# Revisiting the ALMA Band 1 Optics Design

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*Abstract***— In this paper, we revisit the optics design for the ALMA Band 1 cartridge as presented previously by M. Carter and report on progress made towards that end. Since the layout of the ALMA cartridges is not optimised for the lowest frequency band, certain design trade-offs must be made; most importantly the use of a re-focusing lens is required to avoid blocking other bands and the ALMA calibration device assembly. Furthermore, we are motivated to analyse the optics design because close to half of the receiver noise budget is consumed by the optics, mostly due to truncation, reflection, and dielectric loss of the lens and infrared filters. Any small improvement in the optics is worthwhile as its contribution is cascaded through the receiver. Also of significance, the antenna and cryostat layout has changed since the original reports and that related to Band 1 must be clarified and updated.**

## I. Introduction

The Atacama Large Millimetre Array (ALMA) will be the largest millimetre and sub-millimetre radio telescope in the world. It is under construction in the Altiplano region of northern Chile, specifically in the Chajnantor Plateau. This is an extremely dry site at 5000 m altitude. Consequently it is one of the best sites on earth for the measurement of millimetre/sub-millimetre radiation from astronomical sources. ALMA combines an array of 66 antennas designed for continuum and spectroscopic measurements of the early Universe. It will also reveal new information about the birth of stars, planets, and galaxy formations with an angular resolution accuracy of 1". Moreover, it will provide high sensitive and precision imaging between 30 and 950 GHz in 10 bands at the Southern Hemisphere.

Each telescope will have a common cryostat that was specially designed to house all ten receiver bands. The dimensions of this cryostat are 0.97 m in diameter and a 0.62 m in height. Each receiver are designed to measure total power and dual linear polarization state of the received signal at a given frequency. They will be built in a cylindrical structure called *cartridge* which is divided in three section-levels cooled down to 4, 15 and 110 K, respectively. This telescope will be fully functional in about 2012. ALMA Band 1 will offer many unique scientific research capabilities related to the field of radio astronomical observation for low centimeter wavelength ranges. There are several important radio astronomical studies that can be made at this frequency band. Among them, the most interesting ones are the Cosmic Microwave Background radiation (CMB) anisotropies studies, high-resolution Sunyaev-Zel'dovich (SZ) effect imaging of cluster gas at all redshifts, gravitational lenses survey and monitoring, and mapping the cold Inter Stellar Media (ISM) matter at intermediate and high redshift.

The aim of paper is to provide information about the different aspects that involve the design, optimization and construction of a suitable optical system for the 31-to-45GHz receiver that will be part of the prototype receiver for Band 1 of ALMA. Three optical layouts will be presented: (1) a single HDPE lens that also acts as vacuum window – this is the original configuration**[1,2]**, (2) two lenses forming a Gaussian beam telescope where the first lens is cooled, and (3) a single room temperature lens, but using a separate thinner vacuum window, giving more freedom to the choice of material for the lens. In each scenario, the feed is represented as an optimum gain horn and first-order Gaussian beam analysis, i.e., quasioptics, has been used to model the system. Each system is optimized for frequency independent illumination of the secondary and aperture efficiency, and then put into context through a comparison of the predicted receiver noise. Focus efficiency has been placed at a lower priority since it is assumed that the secondary can be refocused.

Progress on component development, including a comparison of different feedhorn designs and modelling will be summarised. There is also considerable interest in either extending or shifting the existing frequency range of 31-45 GHz towards 50 GHz, and consideration of the impact concerning the optics will be provided.

## II. Optical Design

We started our work rechecking and updating some of the antenna and cryostat layout dimensions presented in [1] and **[2]** for the ALMA Band 1 optics. Our work continued with finding an optimum gain horn design that fit the ALMA cassegrain antenna specifications between 31 to 45 GHz frequency band. Once this was achieved, we proceeded to analyse the Gaussian beam propagation **[3]** between the horn and the antenna subreflector at those frequencies, using a thin lens approximation optical design. When a -12.3dB edge taper (this value gives the best ALMA antenna aperture efficiency for our quasioptical system design) for a frequency independent illumination at the subreflector were achieved in the simulations (i.e. when the Gaussian beam radius at the sub reflector is constant at any frequency) then we retrieved from the optimizations result the values of the lens focal distance, its separation from the horn, and the beam radius of the propagating beam between the lens and the subreflector. Thereby, the lens thickness was derived using a bi-hyperbolic lens design, which preserve the face of the propagating beam **[3]** when pass through the lens. Finally, the total noise contribution of the optics was estimated for each one of the proposed optical configuration.

### A. *Optical layout dimensions*

In this section we present the final layout location and dimension of the different optical parameters for this band. Those values are of importance when estimating the truncation losses and the edge tapper of the receiving signal when using quasioptical beam analysis. In Table 1 are summarized the most relevant optical parameters that we used in all our different simulations.

TABLE 1
BAND 1 UPDATED OPTICAL DIMENSIONS

| **PARAMETER** | **VALUE** |
|---|---|
| Distance dewar top center to subreflector rim center | 5.99380 m |
| Distance dewar top center to subreflector apex | 5.88287 m |
| Angle horn to subreflector apex | 2.48 deg. |
| Optimal horn z-distance to dewar top | 93 mm |
| Optimal horn x,y-distance to dewar center | 263.6 mm |
| 15 K and 110 K stage z-distance to dewar top | 83 mm, 51 mm |
| 15 K and 110 K stage clearance aperture diameter | 40 mm, 60 mm |
| Dewar-top hole clearance diameter | 110 mm |

### B. *The Feedhorn*

Figure 1 shows two different horn profile geometries that we studied. The first horn design was proposed by M. Carter **[4]**. In the same figure a similar horn geometry but with a simpler corrugation design is presented. This corresponds to our own horn design, which was developed using the concepts from reference **[5].** Its final geometry was optimized using Ansoft HFSS electromagnetic software **[6]**. Both have the same aperture diameter and total length, but horn 1 has a variable pitch-to-width ratio while for the second horn this parameter is constant.

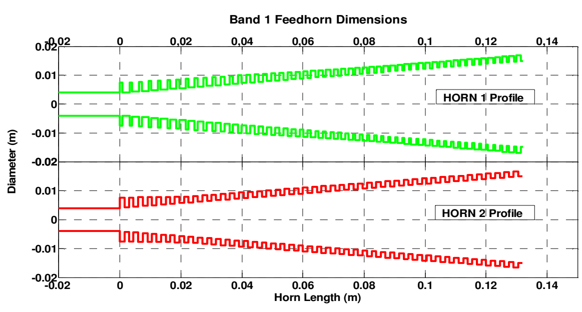


Fig. 1 Corrugated horn 1and 2 geometries.

### C. *Bi-Hyperbolic Lens Design*

An important part of the work was to use different dielectric materials in the simulations to find the one that minimizes the lens thickness and therefore the dielectric losses of the same. Table 1 presents the material properties used for the different investigated optical layout configurations and their optical components. The IR-filters dimensions and properties are also included in this table. Those filters have already being designed by the IRAM for all the ALMA receiver bands **[7]**.

TABLE 2
OPTICAL COMPONENT DIELECTRIC PROPERTIES

| **Dielectric Material for:** | **Material** | **Souranding Temp. (K)** | **Refractive index n** | **Tan loss (e-004)** |
|---|---|---|---|---|
| Lens: | HDPE* | 300, 15 | 1.5259 | 2.73 |
| | Quartz* | 300 | 2.1056 | 0.45 |
| | Silicon* | 300 | 3.4165 | 4.00 |
| Vac.Window: | Quartz* | 300 | 2.1056 | 0.45 |
| IR Filter: | SolidPTFE | 110 | 1.5000 | 3.00 |
| | Gore-Tex | 15 | 1.2000 | 2.00 |

* Refractive index and tan-loss values where averaged from well know experimental measured data taken from **[3]** and **[8]**.

### D. *Studied Optical Configurations*

The technical specifications of the ALMA Band 1 cartridge and cryostat design are presented in **[2]** and **[9].** In both documents is stated that the use of a re-focusing lens device is required to avoid blocking the other receiver bands. That lens will be located between the top of the dewar and the antenna calibration system assembly. Since in the ALMA antennas there will not be moving optical parts, besides the subreflector, the design of the all the ALMA bands optical setups must be frequency independent (i.e. the illumination at the subreflector must approximately be constant for all wavelengths). Thus the antenna efficiency will be maximized. According to **[10]**, the edge taper must be of about 12.3 dB. The studied optical system configuration that we present in this paper consisted in 3 single lens system layouts and a 2-lens optical system. The details of those layouts are the following:

**1) Optical layout 1**: In this configuration a single HDPE lens at 300 K was used. The lens optimal simulation result gave us a diameter was of 20 cm and the total thickness was 5.72 cm. The single lens used here acts also as a vacuum window.

**2) Optical layout 2:** Two HDPE lens system. A small one placed inside the cryostat 15 K stage, and the second one locate between the top of the dewar and the ALMA calibrator device at 300 K.

**3) Optical layout 3:** As in the first optical layout, this system also uses a single lens at 300 K but now we assume that this is made of quartz instead. A quartz vacuum window is also used at the top of the dewar.

**4) Optical layout 3:** Here, the quartz lens used in the previous layout was replaced with a silicon lens design. It also has a quartz vacuum window at 300 K.

## III. Simulation Results

### *A. Horn Radiation and Phase Patterns*

In Figure 2 the simulated radiation pattern performances for horn 1 and horn 2 at 38 and 50 GHz are shown. Figure 3 shows their respective return losses from 30 GHz up to 50 GHz.

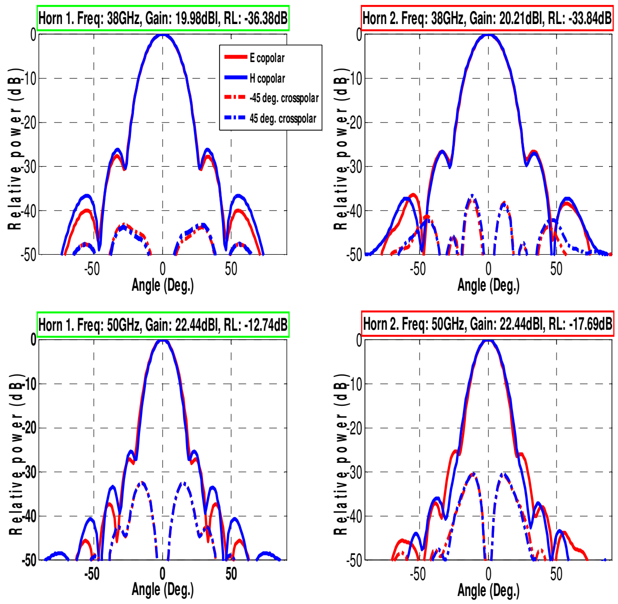


Fig. 2 CST **[11]** and HFSS simulated radiation patterns of the corrugated conical horn 1 and 2, at 38 and 50 GHz.

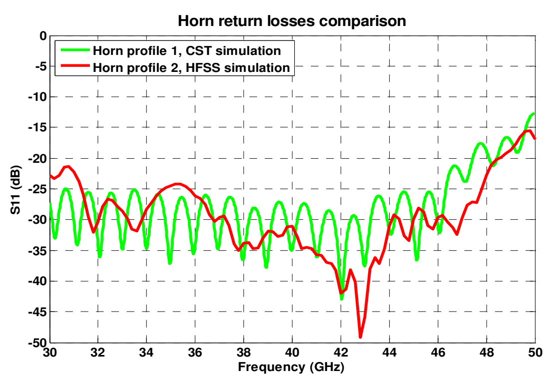


Fig. 3 Simulated return loss for the corrugated conical horn 1 and 2 between 30 to 50 GHz

The simulated radiation patterns and return losses results shows that horn 1 and 2 haves very similar shapes. Although, the cross-polarization levels of horn number 1 are better than the ones obtained with the second horn. Figure 3 shows the far-field phase pattern of horn 1 at different frequencies.

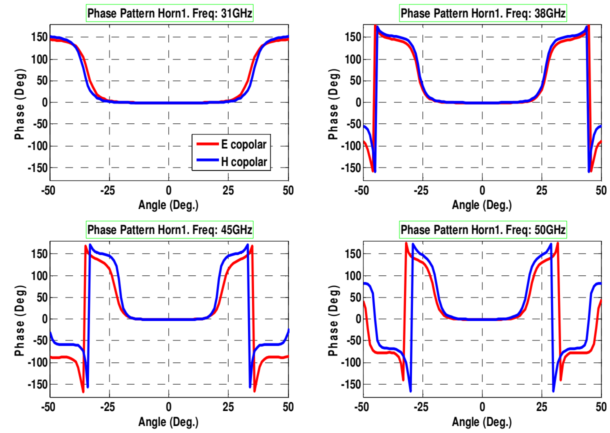


Fig. 4 CST Microwave Studio Simulated far-field phase patterns for the corrugated conical Horn 1 at 31.1, 38, 45, and 50 GHz.

### *B. Quasioptical Beam Analysis*

Quasi-optics analysis of ALMA Band 1 system was carried out using thin lens approximation for the focusing elements. Further on, in this design we optimized very carefully the system total gain and its total noise contribution, taking into account the lens dimensions, its refractive index, thickness, focal distance, and as well as the IR filters dimensions, and material properties. The final simulation results were based on the horn 1 design presented in this paper and the geometry of the ALMA Cassegrain antenna, which details can be found in **[2]**. The final simulated results for the 4 different layouts are presented in Table 3. In Figure 3 the Gaussian beam propagation of the fundamental mode for the optical layout 1 is shown at 31.3, 38, and 45 GHz.

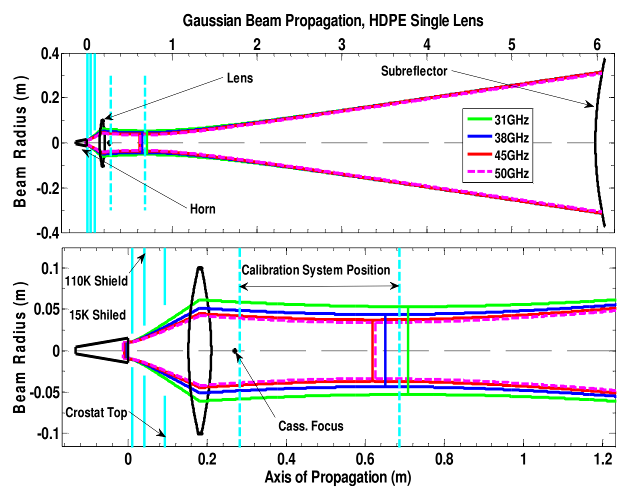


Fig. 5 Gaussian beam propagation between the horn and the antenna subreflector (top) and a magnified view of the same closed to the horn-lens part (bottom).

TABLE 3
BAND 1OPTICAL PARAMETERS FOR THE DIFFERENT LAYOUTS

| | Layout 1 | Layout 2 | Layout 3 | Layout 4 |
|---|---|---|---|---|
| **Lens 1.** | | | | |
| Material: | HDPE | HDPE | Quartz | Silicon |
| Distance to horn [m]: | 0.1812 | 0.2620 | 0.1812 | 0.1812 |
| Focal length [m]: | 0.1750 | 0.1778 | 0.1750 | 0.1750 |
| Diameter [m]: | 0.2000 | 0.2076 | 0.2000 | 0.2000 |
| Thickness [m]: | 0.0578 | 0.0598 | 0.0325 | 0.0194 |
| **Vacuum Window.** | | | | |
| Material: | None | None | Quartz | Quartz |
| Distance to horn [m]: | | | 0.0930 | 0.0930 |
| Diameter [m]: | | | 0.1100 | 0.1100 |
| Thickness [m]: | | | 0.00065 | 0.00065 |
| **Lens2.** | | | | |
| Material: | None | HDPE | None | None |
| Distance to horn [m]: | | 0.0700 | | |
| Focal length [m]: | | 0.0382 | | |
| Diameter [m]: | | 0.0782 | | |
| Thickness [m]: | | 0.0379 | | |
| **Edge Taper [dB].** | | | | |
| 31GHz | -12.32 | -12.43 | -12.32 | -12.32 |
| 38GHz | -12.33 | -12.51 | -12.33 | -12.33 |
| 45GHz | -12.34 | -12.58 | -12.34 | -12.34 |
| 50GHz | -12.35 | | -12.35 | -12.35 |

## E. *Total Gain and Noise Estimations*

After optimizing the illumination efficiency of each one of the optical system layouts, we estimated the total noise contribution of each one optical layout configurations. The gain and noise contribution related to the beam truncations, dielectric losses, and reflection losses of the lens and IR-Filters were included in the overall noise calculations. Truncation and reflection termination temperatures were taken as average of both sides. The reflection losses in the lenses and IR-filters were modelled assuming perfect surface matching. Therefore those losses were estimated to be of about -20 dB for the lens cases and-25 dB for the IR-filters. Focus efficiency of the antenna has been placed at a lower priority since it is assumed that the secondary can be refocused. Figure 6 shows the total optic noise contributions estimated for each one of the systems.

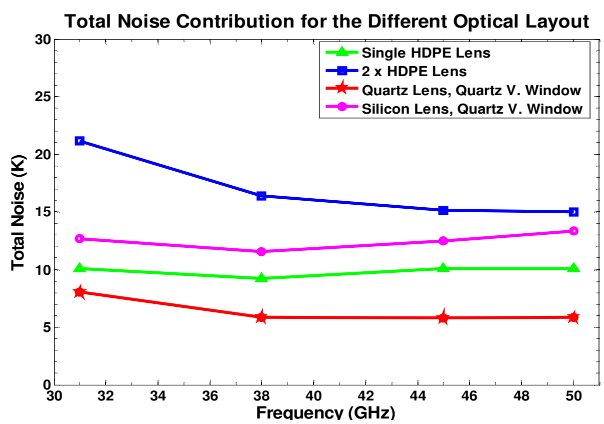


Fig. 6 Total noise estimation of the 4 different studied optical layouts.

Layout 3 (quartz lens + quartz vacuum window) provides the lowest system noise contribution. From the practical and economic point of view, layout 1 (single HDPE lens design) is a more competitive system since it is easier to construct with a CNC machine.

## F. *Surface matching of the lens*

The lens reflection losses were modeled with CST Microwave Studio **[11]** using straight grooves and hole patterns. According to the preliminary results, a hole pattern gives the same performance for both linear polarisations. The simulation results of straight grooves surface matching is presented in Figure 7, while Figure 8 shows the results of the lens hole patterns surface matching. Their corresponding profiles geometries are shown in Figure 8.

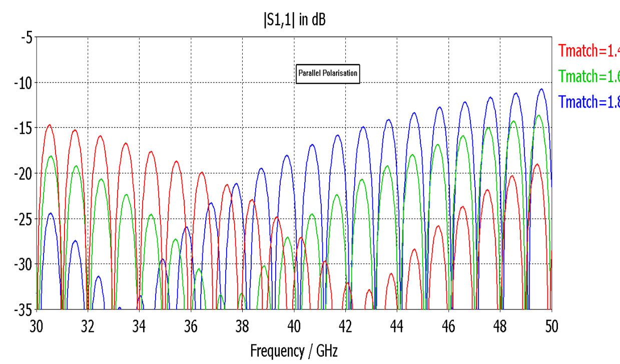


Fig. 7 Straight grooves surface matching between 30 to 50 GHz.

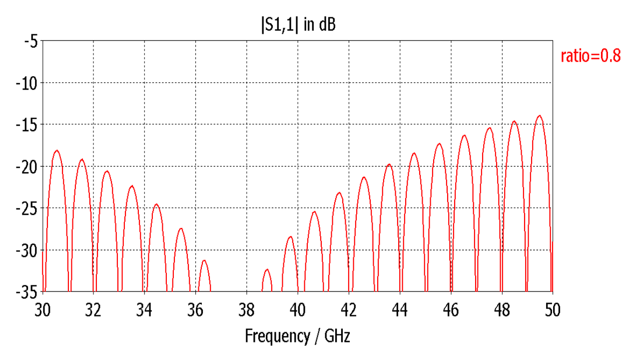


Fig. 8 Hole patterns surface matching between 30 to 50 GHz

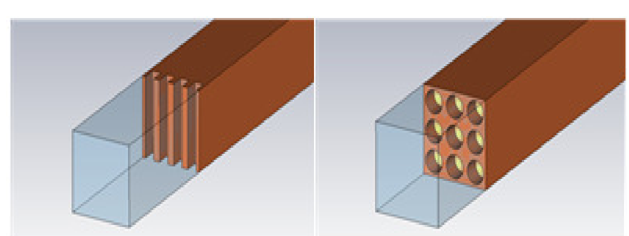

Fig. 8 Straight groove and hole pattern profile geometries.

## IV. CONCLUSIONS AND FUTURE WORK

We have found that the dimensions of the optical parameters as proposed in the ALMA project book were not completely correct. When comparing the horn simulation results designed by M. Carter with our own simpler horn design, we found that both designs have rather similar characteristics although Carter's have slight better cross polarization. The quartz lens optical design (layout 3) gave the best noise performance of all the 4 different optical configuration layouts presented in this paper. However, the single HDPE lens design, originally proposed by ALMA, continues to provide a good noise performance given the layout constraints of the cryostat. Moreover, the main advantage of using a HPDE lens with an antireflection surface matching (e.g. with a machined hole pattern geometry) is that it is easier and less expensive to construct using a CNC lathe machine than using a lens made of quartz.

Before constructing and testing the HDPE lens or the quartz lens, a physical optics analysis of both configurations will be completed using Zemax. This will help to optimize the final shape and optical parameters of the lens. Also, the first horn prototype is being constructed now and will be tested soon.

## ACKNOWLEDGMENT

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