Design of the optical system for ALMA Band 1

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ABSTRACT

This work presents a complete study of the optical system for ALMA band 1, which covers the frequency range from 35 to 50 GHz, with the goal of extending the coverage up to 52GHz. Several options have been explored to comply with the stringent technical specifications, restrictions, and cost constraints. The best solution consists of a corrugated zoned lens, two infrared filters and a spline profiled corrugated horn. The calculated aperture efficiency is better than 75%, while the average noise contribution is lower than 10.3 K. The first prototypes of the system have been constructed and first evaluation results available

Keywords: ALMA, band 1, optics, spline-profile horn, lens, noise temperature, efficiency.

1. INTRODUCTION

The Atacama Large Millimeter Array (ALMA) is the largest millimeter and submillimeter radio telescope in the world. It consists of 66 classical Cassegrain antennas with diameters of 7 and 12 m, divided in two subarrays. It has been constructed in Chile's Atacama Desert at an altitude of 5000 m above sea level. ALMA is providing unprecedented sensitivity and resolution for the study of the origins of the universe; formation of stars, planets and galaxies; and the complex chemistry of the giant clouds of gas and dust [1]. This radio observatory has an operation frequency range between 35–950 GHz divided into 10 bands. Each band has a set of dual linear polarization receivers, one per antenna, that convert the input microwave signals into intermediate frequencies from 4 to 12 GHz. The output signals are then postprocessed to obtain high resolution images using radio interferometric techniques. The quality of the images depends strongly on the noise introduced by the receivers.

In order to minimize this noise, each subsystem has to be optimized, in particular those at the beginning of the chain. Since the receivers' optics are first in the receiver chain of each antenna, achieving good noise temperature and aperture efficiency are fundamental for best sensitivity [2].This paper presents the design and preliminary results of the optical system for the Band 1 receivers of ALMA.

Band 1's optical system combines a series of stringent technical specifications, construction limitationsand cost constraints that require trade-offs with each other. Important specifications are the following. The optical system must cover the frequency range between 35–50 GHz (with the goal of extending the coverage to 35–52 GHz), meet a total aperture efficiency that exceeds 80%, attain an angular alignment of the optical beam within 5 mrad of the nominal direction, and the added noise due to the optics should be close to 10K. The illumination must be frequency independent, thus no mechanical tuning is allowed. If warm optics is present, it cannot interfere with the already-existing common optics of the other bands, the amplitude calibration deviceand Water Vapour Radiometer. Furthermore, the 7 and 12-m antennas use the same front end which leads to different beam tilt angles.

We have performed a comparative study of different alternatives for the ALMA Band 1 optical system using the following approach. First, we studied several optical systems using mode matching and quasioptical techniques. Then, we chose the configuration that achieved the best results and further optimized its components for final manufacturing. Finally, the full system was validated using the finite-element methodandmethod of moments. The proposed solution is currently the baseline design for the final Band 1 production.

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2. OPTICAL DESIGN

Several configurations were explored for the focusing elements and feed horn. We have studied optical systems composed of one warm lens with a separate vacuum window, a single warm lens (acting also as a window), two warm mirrors plus a window, and two lenses (with one cooled lens). Furthermore, we have studied different shapes and materials for the lens. The best performance was obtained for a system consisting of the following elements. A low loss High Density Polyethylene (HDPE)biconvex one-zone Fresnel lens; a thin gore-tex membrane and a grooved surface of Polytetrafluoroethylene (PTFE) as infrared filters at the 15 and 110 K stages; and a compact spline-profile corrugated horn that can be machined from a single block.

2.1 Feed horn design

If a standard corrugated feed horn is used, the resulting narrow flare angle of the horn make it difficult to machine as a single piece; however, the horn may be divided into smaller sections and machined on a lathe as in [3]. In order to shorten the overall length of the feed horn, we propose to use a spline profiled corrugated horn. Therefore, we propose to use a spline profiled corrugated horn. The profile was optimized for achieving the desired performance while constraining it for fabrication as a single piece on a computer-numerical-control (CNC) lathe.

To achieve frequency independent illumination while minimizing truncation through the cryostat's window, a maximum beamwaist of 9.6 mm is required. The characteristics of an ideal Gaussian feed were determined by optimizing a quasioptical model of the Band 1 optics. The profiled horn was then optimized to match the Gaussian feed and achieve low cross-polarization and reflected power. The profile was optimized using a mode-matching software, Microwave Wizard from MICIAN, and a genetic algorithm using the goals shown in Table 1. The main parameters of the resulting horn are shown in Table 2, where only the input waveguide radius was not an optimization parameter. The geometry of the spline-profile corrugated horn is shown in Table 2 and Figure 1.

Table 1: Optimization goals of the profiled feed horn

Frequency [GHz]	**33**	**35**	**38**	**42**	**42.5**	**44**	**47**	**50**	**52**
10 dB point [deg]	19.1	18	16.6	15.4	14.8	14.3	13.4	12.6	12.1
PCL[mm]	5	5.6	6.4	7.7	8.2	10.1	11.2	11.2	12
Crosspolar level [dB]	<-30				<-37				<-30
Reflected power [mm]	<-25				<-30				<-25
Δ 10 dB point [deg]*	<1				<0.3				<1
Δ PCL [mm]*	<2				<1				<2
(*)The difference between the E and H planes									

Table 2: Geometry of the spline-profile corrugated horn

Horn design parameter	Value
Input circular radius (R0)	3.35 mm
Aperture diameter (r31)	31.62 mm
Horn total length	70 mm
Number of corrugations	31
Width of corrugation (C)	0.9
Width of gap (G)	1.22
Depth of gap (Ri – ri)	2.97-1.53 mm

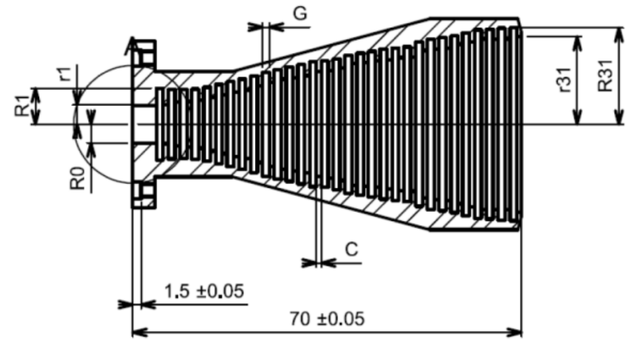

Figure 1: Geometry of the spline-profile corrugated horn

2.2 Design of refocusing elements

2.2.1 Analysis of the different possible options

Single Cold Lens

In order to reduce the noise this was the first option to be studied. A quasioptical analysis shows that to achieve the desired illumination at the subreflector, the refocusing element has to be located above the cryostat top plate. In other words, if the lens is forced to be inside of the cryostat, the beam size at the cryostat aperture exceeds by far the size of the cryostat's window.

Single Warm Lens

In order to optimize the subreflector's illumination with a single warm lens, a quasioptical propagation script was written. The inputs for this script are the beam waist size and position at the horn, while the optimization parameters are the lens position, the focal distance, and the beam radius. It was found that the best results are obtained with a lens located at a distance of 175.2 mm from the horn aperture and a focal length of 172.1 mm. In addition, if we choose an appropriate material, the lens has the advantage of being able to be used as a vacuum window.

Warm and Cold Lenses

A combination of cold and warm lenses was also evaluated. The cold lens was used to obtain a narrower beam to pass the cryostat rim, minimizing the truncation. Accordingly, a warm lens outside of the cryostat was required to obtain the right edge taper on the secondary. The disadvantage of this solution is that the warm lens would still needs to be large, resulting in the same or more signal loss than only a warm lens [3], [4].

Warm Mirrors

The last configuration to be studied was the use of warm mirrors. This configuration has the advantage of producing lower noise contribution than the use of a lens. Moreover, they do not require anti-reflection layers and do not suffer from variations in batch-to-batch material properties, as it is the case for dielectrics. Nevertheless, warm mirrors will require a separate vacuum window, which will need anti-reflection layers. A configuration formed by a standard horn and two warm mirrors was analyzed with a mode matching model. However, it was found that the mirrors would interfere with the robotic arm of the calibration device.

2.2.2 Warm-lens analysis and further optimization

Given the considerations presented above, the warm lens configuration was selected to be further optimized in order to maximize the aperture efficiency and minimize the noise temperature. An important task has been to study the material for the lens design since it will impact the lens thickness and loss. Therefore, a low tangent loss and high dielectric constant are desirable. Furthermore, the lens and the antireflection layer should be easily manufactured. Materials with a high dielectric constant, such as quartz, fused silica and sapphire, require complex antireflection treatment, for instance adding appropriate antireflection layers [5]. Alternatively, a lens and its antireflection layer can be manufactured using plastic materials, such as HDPE and PTFE, through direct CNC machining or injection molds. Since the lens also works as vacuum window, HDPE was chosen over PTFE because it exhibits less creep deformation.

The lens thickness can be reduced using a zoned lens with only one step. By implementing such design, the noise of the optics system can be lowered between 1 and 2 K. Despite the reduction in noise, it can be observed that the use of a zoned lens produces a reduction in efficiency of 0.5% at the lower frequency range.

2.3 Final validation

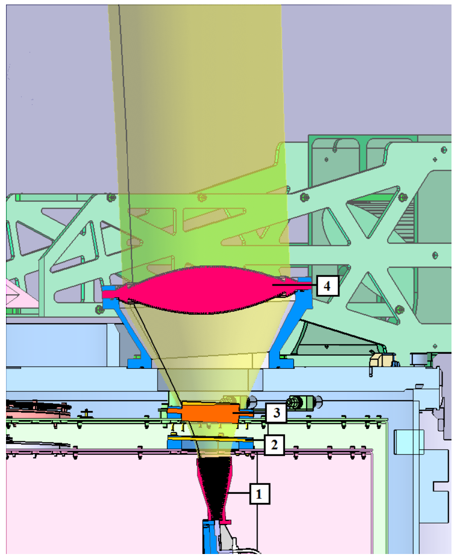

Figure 2: Cross-section of the baseline solution for the Band 1 optics. (1) Spline-profile Feed horn, (2)Gore-tex infrared filter at 15 K, (3) PTFE infrared filter at 110 K, and (4) Biconvex one-zone lens

The full optical system, as shown in Figure 2, was simulated. First, the horn and IR filters were simulated using HFSS, an electromagnetic solver based on the finite-element method. Reflection loss and higher mode orders were studied with a resolution of 50 MHz. The output radiated field was calculated over a near-field sphere with a radius of 175.2 mm, equal to the horn-lens distance. Then, using HFSS-IE (a full-wave integral equation solver), the near-field of the horn and IR filters was used to excite the lens. The resulting output field is then used to calculate the aperture efficiency (including phase, amplitude, cross-polarization, and spill-over efficiencies) assuming an equivalent paraboloid with a diameter equivalent to the secondary diameter and focus equivalent to the resulting telescope focus.

The noise temperature was computed conservativelyconsidering the contribution of each single components, lens, 110 K and 15 K IR filters, as well as truncation in all apertures, including the vertex hole and subreflector spill-over. For the lens and IR filters, the added noise was calculated considering the dielectric losses, truncation and reflections [5]. To estimate truncation losses, multi-mode mode matching simulations were used [5][6]. The reflected power is terminated at a physical temperature equal to the average between the element under analysis and the previous element while inside the cryostat. Truncated power at the vertex hole was terminated at 300 K, while the subreflector spill-over was terminated at 3 K.

2.4 Experiment

In order to characterize the optical system, it has been tested using a vertical planar near-field beam-pattern scanner inside an anechoic chamber [7]. The probe antenna was set in Fresnel zone, and swept an opening equivalent to 40° measuring the near-field co- and cross-polarization patterns.

The near-field was transformed to far-field using a Fast Fourier Transform algorithm [8] and compared with simulation. At the moment of writing, only the horn and 15 K IR filter have been characterized. Final efficiencies and noise temperature results will be confirmed once measurements are completed.

3. RESULTS

3.1 Simulations

3.1.1 Horn

The simulated radiation patterns for the spline-profile corrugated horn at 35, 42.5 and 50 GHz are shown inFigure 3. The patterns exhibit good symmetry down to -20 dB, a cross-polarization level better than -34 dB and side lobes lower than -20 dB. Moreover, the return loss of the horn is lower than -28 dB as shown in Figure 4.

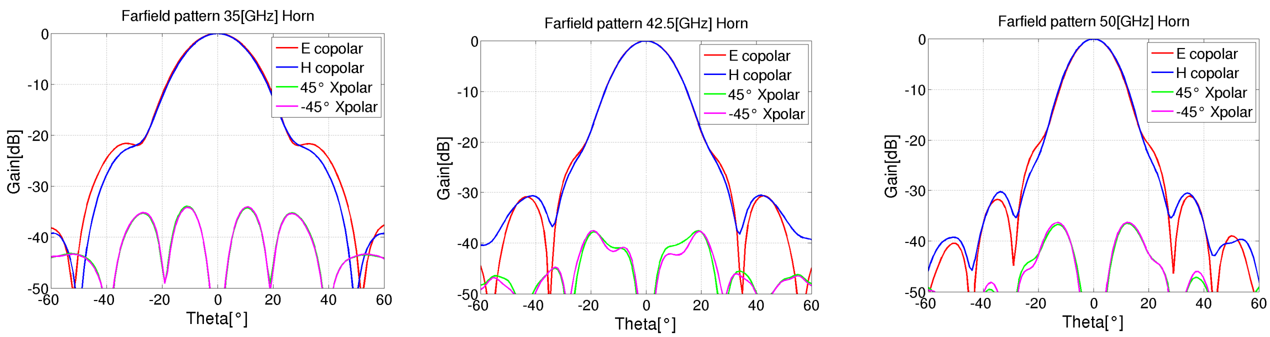

Figure 3: HFSS simulated radiation patterns of the spline-profile corrugated horn at 35, 42.5 and 50 GHz

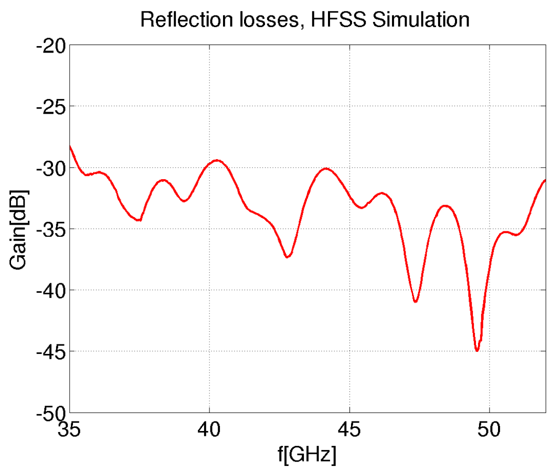

Figure 4: Simulated return loss of the spline-profile corrugated horn

3.1.2 Simulation of the Horn, IR Filters, and Lens Combination

The simulated radiation patterns for the complete optical system at 35, 42.5 and 50 GHz are shown in Figure 5. The patterns exhibit good symmetry to -20 dB, a cross-polarization level better than -22 dB and side lobes lower than -20 dB.

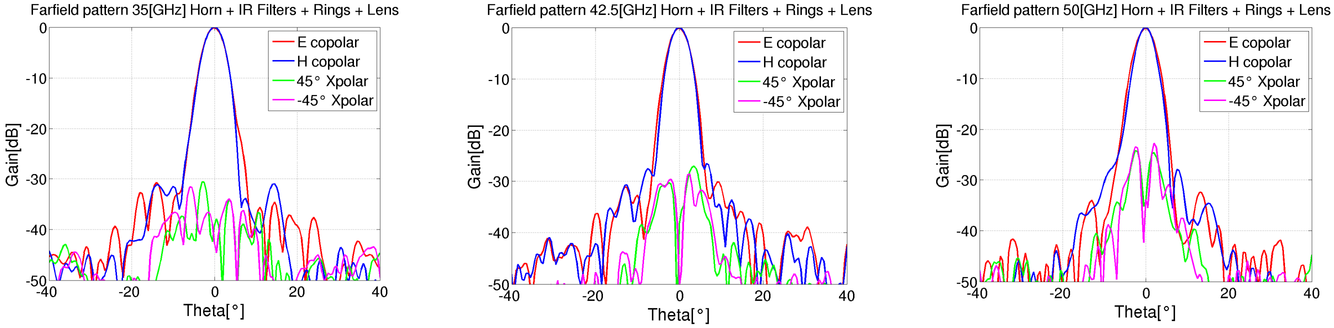

Figure 5: HFSS simulated radiation patterns of the complete optical system at 35, 42.5 and 50 GHz

The aperture efficiency and its components are shown inFigure 6.a. The aperture efficiency for the complete system is between 75% and 79.2%, where the cross-polarization and phase efficiencies are better than 99.5%, the amplitude efficiency is more than 90% and the spillover efficiency is less than 80%. We also compare the efficiencies for the full system and the system without IR filters to show the degradation due to the IR filters. The total noise temperature and the contribution of each single element is shown inFigure 6.b. The total noise is between 9.4 and 11.6 K, where the lens contributes the most to the noise.

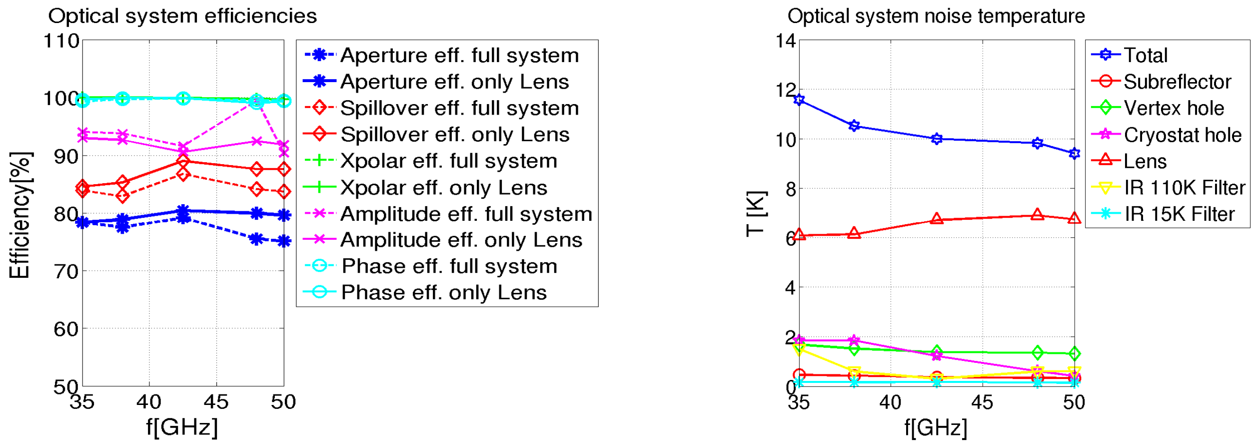

Figure 6: a) HFSS simulated aperture efficiency comparison between the full system (horn, IR filters, and lens)and only horn + Lens from 35 to 50 GHz. b) Noise temperature contribution of each single component from 35 to 50 GHz.

3.2 Measurement results

3.2.1 Horn

The far-field radiation patterns are shown inFigure 7. The copolar measurements are identical to simulation down to -20 dB at all frequencies. The cross-polarization has a maximum difference of 3 dB between the maxima of simulated and measured at 35 GHz.

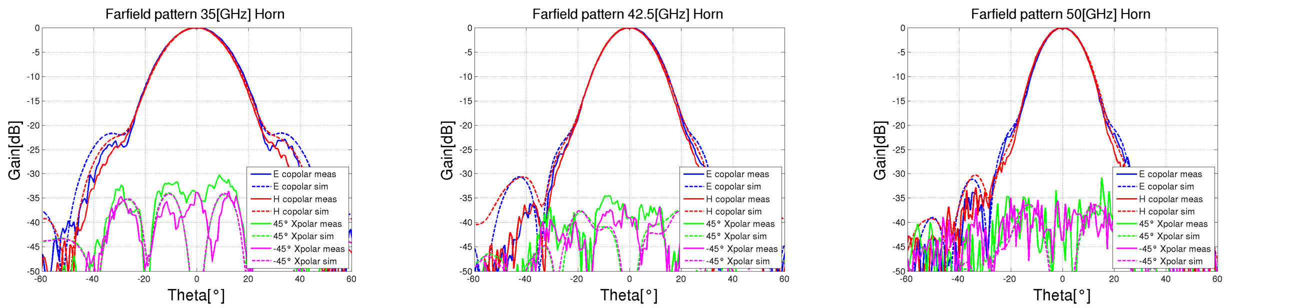

Figure 7: Comparison between simulated and measured radiation patterns of the spline-profile corrugated horn at 35, 42.5 and 50 GHz. Dotted lines correspond to simulation results and straight lines correspond to measurement results.

3.2.2 Measurement of the Horn, 15-K Ring, and 15-K IR Filter Combination

The far-field radiation patterns are shown inFigure 8. The copolar measurements compare well to simulation down to -20 dB across frequency, with maximum differences of 2.5°. The largest difference between the maxima of simulated and measured cross-polarizationis 4 dB.

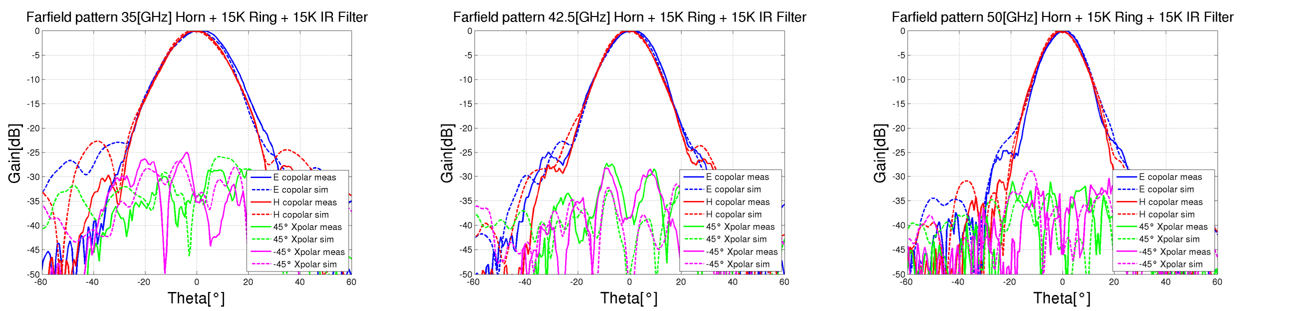

Figure 8: Comparison between HFSS simulated and measured radiation patterns of the horn + IR 15 K filter at 35, 42.5 and 50 GHz.

4. CONCLUSION AND FUTURE WORK

We have presented a complete design of the optical system for ALMA Band 1 that covers the frequency range from 35-50 GHz. The optical system is frequency independent and consists of the following elements. A compact spline-profile corrugated horn, machined from a single block of *duralumin;* a thin *gore-tex* membrane and a grooved surface of *PTFE* as an infrared filter at the 15 and 110-K stages; and a low loss HDPE biconvex one-zone Fresnel lens.Moreover,the warm optics donot interfere with the already-existing common optics or calibration device.

The simulated aperture efficiencies are greater than 75%, slightly lower than the expected, due to truncation and dielectric loss introduced by the filters. It is necessary to mention that the filters have already been constructed and installed in the cryostats. The noise temperature was estimated conservatively, sothe maximum average noise temperature should be less than 10.3 K.

We have successfully constructed a spline-profile corrugated horn. Moreover, the simulation and measurements of radiation patterns agree very well with the HFSS simulations. Final efficiencies and noise temperature results will be confirmed once measurements are completed.

The Band 1 optics design presented throughout this paper is a baseline design. Accordingly, future work may include the effects of the IR filters in the new design in order to improve the efficiency. The first option is to optimize the horn antenna including the degradation of the IR filters. A second option is to optimize the lens to achieve an edge taper nearer to -12.3 dB. The last option is to redesign the IR filter minimizing the truncations.

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