Thermal Design and Analysis of an air cooled X-Band Active Phased Array Antenna

Swadish MS, Sangram Kumar Padhi

Astra Microwave Products Ltd, Hyderabad

swadishms@gmail.com , padhi.sangram@gmail.com

Abstract:

Thermal management plays a crucial role in electronic packaging, especially in defense electronics where the environment is unfavorable and the system has to reliably perform in adverse conditions. Active Phased Array Antennas have all their electronics packaged in a single unit unlike traditional antennas, making the thermal management more complex and critical [1]. This paper presents a guide for effective ducting of air in a typical modern phased array antenna.

INTRODUCTION

The Active Antenna Array works in X- Band and consists of 128 Dual Transmit Receive Modules (DTRM) packaged linearly along its length. The construction consists of 8 planks with 16 DTRMs each and has a FPGA based controller for controlling the DTRMs. The DTRMs use a Power Amplifier (PA) for transmitting and the performance of the PA degrades when the temperature goes above its optimum operating temperature and leading to degraded performance of the antenna [2]. The DTRMs are blind mated with the plank controller. The size and the spacing between the DTRMs has been worked out to fit into the rectangular architecture of the antenna and to make the antenna more compact as shown in fig 1. The heat dissipation of the DTRMs and the Plank Controller is analyzed to compute the quantity of cold air required.

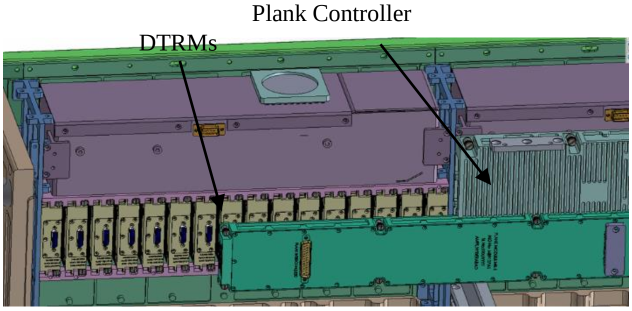

Figure 1 Arrangement of DTRMs and Plank controllers in the antenna

Since the antenna contains 8 planks and the planks are identical in all thermal and mechanical aspects, we consider one single plank for thermal analysis and scale the boundary conditions for the full antenna accordingly.

Scope of Analysis

The difference between a traditional reflector type antenna and a modern phased array antenna in terms of thermal and mechanical aspects can be termed as the packaging of the electronics, mainly the DTRMs behind the antenna. To maintain high system reliability, the heat dissipated by the TR modules must be removed efficiently to maintain the device temperature within their operating range. Also, most of the microwave devices are temperature sensitive, affecting the performance of the Radar system.

The aim of the design is to contain the maximum component at surface of the DTRM package to a maximum of 60° C (Maximum operating temperature of our chosen Power Amplifier). An externally mounted chiller is supplying air through ducting pipes to the inlet of the plank. The design ensures that air is passed along the contour of the fins of the DTRMs. Air at the inlet of the antenna is at temperature of 23°C by the chiller.

Preliminary Design

Each DTRM dissipates 14w of heat and one plank controller dissipates around 56 watts of heat as shown in table 1, but it is observed that the heat flux in the DTRM is more due to the geometry of the DTRMs.

Part	**Heat Dissipated**	**Quantity/ Plank**	**Total Heat in Watts**
DTRMs	14w	16	224
Plank Controller	56w	1	56
Total heat dissipated			280

Table 1 Heat dissipation of the components

Since we are going to consider only one plank for the analysis because it is symmetrical, we take into account 16 DTRMs and one plank controller which make up the complete electronics. So a total heat load of 280 W is used for analysis (from the table). From the energy balance equation, it is calculated that 36 CFM is required to cool the plank, with an allowable temperature rise of 15°C.

To effectively pass cool air through the fins of the DTRMs so that the heat transfer by forced convection is efficient [3], a duct for each plank was planned so that the air is only passed through the fins and does not get diverted and lose its velocity. The construction of the Air duct is shown in fig 2.

Flow rate of air for each DTRM is given by the equation [4],

$$G = \frac{Q*1.72}{\Delta t} \qquad (1)$$

$$G = \frac{14*1.72}{15} = 1.60 \text{ CFM}$$

We calculate the minimum velocity of air required at the exit of each slot by using Bernoulli's equation to ensure our intended cooling requirements are met. The dimension of each slot for the fins in the duct is 80 mm X 5 mm.

$$V = Q/A \qquad (2)$$

Where, Q = flow rate in m^3/sec

A = Area in m

V = velocity in m/s

Minimum Velocity(v) = flow rate / cross section area (3)

v = 1.60 X 0.0283[m^3/sec] / (0.08 x 0.005)

= 1.89 meters / sec at slot of each DTRM.

Preliminary Flow Analysis

Now that we have established the minimum amount of air to be fed into the duct and the velocity of air to be measured at the inlet of the DTRM, we perform an initial thermal analysis keeping in mind the boundary conditions.

The components were modelled using Solidworks and the analysis was done using Mentor Graphics FloEFD. The model is shown in fig 2. The flow source is represented as a fixed flow source.

During the initial iterations, only the duct inside the plank was modelled with its flow sources as shown in fig 3 and the flow was streamlined by adding deflectors to ensure that no vortices are created and velocity of air is maintained all that intended areas [5].

In conclusion, the flow analysis included results for a) air duct alone, b) Air duct and 16 DTRMs, c) Entire plank including plank controller. Flow analysis in the array showed that the DTRMs at the top face (face of the air inlet) had an average airflow rate of 5 m/s as shown in fig4.

Thermal Analysis

The values from the flow analysis are taken as boundary conditions for the thermal analysis and the thermal analysis is done independently for the DTRMs and for the plank controller for an external ambient condition of 45°C.

The model of the DTRM is suitably modified to input the boundary conditions. Flow source is represented as a fixed flow source with input flow as 1.6 CFM for one DTRM, with the data obtained from our earlier flow analysis. The heat dissipating components are modelled as two resistor components with thermal resistance values input from the datasheets. Also, the components that operate only during the transmit phase of the antenna are represented accordingly to the duty cycle and the results are shown in fig 5 and 6.

Flow rate of air for each Plank Controller is given by the equation,

$$G = \frac{Q*1.72}{\Delta t}$$

$$G = \frac{56*1.72}{15} = 6.42 \text{ CFM}$$

The same procedure is followed for the thermal analysis for the plank controller and the flow source is represented as a fixed flow source with input flow as 6.4 CFM. Using Bernoulli's equation, we find out minimum velocity of air required at the exit of the slot.

v = flow rate / cross section area

= 6.42 X 0.0283[m^3/sec] / (0.35 x 0.005) mm / min

= 1.73 meters / sec.at the slot for Plank Controller

In the analysis it is assumed a thin plate over the heat sink is assembled to constrict the air only through the heat sink. The plate fixing has been done by using Loctite 279 (alternative 3M VHB tape) to adapt to the existing plank controller enclosure with no hardware modifications, the analysis results are shown in fig 7 and 8.

Practical tests and Results

With these results from the analysis, the ducts, DTRMs and the plank controller were fabricated. PCB based thermocouples were placed near the critical places where the temperatures has to be monitored and flow sensors were placed at the inlet of the duct and at the exit of the Air Duct. The air is fed from an air cooled chiller with the required flow rate and whose gauge pressure is higher than that of our pressure drop. The tests are done for the maximum duty cycle in which heat dissipated is maximum.

Table 2 shows the average temperature at plank controller and DTRMs and table 3 shows the inlet velocity and outlet velocity of air,

Plank no	Plank controller temp (deg C)		Avg Temp at DTRMs (deg C)	
	Analysis	Measured	Analysis	Measured
1	56.5	56.3	48	49.2
2	59.3	60.5	48.5	49.3
3	58.2	59.2	47.7	48.4
4	60	61.4	47.5	49.8
5	60.5	61.2	49	49.5

6	58.5	59.5	46.5	47.3
7	58.7	59.6	46.3	47.5
8	57.5	58.8	48.2	48.8

Table 2 Analysis values and Measured Temperatures.

Plank no	Inlet velocity air duct (m/sec)		Outlet velocity exit of air duct (m/sec)	
	Analysis	Measured	Analysis	Measured
1	8.6	8.2	6.2	5.8
2	8.5	8.2	5.8	5.5
3	7.5	7.2	5.6	5.2
4	7.0	6.8	5.5	4.8
5	6.5	6.2	5.3	4.6
6	6.5	6.2	5.2	4.8
7	6.4	6.2	5.2	5.0
8	6.5	6.3	5.2	5.0

Table 3 Analysis values and measured air velocities

Conclusions

The following conclusions are drawn based upon the flow and thermal analysis and practical testing done on the prototype antenna.

- The temperature difference between the inlet and outlet of air is determined to be 12°C experimentally.

- The flow is streamlined to ensure that pressure drop across the flow path is minimum, which will help in effectively reducing the size and capacity of air cooled chiller.
- The analysis and practical results show that the air flow is sufficient in maintaining the optimum operating temperatures.

Acknowledgement

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Author Info

Swadish MS received his B.E degree in Mechanical Engineering in 2014 from Visvesvarayya Technological University, Belgaum. He is currently working as an Engineer at Astra Microwave Products, Bengaluru. Areas of interest include Thermal Management for Electronics Packaging and structural analysis.

Sangram Kumar Padhi received his M Tech degree in Thermal Engineering in 2016 from JNTU, Hyderabad. He is currently working as an Assistant Manager at Astra Microwave Products. Areas of interest include Structural Design of Radar Platforms and Systems Engineering.

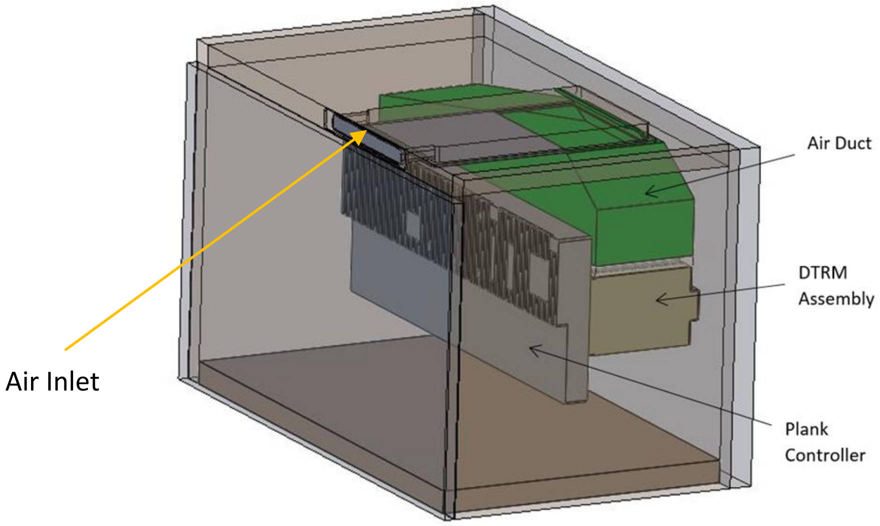

Figure 2 View showing the arrangement of DTRMs, Plank Controller, and Ducting arrangement.

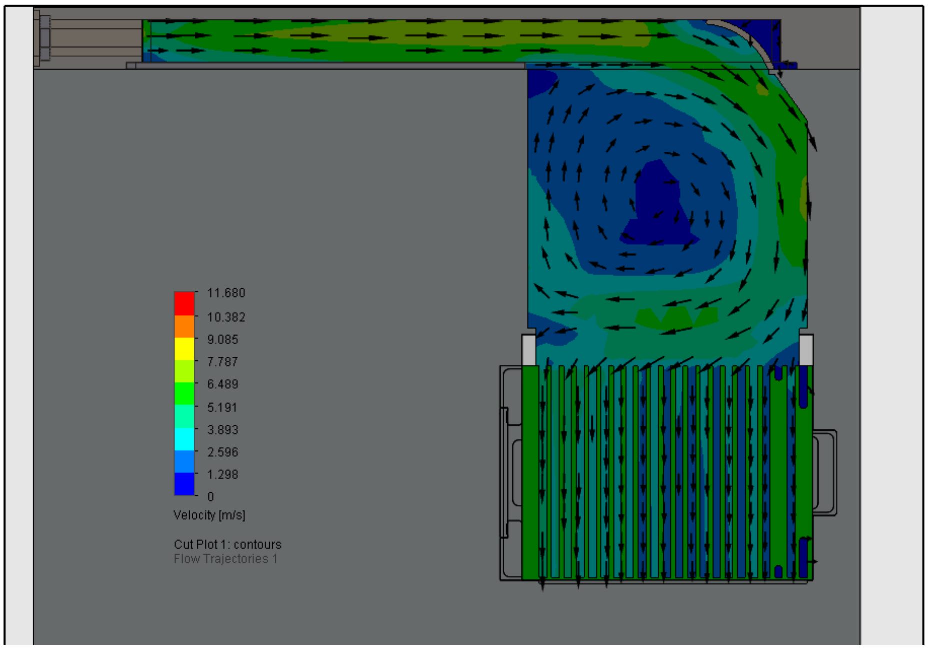

Figure 3 shows the flow path while analyzing only for the DTRMs

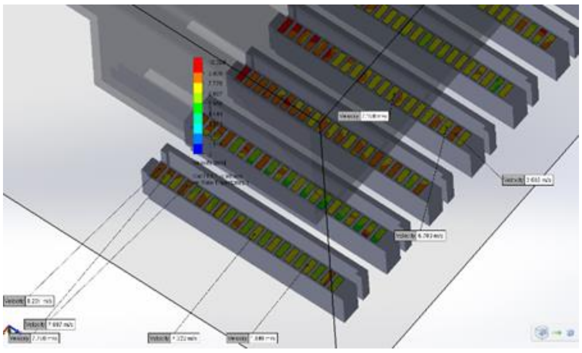

Figure 4 shows the average velocity at the inlet face of the DTRMs

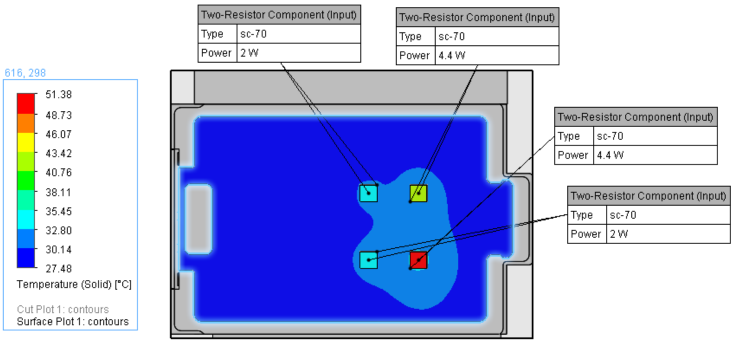

Figure 5 shows the thermal analysis plots for the DTRM

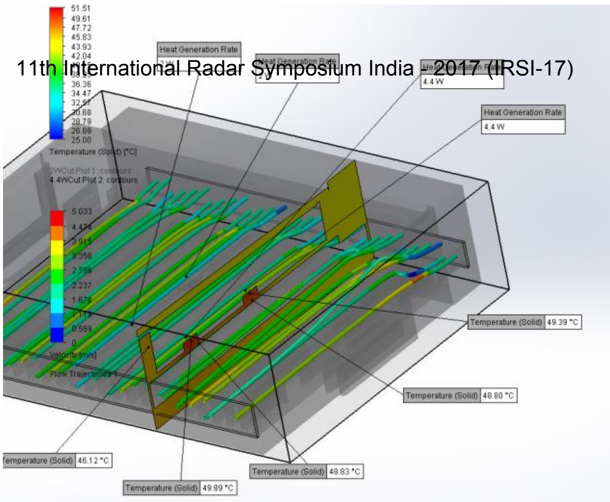

Figure 6 shows the flow path along the DTRMs

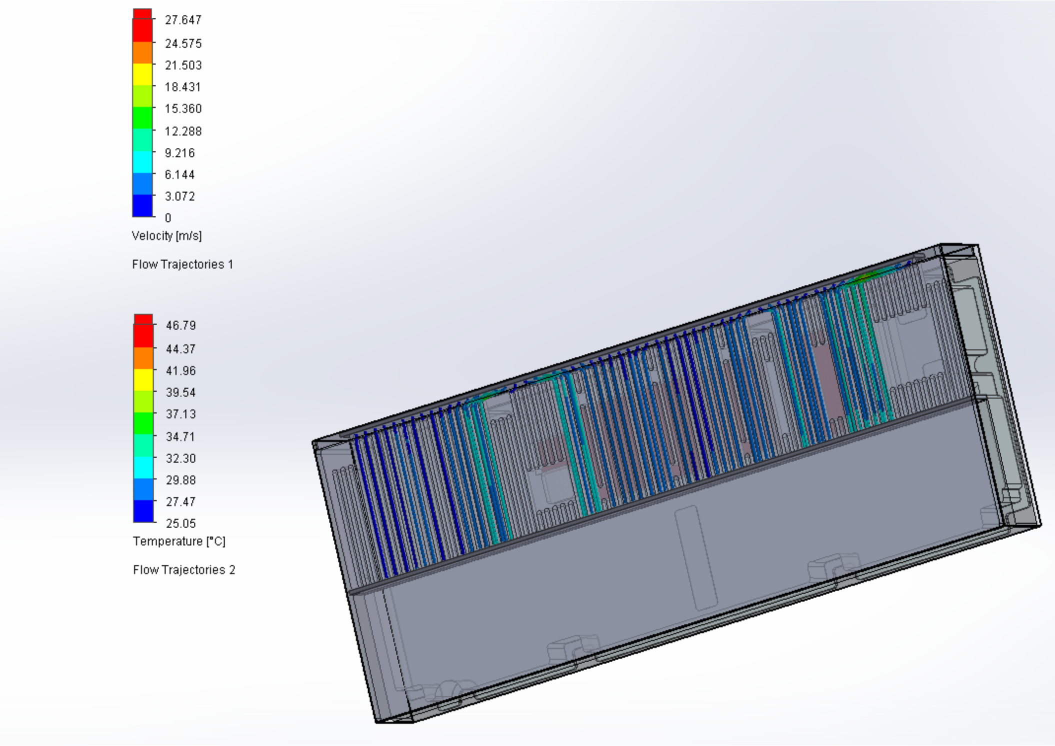

Figure 7 shows the flow path along the fins of the Plank Controller

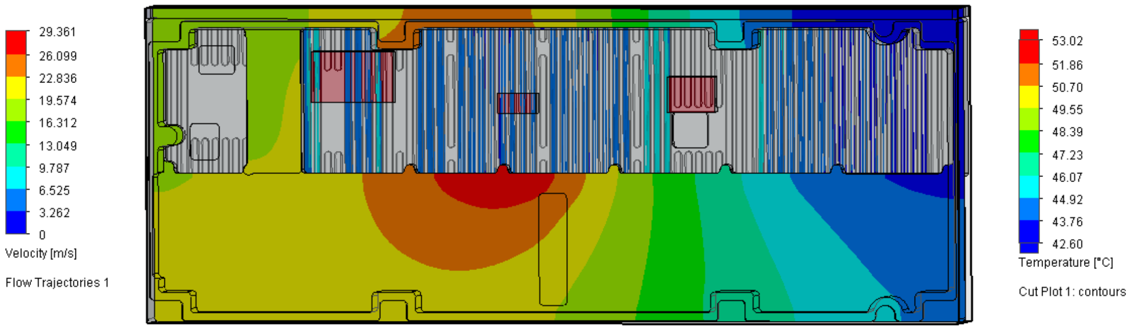

Figure 8 shows the thermal plots for the Plank Controller