Analysis, Simulation and Design of Cryogenic Systems for ALMA Band 5 Prototype Cartridge

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Abstract—**The ALMA frontend is designed for ten separate receivers channels covering 30-960 GHz range; the receiver accommodates these receiver channels as pluggable, fully electrically autonomous cartridges. These cartridges share the same cryogenic cooler. ALMA Band 5 cartridge is a dual-polarization heterodyne receiver employing 2SB SIS mixers with IF band 4-8 GHz and covers the frequency 163-211 GHz. The prototype for the ALMA Band 5 cartridge development is carried out by Group for Advanced Receiver Development (GARD) in Gothenburg, Sweden with the aim to provide six Band 5 cartridges for ALMA Project. The first prototype cartridge is currently being assembled. ALMA Band 5 cartridge is the lowest frequency channel in the ALMA receiver that employs all cold optics and thus has the biggest rim of the mirrors amongst other ALMA bands placed on the 4K cartridge plate. The size of the optics and its supporting brackets puts severe constrains on the design of the receiver. Another important issue of the Band 5 cartridge design, as well as other ALMA cartridges, is a very tight thermal budget. In this report, we present analysis and simulation results for the thermal and mechanical design of the ALMA Band 5 cartridge that has been carried out using different FEM software packages such as CFDesign and ANSYS. We compare simulation results obtained with these software and the analytical calculations. For the mechanical design, the major focus was put on the cartridge and the optics support structure deformation with cooling.**

Index Terms— **ALMA frontend, receiver cartridge, cryogenics, mechanical stress, thermal contraction.**

I. INTRODUCTION

ALMA, the Atacama Large Millimeter/submillimeter Array [1], is an international collaboration between Europe, Japan and North America in cooperation with Chile. ALAM is located at Llano de Chajnantor in the Atacama Desert in northern Chile, 5000 meters above sea level. The array will consist of 50 moveable antennas of 12 meter in diameter and twelve 7-meters diameter antennas. The ALMA receivers will cover the range from 30 GHz and 960 GHz

there ALMA Band 5 receiver cartridge is designed for a frequency range of 163-211 GHz. The prototype cartridge is currently being assembled at GARD's facilities with an intension to supply the ALMA project with six Band 5 cartridges. The basic cartridge structure is built upon a modular approach where the base plate has an operating temperature of 300K followed by 110K, 15K and 4K stages. These are separated by G10 fiberglass tubes for thermal insulation. The blank cartridge structure is designed and manufactured within the ALMA project by Rutherford Appleton Laboratories (RAL).

The major challenge for the cryogenic and mechanical design of the ALMA Band 5 cartridge is the thermal contraction that the structure experience under cooling to these cryogenic temperatures. The optics, which is located at the top of the cartridge, experiences the same thermal contraction and deformation.

II. THERMAL DEFORMATION

We consider deformation of the ALMA Band 5 cartridge as an effect of its cooling down to 4 Kelvin. This gives different degree of the thermal contraction inside the cartridge due to difference in thermal expansion coefficient of the materials. Therefore the internal cartridge parts, such as IF-cables and LO-waveguides, must include some margins to avoid excessive mechanical stress and are shaped with bends for this purpose.

The thermal stages of the Band 5 cartridge are made off different materials such as stainless steel as the bottom, 300 K, aluminum at the 110K stage and copper at both 15K and 4K stages. The optics structure is built of aluminum alloys (EN7075 and ALCA5), because of added weight limitation and good mechanical properties of the aluminum. This allows meeting the 2 kg limit of the added mass at cold stages [2]. The chosen aluminum alloys have reasonable thermal conductivity at cryogenic temperatures and provide cooling of the mixer assembly.

A. Thermal deformation of cartridge and waveguides

Thermal deformation is given by the equation

$$d = L \cdot \int_{T_1}^{T_2} \alpha(T) \cdot dT \qquad (1)$$

where α is the instantaneous coefficient of the thermal

expansion and L is the length of the object under consideration. The simulation program ANSYS is using a similar approach though with some modification.

ANSYS is using secant or average thermal coefficient of expansion (CTE). The thermal strain has the following formula;

$$\varepsilon^{th} = \alpha^{se}(T)*(T - T_{ref}) \qquad (2)$$

where $\alpha^{se}(T)$ is temperature-dependent secant coefficient of thermal expansion and T_{ref} is the temperature at which thermal strain is zero [3]. The CTE data is often available from the material vendor in units of instantaneous CTE. For that, it was needed to be converted to secant form and converted to effective thermal coefficient of expansion. Fig 1 shows the difference between the instantaneous, secant and effective CTE.
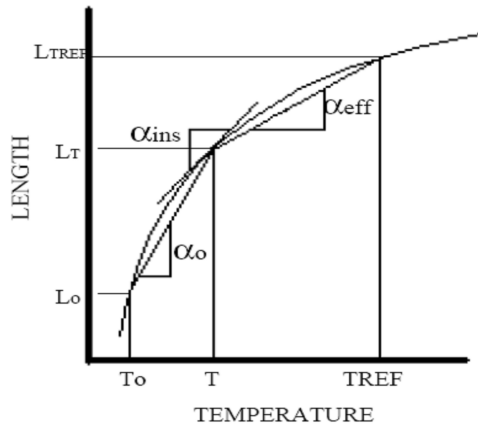

Fig. 1. Instantaneous (α_{ins}), Secant (α_0) and effective (α_{eff}) CTE [4]

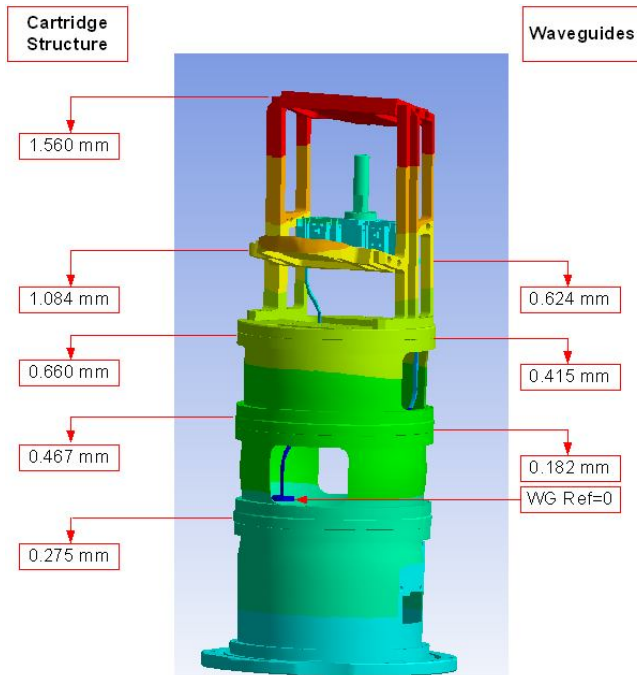The thermal deformation of the cartridge body and the LO waveguides is given in Fig 2.

Fig 2. The cartridge structure and LO waveguides thermal deformation.

The simulation using ANSYS gives the cartridge body deformation of 0.660 mm, Fig.2, which is close to the deformation reported for Band 4 by National Astronomical Observatory of Japan (NAOJ), where the obtained deformation value of the cartridge structure is 0.5 mm against the 300 K base plate [5]. Overall Band 5 cartridge linear contraction including the optics is 1.56 mm and is quite consistent with the analytically (with simplification assumptions on the analyzed geometry) calculated value of 1.408 mm.

B. Thermal deformation of the optics structure

The thermal deformation of the optics was investigated with current design employing the guiding pins of Ø 1.5 and Ø4 mm and M4 screws attaching optics support brackets to the 4K plate, Fig 3.
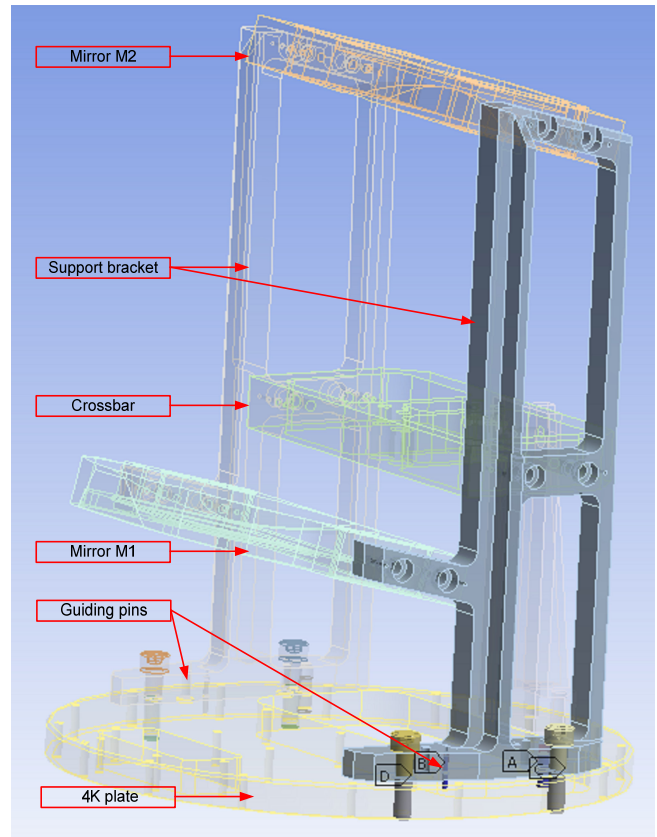

Fig 3. The optics structure with screws and pins attached to the 4K plate.

The major interest for this simulation was concerning the pins and screws deformation under cooling down to 4K as the cartridge 4K plate is made off copper whereas the Band 5 optics employs aluminum allows. The idea was to find out if the pins and screws could hold the optics structure at the required position with respect to the 4K plate. The obtained deformation shows a maximum displacement of the screw and pins of 5-10 micrometer whereas the optics thermal contraction has a maximum of 0.8 mm vertically and 0.3 mm in direction parallel to the 4 K plate. The thermal contraction was taken into account by applying scaling coefficient to the

nominal optics design.

CFDesign Heat Flow Variation (mW)	3	3-7	1

III.   COMPARISSON BETWEEN ANSYS AND CFDESIGN RESULTS

The study of the ALMA band 5 designs was carried out via comparative simulation using the two different specialized software packages, ANSYS [6] and CFDesign [7]. Both employ finite element method (FEM) and can be integrated with Inventor CAD software [8]. Comparison of the both packages was made by simulation of the same model structure, e.g., for the heat flow through UT-085B stainless steel coaxial cables and WR-10 stainless steel waveguide. The coaxial cable was simulated as a 3-layer structure (stainless steel, teflon, brass). The temperature dependence of the physical properties was implemented into the simulation as well. Fig 4 shows the deviation for the simulated heat flow through UT-085B-SS between different pairs of temperature ports: 300K and 110K, 110K and 15K, 15K and 4K. Optimization routine for the length as a compromise between RF losses and heat flow was provided for every temperature stage. The zero level represents analytically calculated value whereas the patterned lines show deviation of the simulated values obtained from simulations by ANSYS and CFDesign.
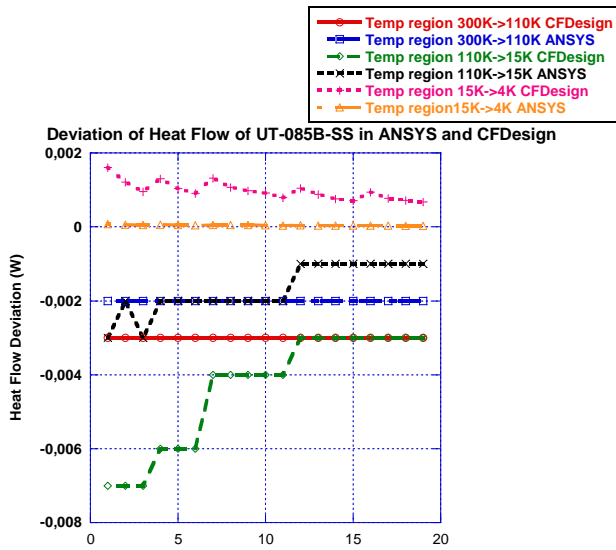
The results of the simulations presented in the TABLE 1 show that ANSYS simulations apparently provide a better fit with the theoretical values giving ANSYS a clear advantage over CFDesign for the simulation of the thermal flow. Nevertheless it should be noted that CFDesign has the advantage of the using of a polynomial interpolation for the material thermal conductivity while ANSYS only has the option for piecewise linear interpolation.

The result is presented in Fig 5a, b and TABLE 2 show the simulation results for the waveguides, following the same approach.
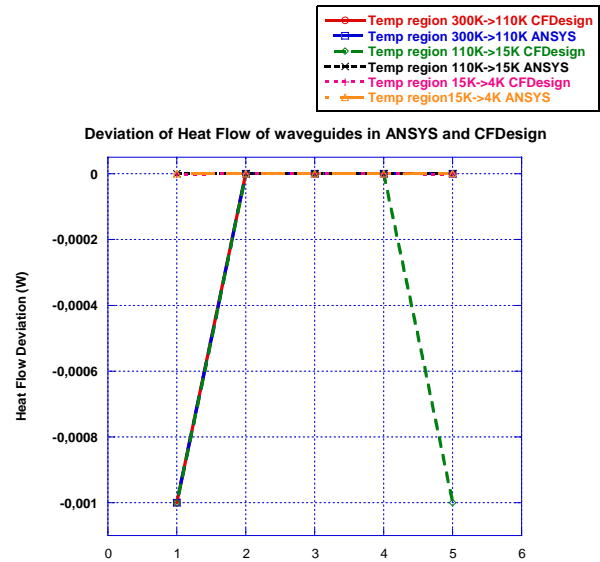

Fig 5a.   Heat flow variation of waveguides with ANSYS and CFDesign compared with analytically obtained values.

Fig 4. Heat Flow variation of coaxial cable UT-085B-SS with ANSYS and CFDesign compared with analyical values

The numbers along the x-axis correspond to the various cable lengths that were studied.

TABLE 1. DEVIATION OF HEAT FLOW POWER OF UT-085B-SS WITH SIMULATED VALUES IN ANSYS AND CFDESIGN SUBTRACTED WITH ANALYTICALLY OBTAINED VALUES.

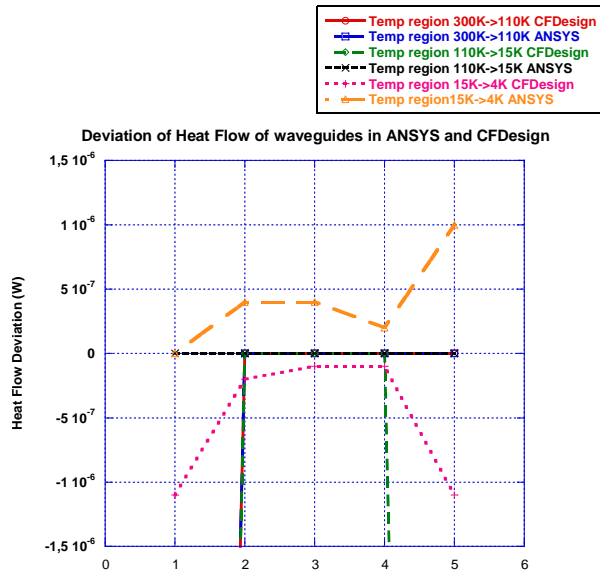| Simulation packages	Temperatures 300K->110K	Temperatures 110K->15K	Temperatures 115->4K
ANSYS Heat Flow Variation (mW)	2	1-3	0.03-0.07

Fig 5b.   Heat flow variation of waveguides with ANSYS and CFDesign compared with analytically obtained values (zoomed in)

For the waveguides, no major difference has been observed

between the simulation programs. This might be because the waveguides do consist of the single material, *i.e.*, stainless steel. Consequently, no errors could be accumulated due to the heat flow passing through different materials, as in the case of the coaxial cables UT-085B-SS.

TABLE 2. DEVIATION OF HEAT FLOW POWER OF WAVEGUIDES WITH SIMULATED VALUES IN ANSYS AND CFDESIGN SUBTRACTED WITH ANALYTICALLY OBTAINED VALUES

Simulation packages	Temperatures 300K->110K	Temperatures 110K->15K	Temperatures 15->4K
ANSYS Heat Flow Variation (mW)	1	0	Max 0.001
CFDesign Heat Flow Variation (mW)	1	1	Max 0.001

IV. CONCLUSION

ALMA Band 5 cartridge and its optical structure have been simulated for thermal deformation caused by cooling down to 4K. Comparison with ALMA Band 4 data shows good agreement for the vertical contraction of the cartridge body of 0.66 mm.. Both tested software packages ANSYS and CFDesign shows acceptable results whereas ANSYS gives more accurate result in comparison with the analytical values, with the CFDesign having an advantage of more convenient material properties setting.

REFERENCES

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[8] Autodesk Inventor 3D software; from AutoDesck Inc., *http://www.autodesk.com/*