Appendix O

Thermal Modeling of CubeSats and Small Satellites

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Abstract

Recently universities and SMEs (Small and Medium Enterprises) have initiated the development of nanosatellites because of their low cost, small size and short development time. The challenging aspects for these satellites are their small surface area for heat dissipation due to their limited size. There is not enough space for mounting radiators for heat dissipation. As a result thermal modeling becomes a very important element in designing a small satellite. A generic thermal model of a CubeSat satellite is presented in this paper. Detailed and simplified thermal models for nanosatellites have been discussed. The detailed model takes into account all the thermal resistors associated with the respective layer while in the simplified model the layers with similar materials have been combined together and represented by a single thermal resistor. The thermal model of complete CubeSat has been presented. The proposed models have been applied to CubeSat standard nanosatellite called AraMiS-C1, developed at Politecnico di Torino. Thermal resistances measured through both models are compared and the results are in close agreement. The absorbed power and the corresponding temperature differences between different points of the single panel and complete satellite are measured. In order to verify the theoretical results, the thermal resistance of the AraMiS-C1 is measured through an experimental setup. Both values are in close agreement.
Detailed thermal model of the CubeSat panel from top to bottom is shown in figure O.1 and will be further explained in the presentation. Simplified thermal model of the CubeSat panel from top to bottom is shown in figure O.2 and will be further explained in the presentation.

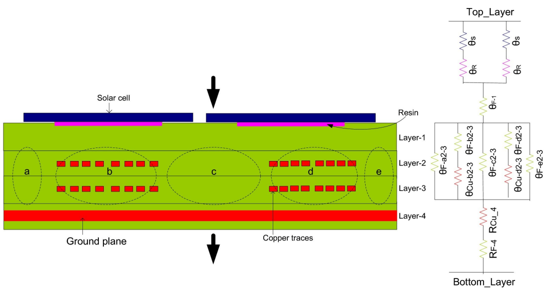

Figure O.1: CubeSat panel cross sectional view and detailed thermal model

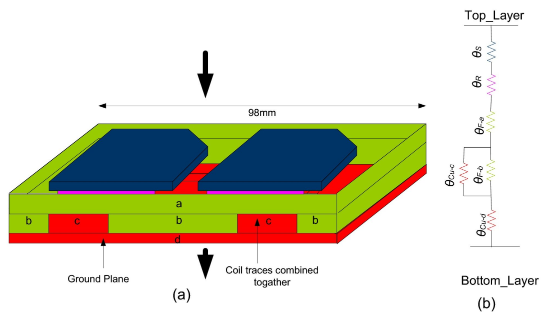

Figure O.2: Panel top to bottom cross sectional view and simplified model

Thermal model of the complete CubeSat is shown in figure O.3 and will be further explained in the presentation.

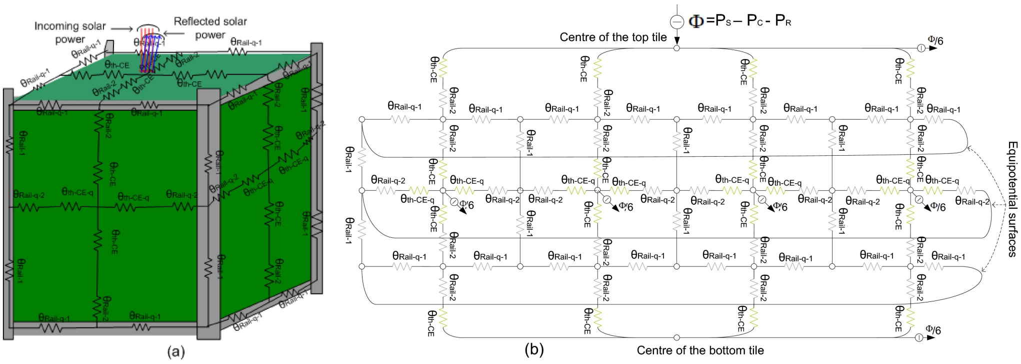

Figure 3: CubeSat satellite and top to bottom thermal model

Figure O.3: CubeSat satellite and top to bottom thermal model

Thernal Modeling of CubeSat Standard NanoSatellites

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Outline

- Introduction to AraMiS project
- Thermal models
  - CubeSat solar panel
    - Detailed model
    - Simplified model
  - Two models applied to AraMiS-C1 tiles (CubePMT &CubeTCT)
- Thermal model of CubeSat
- Thermal resistance of AraMiS-C1
  - CubeSat model
  - Experimental
- Emissivity & absorption coefficient of AraMiS-C1
- Conclusion

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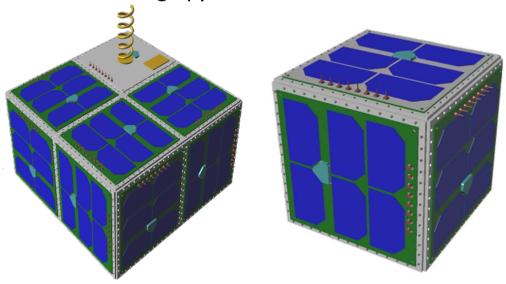
Introduction to AraMiS (I)

- ARAMIS
  - Modular Architecture of NanoSatellites
  - Alternative to CubeSats, for larger and more demanding applications
- Modularity
  - Mechanical
  - Electronic
  - Testing level
  - Reduction of the overall budget
    - development and testing time
- LEO Satellites
- Size
  - 16.5x16.5x16.5 cm3
  - 10x10x10 cm3
- 5 years expected life
- Commercial off the Shelf (COTS)



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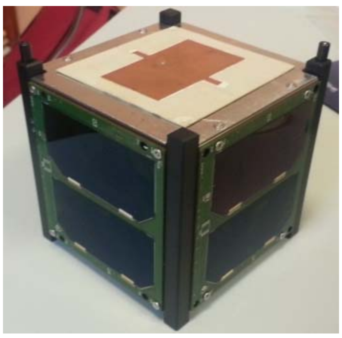
AraMiS-C1

- CubeSat standard nano-satellites
- Based on tiles
- Four power management tiles (CubePMT): EPS & ADCS
- Two telecommunication tiles (CubeTCT): Antennas & RF subsystems
- Size 10x10x10 cm^3
- Mass is 1.3kg
- Room for batteries and payload boards



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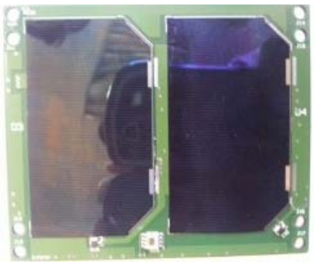
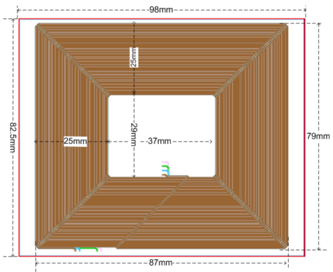
CubePMT

- CubeSat standard Power Management Tile
  - Dimensions 9.8 x 8.25 x 0.16 cm3
  - 8-layers PCB
  - Top layer : Solar panel and sun sensor
  - Bottom layer : electronic subsystems
  - Magnetorquer coil embedded in four internal layers





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Thermal Modeling: Motivation

- Emphasis on nanosatellites (Universities & SMEs)
  - Low cost
  - Small size
  - Short development time
- Challenge
  - Small surface area for heat dissipation
  - Not enough space for mounting radiators
- Thermal modeling

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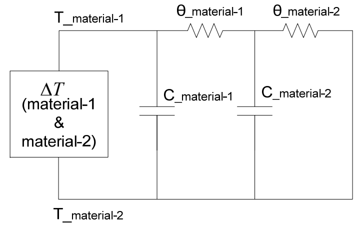
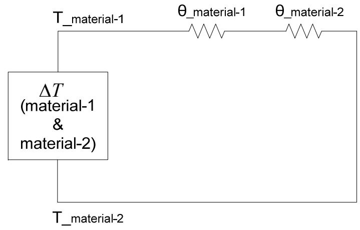
Thermal Resistace

- Heat sources
  - Generated by the satellite subsystems
  - Absorbed from the surrounding
- Some portion of heat is
  - Lost to the surrounding
  - Trapped inside the satellite
- Trapped heat energy
  - Increases temperature of the satellite
  - Depends on the thermal resistance
- Suppose two materials
- Fourier's law of heat conduction

$$\Delta T = P \cdot \theta_{th}$$

$$\theta_{th} = \frac{L}{K \times S}$$





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Thermal Modeling

- Thermal resistor representation
  - θ denotes thermal resistor
  - *F* represents FR4
  - *Cu* represents copper
  - Alphabets (*a, b, c, d, e*) represent the respective subsection and
  - Numbers (*1, 2, 3, 4*) represent the relevant layer
  - For example $\theta_{F\text{-}a2\text{-}3}$ represents the thermal resistor of FR4 material in subsection *a* of layers *2* and *3*

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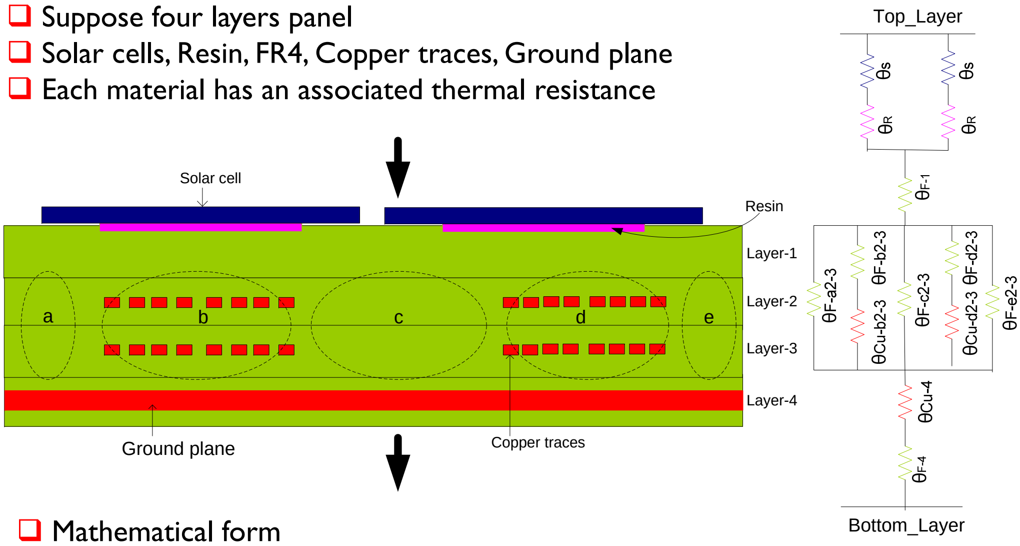
Top to bottom
Detailed thermal model of CubeSat panel

- Suppose four layers panel
- Solar cells, Resin, FR4, Copper traces, Ground plane
- Each material has an associated thermal resistance



- Mathematical form

$$\theta_{th-S1S2} = \frac{\theta_S + \theta_R}{2} + \theta_{F-1} + \theta_{F-a2-3} // (\theta_{Cu-b2-3} + \theta_{F-b2-3}) // \theta_{F-c2-3}$$
$$// (\theta_{Cu-d2-3} + \theta_{F-d2-3}) // \theta_{F-e2-3} + \theta_{Cu\_4} + \theta_{F-4}$$

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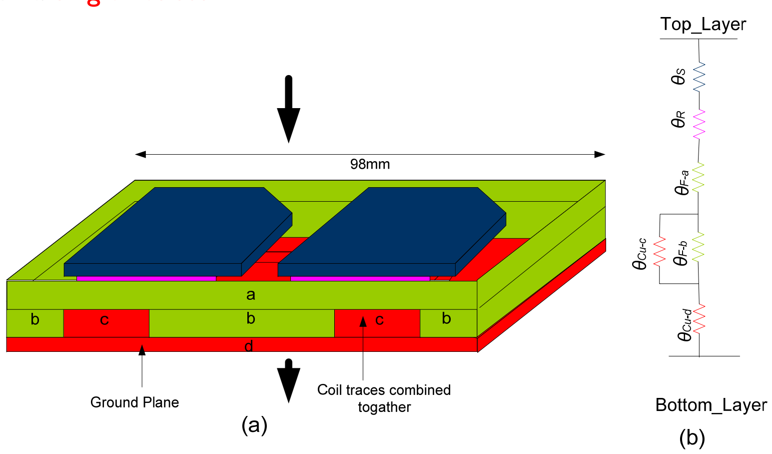
Top to bottom
Simplified thermal model of CubeSat panel

- Layers with similar material combined together
- Assigned a single resistor



- Mathematical form

$$\theta_{th-S1S2} = \theta_S + \theta_R + \theta_{F-a} + \theta_{Cu-c} // \theta_{F-b} + \theta_{Cu-d}$$

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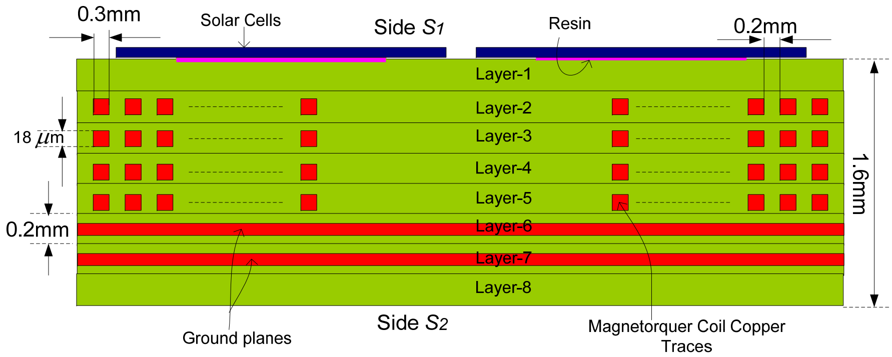
Top to bottom
Resistance of CubePMT (AraMiS-C1)

- CubePMT thermal resistance
  - Simplified Model
  - Detailed Model



- Applying the Detailed Model, $\theta_{th-S1S2} = 2.59K/W$
- Applying the Simplified Model, $\theta_{th-S1S2} = 2.58K/W$

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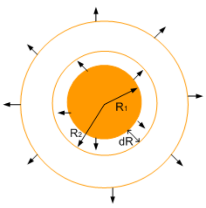
Centre to Edge
Detailed thermal model of CubeSat Panel



$$dT = Pd\theta$$

$$d\theta = \frac{L}{KA} = \frac{dR}{K2\pi R.h}$$

$$P = P_d\alpha\pi R^2$$

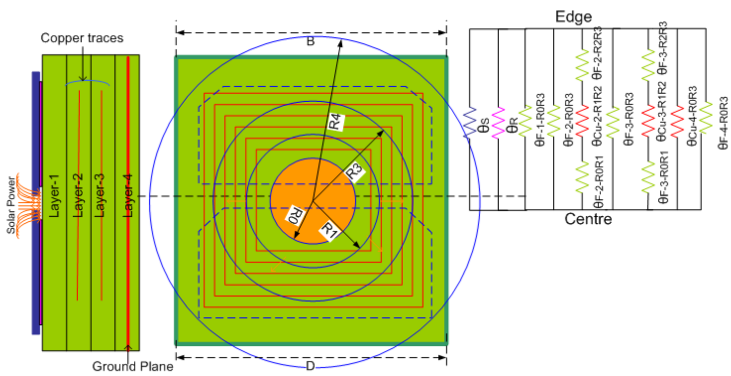
$$dT = P_d\alpha\pi R^2\frac{dR}{K2\pi R.h} = \frac{P_d\alpha}{2Kh}RdR$$

$$\int_0^{R_T} dT = \frac{P_d\alpha}{2P_dKh}\int_0^{R_T} RdR = \frac{\alpha R_T^2}{4K\cdot h}$$

$$\Delta T = \frac{\alpha P_d R_T^2}{4Kh}$$

$$\Delta T = P\cdot\Delta\theta$$

$$\Delta\theta = \frac{\Delta T}{P} = \frac{\frac{\alpha P_d R_T^2}{4Kh}}{P_d\cdot\pi\cdot R_T^2} = \frac{\alpha}{4\pi Kh}$$



$$\theta_{CE} = \theta_S // \theta_R // \theta_{F\_1} // \theta_{F\_2} // (\theta_{F\_2} + \theta_{Cu\_2} + \theta_{F\_2})$$
$$// \theta_{F\_3} // (\theta_{F\_3} + \theta_{Cu\_3} + \theta_{F\_3}) // \theta_{Cu\_4} // \theta_{F\_4}$$

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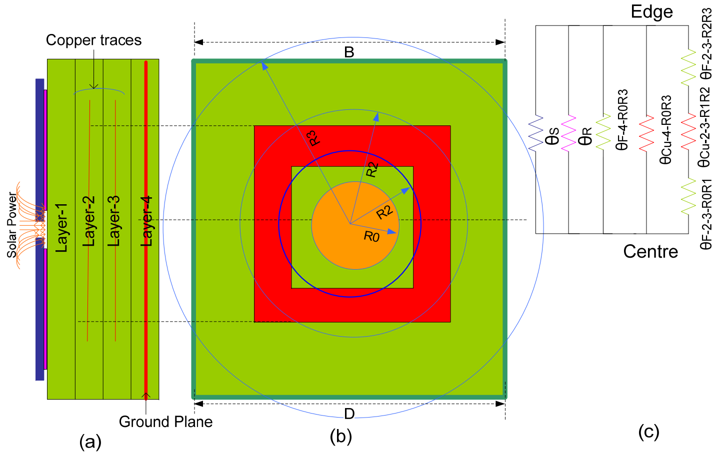
Centre to Edge
Simplified Thermal Model of CubeSat Panel



$$\theta_{th-CE} = \theta_S \,//\, \theta_R \,//\, \theta_{F-4-R_0R_3} \,//\, \theta_{Cu-4-R_0R_3}$$
$$//(\theta_{F-2-3-R_0R_1} + \theta_{Cu-2-3-R_1R_2} + \theta_{F-2-3-R_2R_3})$$

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Centre to Edge
Thermal Resistance of CubePMT & CubeTCT

- CubePMT
  - Detailed Model

$$\theta_{CE-P} = (\theta_{F-3} + \theta_{Cu-2} + \theta_{F-1}) \,//\, \theta_{Cu-4} \,//\, \theta_{F-5} \,//\, \theta_{Pos}$$

$$\boxed{\theta_{CE-P} = 3.45K/W}$$

  - Simplified Model,

$$\theta_{CE} = \theta_S \,//\, \theta_R \,//\, \theta_{F\_1} \,//\, \theta_{F\_2} \,//(\theta_{F\_2} + \theta_{Cu\_2} + \theta_{F\_2})$$
$$//\, \theta_{F\_3} \,//(\theta_{F\_3} + \theta_{Cu\_3} + \theta_{F\_3}) \,//\, \theta_{Cu\_4} \,//\, \theta_{F\_4}$$

$$\boxed{\theta_{CE-P} = 3.40K/W}$$

- CubeTCT
  - Simplified Model,

$$\theta_{CE-P} = \theta_{Cu} \,//\, \theta_F$$

$$\boxed{\theta_{CE-C} = 2.64K/W}$$

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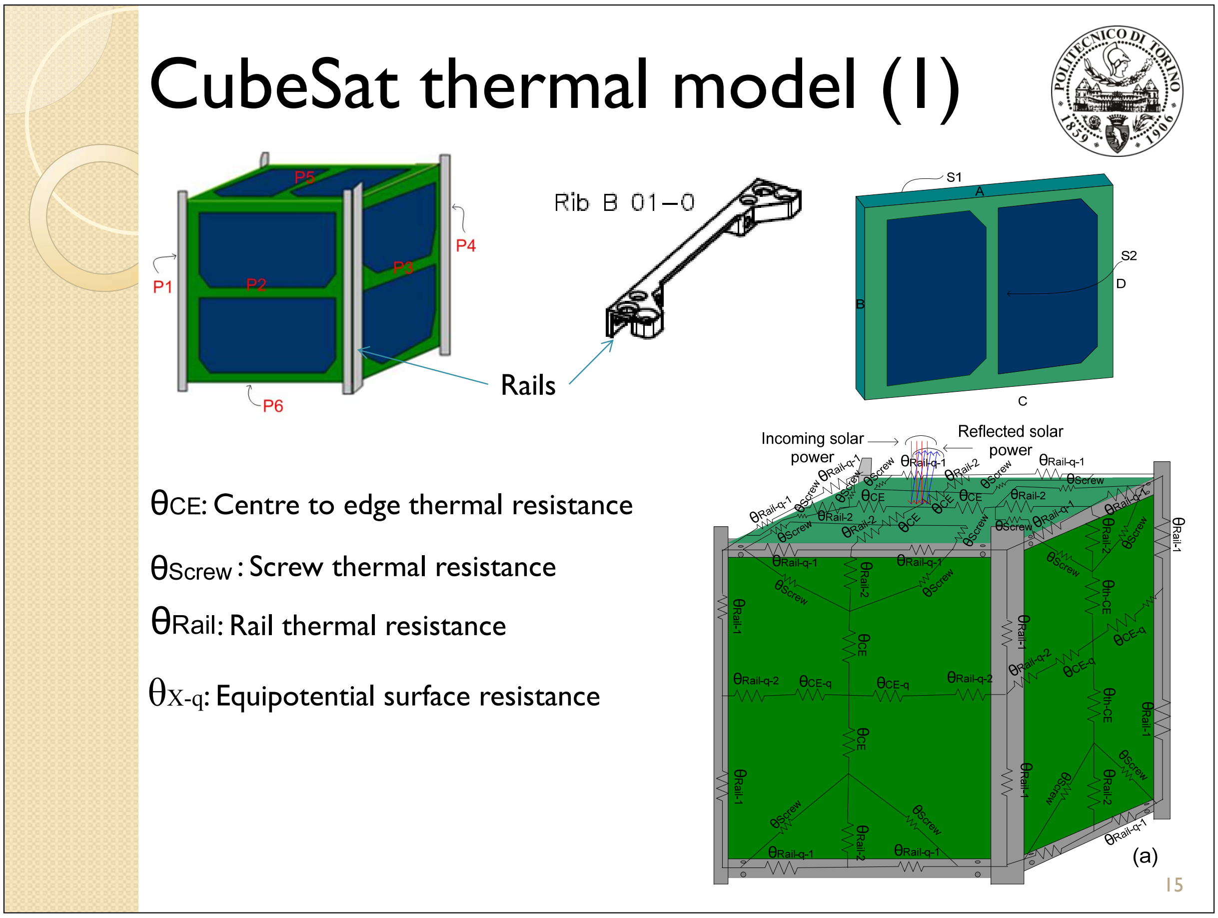
CubeSat thermal model (I)
P1
P2
P3
P4
P5
P6
Rails
Rib B 01–0
S1
S2
A
B
C
D
θCE: Centre to edge thermal resistance
θScrew : Screw thermal resistance
θRail: Rail thermal resistance
θX-q: Equipotential surface resistance
Incoming solar power
Reflected solar power
(a)
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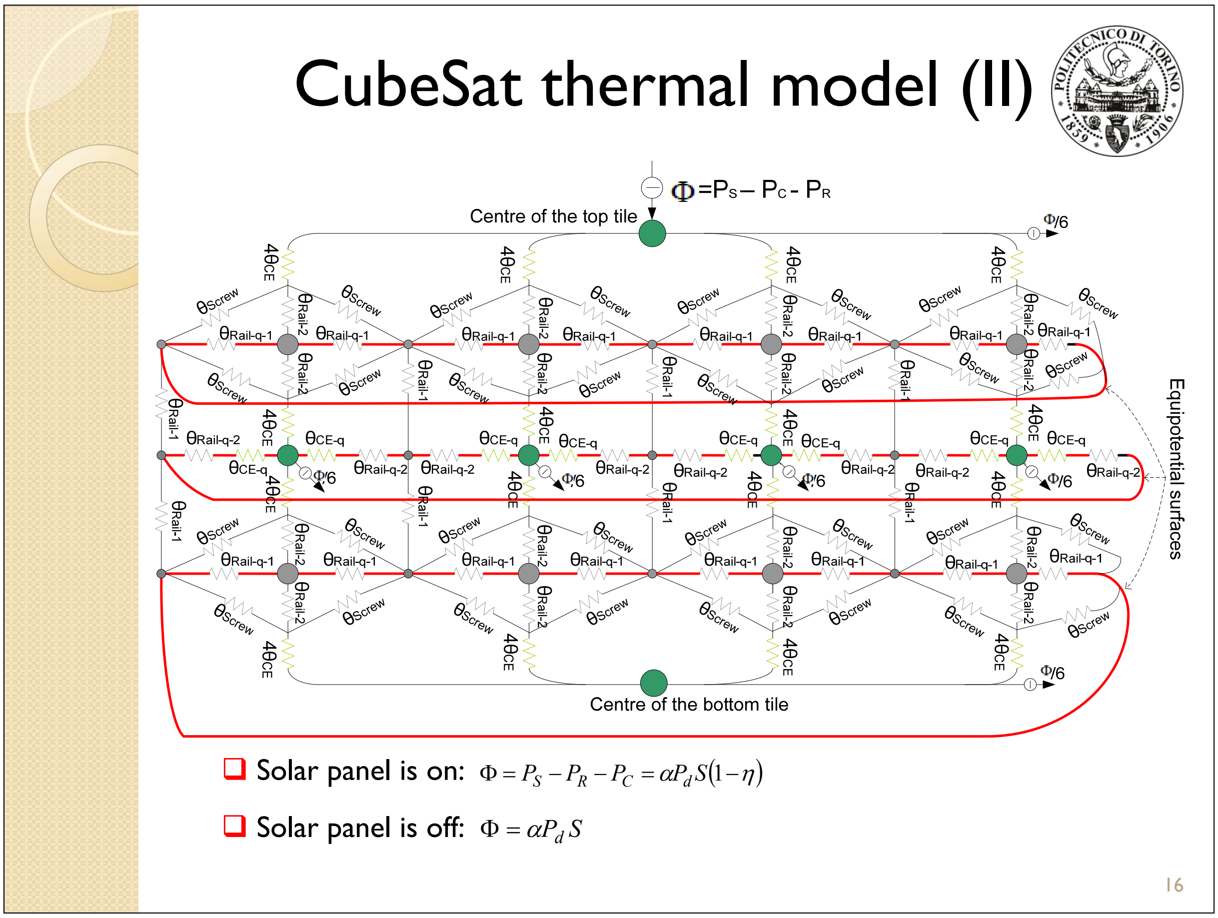
CubeSat thermal model (II)
Φ =PS – PC - PR
Centre of the top tile
Φ/6
Centre of the bottom tile
Equipotential surfaces
Solar panel is on: $\Phi = P_S - P_R - P_C = \alpha P_d S(1-\eta)$
Solar panel is off: $\Phi = \alpha P_d S$
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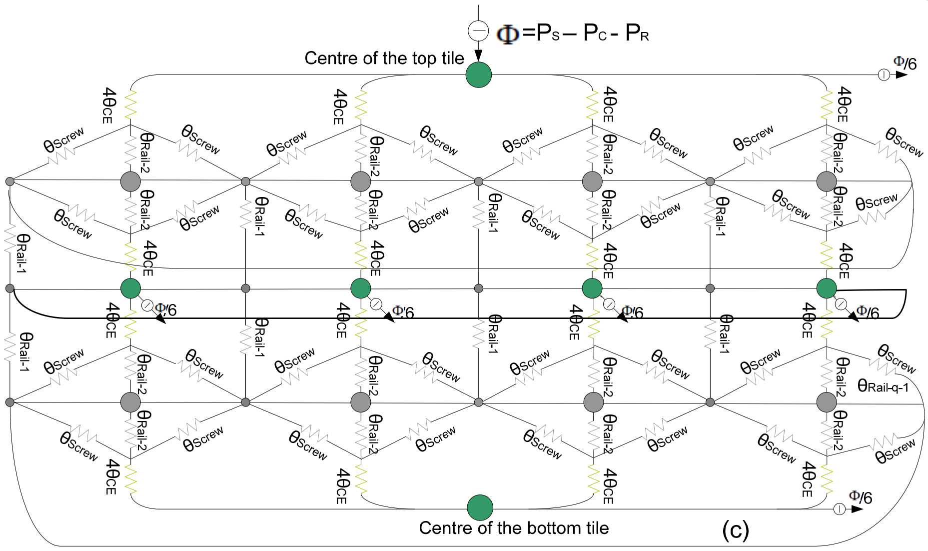
CubeSat thermal model (III)



$$\theta_{th} = 2\left(\frac{4\theta_{CE} + \theta_{Rail-2} \,//\, \frac{\theta_{Screw}}{2}}{4}\right) + 2\left(\frac{4}{4\theta_{CE} + \theta_{Rail-2} \,//\, \frac{\theta_{Screw}}{2}} + \frac{4}{\theta_{Rail-1}}\right)^{-1}$$

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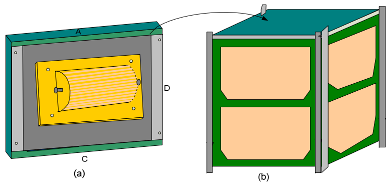
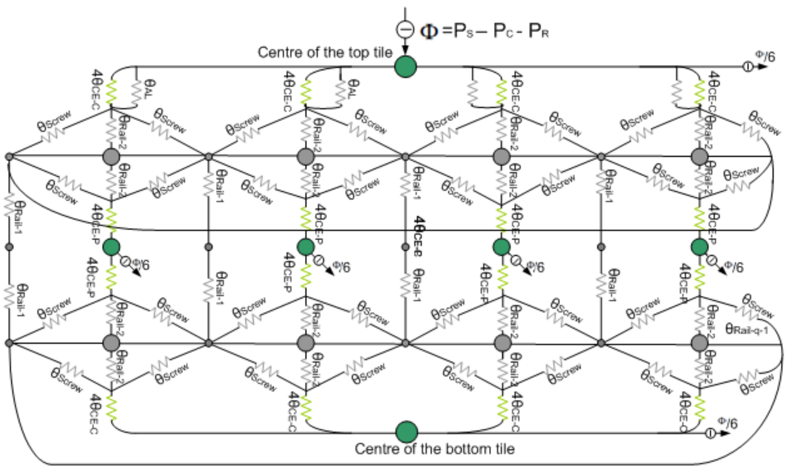
Thermal Resistance of AraMiS-C1

- Theoretical Measurement using CubeSat Model
- Experimental Setup
  - Thermal Resistor with CubeTCT attached through aluminum tile.
  - Thermal model





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AraMiS-C1 Thermal Resistance

$$\theta_{th} = \left(\frac{4\theta_{CE-C} // 4\theta_{Al-tile} + \theta_{Rail-2} // \frac{\theta_{Screw}}{2}}{4} \right) + \left(\frac{4\theta_{CE-C} + \theta_{Rail-2} // \frac{\theta_{Screw}}{2}}{4} \right) + 2\left(\frac{4}{4\theta_{CE-P} + \theta_{Rail-2} // \frac{\theta_{Screw}}{2}} + \frac{4}{\theta_{Rail-1}} \right)^{-1}$$

$$\theta_{CE-P} = 3.45K/W$$

$$\theta_{CE-C} = 2.64K/W$$

$$\theta_{Al-Tile} = \frac{0.11}{210W/(Km) \cdot 4\pi \cdot 6mm} = 0.018K/W$$

$$\theta_{Screw} = \frac{0.11}{210W/(Km) \times 4\pi \times 6mm} = 5.64K/W$$

$$\theta_{Rail-A} == \frac{100mm}{210W/mK \times (2mm \times 10mm + 2mm \times 8mm)} = 13.23K/W$$

$$\theta_{Rail-1} = \frac{\theta_{Rail-A}}{2} = 6.6K/W$$

$$\theta_{Rail-B} = \frac{L}{K_{Al} \times S} = \frac{12mm}{210W/mK \times (2mm \times 100mm)} = 0.3K/W$$

$$\theta_{Rail-2} = 2 * \theta_{Rail-B} = 0.6K/W$$

$$\theta_{th} = 5.15K/W$$

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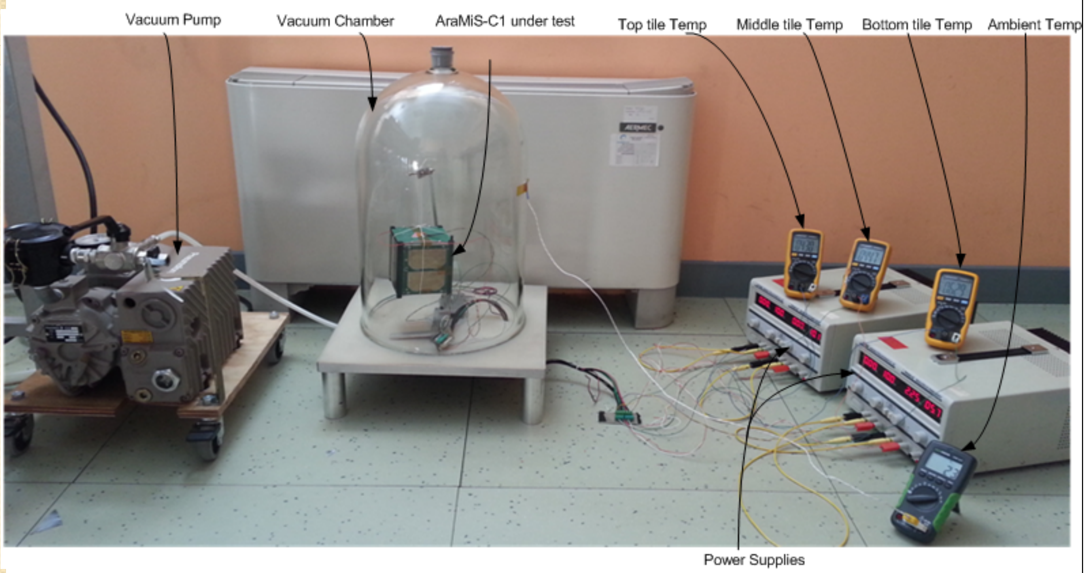
Practical Measurement Setup



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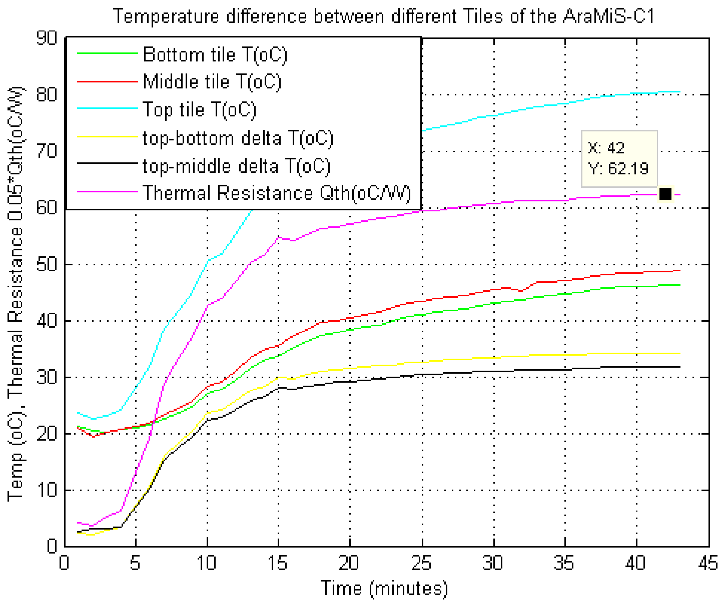
Practical Results



$$\theta_{th} = \frac{\Delta T}{P} = \frac{\frac{\alpha P_d R_T^{2}}{4Kh}}{P_d \cdot \pi \cdot R_T^{2}} = \frac{\alpha}{4\pi Kh}$$

$$\theta_{th} = 3.1K/W$$

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ACS: Magnetorquer Coil

- Magnetorquer coil is embedded in four internal layers
- Thermal Modeling

$$P_o = P_d + P_I$$

- Stefan-Boltzmann's law :

$$P_o = \alpha_o \sigma T_o^{4} S + \alpha_L \sigma T_o^{4} S_L$$

$$\alpha_o \sigma T_o^{4} S + \alpha_L \sigma T_o^{4} S_L = P_d + P_I$$

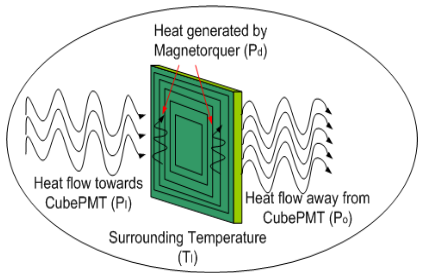
At steady state, Pd=0

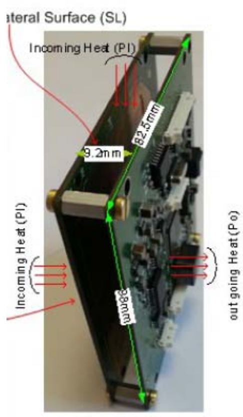
$$\alpha_I \sigma T_I^{4} S + \alpha_L \sigma T_I^{4} S_L = P_I$$

$$\alpha_o \sigma T_o^{4} S + \alpha_L \sigma T_o^{4} S_L = P_d + \alpha_I \sigma T_I^{4} S + \alpha_L \sigma T_I^{4} S_L$$

$$T_o = \sqrt[4]{\frac{P_d + \alpha \sigma T_I^{4} S + \alpha_L \sigma T_I^{4} S_L}{\alpha \sigma S + \alpha_L \sigma S_L}}$$

$$\alpha = \frac{P_d - \alpha_L \sigma S_L \left(T_o^{4} - T_I^{4}\right)}{\sigma S \left(T_o^{4} - T_I^{4}\right)}$$





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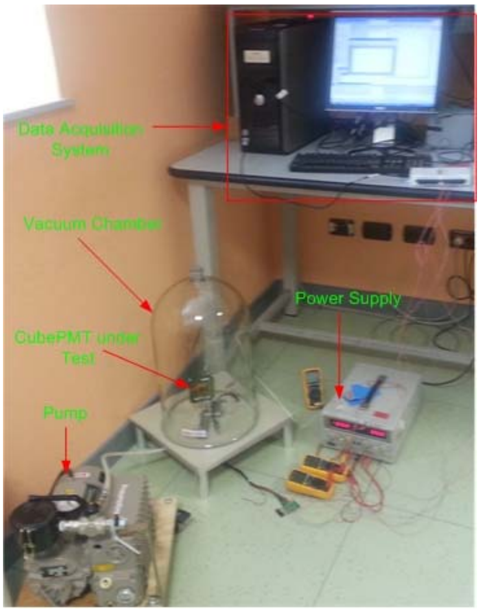
Magnetorquer Coil: Thermal Modeling

- Emissivity Measurement at Infra Red Wavelength
  - Ability of a surface to emit energy by radiation
  - Surfaces with different colors have different emissivity values
  - Voltage, current, temperature are captured



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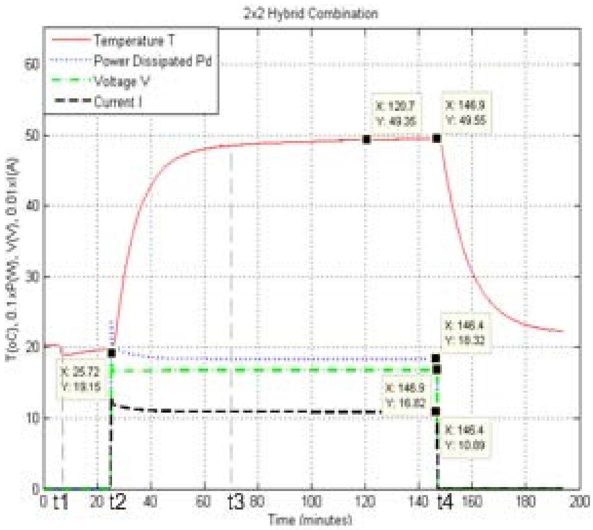
Magnetorquer Coil: Emissivity



Parameter	Value
σ	5.6703×10^{-8} Wm^{-2}K^{-4}
T_I	292.34K
T_o	322.69K
S	0.01617m^2
S_L	0.003321m^2
P_d	3.623W
α_L	1

$$\alpha = \frac{P_d - \alpha_L \sigma S_L \left(T_o^{\,4} - T_I^{\,4}\right)}{\sigma S \left(T_o^{\,4} - T_I^{\,4}\right)}$$

- The resulting emissivity (α) value 0.9.

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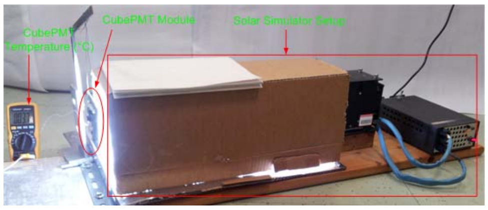
Absorption Coefficient (a) at Visible Light

- CubePMT was illuminated through a solar simulator (AM0 intensity)
- Temperature start increasing
- Temperature reached steady state (74°C), solar simulator switched off.
- Voltage was applied to the magnetorquer coil,
- Increase voltage step by step, Current and temperature was measured. At 74°C, the corresponding voltage and current

$$P_{solar} = P_{electrical} \qquad \because P_{solar} = aP_d A$$

$$P_{electrical} = VI$$

$$\Rightarrow a = \frac{VI}{P_d A}$$



Parameter	Value
Applied voltage (V)	14.24 V
Current (I)	700 mA
Solar power density (P_d)	1366 W/m^2
CubePMT surface area (A)	0.008085 m^2

- The resulting emissivity (α) value 0.903

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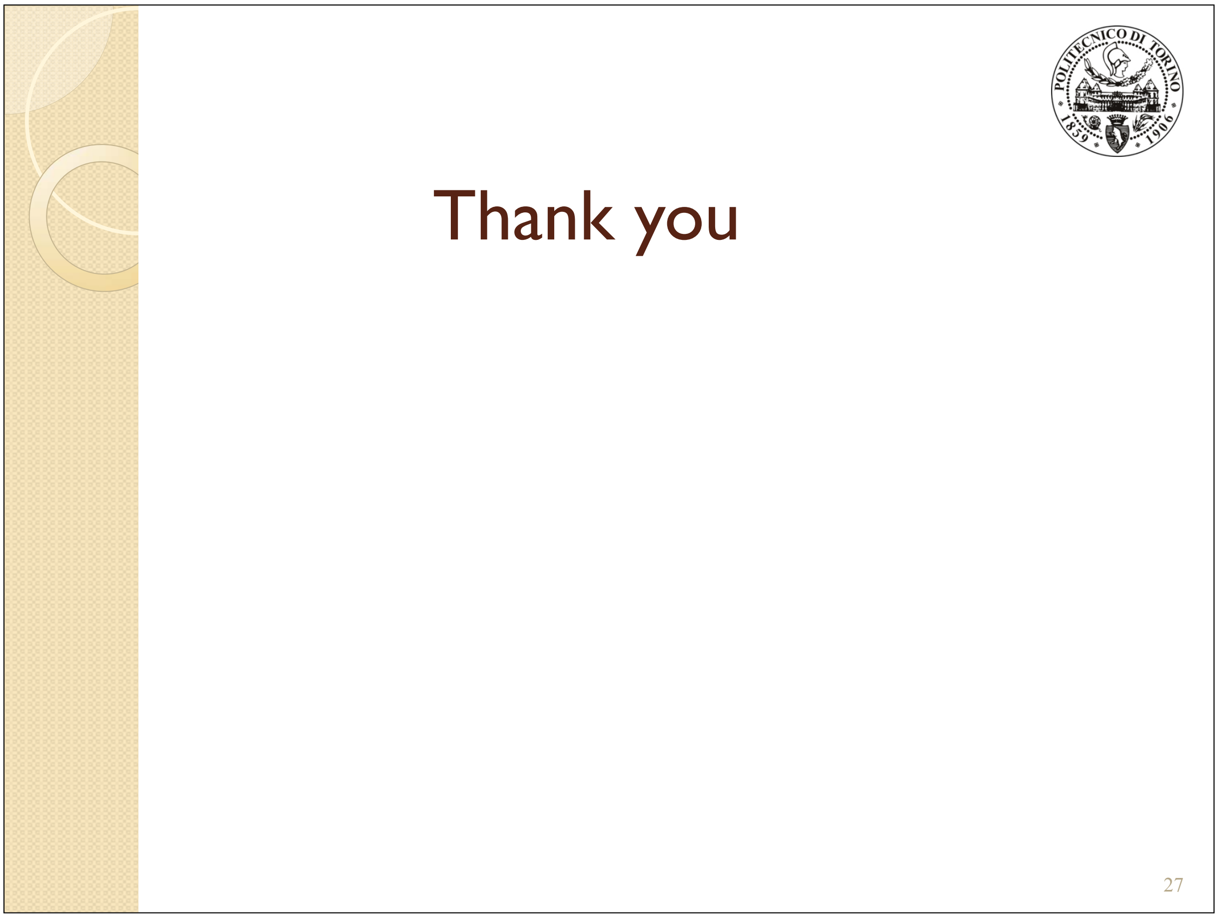
Conclusion

- Thermal resistance of CubePMT measured through detailed & simplified models
  - Have almost same value
  - Verify the authentication of the proposed models
- CubeSat model was applied to AraMiS-C1
  - Theoritical & practical thermal resistance have close value
  - Varify the validity of the proposed model


POLITECNICO DI TORINO
1859 1906
Thank you
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