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ALMA Band 6 Prototype Cartridge: Design and Performance

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Abstract: This paper describes the design and performance of the initial Band 6 (211-275 GHz) ALMA cartridges. The incoming beam is coupled by 4-K reflecting optics to a scalar horn followed by an orthomode transducer. Each polarization is down-converted in a sideband-separating SIS mixer integrated with a pair of 4-12 GHz IF preamplifiers. Stringent thermal management and LO loss requirements are satisfied by using an overmoded stainless-steel waveguide between the LO triplers on the 100-K stage and the 4-K mixers. For ease of maintenance, all connections into the vacuum vessel are "blind mating."

Introduction

The Atacama Large Millimeter Array (ALMA)[†] is a radio telescope with 64 antennas under construction in the Atacama desert in northern Chile. The front-ends for ALMA will each consist of a 4-K cryostat with ten insertable receivers (called cartridges) covering the frequency range 31 to 950 GHz. Each cartridge will operate simultaneously in two linear polarizations. A block diagram of the Band 6 (211-275 GHz) cartridge, showing the main interfaces, is given in Fig. 1, and an overall view of the cartridge is shown in Fig. 2.

The cartridge consists of three cold stages with operating temperatures of 4 K, 20 K, and 90 K, and a room-temperature base-plate which acts as the vacuum barrier. The stages are supported on cylindrical G-10 glass-epoxy spacers. The 90-K stage has mounted on it two LO triplers and heat sinks for the LO waveguide, IF coaxial cables and wiring. The 20-K stage has only heat sinks for the LO waveguide, coax cables and wiring, while the 4-K stage has the mirrors, horn, OMT, mixer-preamps, IF hybrids and heat sinking for the LO waveguide, coax cable and wiring.

The RF signal enters the cartridge through a vacuum window and infrared filters, which are part of the outer vacuum vessel. Two off-axis ellipsoidal mirrors mounted on the cartridge 4-K plate couple the beam to the scalar feed horn (see section on optics). The two polarizations are then split in an orthomode transducer (OMT). Each polarization channel uses a sideband-separating mixer-preamp containing two DSB component mixers. Each component mixer requires an independent, six-wire bias supply, and each preamplifier uses a nine-wire bias supply. Protection circuits are installed on the vacuum side of the hermetic connector to protect the mixers and the preamps from over-voltage and static discharge. The two IF outputs from the mixer-preamp are connected via phase-matched cables to a quadrature hybrid. This provides the two sidebands at separate outputs, both of which are brought out of the cartridge. Switching between sidebands can also be achieved by changing the polarity of the bias on one of the component mixers.

[†]The Atacama Large Millimeter Array (ALMA) is an international astronomy facility. ALMA is an equal partnership between Europe and North America, in cooperation with the Republic of Chile, and is funded in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC), and in Europe by the European Southern Observatory (ESO) and Spain. ALMA construction and operations are led on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI), and on behalf of Europe by ESO.

[#]The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

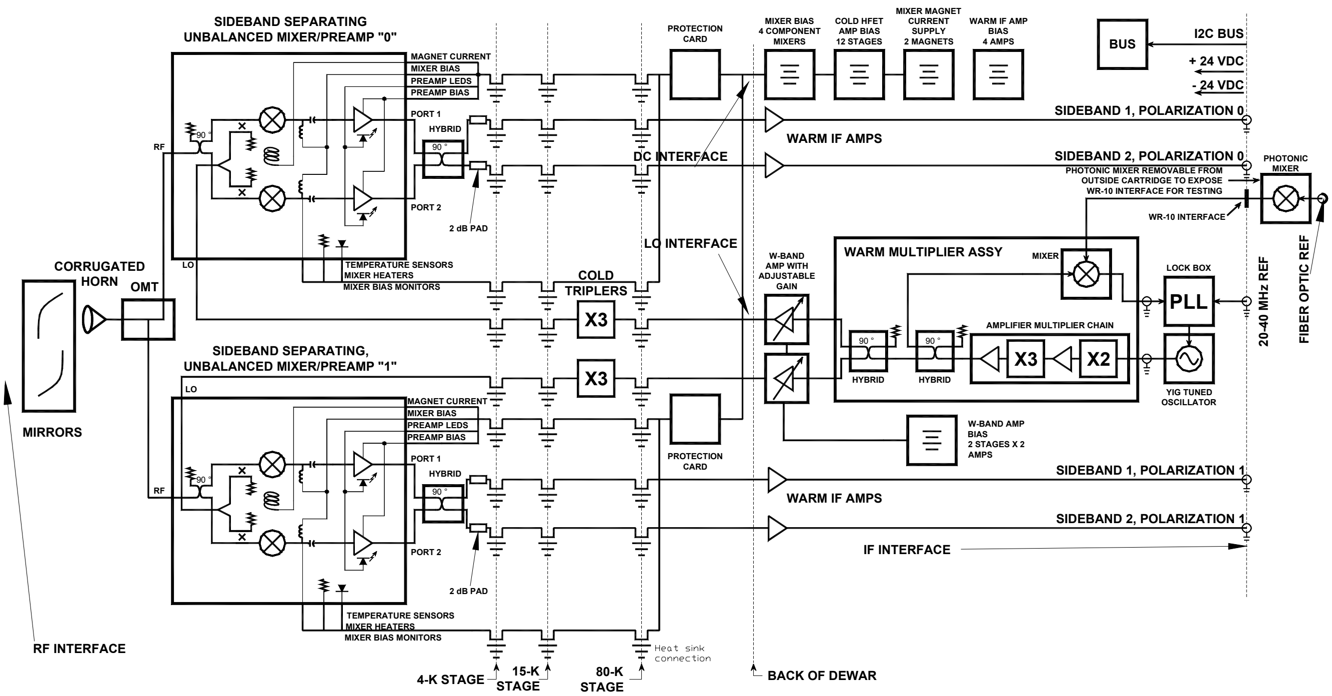

Fig. 1. Block diagram of cartridge.

< Quaternary mirror

< Feed horn

< Tertiary mirror

< 4 K plate

< 20 K plate

< 90 K plate

< Room temperature base-plate and vacuum flange.

Fig. 2. View of complete cartridge.

Temperature sensors are installed on each SIS mixer body and on the 90 K, 20 K and 4 K cartridge stages to facilitate troubleshooting the cartridge.

SIS mixers require a magnetic field across the junction to suppress Josephson currents. Each polarization uses a single superconducting coil and bifurcated pole pieces to concentrate the magnetic fields at each component mixer. Two independent magnet supplies are required per cartridge to deliver current to the superconducting coils.

On cooling, magnetic flux may be trapped in SIS mixers and can change the magnetic field required to suppress Josephson currents. In mixers with multiple junctions, such as the four-junction designs used in Band 6, trapped flux can affect the individual junctions to different degrees. Heating the mixer briefly above the superconducting critical temperature, typically to about 10 K for the niobium mixers used in this design, can eliminate trapped magnetic flux. Heaters are mounted on each mixer-preamp for this purpose.

In addition to the IF preamplifiers on the mixers, four additional amplifiers, one for each IF output, are located in the room temperature area on the back of the cartridge to increase IF output power levels prior to routing to the IF selector switch.

System Components

Optics and Horn

The RF signal enters the corrugated horn via two off-axis ellipsoidal mirrors thermally anchored to the 4-K plate. A Finite Element Analysis (FEA) indicates that the optical structure achieves better than the required deflections under gravity.

The original optics design was given in ALMA memo #362 [1]. This design was analyzed using GRASP software [2] which indicated that modification was required to obtain the desired performance. The new design [3] was manufactured and measured in the IRAM near-field antenna range. Measured results are shown in Figs. 3 and 4.

Figure 3 shows the beam waist radius (-8.7 dB radius) determined from the near-field measurements. Also shown are the expected waist radii for a Gaussian beam with 12 dB taper at the edge of the telescope secondary mirror, and the target of 10 dB edge taper from the Physical Optics (PO) calculations (curves overlap). Figure 4 gives the position of the waist (and the target position) relative to the mirror on the 4-K plate.

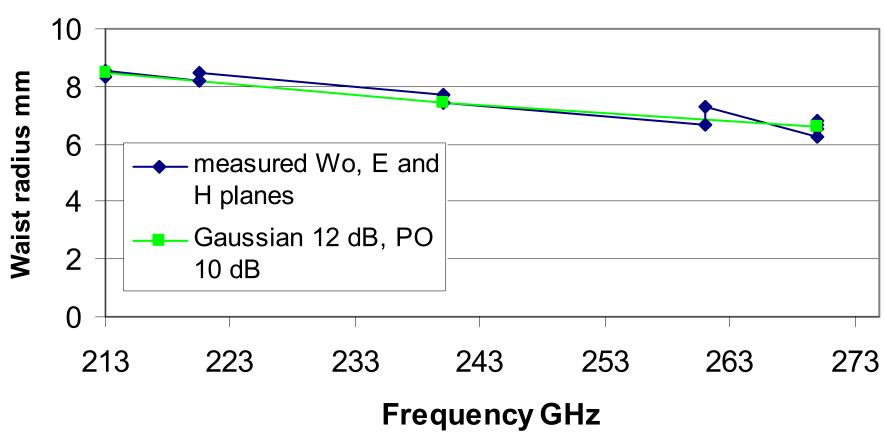

Fig. 3. Beam waist radii determined from the near-field measurements.

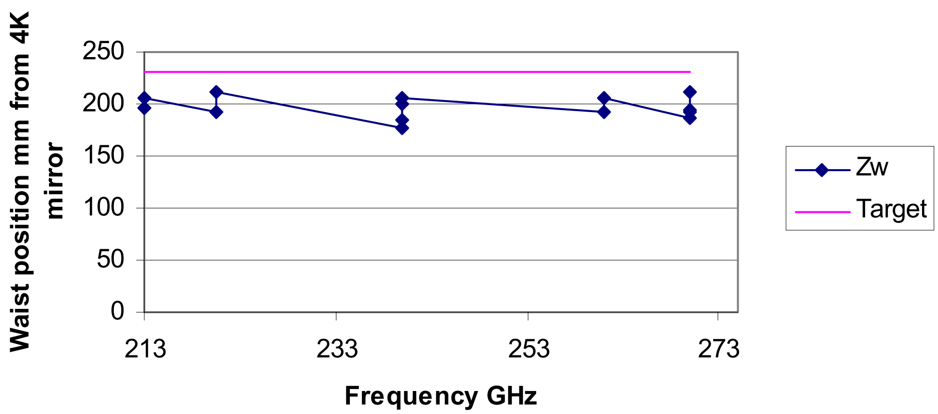

Fig. 4. Beam waist position (mm) above the 4 K tertiary mirror.

The original optics design also includes the requirements for the windows and infrared filters which are part of the outer vacuum container and not part of the cartridge. For the cartridge to meet the noise temperature specification, the window should have a loss of < 1% and a S_{11} < -20 dB, and each of the IR filters on the 90 K and 20 K shields should have a loss of < 1% and a S_{11} of < -20 dB [1].

Mechanical Finite Element Analysis of the Optical Mount

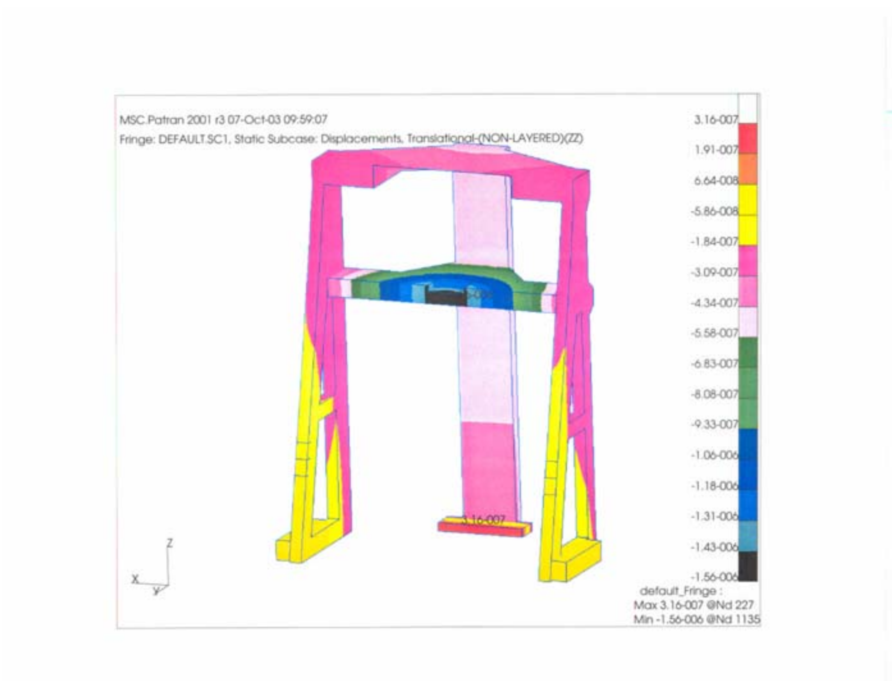

Fig. 5. Structure analyzed in FEA.

The Finite Element Analysis program MSC Patran was used to analyze the optics support structure shown in Fig. 5. The structure includes the frames and cross supports modeled as a single unit (*i.e.*, the frame was assumed to be a solid structure with no bolted sections), with masses of the components represented as point masses. These were 100g for the mirror directly above the mixer, 750g for all the components supported off the horn (OMT, mixer-preamps and one hybrid) and 20g for the hybrid attached on the right A frame. Two cases were analyzed, the first one with gravity in the *z* direction, and the second one with gravity in the *y* direction. Contour plots of the displacements in the *y* and *z* directions for both cases were made and Fig. 5 shows an example. The results indicate that the structure sags slightly in the -*z* direction under gravity in the -*z* direction. The quaternary mirror drops by 0.4 μm relative to the 4 K plate and the horn by 1.45 μm and both shift to the -*y* direction by approximately 0.8 μm. All other displacements in this case are less than 0.1 μm. With gravity in the *y* direction, both horn and mirror sag by approximately 0.8 μm with a shift in the *y* direction of 5.5 μm; all other displacements are less than 0.1 μm. According to the tolerance analysis for ALMA Band 6 [4], the horn may move relative to the quaternary mirror by 20 μm and the whole assembly relative to the tertiary mirror by 80 μm and relative to the base plate by 80 μm. So the calculated shifts are well within the tolerances for this band.

OMT

An orthomode transducer (OMT) is a passive waveguide device that separates the signal received by the feed horn into its two orthogonal linearly-polarized components. The original Band 6 design, as given in [5], has been modified to locate the two outputs opposite one another, thus allowing both mixer-preamps to be mounted directly on the OMT.

The goals for the OMT are: frequency range 211-275 GHz (fractional bandwidth > 0.4), with a return loss > 20 dB, an insertion loss < 0.2 dB, isolation > 40 dB.

The first OMT has been delivered and is being used in the prototype cartridge.

Mixers

The cartridge contains two sideband-separating SIS mixer-preamplifiers with separate signal and LO waveguide ports. There are no mechanical tuners. The design uses two simple DSB component SIS mixers in a single mixer block containing waveguide hybrids, LO power dividers and LO couplers (see paper by Kerr *et al.* in these Proceedings). Approximately -23 dB of the LO power is coupled to each of the building block mixers. Mixer heaters allow raising the physical temperature of the mixer junction above its critical temperature to remove trapped flux. The mixer heaters are Mini-Systems MSR thick-film resistors on alumina substrates with case size 2412 rated at 2W dissipation. The mixer heater is epoxied to a copper block which is bolted onto the mixer body.

Preamps

The IF preamplifiers directly connected to the IF ports of the SIS mixer are three-stage HFET MIC amplifiers with indium phosphide devices. The preamplifier covers 4 to 12 GHz when measured in a 50 Ω system, and has an equivalent noise temperature of 4-8 K with 30 dB of gain (see paper by Kerr *et al.* in these Proceedings).

IF

Four IF lines, two per polarization, are brought out of the cartridge on 2.18 mm (0.085 inch) outside diameter cable with stainless-steel inner and outer conductors. The interface between the cartridge and the rest of the system is at the rear of the base-plate of the cartridge, which holds the LO, bias, and monitor and control electronics. The interface for IF power is a "blind mate" BMA connector (Mil-Spec 83513).

To reduce passband ripple from VSWR effects, cold 2-dB attenuators are inserted at the outputs of the IF hybrids.

LO

There is a separate LO for each polarization to provide independent LO level control for each mixer. The LO interfaces on the base-plate of the cartridge are "blind mate" WR-10 waveguide flanges and include the waveguide vacuum window and waveguide feed-through. The "blind mate" interfaces simplify the removal of the cartridge warm electronics and LO modules by eliminating the need to open the cryostat. Inside the cartridge, there is a 75-mm stainless-steel WR10 waveguide between the 300 K base-plate and the 90 K stage for each polarization. Mounted to the 90 K stage is a settable attenuator (Custom Microwave LA10R –which consists of a movable piece of nichrome-metalized mylar, inserted in a section of WR10 waveguide) and another 75 mm section of coin-silver waveguide before the final multiplier (X3). The output of the final multiplier (WR-3) is tapered back to WR-10 for the stainless-steel waveguide run to the 4 K plate. For thermal reasons, this waveguide is stainless-steel but is over-moded to reduce losses (see [6]). The over-moded waveguide tapers back to WR-3.4 before the bends necessary to connect the waveguide to the mixer assembly. Fundamental waveguide modes are used in the bends to reduce the possibility of coupling to higher order modes which could lead to significant LO power loss from resonances.

Wiring

The Band 6 cartridge requires 96 wires between the vacuum flanges and the 4 K plate. Four ribbon cables are used; they consist of 36 AWG phosphor-bronze wires, twisted in pairs, and then 12 pairs (24 wires) are woven into a ribbon.

To reduce the risk of electrostatic discharge damaging the mixers, all bias wires to the mixers and preamps pass through a protection circuit mounted in the DC wiring, in vacuum but at room temperature.

All wiring is heat sunk at each of the stages (90 K, 20 K, and 4 K) to reduce the thermal loading on the following stage and on the mixers-preamps.

Thermal Considerations

Table 1 gives the allowed and achieved static heat loads for the cartridge. This includes the conduction of the 96 phosphor-bronze wires, four stainless-steel IF cables and the two LO waveguides.

Table 1: Cartridge thermal load with mixer-preamps and LO off.

Stage temperature	Allowed	Calculated
100 K	400 mW	375 mW
20 K	95 mW	69 mW
4 K	5 mW	1.8 mW

Table 2 gives the added loads when the cartridge is "on" – warming up or in operation.

Table 2: Additional cartridge thermal load with mixer-preamps and LO on.

Stage Temperature	Allowed	Calculated
100 K	833 mW	40 mW
20 K	67 mW	0
4 K	36 mW	36 mW

The "cartridge on" calculations include 7 mW of power dissipation in each preamp, the bias for the mixers and magnet currents at 4 K, and the LO power dissipated in the triplers operating at 90 K. All other loads (radiation, conduction between the stages) are excluded.

Measurements of the Prototype Cartridge

Typical measurements of single-sideband noise, sideband rejection, and gain (including cables to room temperature) for the mixer-preamp at a single LO frequency of 240 GHz are given in Fig. 6. The measurements were made at 1-GHz steps over the IF range (4-12 GHz). Figures 7 and 8 are the first measurements of a completed cartridge and show single-sideband noise temperature, sideband rejection, and gain. These data were collected with the LO frequency changed in 10-GHz steps and IF stepped by 1 GHz. The cause of the poor image rejection in polarization 1, not present in the mixer-preamp tested alone, is under investigation.

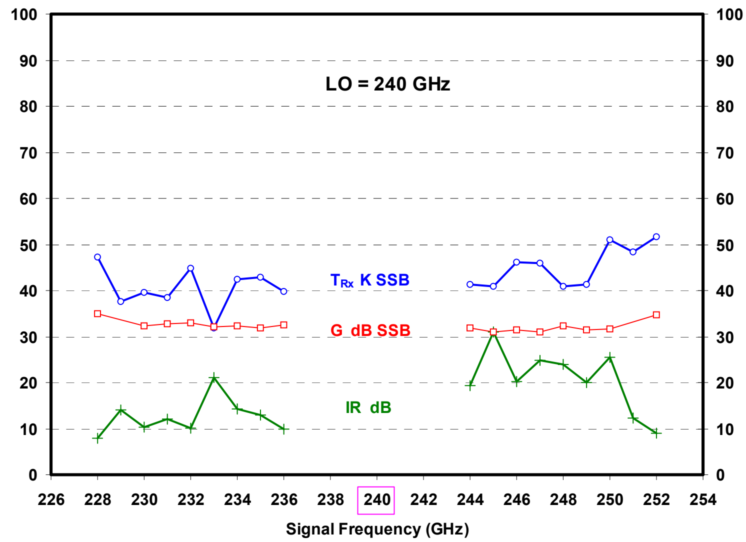

Fig. 6. Single-sideband noise, sideband rejection and gain of a mixer-preamp in both sidebands at an LO frequency of 240 GHz.

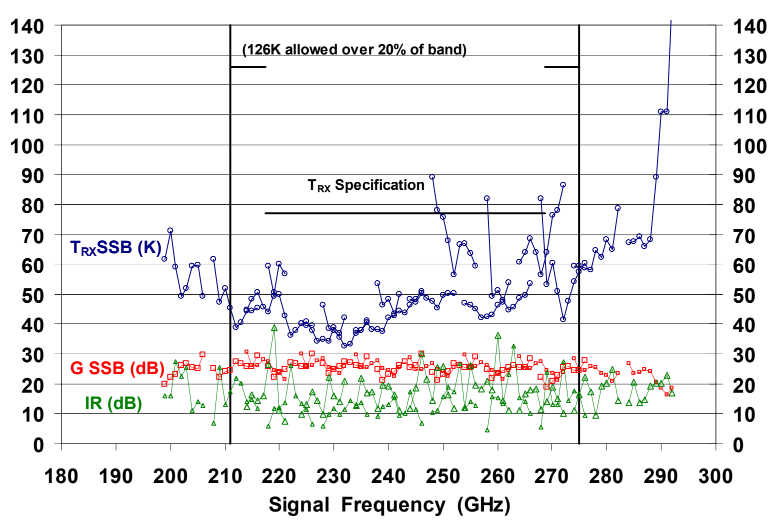

Fig. 7. Cartridge noise temperature, gain and image rejection for polarization 0, mixer heated to 4.2 K.

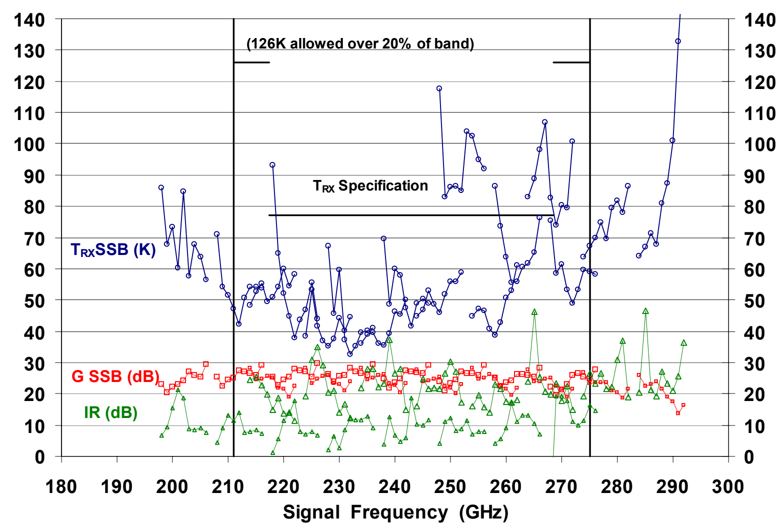

Fig. 8. Cartridge noise temperature, gain and image rejection for polarization 1, mixer heated to 4.2 K.

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