Design of an Optical Beam Combiner for Dual-Frequency Observation with ALMA

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Abstract— The aim of this work is to improve high-frequency calibration data on long baseline observations for the ALMA antennas. A dual-frequency atmospheric phase error calibration method is proposed and will be implemented by the simultaneous observation in two ALMA Bands, specifically 6 and 9, coupled by means external optics in a few baselines. This method is envisioned to demonstrate the advantage of receiving signals simultaneously at different frequencies from the same point of the sky. It will permit an increase of accuracy in determining the phase correction needed to reduce the effects of the atmosphere and, therefore, it will enable higher resolutions when imaging at high frequencies using the ALMA interferometer. While maintaining the existing receiver optics, an optical layout that couples Bands 6 and 9 is proposed. Here we demonstrate that very limited impact on the existing ALMA system is needed. Furthermore, we present in detail the optical layout, made within the formalism of ray optics. The initial results demonstrate the feasibility of the proposed system.

INTRODUCTION

At the present, the Atacama Large Millimeter/Submillimeter Array (ALMA) [1] represents the largest astronomical project in existence, which is composed by 66 high precision antennas with advanced technology [2]. Despite being located in one of the best sites for performing mm and submm radio astronomy (Chajnantor plateau located at the Atacama Desert in northern Chile) [3], ALMA is not exempt from image degradation caused by atmospheric effects or instabilities in the instruments. To ensure that it operates at its full potential during the next years and decades it is necessary to maintain a continuous development program.

As a part of this program we propose to develop a dual-frequency atmospheric phase-error calibration method using ALMA Bands 6 (211-275 GHz) and 9 (602-720 GHz) by means of external optics on a few ALMA baselines employing existing ALMA receivers. This method is devised to demonstrate the advantages of receiving signal simultaneously at different frequencies from the same area of the sky. When implemented, it will permit an increase of accuracy in determining phase correction due to atmosphere, improve UV coverage, double instantaneous frequency coverage for line searches and improve cross calibration between different bands. This project involves designing an optical system for combining the beams of existing Bands 6 and 9, implementing limited modifications of signal transfer at few ALMA antennas and making dual-frequency observations with ALMA. Here we demonstrate that very limited impact on the existing ALMA system is needed and present the optical layout that it will be used.

In this work, we present the results obtained so far in the development of this dual band optical calibration device. We start with a general background about elliptical mirrors and how these can be used to reduce losses in the system. Then, the space constraints to mount the system are presented along with the proposed layout that allows splitting the beam and redirect it into Bands 6 and 9. Finally, the mechanical design of the proposed structure to make dual-frequency observation possible, using ALMA telescope, is presented.

THEORETICAL BACKGROUND

Elliptical mirrors are widely used in the high-frequency ALMA bands, because they allow the focal plane to fit the incident beam coming from the secondary reflector to their respective receiver. An illustration of a general two elliptical mirror set-up is shown in figure 1. When off-axis mirrors are used, it is unavoidable to introduce distortion to the beam. However, the parameters of this kind of system are chosen to reduce this effect. Among those parameters, the bending angle (α_1, α_2) must be kept as small as possible in order to guarantee minimal distortion losses (L_{dist}) and cross-polarization losses (L_{dist}). The total distortion loss (or polarization loss, since both formulas differ just by a factor 2) can be calculated subtracting the effect introduced by each mirror [4],

$$L_{dist} = \left| \frac{w_1{}^2 tan^2(\alpha_1)}{8\, f_1{}^2} - \frac{w_2{}^2 tan^2(\alpha_2)}{8\, f_2{}^2} \right| \quad (1)$$

where w corresponds to beam radius at the mirror surface, α to the bending angle and f to the focal distance of the mirror.

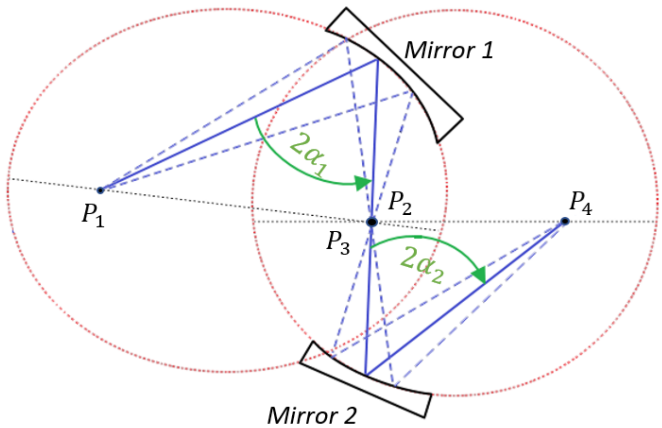

Figure.1 - Optical layout to minimize distortion using two elliptical mirrors. The main ray is represented by the blue solid line and the marginal rays are represented by the blue dashed lines. The point P_1, P_2, P_3, P_4 correspond to focal points of the ellipse defined by the mirror 1 and 2 respectively.

Symbol	Quantity	Value in (mm)
Φ	Maximum Radius	73
L	Maximum Length	188
H	Maximum Height	185

Table I Dimensions of the Safe Work Zone

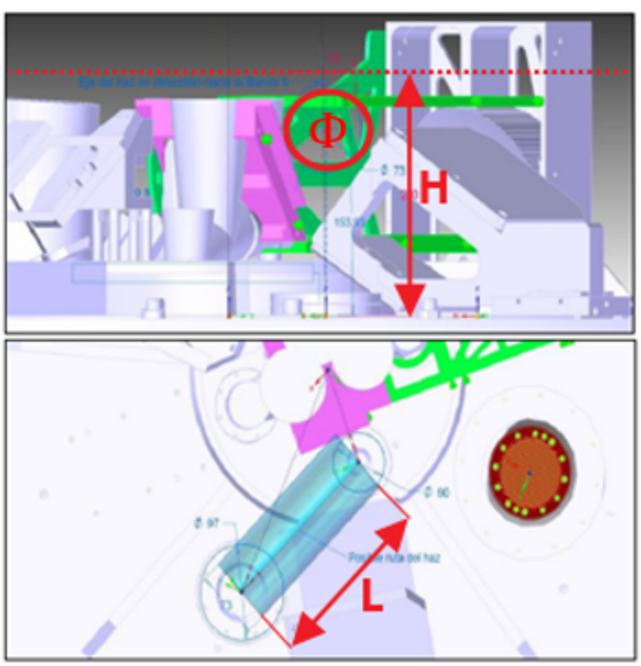

Fig. 2 The top and bottom pictures show, respectively, a side and top view of the Safe Work Zone.

SAFE WORK ZONE and OPTICAL DESIGN

As starting point, it is important to highlight that not all space inside the cryogenic chamber is available to be used in this optical system. There already exist many optical, electronic and calibration devices for every one of the bands. For this reason,
is important to define a Safe Work Zone (SWZ), which guarantees that the beam will not crash with any object in its path, producing undesirable effects such as diffraction or interference if appropriate measures are not taken. Figure 2 (top) shows the straight path starting from Band 6 and ending in 9. This figure shows that there is a bracket (part of external optics of Band 4) blocking the path. To avoid this obstacle and any other that could appear in the optical path of the beam, the first goal is to clearly identify the SWZ by means of inspecting the CAD file of the cryogenic chamber, which is available in the ALMA database. Figure 2 (bottom) shows a top view of the SWZ, whose dimensions are presented in table I.

OPTICAL DESIGN

Since the different bands in ALMA are spatially separated in the focal plane, as shown in figure 2, the beams of the two band must be combined optically in order to perform simultaneous dual-band observations. An optical first order system has been designed following a geometrical optics approximation and using Zemax software. Using geometrical optics rather than Quasioptics is acceptable, because in the near field approximation geometrical optics describes a beam which envelops the Gaussian beam. This condition guarantees that both beams will follow the same optical path. However, it is important to be aware that the diameter of each reflecting element in the system must be chosen following Quasioptical approach, i.e., using at least a diameter of $4w$, where w corresponds to beam radius at any element surface. This condition guarantees that 99.97 % of the power of the beam will be transmitted after each reflection.

Figure 3 shows the optical layout of the proposed beam-combining system. The concept is to use a dichroic beam splitter surface ("dichroic" in short) to separate the Band 6 and 9 beams. The beam of Band 6 is reflected and then redirected to its respective window by an optical re-imaging system, consisting of five mirrors, two elliptical and three flat. The incidence angle upon the dichroic filter is kept as low as possible (~17.5 degree) to decrease the insertion losses [5]. The idea of using two elliptical mirrors in this system is that the beam distortion (produced by each mirror) can be compensated by properly matching their foci [6]. Other advantage of using elliptical mirrors is that the beam shape could be easily matched, in order to change the beam features as little as possible [7]. The beam of Band 9 is transmitted through the dichroic without any major changes. One of the main reasons that we chose for this arrangement is that dichroic tend to work better when the high frequency is transmitted.

All the optical components must be properly aligned, both in lateral offset and angle, for achieving high levels of efficiency. However, this situation is not realistic and the misalignments present in the system should be corrected. A tolerance analysis (not presented here) has been performed and its objective is to know how sensitive the proposed system is to any angle misalignment and how the focus matching between the bands 6 and 9 will change. This analysis shows that the best elements in the system to correct any misalignment are the flat mirror 1 and

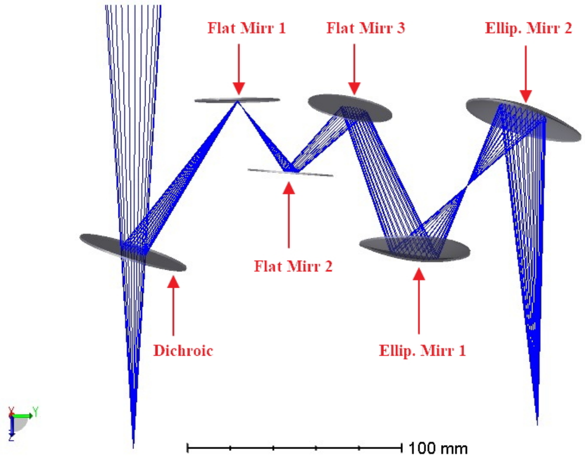

Fig. 3 Optical design of the beam combiner system made using Zemax software. The design has been made using a geometrical optical approximation by means of the Zemax sequential system option.

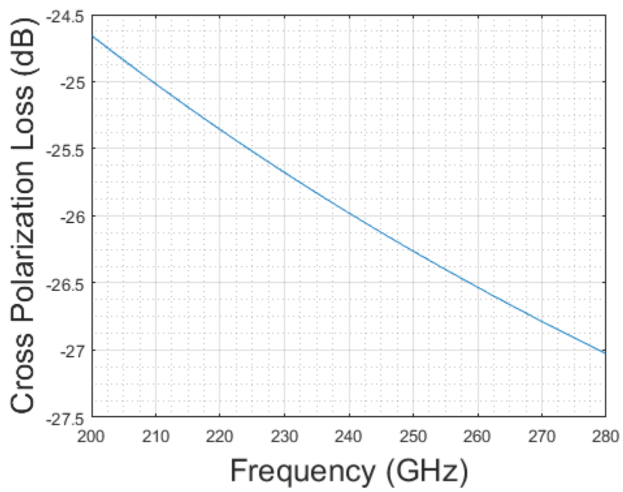

Fig. 4 Cross polarization loss as function of the frequency. The frequency range spans that cover by Band 6. The loss has a value of -26 dB at the central point.

the elliptical mirror 2, since they provide a maximally decoupled adjustment in either offset or angle. These mirrors will be equipped with micrometer screws for manual adjustment.

For the Band 9 beam, any deterioration is purely due to the dichroic. Typical transmission of a modern mesh-type dichroic is of the order of 92% [8], giving a noise temperature increase of about 25K for Band 9. The polarization purity is expected to be reduced no more than a few dB.

For Band 6, the situation is more complicated. Reflection of the dichroic, typically of the order of 96% [8], will increase the noise temperature by at most 12 K. We believe that subsequent loss in the beam can be quite low when high-quality mirrors are used in the re-imaging optics. Figure 4 shows the cross-polarization losses calculations as described by equation 7. The plot shows a cross-polar deterioration of about -26 dB at central frequency. For an eventual full deployment, this may be considered too high, but for a proof of concept demonstrator we deem it acceptable.

Element	Beam Radius (mm)	Element Diameter (mm)
Dichroic	10.03	55.0
Flat Mirror 1	8.65	40.0
Flat Mirror 2	8.52	40.0
Flat Mirror 3	8.91	40.0
Elliptical Mirror 1	10.79	52.0
Elliptical Mirror 2	11.66	55.0

Table II Beam radius at each element of the beam combiner system and actual size of each element. The beam radius has been calculated according to Quasioptical beam formula and the element diameter correspond to 4 times the beam radius plus an extra margin to compensate any possible misalignment.

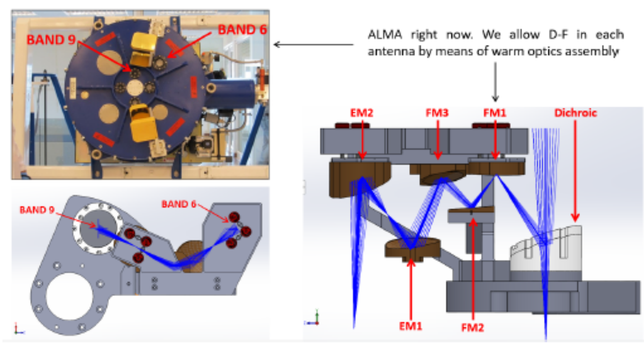

Fig. 5 Top view of ALMA cryostat (left top) showing the actual layout of the Bands. The left bottom image shows a top view of the support structure for the beam combiner assembly. A side view of the system is shown on the right side.

MECHANICAL DESIGN

In order to make dual-band observations possible, we propose to insert an optics assembly directly on top of the front-end cryostat, containing the dichroic and the re-imaging optics.

Figure 5 shows the current design of the support structure for this assembly. The dichroic will be located above the Band 9 vacuum window, allowing the beam to pass almost unmodified. On the other hand, the new Band 6 beam, now coaxial with the Band 9 beam, will be reflected by the dichroic and re-imaged by the set of mirrors into the original Band 6 focal point.

One of the most important requirement to accomplish by the whole support structure is that this should be linked to the cryostat without major modification, i.e., no drilling or using pieces that might endanger the optimal operation of other components previously installed. Furthermore, using any hole that might be used for the already set-up components is not allowed. This structure has been designed to operate exclusively in the 12- meter diameter antennas. Since the space restrictions in those with 7-meter diameter are higher [9], due to additional components aimed to compensate the difference in the optical path length of the beam for both antennas. As those components are not present in the 12-meter configuration, some extra holes (used to link those components) are available to be used. Those holes will be used to link the support structure to the cryostat. In order to fix the structure, the main support of the structure was designed thick enough to resist the weight of all the other components and with as little impact as possible on the alignment of the system due to either mechanical vibrations or elastic deformation of the parts.

Finally, an analysis involving a Quasioptical approach calculations, has been performed. This provides the real size that each element of the beam combiner system must have in order to reduce the spillover produced by the multiple reflections which the Band 6 beam is undergone along through its optical path. The values with the real diameter of each element are presented in table II. These values are minimal recommended to guarantee a negligible spillover of the beam.

Conclusions

An innovative and low distortion first order system, within the geometrical optics formalism, have been proposed. This system uses mirrors (two elliptical and three flat), which keeps the losses in a minimum level. Any misalignment presented in the system could be corrected, in principle, by tilting those mirrors equipped with micrometer screws. Additionally, a Quasi-Optical model has been used to corroborate the feasibility of this proposed design and calculate the suitable size of each system element.

This works demonstrate that the available space is enough to mount the support structure beam combiner system. This structure has been designed to do not interfere with other components of the cryostat and make its installation simple. Normal operation of the telescope will not be affected by this structure.

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