EVLA Correlator Rack

Thermal Performance

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Mark Halman, November 29, 2005

ABSTRACT

This document details a method of predicting the operating temperature of critical components within a complete Station or Baseline Correlator rack. These racks, to be located at an altitude of 2100m are to be cooled by a fixed volume of air, drawn out of the top of the rack by exhaust fans. Because the fixed volume is in the heated exhaust and air density changes with both temperature and altitude, the calculated performance of heatsinks and hence operating temperatures of components mounted thereon need to be compensated for air density changes as well as total power. Power levels have been estimated for the Baseline, Station and Fanout boards. A spreadsheet has been used to calculate the many variables, and to allow operating conditions to be adjusted easily. The spreadsheet yields results consistent with measured data on a physical model.

Introduction

To test the feasibility of air-cooling of a correlator rack, it was decided to build a thermal test rack. This rack was tested dissipating up to 10 kW under various airflow conditions. One factor that was not tested was that of the effect of reduced air pressure and density, as will be the case at the VLA site.

Testing so far has been conducted at DRAO at an altitude of ~550 m. Heatsink and fan manufacturers' data assumes 1 atmosphere [0 m] and 20 ^{o}C [NTP]. Thus heatsink performance, fan performance and air cooling properties all need de-rating for the conditions at 2100 m. Corrections also need to be made for the variable airflow rate and the corresponding change in performance of the heatsinks.

A spreadsheet has been written in an effort to model these effects and calculate component junction temperatures, internal airflow requirements and to determine HVAC supply capacity.

The use of a spreadsheet also allows different performance variables to be tested, such as airflows, heatsink types, interface materials, chip dissipation and total power levels.

The calculation of the operating temperature has been separated into two parts. Air temperature and heatsink temperature.

1. Air temperature rise

All components inside the racks, including those that are not mounted on the heatsinks that are dissipating power, contribute to air temperature rise.

Air density at the altitude of the VLA site is reduced by approximately 15% compared to that at sea level, 1 Atm or 0 m altitude. Temperature rise is higher as a result.

There is also a significant air density change associated with heating of the rack load [4% at ~10 kW]. This is important because the exhaust fans move a fixed volume of air and, are located in the heated air stream. Each time a different total power level is entered, both the density and temperature of the air change. The spreadsheet iterates to converge on a solution.

There is a temperature gradient within the rack due to the mechanical arrangement wherein one subrack is located above the other subrack. The temperature of the air at the heatsink is referred to as local ambient and is the *effective* air temperature seen by the heatsink.

2. Heatsinks temperature rise

The thermal resistance of the heatsink-to-ambient is denoted by R_{sa}. The value of R_{sa} is not fixed and must be corrected for the change in air density and airflow velocity each time a new value of total power is entered into the spreadsheet. There is also a correction for the size of the heatsinks as our finished part is machined down from a stock extrusion.

The critical ASIC and FPGA components are mounted on the heatsinks and the junction temperatures for these are calculated in the standard way, [ie. using R_{jc} and R_{cs}].

Air Temperature rise

The change in temperature is determined using the Volumetric Heating Capacity [VHC] of the total air volume. Correction for density, altitude and temperature are made in the expression detailed in the section, “Air density correction” [2]. It should be noted that in a fixed volume arrangement a small change in temperature will create a small change in density which will then create another change in temperature and so on. As mentioned this is an iterative process handled by the spreadsheet.

Several variables are estimated, calculated or taken from manufacturers’ data sheets, they are,

1. Power dissipation of all components – estimated or data sheet.
2. Supply air inlet temperatures – specified.
3. Cooling air density – calculated for altitude and temperature.
4. Cross sectional area to the airflow – taken from drawings.
5. Pressure loss in the system – calculated and measured.
6. Total air volume – calculated from the fan manufacturer’s fan flow curves.

Once these variables are known it is possible to calculate air temperature rise [1].

Using volumetric heat capacity

$\Delta T_a = k\ P\ /\ V$

Where,

V	=	Volume in m^3/h
P	=	Power dissipated in the air stream, Watts
ΔT_a	=	Temperature change ^oC
k	=	$1 / Cp\ \psi$ [volumetric heat constant]
Cp	=	Isobaric specific heat capacity of air ~ 0.27 Wh/kg K at expected temps
ψ	=	Air density 1.2255 kg/m^3 at 20^oC and 1 Atm

For applications at low altitude and where density changes are small, k can be set to 3.1
In the case of the correlator, dissipating large amounts of power at altitude a correction must be made.

Air density correction

Density can be re-calculated for any altitude up to 18000 m and temperature using, [2]

$$\psi = \left(288.15K \big/ TemperatureK \right) \times 10^{\left(\frac{-Altitude}{18000m}\right)} \times 1.2255 kg/m^3$$

Temperature gradient

Due to the fact that the heatsinks are located in a temperature gradient, the effective temperature of the air supplying the heatsink, referred to as local ambient air temperature T_a is,

$T_a = F(\Delta T_a) + T_{inlet}$

Where,

T_{inlet}	=	The cold air supply temperature provided by the HVAC system
F	=	Some fraction of the overall heat gain of the air stream.

In the case of the upper subrack, the local supply air has been heated by the fraction of the total load that is below [the lower subrack and the fanout boards]. There is also a small correction made due to the large size of heatsink[3]. This small correction [~1.3 ^oC at 10 kW], for average temperature across the heatsink, was determined experimentally.

Heatsink Temperature

The temperature rise of the heatsink is simply total power dissipated on the heatsink multiplied by the thermal resistance of the heatsink.

$$\Delta T_s = P_s R_{sa}$$

In practice R_{sa} is not a fixed value, it varies with density and air velocity. Additional variables have to be calculated.

1. Air temperature T_a – calculated
2. Cross sectional area to the airflow – taken from drawings.
3. Air velocity – Air volume divided by cross sectional area [also measured].
4. Heatsink performance R_{sa} – manufactures' datasheets recalibrated for air velocity, density and size.

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The operating temperature of the heatsink is the simply temperature rise of the heatsink plus the ambient air temperature,

$$T_s = \Delta T_s + T_a$$

Junction Temperature

In the case of the digital filter chips that are cooled in the conventional way [Fig 1 – right hand side] the expression is,

$$T_j = (R_{jc} + R_{cs})P_{Chip} + T_s$$

Where
R_{jc} thermal resistance Junction to case – data sheet
R_{cs} thermal resistance of the interface material – data sheet

In the case of the correlator ASIC chip, the minimum thermal resistance path is not through the case top but through the case bottom, junction to ball. The heatsink is mounted on the other side of the PCB and connects to the case bottom using a machined post, thermal vias [solder filled] and an interface material. [Fig 1 left hand side]

The thermal path is junction to ball, ball to via, via to interface and interface to heatsink.

Note. Junction to ball is still referred to as junction to case.

The Junction temperature in the case of the ASIC chip is,

$$T_j = (R_{jc} + R_{cv} + R_{vs})P_{Chip} + T_s$$

Where

R_{jc} thermal resistance Junction to case
– supplied by the chip manufacturer

R_{cv} thermal resistance of the thermal vias
– calculated using the sum of the parallel thermal resistance paths of the copper vias [including the solder fill].

R_{vs} thermal resistance interface material
– a thin deformable metal pad used to couple the PCB to the heatsink. We propose using -electrically conductive- Indium metal for this purpose, with a thermal conductivity value of ~81 W/mK

The spreadsheet calculates both possible thermal paths for correlator board chips and two values for T_j are returned. Digital filter chips are coupled to the heatsink in the conventional way, and only one value of T_j is calculated.

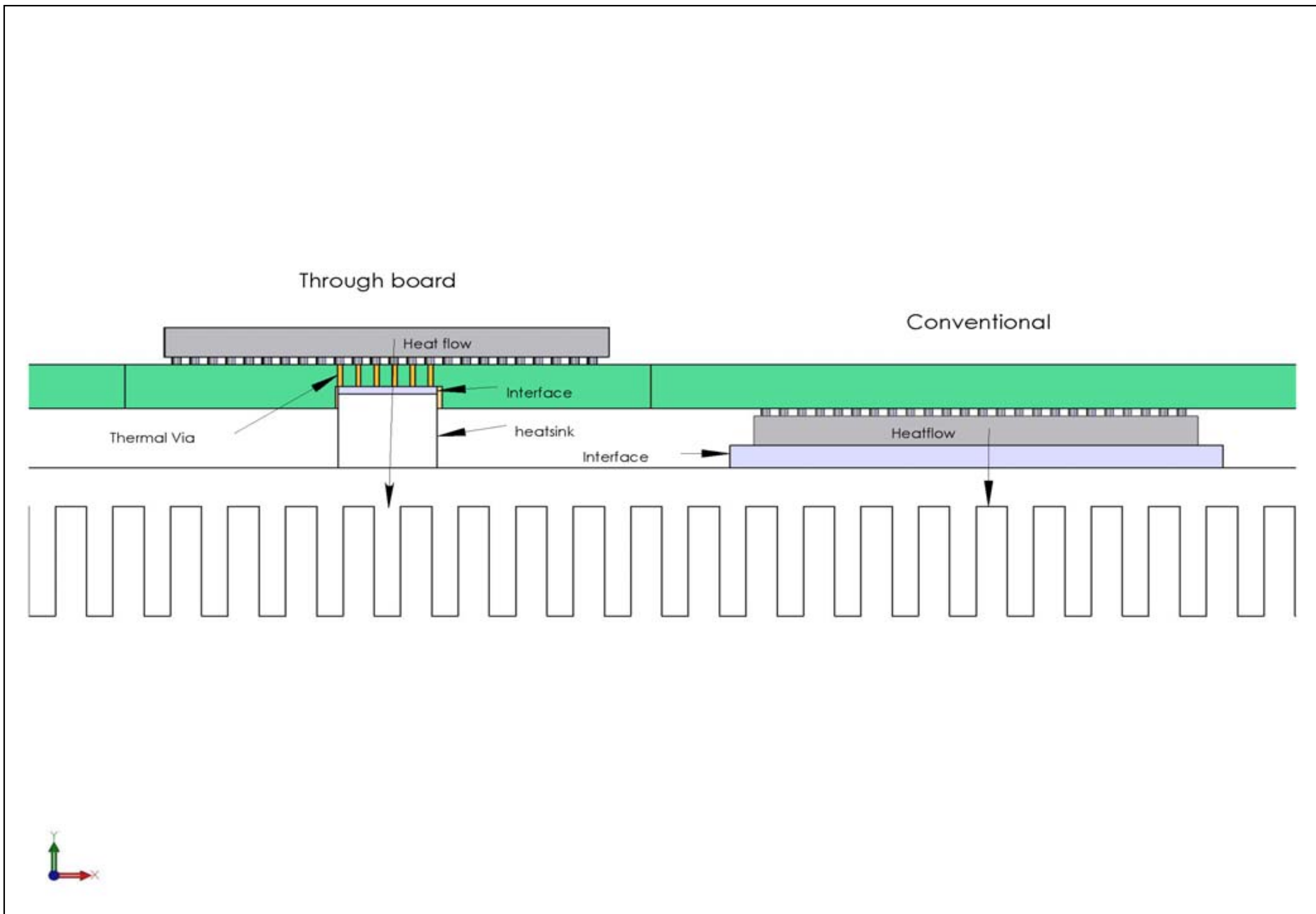

Figure 1 Heat flow paths - ASIC [through board] and FPGA [conventional]

The Spreadsheet

The spreadsheet is entitled, "A25031D0001_Thermal performance_correlator_V1.0_Nov29-05.xls" and may be found on the Widar web page. There are two separate pages "Baseline" and "Station".

Input Variables

Shown in tabular form with a short description, not to be confused with the spreadsheet. The description applies to either sheet.

Variable	Notes
Air inlet temperature	The supply temperature from the HVAC.
Altitude	Enter this value in meters.
Fan speed %	We expect to run the fans at ~80%
Number of fans	May be used to simulate fan failure.
Junction to case resistance	Supplied by chip manufacturer.
Junction to ball resistance	Supplied by chip manufacturer.
Chip size	Data sheet.
Interface resistance [conventional]	Data sheet, interface manufacturer.
Qty of Correlator chips	64
Watts per chip	3.5 W ASIC, 6.5W FPGA
Additional load heatsink	Used to account for other heatsink loads such as DDRAM, LTA etc.
Additional board load	Power supplies and other parts.
Other rack loads	The 6 U subrack and contents, – anything else.
Duct size	Physical cross section of the 12U subrack.
Interface size	The indium pad or the elastomer
Interface bulk conductivity	The indium pad or the elastomer
Interface R conventional. Baseline board only	Elastomer pad R value, secondary thermal path.
Heatsink thermal resistance [2 point]	Curve fit of manufacturers data.
Heatsink type factor	1 for bonded, 1.2 for extruded.
Heatsink and Board cross section	Taken from CAD files.
Number of boards	Per subrack 0-9 – used to total power.
Thermal via size and quantity	These values set by board manufacturing process.
Conductivity copper and solder	Standard values.

Calculated results

Variable	Notes
Air density	At the exit.
Air velocity through duct	Required for calculation of R_{sa}.
System pressure	Required for calculation of fan performance.
Total air volume [at the exit]	Useful for HVAC requirements.
Exit air temperature	Useful for HVAC requirements.
Total cross sectional area [locked to 8]	Used for air velocity calculation.
Heatsink thermal resistance	The actual R_{sa} used for temperature calculations.
Heatsink temperatures [both types]	Maximum value returned.
Correlator ASIC junction temperature	Maximum value returned, top row.
Digital filter FPGA junction temperature	Maximum value returned, top row.
Sum of resistance of parallel paths	R_{cv} through the PCB. [via and fill]
Interface resistance [Indium]	$R_{vs.}$ calculated.
Total rack heat load	Useful for HVAC requirements [includes fans].
Other variables not detailed here, are either obvious or of little use external to the spreadsheet.	

Notes.

The spreadsheet shows input variables in a blue font, calculated results are black on a grey background, and important values are bold red.

Heatsink performance is corrected for size, and air density and flow between 3.0 and 5.5m/s.

Fan speed is entered as % of maximum. Fan performance curve of flow vs. pressure has been approximated as a straight line between 3.0 to 5.5m/s. Fan speed is only useful for speeds of > 30% due to fan performance non-linearity.

The value heatsink type factor is to allow other types of heatsink technology to be assessed, bonded =1 extruded =1.2

The cross sectional area is locked to a quantity of 8 boards. If fewer boards are to be modeled then it is assumed a blocking plate will be installed to compensate. This doesn't effect the power calculations, which are based on number of boards.

For HVAC requirements 100 W per fan is added to the total load for the heat dissipated by the fan motors mounted externally on the top of the rack.

Sections of the spreadsheet, other than input variables, are protected with the password widar to prevent inadvertent damage.

The default values in the spreadsheet shown on the following pages include the current best estimates of power dissipation.

Air density calculator [temperature & altitude]			
Air dT calculator			
Chip temp calculator		**Baseline board**	
	Enter value	***Calculated result***	
Air inlet temp C	10	Exit Air temp C	**23.45**
Altitude m	2100	Total air flow m^3/h	**2510**
Fan Speed %	70	Total air flow CFM	**1477**
Number of fans	4	Exit Air density kg/m^3	0.9102
Junction -case resistance C/W	4	Exit Air temp K	296.60
Junction -ball resistance est	0.1	Air velocity through Duct m/s	4.32
Chip size mm	27	Delta T Air	13.45
Interface R C/W [conventional]	0.5	Air mass flow kg/s	0.63
Qty correlator chips on heatsink	64	Duct size clear m^2	0.161
Average watts / chip	3.5	Heatsink thermal resistance current C/W	0.063
Additional load heatsink W	64	Heatsink load W	288
Additional load board W	150		
Other rack loads -fanout W	150	Heatsink temp top row	37.18
Duct Depth m	0.40	Die temp coupled by case	**52.93**
Duct Width m	0.54	Die temp with heatsink using vias	**44.79**
Indium interface size m		**Correlator chip status [<45C]**	**OK**
x [width] m	0.009	Total power correlator rack W	8582
y [length] m	0.006		
z [thickness] m	0.005		
Bulk conductivity W/mK	81	Interface resistance C/W	
Heatsink Calibration		[formula 1/(W/mK)(A/t)]	1.143
Datasheet values		System pressure Pa	127
low flow m/s at NTP	3	Fan Flow m^3/h	896
high flow m/s at NTP	5.1	Duct fill factor %	25
Heatsink type factor	1.00	Heatsink Rsa max min	
Duct Fill		Rsa max bonded [corrected for size]	0.056
Heatsink cross section mm^2	4631	Rsa min bonded [corrected for size]	0.044
Board cross section chips +pcb	2200	thermal resistance change	0.012
Number of boards per sub rack	8	board assy cross section mm^2	6831
Via Cooling		Total cross section mm^2 [nominal 8 bds]	54648
QTY vias	70.00	solder R	408.46
Conductivity fill solder	28.00	solder cross section	1.46E-07
Conductivity copper	385.00	total R of parallel solder	5.84
via outer radius mm	0.25	total R of parallel vias	1.10
via inner radius mm	0.22	Area/thickness solder	8.74E-05
PCB thickness m	1.68E-03	sum of resistance of parallel paths C/W	0.93
Pressure loss measured Pa	140	via cross section m^2	5.63E-08
Constants		Thermal resistance per via C/W	77.34
Specific heat Air Cp kJ/kg.K	1.005	Area/thickness via	3.36E-05
Watthour to kJ	0.278		
C0 curve fit Temp K	288.16		
C1 curve fit altitude m	18000		
C2 curve density kg/m^3	1.2255	C4 volumetric heat constant	3.93

Air density calculator [temperature & altitude]			
Air dT calculator			
Chip temp calculator		**Station board**	
	Enter value	***Calculated result***	
Air inlet temp C	13	Exit Air temp C	**21.52**
Altitude m	2100	Total air flow m^3/h	**3048**
Fan Speed %	85	Total air flow CFM	**1793**
Number of fans	4	Exit Air density kg/m^3	0.9161
Junction -case resistance C/W	0.5	Exit Air temp K	294.67
		Air velocity through Duct m/s	5.25
		Delta T Air	8.52
Qty Filter chips on heatsink	35	Air mass flow kg/s	0.78
Average watts / chip	6.5	Duct size clear m^2	0.161
Additional load heatsink W	30	Heatsink thermal resistance current C/W	0.064
Additional load board W	100	Heatsink load W	257.5
Other rack loads -TGB W	50		
Duct Depth m	0.40	Heatsink temp top row	35.19
Duct Width m	0.54	Die temp	**42.40**
Interface size m		**Filter chip status [<45C]**	**OK**
x [width] m	0.027	Total power station rack W	6650
y [length] m	0.027		
z [thickness] m	0.00102		
Bulk conductivity W/mK	2.3		
Heatsink Calibration		Interface resistance C/W	
Datasheet values		[formula 1/(W/mK)(A/t)]	0.608
low flow m/s at NTP	3	System pressure Pa	127
high flow m/s at NTP	5.1	Fan Flow m^3/h	896
Heatsink type factor	1.00	Duct fill factor %	25
[1.2 for monolithic +20% Rsa]		Heatsink Rsa max min	
Duct Fill		Rsa max bonded	0.065
Heatsink cross section mm^2	4631	Rsa min bonded	0.050
Board cross section chips +pcb	2200	thermal resistance change	0.015
Number of boards per sub rack	8	board assy cross section mm^2	6831
		total cross section mm^2 [nominal 8 bds]	54648
Pressure loss measured Pa	140		
Constants			
Specific heat Air Cp kJ/kg.K	1.005		
Watthour to kJ	0.278		
C0 curve fit Temp K	288.16		
C1 curve fit altitude m	18000		
C2 curve density kg/m^3	1.2255	C4 volumetric heat constant	3.91

Results

The spreadsheet was originally written in an attempt to determine the HVAC requirements of the correlator at the altitude of the VLA site, and to determine the junction temperatures of the digital filter FPGAs and correlator ASICs under conditions different from those tested in the thermal mock up.

Using the spreadsheet it can be shown that the junction temperatures of both the Correlator ASIC and FPGA chips can be maintained at temperatures below 45 °C [the design goal].

With this goal in mind, variables have been entered to show the range of air temperatures and flows possible in a baseline rack populated by 16 Baseline boards at 3.5W/chip.

Inlet temperature	Fanspeed	Junction temp	Exhaust air temp
13 °C	85% [~1800 CFM]	44.2 ° C	24.1 ° C
10 °C	70% [~1500 CFM]	44.8 ° C	23.5 ° C

To demonstrate the effects of altitude, the same power levels are shown as if dissipated at sea level. This will be the case at Jodrell Bank [60 m].

Inlet temperature	Fanspeed	Junction temp	Exhaust air temp
16 °C	70% [~1500 CFM]	44.8 ° C	26.5 ° C
13 °C	57% [~1200 CFM]	44.7 ° C	25.8 ° C

While only a model, the spreadsheet does give results very close to measured experimental results. When the test results conducted at DRAO on the thermal mock up are entered into the spreadsheet, the error was within 5%.

Using the spreadsheet, operating temperatures can be modeled for different power levels, flows, and fan fault conditions. Different heatsink types can be assessed and alternate cooling paths, e.g. thermal vias, evaluated.

It should be noted that the correlator chips are expected to run at different temperatures, dependant on their location. The temperatures returned are the maximum temperatures on the top row of chips located in the upper subrack. This accounts for only 1/16 of all correlator chips, the remainder will run cooler, by as much as 15 °C.

Glossary

VHC. –Volumetric heat capacity, describes the ability of a given volume of a substance to store heat while undergoing a given temperature change, but without undergoing a phase change. It is different from specific heat capacity in that the VHC depends on the volume of the material, while the specific heat is based on the mass of the material. If given a specific heat value of a substance, one can convert it to the VHC by multiplying the specific heat by the density of the substance. VHC is referred to as advective cooling in aerospace literature.

NTP – Normal Temperature and Pressure, is defined as air at 20°C (293.15 K) and 1 atm 101.325 kPa and density 1.204 kg/m^3. NTP are the conditions used for testing and documentation of fan capacities.

ISA – International Standard Atmosphere is defined as 101.325 kPa, 15C and 0% humidity. It is the reference value of temperature and density used in the air density calculation. Note. The discrepancy between NTP and ISA reference temperatures is ignored in the calculation, as the change in density associated is negligible.

P – Refered to as 'power dissipated' in the context of this document. Called P_{chip} and P_s in thermal calculations. Note. Q – Thermal transfer rate, is the term conventionally used in electronic cooling calculations and the reference documents.

s – [heat]sink

ASIC – Application Specific Integrated Circuit. –Used for the correlator chips – located on the Baseline board.

FPGA – Field Programmable Gate Array. – Used for the FIR Digital filter chips – located on the Station board.

PCB – Printed Circuit Board

R $_{sa}$ – Thermal resistance of the heatsink, also referred to as Rsa in the spreadsheet due to font limitations. R_{sa} is the term used by heatsink manufacturers.

k – Volumetric heat constant, called C4 in the spreadsheet.

Die – Also referred to as Junction . It is assumed they are at the same temperature.

T_a – Local ambient temperature. HVAC Supply temperature could be considered ambient but is called Inlet temperature. Local ambient refers to different temperatures within the rack temperature gradient and is dependant on which heatsink is being referred to. It is the effective supply air temperature to the heatsink.

References.

[1] Volumetric Heat Capacity -CRC [rubber book] also,

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[3] R-Theta corp. Application notes.