Alternative Optics Design for the ALMA band 1 Receiver (35-52 GHz)

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Abstract**—The Atacama Millimeter/Sub-millimeter Array (ALMA) is one of the most powerful telescopes built to date. All the receivers that cover the 10 frequency bands (35-950 GHz) in ALMA must comply with stringent requirements in order to perform astronomical observations, in particular, low noise temperature and high aperture efficiency. The ALMA band 1 receiver optics (35-52 GHz) are composed of a corrugated horn antenna and a dielectric lens. They have proved difficult to design because of the large bandwidth to cover and truncation effects in cryostat apertures. This paper presents a design which meets the stringent ALMA requirements.**

Index Terms**—Radio astronomy, mm-wave antenna, lens**

I. INTRODUCTION

ALMA [1] is a radio astronomical telescope composed of 66 12-meter and 7-meter Cassegrain reflector antennas located at 5000 meters above sea level in the Atacama Desert in Chile. It has been built by North America, Europe and East Asia in collaboration with Chile. When the telescope is completed, it will observe in all atmospheric windows between 35 and 950 GHz. This large bandwidth has been divided into 10 different bands for practical implementation and all the receivers for each band must comply with stringent specifications. The receiver for the lowest frequency band covered by ALMA, the band 1, is currently under development. Two of the most challenging requirements for this receiver are the aperture efficiency at the secondary mirror and the receiver noise temperature. Both of them depend on the receiver optics.

So far, design efforts have failed to achieve band 1 receiver optics designs which meet ALMA aperture efficiency specifications and show reasonable spillover efficiency and low noise performance. This paper presents the first ALMA compliant designs.

II. ALMA BAND 1 RECEIVER

The ALMA band 1 receiver is a cryogenically-cooled dual-polarization SSB (Single Side Band) receiver for the 35-52 GHz atmospheric window. The receiver is composed of some optics to collect the incoming astronomical radiation, an OMT to separate orthogonal polarizations, two Low Noise Amplifiers (LNA) to amplify the weak incoming signals and some extra components for extra amplification, filtering and down-conversion to intermediate frequencies in the 4-12 GHz range.

Receiver optics, shown in Fig. 1, are composed of a corrugated horn, located in the 15K stage of the cryostat, and a lens, which is the cryostat window and provides the vacuum seal. The optical beam must go through two apertures in the ALMA cryostat shields at 15K and 110K, which are covered by dielectric infrared filters. The size of these apertures and the lens are limited by thermal and mechanical reasons. They are electrically small and introduce considerable beam truncation. IR filters will also affect the radiation characteristics of the corrugated horn due to impedance coupling effects [2]. All these considerations make the optical design challenging.

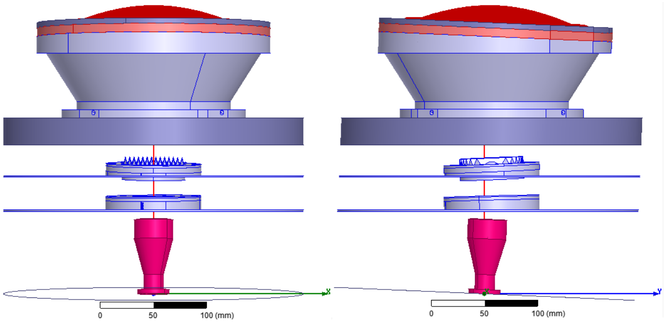

Fig. 1. ALMA band 1 optics (35-52 GHz). The horn and lens are tilted to point at the center of the Cassegrain antenna secondary mirror. IR filters are tilted to avoid standing waves due to reflections

III. SOME ALMA REQUIREMENTS

A. Aperture Efficiency at Secondary Mirror

The main ALMA requirement for ALMA band 1 receiver optics is the Aperture Efficiency at Secondary Mirror, which must be greater than 80% from 35 to 50 GHz (52 GHz if possible). Therefore, the fractional bandwidth of the receiver optics is around 40% (17 GHz at fc = 42.5 GHz).

The ALMA band 1 receiver is a dual-polarization receiver and must detect orthogonal linear polarizations. For a given polarization, the Aperture Efficiency is defined as the product of the Spillover, Amplitude, Phase and Polarization efficiencies.

B. Receiver Noise Temperature

The SSB noise temperature specification for ALMA band 1 is 25 K over 80% of the band, and 32 K at any frequency. The main contributors to noise are the LNA and the loss in the optics lens. This loss is proportional to the lens thickness.

On the other hand, the spillover noise will also contribute to the total system noise. For band 1, the spillover efficiency at the lower frequencies is low due to truncation at the lens. This increases the spillover noise. Although not a formal requirement, the spillover efficiency must not be low [3].

IV. ALMA BAND 1 OPTICS DESIGN

So far, design efforts have not achieved 80% efficiency in all of the ALMA band 1 bandwidth [4]. The fundamental reasons behind this are truncation at the lens and the choice of the feed horn. The incoming radiation from the Cassegrain antenna can be roughly approximated at the lens aperture by an Airy pattern determined by the size of the secondary mirror. The receiver aperture efficiency will improve if the optics can exactly match this Airy pattern [5]. Since truncation in the lens limits the power of the Airy pattern available for the receiver, the total power that can be matched by the optics is limited and so is the maximum aperture efficiency. The highest achievable aperture efficiency for a given lens diameter can be approximately calculated as a function of frequency by integrating the power of the Airy pattern at the lens aperture. Results of this integration are presented in Fig. 2.

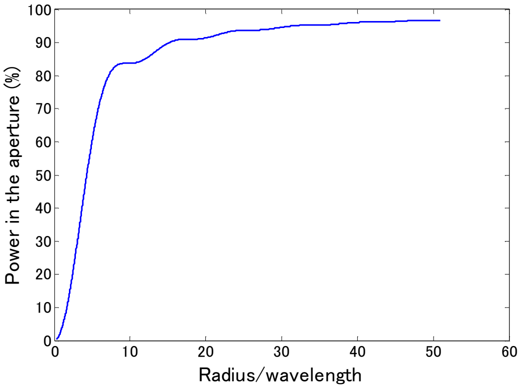

Fig. 2. Percentage of power of the Airy pattern coming from the ALMA antenna secondary mirror within a given radius at the lens aperture in terms of the wavelength

The maximum radius of the ALMA band 1 lens is 95 mm due to mechanical reasons. TABLE I presents the maximum aperture efficiency achievable at different band 1 frequencies. In short, in the case of a frequency independent design, the maximum aperture efficiency which can be achieved is 84%.

TABLE I. MAXIMUM APERTURE EFFICIENCY FOR A R=95 MM LENS

Freq (GHz)	Wavelength (mm)	95 mm / wavelength	Power in lens aperture (%)
35.0	8.57	11.08	84.1
42.5	7.06	13.46	87.4
50.0	6.00	15.83	90.5

In the case of ALMA band 1, high-performance long conical horns with small opening angles (as usually preferred in radio astronomy) are bulky and difficult to manufacture in one piece. Therefore, past optical designs have been based on short spline-profile corrugated horns. Previous horns intended to have the same performance as long conical horns, this is, they aimed at radiating a hybrid HE_{11} mode, which is up to 98% fundamentally Gaussian. The first idea behind the alternative designs described in this paper is to get a more Gaussian feed. Lens profiles, as in the case of a hyperbolic lens, are usually derived using ray tracing approximations. At mm-waves, hyperbolic lenses work generally well, but performance is not optimal, since radiation cannot be precisely approximated by optical rays. On the other hand, the propagation of the fundamental Gaussian mode and its interaction with a hyperbolic lens are well described by the same matrices as for ray tracing [6]. This somehow shows that fundamental Gaussian beams are in some aspects similar to optical rays. Therefore, if the feed is more Gaussian, the lens profile will work better.

In terms of aperture efficiency, fundamental Gaussian beams are not optimum, since they can only achieve a theoretical maximum aperture efficiency of 81.5% [7]. However, truncation at the lens rim adds higher-order mode content to the beam coming from the feed and transformed by the lens. This higher-order mode content will increase the aperture efficiency if successfully matched to the Airy pattern under discussion, from 81.5% to a maximum 84% efficiency. In practice, it is difficult to control this match and the optimization of aperture efficiency relies on full-wave EM simulations.

The Gaussian horn profiles described in [8] constitute a mode transformer from the HE_{11} mode in a corrugated waveguide to a fundamental Gaussian mode. Resulting beams are up to 99% fundamentally Gaussian. This 1% increase is not much, but has proved critical in this case.

Lens design is also important to achieve aperture efficiencies above 80% and to introduce as little noise as possible. Two cases of lenses have been studied: plano-hyperbolic (one side of the lens is hyperbolic and the other is plane) and bi-hyperbolic (both sides are hyperbolic). The first case is slightly thinner than the latter, but the efficiencies achieved are slightly lower. In addition, the flat surface on the outer part of the lens degrades the lens reflection loss. For all this, a bi-hyperbolic lens has proved more adequate for this design. In any case, in order to reduce lens thickness, it is convenient to use Fresnel lenses [9]. The position of the Fresnel zone is very important and the achievable bandwidth depends on it. The fractional bandwidth of a lens with one zone is around 25%, which is less than the ALMA band 1 bandwidth. Therefore, the zone must be introduced in a way that does not modify the existing fields much. It has been found that a zone almost at the lens edge achieves a 40% fractional bandwidth and reduces the thickness almost 20%. The reason of the large achieved bandwidth is that the zone is only illuminated by side lobes and does not affect the main beam much.

HDPE has been chosen as the lens material due to good electrical and mechanical properties. Anti-reflection layers based on artificial dielectrics [10] have been included in the lens design. Two possibilities have been considered: grooves carved in the lens and corrugations protruding out of it. Simulations showed that the first case yielded better efficiencies. Moreover, lens thickness is reduced with respect to the second option.

In order to simplify fabrication, the lens hyperbolic profiles have been approximated by flat steps. The value of the step equals the value of the hyperbola in the middle point of the step. Like this, all surfaces of the lens are parallel or perpendicular to the lens axis of revolution, which makes machining easier. This is shown in Fig. 3.

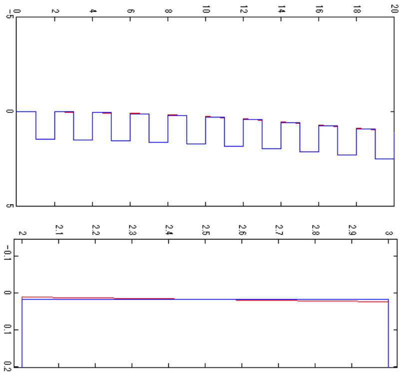

Fig. 3. (Top) Detail of lens hyperbolic profile (Bottom) Approximation of hyperbolic profile (in red) by steps (in blue)

The hybrid Mode-Matching + Method-of-Moment EM software WaspNET has been used for the design and optimization of the corrugated horn and the lens. Fig. 4 and 5 show the corrugated horn profile and typical radiation patterns, respectively. The horn aperture radius is 17.93 mm and the total length of the corrugation section is 78.44 mm. Reflection loss is better than -30 dB across the band. Fig. 6 shows the schematic of the performed simulations including the lens. Truncation at lens level has been considered. Convergence of simulations has been carefully checked. The best results have been achieved with a bi-hyperbolic lens with focal length of 181 mm placed 155 mm away from the horn aperture (this distance is from horn aperture to lens vertex). Results have been used to calculate the efficiencies reported in Fig. 7. Aperture efficiencies are above 81% and spillover efficiencies are better than 89% in all the band. The total thickness of the lens is about 42 mm (with an 8 mm central slab for mechanical strength), which translates into around 15% noise temperature reduction with respect to [4].

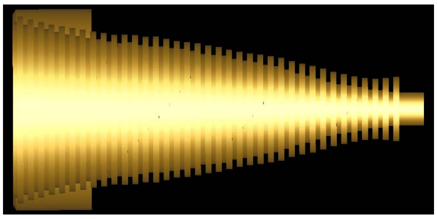

Fig. 4. Profile of the designed 99% fundamental Gaussian corrugated horn

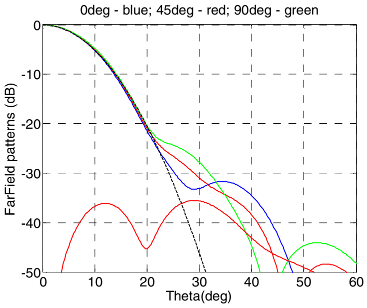

Fig. 5. Radiation patterns of the designed horn at 44 GHz (fundamental Gaussian mode in black)

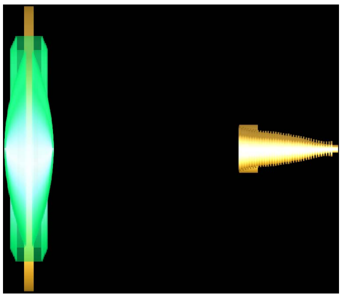

Fig. 6. Schematic of the simulation of ALMA band 1 optics in WaspNET

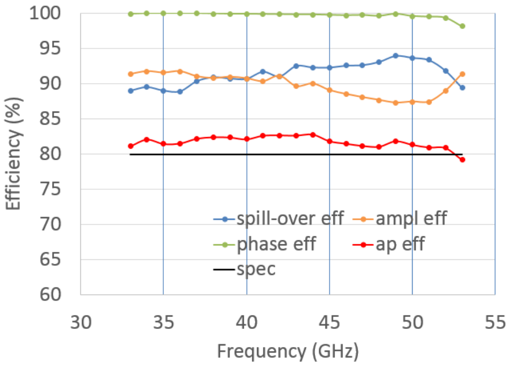

Fig. 7. Efficiency calculation based on WaspNET simulations

V. SECOND ITERATION DESIGN

The design of the corrugated feed horn has been modified in order to improve performance in a second iteration of the optics design. The horn optimization has been carried out at University of Chile. The optimization goals were to get extremely Gaussian radiation patterns with very low cross-polarization and with less corrugations than the previous design. The resulting horn is shown in Fig. 8. The aperture radius is 15.63 mm and the length is 66.16 mm.

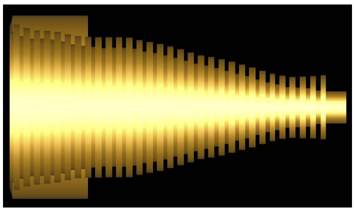

Fig. 8. Profile of the latest ALMA band 1 corrugated horn

Radiation patterns at 42.5 GHz are presented in Fig. 9 and are typical across the band. They show very good beam symmetry and low cross-polarization.

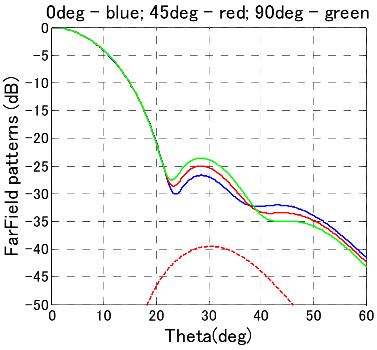

Fig. 9. Radiation patterns of the latest horn at 42.5 GHz

The lens design has been modified slightly in order to optimize aperture efficiency and minimize thickness. The resulting focal length is 180 mm and the horn-lens distance is the same as in the previous design, 155 mm. The final lens profile is presented in Fig. 10. The total central thickness is 40.8 mm (with an 8 mm central slab).

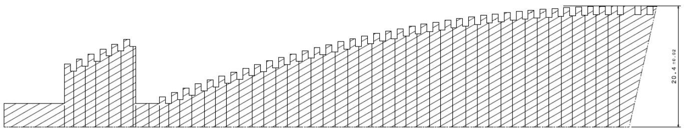

Fig. 10. Detail of the bi-hyperbolic lens profile to be used for ALMA band 1 optics. The profile is the same on both sides of the lends. The axis of revolution is located in the thickest part of the lens (on the right). The Fresnel zone is located close to the outer edge of the lens. The central thickness is 40.8 mm.

This design has been simulated with WaspNET and the resulting far-fields have been used for the efficiency calculation shown in Fig. 11. Aperture efficiencies are better than 81.8% and are within 82-83% in most of the band. Spillover efficiency is greater than 90%. The result is quite frequency independent, which is useful in radio astronomy.

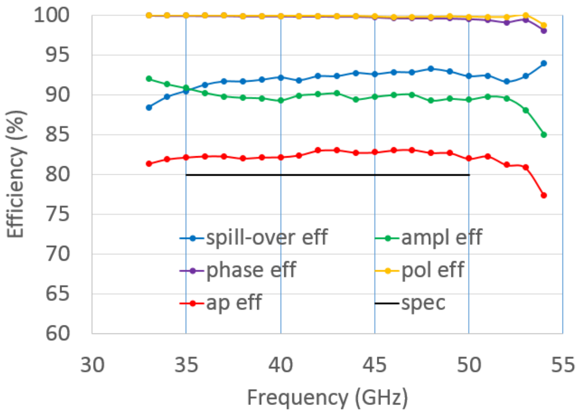

Fig. 11. Efficiency calculation of the latest ALMA band 1 design

VI. CONCLUSIONS

Two optical designs based on corrugated horns with extremely Gaussian behavior and Fresnel bi-hyperbolic HDPE lenses have yielded efficiencies greater than 80% at all ALMA band 1 frequencies, with good spillover efficiency and noise temperature. The latest design will be used as the baseline design towards the ALMA band 1 Critical Design Review to be held in 2015. This design is now being prototyped and it will be measured in the near future to confirm these simulation results.

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