Design and evaluation of ALMA band 9 quasioptical system

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ABSTRACT

The Atacama Large Millimeter Array (ALMA) project requires the development of reliable quasi-optical systems with requirements similar to the ones in space. The operating condition for optical elements of higher frequency channels are similar to the conditions in spacecraft, since these elements are contained within the ALMA cryostat in high vacuum and at cryogenic temperatures. The remote terrain of the Atacama Desert and the scale of project suggest that a significant effort should be made to ensure high reliability of the system. Therefore the techniques, common to a space mission are applied with this development.

In this report we would like to present the design of the quasi-optical system for ALMA band 9 (600-702 GHz) containing elements typical to a space system. A design assumptions and details will be presented for a frequency independent system. A measurement of near field antenna beam pattern (phase and amplitude) will be presented and comparison with theoretical predictions will be made.

1. INTRODUCTION

1.1 ALMA instrument

The Atacama Large Millimeter Array (ALMA) is an interferometric array of 64 heterodyne receivers. It is located at high altitude of 5000 meters in the northern Chile. This array is being built in collaboration between North America and Europe (represented by European Southern Observatory) with a possibility of Japan joining the project at a later stage.

Fig. 1 An artist impression of ALMA front-end cryostat holding 10 cartridge subsystems. Design is done by Rutherford Appleton Laboratory (UK).
The band 9 receiver optics has the following main design goals: a) all optics is mounted in the cartridge structure shown in fig. 2; b) the LO power source is located on the 90 K stage of the cartridge; c) most of the optics is located at 4 K level since SIS mixer technology is used; d) two orthogonal linear polarizations should be received from the sky; e) the secondary mirror edge illumination taper should be 12 dB and should not depend on frequency within ALMA band 9; f) design should be based on the reflective optics elements and five waists size beam should be put through; g) Cross polarization signal level should be less than -20 dB from the power in the main polarization.

ALMA antenna is a classical Cassegrain system. The primary mirror diameter is about 12 m, secondary mirror diameter is 0.75 m, and the distance from antenna secondary mirror to focus is 6 m. Antenna beam towards receiver is #8 angular size. This is an input beam for band 9 receiver. The receiver position is 0.1 m offset from main symmetry axis of antenna.

Additional attention should be paid to the small series production of the optics. ALMA project requires 64 receivers to be built. Because of this requirement it was decided to build all the optics using conventional CNC machining and make machining tolerances sufficiently tight to skip the additional alignment procedure by a laser beam.

Since the frequency with band 9 is much lower than that of optical light only 7 micron RMS mirror roughness is required, and the tightest tolerance for this particular design is about 40 microns. These parameters are well within reach of conventional CNC machining techniques. Note that 7 micron RMS will not allow the optical checks for mirror alignment and therefore use of an submm wave antenna beam pattern measurement system is essential to assess the quality of optical system. In order to verify the design concept of using direct CNC machining for these frequencies, a simple model for a signal chain – a two-mirror block has been built, together with a mixer horn, the details of it will be presented later in the section about measurement results.

2.2 Signal path

Drawing of signal path is presented in fig.~3. Telescope focus is located in the point FP. Two elliptical mirrors (M3, M4) are used to reimage the secondary mirror of telescope (M2) into the mouth of a mixer horn with the size, that is appropriate for 12 dB edge taper. The quarterly focal point (the second focal point of mirror M4) coincides with an apex of the corrugated horn H1. This construction allows for
frequency independent coupling of the telescope beam to a corrugated horn feed. Mirror diameters are chosen to put through a 5 w size beam.

An absorber plate is mounted behind each of beamsplitters for both polarizations to dump LO power that is not coupled into the beam.

2.4 Opto-mechanical design

The layout that is briefly described below has to be realized in practice, i.e. mirrors, beamsplitters, grids and mixer horns have to be mounted within a certain tolerances with respect to each other and optics should be aligned. A tolerance budget was made for current optics layout indicating that 40 micron displacement is the highest requirement for displacement to produce 1% of efficiency loss [3,4].

The main idea of the design is to make all the parts in using CNC machining techniques observing tolerances. In this way all optics will be aligned upon assembly and no additional measures, like shimming or putting a lazer beam through are not required. This allows for significant easing of requirements for mirror accuracy, grid foil flatness and beamsplitter flatness.

For example, as it can be seen from layout, mirrors M4, M5 and M4’, M5’ are pointing downwards. It is the most natural to make them out of one block in one CNC machining run. All beamsplitters and grids can be mounted in the block, also containing a mirror M3, which is directly machined in it. This concept is presented in fig. 4. The two blocks, bottom and top are bolted to each other within the required tolerances.

2.5 Prototype mirror block

In order to verify if a selected machining techniques or design approach works a simplified model of a signal path consisting of two mirrors M3, M4 and mixer horn mount has been built. It is shown in fig. 5.
has a phase difference of Pi. These reflections are added destructively. This method allows effectively suppress parasitic effects due to first order reflections for beams, close to a parallel. Band 9 receiver f/8 beam is close enough to achieve good standing wave suppression without degrading the quality of measurement itself. Additionally, an absorber plate around the source was used to decrease the level of reflections.

A small approx 2 x 1 mm flared waveguide probe was used as a radiation source. Its antenna beam is much wader than receiver f/8. No correction for source beam pattern is needed for analyzing results of measurements.

3.3 Room Temperature detector and saturation

An SLED (super lattice electronic device) [7] was mounted instead of an SIS junction in one of our mixer holder. That allows for using it mechanically with exactly the system which is going to be cooled down. This detector potentially has better conversion efficiency as conventional diode. Although, no specific matching circuit was designed to couple the SLED to an RF environment, signal to noise ratio of 72-80 dB has been obtained for all frequencies in ALMA band 9, using about 50-70 microwatt as an input signal. All measurements were done at room temperature. The SLED was pumped subharmonically. 36th harmonics of LO was typically used.

Since SLED is relatively new detector device for this type of measurements, a special attention was paid for detector saturation by the input signal. To check this effect, a measurements were done for the same beam of corrugated horn and scanning ranges while changing source output power. Results of this measurement are presented in fig. 6 and 7 for amplitude and phase respectively. No significant compression was found in the data as well as phase appears to be stable even for very significant drop (-33 dB) of input signal power.

![Fig. 5 A prototype two-mirror block for evaluating production techniques.](image_url)
4. MEASUREMENT RESULTS

4.1 Laser beam propagation

The two-mirror block, presented in fig. 5 was produced by a CNC machining technique. Mirror surfaces were machined by a ball mill in the 5-axis CNC machine. After light polishing, the surface quality was good enough to put through a laser beam. The beam itself can be visualized by applying a water vapour fog during long time exposure of digital camera. The result is shown in fig. 8.

Intermediate (tertiary focus) and final (quarterly focus) are clearly visible. Some beam splitting can be visible at lower right corner of the picture. This is due to approximation errors that occur during milling of the mirror surface. Note that frequency, at which the effect occurs, is 1000 times higher than the required frequency.

4.2 RF beam pattern measurement and analysis

A 2-D plot of amplitude and phase beam distributions are shown in fig. 9 and 10 respectively. The mirror symmetrical axis coincide with Y-axis of scanner. One can see that a central maximum has a symmetrical shape both in phase and amplitude. A low levels of sidelobes is observed. A round ring structure at lower levels can be explained by periodical deviations of mirror shape from nominal curve due to machining strokes of the mill tool.

Amplitude and phase information allows to calculate an overlap integral of the measured data with fundamental mode Gaussian beam. Ideally, this beam has six parameters, which can be determined from the data by maximizing Gaussian beam coupling: beam waist size, waist position (X,Y,Z), and two beam tilt angles. If the scanning plane is referenced to a mirror surface by a calibration device, obtained parameters allow to conclude if the production errors are still
acceptable and what the efficiency loss can be. The Gaussisity of the beam shown in fig. 9-10 is about 98%, which is very close to an ideal situation. The waist size, offsets and tilt angle are within the required tolerances. It produces less than 1% efficiency loss, compared with an ideal case.

Measured beam cross-sections both for symmetrical (Y) and asymmetrical (X) mirror axes are shown in fig. 11-14. These measurements were done for several frequencies in ALMA band 9. Note that beam quality maintains over whole frequency range except the lowest frequency. At the lowest frequency, some deviation can be explained by a corrugated horn beam pattern change. A new horn design is underway.

As expected, the beam is largely symmetrical for symmetrical mirror axes. Visible operations effects are present in the cuts along the asymmetrical mirror axes. These effects, give rise to a beam tilt with respect to a nominal beam direction. Beam tilt, determined from measurements, is still within the required boundaries.

Finally, a far field antenna beam pattern can be determined from the 2-D data of fig. 9-10 by means of Fourier transform. The resulting amplitude angular distribution is shown in fig. 15 and central part of the distribution is shown in fig. 16 compared with the angular size of ALMA antenna secondary mirror. Since mirror is in the far field zone of the waist, this gives a good indication of the illumination edge taper. From fig. 16 one can conclude that the edge taper is very close to the required 12 dB and illumination pattern of the secondary is well centred. A semi-round fringes are visible at the beam pattern at very low signal levels. These fringes are again due to approximation error of the CNC machine (and due to tool movement stroke direction). However, still visible, these effects do not degrade significantly the illumination pattern at the secondary mirror.

Periodical mirror surface deviations produce a various peaks at far field pattern, see fig. 15. The angle of these peaks allows to determine the period of these deviations. Random deviations with white spectrum result in increase of a spill over from the main beam towards all directions uniformly. Good signal to noise level obtained in the figure and low level of peaks due to periodical deviations suggests that the selected production technique is sufficient for application in ALMA band 9 receiver.

5. CONCLUSION

An opto-mechanical layout of ALMA band 9 receiver is proposed. A production method of direct CNC machining of mirror surfaces and alignment of optics by assembly was demonstrated by building a prototype optics system and developing a near field beam pattern measurement system. The proposed technique proves
to be successful and can be applied for not only for ALMA band 9 but also for any ground based or space instrument requiring to build many copies of optics, for instance a free flying interferometer.

A super lattice electronic device (SLED) detector was successfully used as a replacement of an SIS junction for room temperature evaluation of optics layout. A signal to noise level as high as 80 dB has been achieved for 30 Hz detection bandwidth at 672 GHz signal frequency.

6. ACKNOWLEDGEMENT

The authors would like to thank Mark Harman of RAL for the overall design of the cartridges and cryostat that were given in section 1.2 We would also like to thank Fabrice Coq for the help in making the measurements. Authors also would like to thank Paveliev D.G. for providing SLED devices and Th. De Graauw for stimulating discussions.

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