



MINISTÉRIO DA CIÊNCIA E TECNOLOGIA  
**INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS**

# ***PCB Effective Thermal Conductivity for Spacecraft Electronic Boxes Thermal Analysis and Design***

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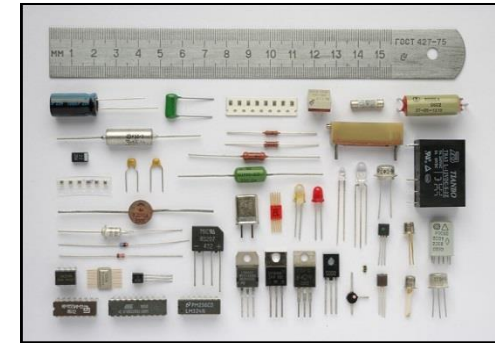
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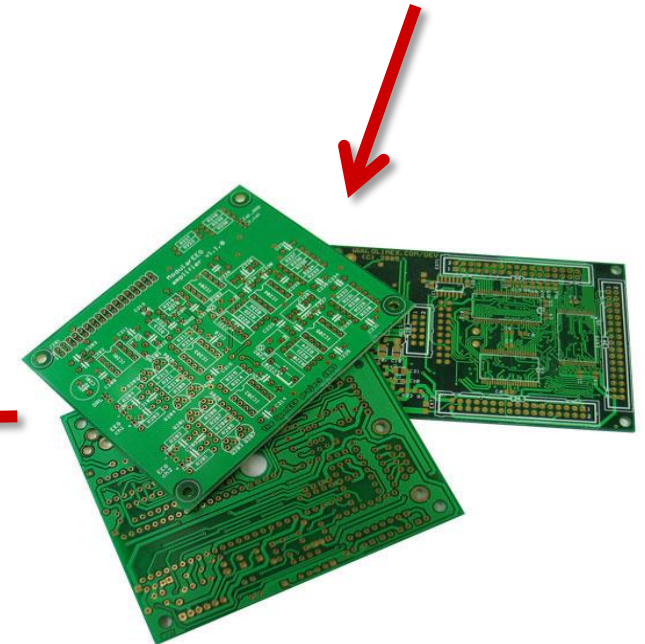
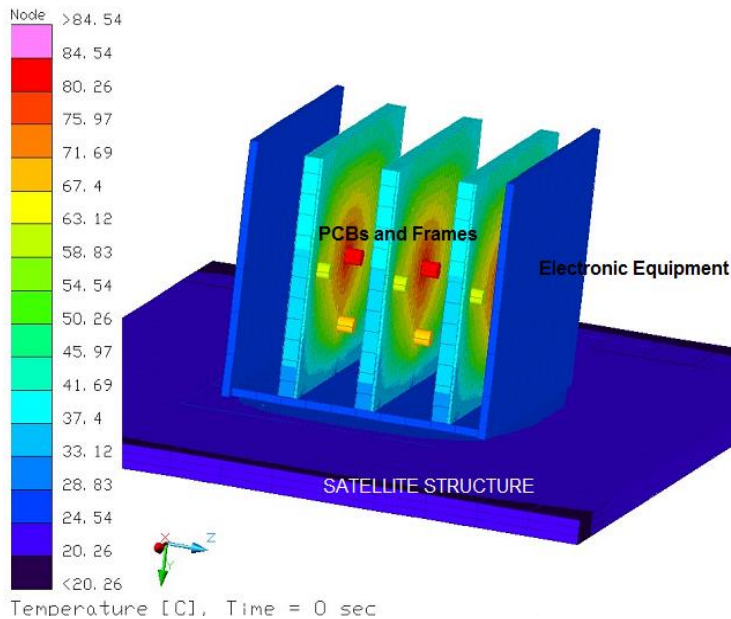
Spacecraft Thermal Control Workshop, El Segundo, California, March 24-26, 2015

# The problem

**Electronic components** are mounted over **Printed Circuit Boards (PCB)** which are fixed to built-in **frames** in the electronic **box** thermally connected to the **satellite structure** (normally honeycomb sandwich panels).



Electronic components



Printed Circuit Boards - PCBs



# The problem

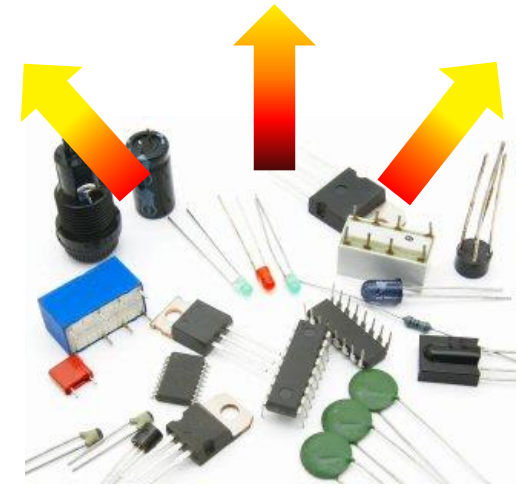
Electronic components **generate heat** while operating, which must be dissipated to avoid **overheating**.

The **components reliability is directly related to its operational temperature**. Thus, thermal analysis and design of electronics shall be accurate for hot conditions. **The operational temperature limits should never be exceeded.**

$$MTF = Ae^{\left(-\frac{E_a}{kT}\right)}$$

mean time to failure

For **Space applications**, **conduction along the PCB** is the only way to spread the heat from the small areas where the components are mounted, once there is no pressurized air to apply convection based cooling technics.





# The effective thermal conductivity ( $k_{\text{eff}}$ )

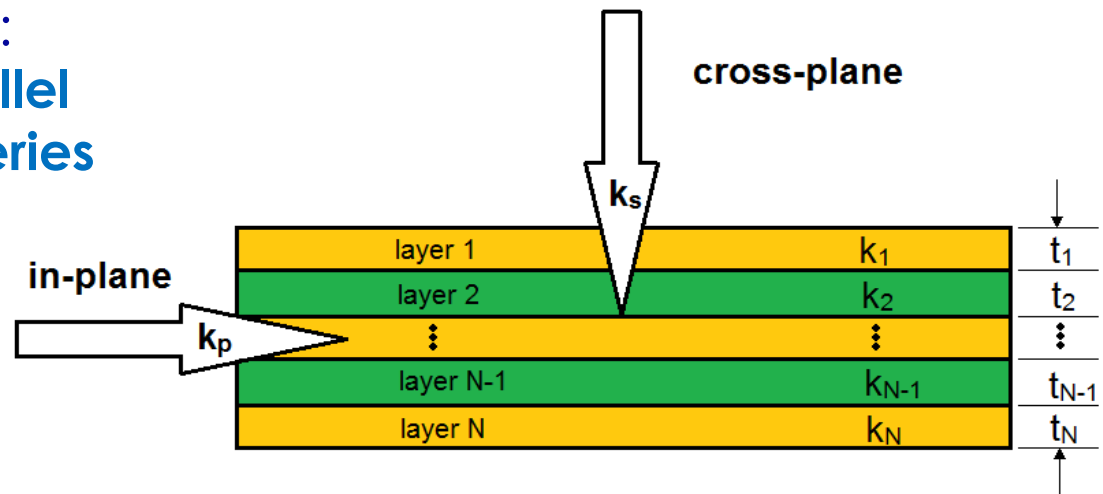
PCBs are basically made of **FR4 ( $k \sim 0.25 \text{ W/mK}$ )** and **copper ( $k = 398 \text{ W/mK}$ ) lines**. Therefore, the analysis of the thermal conduction is not a trivial task.

In this context, the thermal analysis of the conduction along the PCB is simplified by the use of **effective thermal conductivity ( $k_{\text{eff}}$ )**. Such parameter considers that a single value of thermal conductivity could be applied to a single layer plate (isotropic) and present a similar thermal behavior that a multilayer board does.

There are some simplified methods used to determine the canonical thermal conductivities:

$k_p$ : in-plane, or **in parallel**

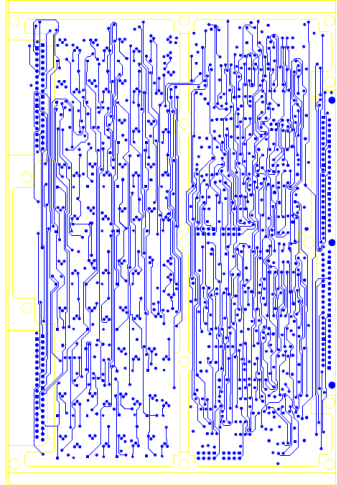
$k_s$ : cross-plane, or **in series**



# Canonical simplified analytical methods to calculate the effective thermal conductivities

parallel

series

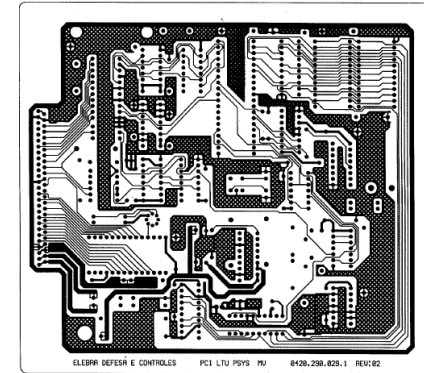


$$k_p = \frac{\sum_{i=1}^N k_i f_{ai} t_i}{\sum_{i=1}^N t_i}$$

**In-plane conductivity**

$$k_s = \frac{\sum_{i=1}^N t_i}{\sum_{i=1}^N \frac{t_i}{f_{ai} k_i}}$$

**Cross-plane conductivity**



Where  $f_{ai}$  is the copper covering percentage factor of the layer (for the FR4 layers,  $f_{ai}$  is 1)

## Canonical means

$$\bar{k}_{ma} = \frac{(k_s + k_p)}{2}$$

**Arithmetic Mean**

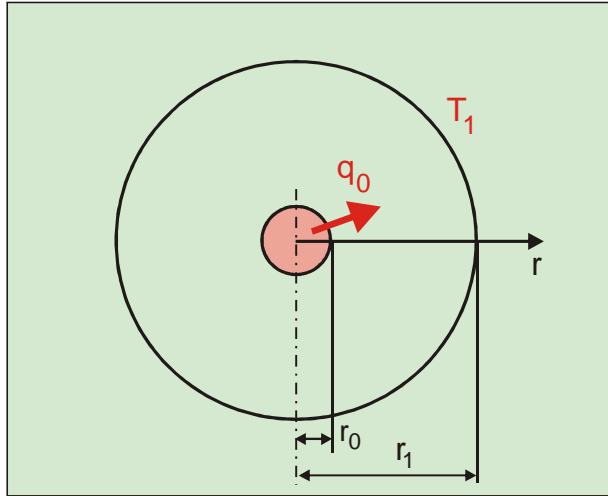
$$\bar{k}_{mg} = \sqrt{k_s k_p}$$

**Geometric Mean**

$$\bar{k}_{mh} = \frac{2k_s k_p}{(k_s + k_p)}$$

**Harmonic Mean**

# Effective thermal conductivity uncertainty effect



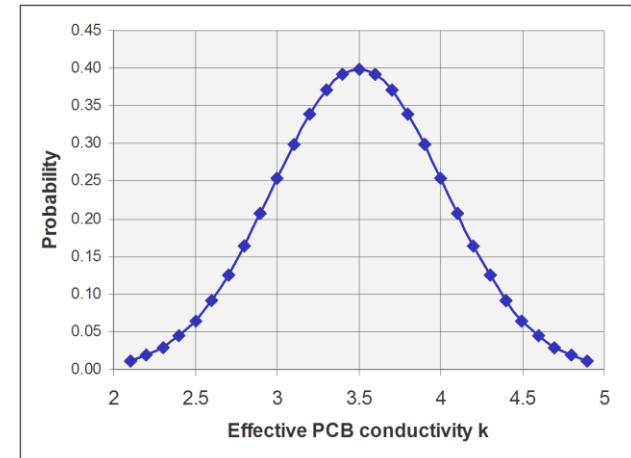
$$T(r) = T_0 + \frac{Q}{4\pi k \delta} \left( 1 - \left( \frac{r}{r_0} \right)^2 \right)$$

$$0 \leq r \leq r_0$$

$$T(r) = T_1 + \frac{Q}{2\pi k \delta} \text{Ln} \left( \frac{r_1}{r} \right)$$

$$r_0 \leq r \leq r_1$$

$$p(k) = \frac{e^{-\frac{(k-\bar{k})^2}{2(\Delta k)^2}}}{\sqrt{2\pi}}$$



Average temperature at the component mount area

$$\bar{T}_b = T_1 + \frac{Q}{8\pi k \delta} \left( 1 + 4 \text{Ln} \left( \frac{r_1}{r_0} \right) \right)$$

We assume that  $k_{\text{eff}}$  of PCB has an uncertainty with normal distribution. Thus,  $k$  on the denominator causes the undesirable distortion of  $T_b$  the distribution



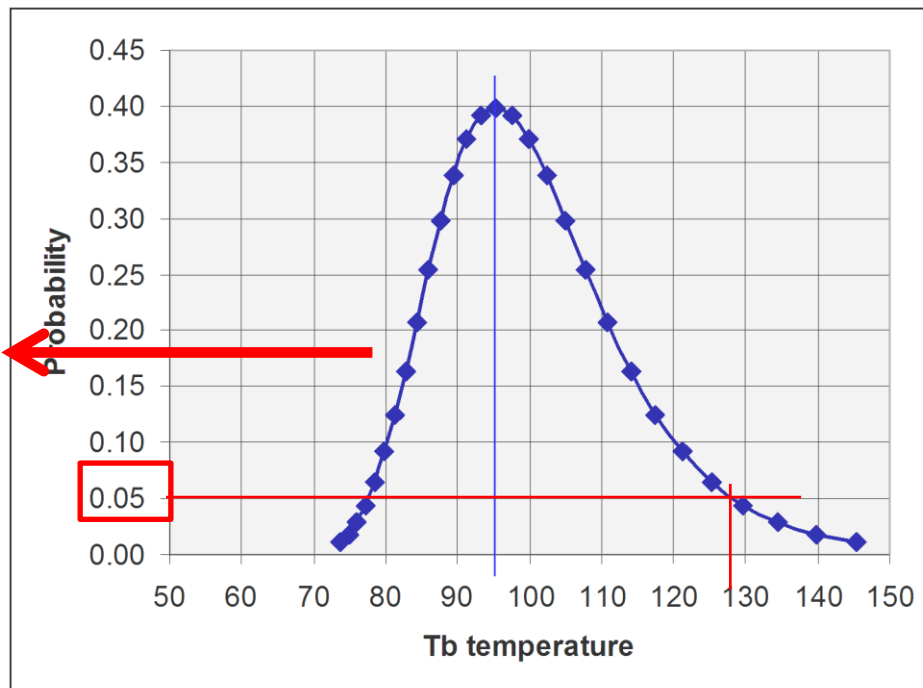
# Effective thermal conductivity uncertainty effect (example)

## Example:

$Q = 1 \text{ W}$ ,  $\delta = 1.6 \text{ mm}$ ,  $k = 3.5 \text{ W/m/K}$ ,  $r_0 = 5 \text{ mm}$ ,  $r_1 = 50 \text{ mm}$ ,  $T_1 = 20 \text{ }^\circ\text{C}$

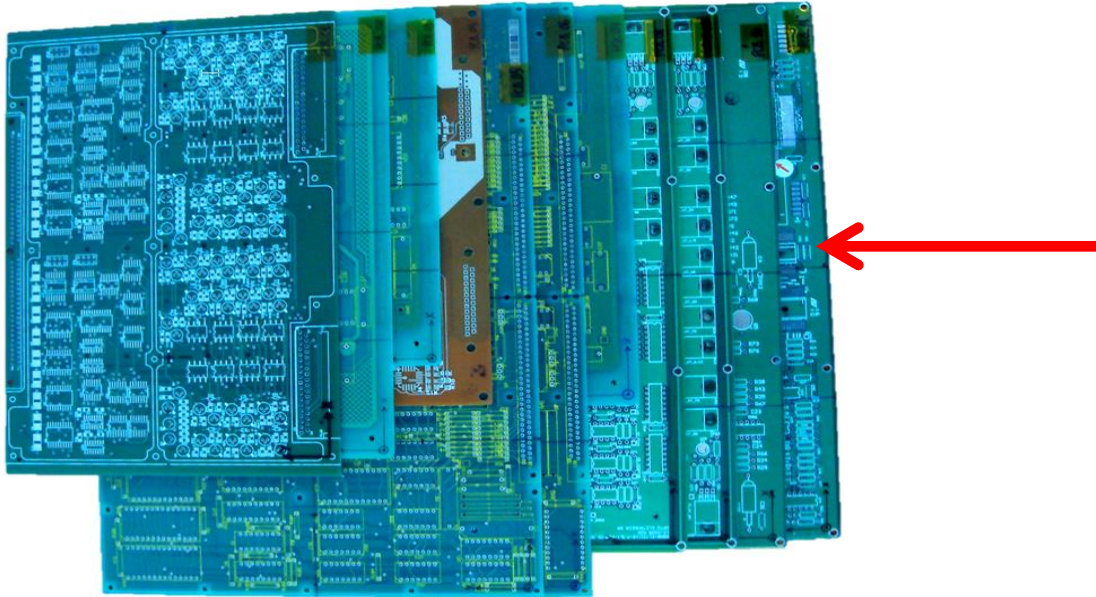
Assuming a "small"  $k$  deviation of  $\pm 15\%$  may cause  $T_b$  temperature deviation up to  $32.3 \text{ }^\circ\text{C}$  from average value of  $95.2 \text{ }^\circ\text{C}$ , in the 0.95 confidence interval.

$k$  on the denominator causes the **undesirable** distortion



**Conclusion:** It is very important to know the uncertainty range of PCB  $k_{\text{eff}}$ !

# Canonical effective conductivities – PCB samples



**11 real satellite PCB samples**  
(2 and 6 copper layers)

**Isotropic  $k_{\text{eff}}$**

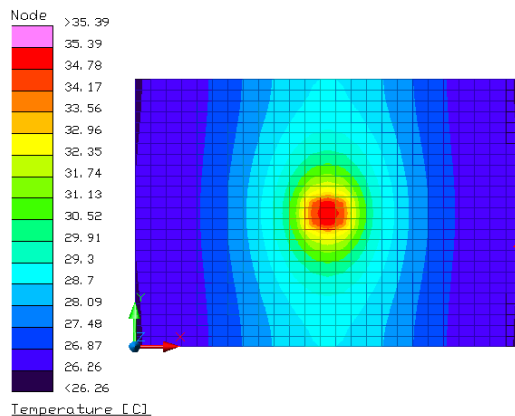
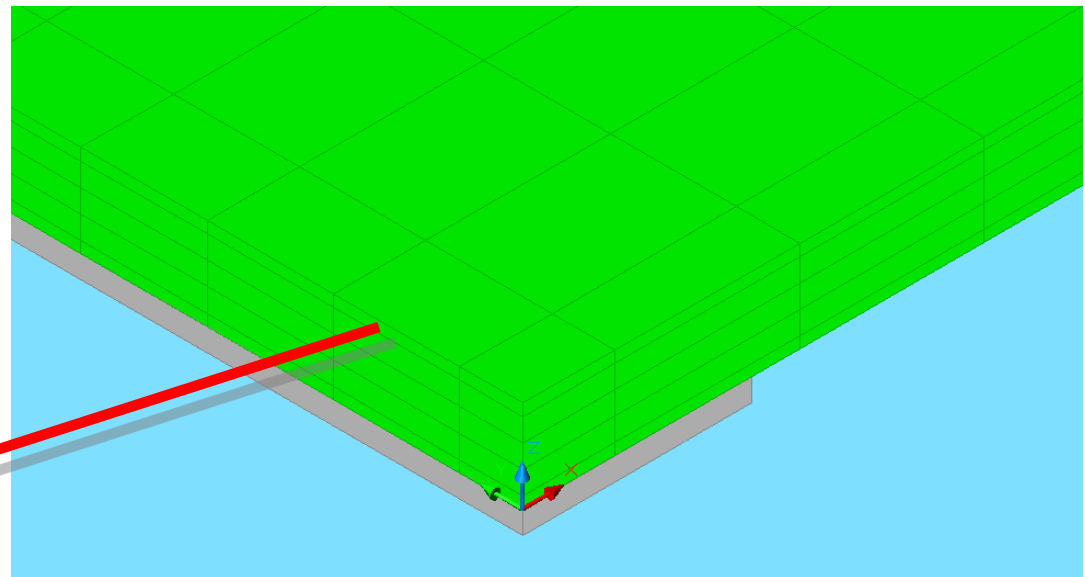
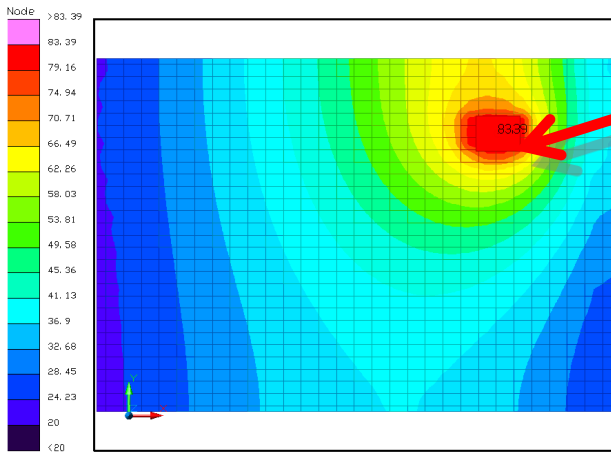
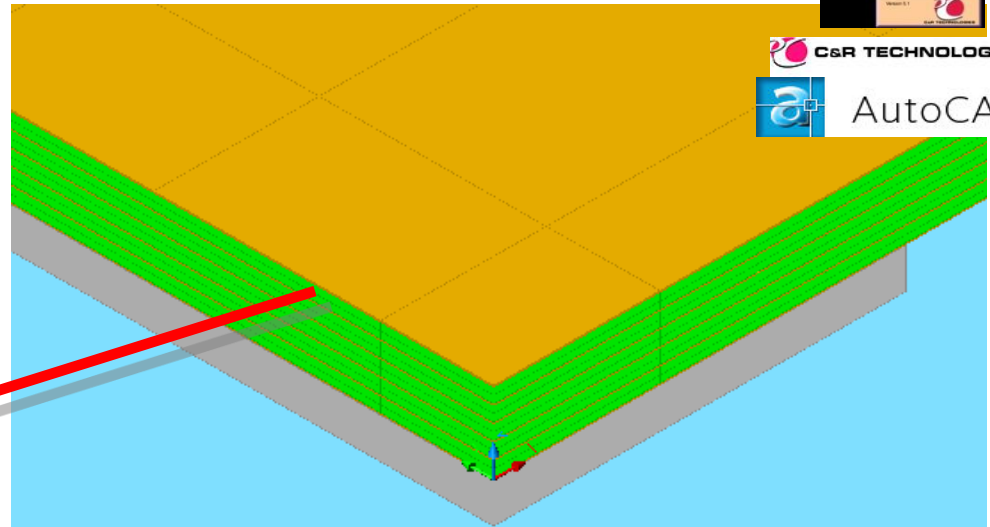
Board sample	Number of layers	$k_p$ (W/mK)	$k_s$ (W/mK)	Arithmetic Mean (W/mK)	Geometric Mean (W/mK)	Harmonic Mean (W/mK)
PCB_01	6	15.23	0.22	7.73	1.84	0.44
PCB_02	2	5.16	0.21	2.59	1.03	0.40
PCB_03	2	5.16	0.21	2.59	1.03	0.40
PCB_04	6	64.96	0.33	32.64	4.63	0.66
PCB_05	6	21.09	0.23	10.66	2.20	0.46
PCB_06	6	21.87	0.23	11.05	2.24	0.46
PCB_07	2	4.18	0.21	2.20	0.93	0.39
PCB_08	6	16.97	0.21	8.59	1.91	0.42
PCB_09	6	16.66	0.21	8.44	1.89	0.42
PCB_10	6	23.73	0.22	11.97	2.26	0.43
PCB_11	6	32.37	0.22	16.29	2.64	0.43



# Thermal Desktop<sup>®</sup> TMM

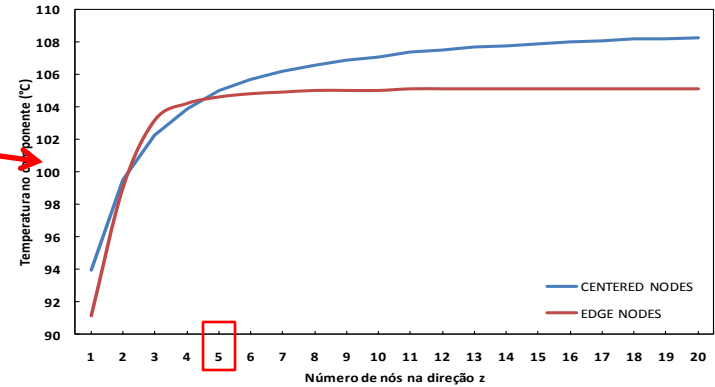


- Detailed model (multilayer)
- Simplified isotropic model ( $k_{\text{eff}}$ )
- Simplified anisotropic model ( $k_p$  and  $k_s$ )

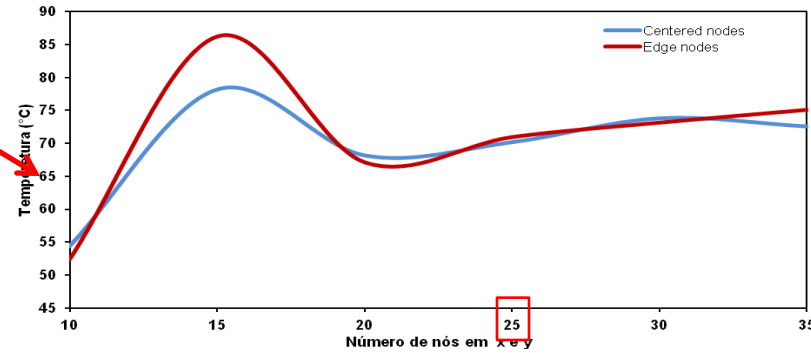


# Numerical mesh investigation (TMM)

❑ Nodes in z (cross-plane)



❑ Nodes in xy (in-plane)



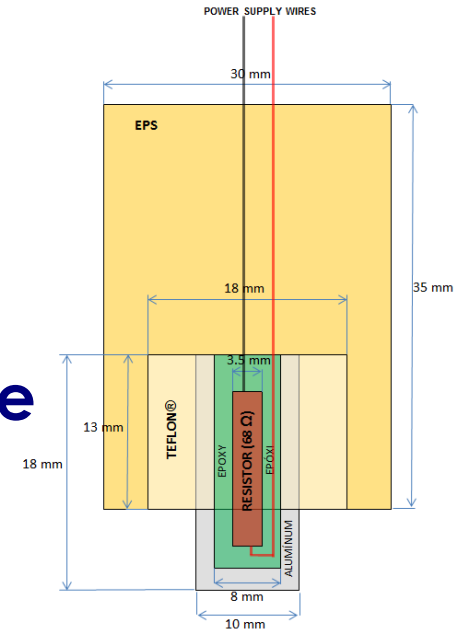
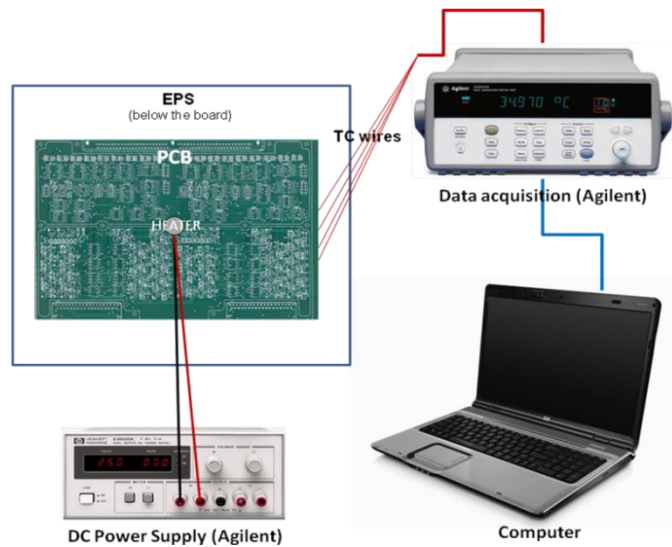
❑ Parâmetros numéricos adicionais

❑ Component size influence:  
**Uncertainty of  $\pm 3.2\%$**

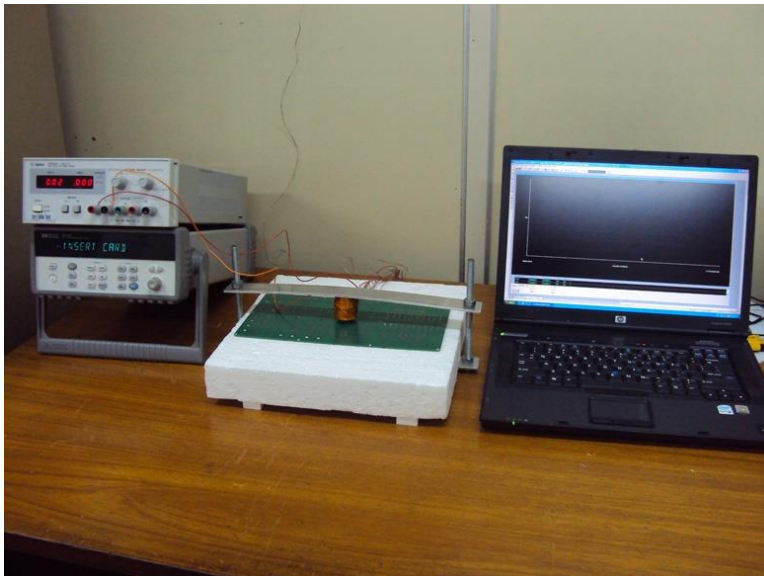
Position	Size1 (W/mK)	Size2 (W/mK)	Size 3 (W/mK)	Deviation(%)
1	7.73	7.36	7.36	2.84
2	8.26	7.98	8.02	1.87
3	7.70	7.33	7.33	2.82
4	7.96	7.49	7.21	5.00
5	8.28	8.00	7.81	2.92
6	7.86	7.44	7.19	4.56
7	7.91	7.47	7.22	4.64
8	8.40	8.05	7.87	3.33
9	7.85	7.43	7.20	4.40
10	8.11	7.83	7.67	2.79
11	8.15	8.01	7.84	1.92
12	8.10	7.82	7.66	2.82
13	8.15	8.01	7.84	1.94



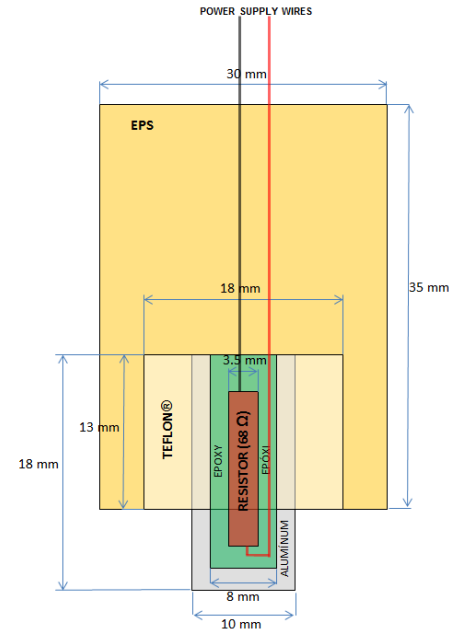
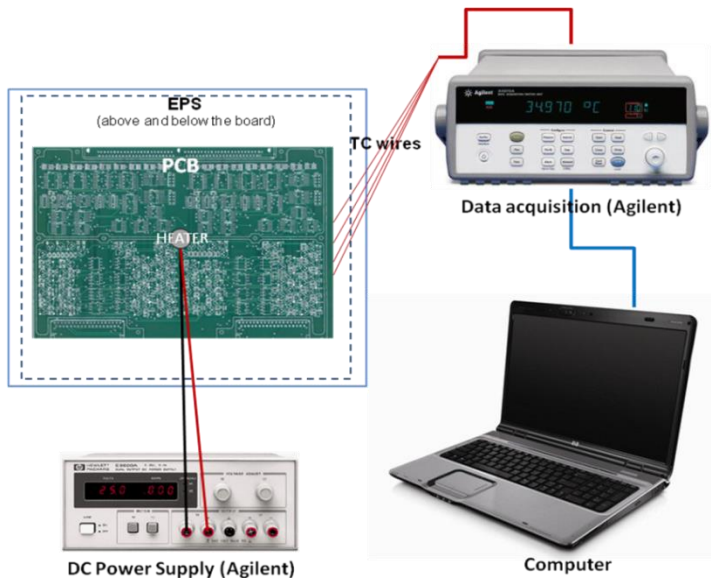
# Natural convection test – steady state



- Easy to execute
- Long-running
- Convection heat transfer uncertainties
- Thermal coupling between heater/PCB/EPS uncertainties
- Effective emissivity of the PCB uncertainty



# Insulated test – transient

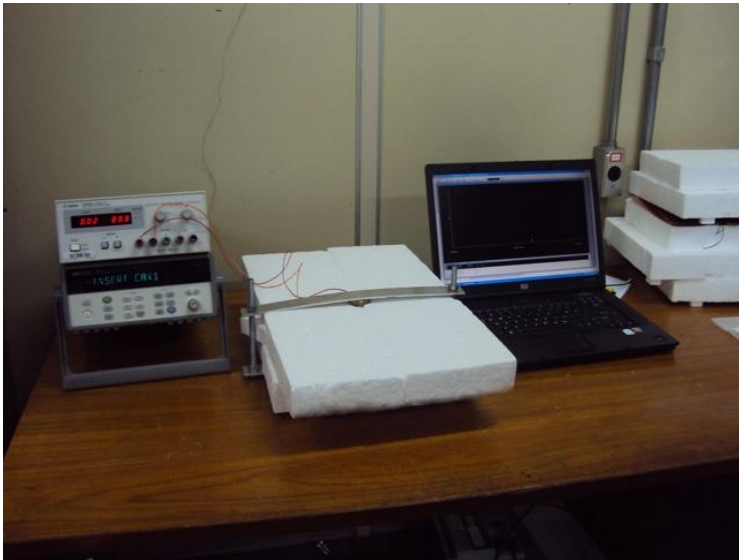


- Easy to execute

- Fast-running

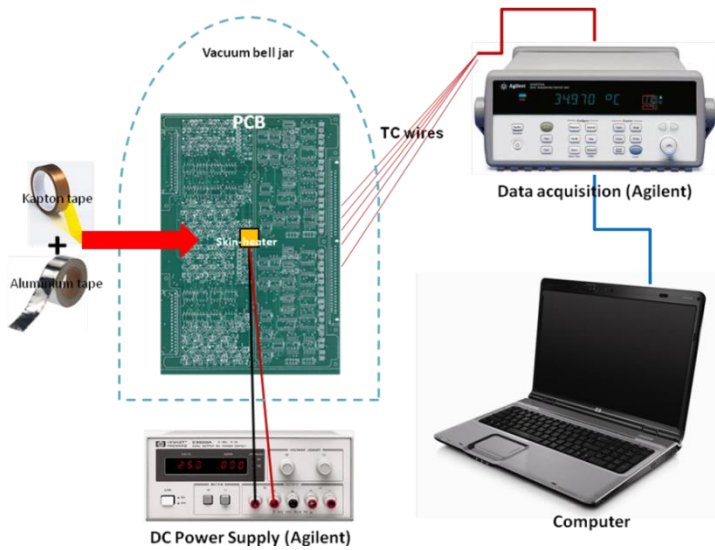
- EPS convection coefficient uncertainty

- Thermal resistance between heater/PCB/EPS uncertainties

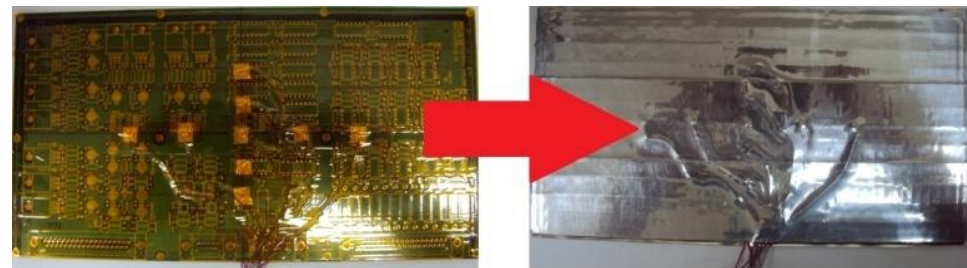


# Vacuum test – steady state

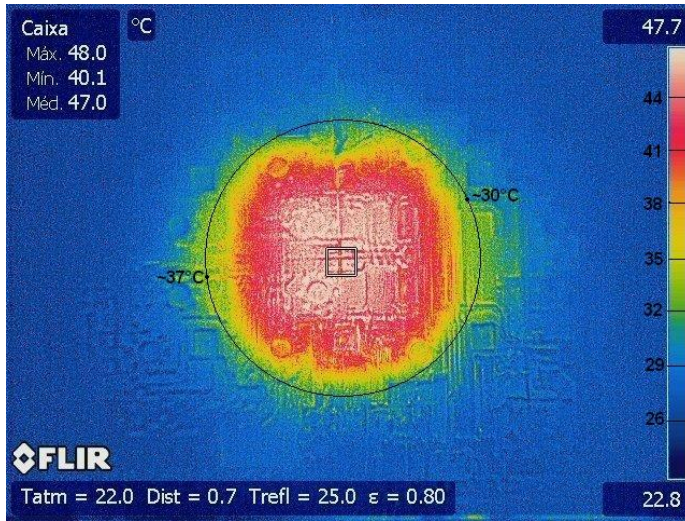
# VALIDATION



- No convection
- It takes time to prepare the setup
- Uncertainties on thermal contacts
- If MLI blanket is used, all its uncertainties shall be considered







**Non-homogeneous distribution of copper lines**

$$37^{\circ}\text{C} - k_{\text{eff}} = 2 \text{ W/m}^{\circ}\text{C}$$

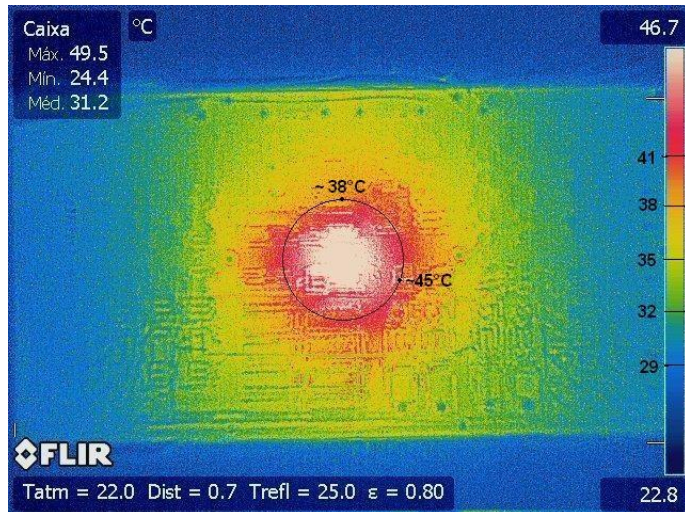
$$30^{\circ}\text{C} - k_{\text{eff}} = 4 \text{ W/m}^{\circ}\text{C}$$

**Deviation = ±55%**



Deviation observed from other methods

**±37.1%**



$$45^{\circ}\text{C} - k_{\text{eff}} = 11 \text{ W/m}^{\circ}\text{C}$$

$$38^{\circ}\text{C} - k_{\text{eff}} = 18 \text{ W/m}^{\circ}\text{C}$$

**Deviation = ±24%**

**±39.8%**





# Test types

- **TRANSIENT with convection:**

All 11 PCBs, 3 different positions (33 tests)

- **STEADY STATE with convection:**

All 11 PCBs, 1 position (center) (11 tests)

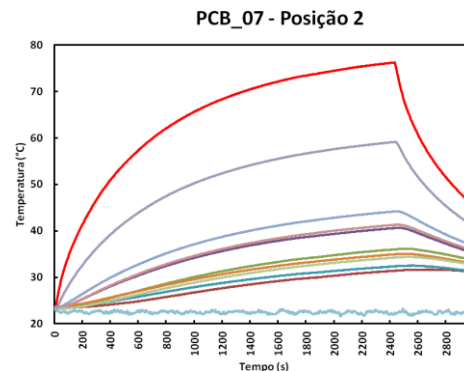
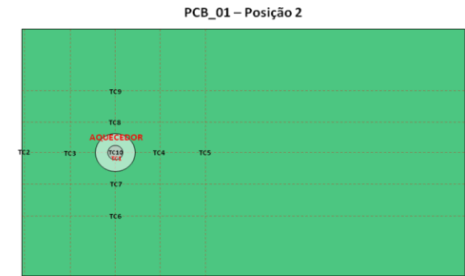
- **TRANSIENT in vacuum:**

Only for PCB\_08 – validation (4 tests)

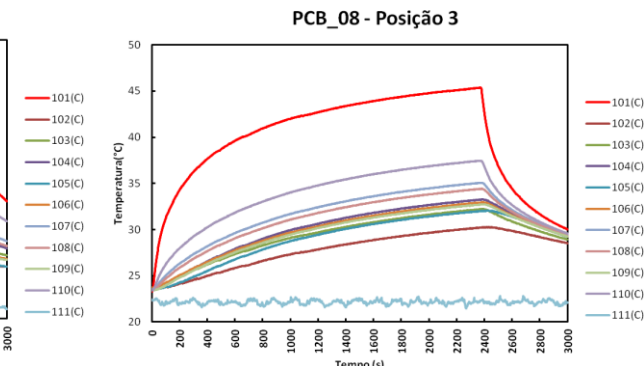
- **IR IMAGING:**

Only for PCB\_08 and PCB\_12 – validation (2 tests)

**Typical curves for the transient tests**



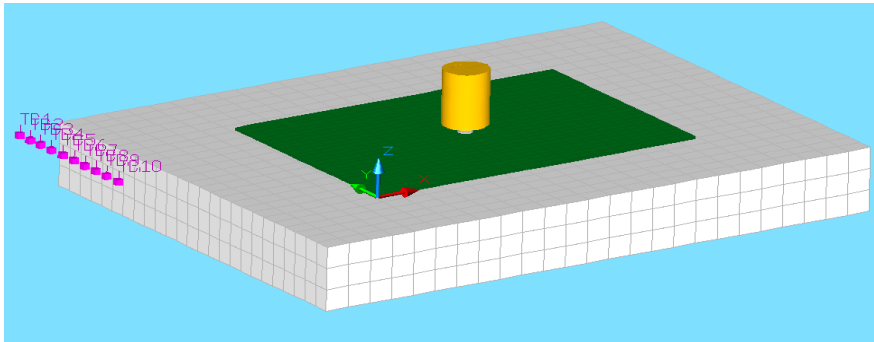
2-layers PCB



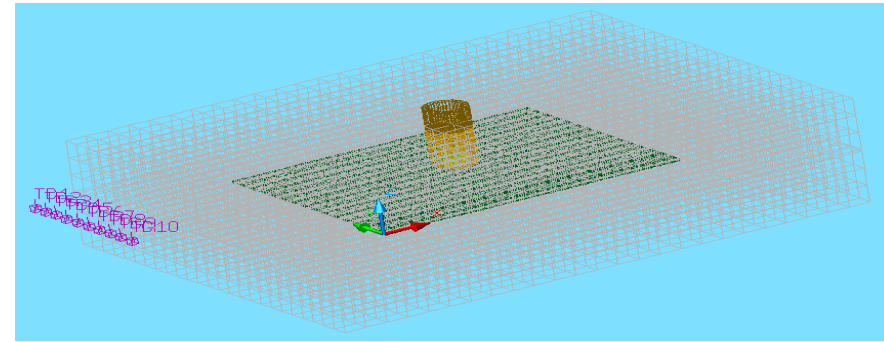
6-layers PCB

# Adjustment Procedure

## Steady State (22 TMMs)



## Transient (66 TMMs)



$$\min_{k_{eff}} \delta T = \sqrt{\frac{1}{N_{TC}} \sum_{i=1}^{N_{TP}} (T_{x,i} - T_{m,i})^2}$$

$$\min_{k_{eff}} \delta T = \sqrt{\frac{1}{N_{\tau}} \frac{1}{N_{TC}} \sum_{j=1}^{N_{\tau}} \sum_{i=1}^{N_{TC}} (T_{x,i}(\tau_0 + j\Delta\tau) - T_{m,i}(\tau_0 + j\Delta\tau))^2}$$

$$\min_{k_{p,eff}, k_{s,eff}} \delta T = \sqrt{\frac{1}{N_{TC}} \sum_{i=1}^{N_{TC}} (T_{x,i} - T_{m,i})^2}$$

$$\min_{k_{p,eff}, k_{s,eff}} \delta T = \sqrt{\frac{1}{N_{\tau}} \frac{1}{N_{TC}} \sum_{j=1}^{N_{\tau}} \sum_{i=1}^{N_{TC}} (T_{x,i}(\tau_0 + j\Delta\tau) - T_{m,i}(\tau_0 + j\Delta\tau))^2}$$



# Adjustment RESULTS

## PCB\_01

ANISOTROPIC			
TRANSIENT	$k_{p,eff}$ (W/m°C)	$k_{s,eff}$ (W/m°C)	$\Delta T$ (°C)
Position 1	5.9	0.30	2.7
Position 2	7.5	0.30	1.4
Position 3	6.5	0.30	1.8
STEADY STATE	$k_{p,eff}$ (W/m°C)	$k_{s,eff}$ (W/m°C)	$\Delta T$ (°C)
Position 1	5.6	0.40	1.2
ISOTROPIC			
TRANSIENT	$k_{eff}$ (W/m°C)		$\Delta T$ (°C)
Position 1	3.9		2.6
Position 2	5.7		1.4
Position 3	5.5		1.9
STEADY STATE	$k_{eff}$ (W/m°C)		$\Delta T$ (°C)
Position 1	5.4		2.6

**AVERAGES:**  $\mu_{k_{eff}} = 5.1$  W/m°C       $\mu_{k_{p,eff}} = 6.4$  W/m°C       $\mu_{k_{s,eff}} = 0.33$  W/m°C

## PCB\_02

ANISOTROPIC			
TRANSIENT	$k_{p,eff}$ (W/m°C)	$k_{s,eff}$ (W/m°C)	$\Delta T$ (°C)
Position 1	1.3	0.70	2.4
Position 2	1.9	0.30	2.3
Position 3	2.0	0.30	1.7
STEADY STATE	$k_{p,eff}$ (W/m°C)	$k_{s,eff}$ (W/m°C)	$\Delta T$ (°C)
Position 1	2.3	0.30	1.3
ISOTROPIC			
TRANSIENT	$k_{eff}$ (W/m°C)		$\Delta T$ (°C)
Position 1	3.2		2.2
Position 2	1.2		3.0
Position 3	1.9		1.6
STEADY STATE	$k_{eff}$ (W/m°C)		$\Delta T$ (°C)
Position 1	2.3		1.7

**AVERAGES :**  $\mu_{k_{eff}} = 2.2$  W/m°C       $\mu_{k_{p,eff}} = 1.9$  W/m°C       $\mu_{k_{s,eff}} = 0.40$  W/m°C



# Adjustment RESULTS

PCB	$\mu_{keff}$ (W/m <sup>2</sup> C)	$2\sigma_{keff}$ (W/m <sup>2</sup> C)	Deviation $2\sigma_{keff}$ (%)	$\mu_{kp,eff}$ (W/m <sup>2</sup> C)	$2\sigma_{kp,eff}$ (W/m <sup>2</sup> C)	Deviation $2\sigma_{kp,eff}$ (%)	$\mu_{ks,eff}$ (W/m <sup>2</sup> C)	$2\sigma_{ks,eff}$ (W/m <sup>2</sup> C)	Deviation $2\sigma_{ks,eff}$ (%)
PCB_01	5.1	1.6	31.4	6.4	1.6	25.0	0.33	0.10	30.3
PCB_02	2.2	1.6	72.7	1.9	0.8	42.1	0.40	0.40	100.0
PCB_03	1.4	0.2	14.3	1.7	0.4	23.5	0.23	0.06	26.1
PCB_04	7.7	0.6	7.8	14.3	2.4	16.8	0.23	0.10	43.5
PCB_05	6.2	2.0	32.3	8.6	3.8	44.2	0.26	0.18	69.2
PCB_06	6.9	3.0	43.5	8.9	3.6	40.4	0.30	0.08	26.7
PCB_07	2.8	3.0	107.1	2.1	0.8	38.1	0.26	0.12	46.2
PCB_08	10.0	4.2	42.0	13.0	4.0	30.8	0.25	0.14	56.0
PCB_09	8.8	2.6	29.5	12.0	3.6	30.0	0.23	0.06	26.1
PCB_10	9.7	2.4	24.7	11.6	4.2	36.2	0.25	0.08	32.0
PCB_11	13.4	0.4	3.0	18.9	1.8	9.5	0.23	0.06	26.1
	<b>Average <math>\Delta k_{eff}</math></b>		<b>±37.1%</b>	<b>Average <math>k_{p,eff}</math></b>		<b>±30.6%</b>	<b>Average <math>k_{s,eff}</math></b>		<b>±43.8%</b>

**DEVIATIONS:** due to irregular distribution of conductive paths and holes

# Proposed correlation for $k_{p,eff}$ with normally-distributed factor $\xi$

$$k_{p,eff} = \frac{\sum_{i=J[1]} k_{FR4} t_i + \xi \sum_{i=J[2]} f_{ai} k_{Cu} t_i}{\sum_{i=1}^N t_i}$$

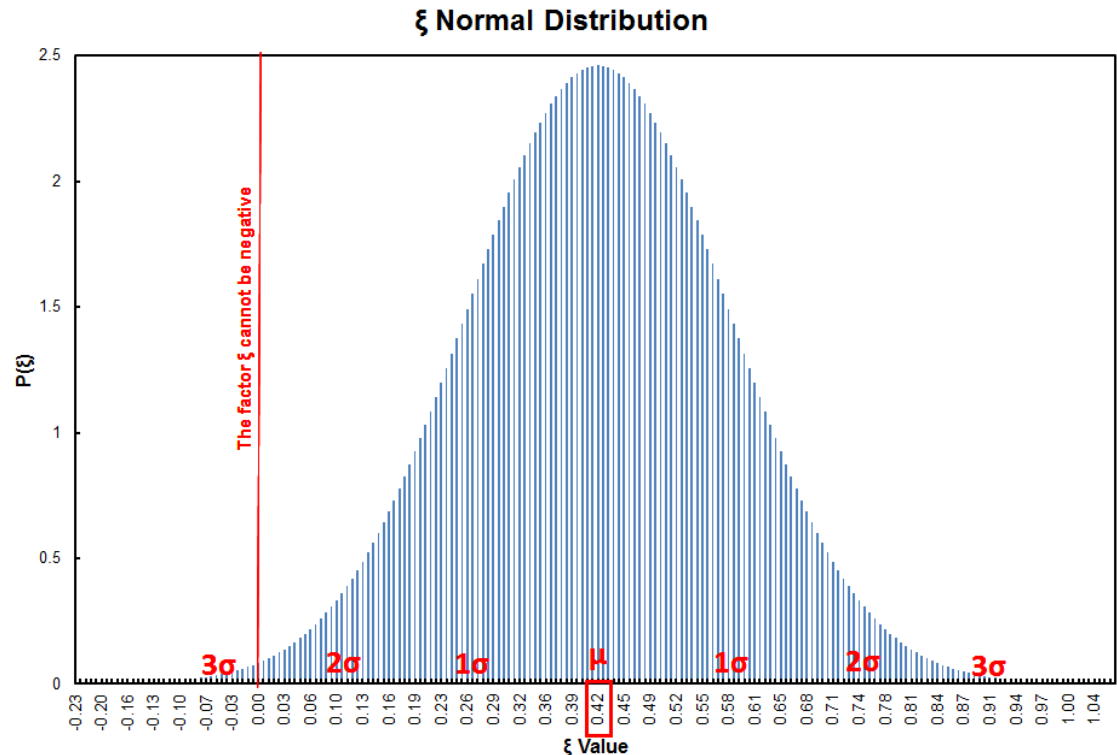
where: N – number of layers  
 $t_i$  – thickness of each layer  
 J[1] – FR4 layers set  
 J[2] – Cu layers set

$$\xi_{ave} = 0.42$$

$$\xi_{min} = 0.10 \text{ (- } 2\sigma\text{)}$$

$$\xi_{max} = 0.74 \text{ (+ } 2\sigma\text{)}$$

$$\sigma_{\xi} = 0.16$$



# Proposed correlation for $k_{s,eff}$ with normally-distributed factor $\zeta$

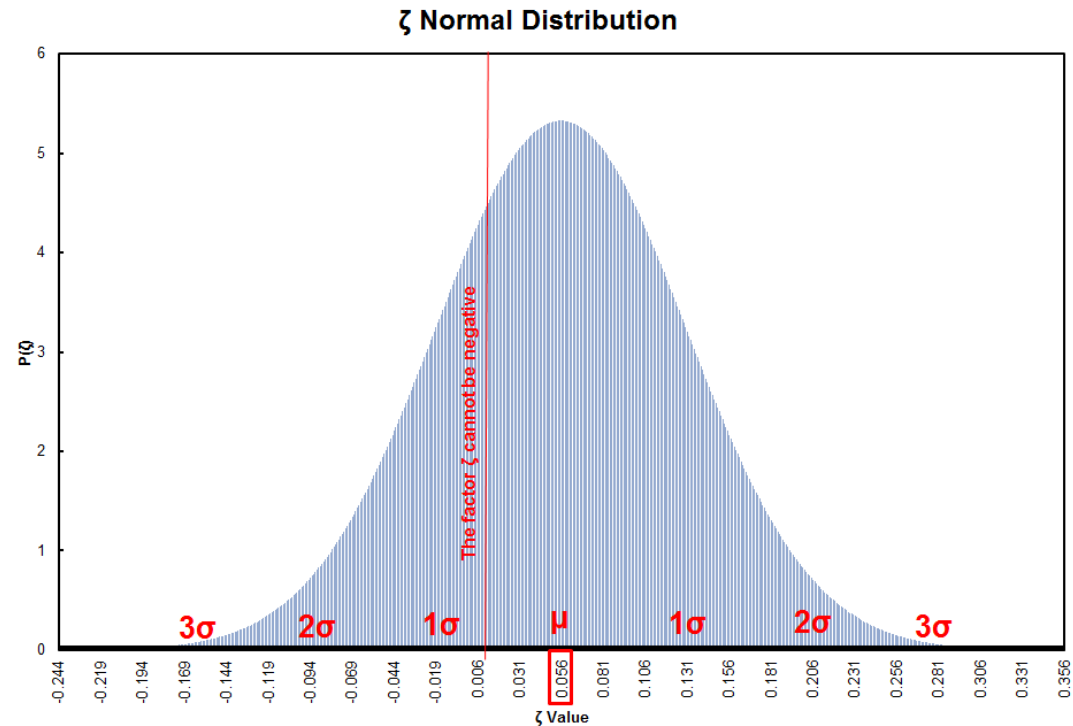
$$k_{s,eff} = (1 - \zeta f_h) \frac{\sum_{i=1}^N t_i}{\sum_{i=1}^N \frac{t_i}{f_{ai} k_i}} + \zeta f_h k_{Cu}$$

$$\zeta_{ave} = 0.056$$

$$\zeta_{min} = 0 \text{ (- } 2\sigma\text{)}$$

$$\zeta_{max} = 0.206 \text{ (+ } 2\sigma\text{)}$$

$$\sigma_{\zeta} = 0.075$$







## Isotropic $k_{eff}$ model: Weighted Arithmetic Mean (MAP)

$$k_{eff} = \alpha k_{p,eff} + \beta k_{s,eff}$$

Set	$\alpha$	$\beta$
2 layers	0.89	0.11
6 layers	0.73	0.27
All	0.74	0.26

$$k_{eff} = 0.74k_{p,eff} + 0.26k_{s,eff}$$



## Isotropic $k_{eff}$ model: Weighted Geometric Mean (MGP)

$$k_{eff} = k_{p,eff}^{\alpha} k_{s,eff}^{\beta}$$

Set	$\alpha$	$\beta$
2 layers	0.94	0.06
6 layers	0.92	0.08
All	0.92	0.08

$$k_{eff} = k_{p,eff}^{0.92} k_{s,eff}^{0.08}$$



## Isotropic $k_{eff}$ model: Weighted Harmonic Mean (MHP)

$$k_{eff} = \frac{1}{\frac{\alpha}{k_{p,eff}} + \frac{\beta}{k_{s,eff}}}$$

Set	$\alpha$	$\beta$
2 layers	0.98	0.02
6 layers	0.99	0.01
All	0.99	0.01

$$k_{eff} = \frac{1}{\frac{0.99}{k_{p,eff}} + \frac{0.01}{k_{s,eff}}}$$



# The mean choice

Set	Average deviations from $k_{eff}$ (%)		
	MAP	MGP	MHP
All	15.76	14.34	14.51
2 layers	11.84	12.64	14.63
6 layers	14.65	14.08	14.13
Average	14.08%	13.69%	14.42%

The best weighted mean: Weighted Geometric Mean (MGP)

Small deviation between the means ( $\pm 2.5\%$ )

Comparative example:

PCB_11				
Simplified Canonical Method				
$k_p$ (W/m <sup>2</sup> C)	$k_s$ (W/m <sup>2</sup> C)	$k_{eff}$ MA (W/m <sup>2</sup> C)	$k_{eff}$ MG (W/m <sup>2</sup> C)	$k_{eff}$ MH (W/m <sup>2</sup> C)
32.37	0.22	16.29	2.64	0.43
Weighted Means Method				
$k_{p,eff}$ (W/m <sup>2</sup> C)	$k_{s,eff}$ (W/m <sup>2</sup> C)	$k_{eff}$ MAP (W/m <sup>2</sup> C)	$k_{eff}$ MGP (W/m <sup>2</sup> C)	$k_{eff}$ MHP (W/m <sup>2</sup> C)
13.69	0.29	10.21	10.07	9.40



# Practical guide – ANISOTROPIC model

## Necessary data:

- FR4 thermal conductivity –  $k_{FR4}$  [W/(mK)]
- Copper thermal conductivity –  $k_{Cu}$  [W/(mK)]
- PCB total area -  $A_{PCB}$  [m<sup>2</sup>]
- Total PCB thickness -  $t_{PCB}$  [m]
- Thickness of each copper layer –  $t_{Cu,i}$  [m]
- Total thickness of all FR4 layers –  $t_{FR4}$  [m]
- Copper traces coverage factor for each conductive layer -  $f_{a,i}$
- Through holes metalized area factor –  $f_h$

## In-plane effective thermal conductivity ( $k_{p,eff}$ )

$$k_{p,eff} = \frac{k_{FR4}t_{FR4} + 0.42 \left( \sum_{i=J[2]} f_{a,i} k_{Cu} t_{Cu,i} \right)}{t_{PCB}}$$

$$k_{p,eff}^{\min} = \frac{k_{FR4}t_{FR4} + 0.10 \left( \sum_{i=J[2]} f_{a,i} k_{Cu} t_{Cu,i} \right)}{t_{PCB}}$$

## Cross-plane effective thermal conductivity ( $k_{s,eff}$ )

$$k_{s,eff} = (1 - 0.056f_h) \frac{t_{PCB}}{\left( \frac{t_{FR4}}{k_{FR4}} + \sum_{i=J[2]} \frac{t_{Cu,i}}{f_{a,i} k_{Cu}} \right)} + 0.056f_h k_{Cu}$$

$$k_{s,eff}^{\min} = \frac{t_{PCB}}{\left( \frac{t_{FR4}}{k_{FR4}} + \sum_{i=J[2]} \frac{t_{Cu,i}}{f_{a,i} k_{Cu}} \right)}$$



# Practical guide – ISOTROPIC model

Isotropic thermal conductivity from  $k_{p,eff}$  e  $k_{s,eff}$

$$k_{eff} = (k_{p,eff})^{0.92} \cdot (k_{s,eff})^{0.08}$$

$$k_{eff}^{min} = 0.935 (k_{p,eff}^{min})^{0.92} \cdot (k_{s,eff}^{min})^{0.08}$$

→ Uncertainty due to the frames on the edges (typical configuration)

## Effective thermal conductivities for electronics thermal design

- ❑ Operational temperature limits →  $k_{p,eff}^{min}$   $k_{s,eff}^{min}$   $k_{eff}^{min}$
- ❑ Derated operational temperature limits →  $k_{p,eff}$   $k_{s,eff}$   $k_{eff}$





# CONCLUSIONS

- ❑ 2 types of tests , 2 validation tests
- ❑ Correlations with introduced normally-distributed factors to calculate  $k_{p,eff}$  e  $k_{s,eff}$  with uncertainty margins
- ❑ We believe the results are applicable for other PCBs of typical satellite platforms, once the introduced factors represent the layout variety of conductive paths, based on statistic of 11 different PCBs
- ❑ These factors are dimensionless, they have established normal distribution, and do not depend on PCB parameters such as number of layers, percent of copper coverage of each layer and number of metallized crossing holes
- ❑ Isotropic model - Better approximation of  $k_{eff}$  from  $k_{p,eff}$  and  $k_{s,eff}$ : MGP
- ❑ Uncertainty ( $2\sigma$ ) due to conductive paths irregularity
  - $k_{eff}$  -  $\pm 37.1\%$
  - $k_{p,eff}$  -  $\pm 30.6\%$
  - $k_{s,eff}$  -  $\pm 43.8\%$
- ❑ Practical approach on how to use the correlations for electronics thermal design