Satellite Thermal Control Engineering
prepared for "SME 2004"

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Satellite Thermal Control Engineering

What you will learn?

1. heat transfer basics
   - conduction
   - radiation
   - importance of thermo-optical properties

2. satellite energy balance
   - from ground to space
   - simple satellite thermal behaviour

3. role
   - why thermal control required?

4. design
   - what is thermal design?
   - which types of S/C design exist?

5. means
   - what to control the flux/temperatures
1. Heat Transfer Basics

Thermal Control Engineering

1. heat transfer basics
2. satellite energy balance
3. role
4. design
5. means

ROSETTA* FM in LSS, dec01

*without Solar Panels
1.1 Satellite Heat Transfer Modes

1. Heat Transfer Basics

1.1 satellite heat transfer modes

1.2 conduction

1.3 radiation

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1.1 Satellite Heat Transfer Modes

- **Conduction**
  - between any body
  - eventually by contact through an interface

- **Radiation**
  - main mode of heat transfer in vacuum/space

- **Convection**
  - manned tended satellites (ISS, shuttle, launchers, ascent...)

- **Ablation**
  - combination of 3 and chemical reaction (re-entry vehicles)
1.2 Conduction

1. Heat Transfer Basics
   1.1 satellite heat transfer modes
   1.2 conduction
   1.3 radiation

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1.2 Conduction

• **Definition**
  - propagation of energy from particle to particle
  - in solid, liquid or gaseous continuous matter, homogeneous or not
  - without matter displacement

• **Fourier’s Law**
  \[ \vec{q} = -k \nabla T \]

- \( \vec{q} \) is the heat flow rate vector (W/m\(^2\))
- \( k \) is the material thermal conductivity (W/m\(^2\).K)
- one-dimensional conduction

\[ Q = \frac{k A}{l} (T_h - T_c) \]
Thermal Conductivity

- Copper
- Aluminium
- AA5083-T0
- 304 ss
- G-10 // to warp
- Ti
- Epoxy
- PE //
- Cu-Ni (70-30)
- Brass Cu-Zn (90-10)
- Mylar PET amorphous
1.3 Radiation

1. Heat Transfer Basics
   1.1 satellite heat transfer modes
   1.2 conduction
   1.3 radiation

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1.3 Radiation

- **Characteristics**
  - propagation of electro-magnetic energy in straight line
  - between surfaces separated by
    - absorbing, scattering media
    - or in vacuum
  - hence without matter displacement
  - reflected, absorbed or transmitted on surrounding bodies

- **Source**
  - thermal agitation of particles
1.3 Radiation - Black Body

- **Black Body**
  - is real or fictitious surface
  - that absorbs all incident radiant energy i.e.
    - from every direction
    - at every wavelengths
  - isotropic emitter
    - radiated energy depends only on temperature

- **Black Body Emitted Energy**

  Planck's Law
  \[
  E_{\lambda,T} = \frac{2\pi h c^2}{\lambda^5} \frac{h c}{e^{\frac{h c}{k_B \lambda T}} - 1} (W/m^2 \mu m)
  \]

  Stefan-Boltzmann's Law
  \[
  E_{bb,T} = \sigma T^4 (W/m^2)
  \]

\[\begin{align*}
\alpha(\theta, \lambda) &= \alpha = 1 \\
\varepsilon(\theta, \lambda) &= \varepsilon = 1
\end{align*}\]
1.3 Radiation – Black Body

Planck and Stefan-Boltzmann Laws

\[ E_{\lambda, T} = \frac{2 \pi \sigma \lambda^5}{e^{\frac{\lambda}{kT}} - 1} \]

\[ E_{\lambda, T} = \sigma T^4 \]

- SUN: \( 5776 \text{ K} \)
- EARTH: \( 255 \text{ K} \)

Area = \( \sigma T^4 \)
1.3 Radiation - Real Body

- can absorb, reflect or transmit radiation energy

\[ \Phi_\lambda \text{ incident} \quad \rho_d \Phi_\lambda \text{ diffusely reflected} \quad \rho_s \Phi_\lambda \text{ specularly reflected} \quad \alpha \Phi_\lambda \text{ absorbed} \quad \tau \Phi_\lambda \text{ transmitted} \]

- all parameters are wavelength and angular dependent

- general case: semi-transparent

\[ \alpha(\lambda) + \rho(\lambda) + \tau(\lambda) = 1 \]

\[ \rho = \rho_s + \rho_d \]

- opaque

\[ \tau(\lambda) = 0 \]

hence

\[ \alpha(\lambda) + \rho(\lambda) = 1 \]
1.3 Radiation - Real Body

- **Surface Emissivity**
  - ratio of surface radiated energy to that of a black body at the same $T$
  - always <1 for a real surface

\[
\varepsilon(\theta, \lambda) = \frac{\int_0^\infty \alpha_{\lambda,T} E_{\lambda,T} \, d\lambda}{\int_0^\infty E_{\lambda,T} \, d\lambda} < 1
\]

for a black body $\varepsilon(\theta, \lambda) = \varepsilon = 1$

- depends on direction $\theta$ and wavelength $\lambda$ of emitted energy
- therefore can be
  - directional (d) or hemispherical (h)
  - spectral (s) or total (t)
  - averaged over all directions, wavelengths or both
1.3 Radiation - Real Body

- **Surface Absorptivity**
  - ratio of surface absorbed energy to incident energy
  - always <1 for a real surface

\[
\alpha(\theta, \lambda) = \frac{\int_0^\infty \alpha_{\lambda,T} E_{\lambda,T} d\lambda}{\int_0^\infty E_{\lambda,T} d\lambda} < 1
\]

for a black body \( \alpha(\theta, \lambda) = \alpha = 1 \)

- depends on incident energy direction \( \theta \) and wavelength \( \lambda \)
- therefore can be
  - directional (d) or hemispherical (h)
  - spectral (s) or total (t)
  - averaged over all directions, wavelengths or both
1.3 Radiation - Real Body

• Absorptivity vs Emissivity
  - for a given direction $\theta$ and at any wavelength $\lambda$

2nd Kirchoff’s Law

$$\alpha(\theta, \lambda) = \varepsilon(\theta, \lambda) \quad \forall \theta, \forall \lambda$$

- in general hemispherical total values are different

$$\alpha \neq \varepsilon$$

because

- $\alpha$ and $\varepsilon$ have a strong wavelength dependence

- source temperature of incident radiation (Sun at 5776 K) different than surface temperature (satellite -250 -> 300°C)
1.3 Radiation - Real Body

- Solar Absorptivity $\alpha_S$ and Hemispherical Emissivity $\varepsilon_H$

$\alpha_S$ is the solar absorptivity $\Rightarrow$ refers to UV wavelengths
$\alpha_S = \varepsilon_S$ integrated over 0.2-2.8 $\mu$m i.e. 95% solar spectrum

$\varepsilon_H$ is the hemispherical emissivity $\Rightarrow$ refers to IR wavelengths
$\alpha_H = \varepsilon_H$ integrated over 5-50 $\mu$m i.e. body at -250/300°C

but $\alpha_S \neq \varepsilon_H$ because the spectra are different
1.3 Radiation - Data

- **Spectral Reflectance** $\rho$
  - Zinc Oxide Potassium Silicate Coating

- **Black Body Emittance**
  - integration over solar (5776K) wavelengths
    - $\alpha_s=0.20$
  - integration over infrared black body (300K) wavelengths
    - $\varepsilon_h=0.87$

![MAP PSG120-FD Reflectance](image)
1.3 Radiation - Data

- Typical Values

<table>
<thead>
<tr>
<th>Finish</th>
<th>$\alpha_S$</th>
<th>$\epsilon_H$</th>
<th>$\alpha_S/\epsilon_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VD Au</td>
<td>0.23</td>
<td>0.03</td>
<td>9.20</td>
</tr>
<tr>
<td>VDA</td>
<td>0.15</td>
<td>0.05</td>
<td>3.00</td>
</tr>
<tr>
<td>black paint</td>
<td>0.94</td>
<td>0.81</td>
<td>1.16</td>
</tr>
<tr>
<td>white paint</td>
<td>0.20</td>
<td>0.88</td>
<td>0.23</td>
</tr>
<tr>
<td>SSM (Ag 2 mils)</td>
<td>0.10</td>
<td>0.60</td>
<td>0.17</td>
</tr>
<tr>
<td>OSR</td>
<td>0.09</td>
<td>0.82</td>
<td>0.11</td>
</tr>
</tbody>
</table>
1.3 Radiation - Black Body

- Radiated Energy between Black Bodies

\[ Q_{ij} = A_i F_{ij} \sigma \left( T_i^4 - T_j^4 \right) \]

with \( F_{ij} \), the view factor between surface i and surface j

or

\[ Q_{ij} = A_i \sigma \left( T_i^4 - T_j^4 \right) \]

when \( F_{ij} = 1 \)
2. Satellite Energy Balance

Thermal Control Engineering

1. heat transfer basics
2. satellite energy balance
3. role
4. design
5. means

ROSETTA* FM in LSS, dec01

*without Solar Panels
2. Satellite Energy Balance

WHAT HAPPENS from
GROUND
to
SPACE?
2. Satellite Energy Balance - Thermal Environment

• Ultra-high Vacuum, $10^{-14} \text{ bar} < p < 10^{-17} \text{ bar}$ => no convection
  - temperature levels

• Deep Space, @ 2.7 K
  - imbalance, temperature levels and gradients

• Solar Eclipse
  - SSO SPOT, ENVISAT 32 mn
  - GEO MSG 72 mn
  - HEO CLUSTER 5 h max
2. Satellite Energy Balance - Thermal Environment

- intense Solar Flux, $SC=1367 \text{ W/m}^2 \text{ @ 1 AU}$
  - imbalance, temperature levels and gradients

$$\Phi_s = \frac{SC}{d_s^2}$$
2. Satellite Energy Balance - Thermal Environment

- **Albedo Flux**
  - reflected by Sun illuminated side of Planet
  - albedo = ratio of solar reflected energy to local solar flux
  - Earth albedo
    
    \[ a_E = 0.33 \pm 0.13 \text{ equivalent to } 410 \text{ W/m}^2 \]
  - \( a_E \) varies with landscape
    - clouds 0.4-0.8
    - forest 0.05-0.10
    - ocean 0.05

- **Planet Flux**
  - infrared energy radiated by the Planet
  - Earth=blackbody @255 K (-18 °C)
  - equivalent to 240 W/m²
Equilibrium Temperature of a Sphere from Ground to Space

Temperature (degC) vs. Altitude (km)

- Black
- White
- Gold
- Air
2. Satellite Energy Balance - Black Sphere

- **Assumptions**
  - satellite=black sphere hence $\alpha=\varepsilon=1$
  - infinitely conductive, deep space at 0 K
  - low orbit around Earth
- **in Sun**
  - no Planet, no albedo

\[
\left(\pi \, r^2\right) q_s = \left(4 \pi \, r^2\right) \sigma \, T^4
\]

\[
\frac{q_s}{4} = \sigma \, T^4
\]

$T = 5^\circ C$
2. Satellite Energy Balance - Black Sphere

- in Sun with Earth
  - no albedo

\[
\left( \pi r^2 \right) q_s + F \left( 4 \pi r^2 \right) \sigma T_E^4 = \left( 4 \pi r^2 \right) \sigma T^4
\]

\[
\frac{q_s}{4} + \frac{\sigma T_E^4}{2} = \sigma T^4
\]

\( T = 27^\circ C \)  \( \Delta T = 22^\circ C \)
2. Satellite Energy Balance - Black Sphere

- in Sun with Earth and Albedo

\[
\left(\pi r^2\right) q_S + F(4\pi r^2)\sigma \bar{T}_E^4 + F(4\pi r^2) a q_S = \left(4\pi r^2\right)\sigma \bar{T}_E^4
\]

\[
\left(\frac{1}{4} + \frac{a}{2}\right) q_S + \frac{\sigma \bar{T}_E^4}{2} = \sigma \bar{T}^4
\]

\(\bar{T} = 56^\circ C\)

\(\Delta \bar{T} = 29^\circ C\)
2. Satellite Energy Balance - Real Body

\[
q_s = F_{i,s} A_i a_i \quad \text{solar absorbed}
\]

\[
q_s a F_{i,a} A_i a_i \quad \text{albedo absorbed}
\]

\[
Q_r = e_i A_i F_{i,\text{space}} s (T_i^4 - T_{\text{space}}^4) \quad \text{radiated to deep space}
\]

\[
Q_p = e_i A_i F_{i,p} s (T^4 - T_p^4) \quad \text{radiated to planet}
\]
2. Satellite Energy Balance - Real Body

• Real Body in Sun
  - assumes that body in infinitely conductive, no albedo, no planet flux
  - assumes that sink temperature is 0 K (not far from deep space)

\[ T = \frac{4 \sqrt{\frac{\alpha}{\varepsilon}} F_s}{4 \sqrt{\frac{A_s}{A}}} q_s \]

where \( F_s \) is the projected area

\[ F_s = \frac{A_s}{A} \]

T is independent of area \( A \)
depends only of \( \alpha/\varepsilon \)

with \( q_s = 1367 \) W/m\(^2\)
For $\theta=0$, $T_S = 0$ K and $q_s = 1367$ W/m$^2$

<table>
<thead>
<tr>
<th>(W/m$^2$)</th>
<th>(\text{-})</th>
<th>black body</th>
<th>white paint PSG120-FD</th>
<th>black paint Electrodag 501</th>
<th>VDAu</th>
<th>VDA</th>
<th>sand-blasted Al</th>
<th>black CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>$\alpha$</td>
<td>1.00</td>
<td>0.20</td>
<td>0.94</td>
<td>0.23</td>
<td>0.15</td>
<td>0.20</td>
<td>0.90</td>
</tr>
<tr>
<td>1367.0</td>
<td>$\varepsilon$</td>
<td>1.00</td>
<td>0.88</td>
<td>0.81</td>
<td>0.025</td>
<td>0.05</td>
<td>0.20</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>$\alpha/\varepsilon$</td>
<td>1.00</td>
<td>0.23</td>
<td>1.16</td>
<td>9.20</td>
<td>3.00</td>
<td>1.00</td>
<td>1.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface</th>
<th>$F_S$</th>
<th>$A_p / A$</th>
<th>Steady-State Temperature (degC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-s plate</td>
<td>1</td>
<td>1.00</td>
<td>121 -1</td>
</tr>
<tr>
<td>2-s plate</td>
<td>1/2</td>
<td>0.50</td>
<td>58 -44</td>
</tr>
<tr>
<td>cylinder</td>
<td>1/\pi</td>
<td>0.32</td>
<td>23 -69</td>
</tr>
<tr>
<td>sphere</td>
<td>1/4</td>
<td>0.25</td>
<td>5 -81</td>
</tr>
<tr>
<td>cube</td>
<td>1/6</td>
<td>0.17</td>
<td>-21 -99 -12</td>
</tr>
</tbody>
</table>

Play with $\alpha/\varepsilon$ ratio
2. Satellite Energy Balance - Real Body

- **Steady-state: General Case**
  - assumes that body in infinitely conductive
  - solar, albedo and planet fluxes
  - view factor to sink temperature at \( T_s \neq 0 \) K

\[
q_a = a q_s - q_p
\]

- \( F_s, F_a, F_p \) solar, albedo, planet factors (\(-\))
- \( q_s, q_a, q_p \) solar, albedo, planet fluxes (W/m\(^2\))

- \( a \) albedo factor (\(-\))
- \( \alpha \) solar absorbtivity (\(-\))
- \( T_s \) sink temperature (K)
- \( \varepsilon \) infrared emissivity (\(-\))
- \( B_s \) Gebhart factor to sink (\(-\))
- \( A \) radiative area (m\(^2\))
- \( Q \) power dissipation (W)

\[
\varepsilon A B_s \sigma (T^4 - T_s^4) = \alpha F_s A q_s + \alpha F_a A q_a + \varepsilon F_p A q_p + Q
\]
2. Satellite Energy Balance - Real Body

when sink $T_s$ surrounds ($B_S=1$) body at $T$ and only solar flux $q_s$

\[
T = 4 \sqrt{\frac{\alpha}{\varepsilon} \left( F_s + a F_a \right) q_s + \frac{F_p}{B_S} T^4 + T_s^4 + \frac{Q}{\varepsilon A B_S \sigma}}
\]
2. Satellite Energy Balance - Examples

ULYSSES (1989)
2. Satellite Energy Balance - Examples

ISO
(1995)
2. Satellite Energy Balance - Examples
3. Role

Thermal Control Engineering

1. heat transfer basics
2. satellite energy balance
3. role
4. design
5. means

*without Solar Panels

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3. Role

- maintain within Specified Ranges
  - temperatures
  - temperature gradients (K/length)
  - temperature stability (K/time)
  - radiative/conductive heat flow (W)

On Board Data Compression Unit (ALS)

SPOT 5 Solid State Recorder (ALS)
3. Role

• of What?
  - electronic units
  - instrument e.g. optical bench
  - S/C structure
  - interface between modules

Visual Monitoring Camera (AST)
3. Role - Typical Requirement

- **Narrow Temperature Ranges**
  - electronics equipment
    - classical equipment: \([-10, +40]\) °C
    - battery: \([0, +20]\) °C
    - propulsion system: \([+10, +50]\) °C

- **limited Temperature Gradients**
  - \(\Delta T\) < 5°C across optical instrument (1.5 m)
  - \(\Delta T/\Delta x\) < 2°C/m for structural element
  - \(\Delta T\) < 5°C between MMH and NTO tanks

- **Stable Temperatures**
  - \(\Delta T/\Delta t\) < 5 K/h for typical electronic unit
  - \(\Delta T/\Delta t\) < 0.1 K/\(\text{mn}\) for CCD camera
  - \(\Delta T/\Delta t\) < 100 µK/\(\text{mn}\) for cryogenic telescope

- **Why is it so important?**
  - low temperatures for reliability of components
  - narrow temperature ranges for sensitivity of detectors, units
  - small temperature gradients for pointing of instruments, S/C
4. Design

Thermal Control Engineering

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*without Solar Panels

ROSETTA* FM in LSS, dec01
4. Design

\[
(mC_p)_i \frac{dT_i}{dt} = \sum_j C_{ij} (T_j - T_i) + \sum_j R_{ij} s (T_j^4 - T_i^4) + \sum_j F_{ij} (T_j - T_i) + Q^i + Q^e
\]

* incl. to space  
* excl. to planet

**stored energy**  
**conducted* flux**  
**radiated* flux** (not visualised)  
**fluid flow**  
**internal loads**  
**external loads**
4. Design

Balance HEAT FLOWS to fulfil REQUIREMENTS results in TEMPERATURES

- through Heating
  - absorb from external sources (solar, albedo, planet IR)
    - selective coatings
  - use the internal sources
    - electronic dissipations, MLI insulation efficiency
  - dissipate heat internally
    - heater
    - RTG, RHU
4. Design

- transfer heat from hot area
  - conduction, radiation
  - latent heat of evaporation/condensation

- or through Cooling
  - reject to deep space (3 K)
    - with low $\alpha/\varepsilon$ radiative coatings on radiators
  - transfer heat to cold area
    - by conduction,
    - radiation
    - through condensation/boiling in fluid loops or heat pipes
  - through cryogenic techniques
    - cryostats
    - coolers (Peltier, Joule-Thomson...)
  - ablation
4. Design – Radiative Concept

• **Principle**
  - when internal power dissipation small w.r.t. external absorbed energy
  - balance between
    - absorbed incident radiant energy (solar…)
    - emitted radiant energy ($\sigma T^4$)

• **Characteristics**
  - no insulation
  - average temperature driven by
    - external fluxes
  - local temperature hot spots still possible

• **Application: PROBA1**
4. Design - Insulated Concept

• **Principle**
  - when heat source irradiates few sides
    • Sun, planet IR (Mercury, Mars, Moon)
  - balance between
    • internally dissipated power (P)
    • emitted radiant energy ($\sigma T^4$)

• **Characteristics**
  - insulation of Sun illuminated sides (MLI)
  - shadow sides
    • with high IR emissivity
    • radiate to deep space => RADIATORS
  - preferred attitude for radiators
  - average temperature driven by
    • internal power dissipation
  - local temperature hot spots still possible
4. Design - Insulated Concept

- Advantages w.r.t. Radiative Concept
  - less sensitive to
    - eclipses
    - external loads changes
  - temperatures are more uniform
  - little ageing of unirradiated coatings

We are between those 2 CONCEPTS
5. Means

Thermal Control Engineering

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5. Means - Limitations

- **Cooling Limitations**
  - radiator 100 mW at 100 K for 0 W dissipation
  - cryo-coolers 1 W at 50 K for 100 W dissipation
  - liquid He few mW at 4 K for 1 ton/2 years

- **Heat Transport Limitation/Performance**
  - conduction (pure Al tube k=200 W/m.K)
    
    \[
    \begin{align*}
    1.5 \text{ W @20°C} & \quad l=1.00 \text{ m} \quad \varnothing=2 \text{ cm} \quad \Delta T= 25 \text{ K} \quad m= 0.8 \text{ kg} \\
    11 \text{ kW @20°C} & \quad l=0.70 \text{ m} \quad \varnothing=4.04 \text{ m} \quad \Delta T= 3 \text{ K} \quad m= 24 \text{ t}
    \end{align*}
    \]
  - heat pipe (Al tube)
    - 11 kW @20°C l=0.70 m \( \varnothing=2.5 \text{ cm} \) \( \Delta T= 3 \text{ K} \) \( m= 2 \text{ kg} \)
  - radiation (from a black surface \( \varepsilon=1 \))
    \[
    \begin{align*}
    11 \text{ kW @20°C} & \quad A= 88 \text{ m}^2 \quad \Delta T= 25 \text{ K} \\
    11 \text{ kW @20°C} & \quad A= 27 \text{ m}^2 \quad \Delta T= 290 \text{ K}
    \end{align*}
    \]
5. Means

**Passive**
- RADIATION
  - coating
  - absorber
  - MLI blanket
  - radiator
- LATENT HEAT-ABLATION
  - TPS
  - PCM

**Active**
- HEATERS
  - thermostat control
  - electronic control
  - ground control
- HEATPIPES - FLOOPS
  - fixed/variable conductance
  - loop heat pipe
  - monophasic/diphasic fluid
- LOUVRES
  - mechanical
  - electrical

**Conduction**
- structural material
  - doubler, filler, adhesive
  - washer, strap, bolt, tyrap, stand-off
  - foam

**Energy Transfer**
- $\alpha \phi_s A$
- $\varepsilon A \sigma T^4$
- $k \frac{A}{l} \Delta T$
5. Means

- **Passive Systems Pros/Cons**
  - no mechanical moving parts or moving fluids, no power consumption
    - simple to design/implement/test
    - low mass and cost
    - highly reliable
  - BUT low heat transport capability
    - except heat pipes

- **Active Systems Pros/Cons**
  - mechanical moving parts or moving fluids or electrical power required
    - complex design
    - generate constraints on S/C design and test configurations
    - high mass and cost
    - less reliable than PTC means
5. Means - PTC - Radiation, Coatings

- controls Heat absorbed by External S/C Surfaces
  - with $\alpha$, solar absorptivity

- controls Heat radiated to Space
  - with $\varepsilon$, IR emissivity

Coated Sphere Equilibrium Temperature in Sun

$\frac{\alpha}{\varepsilon} = 10$ 500 K
$\frac{\alpha}{\varepsilon} = 2$ 337 K
$\frac{\alpha}{\varepsilon} = 1.5$ 314 K
$\frac{\alpha}{\varepsilon} = 1$ 284 K
$\frac{\alpha}{\varepsilon} = 0.75$ 264 K
$\frac{\alpha}{\varepsilon} = 0.5$ 238 K
$\frac{\alpha}{\varepsilon} = 0.25$ 200 K
5. Means - PTC - Radiation, MLI Blankets

- **Purpose**
  - Insulating material
  - Acts as a radiation barrier
  - Decreases heat flow inside S/C
    - Sun, albedo, IR planet
    - Ascent aerothermal after fairing jettison
    - ME/ABM firing
  - Decreases heat losses from S/C
    - IR energy

- **Principle**
  - Stack of n layers with low emissivity $\varepsilon$
  - Connected only by radiation with limited contact areas
  - Equivalent to reduce the emissivity by $n$
5. Means - PTC - Radiation, MLI Blankets

- **Standard MLI**
  - stack of thin polymer foils
    - Kapton®, Mylar® (5-25 foils)
  - separated (avoid contact) by
    - spacer/mesh (Dacron®/Trevira®)
    - embossed, crinkled
    - perforated or not
  - 1 x bka/VDA-net unperf. 1 mil space exposed side
  - 3-23 x VDA/my/VDA-net perf. 0.25 mil internal layers
  - 1 x VDA/my or ka/VDA perf. 1 mil innermost layer
- attachment
  - stand-offs + clip washers
  - sewed/glued velcro
  - dacron yarn
5. Means - PTC - Radiation, Radiators

- **Purpose**
  - cool detectors, optical components, mirrors
  - improve the performances of
    - Scientific P/L (all wavelength ranges)
    - Earth observation (mainly IR)

- **Principle**
  - direct coupling to deep space @2.73 K
  - heat lift decreases in $T^4$
    - $6 \text{ W/m}^2 \text{ @100K}$

\[ Q_{\text{space}} = Q_{\text{electric}} + Q_{\text{losses}} \]
5. Means - PTC - Radiation, Radiators

INTEGRAL STM
5. Means - PTC - Conduction, Increase

- **Structural Material Selection**
  - Al alloy 120-170 W/m.K
  - Ti alloy 7-15 W/m.K
  - steel 10-40 W/m.K

- **Thermal Doublers**
  - spread heat dissipation under unit
  - 1 mm thick Al alloy sheet

- **Straps/Braid (detector to radiator)**
  - Cu, Al alloy wrapped in MLI/SLI
  - short < 10 cm

- **Contact Area**
5. Means - PTC - Conduction, Increase

• Interface Fillers
  - better unit to S/C conductance
  - graphite (Sigraflex®)
    • laminated graphite sheet
    • electrical conductor
    • thickness 0.25 mm
  - silicone elastomer (Cho-therm® 1671)
    • silicone binder, filled with boron nitride particles, reinforced with fibreglass cloth
    • electrical isolator
5. Means - ATC - Louvres

- **Purpose**
  - dumps more/less power to space
  - accommodate extreme variation of energy
    - internal power
    - solar fluxes (interplanetary S/C)
  - with little temperature change
  - save heater power

- **Principle**
  - blades covering a standard radiator
  - 16 blades on bearings rotates
  - opens/closes radiator to deep space
    - variation of IR emittance $\varepsilon$
  - actuator: bi-metallic spring sensing the radiator temperature
5. Means - ATC - Louvres

SENER Louvre on ROSETTA* PFM

Louvres on CASSINI-HUYGENS

*without Solar Panels
5. Means - ATC - Heaters

- **Purpose**
  - additional source of heat inside S/C
    - replace power when unit is switched-off
    - warm up dormant units prior to swon
    - control temperature and gradient
5. Means - ATC - Heaters

ROSETTA FM Heaters

Battery 2

Battery 3

TC 391

PCU

ROSETTA FM ROSINA DPU

heaters

heaters
5. Means - ATC - Heaters

ROSETTA FM OSIRIS PEM-H

ROSETTA FM Thruster 12A

- self-redundant heaters
- FCV

glue

self-redundant heaters
5. Means - ATC - Heat Pipes

- **Purpose**
  - transport heat by convection with small $\Delta T$
  - avoid temperature gradients

- **Principle**
  - liquid vaporizes at evaporator
  - gas flows to cold end
  - gas condensates at cold end
  - liquid returns by capillary forces
5. Means - ATC - Heat Pipes

Telecom Panel Heat Pipe (Swales)

Ø 12 mm

bi-tube

saddle