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Authors	SCHIAFFINO, Marco; PERINI, FEDERICO; MATTANA, Andrea; MONARI, Jader
Affiliation of first author	IRA Bologna
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AAVS2 “SmartBoxes” - Thermal evaluation and improvements

M. Schiaffino¹, F. Perini¹
A. Mattana¹, J. Monari¹

1 – INAF - Istituto di Radioastronomia

Summary

Introduction.....	3
AAVS2 SmartBox thermal analysis	3
Lab test	4
CFD Model	4
Results	8
Solar irradiation	9
CFD Model	9
Results	11
24h transient	12
CFD Model	12
Results	12
The Quick and Dirty solution	13
Step 01 - Aluminum block for TX module plate and power supply plate – SB Box connection	13
CFD Model	13
Results	13
Step 02 - Aluminum blocks + heatsink	14
CFD Model	14
Results	14
Solutions comparison	16
Q&D - Lab test version.....	17
CFD Model	17
Results	17
The Quick and Dirty solution in a 24h transient scenario	18
CFD Model	18
Results	18
Conclusions.....	19
Appendix.....	20
Thermal analysis evaluation	20
TEST 01: Original SmartBox mockup	20
TEST 02: Quick and Dirty SmartBox mockup	24
TEST 03: Original SmartBox mockup + TX module	27
TEST 04: Quick and Dirty SmartBox mockup + TX module	29
Figure List.....	31
Table List.....	32

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).

In the original version of SmartBox, the body of the box and the cover is made by two white painted/galvanized old mild steel metal plates. Inside the box there is another galvanized mild steel metal plate (connected to the box between a metal studs) on which the 16 FEMs are fixed.

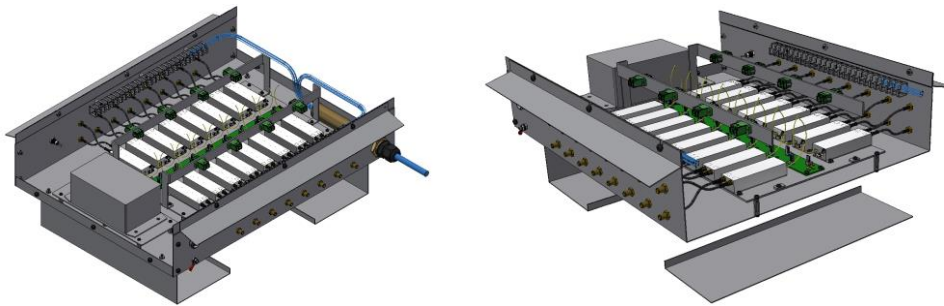


Figure 1 - AAVS2 SmartBox design

The power supply is also fixed on a galvanized metal plate, connected to the box by metal studs.

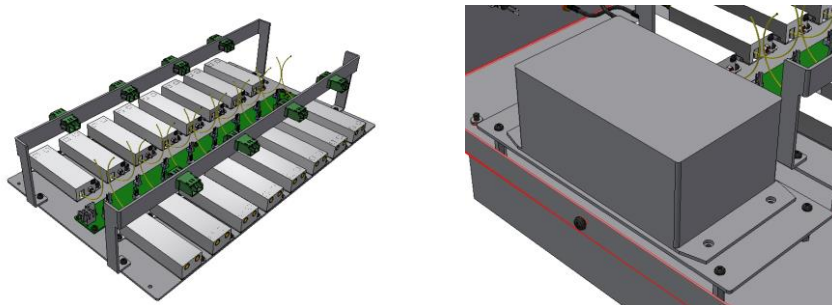


Figure 2 - TX modules plate and Power supply plate

The high temperatures reached by the optical modules made it necessary to perform a thermal analysis of the system, as well as evaluate possible improvements and modifications to the SmartBox. 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 SmartBox thermal analysis

The purpose of the analysis was to define the operating temperature of the TX modules inside the SmartBox in order to optimize the mechanics of the model. The first phase of the analysis focused on the study of the original SmartBox, installed for AAVS2.

The models produced were:

- “Lab test” (a model with 15 dummy TX modules and 1 complete TX module, without environment boundary conditions);
- “Solar irradiation” (a model with 16 dummy TX modules and stationary environment boundary conditions);
- “24h transient” (a model with 16 dummy TX modules and transient in time environment boundary conditions).

Lab test

This study refers to a model not affected by external environmental conditions such as sun or wind, but only by a constant temperature of the external air, as if it were contained inside a thermostat-controlled laboratory. To simplify the simulation, fifteen “dummy TX modules” and one “complete TX module” were modeled on the "TX modules plate" inside the SmartBox.

CFD Model

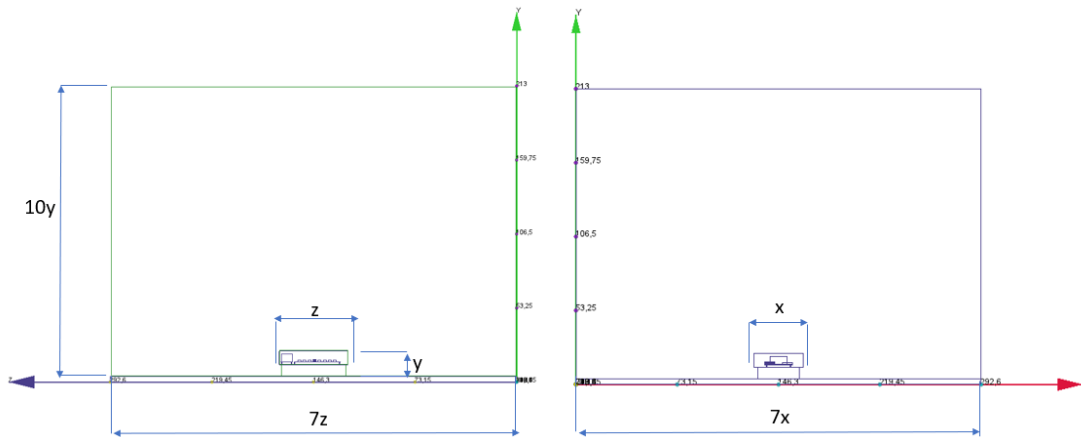


Figure 3 - AAVS2 SmartBox CFD model

This analysis refers to a static version (NO time/temperature transient).

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

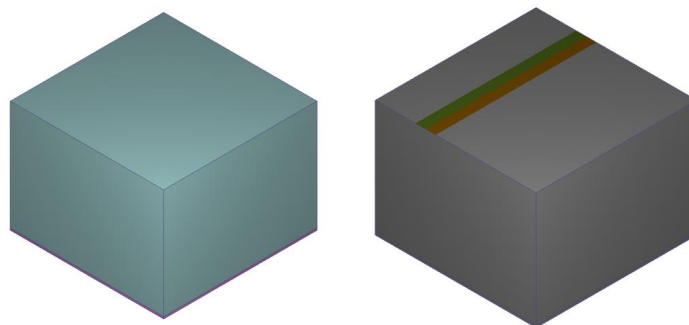


Figure 4 - External air material and boundary conditions

Boundary conditions: **Pressure:** 0 Pa in the top surface;

Film coefficient: 2 W/(m²*K) in a 40°C reference temperature.

- Internal air

Material: air - Variable properties as the scenario changes

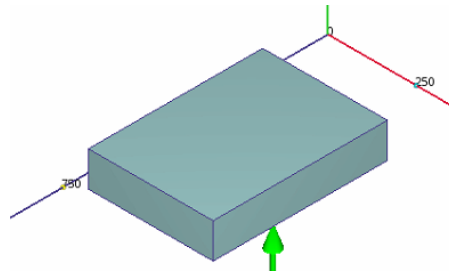


Figure 5 - Internal air material and boundary conditions

- Top cover – SmartBox body

Material: painted/galvanized old steel

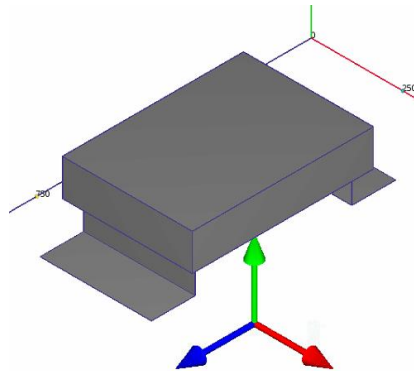


Figure 6 - External body material

- Internal plates – studs

Material: steel (internal plates)

Material: Nickel plated Brass (studs)

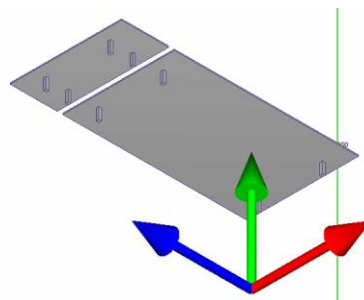


Figure 7 - Internal elements material

- Ground

Material: Expanded polystyrene

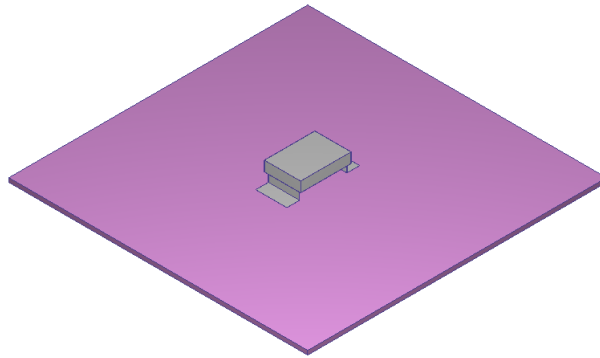


Figure 8 - Ground material

- Distribution board

Material: Printed circuit board

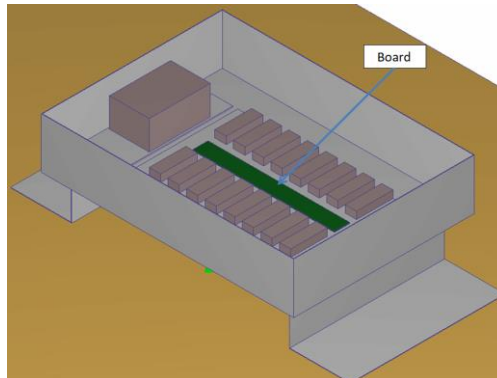


Figure 9 - PCB material

- Power supply

Material: Aluminum

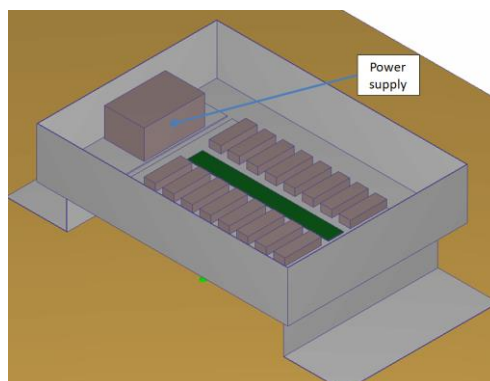


Figure 10 - Power supply material and boundary conditions

Boundary conditions:

Total heat generations – constant with temperature: 4W

- “Dummy” TX module

Material: Aluminum

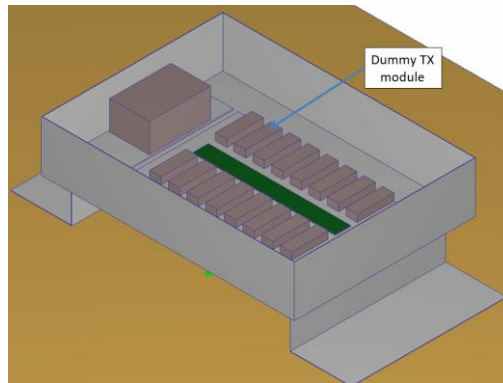


Figure 11 - "Dummy" TX module material and boundary conditions

Boundary conditions:

Total heat generations – variable with temperature

T [°C]	P [W]
25	0.743
35	0.788
45	0.828
55	0.888
65	0.971
75	1.081
80	1.162
85	1.288

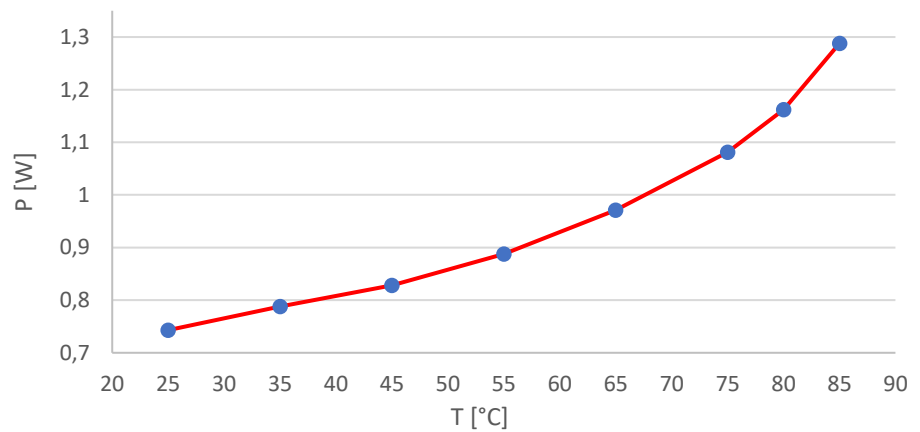


Table 1 - Total heat generation variable with temperature "Dummy TX module"

- “Complete” TX module

See the document “AAVS2 “TX module” - Thermal evaluation and improvements”.

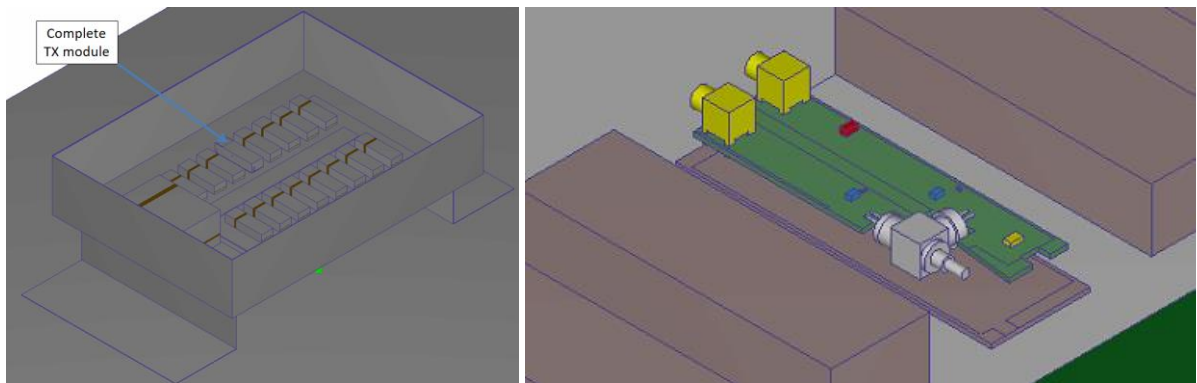


Figure 12 - "Complete" TX module

Results

The results of the simulation of the current SmartBox show our expectations and feeling from the field. The heat cannot be dissipated to the outside and remains imprisoned inside the box increasing enormously the temperature of each active sub-element.

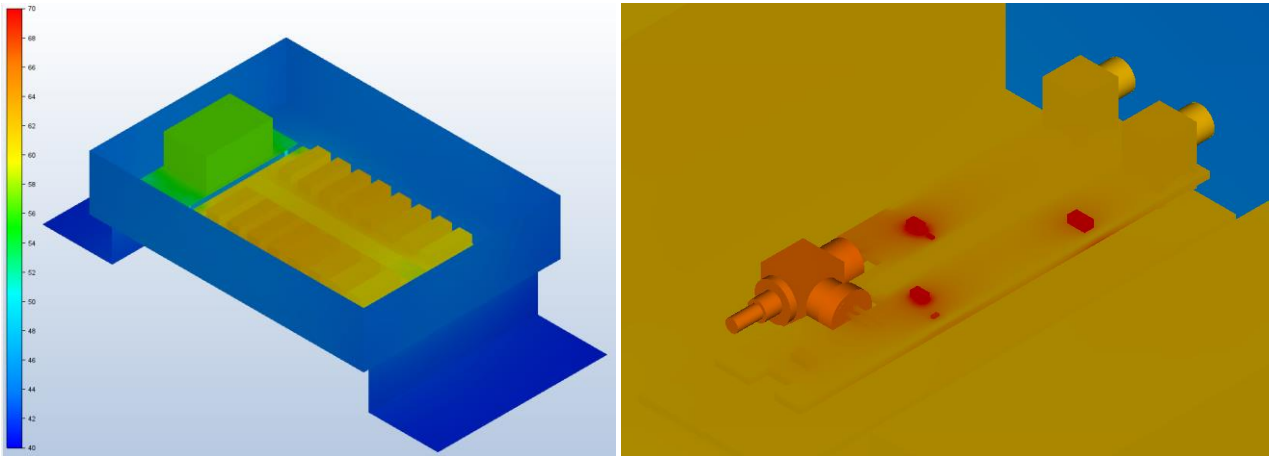


Figure 13 - Temperature distribution of the AAVS2 SmartBox - "Lab test"

	T_{Avg} [°C]
Internal Air	50,1
TX Module box	62,5
Bosa case	66,6

Table 2- Average temperature of the main components

Thus, the sub-elements of the box are at a much higher temperature than the box itself, in practice the internal elements are thermally insulated from the external environment, not allowing heat dissipation.

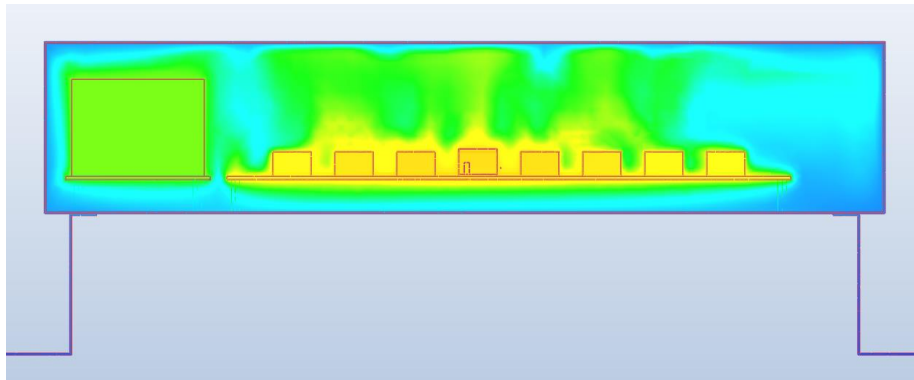


Figure 14 - TX modules thermally isolated towards the outside

Solar irradiation

This study represents a model similar to the previous one, but with different boundary conditions, in fact, in addition to a fixed environmental temperature, solar radiation was added, assuming a latitude and longitude similar to the MRO site, at 2.30 pm of 10 December 2019. In the “TX modules plate” there are sixteen “dummy” Tx modules.

CFD Model

The external air and ground volumes are increased compared to the previous simulation, to take into account solar radiation.

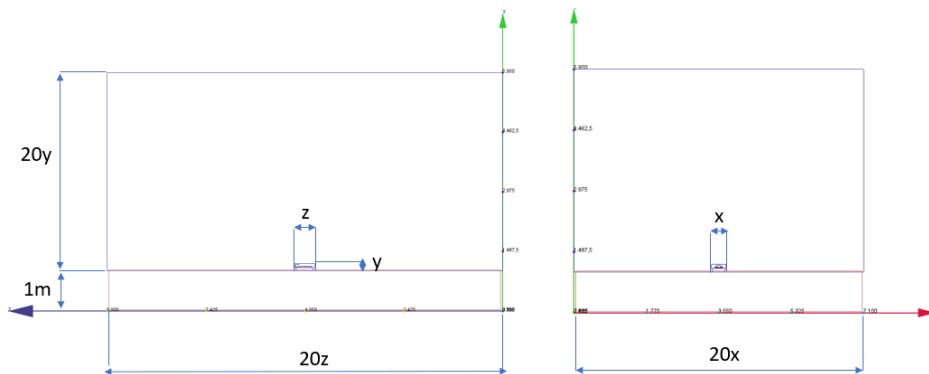


Figure 15 - CFD model - Solar irradiation version

This analysis refers to a static version (NO time/temperature transient).

The elements that differ from the previous simulation are:

- External air

Material: air - Variable properties as the scenario changes

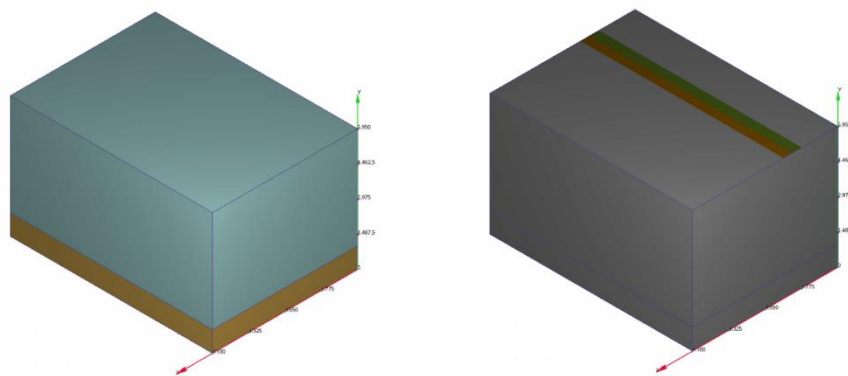


Figure 16 - External air material and boundary conditions - Solar irradiation version

Boundary conditions: **Pressure:** 0 Pa in the top surface;

Film coefficient: $2W/(m^2 \cdot K)$ in a $42^\circ C$ reference temperature.

Solar thermal flux: 2019/12/10, 02:30 pm – Latitude: $-26^\circ 42'$ – Longitude: $116^\circ 40'$

- Ground

Material: Sandy soil

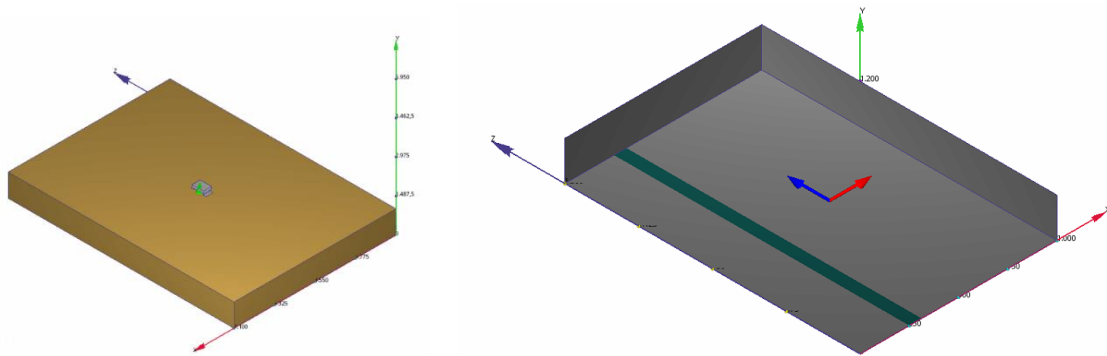


Figure 17 - Ground material and boundary conditions - Solar irradiation version

Boundary conditions:

Temperature: 20°C in the bottom surface

- Sixteen “Dummy” TX module

Material: Aluminum

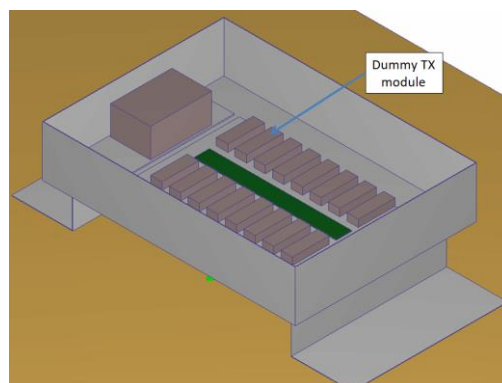


Figure 18 - Dummy TX module material and boundary conditions - Solar irradiation version

Boundary conditions:

Total heat generations – variable with temperature

T [°C]	P [W]
25	0.743
35	0.788
45	0.828
55	0.888
65	0.971
75	1.081
80	1.162
85	1.288

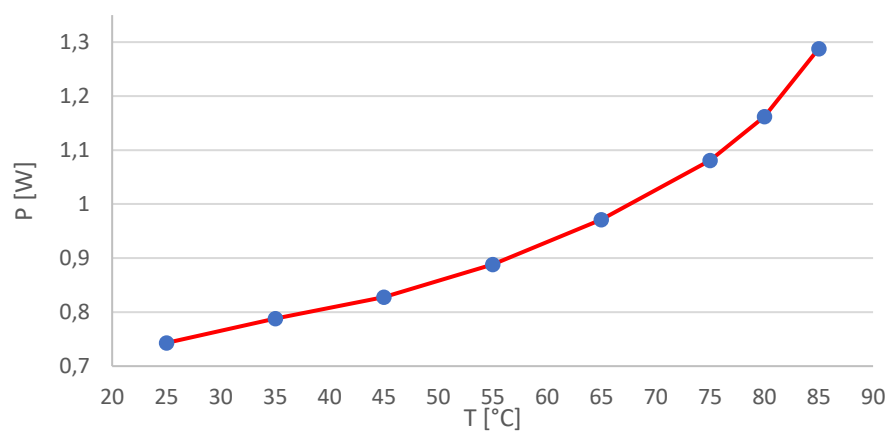


Table 3 - Dummy TX Module consumption variable with the external temperature

Results

The simulation highlights a high temperature of the TX modules and a high thermal insulation of the TX modules towards the outside.

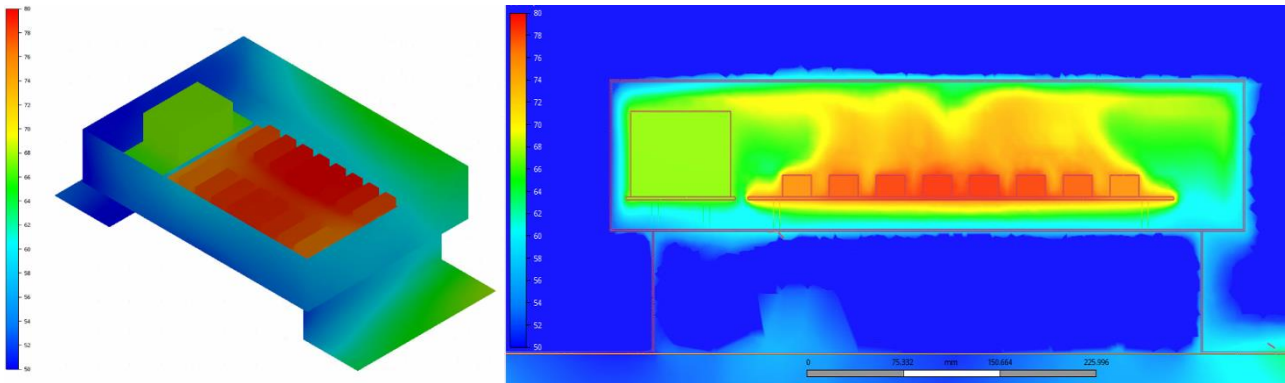


Figure 19 - Temperature distribution inside the SmartBox - Solar irradiation version

The temperature of the TX modules on the edge of the plate is lower than the central ones, and the temperature difference is 4°C (80,2°C Vs 76,1°C).

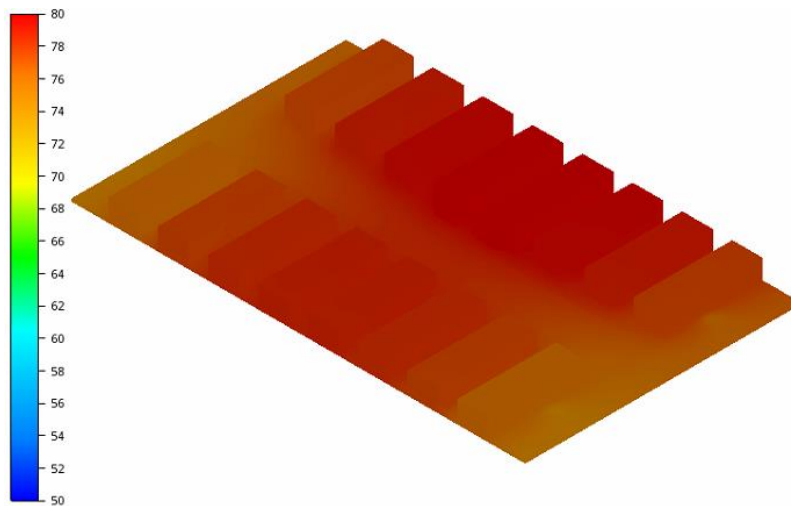


Figure 20 - Temperature difference between TX modules

24h transient

This analysis refers to a transient version (time/temperature transient). The objective of this analysis is to evaluate the thermal variation of the optical modules between day and night.

Inside the box there are sixteen “dummy” Tx modules installed to the “TX Module plate”.

CFD Model

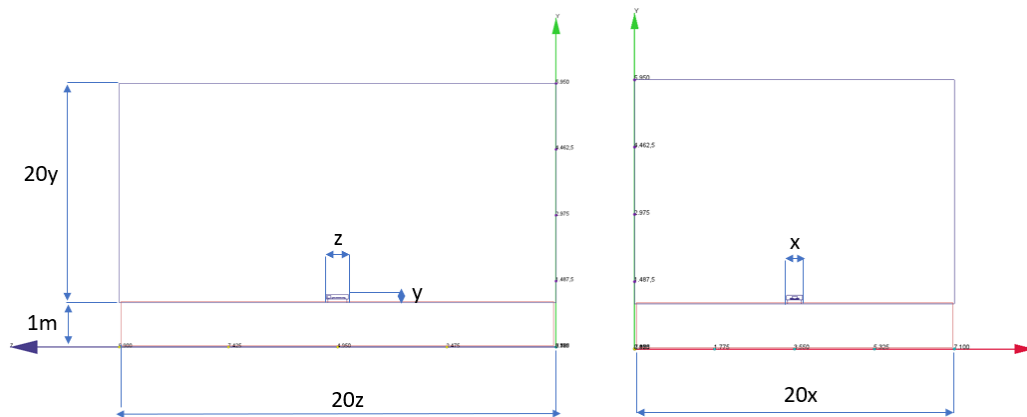


Figure 21 - CFD Model - 24h transient version

The model is the same of “solar irradiation” except:

- External air

Boundary conditions:

Film coefficient (heat transfer coefficient): $2 \text{ W}/(\text{m}^2 \cdot \text{K})$ variable external reference T for the transient scenario in the Top surface.

Solar thermal flux: 2019/12/10, 00:00 to 23:59 – Latitude: $-26^\circ 42'$ – Longitude: $116^\circ 40'$

Results

The temperature of the hottest module varies from the $78,6^\circ\text{C}$ at the 02:10 pm to the $50,9^\circ\text{C}$ at the 03:10 am, with a temperature offset of $27,7^\circ\text{C}$.

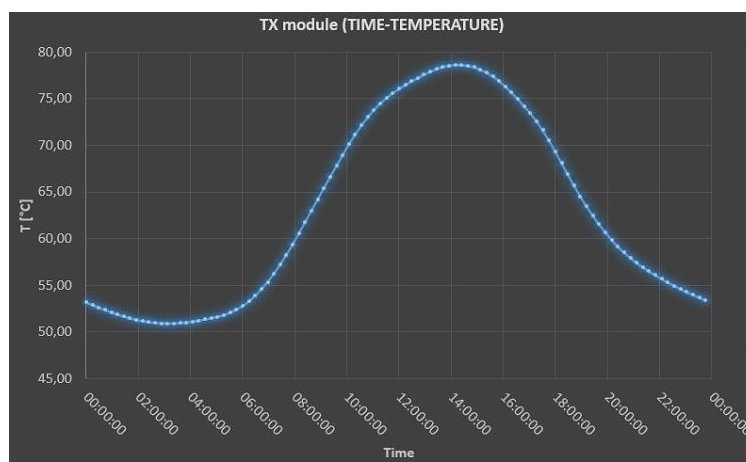


Figure 22 - Temperature trend of the hottest optical module in 24 hours – AAVS2 version

The Quick and Dirty solution

Some modifications to the AAVS2 SmartBox have been evaluated to reduce the thermal isolation of the TX modules towards the outside with the aim of reducing the temperature of the modules. The changes in question had to be quick to implement and were named Quick and Dirty solution.

Step 01 - Aluminum block for TX module plate and power supply plate – SB Box connection

In order to have a better connection between the “TX module plate” – Power supply and the SB body, we use an aluminum blocks instead the metal studs. Thermal pads are placed between the aluminum blocks and the SB case.

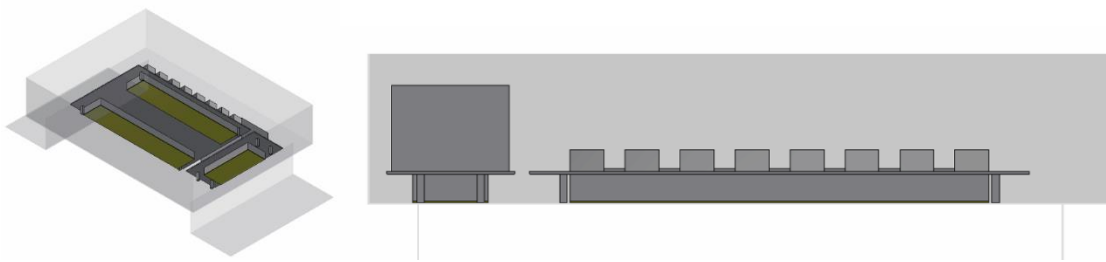


Figure 23 - CAD model for Quick and Dirty step 1

CFD Model

The model is the same of “solar irradiation” with the addition of aluminum blocks and pads.

Results

The temperature inside the SmartBox is lower and more uniform.

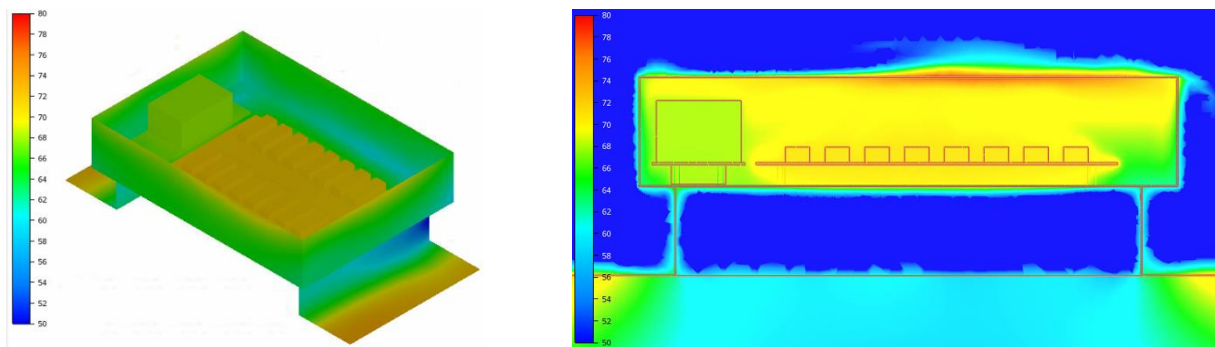


Figure 24 - Temperature distribution inside the SmartBox - Q&D step 1

The heat exchange surface towards the outside is small.

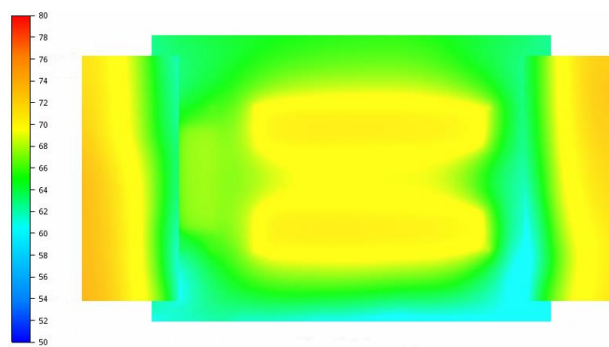


Figure 25 - Q&D step 1 heat exchange to the outside

There is a reduction and greater uniformity of the temperature of the modules (from 74°C to 75,2°C).

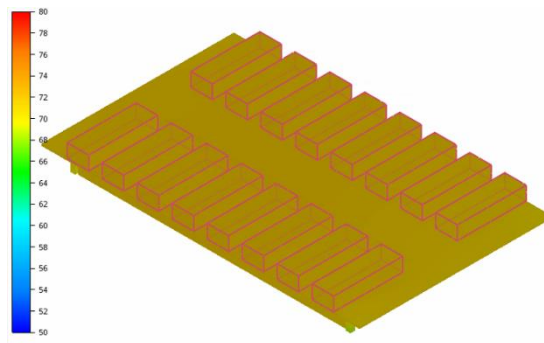


Figure 26 - TX modules temperature for Q&D step 1

Step 02 - Aluminum blocks + heatsink

In order to increase the thermal exchange surface, a commercial heatsink (like AAVID THERMALLOY EK/B/300 - 300x300x40mm - thermal resistance: 0.3K/W) is fixed under the SmartBox.

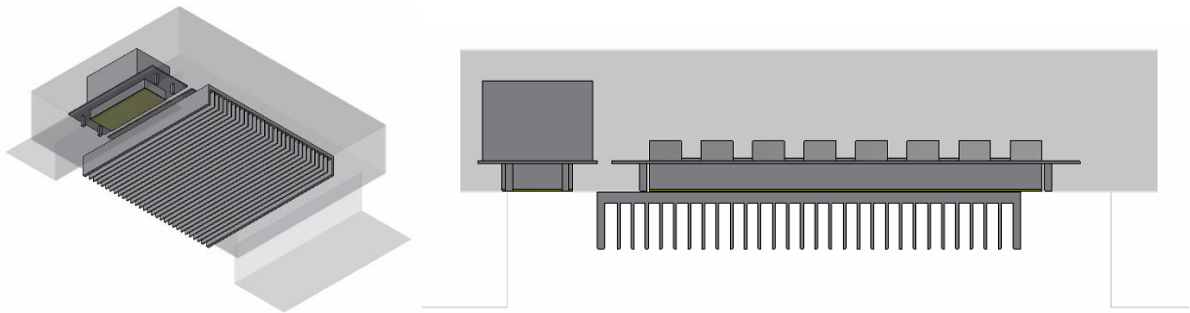


Figure 27 - CAD model for Quick and Dirty step 2

CFD Model

The model is the same of “solar irradiation” with the addition of aluminum blocks, heatsink and pads.

Results

The temperature inside the SmartBox is lower and more uniform.

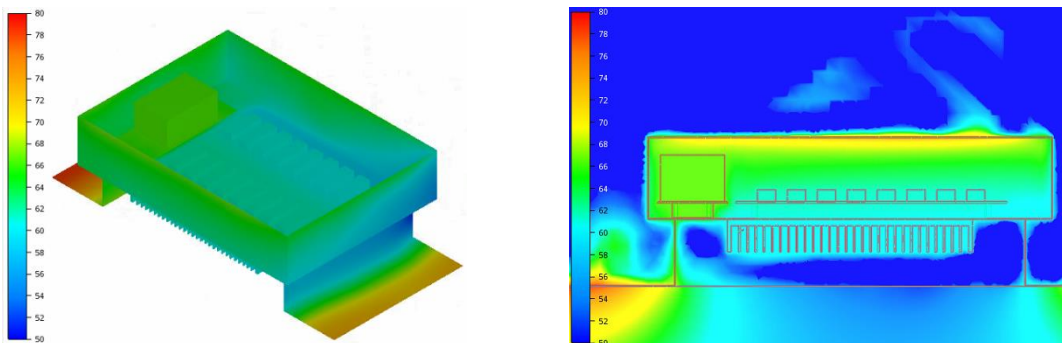


Figure 28 - Temperature distribution inside the SmartBox - Q&D step 2

The heat exchange surface towards the outside is bigger and more effective.

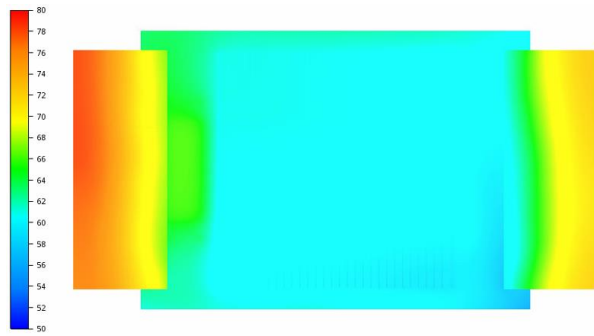


Figure 29 - Q&D step 2 heat exchange to the outside

There is a further reduction of the temperature of the modules (from 60,7°C to 61,9°C).

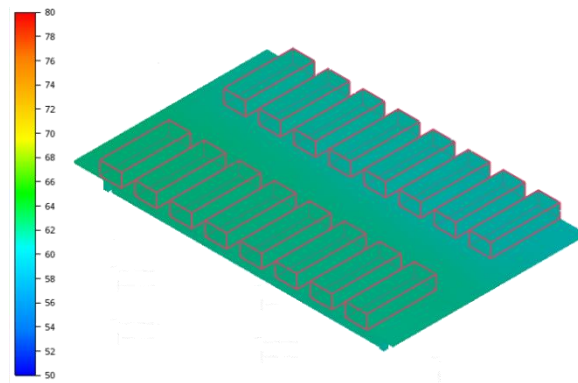


Figure 30 - TX modules temperature for Q&D step 2

Solutions comparison

In the table below, the results of the various simulated steps have been compared.

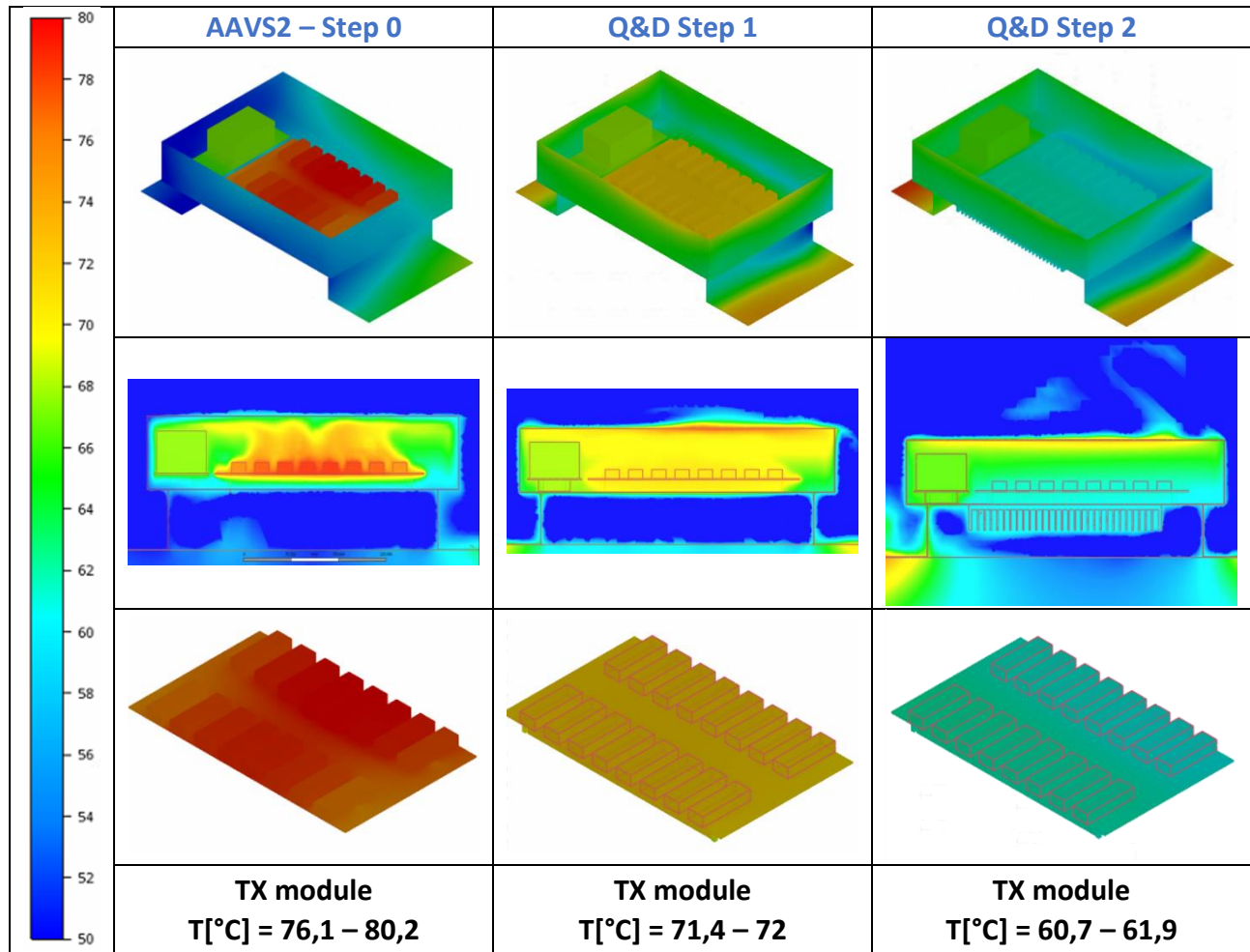


Table 4 - Q&D steps results comparison

The study of the Q&D model highlighted the following characteristics:

- Good connection of the active parts to the outside
- Large heat exchange surface

Q&D - Lab test version

The objective of this simulation is to evaluate the behavior of the Q&D version SmartBox in a controlled environment such as a thermostatic laboratory, excluding the effect of solar radiation. Inside the box there are fifteen “dummy” Tx modules and one complete Tx module installed to the “TX module plate”, like the “Lab test” of the original version.

CFD Model

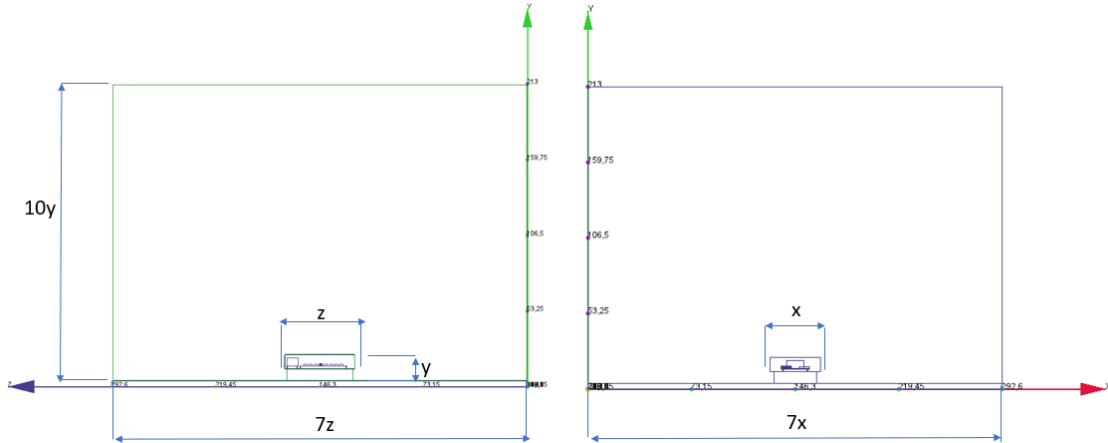


Figure 31 - CFD model of Q&D "Lab test" version

This analysis refers to a static version (NO time/temperature transient). It is similar to the AAVS2 “Lab test” with the addition of aluminum blocks and heatsink.

Results

The simulation results confirm a low operating temperature of the TX modules, thanks to a high thermal conductivity of the system towards the outside.

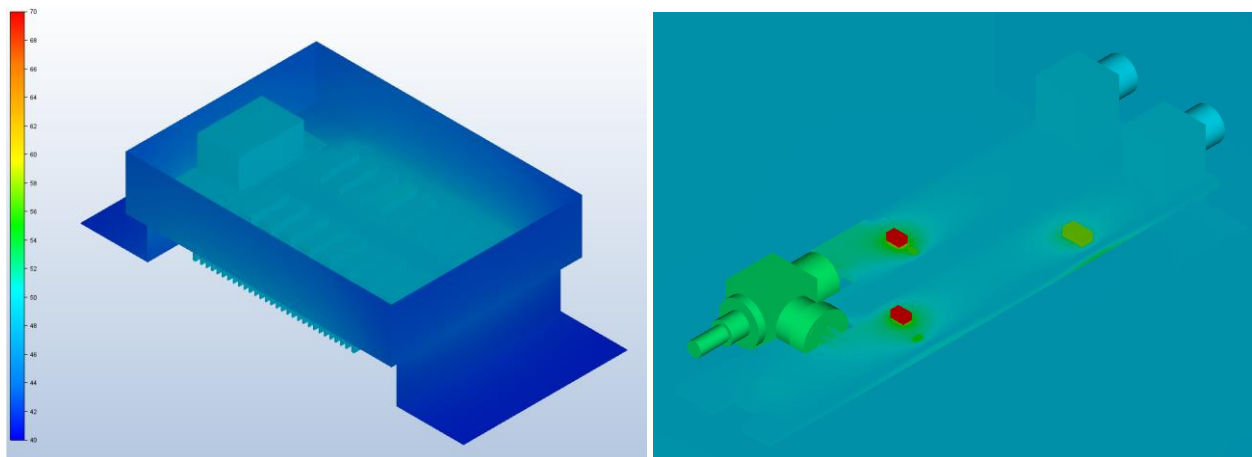


Figure 32 - Temperature distribution inside the SmartBox and inside the TX module - Q&D "Lab test" version

	T_{Avg} [°C]
Internal Air	45,8
TX Module box	48,9
Laser case	52,9

Table 5 - Average temperature of main element of the simulation

The Quick and Dirty solution in a 24h transient scenario

This simulation aims to evaluate the behavior of the Q&D version in 24 hours, evaluating the temperatures reached during the day and at night.

CFD Model

This analysis refers to a transient version (time/temperature transient).

The model is the same of “24h transient” with the addition of aluminum blocks, heatsink and pads.

Results

The temperature of the hottest module varies from the 59,9°C at the 02:00 pm to the 34,1°C at the 03:00 am, with a temperature offset of 25,8°C.

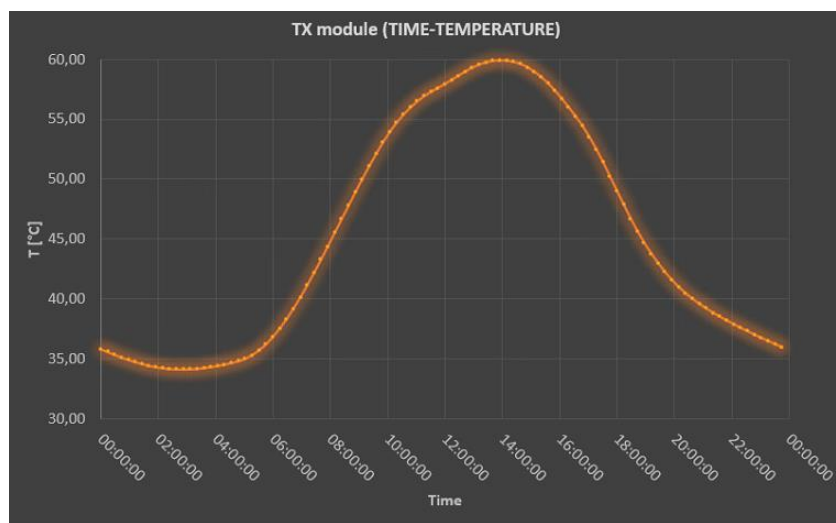


Figure 33 - Temperature trend of the hottest optical module in 24 hours – Q&D version

Conclusions

With the simulations carried out it was demonstrated that the SmartBox used for AAVS2 did not allow for correct dissipation of the heat of the components inside it, dangerously increasing its operating temperature. The "Lab test" comparison of the Q&D version compared to the original AAVS2, indicated a significant reduction in the operating temperatures of the most critical components.

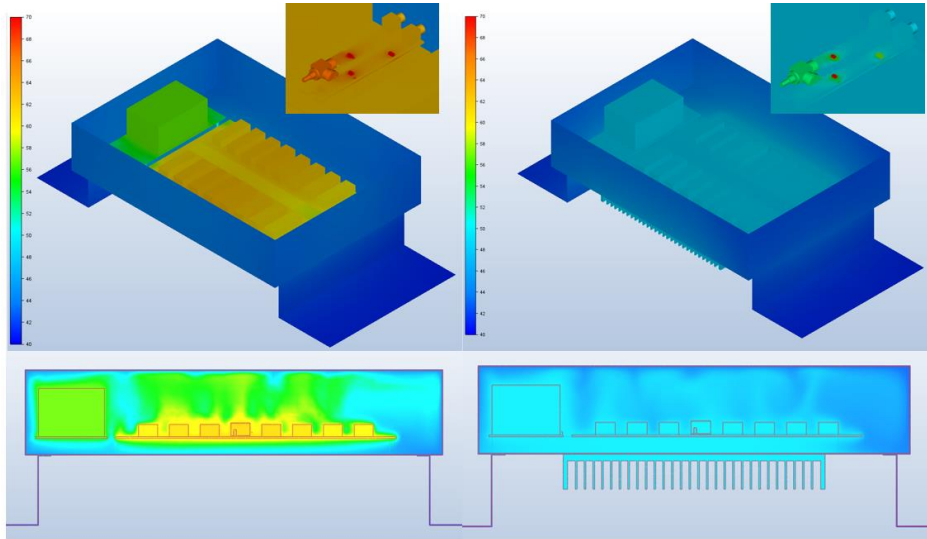


Figure 34 - Comparison of the temperature distribution inside the SmartBox and inside the TX module - AAVS2 vs Q&D "Lab test" version at 40°C external temperature

	T_{Avg} [°C] AAVS2 Original	T_{Avg} [°C] Q&D
Internal Air	50,1	45,8
TX Module box	62,5	48,9
BOSA case	66,6	52,9

Table 6 - Comparison of the average temperature of the principal components in the two SmartBox versions

The graph below shows the difference between the transient scenarios of AAVS2 original version (in blue) and the Q&D version (in orange).



Figure 35 - Transient scenarios comparison

The results obtained with the Q&D solution show a significant reduction of the operative temperature of the TX modules and greater uniformity of the temperatures of the modules inside the SmartBox, but only a slight improvement of the thermal inertia.

Appendix

Thermal analysis evaluation

Laboratory measurements were performed in order to evaluate the reliability of the simulations performed and the models used.

TEST 01: Original SmartBox mockup

Set Up

The first test carried out consists of a mockup of the AAVS2 SmartBox, which shares the main geometries, in particular the plate separated from the body of the SmartBox by columns. On this metal plate, 6 resistors simulated thermal load. A thermal sensor was placed in the center of the plate in order to measure its temperature.

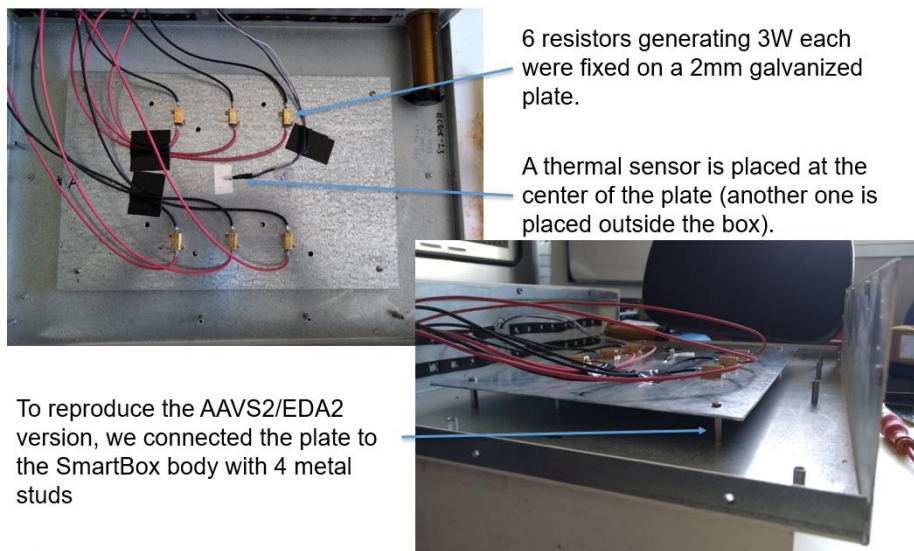


Figure 36 - TEST-01 Set Up

A simplified design of the same SmartBox mockup was created and a thermal simulation was carried out, in order to verify the temperature obtained in the center of the plate and measured by the temperature sensor.

CFD model

This analysis refers to a static version (NO time/temperature transient).

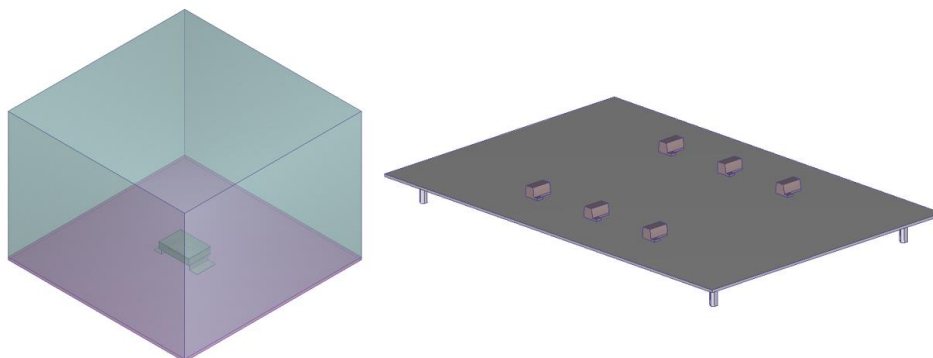


Figure 37 - CFD model of TEST-01

The elements of the model are:

- External air

Material: air - Variable properties as the scenario changes

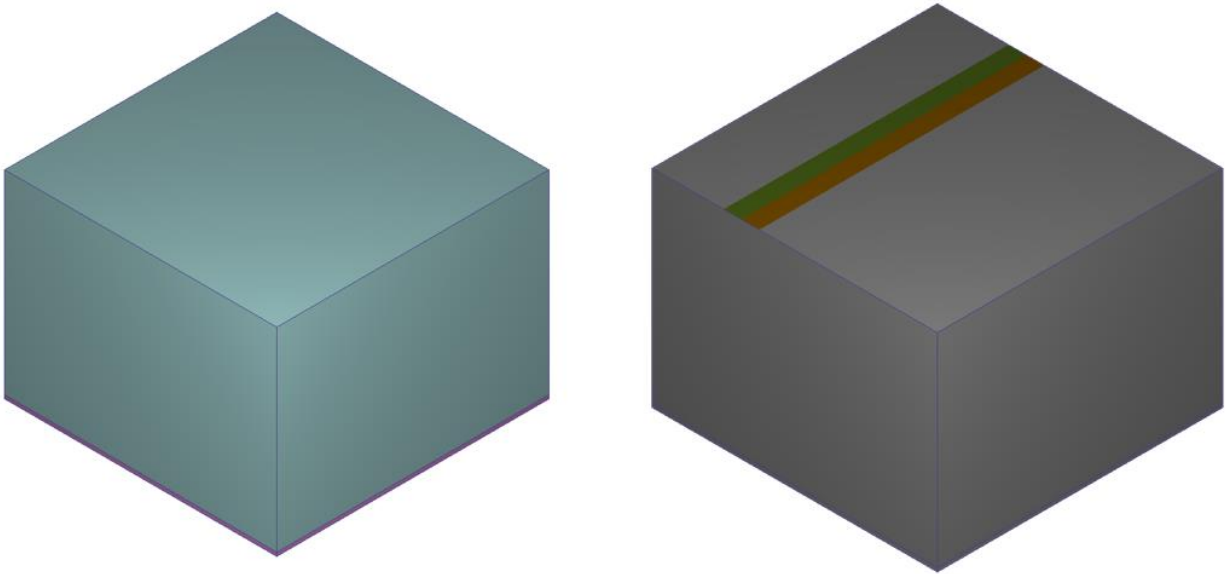


Figure 38 - TEST-01 external air material and boundary conditions

Boundary conditions: **Pressure:** 0 Pa in the top surface;

Film coefficient: $2W/(m^2 \cdot K)$ in a $29,4^\circ C$ reference temperature.

- Internal air

Material: air - Variable properties as the scenario changes

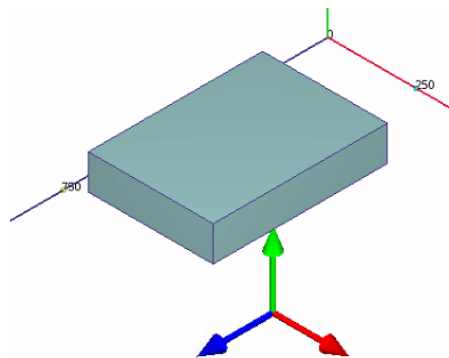


Figure 39 - TEST-01 internal air material and boundary conditions

- Top cover – SmartBox body

Material: painted/galvanized old steel

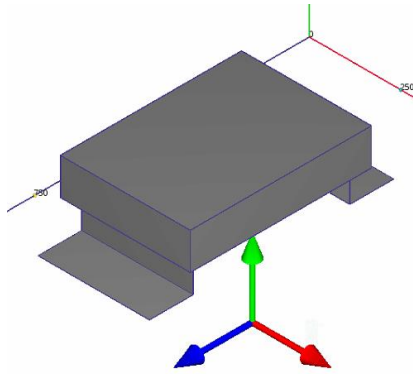


Figure 40 - TEST-01 External body material

- **Internal plate – studs**
Material: steel (plate)
Material: Nickel plated Brass (studs)

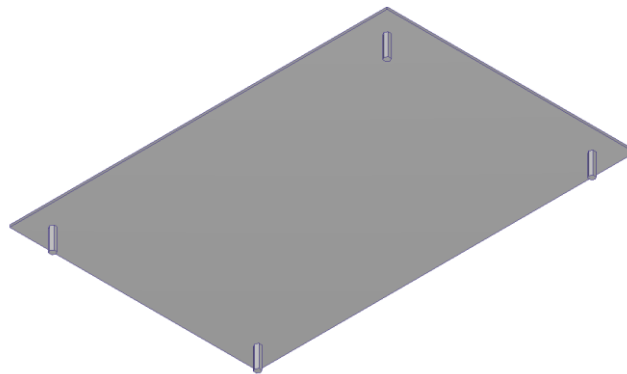


Figure 41 - TEST-01 Internal plates material

- **Ground**
Material: Expanded polystyrene

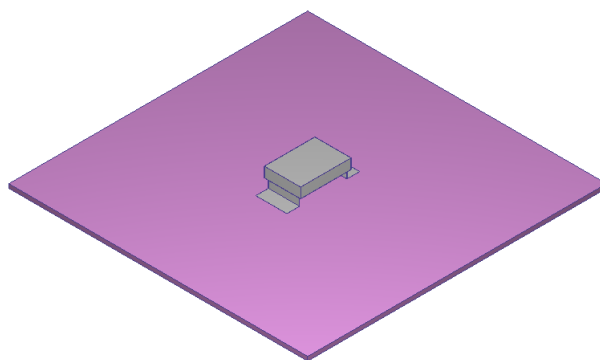


Figure 42 - TEST-01 Ground material

- **Resistors**
Material: Aluminum

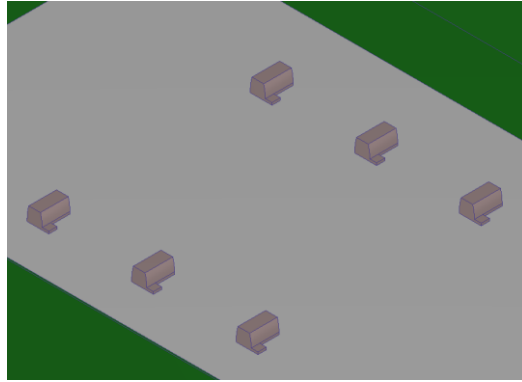


Figure 43 - TEST-01 Resistors material and boundary conditions

Boundary conditions: Total heat generations – 3W

Results

The temperature distribution of the simulated model is shown in the image below, and the comparison between the temperature sensor measurement and the simulation is shown in the table.

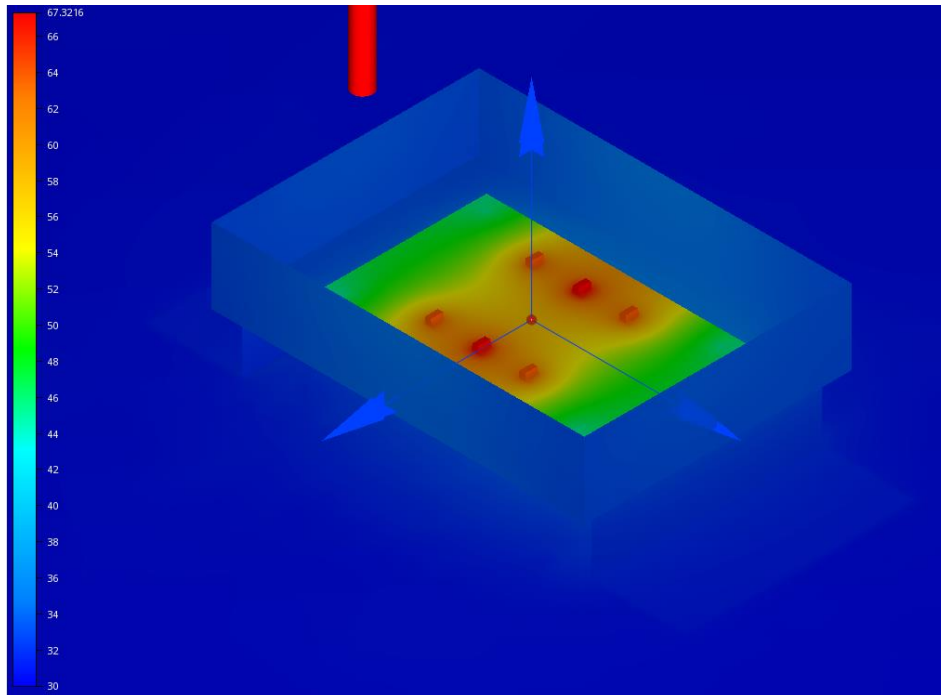


Figure 44 - TEST-01 Temperature distribution

T [°C]	AIR	Center of plate
MISURATED	29,4	57,1
SIMULATED	29,4	57,3

Table 7 - TEST-01 Temperature comparison between measurement and simulation

The value measured by the Mockup prototype matches well with the simulated model, deceeding a good reliability of the AAVS2 style SmartBox model.

TEST 02: Quick and Dirty SmartBox mockup

Set Up

The second test carried out consists of a mockup of the Q&D SmartBox, which shares the main geometries, in particular the plate connected to the body of the SmartBox by the aluminum block and the heatsink at the bottom. On this metal plate, 6 resistors simulated thermal load. A thermal sensor was placed in the center of the plate in order to measure its temperature.

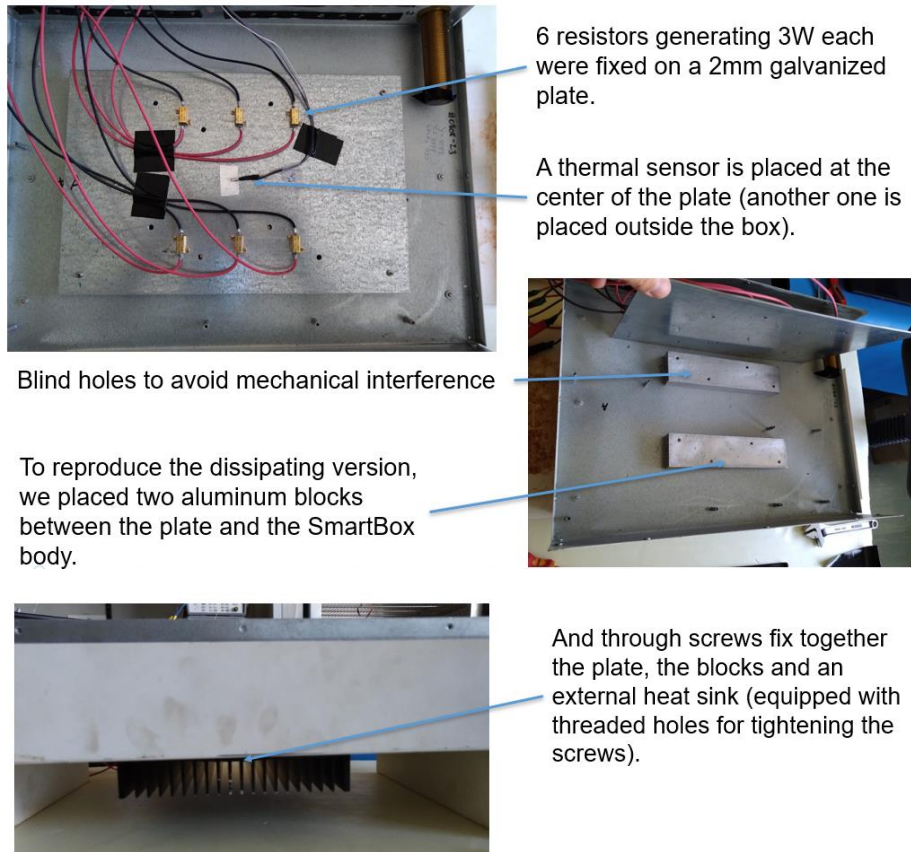


Figure 45 - TEST-02 Set Up

A simplified design of the same SmartBox mockup was created and a thermal simulation was carried out, in order to verify the temperature obtained in the center of the plate and measured by the temperature sensor.

CFD model

This analysis refers to a static version (NO time/temperature transient).

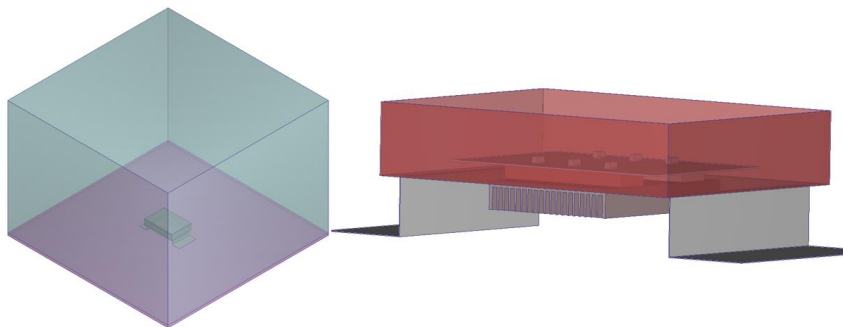


Figure 46 - TEST-02 CFD model

The model under consideration is similar to TEST-01, except:

- **External air**
Material: air - Variable properties as the scenario changes

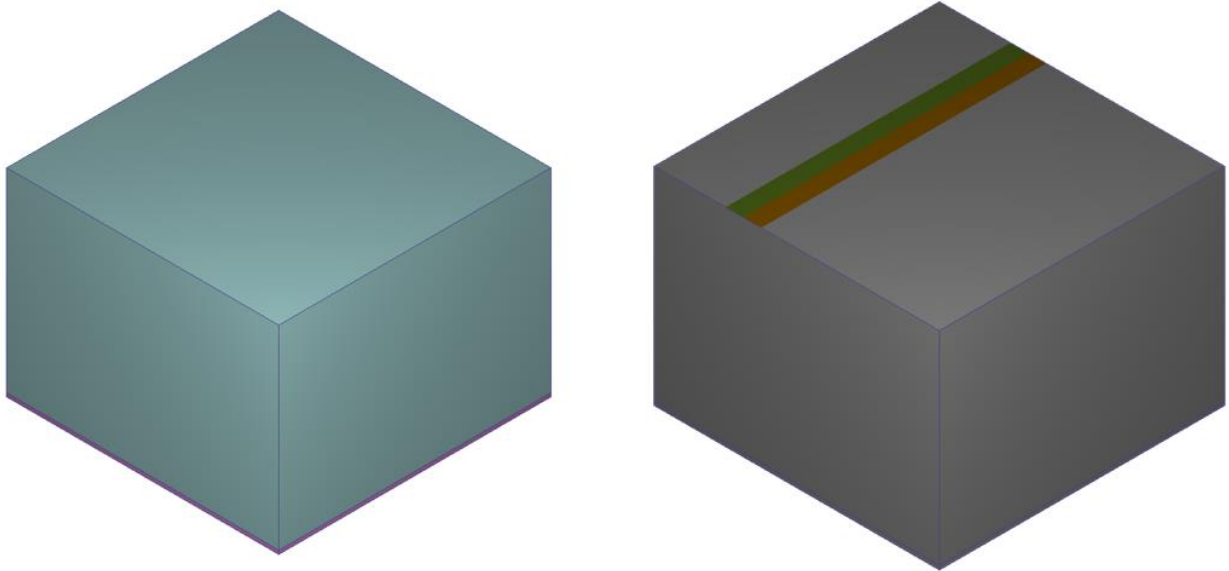


Figure 47 - TEST-02 External air material and boundary conditions

Boundary conditions: **Pressure** 0 Pa in the top surface;

Film coefficient: $2\text{W}/(\text{m}^2\cdot\text{K})$ in a $26,7^\circ\text{C}$ reference temperature.

- **Aluminum blocks and heatsink**
Material: Aluminum (blocks)
Material: Aluminum black anodized (Heatsink)

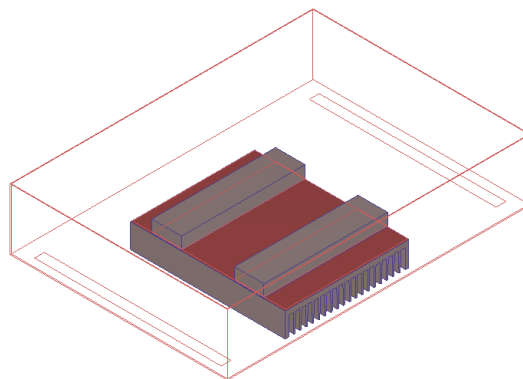


Figure 48 - TEST-02 Aluminum blocks and Heatsink materials

Results

The temperature distribution of the simulated model is shown in the image below, and the comparison between the temperature sensor measurement and the simulation is shown in the table.

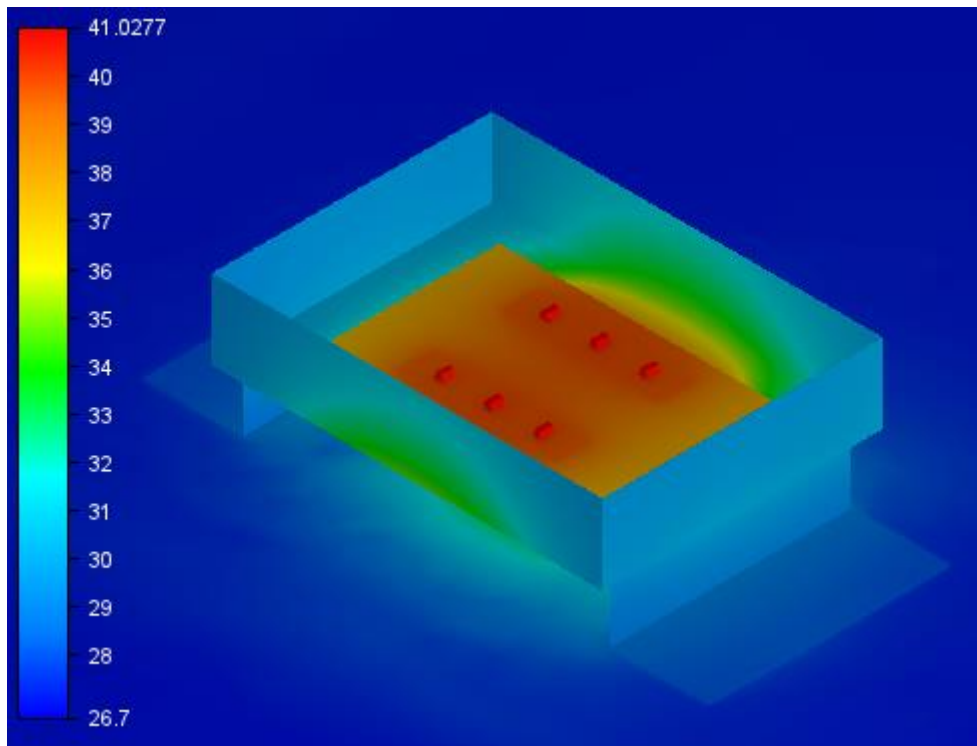


Figure 49 - TEST-02 Temperature distribution

T [°C]	AIR	Center of plate
MISURATED	26,7	38,8
SIMULATED	26,7	39,4

Table 8 – TEST-02 Temperature comparison between measurement and simulation

The value measured by the Mockup prototype matches well with the simulated model, decreasing a good reliability of the Q&D style SmartBox model.

TEST 03: Original SmartBox mockup + TX module

Set Up

The Set Up was the same of the TEST-01, by adding a complete module instead of one resistor. Two additional temperature sensors were used to measure the temperature of the module case and the BOSA it contains.

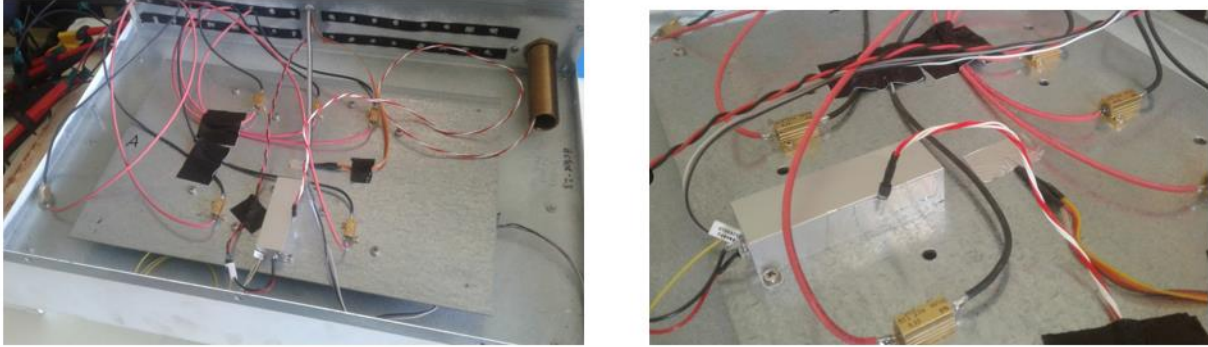


Figure 50 - TEST-03 Set Up

A simplified design of the same SmartBox mockup was created and a thermal simulation was carried out, in order to verify the temperature obtained in the center of the plate and measured by the temperature sensor.

CFD model

This analysis refers to a static version (NO time/temperature transient).

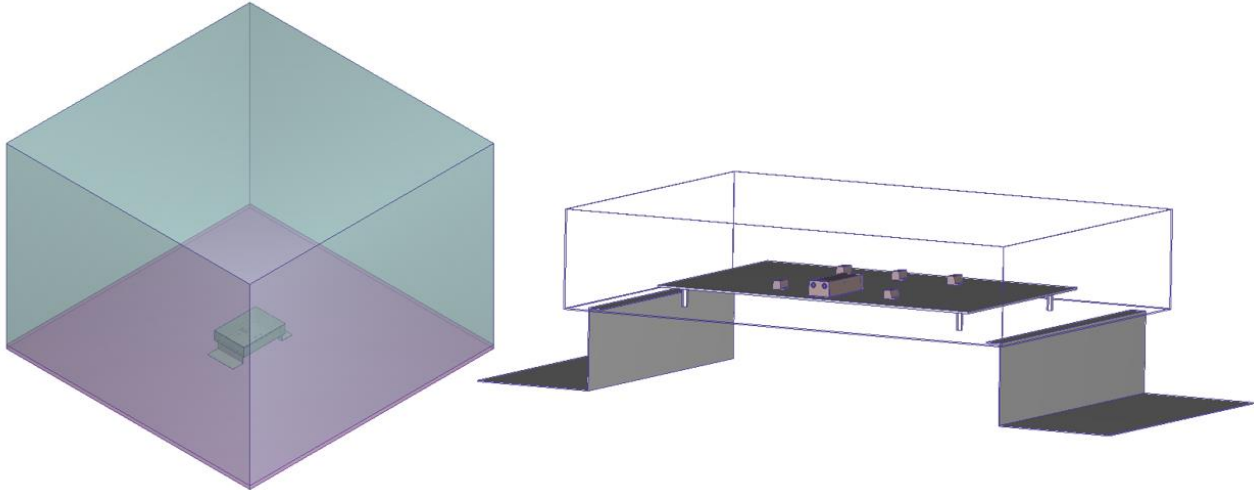


Figure 51 - TEST-03 CFD model

The model is the same of "TEST-01" adding one complete TX module and with 28,4°C of reference temperature of the film coefficient of the top surface of the external air.

Results

The temperature distribution of the simulated model is shown in the image below, and the comparison between the temperature sensor measurement and the simulation is shown in the table.

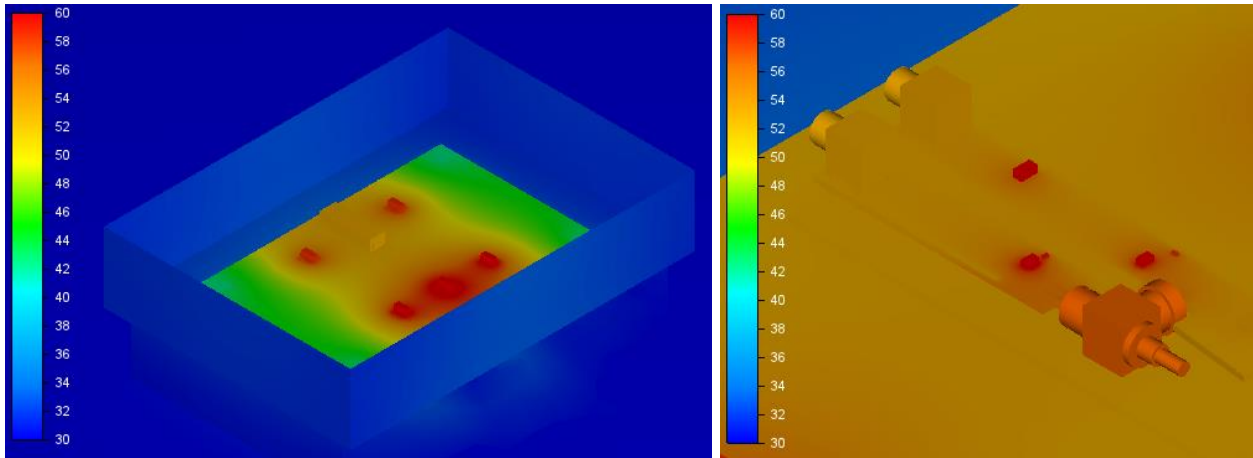


Figure 52 - TEST-03 Temperature distribution

T [°C]	AIR	Center of plate	TX Box	Bosa
MISURATED	28,4	53,6	53,2	57,3
SIMULATED	28,4	53,3	53,3	56,9

Table 9 - TEST-03 Temperature comparison between measurement and simulation

The value measured by the Mockup prototype matches well with the simulated model, decreeing a good reliability of the AAVS2 style SmartBox model + complete TX module.

TEST 04: Quick and Dirty SmartBox mockup + TX module

Set Up

The Set Up was the same of the TEST-02, by adding a complete module instead of one resistor. Two additional temperature sensors were used to measure the temperature of the module case and the BOSA it contains.

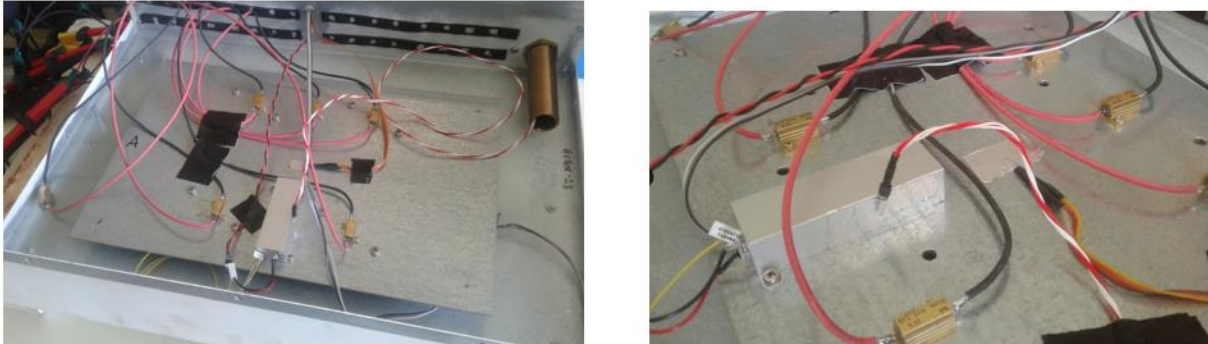


Figure 53 - TEST-04 Set Up

CFD model

This analysis refers to a static version (NO time/temperature transient).

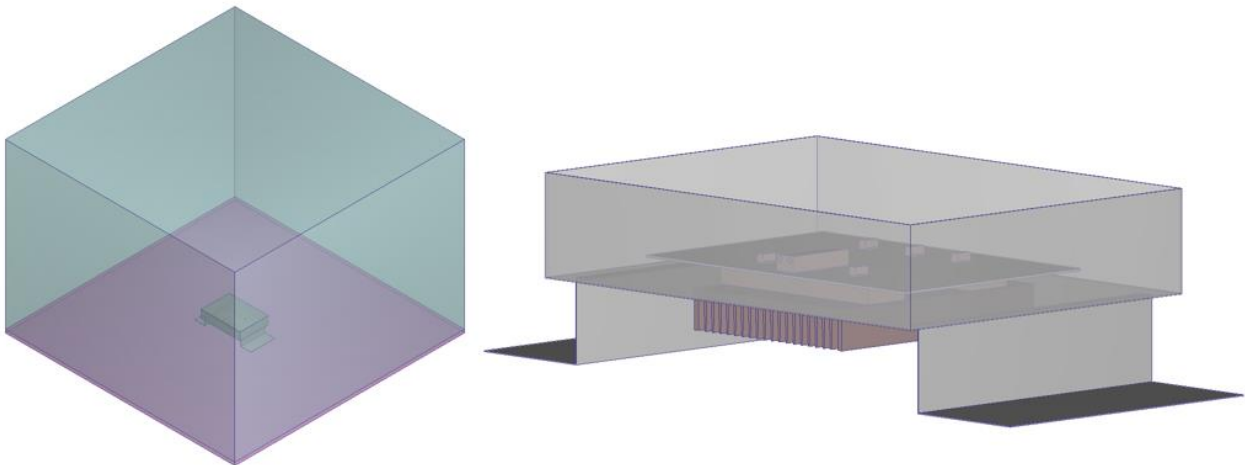


Figure 54 - TEST-04 CFD model

The model is the same of "TEST-02" adding one complete TX module and with 29°C of reference temperature of the film coefficient of the top surface of the external air.

Results

The temperature distribution of the simulated model is shown in the image below, and the comparison between the temperature sensor measurement and the simulation is shown in the table.

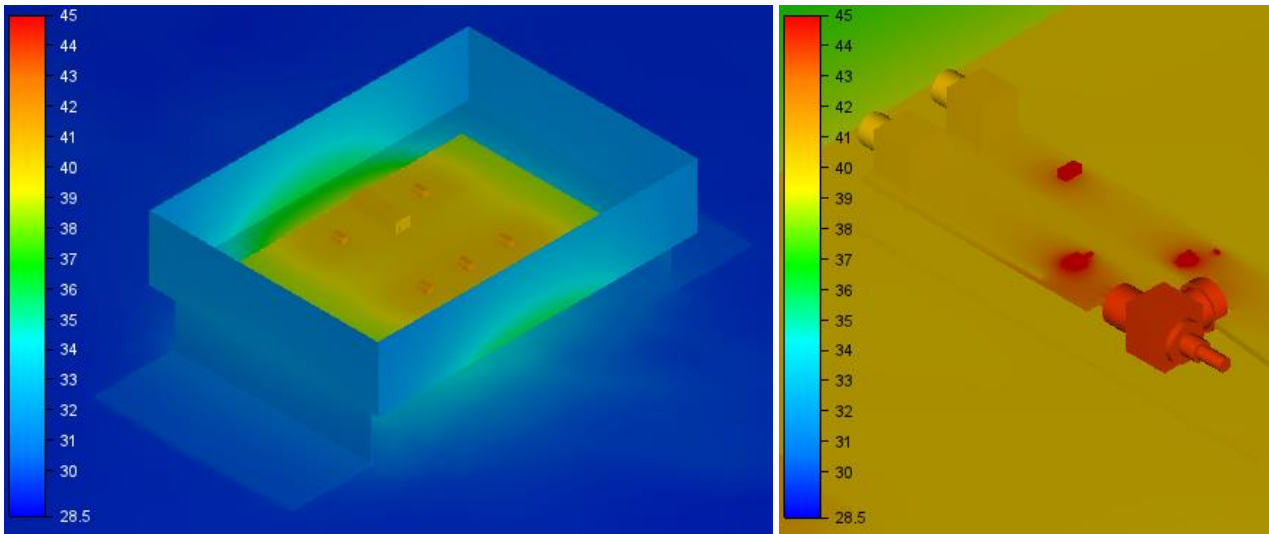


Figure 55 - TEST-04 Temperature distribution

T [°C]	AIR	Center of plate	TX Box	Bosa
MISURATED	29	39,4	40,3	43,6
SIMULATED	29	39,9	40,3	43,7

Table 10 - TEST-04 Temperature comparison between measurement and simulation

The value measured by the Mockup prototype matches well with the simulated model, decreasing a good reliability of the Q&D style SmartBox model + complete TX module.

Figure List

Figure 1 - AAVS2 SmartBox design	3
Figure 2 - TX modules plate and Power supply plate	3
Figure 3 - AAVS2 SmartBox CFD model	4
Figure 4 - External air material and boundary conditions	4
Figure 5 - Internal air material and boundary conditions	5
Figure 6 - External body material	5
Figure 7 - Internal elements material	5
Figure 8 - Ground material	6
Figure 9 - PCB material	6
Figure 10 - Power supply material and boundary conditions	6
Figure 11 - "Dummy" TX module material and boundary conditions	7
Figure 12 - "Complete" TX module	7
Figure 13 - Temperature distribution of the AAVS2 SmartBox - "Lab test"	8
Figure 14 - TX modules thermally isolated towards the outside	8
Figure 15 - CFD model - Solar irradiation version	9
Figure 16 - External air material and boundary conditions - Solar irradiation version	9
Figure 17 - Ground material and boundary conditions - Solar irradiation version	10
Figure 18 - Dummy TX module material and boundary conditions - Solar irradiation version	10
Figure 19 - Temperature distribution inside the SmartBox - Solar irradiation version	11
Figure 20 - Temperature difference between TX modules	11
Figure 21 - CFD Model - 24h transient version	12
Figure 22 - Temperature trend of the hottest optical module in 24 hours – AAVS2 version	12
Figure 23 - CAD model for Quick and Dirty step 1	13
Figure 24 - Temperature distribution inside the SmartBox - Q&D step 1	13
Figure 25 - Q&D step 1 heat exchange to the outside	13
Figure 26 - TX modules temperature for Q&D step 1	14
Figure 27 - CAD model for Quick and Dirty step 2	14
Figure 28 - Temperature distribution inside the SmartBox - Q&D step 2	14
Figure 29 - Q&D step 2 heat exchange to the outside	15
Figure 30 - TX modules temperature for Q&D step 2	15
Figure 31 - CFD model of Q&D "Lab test" version	17
Figure 32 - Temperature distribution inside the SmartBox and inside the TX module - Q&D "Lab test" version	17
Figure 33 - Temperature trend of the hottest optical module in 24 hours – Q&D version	18
Figure 34 - Comparison of the temperature distribution inside the SmartBox and inside the TX module - AAVS2 vs Q&D "Lab test" version at 40°C external temperature	19
Figure 35 - Transient scenarios comparison	19
Figure 36 - TEST-01 Set Up	20
Figure 37 - CFD model of TEST-01	20
Figure 38 - TEST-01 external air material and boundary conditions	21
Figure 39 - TEST-01 internal air material and boundary conditions	21
Figure 40 - TEST-01 External body material	22
Figure 41 - TEST-01 Internal plates material	22
Figure 42 - TEST-01 Ground material	22
Figure 43 - TEST-01 Resistors material and boundary conditions	23
Figure 44 - TEST-01 Temperature distribution	23
Figure 45 - TEST-02 Set Up	24

Figure 46 - TEST-02 CFD model.....	24
Figure 47 - TEST-02 External air material and boundary conditions	25
Figure 48 - TEST-02 Aluminum blocks and Heatsink materials	25
Figure 49 - TEST-02 Temperature distribution	26
Figure 50 - TEST-03 Set Up	27
Figure 51 - TEST-03 CFD model.....	27
Figure 52 - TEST-03 Temperature distribution	28
Figure 53 - TEST-04 Set Up	29
Figure 54 - TEST-04 CFD model.....	29
Figure 55 - TEST-04 Temperature distribution	30

Table List

Table 1 - Total heat generation variable with temperature "Dummy TX module"	7
Table 2- Average temperature of the main components.....	8
Table 3 - Dummy TX Module consumption variable with the external temperature	10
Table 4 - Q&D steps results comparison	16
Table 5 - Average temperature of main element of the simulation	17
Table 6 - Comparison of the average temperature of the principal components in the two SmartBox versions.....	19
Table 7 - TEST-01 Temperature comparison between measurement and simulation	23
Table 8 – TEST-02 Temperature comparison between measurement and simulation.....	26
Table 9 - TEST-03 Temperature comparison between measurement and simulation	28
Table 10 - TEST-04 Temperature comparison between measurement and simulation	30