Number	304
Publication Year	2024
Acceptance in OA@INAF	2024-04-11T09:09:59Z
Title	þÿ A A V S 2 T X m o d u l e - T h e r m a l e v a l u a t i o n a
Authors	SCHIAFFINO, Marco; PERINI, FEDERICO; RUSTICELLI, SIMONE; MATTANA, Andrea; MONARI, Jader
Affiliation of first author	IRA Bologna
Handle	http://hdl.handle.net/20.500.12386/35048; https://doi.org/10.20371/INAF/TechRep/304

AAVS2 “TX module” - Thermal evaluation and improvements

M. Schiaffino[1], F. Perini[1], S. Rusticelli
A. Mattana[1], J. Monari[1]

1 – INAF - Istituto di Radioastronomia

Summary

Introduction

SKA-Low is the low-frequency radio telescope of the SKA Observatory, being built at the Murchison Radio-astronomy Observatory (MRO) site in Western Australia. In its current design, SKA-Low will consist of more than 130,000 fixed antennas, arranged into 512 stations. Each station will be composed of 256 SKALA4.1 dual-polarization log-periodic antennas, pseudo-randomly distributed within a circular area of about 40 m diameter.
The Aperture Array Verification System 2 (AAVS2), operational since late 2019, is a full-size engineering prototype station deployed at the MRO site.
The 256 antennas of this test array are grouped by 16 in “Tiles” and connected to 16 "SmartBoxes" (SB), elements designed to contain the power and signals distribution of each tile. Each SB hosts 16 FEMs (front-end modules) that are optical TX modules capable to handle the 2 antenna polarization signals (2 RF chains) into a common transmission medium by using different optical wavelength (WDM technology).
An overheating of the AAVS2 SmartBoxes required a study of the operating temperature of the TX Module (and its main components) inside the SmartBoxes, and an evaluation of the working condition.
This document describes the phases of the study carried out on the TX module and the definition of an optimized model, integrating the data obtained. The thermal simulations illustrated below were created using the Autodesk CFD software, a computational fluid dynamics simulator with which it is also possible to analyze heat transfer and fluid flow design.

AAVS2 TX module analysis

The objective of the analysis is the determination of the operating temperature of the module and the definition of any measures to improve its functioning.
The first phase of the work was the determination of the most critical components and boundary conditions, to create a simplified geometry of the TX module, suitable to be managed by the simulator.
The elements that compose the module used for AAVS2 are the printed circuit board (which houses two RF chains and the BOSA, a WDM laser operating at wavelengths of 1270 nm and 1330 nm) and the aluminum case capable of containing the card, in addition to the lid also equipped with fixing interfaces.
The table below summarizes the main components of the module and their consumption relative to the reference ambient temperature. The channel to which each individual component belongs is also indicated.

Schematic Part	Device	Wavelength [nm]	$P_{25°}$ [W]	$P_{35°}$ [W]	$P_{45°}$ [W]	$P_{55°}$ [W]	$P_{65°}$ [W]	$P_{75°}$ [W]	$P_{80°}$ [W]	$P_{85°}$ [W]
IC2	AWG0123E	1270	0.138	0.141	0.144	0.147	0.150	0.153	0.155	0.156
IC1	AWG0123E	1330	0.138	0.141	0.144	0.147	0.150	0.153	0.155	0.156
IC3	LDCL015	1270	0.121	0.131	0.139	0.151	0.170	0.196	0.213	0.241
IC6	LDCL015	1330	0.121	0.128	0.134	0.145	0.156	0.168	0.178	0.190
Q1	BC817	1270	0.025	0.030	0.034	0.040	0.050	0.064	0.074	0.090
Q2	BC817	1330	0.025	0.028	0.031	0.036	0.042	0.048	0.053	0.060
R24	1005	1270	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
R10	1005	1330	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
R45	1005	1270	0.006	0.009	0.012	0.016	0.025	0.041	0.055	0.081
R28	1005	1330	0.006	0.008	0.010	0.013	0.018	0.023	0.028	0.036
LD	LASER	1270	0.030	0.036	0.041	0.048	0.060	0.077	0.089	0.108
LD	LASER	1330	0.028	0.031	0.034	0.040	0.046	0.053	0.058	0.064
L19	LNA choke	1270	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
L17	LNA choke	1330	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
D3	SMCJ5V0(C)A		0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
D1	DFLS130L		0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
		P_{TOT} [W]	0.743	0.788	0.828	0.888	0.971	1.081	1.162	1.288

Table 1 - Component consumption

CAD model - Main elements

Finally, a simplified model of the TX module was created, containing all the main components previously defined. The images below show the models used for the simulations.

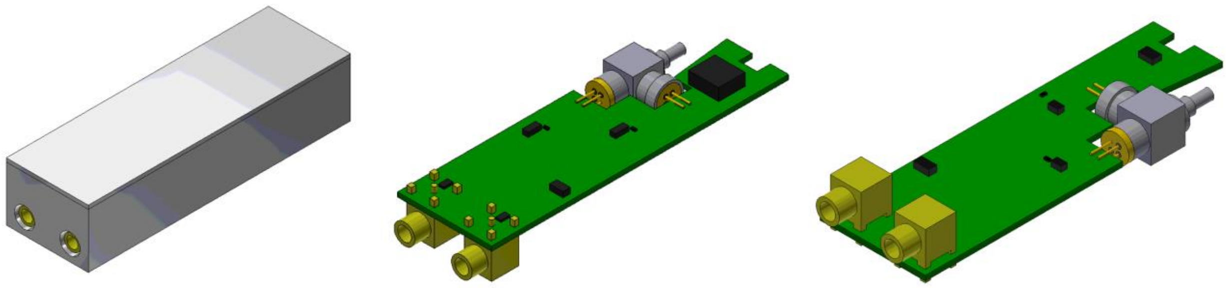


Figure 1 - Complete Optical TX – PCB bottom e top view

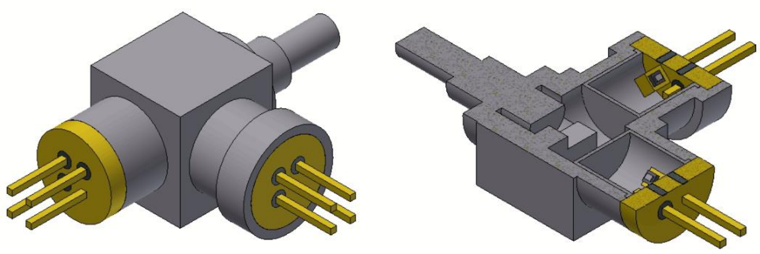


Figure 2 - BOSA, whole and in section, hosting the two photodiodes

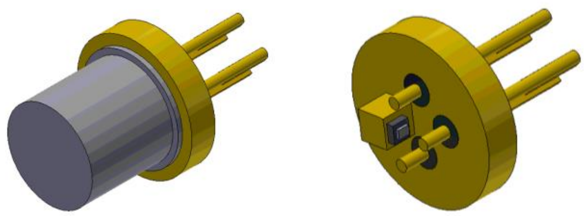


Figure 3 - Photodiode

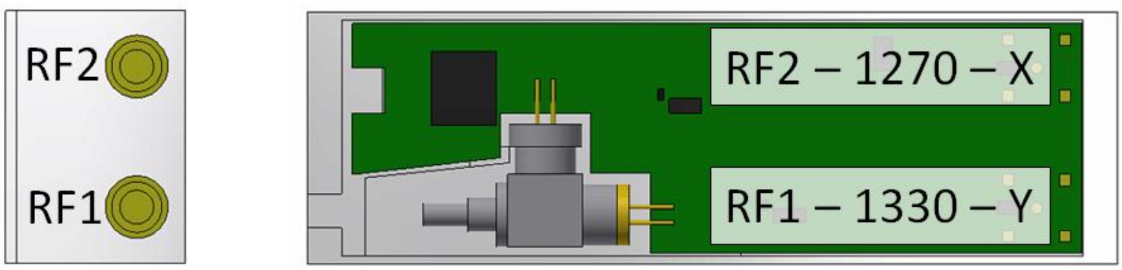


Figure 4 - TX module – polarizations/channels

CFD model

The analysis will be performed at various reference ambient temperatures (27.1° - 40° - 50° - 55° - 60° - 65°). These temperatures are constant for each scenario (thermal chamber type without ventilation).

The geometry of the system under analysis is indicated in the image below. The TX module is placed inside a suitably sized volume of air.

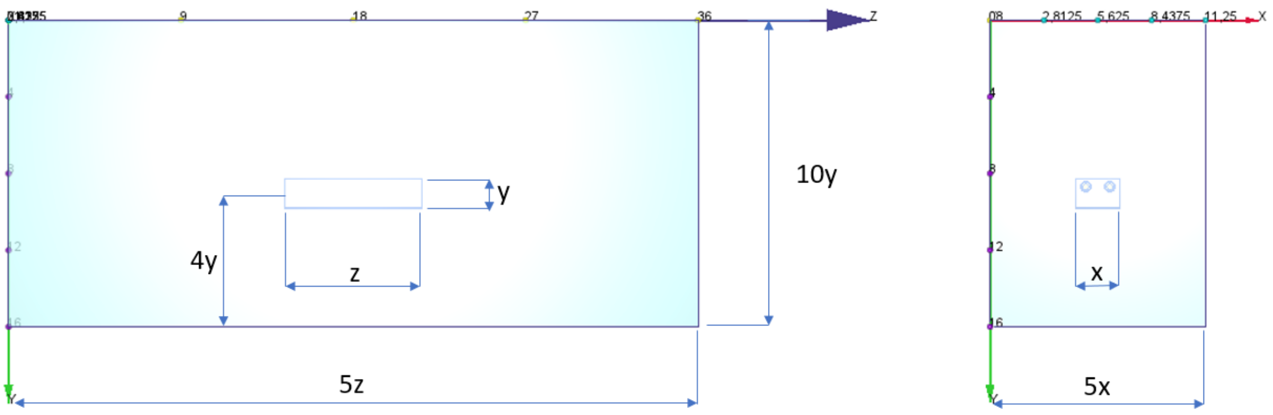


Figure 5 - Standalone TX Module model

The individual elements of the assembly, defined both as material and as boundary conditions, are:

- External Air
  Material: Air – Variable properties as the scenario changes

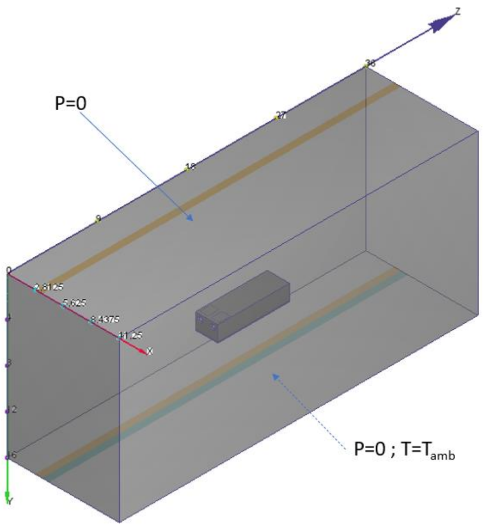


Figure 6 - External air boundary conditions

Boundary conditions:
Pressure: 0 at Top and Bottom site
Temperature = Ambient temperature at the bottom site

- Box and cover/lid
  Material: Aluminum

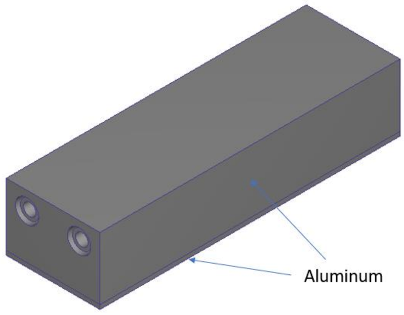


Figure 7 - Box and cover

- Internal air (inside the case and inside the BOSA)
  Material: Air – Variable properties as the scenario changes

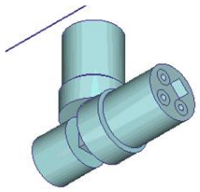


Figure 8 - Internal air

- PCB
  Materials

  PCB: custom PCB board – 1mm thickness – 4 layers

  - Layer 1: 0.035mm copper (20% metal)
  - Layer 2: 0.035mm copper (85% metal)
  - Layer 3: 0.035mm copper (85% metal)
  - Layer 4: 0.035mm copper (20% metal)
  - Dielectric: FR4

  Effective plane conductivity: 0.0206512 W/(mm*K)

  Effective normal conductivity: 0.000313842 W/(mm*K)

  Connectors: Brass

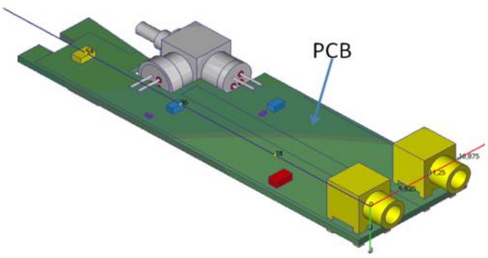


Figure 9 - TX Module PCB

- AWG0123E
  Material: Compact Thermal model

  Theta JB: 150 C/W

  Theta JC: 70.1 C/W

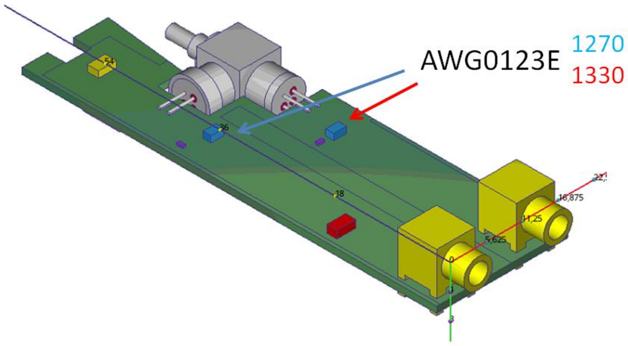


Figure 10 - Compact thermal model AWG0123E

Boundary conditions:
Total heat generations – variable with temperature - equal between 1270 and 1330

T [°C]	P [W]
25	0.138
35	0.141
45	0.144
55	0.147
65	0.150
75	0.153
80	0.155
85	0.156

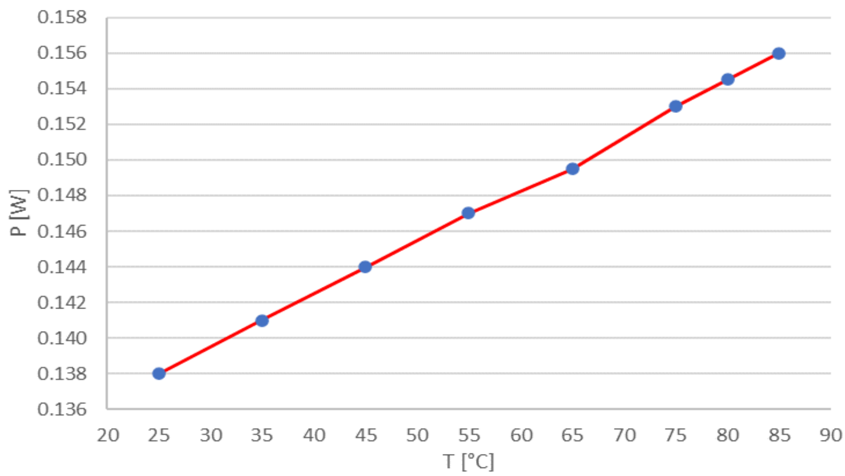


Table 2 - Total heat generation variable with temperature AWG0123E

- LDCL015
  Material: Compact Thermal model

  Theta JB: 35 C/W

  Theta JC: 81 C/W

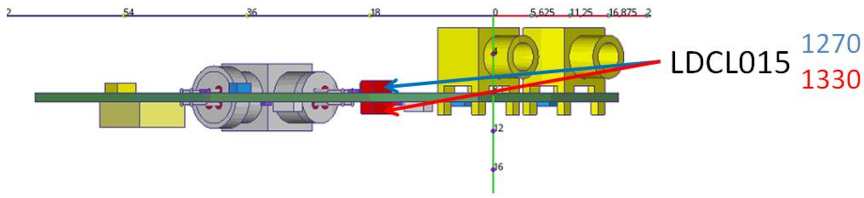


Figure 11 - Compact thermal model LDC015

Boundary conditions:
Total heat generations – variable with temperature - different between 1270 and 1330

T [°C]	P_{1270} [W]	P_{1330} [W]
25	0.121	0.121
35	0.131	0.128
45	0.139	0.134
55	0.150	0.144
65	0.168	0.155
75	0.196	0.168
80	0.213	0.178
85	0.241	0.190

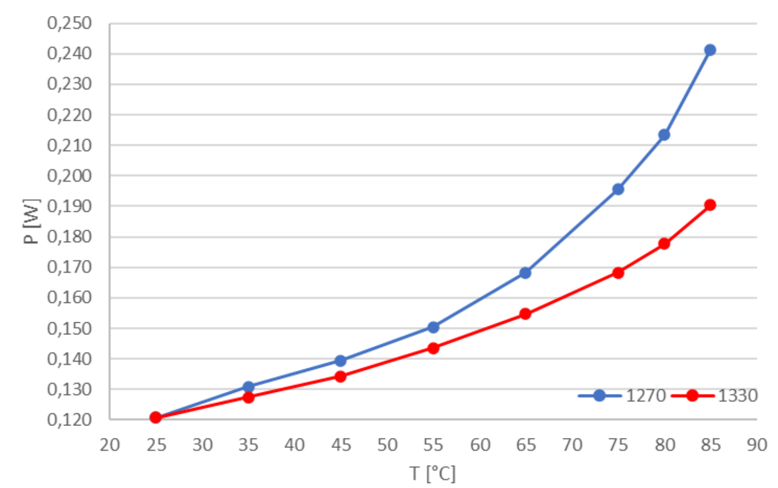


Table 3 - Total heat generation variable with temperature LDC015

- DFLS130L – R24 – R10

Materials:
DFLS130L: Compact Thermal model

Theta JB: 10 C/W

Theta JC: 70 C/W

R24 and R10: Compact Thermal model

Theta JB: 60 C/W

Theta JC: 40 C/W

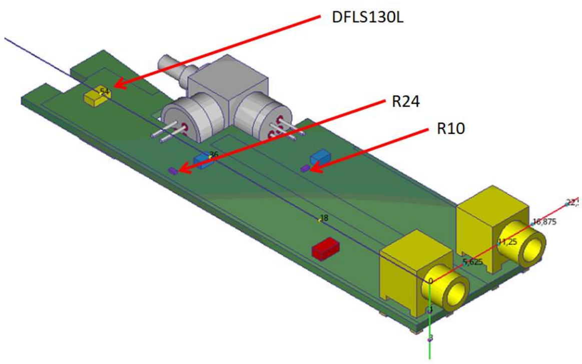


Figure 12 - Compact thermal model DFLS130L, R24, R10

Boundary conditions:
Total heat generations – constant with temperature

DFLS130L: 0,01W

R10 and R24: 0,03025W

- BC817

Materials: Compact Thermal model

Theta JB: 350 C/W

Theta JC: 70 C/W

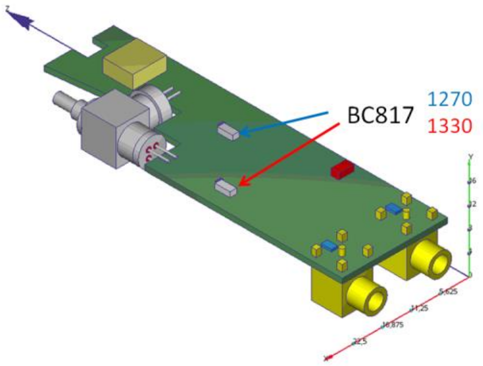


Figure 13 - Compact thermal model BC817

Boundary conditions:
Total heat generations – variable with temperature - different between 1270 and 1330

T [°C]	P_{1270} [W]	P_{1330} [W]
25	0.025	0.025
35	0.030	0.028
45	0.034	0.031
55	0.040	0.036
65	0.050	0.042
75	0.064	0.048
80	0.074	0.053
85	0.090	0.060

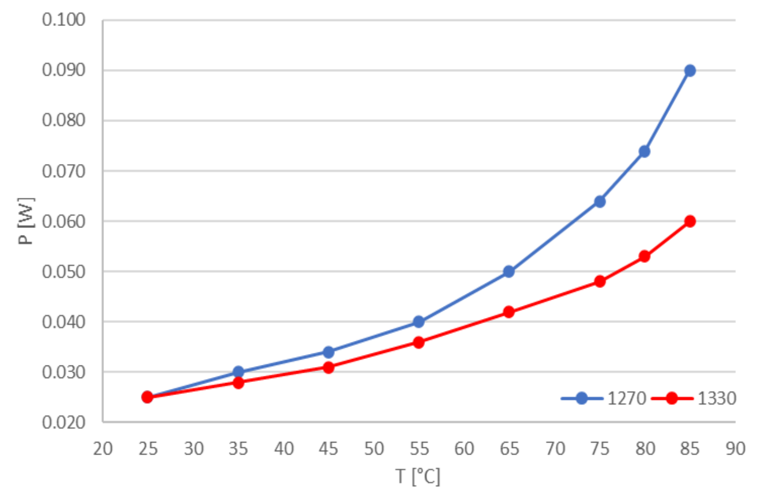


Table 4 - Total heat generation variable with temperature BC817

- SMCJ5V0(C)A – L17 – L19

Materials:

SMCJ5V0(C)A: Compact Thermal model

Theta JB: 28 C/W

Theta JC: 70 C/W

L17 and L19: Compact Thermal model

Theta JB: 36 C/W

Theta JC: 24 C/W

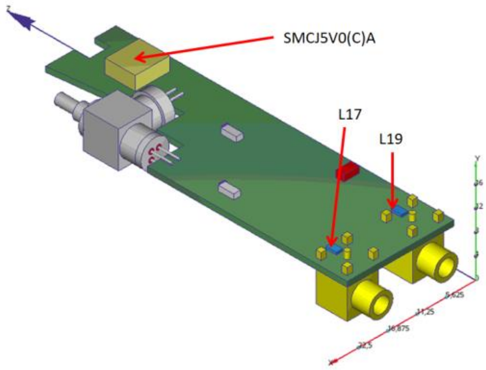


Figure 14 - Total heat generation variable with temperature SMCJ5V0(C)A, L17, L19

Boundary conditions:
Total heat generations – constant with temperature

SMCJ5V0(C)A: 0.01W

L17 and L19: 0.01248W

- R28 e R45
  Materials: Compact Thermal model

  Theta JB: 60 C/W

  Theta JC: 40 C/W

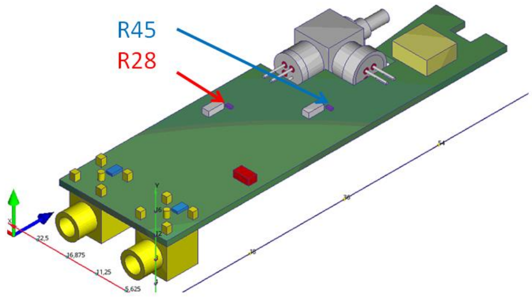


Figure 15 - Total heat generation variable with temperature R28, R45

Boundary conditions:
Total heat generations – variable with temperature - different between 1270 and 1330

T [°C]	P_{1270} [W]	P_{1330} [W]
25	0.025	0.025
35	0.030	0.028
45	0.034	0.031
55	0.040	0.036
65	0.050	0.042
75	0.064	0.048
80	0.074	0.053
85	0.090	0.060

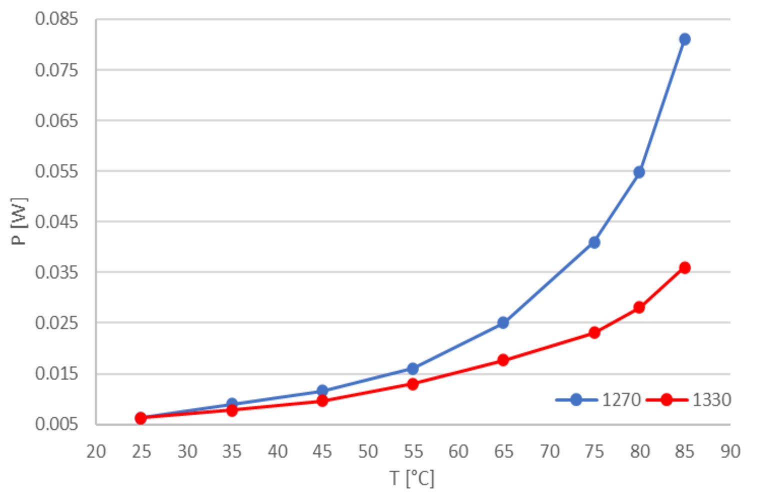


Table 5 - Total heat generation variable with temperature R28, R45

- BOSA

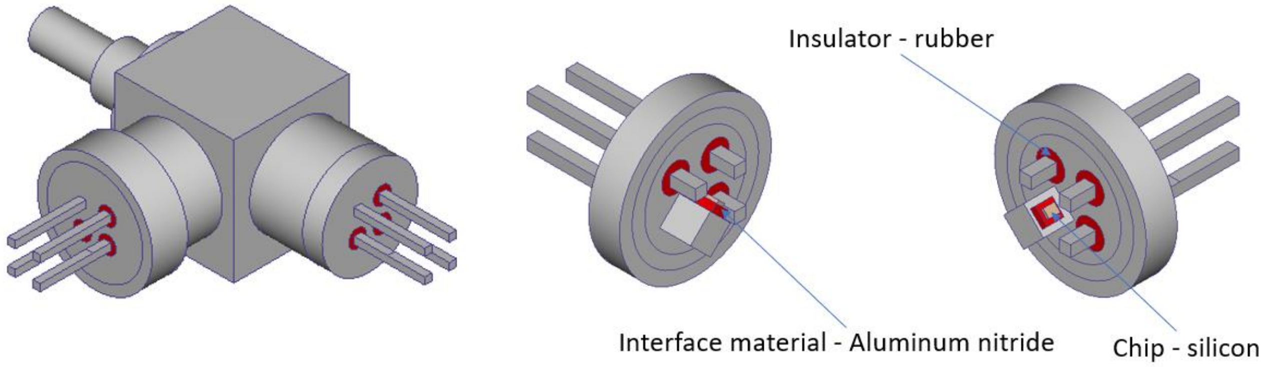


Figure 16 - BOSA materials

Materials:

External body, pins, cover diodes: steel

Insulator: silicone rubber

Interfaces material: aluminum nitride

Chips: silicon

Boundary conditions:

Total heat generations of the two chips – variable with temperature - different between 1270 and 1330

T [°C]	P_{1270} [W]	P_{1330} [W]
25	0.030	0.030
35	0.036	0.031
45	0.041	0.034
55	0.048	0.040
65	0.060	0.046
75	0.077	0.053
80	0.089	0.058
85	0.108	0.064

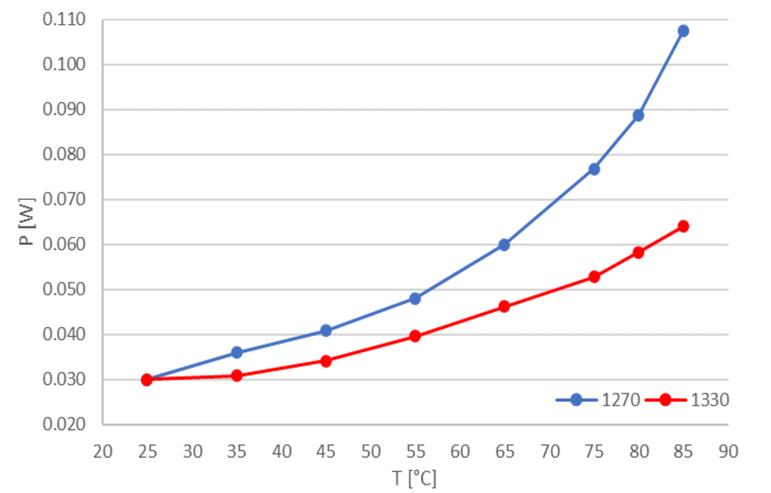


Table 6 - Total heat generation variable with temperature BOSA internal chips

Results

The results obtained from the simulations have been summarized in the following images and tables.

T_{ext} [°C]	T_{case} [°C]	T_J IC1 [°C]	T_J IC2 [°C]	T_J IC3 [°C]	T_J IC6 [°C]	T_J Q1 [°C]	T_J Q2 [°C]	T_J LD_{1270} [°C]	T_J LD_{1330} [°C]	T_{laser} [°C]
27,1	42.1	69.6	68.5	49.7	51.5	52.9	52.8	46.7	46.6	45.6
40	55.8	84.2	83	64.1	66	68.8	68	61.1	60.9	59.7
50	66.6	95.6	94.4	75.5	77.3	81.5	80.4	72.5	72.3	70.9
55	72	101.4	100.2	81.3	83.2	88.2	86.8	78.4	78.1	76.7
60	77.6	107.2	106	87.4	89.2	95.7	93.6	84.6	84.3	82.7
65	83.2	113.2	112	93.6	95.3	103.3	100.4	90.8	90.4	88.7

Table 7 - Junction temperatures of the Chips or average temperatures of the components at different ambient temperatures – base version

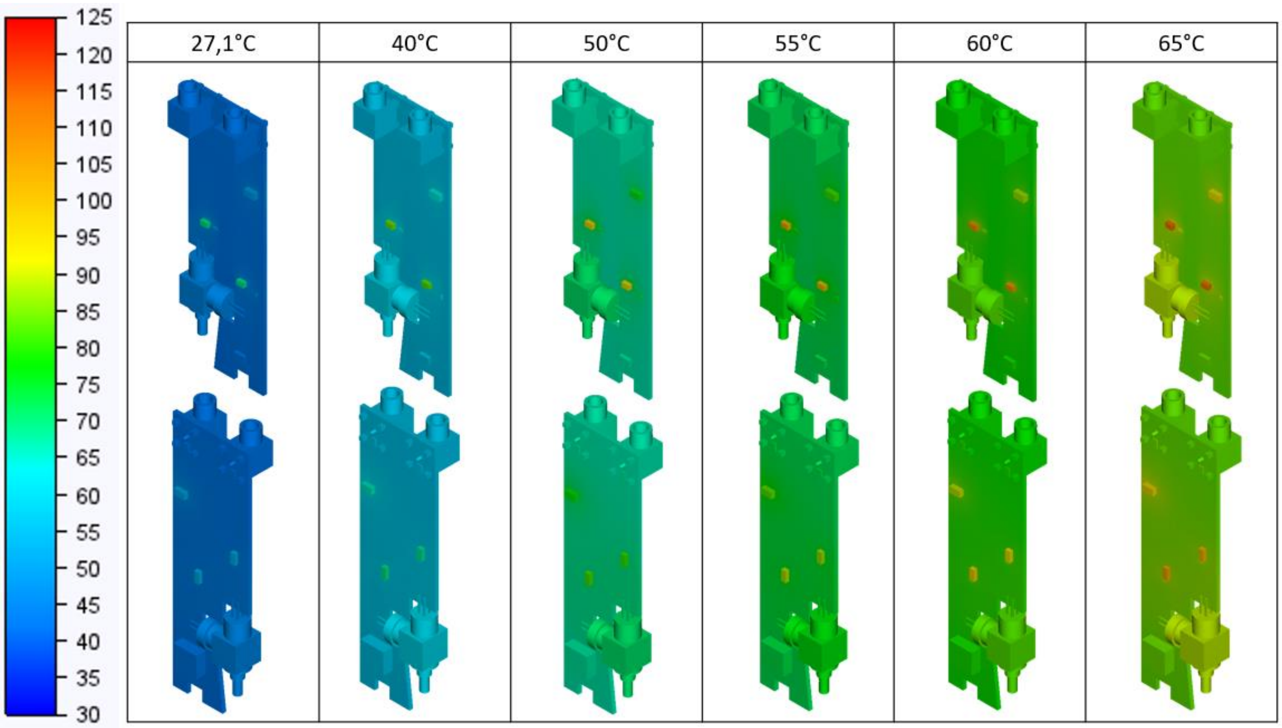


Figure 17 - Temperature distribution of the various scenarios referred to the same scale – base version

The following graphs indicate the temperature variation of the components under examination at the external reference temperatures. The black line, if indicated, shows the maximum possible operating temperature of the component under test.

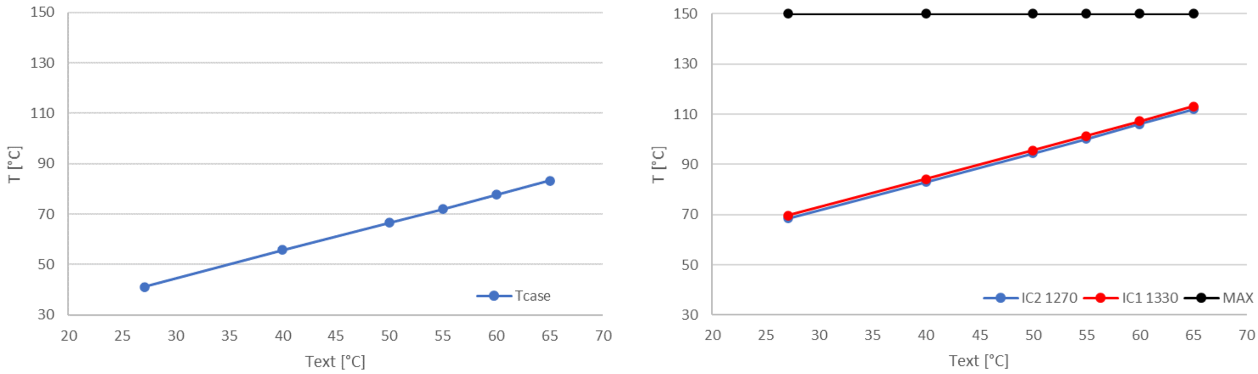


Figure 18 - Simulated temperature trend of aluminum case and AWG0123E (IC1 and IC2) of the base version

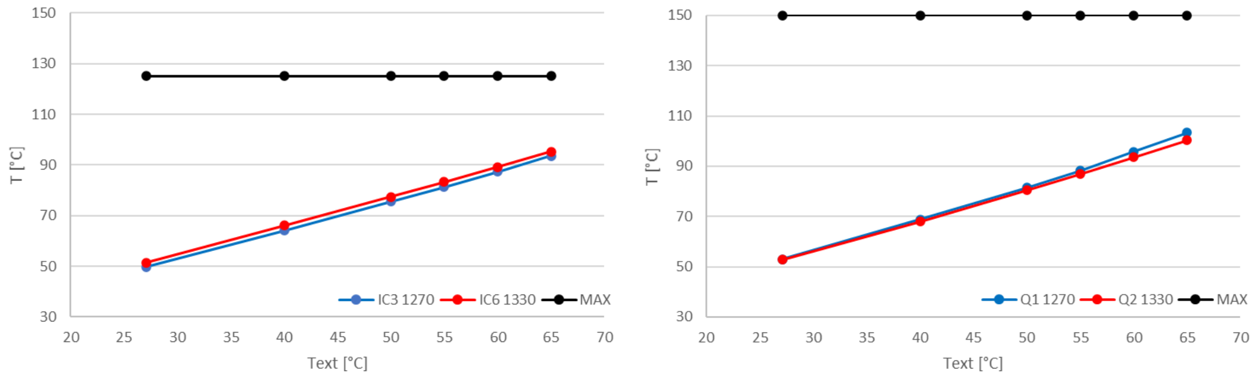


Figure 19 - Simulated temperature trend of LDCL015 (IC3 and IC6) and BC817 (Q1 and Q2) of the base version

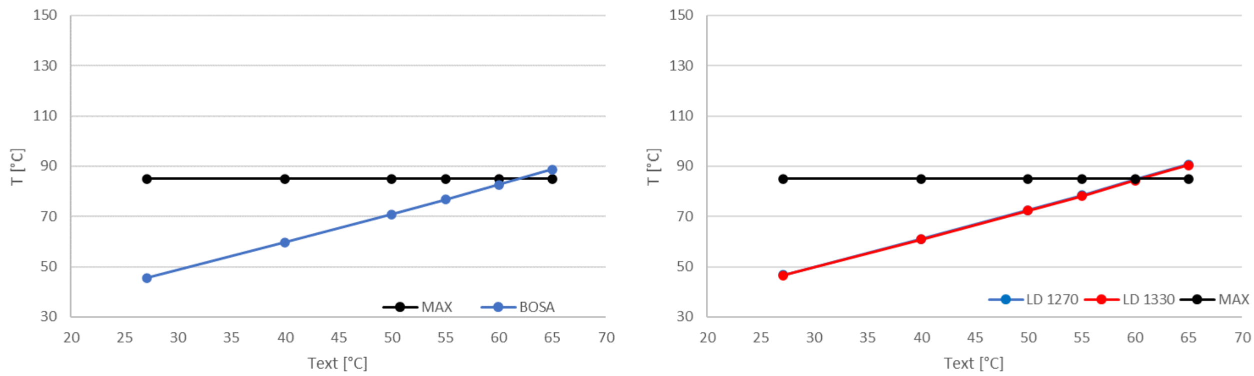


Figure 20 - Simulated temperature trend of BOSA case and BOSA internal chips (LD 1270 and 1330) of the base version

The BOSA and the chips inside exceed the specific temperature at an external (ambient) temperature above 60°C.

TX module thermal mitigation

The previously study is similar to the original version of SmartBox integration, where the TX modules are placed in a simple plate thermally isolated to the external ambient. As indicated in the previous graphs, it is necessary to reduce the temperature of the board, especially for the BOSA.

Two different solutions are studied in order to reduce the temperature of the BOSA:

- Reduce the thermal resistance to the ambient.
- Increase the thermal contact of the BOSA to the TX case.

Thermal resistance reducing

In order to reduce the thermal resistance, a simple Heatsink (SK 81 75 SA - Fischer Elektronik - thermal resistance: 2,5 K/W) is connected to the TX Module.

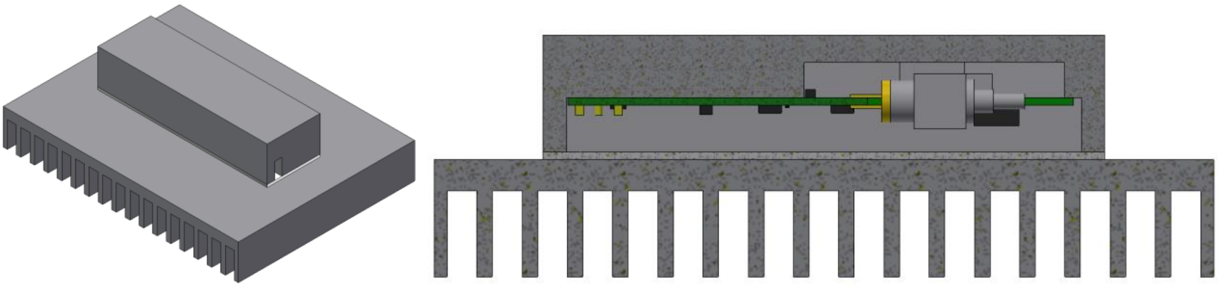
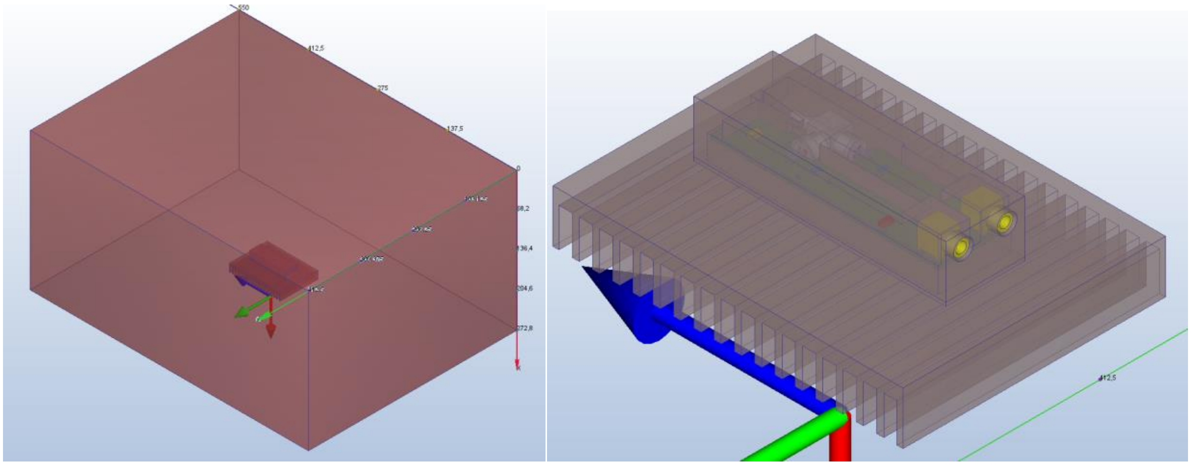


Figure 21 - TX Module assembled to the Heatsink

CFD model

The elements, materials and boundary condition are the same of the AAVS2 Tx module, except for the addition of the heatsink.



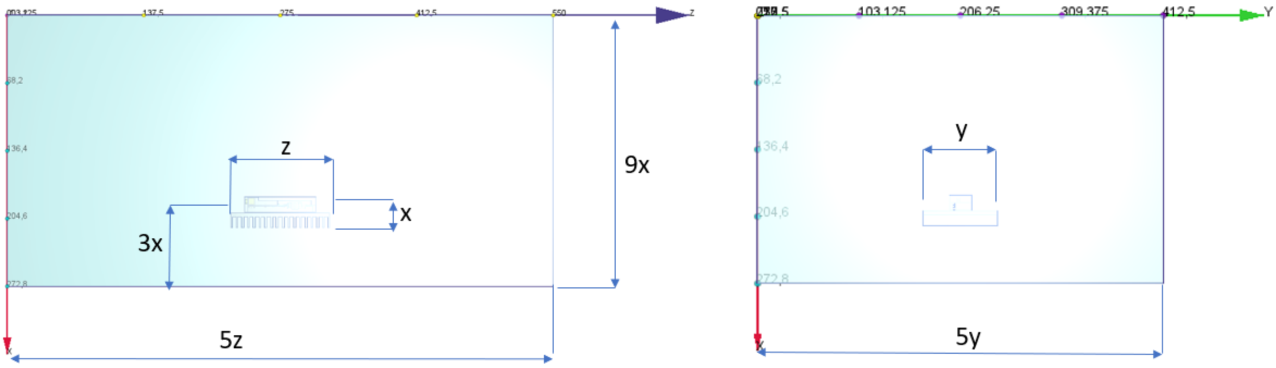


Figure 22 - TX Module +HS CFD model

Results

The results obtained from the simulations have been summarized in the following images and tables as before.

T_{ext} [°C]	T_{case} [°C]	T_J IC1 [°C]	T_J IC2 [°C]	T_J IC3 [°C]	T_J IC6 [°C]	T_J Q1 [°C]	T_J Q2 [°C]	T_J LD_{1270} [°C]	T_J LD_{1330} [°C]	T_{laser} [°C]
27,1	33,1	60,3	58,5	40,1	42,1	43,7	43,6	37,5	37,5	36,4
40	45,5	73,5	71,6	53,1	55,1	58,3	57,6	50,6	50,5	49,3
50	55,4	84,1	82,1	63,7	65,7	70,1	68,9	61,2	61	59,6
55	61,1	90,1	88,1	69,7	71,8	77	75,6	67,3	67,1	65,6
60	65,9	95,1	93,1	74,9	76,9	83,6	81,5	72,6	72,2	70,8
65	71,5	101,1	99	81,1	83	91,2	88,3	78,9	78,5	76,8

Table 8 - Junction temperatures of the Chips or average temperatures of the components at different ambient temperatures – Heatsink version

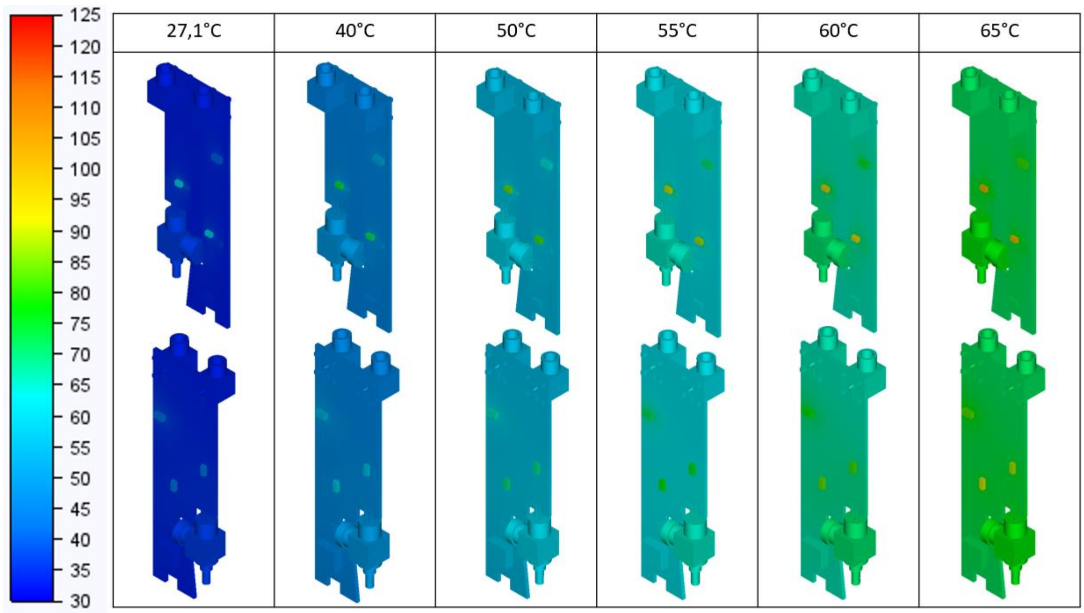


Figure 23 - Temperature distribution of the various scenarios referred to the same scale – Heatsink version

The following graphs indicate the temperature variation of the components under examination at the external reference temperatures. The black line, if indicated, shows the maximum possible operating temperature of the component under test.

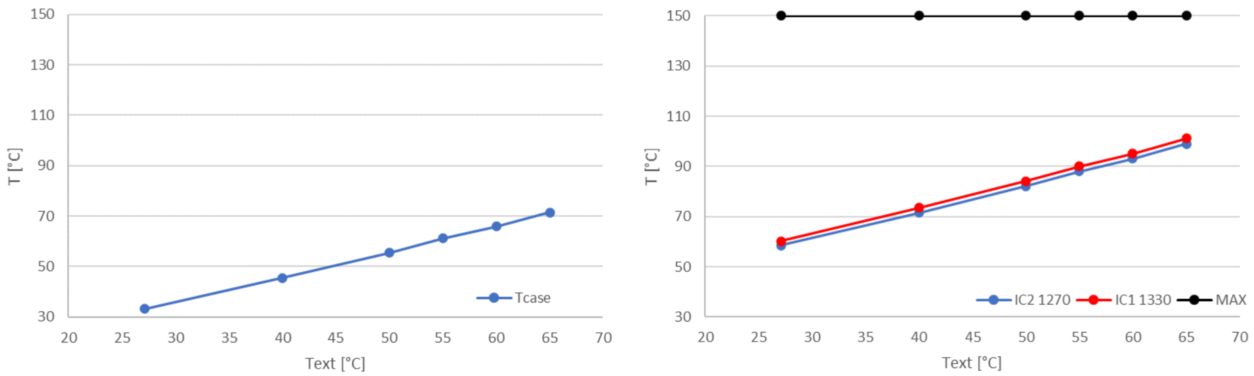


Figure 24 - Simulated temperature trend of aluminum case and AWG0123E (IC1 and IC2) of the Heatsink version

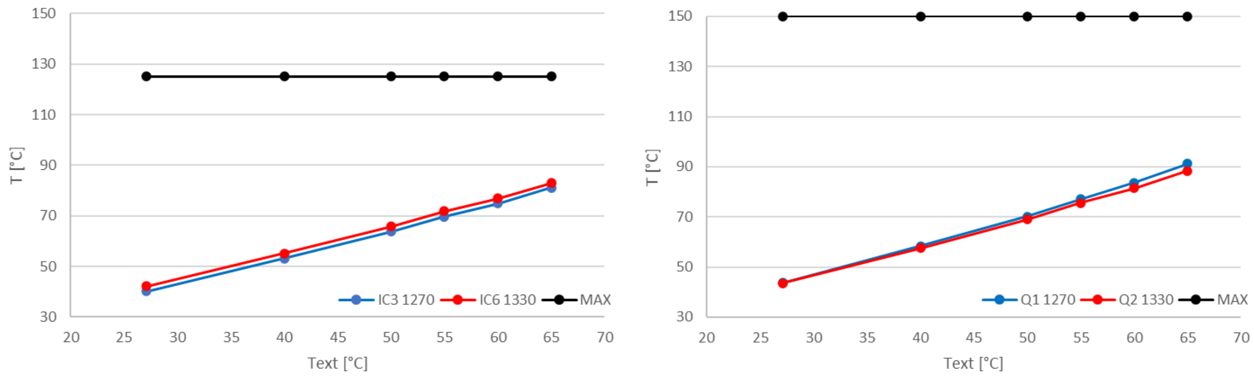


Figure 25 - Simulated temperature trend of LDCL015 (IC3 and IC6) and BC817 (Q1 and Q2) of the Heatsink version

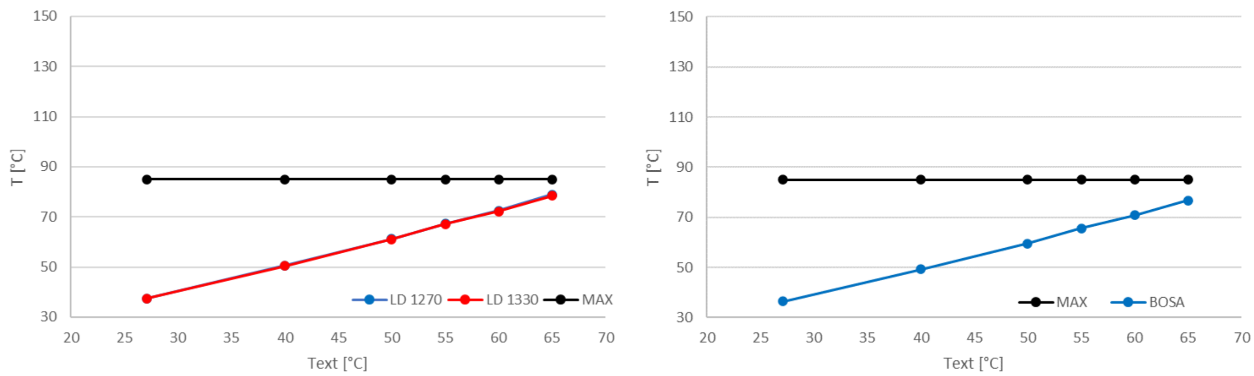


Figure 26 - Simulated temperature trend of BOSA case and BOSA internal chips (LD 1270 and 1330) of the Heatsink version

The temperature of the BOSA is lower than the maximum allowable temperature of the component, in this configuration.

The following graph highlights the improvement in the working conditions of the BOSA in the version with the heatsink (blue curve) compared to the version without the heatsink (red curve).

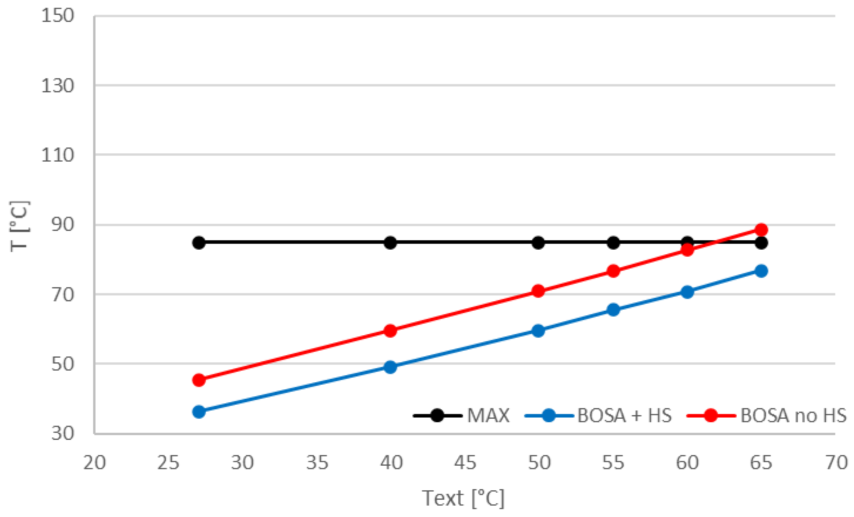


Figure 27 - BOSA Temperature – TX module Vs TX module + HS

"BOSA – TX case – ambient" Thermal contact increasing.

In the actual version of TX module, there isn't s a direct "thermal contact" to the BOSA and the TX case. The generated heat flows from the BOSA to the TX box through the PCB. And the TX Box is connected to the "heatsink" (or the SmartBox itself) by the cover.

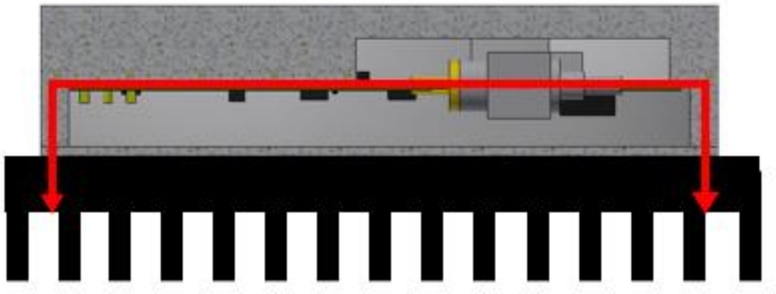


Figure 28 - AAVS2 thermal contact

In order to increase the thermal contact to the BOSA from the environment, it is necessary to connect directly the BOSA to the TX Box and the TX module body to the Heatsink (not from the cover).

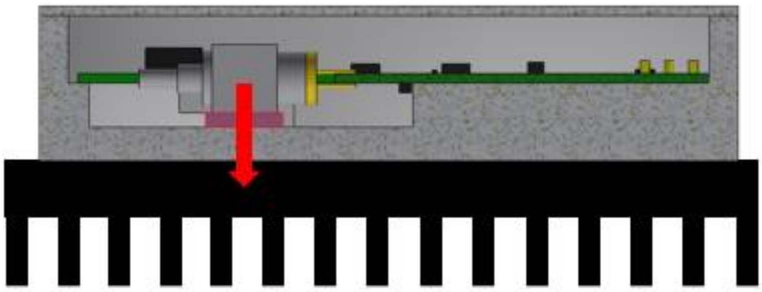


Figure 29 - Optimized thermal contact

To obtain this, a new TX module case had to be designed, which allows the connection of the bosa by thermal pad and fixing directly to the heat sink.

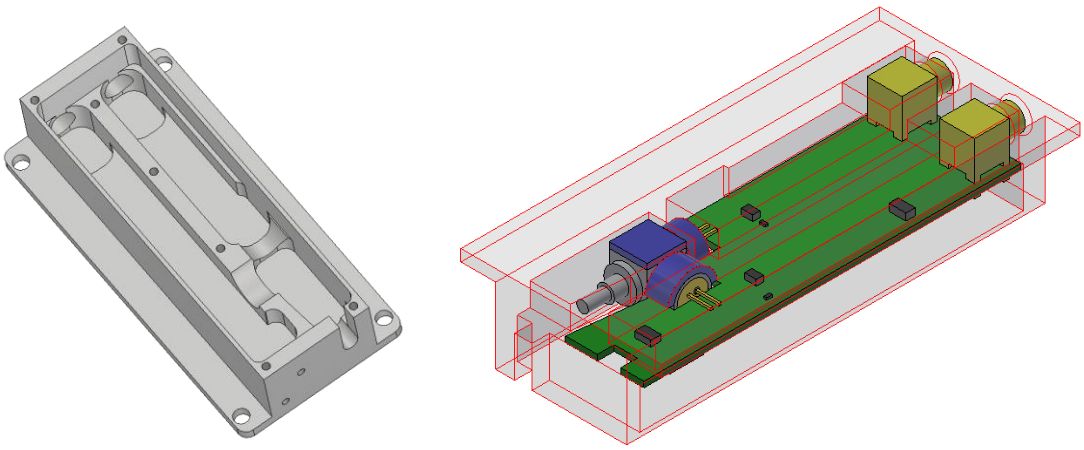


Figure 30 - New TX Module case prototype

CFD model

The elements, materials and boundary condition are the same of the Tx module + HS, except for the new body of the TX module and the insertion of three thermal pads.

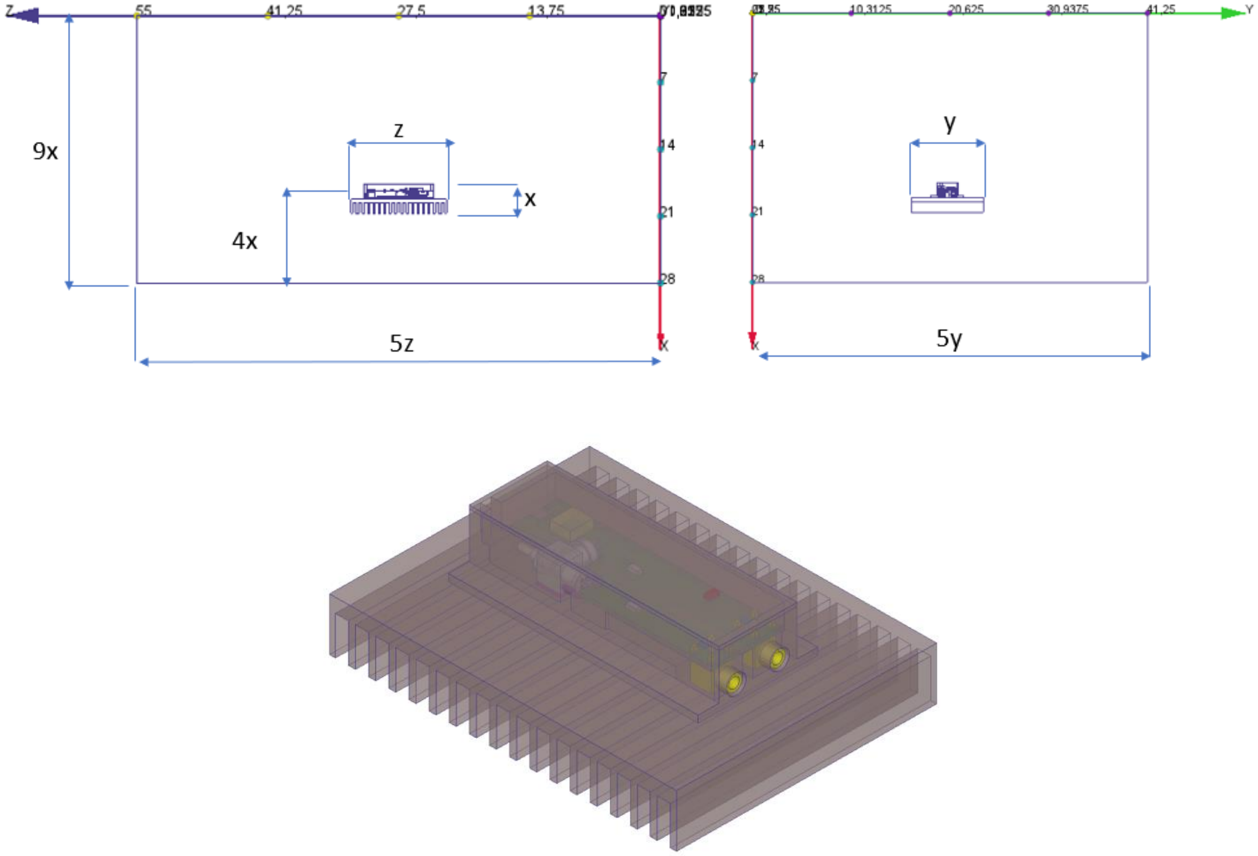


Figure 31 - Optimized case + HS CFD Model

- Thermal Pad (RS)
  Materials: Custom Thermal pad

  Conductivity: 4 W/(m*K)

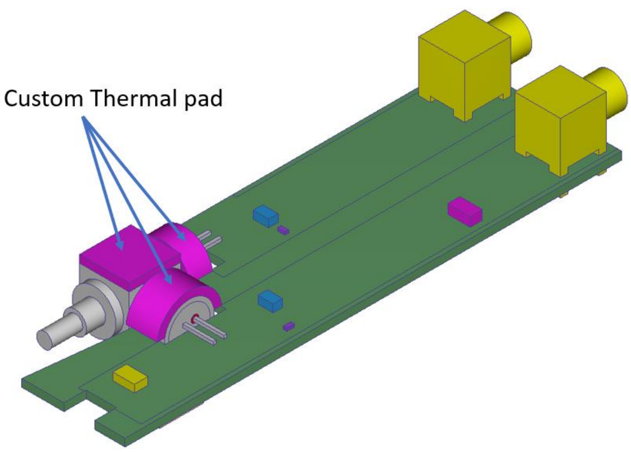


Figure 32 - Thermal pads modeling

Results

The simulation result shows thermal values comparable to the version with only the cooler installed, except for the BOSA temperature, which is significantly reduced in the version with thermal pad.

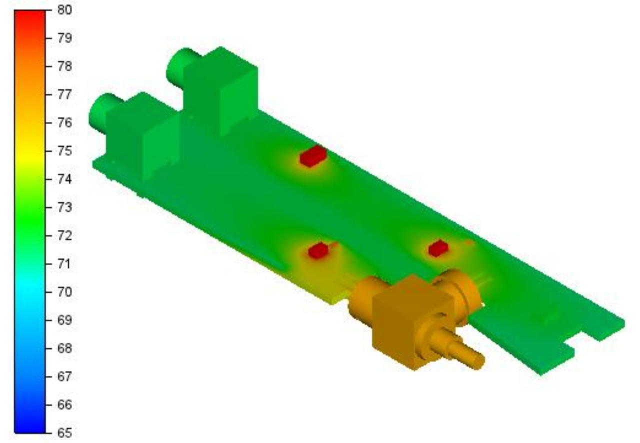
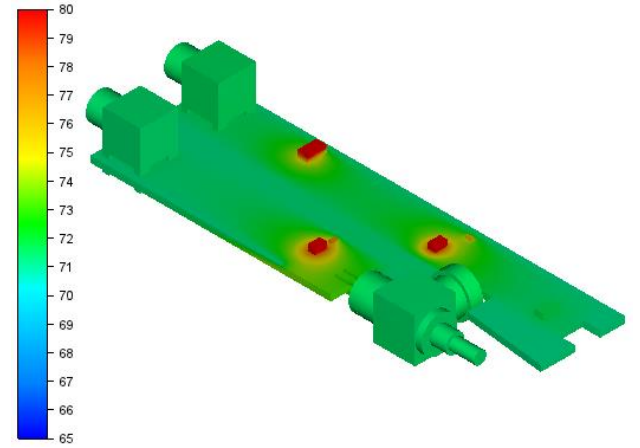
T Ambient 65° - no thermal PAD (T scale 65° - 80°C)	T Ambient 65° - + thermal PAD (T scale 65° - 80°C)
	
T case TX = 71,5°C	T case TX = 71,2°C
T BOSA = 76,8°C	T BOSA = 71,6°C
T Chip 1270 Photodiode =78,9°C	T Chip 1270 Photodiode = 73,8°C
T Chip 1330 Photodiode = 78,5°C	T Chip 1330 Photodiode = 73,3°C

Table 9 - Temperatures obtained from the HS system compared with HS + thermal pad version

The following graphs indicate the temperature variation of the Bosa and case at the external reference temperatures. The left-one is referred to the version without thermal pads, the right graph is referred to the version with pads.

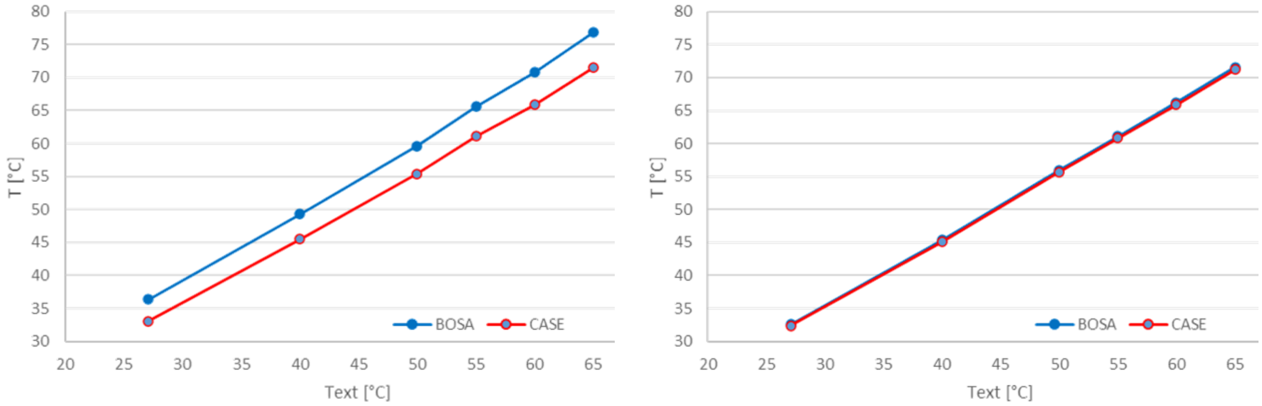


Figure 33 - Temperatures obtained from the HS system compared with HS + thermal pad version

Conclusions

The simulations confirmed an incorrect working condition of the TX modules contained inside the AAVS2 SmartBoxes. This information allowed us to optimize the TX module project, contributing to the realization of the design that will be used for the implementation in AAVS3 (the next verification station under construction at the MRO site).

The features to be implemented in the project are:

- Direct contact by thermal pads between the Bosa and the module case;
- Fixing the BOSA by connecting the case directly to the SmartBox (avoiding connection through the lid);
- The contact surface of the SmartBox on which the TX modules are to be connected must have adequate thermal conductivity towards the outside and mass.

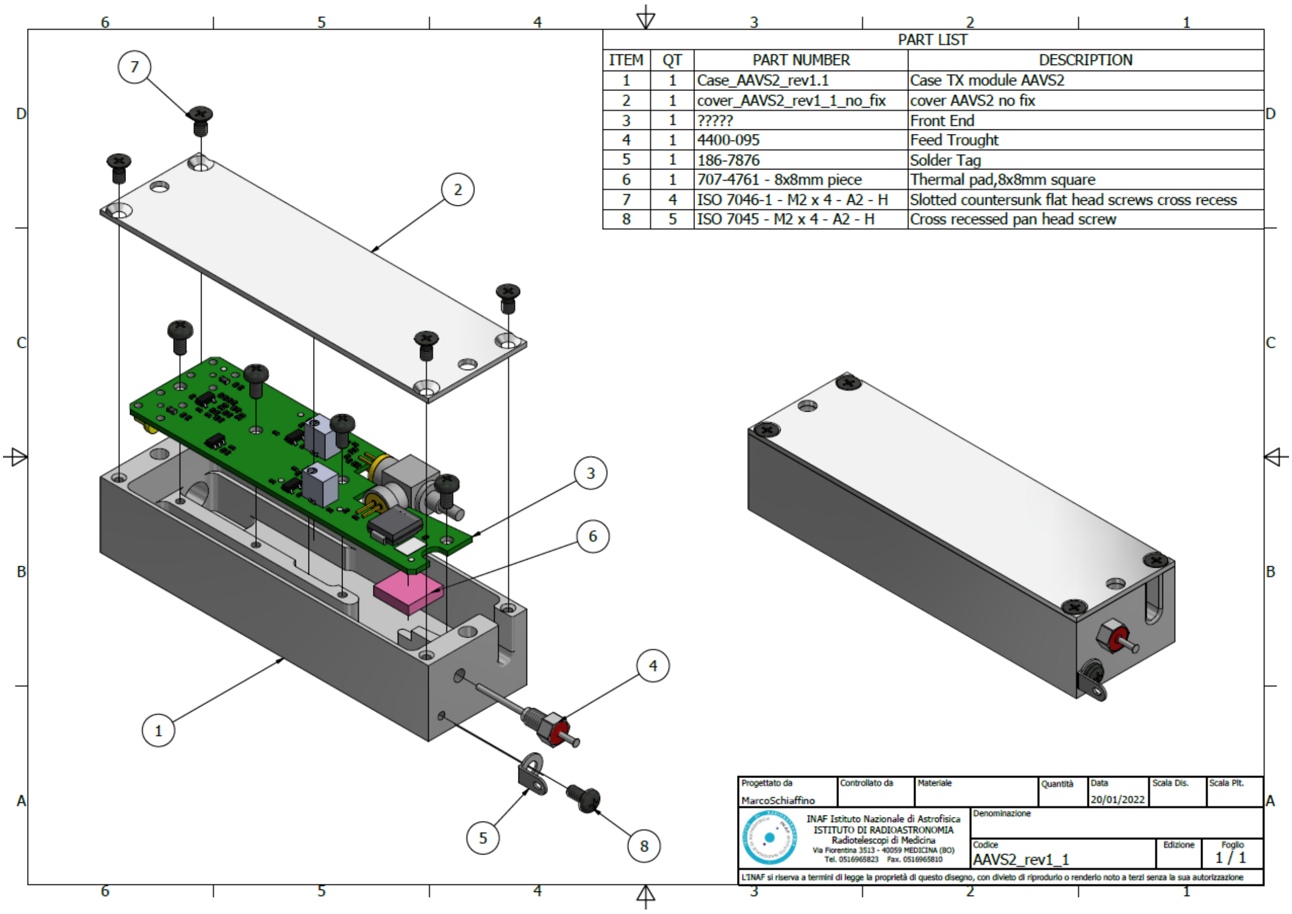


Figure 34 - AAVS2 revised model for AAVS3

Appendix

Thermal analysis evaluation

Some laboratory measurements were performed in order to evaluate the reliability of the simulations made and the models used.

TEST 01: AAVS2 case + HS in thermal chamber

The first test was carried out for the “TX module + heatsink” version.

Set Up

To carry out the measurements, the following set-up is implemented.
The device under test (DUT) was placed inside a cardboard box, in order to limit, as much as possible, the effect of the increasing of the natural convection generated by the fan.
Three temperature sensors were used in order to detect the temperatures of three fundamental elements, namely the air contained inside the cardboard box, the temperature of the side of the TX module case and the temperature of the BOSA case.

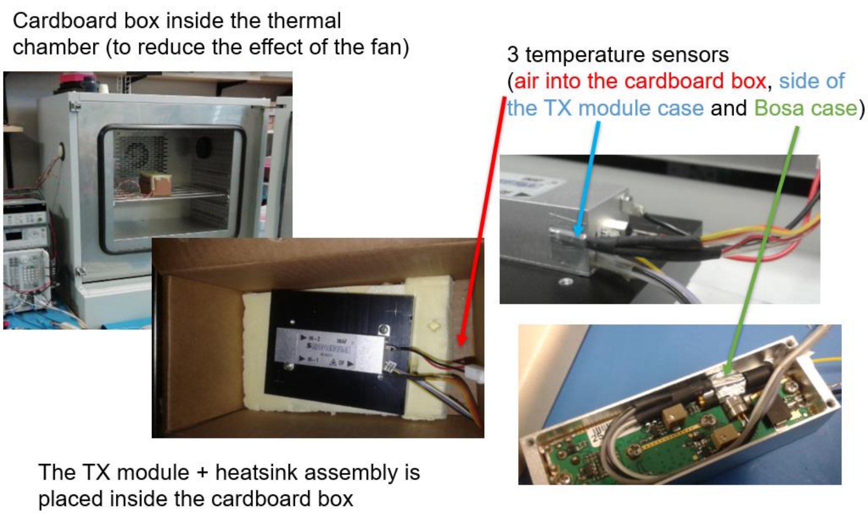


Figure 35 - Evaluation test set-up

Results

Two measurements were carried out at two constant temperatures (50° and 60°) inside the thermal chamber, and the results obtained were reported in the table below.

50°C thermal chamber	BOSA	TX case	Real external air
Measured	59,9°C	55,8°C	50,3°C
Simulated	59,6°C	55,4°C	50,0°C

Table 10 - Heatsink version temperature comparison at T_{amb} = 50°

60°C thermal chamber	BOSA	TX case	Real external air
Measured	71,2°C	66,7°C	60,6°C
Simulated	70,8°C	65,9°C	60,0°C

Table 11 - Heatsink version temperature comparison at T_{amb} = 60°

\

TEST 02: Dissipating case + HS in thermal chamber

The second test was carried out for the “TX module with optimized case + Thermal Pad + Heatsink” version.

Set Up

The measurement set-up set was the same implemented in the previous test, except for the replacing the TX module case with the optimized version and adding the thermal pads to create the direct thermal contact between Bosa and TX case.

Figure 36 - Optimized case + thermal pads set-up

Results

Two measurements were carried out at two constant temperatures (50° and 60°) inside the thermal chamber, and the results obtained were reported in the table below.

50°C thermal chamber	BOSA	TX case	Real external air
Measured	56,0°C	55,4°C	50,4°C
Simulated	56,0°C	55,7°C	50°C

Table 12 - HS + thermal pad version temperature comparison at T_{amb} = 50°

60°C thermal chamber	BOSA	TX case	Real external air
Measured	66,1°C	65,2°C	60,5°C
Simulated	66,2°C	65,9°C	60,0°C

Table 13 - HS + thermal pad version temperature comparison at T_{amb} = 60°

Figure List

Table List