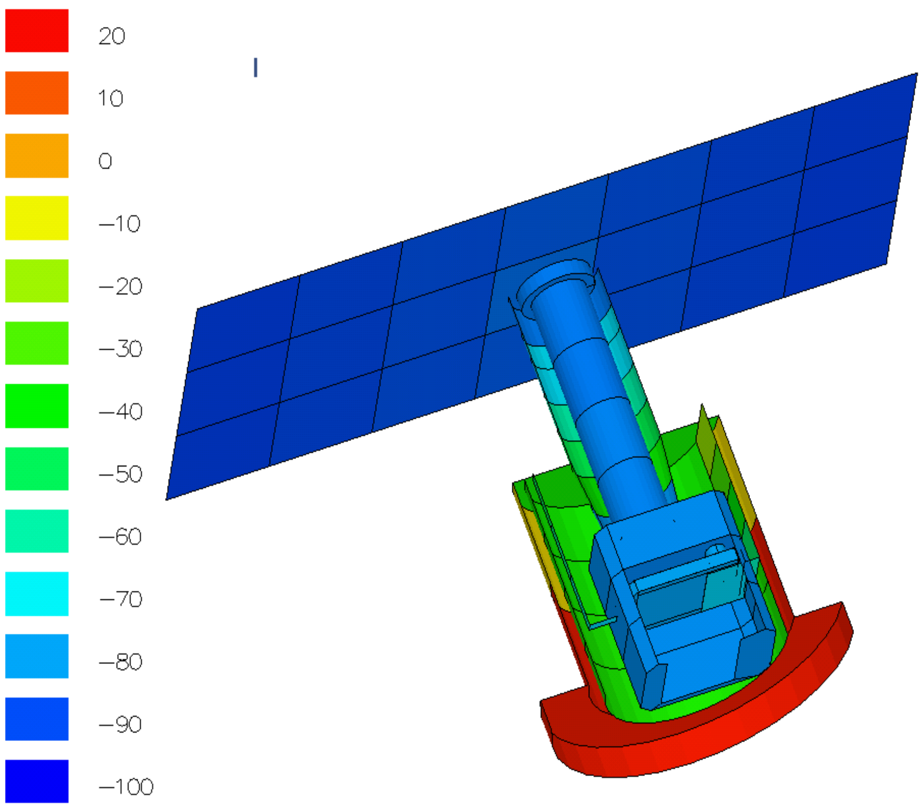
Sun Earth Connection Coronal and Heliospheric Investigation

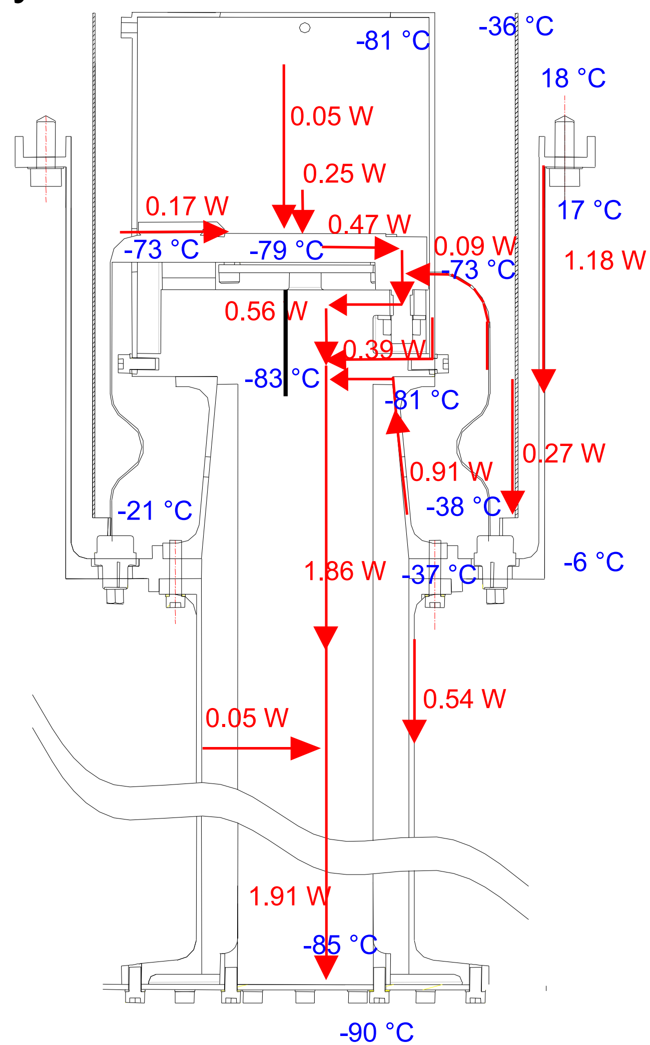




SECCHI COR-1 FPA

FPA = Focal Plane Assembly = detector assembly



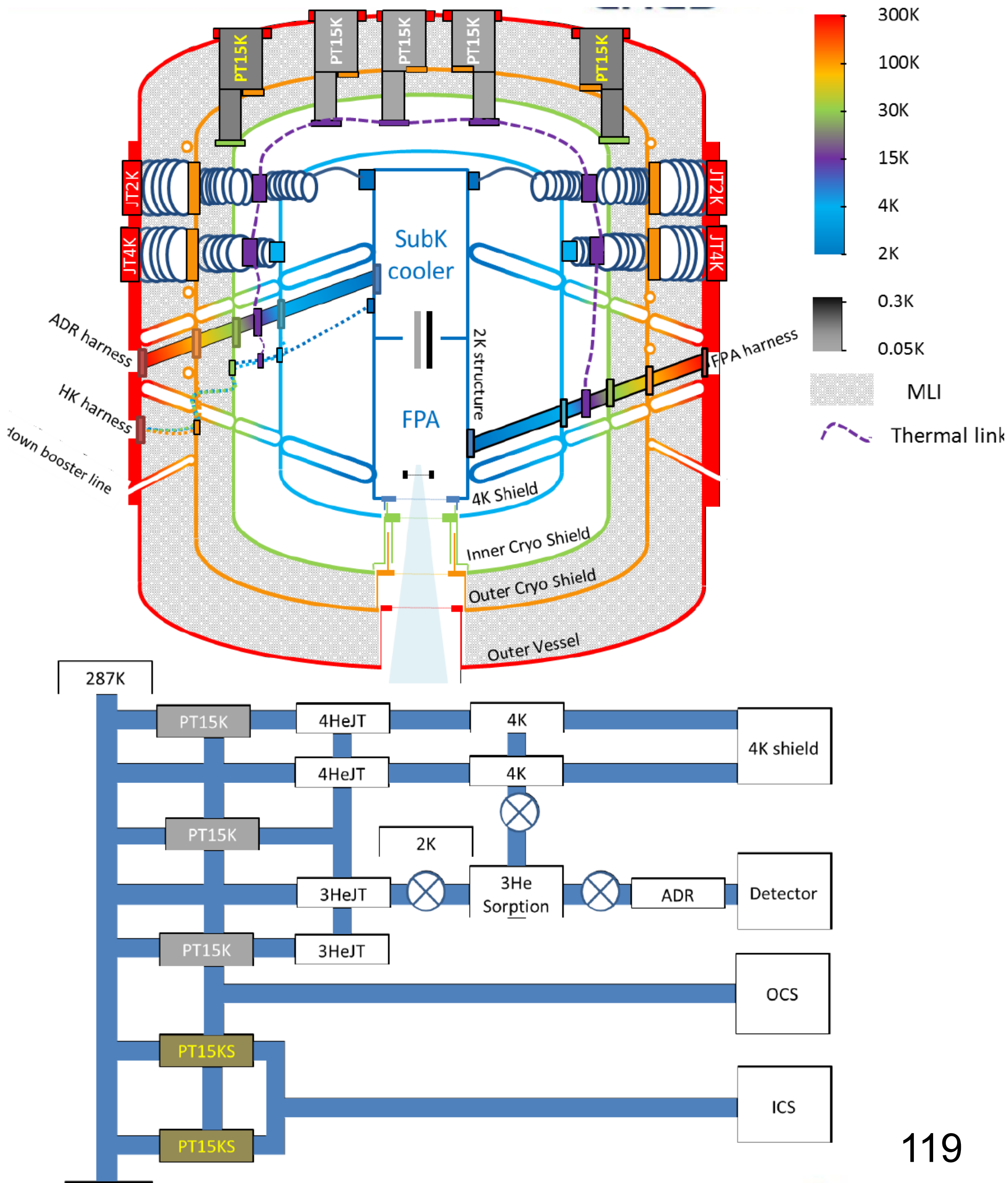


X-IFU onboard Athena

L-class ESA mission

X-ray observatory

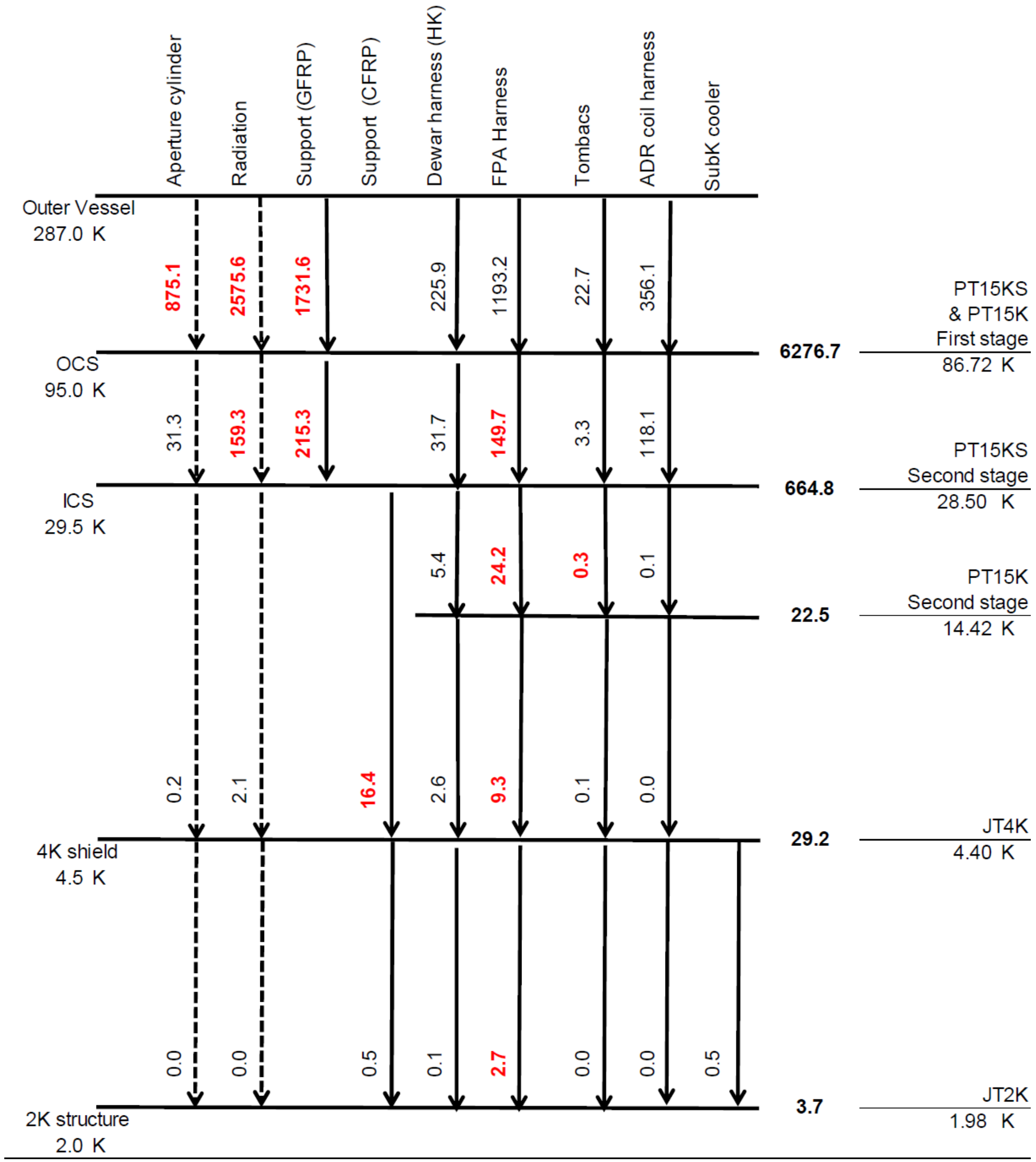
12m long S/C



X-IFU thermal budget

Few mW @ 2K

<1µW @ 50mK



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(active vs. passive control) & (worst case approach,…)

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(thermal balance, thermal cycling, solar simulator,…)

Test to reduce uncertainties…

"When using a mathematical model careful attention must be given to uncertainties in the model."

Report of the Presidential Commission on the Space Shuttle Challenger Accident, Appendix F - Personal observations on the reliability of the Shuttle by Richard. P. Feynman

A chamber to remove convection

Goal: to be representative of the thermal environment

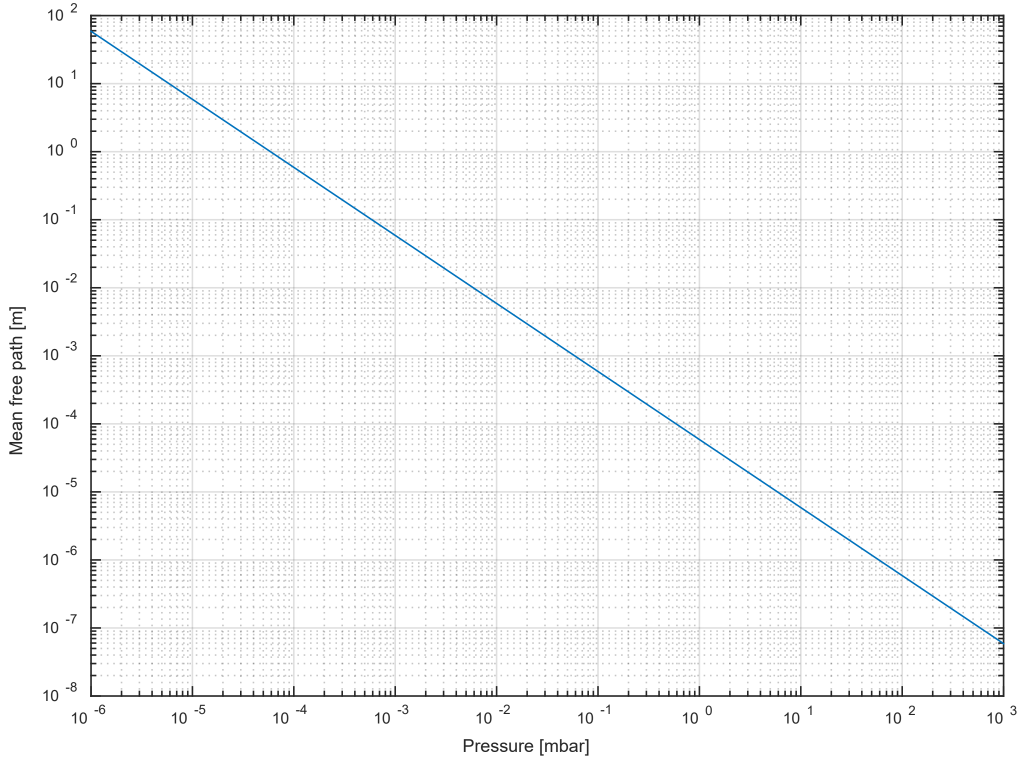
Pressure: related to the mean free path of molecules

Typically P~10^{-6} mbar (~pressure @ 200km)

Mean free path of molecules

$$L_{MFP} = \frac{RT}{\sqrt{2}\pi d^2 N_A P} = \frac{k_B T}{\sqrt{2}\pi d^2 P}$$

N_2 mean free path @300K ($d \sim 4\text{Å}$):



Residual pressure heat transfer

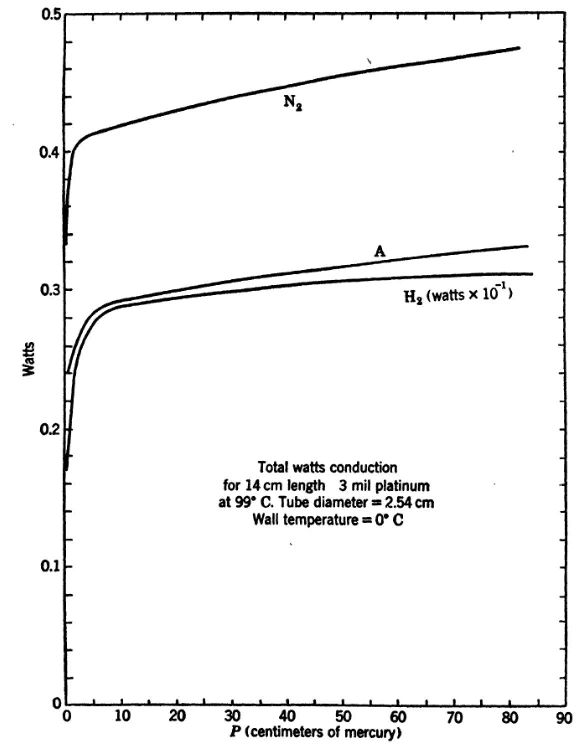
Knudsen number:

$$K_n = L_{MFP}/L_e$$

$L_{MFP} \gg L_e$ (in practice $K_n > 3$): free molecular conduction

molecules directly impinging surfaces without any intermediate collision,

heat exchange $\propto$ to the amount of gas (pressure)



$L_{MFP} \ll L_e$ (in practice $K_n < 0.3$): viscous conduction

independent of pressure,

heat transferred through shocks between molecules

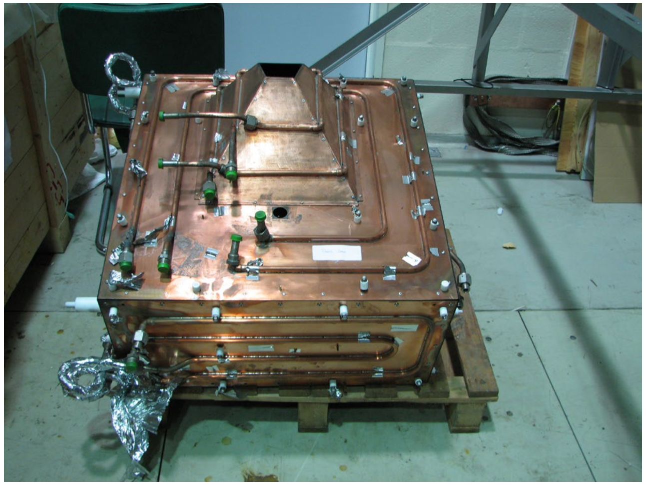
$L_{MFP} \approx L_e$: transition regime

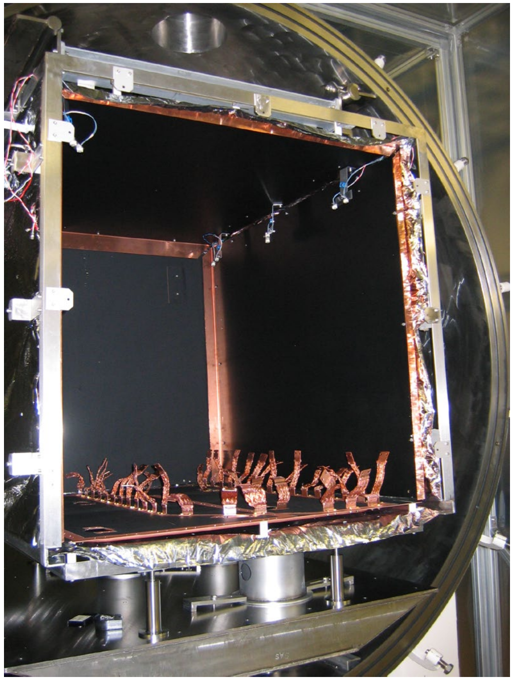
A thermal shroud

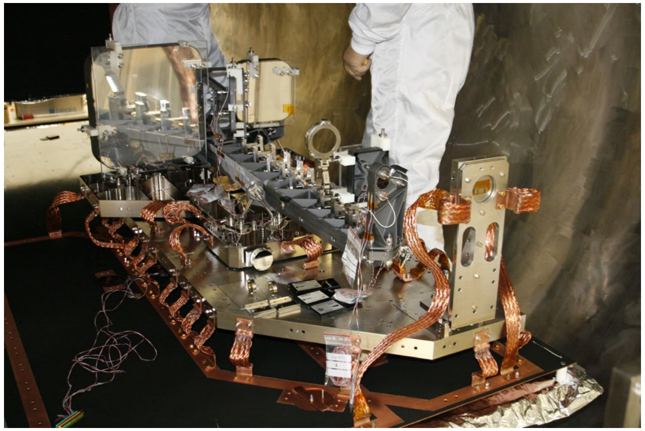
Usually made of copper panels, painted in black, with tubing network in which flows a fluid (LN_2, GN_2, He).

Insulated from the chamber

Good radiative coupling with specimen (black)

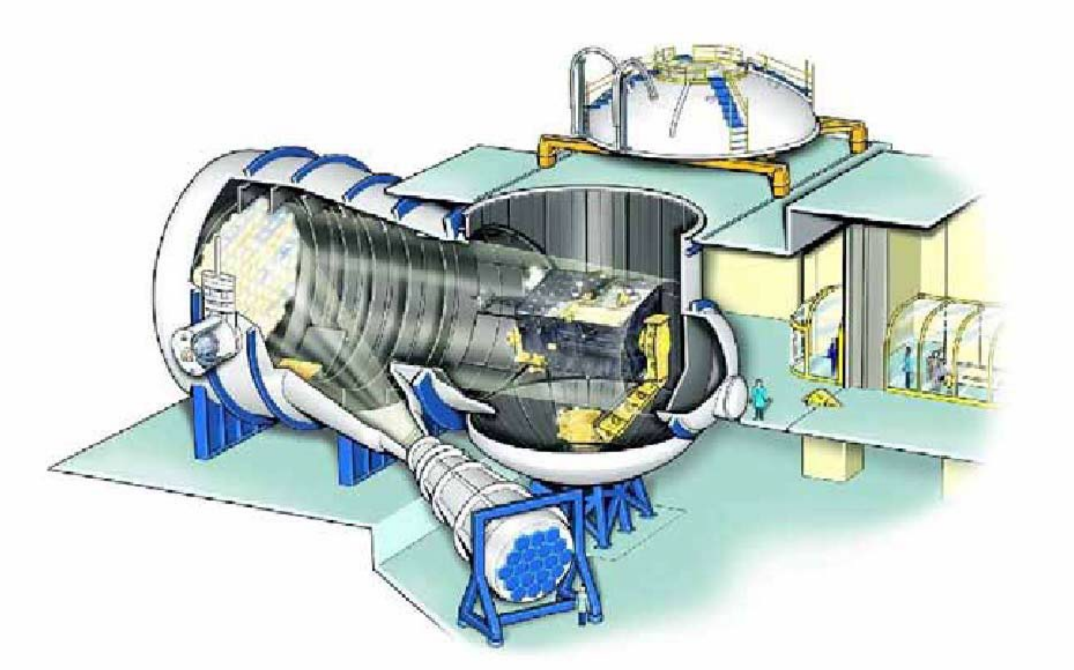




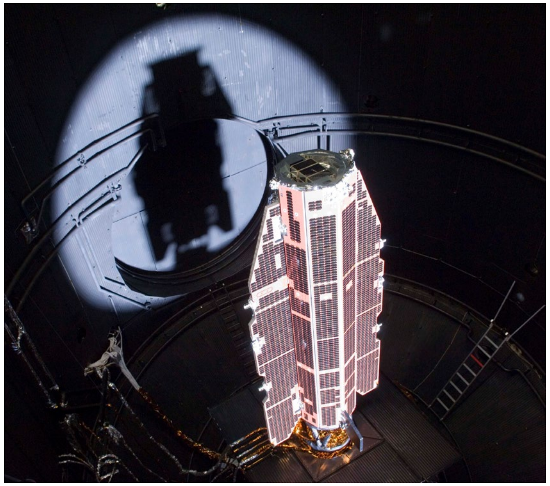


How to simulate the Sun?

Solar simulator or heaters/equivalent IR (assuming known α)



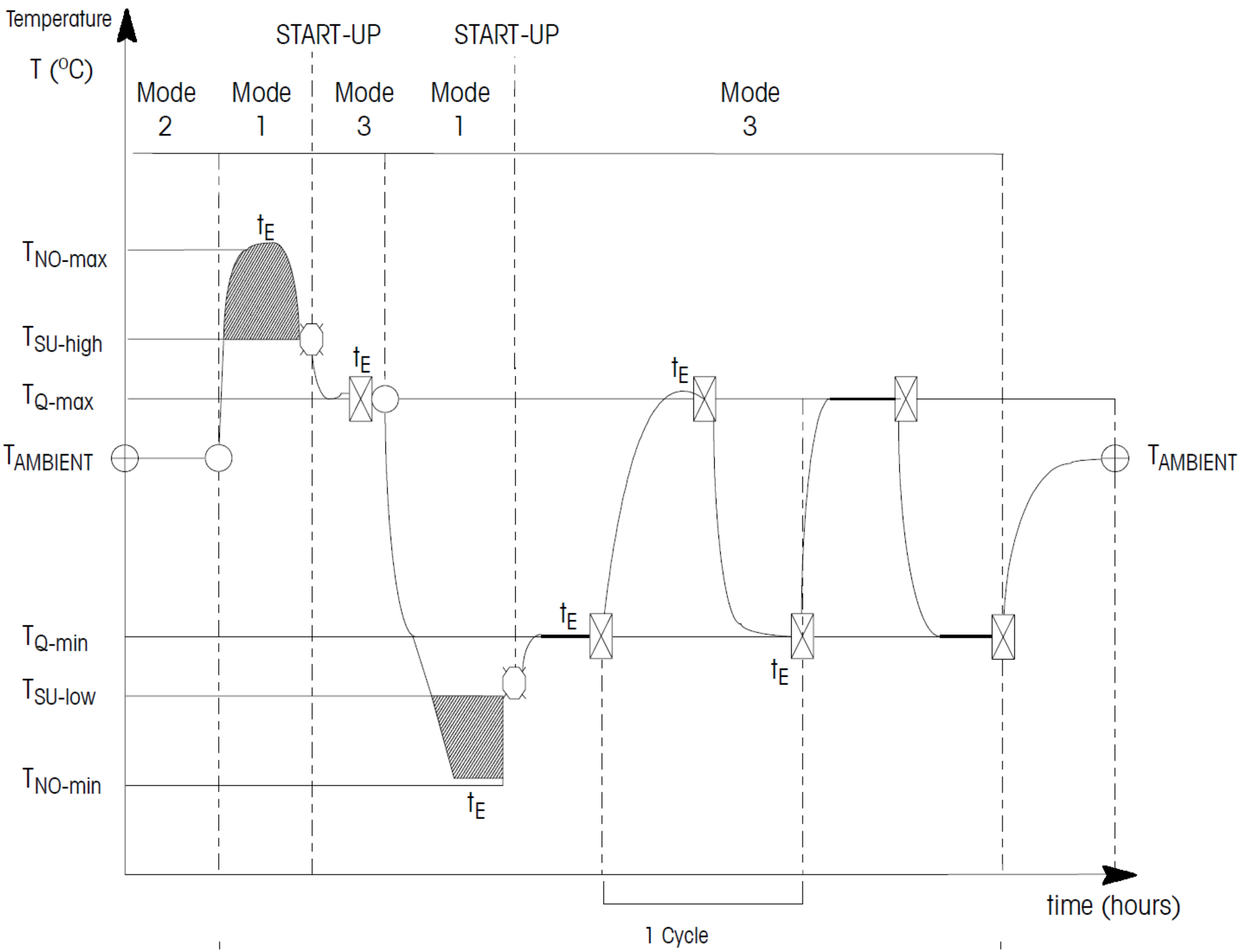
The Large Space Simulator



GOCE in the LSS

Thermal balance + thermal cycling

often combined



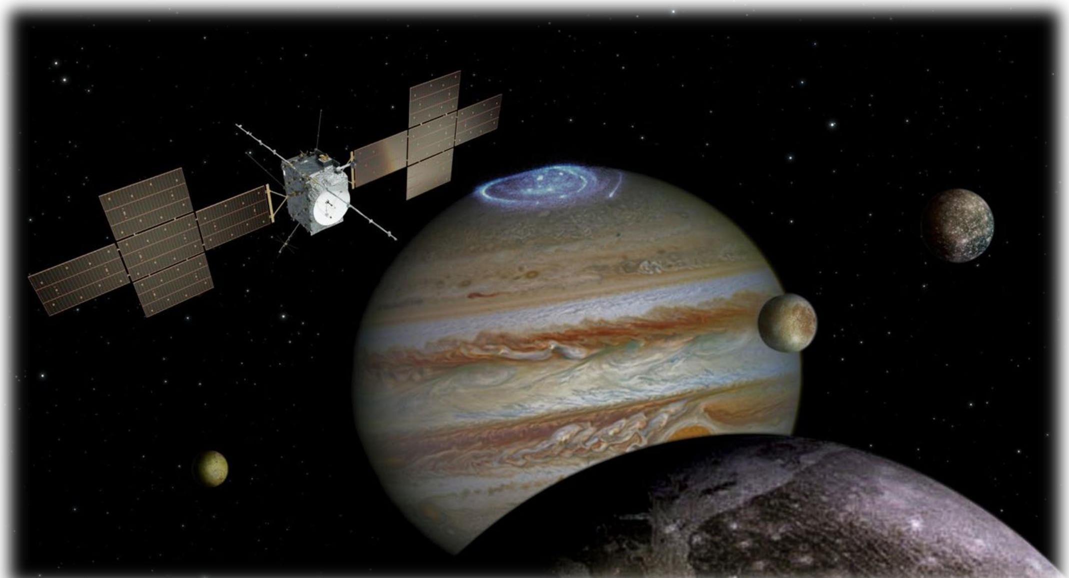
JUICE & Europe Clipper solar panels testing

Jupiter Icy Moons Explorer (JUICE)

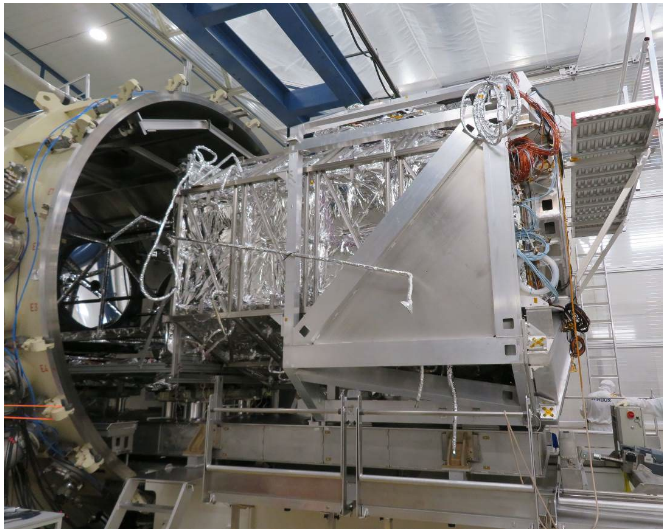
43K (-230°C) → 433K (160°C)

Prohibitive test duration (>200 cycles) with classical facility

→ Wide Range Thermal Facility



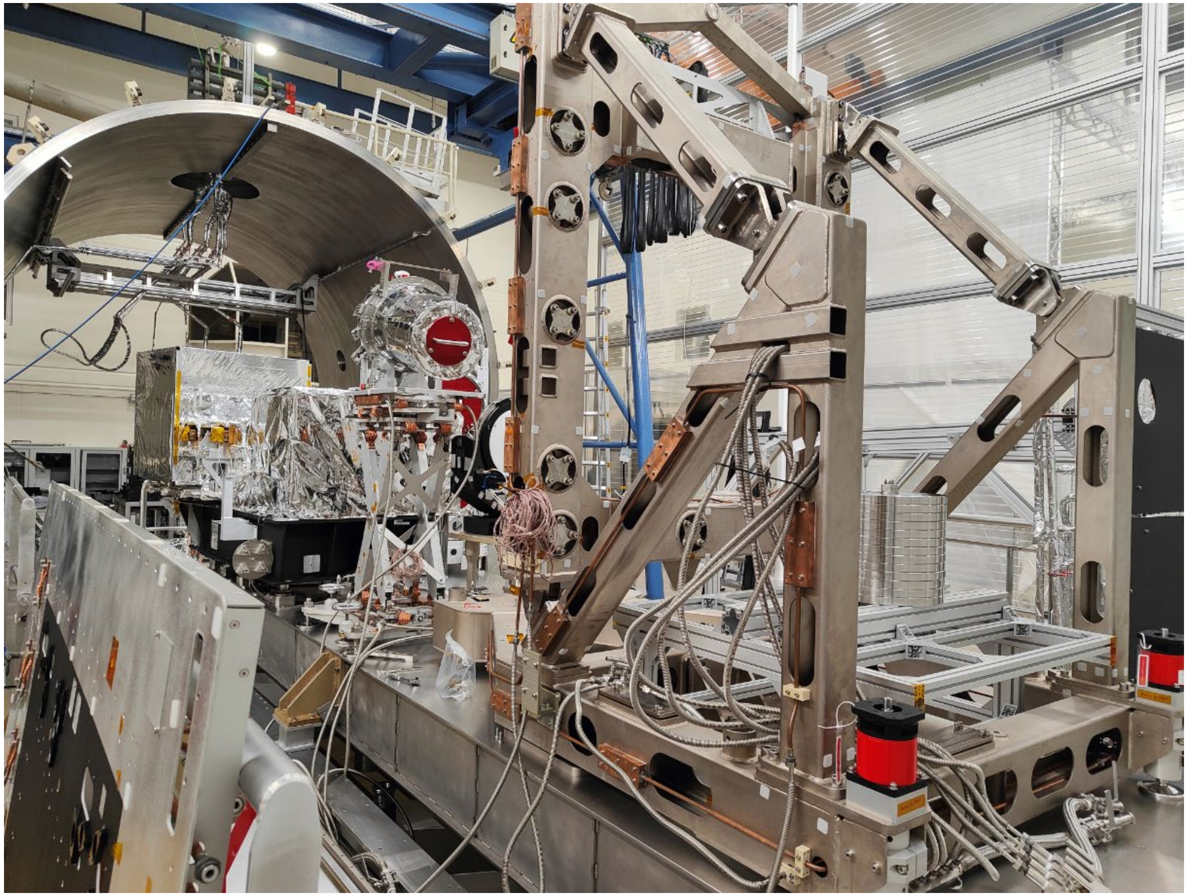
EUCLID PLM testing at CSL



MTG IRS optical thermal performance test

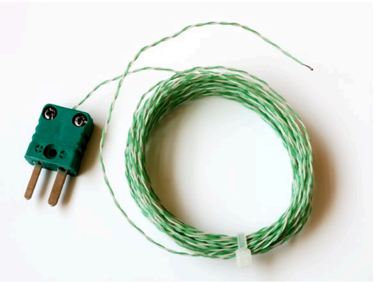
Test setup preparation

Extremely sensitive to contamination (detector cooled ~50K)



Different types of thermal sensors

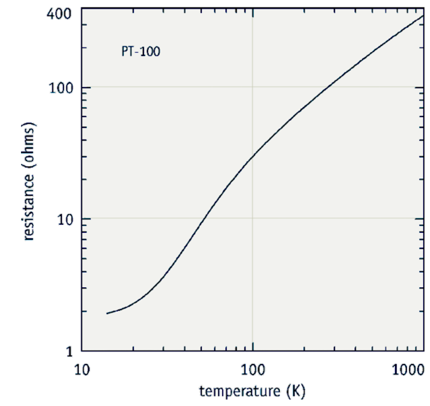
Thermocouples (Seebeck effect): type K, J, T…



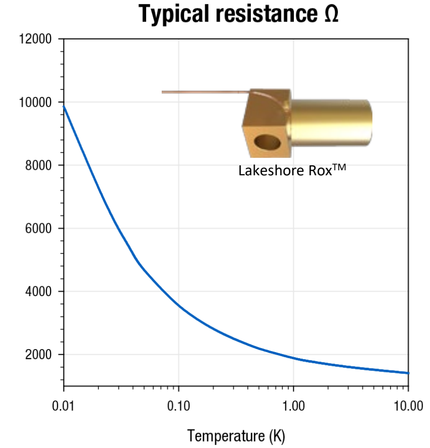
Resistance temperature detectors (RTD):

Positive RTD: PT100 (4 wires), PT1000,…

Negative RTD

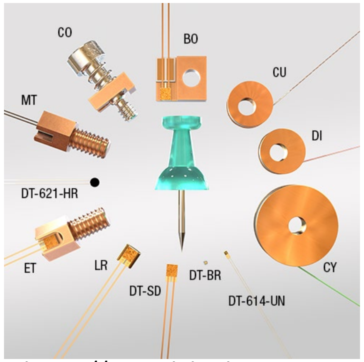


Thermistors (generally a ceramic or polymer)



https://www.lakeshore.com

Diodes (lakeshore)

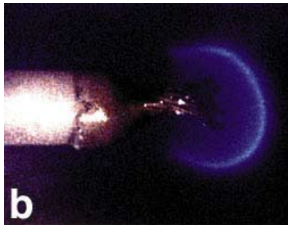


https://www.lakeshore.com

Effects of gravity on thermal design

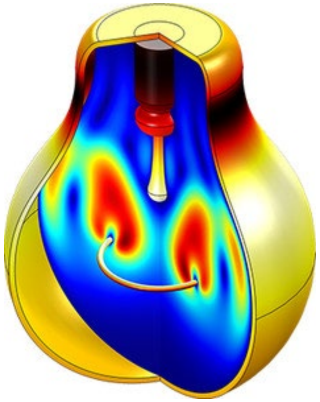
Very difficult to test (parabolic flights…)

Heat pipe operating horizontally or with evaporator below the condenser (gravity helps capillarity forces)



UVN instrument (Sentinel 4):

- on-orbit calibration with incandescent light bulb
- Thermal behavior in micro-gravity: no more free convection
- Modification of the filament T° → modification of the emission spectrum ?

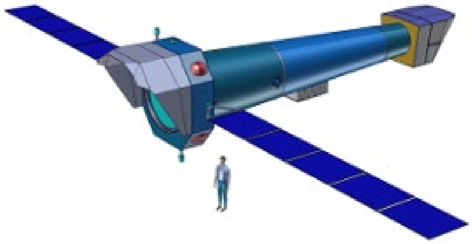


Thermal control, a mission driver!

ISO (1995-1998†)

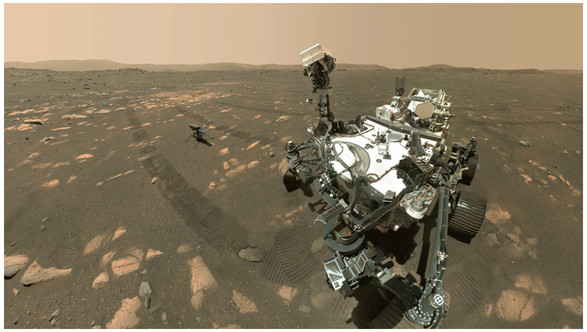
Solar Orbiter (2020)

Athena
(2035)



JWST
(2021)

Planck & Herschel
(2009-2013†) (2009-2013†)



MSL/Curiosity (2011)
Mars2020/Perseverance (2020)

Hubble
(1990)

? →

References

Spacecraft Thermal Design Handbook, D. Gilmore

Spacecraft Systems engineering, P. Fortescue *et al.*

ECSS

Sheldahl Red Book

Conception d’expériences spatiales, P. Rochus, Ulg

Scientific Foundations of Vacuum techniques, Dushman, 1949