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# ALMA Band 2+3 (67-116 GHz) optics

## Design and first measurements

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**Abstract**—The ALMA telescope is one of the largest on-ground astronomical projects in the world. It has been producing great scientific results since the beginning of operations in 2011. Of all the originally planned bands, band 2 (67-90 GHz) is the last band to be implemented into the array. Recent technological progress has opened the possibility to combine bands 2 and 3 (84-116 GHz) into a single wideband receiver. This paper describes the first efforts to design wideband optics which cover both bands, from 67 to 116 GHz, using a profiled corrugated horn and a modified Fresnel lens. First measurements were performed at ESO in Dec15-Jan16 and showed good agreement with simulations.

**Keywords**—ALMA; radio astronomy receivers; wideband optics; corrugated horns; dielectric lens

### I. INTRODUCTION

The Atacama Large Millimeter-submillimeter Array (ALMA) [1] is currently the largest operative radio astronomical observatory on ground. It has been built as a collaboration between Europe, North America, East Asia and Chile. The telescope is composed of 66 12-m and 7-m diameter antennas located at 5000 m altitude in the Atacama Desert, Northern Chile. It covers all atmospheric windows from 35 to 950 GHz. Such a large frequency range has been divided into 10 different bands for practical implementation. All bands except band 2 (67-90 GHz) have been implemented in the telescope or there are plans to do so. Currently, there are several proposals for the implementation of the band 2. Among those, a collaboration between institutes in Europe (INAF, ESO, Univ. Manchester, RAL), Chile (UdC) and Japan (NAOJ) is looking into the possibility of implementing a receiver which covers bands 2 and 3 simultaneously, from 67 to 116 GHz (54% fractional bandwidth). In terms of optical design, INAF and UdC have contributed designs for corrugated feed horns and orthomode transducers (OMT), NAOJ has contributed optical designs based on dielectric lenses for both feed horns, and ESO (together with INAF) has contributed with the preparation of a measurement setup to characterize the two prototype receiver optics. This paper describes the optical designs performed at NAOJ, together

with measurement results obtained by a joint effort by all partners in a measurement campaign in Dec15-Jan16.

### II. OPTICAL DESIGNS FOR ALMA BAND 2+3

#### A. Corrugated Horns and OMTs

The first key component in the optical design of ALMA band 2+3 optics is the receiver feed horn. Two compact corrugated feed horns have been designed and fabricated by INAF and UdC. The design by INAF is based on a sin-squared profile with corrugations with variable depth and length in the throat section in order to achieve the required bandwidth [2]. The design by UdC is based on a spline profile and direct optimization of the parameters of all corrugations in the horn. Results show horns with good reflection loss, low cross-polarization, low sidelobes and good beam symmetry. INAF horn has been fabricated by stacking metal rings with individual corrugations, whereas UdC horn has been fabricated by direct machining of aluminum. ALMA receivers must provide simultaneous detection of orthogonal linear polarizations. In the case of ALMA band 2+3, this polarization discrimination capability is provided by an OMT just after the feed horn. INAF and UdC have contributed two different designs of OMTs, both based on turnstile junctions.

#### B. Dielectric Lens

Of all possible optical designs, the most straightforward is the use of a dielectric lens on top of the cryostat, as initially considered for ALMA band 2 in the original ALMA optical design [3]. Recently, NAOJ has contributed lens optics designs for the ALMA band 1 (in collaboration with UdC and ASIAA) [4] and band 2 (in collaboration with NRAO) [5] receivers. In both cases, low noise high aperture efficiency optical designs were achieved using a modified Fresnel lens made of HDPE, which has low loss and high mechanical strength. This last characteristic is very important, because these lenses are used as vacuum windows in the ALMA cryostat and must endure high mechanical stress and hold vacuum. All the know-how acquired during those previous designs has been applied to the design of

band 2+3 wideband optics. Firstly, the two existing feed horns have been modeled by Gaussian beam fitting and quasi-optical parameters (waist size and position within the horn) have been derived. These have been used to obtain frequency-independent quasi-optical designs [6] with one focusing element, considering the geometry and mechanical constraints of the ALMA front-ends and antennas. The design variables are the distance between the horn and the lens, between the lens and the telescope secondary mirror, and the focal length of the lens. These two preliminary designs, one for each horn, have then been used as the starting point of parametric analyses using the hybrid mode-matching/body-of-revolution method of moments provided by the commercial software WaspNet. Firstly, bi-hyperbolic lenses were used for both designs in order to account for the effects of truncation at the lens rim and to properly implement the anti-reflection (AR) coating based on grooves on the hyperbolic surfaces of the lens. Secondly, once good optics based on bi-hyperbolic lenses were obtained, the lens was substituted by a Fresnel lens. As described in [4], the bandwidth limitation of the Fresnel lens can be overcome by using a single zone and placing it close to the lens edge. Like this, the lens thickness and loss associated to it are reduced, and the required performance is achieved in the whole bandwidth. After the design is completed, some mechanical modifications are implemented on the lens in order to simplify fabrication and further reduce loss. In particular, the AR coating near the zone transition is removed, and the hyperbolic shape in the lens corrugations is approximated by flat steps. Final simulations are performed in order to guarantee performance is not degraded by these changes. The schematic of the optics design for INAF horn is presented in Fig. 1, together with a photograph of the full optics assembly.

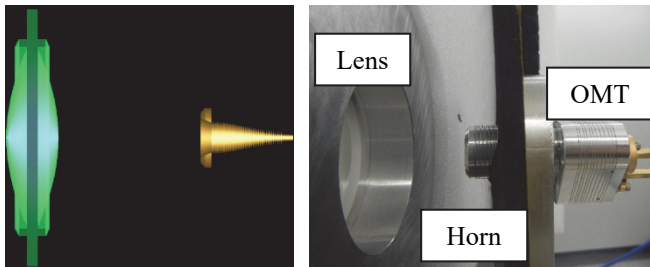


Fig. 1. (Left) Schematic of ALMA band 2+3 optics using INAF corrugated horn and a modified Fresnel lens made of HDPE. (Right) Photograph of the assembly of the optics for INAF horn and OMT

The main optical requirements to meet are minimum loss, aperture efficiency greater than 80%, and polarization efficiency on the secondary mirror greater than 99.50% (or integrated cross-polarization on the secondary less than -23 dBc). The aperture efficiency is defined as the product of spillover, taper, and phase efficiency at the secondary mirror of the ALMA antenna, and full-pattern polarization efficiency. The aperture efficiency specification is very challenging for acceptable lens sizes. The maximum achievable aperture efficiency can be approximately calculated by considering the percentage of power coming from the telescope which is within the lens aperture and can go through it into the ALMA cryostat. The field distribution at the lens aperture is approximately an Airy pattern and can be integrated analytically. The larger the lens diameter is, the more in-coming power can be received. However, the lens

diameter is limited by thermal and mechanical considerations to only 92 mm. Under these limitations, the maximum theoretical aperture efficiency is given in Fig. 2. Compliant values can be easily achieved in the upper edge of the band, but are hard to achieve at the lower end of the band. Considering all this, two different optical designs with the performance shown in Fig. 2 have been provided for the two existing horns. The total lens thickness is 24.48 mm and 22.38 mm, for INAF and UdC horns, respectively, with a 5 mm central slab for mechanical strength. The highest noise temperature associated to both lenses (at 116 GHz) is 6 K and 5.4 K, respectively.

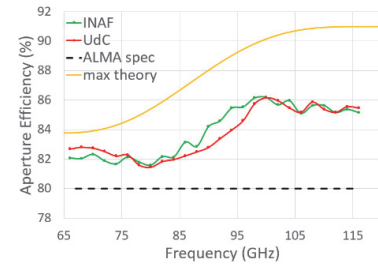


Fig. 2. Results of aperture efficiency calculations from MM-MoM simulations of the optics designed for INAF and UdC horns, compared with the ALMA specification and maximum theoretical values

### III. MEASUREMENT RESULTS

A beam measurement system has been established at ESO for the characterization of both ALMA band 2+3 optical designs. Prototypes have been fabricated and optical systems have been characterized in Dec15-Jan16. Preliminary measurement results show good agreement with simulations in general, as shown in Fig. 3. Improvement of polarization performance of UdC optics will be attempted in the near future.

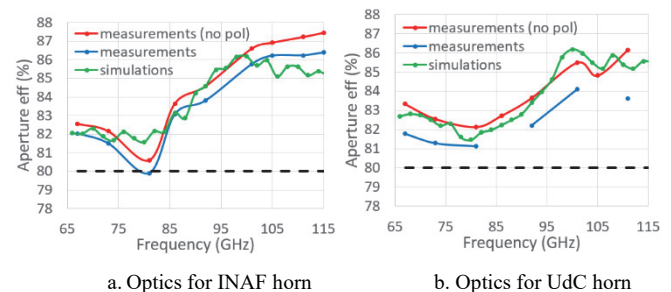


Fig. 3. Preliminary results of aperture efficiency calculations from measurements with prototype components, compared with simulations. Data labeled measurement (no pol) considers polarization efficiency = 100%

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