Next Generation Very Large Array Memo # 32

ngVLA Community Studies Report: Feed and Receiver Development at NRC Herzberg

L. Locke, L.B.G. Knee, F. Jiang, V. Reshetov
Herzberg Astronomy and Astrophysics Research Centre
National Research Council of Canada
and
L.A. Baker
Consultant

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1 Introduction

The Millimetre Instrumentation Group (MIG) at NRC Herzberg in Victoria, Canada develops and builds single-feed and multi-feed radioastronomy receiver systems for centimetre- and millimetre-wave astronomy as well as conducting research and development for critical receiver component technologies such as low noise amplifiers (LNAs). In the past the MIG has provided single-pixel heterodyne receivers for the James Clerk Maxwell Telescope and more recently the 73-cartridge Band 3 (84–116 GHz) receiver system for ALMA. Current development efforts include enhancements and upgrades to the Band 3 system, wideband high-sensitivity LNAs for MeerKAT and SKA, and cryogenic phased array feed receiver development for centimetre wavelengths. In a number of areas current MIG work complements the development and testing of the composite antennas program at NRC Herzberg in Penticton as well as being of potential interest for ngVLA development:

• W-band Receivers - development of a corrugated horn feed W-band receiver for field testing of the NRC DVA2 offset Gregorian composite materials telescope and for possible ALMA upgrades. This work builds upon the ALMA Band 3 system, but has key differences such as replacement of the $T_{\mathrm{Phys}} \sim 4$ K SIS mixer with a $T_{\mathrm{Phys}} \sim 20$ K MMIC system and an expansion of the IF from 4 GHz per sideband/polarization to 8 GHz. A number of options for LO distribution, down-conversion, and sideband separation are being explored.

• Vivaldi Phased Array Receivers - development of cryogenic PAF receivers for use in the centimetre- and millimetre-wavelength bands. Thin blade-type and thicker bullet-type Vivaldi feeds are being developed and at present a cryogenic PAF receiver for use in the 2.8 to 5.2 GHz range is actively under development. Traditionally Vivaldi feeds are used in phased array feeds to expand the field of view with respect to a single pixel feed with a small increase in receiver temperature due to the mutual coupling between the closely packed antenna elements. However instead of multiple beams used to increase the field of view, a small number of Vivaldi elements can be summed to form a single beam with adjustable beam weights to optimize either gain, beam shape, or antenna efficiency, depending on the desired application. In this way, effectively a single-pixel dual-polarization receiver can be made that easily covers the wide bandwidths without the use of an inherently narrow-band OMT.

• Q-band Receivers - development of a corrugated horn feed and cryogenic receiver for Q-band. This system is being developed as a possible technology for the Q-band system envisaged for the ngVLA and as a system for testing the high-frequency performance of the DVA2 composite antenna. This development builds on the development done at NRC Herzberg for the ALMA Band 1 receiver, in particular for the Band 1 OMT and preliminary development done for the LNA. A number of different design trade-offs are being explored, including using a fixed LO frequency to down-convert the entire RF band into one contiguous sideband or a tunable LO with a narrower IF. This Q-band receiver effort is the focus of this report.

2 Q-band Receiver Project Status

The goal for the Q-band receiver project is to design, build, and qualify a complete Q-band receiver prototype system for field operation. The receiver will be tested on the Dish Verification Antenna 2 (DVA2) at NRC Herzberg in Penticton. DVA2 is a single-piece rim-supported composite materials antenna having an unblocked aperture offset Gregorian design (feed up). Currently under construction, DVA2 has a primary surface accuracy goal of 350 μm RMS (Ruze efficiency 0.82 at 30 GHz and 0.58 at 50 GHz) in order to extend the useable frequency range up to 50 GHz. One of the objectives of our Q-band receiver development is to establish the antenna performance parameters of DVA2 at its high-frequency limit.

This document outlines the conceptual design and construction progress as of October 2017 of the Q-band receiver. Currently the cryostat, low noise amplifier, noise injection circuitry, and downconverter are in the design phase. The orthomode transducer (OMT) is already designed, machined, and tested as it is practically identical (except for a flange detail) to the ALMA Band 1 OMTs - which are being mass-produced by NRC for ALMA. Initial design of the feed horn involved frequency-scaling scaling a known design, verifying the beam patterns, and proving the machinability of the corrugations fine detail. The results were successful thanks to the excellent machining capabilities present in NRC's Design ad Fabrication Services group. Further refinement of the feed horn design to incorporate the dewar and telescope optics is ongoing.

The following sections detail the overall specifications. At the end of this report we provide an outlook of the planned future progress of the Q-band receiver project for DVA2 testing and the plans for further development more directly targeted towards the ngVLA.

3 System Design - Electrical

The overall specifications for the Q-band receiver are shown in Table 1.

The electrical block diagram of the cryogenic dewar, the post-amplification and filtering module, the downconverters, the fibre transmitter/receiver, the analog-to-digital converters, and the spectrometer are shown in Figure 1 and the major functions described in the following paragraph. A cryogenic environment provided by a 2-stage Gifford-McMahon cryopump system allows for 16 K and 70 K stages. The feed horn antenna, the OMT, the directional couplers, and the low noise amplifiers (LNAs) are all thermally sinked to the 16 K stage. Note the early design choice to put the feed horn inside the cryostat. This provides a noise advantage with respect to an ambient-temperature feed and avoids ambient-to-cryostat transition thermal design issues, but the relatively large feed opening angle required by the DVA2 optics

RF frequency range	35-50 GHz
Polarization	dual-linear
Receiver Noise Temperature	T_{RX}~25 K
Optics	Optimized for DVA2 telescope [1]
LNA Noise Temperature	T_{LNA}<12 K
Calibration	Noise injection via directional coupler preceding LNA
	Remote monitor and control ability

Table 1: Q-band receiver specifications

means a larger cryostat window. A description of the connections between the receiver, the compressor and the cabling off the telescope to the control building is outlined in Figure 2.

Cryostat Interior to the cryostat on the 16 K stage are: the feed horn, the OMT, two 30 dB directional couplers for noise injection, and two low noise amplifiers. The noise injection circuitry, including a noise diode and a 2-way power splitter, are on the cryostat's 300 K stage.

Post-amplification Outside the cryostat is a module for filtering and post-amplification which conditions the signal and provides more amplification before down-converting.

Downconverter After filtering and post-amplification, the signals are down-converted from the RF band of 35-50 GHz to the IF band of 1.25-2.50 GHz. This subsystem is still under design and it is important to note that this 1.25 GHz wide IF band is determined by limitations in the readily-available in-house digital systems and are not fundamental to the receiver.

Fibre Transmitter At the output of the downconverter, a commercial fibre transmitter with coaxial input and fibre output sends the IF signals from the telescope to the control building.

Fibre Receiver The fibre leaves the platform and is routed through the azimuth turn-head and pedestal base of the telescope, illustrated in Figure 2. It is further routed through a buried conduit to the control building, where it enters the fibre receiver.

ADC and Spectrometer The the analog-to-digital converter (ADC) is a commercial unit (Nutaq ADC5000) sampling in the second Nyquist zone at 2.5 GHz. The 4096-channel spectrometer is capable of 310 kHz resolution.

4 Cryostat Design - Mechanical

The cryostat layout is shown in Figure 3. The two-stage Gifford-McMahon cryopump and cold finger dimensions dictate the locations of the two cryogenic 16 K and 70 K plates along the axial direction. A 70 K heat shield will surround the interior 16 K components. Not shown is a multilayer insulation blanket that will surround all the 16 K components with the exception of the feed horn. The 16 K cold finger mechanically supports and is thermally connected to the feed horn, OMT, couplers, and LNAs. Thermal insulation is provided by stainless steel coaxial cables connecting the LNA outputs through the 70 K stage and the 300 K dewar output flange. The noise source and power divider are placed on the 300 K flange in order to avoid unnecessary heat loading on the cold stages. The following sections outline the design and status for the various receiver components along with interface details and transmission methods.

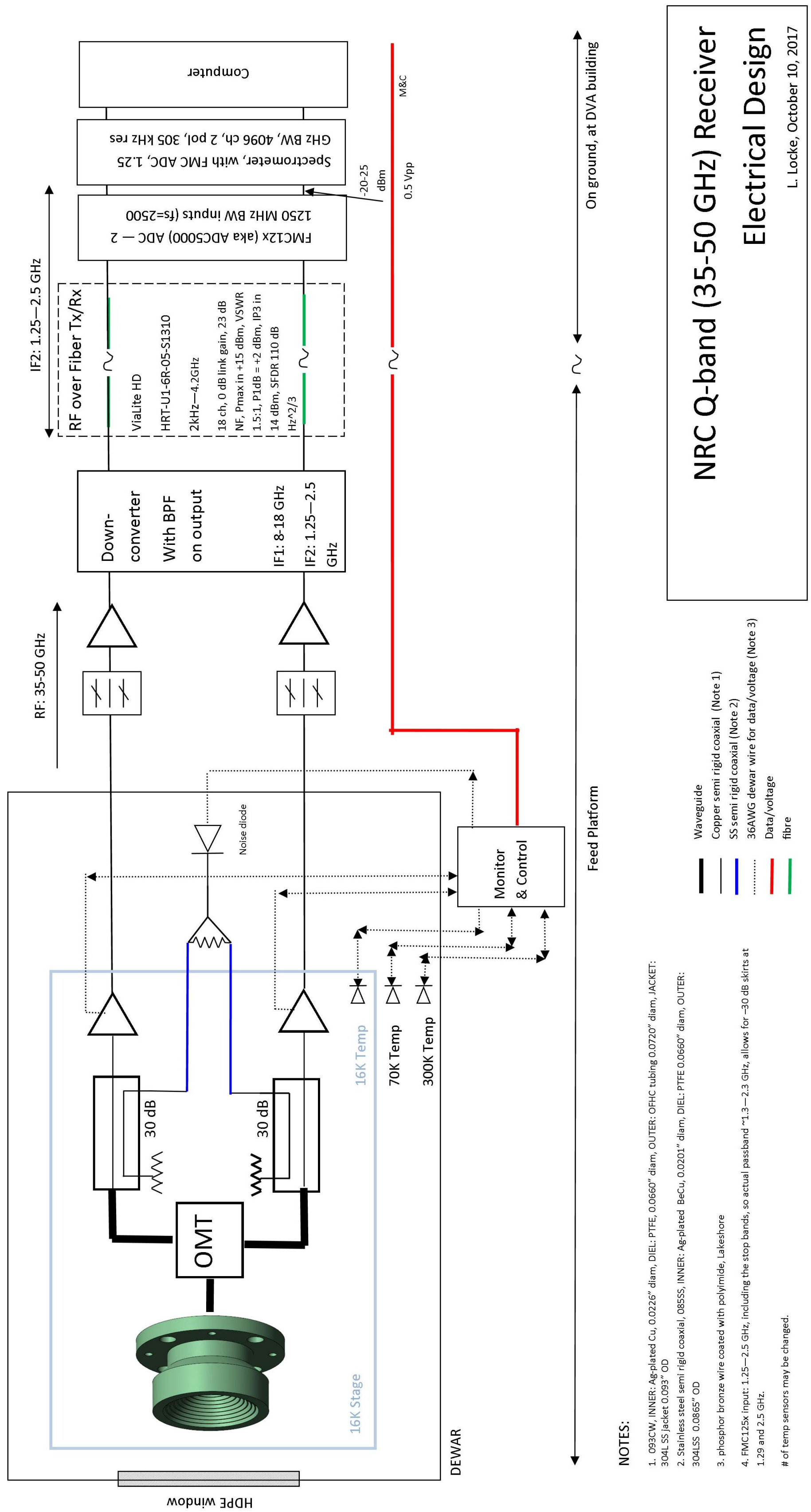


Figure 1: Q-band receiver electrical block diagram

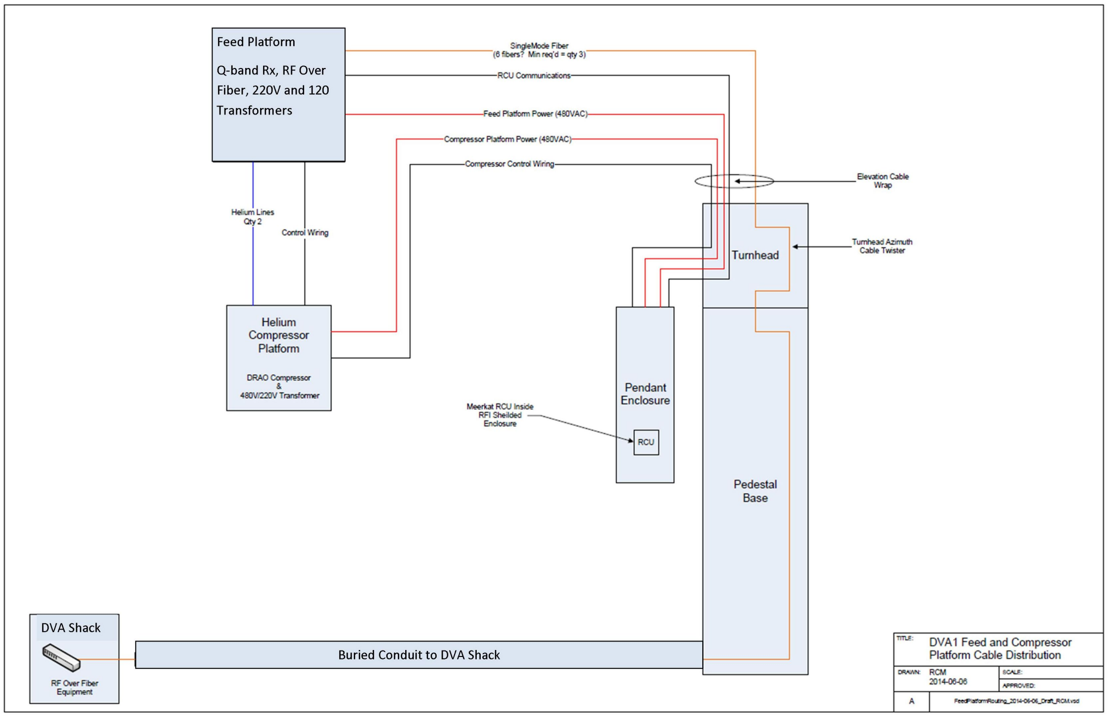


Figure 2: DVA2 telescope receiver and compressor platform cable distribution

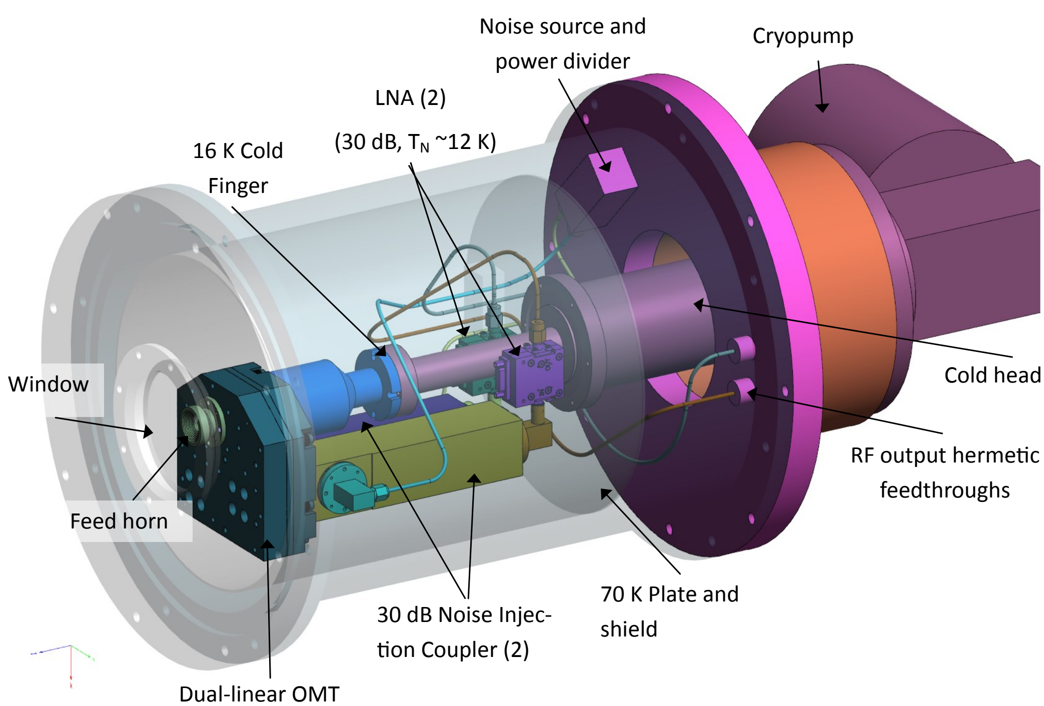


Figure 3: Cryostat mechanical design CAD layout

5 Feed Horn

The Q-band receiver system will be installed and tested on the DVA2 antenna and thus requires a feed horn which is matched to the wide-angle DVA2 optics designed for a feed pattern which tapers to -16 dB at the presented opening half-angle of 55° [1] with our design choice of covering the 35 to 50 GHz RF range.

Previously a feed horn was designed and manufactured for the DVA1 antenna covering the 0.75 to 1.5 GHz octave band (L-band). When modelled in the DVA1 optics the L-band feed horn produced excellent performance [2] which has been partially verified with on sky measurements [3]. The Q-band required design was produced by simply scaling the L-band design. The scaled L-band frequencies corresponding to the 35 to 50 GHz requirement are 0.83 to 1.18 GHz. The scaling ratio was determined by matching the input diameter of the horn waveguide to the output diameter of the existing OMT covering this band. Using this scaling ratio of 1/42.3045 allows the interpretation of the L-band simulated results at Q-band.

The basic design of the the feed horn is a variant of a "choke ring" type with extended corrugations which improve the bandwidth and beam characteristics. It is smaller than a typical feed horn with radial corrugations partly because there is no mode converter section. The axial corrugation configuration allows the design to be much shorter than typical which is useful at L-band. The feed horn, shown in Figure 4 was manufactured at NRC Herzberg in Victoria from Aluminum 6063, chosen to match the OMT's material.

The simulated input match S_{11} in Figure 5 starts at -21.8 dB at the low end (35 GHz), falling to below -30 dB at 42.1 GHz and staying below -30 dB past the upper band edge at 50 GHz. These results are for an Aluminum feed horn in free space. The receiver design has the horn inside the dewar, cooled to 16 K, and this requires a window in front of the horn. The window will inevitably degrade the match and the pattern somewhat so the design of the window will have to minimize this degradation.

The rotational symmetry of the co-polar feed horn pattern is excellent since this scaled band is in the single mode portion of the circular waveguide. (see Figures 6, 7, and 8). In the worst case the variation on the edge of the subreflector is 2% to 3% peak to peak. This has almost no discernible effect on the symmetry of the main beam on the sky.

The cross polarization of the horn pattern is the usual "four leaf clover" structure with alternating phases (see Figures 6 and 7). The maximum cross-polar value at (35, 42.5, 50) GHz is (30.0, 28.1, 30.7) dB respectively below the main beam peak (at +13.1 dB) with the cross-polar peaks well away from the $\theta = 0$ axis at $\theta = (35, 30, 22)°$. This pattern leads to low main beam cross polarization in the main beam with the peak well outside the -3 dB point on the main beam. The main beam cross polarization is below -30 dB inside the -3 dB points.

Feed to OMT	Circular waveguide, 6.7 mm diameter, Flange UG383/U MIL-F-3922/67B-006
OMT to directional coupler	Rectangular waveguide, WR 22, Flange UG383/U MIL-F-3922/67B-006
Directional coupler to LNA	2.4 mm coaxial connector
Directional coupler to power divider	Adapter, WR 22 to 2.4 mm
LNA to coaxial cable	2.4 mm coaxial connector

Table 2: Component interface details

Figure 4: Machined feed horn S/N 01

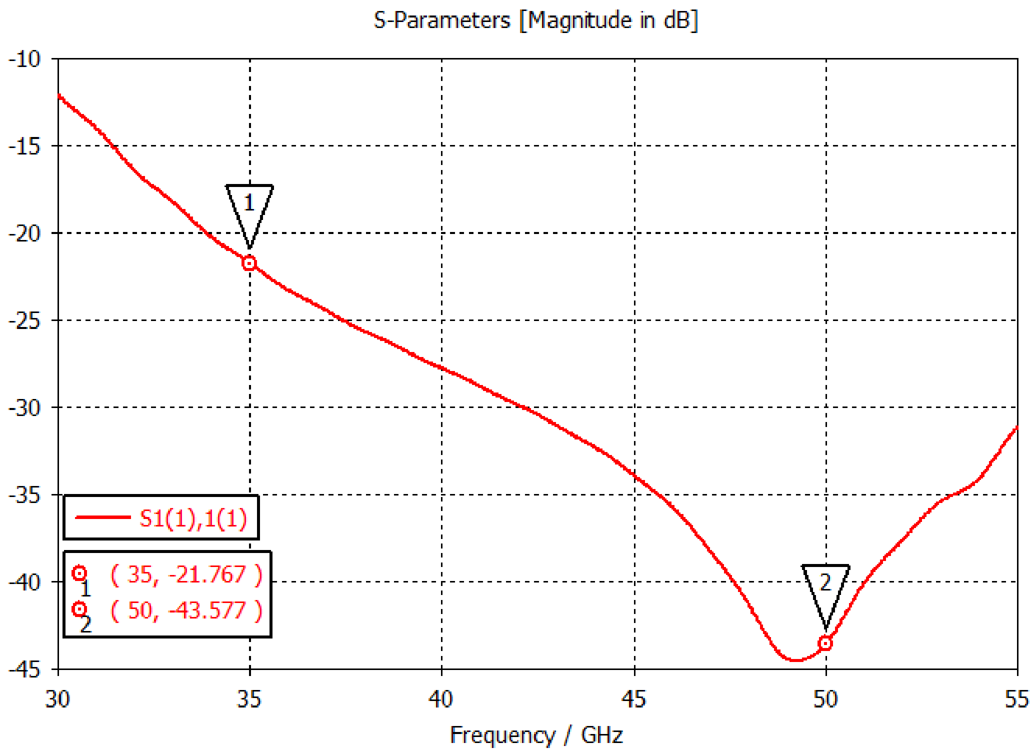


Figure 5: Feed horn simulated S_{11} versus frequency

The next stages of design will include simulations of the effects of the dewar window with dewar metal in proximity and simulations of the feed horn and dewar placed at focus of the DVA2 optics, optimizing the horn for maximum aperture efficiency.

6 Orthomode Transducer

The dual-linear OMT is modelled after the ALMA Band 1 production unit, described as the Version 3 OMT in [4] and [5] with specifications listed in Figure 3. It is a cryogenic 3-layered design with very low cross-polarization leakage and excellent performance in the 35-50 GHz band. The input is 6.7 mm circular waveguide , the output is WR 22 rectangular waveguide as seen in the ALMA Band 1 production unit in Figures 10a and 10b. Note that for the Q-band receiver, the output port detail will be modified from the ALMA Band 1 model shown in the figure in order to mate with the commercial directional coupler. ALMA Band 1 units have been designed, built and cryogenically tested at NRC Herzberg in Victoria and have achieved consistent machining and assembly, and highly repeatable performance. The room temperature RF performance of units S/N 01 through 05 are displayed in Figure 11 and the cryogenic performance is demonstrated in [5]. The RF performance of a typical ALMA Band 1 production model is shown in Figure 11.

7 Internal Calibration Unit

Internal power source measurements for cryogenic receivers are used for receiver system diagnostics as well as for measurement calibration purposes. It is traditionally performed using a noise diode to inject noise

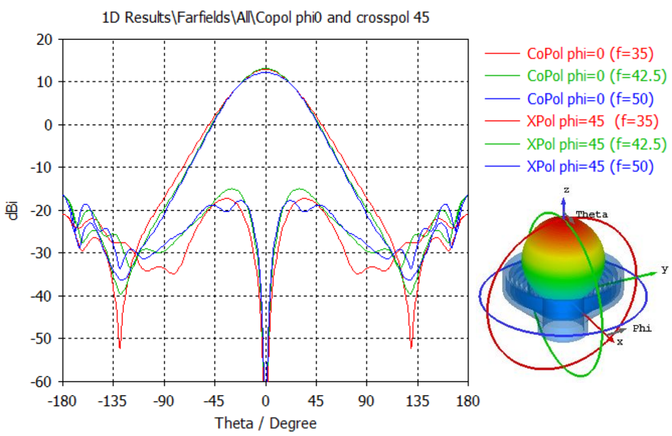


Figure 6: Simulated Q-band feed horn beam patterns for 35, 42.5, and 50 GHz - directivity (dBi) vs $\theta(°)$, co-polar $\varphi = 0°$, and cross-polar, $\varphi = 45°$. Inset: 3D co-polar beam at 42.5 GHz

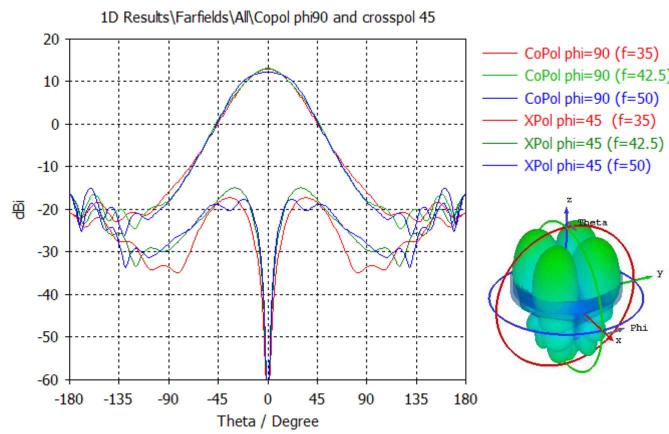


Figure 7: Simulated Q-band feed horn beam patterns for 35, 42.5, and 50 GHz - directivity (dBi) vs θ (°), co-polar $\varphi = 90°$, and cross-polar, $\varphi = 45°$. Inset 3D cross-polar beam at 42.5 GHz

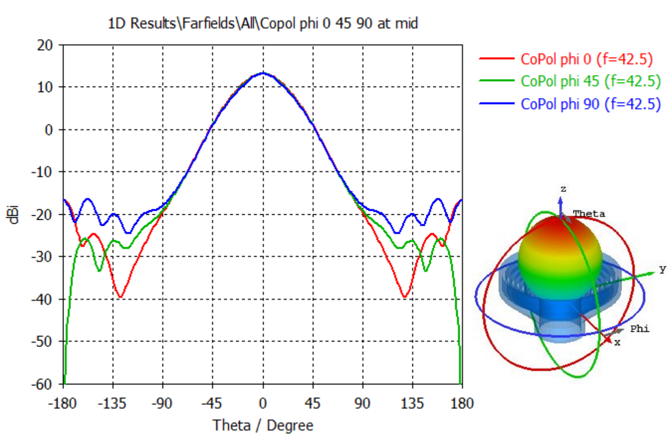


Figure 8: Simulated Q-band feed horn beam patterns, midband at 42.5 GHz - directivity (dBi) vs $\theta(°)$, co-polar $\varphi = 0°, 45°, 90°$. Inset 3D co-polar beam at 42.5 GHz

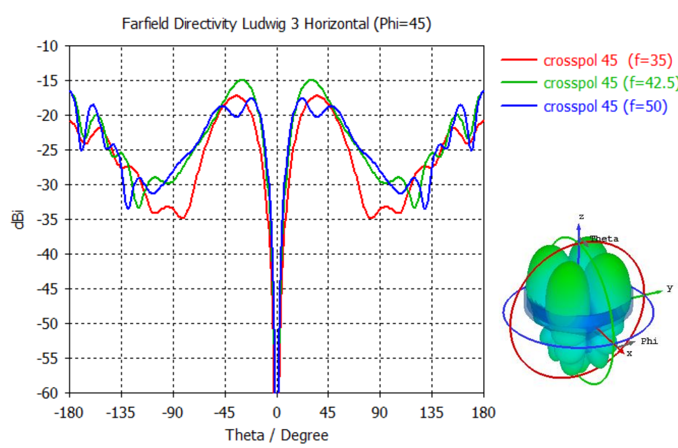
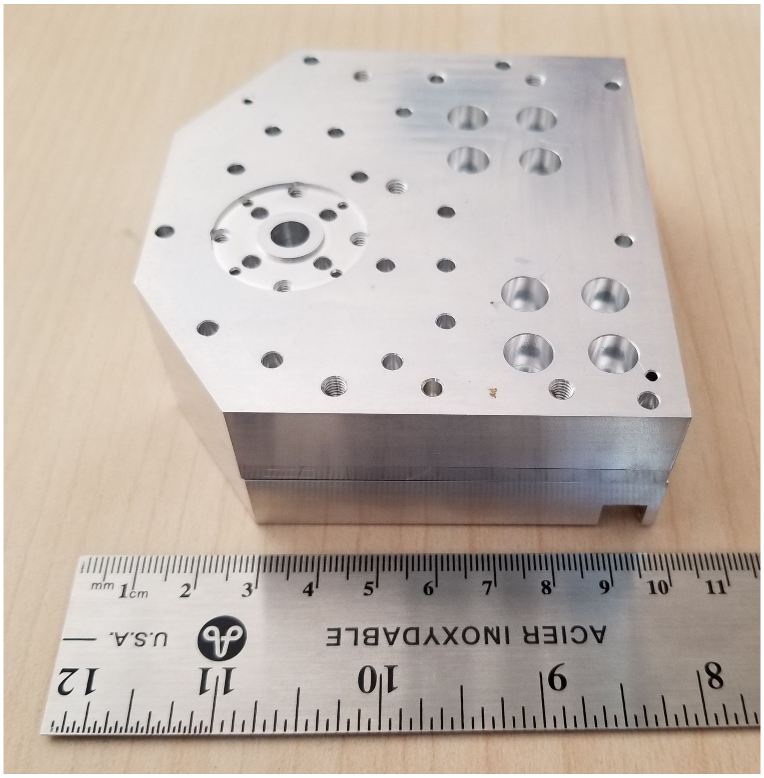


Figure 9: Simulated Q-band feed horn beam patterns at 35, 42.5, and 50 GHz - directivity (dBi) vs $\theta(°)$, cross-polar, $\varphi = 45°$. Inset 3D cross-polar beam at 42.5 GHz

S_{11}(reflection)	< -20 dB
S_{21}, S_{31}(thru)	> -0.6 dB
S_{21}, S_{31}(cross)	< -40 dB
S_{32}(isolation)	< -45 dB

Table 3: OMT specifications



(a) Input face: circular waveguide port

(b) Output face: 2 x WR 22 waveguide ports

Figure 10: ALMA Band 1 machined OMT

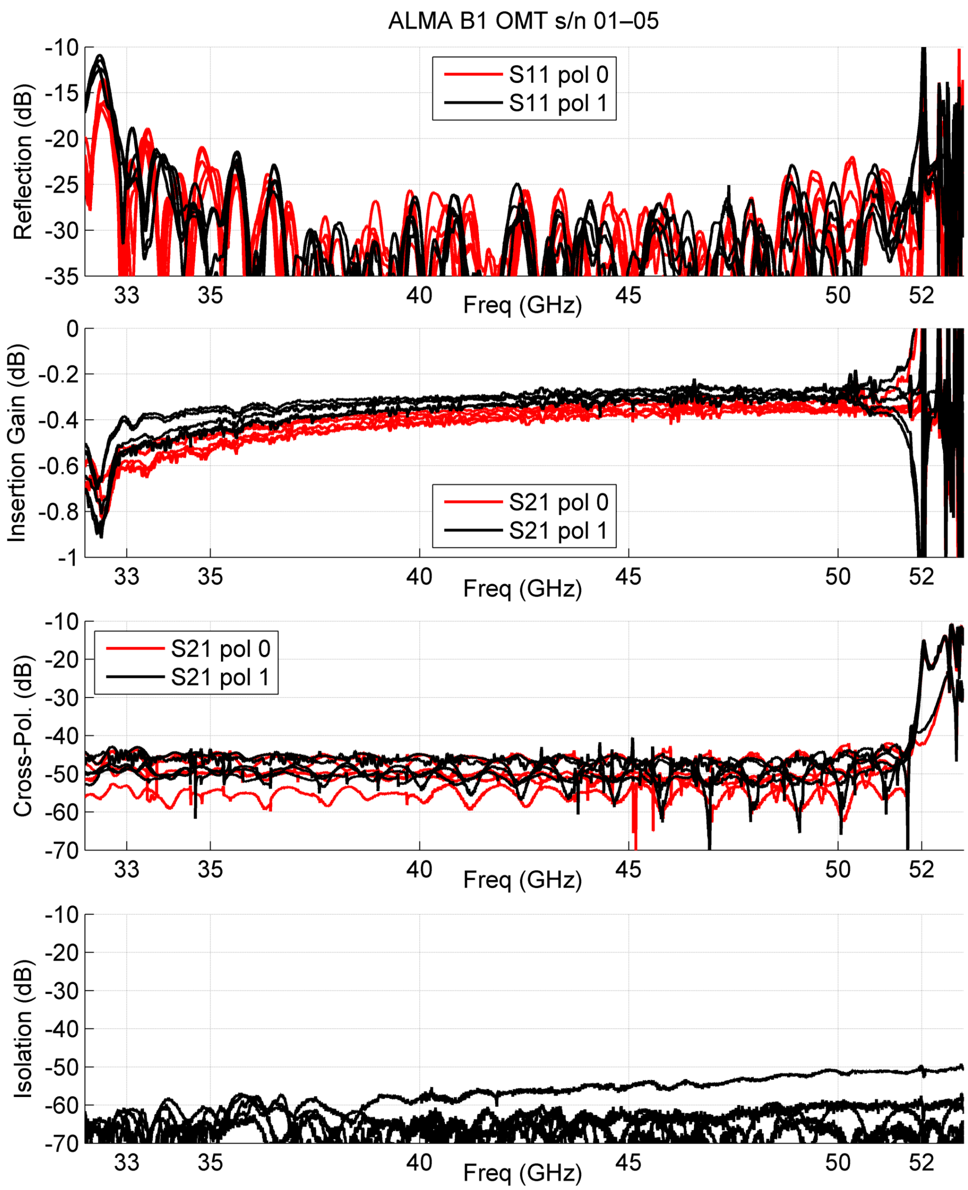


Figure 11: Measured room temperature RF performance of OMTs S/N 01-05

Frequency	35-50 GHz
Gain, S_{21}	$>$ 30 dB
Input match, S_{11}	$<$ -10 dB
Output match, S_{22}	$<$ -10 dB
Isolation, S_{12}	$<$ -50 dB
Noise	$<$ 12 K

Table 4: Low noise amplifier specifications

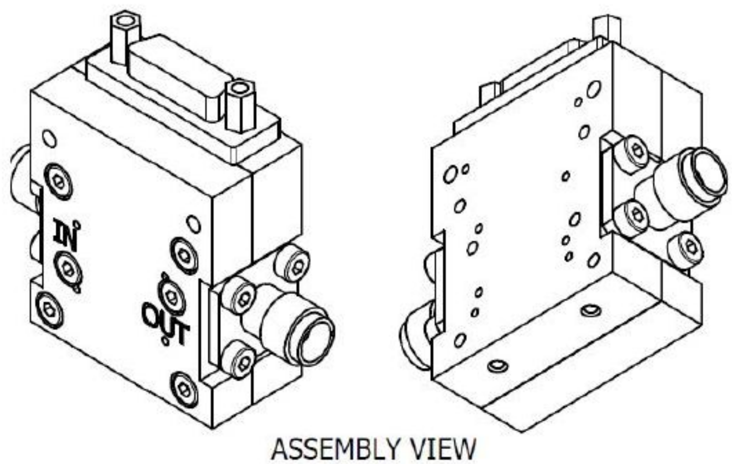


Figure 12: Low noise amplifier body - mechanical drawing

via directional couplers placed after the OMT outputs and before the LNA inputs. Usually the injected noise level is set to approximately 5-10% of the total system noise temperature, i.e. T_{cal} is between 1-2 K [6, 7] in order to ensure the receiver remains in its linear response regime when the calibration signal is turned on. For the Q-band receiver the noise diode and power splitter will be placed on the 300 K stage inside the cryostat in order to shield the circuit from signals external to the cryostat and to reduce the heat loading on the 16 K stage (the power dissipation of a noise diode is typically several hundred mW). Commercial 30 dB directional coupler units with WR 22 waveguide ports are available. Two WR 22-coaxial adapters are placed on the coupled and output ports of the directional couplers. Both coupled ports lead to the 3 dB power divider on the 300 K stage via stainless steel coaxial cables. The output port of the directional coupler leads directly to the LNA. This can be seen in the receiver block diagram in Figure 1. The internal calibration unit will be assembled and tested within the next few months.

8 Low Noise Amplifiers

A low noise amplifier with the specifications in Table 4 is currently under design. A 5-stage discrete amplifier design is underway and will be built and testing within the next several months. A MMIC version of the amplifier is also under development and will be available on a longer timescale.

NRC Q-Band Rx		Phys. Temp	NF/C	Gain	Gain	Tcomp	Trx
2017 10		(K)	(dB)	(dB)	(linear)	(K)	(K)
Dewar	HDPE Weather Window	300		-0.01	0.9977	0.692	0.69
	Feed Horn	16		-0.05	0.9886	0.186	0.88
	OMT	16		-0.25	0.9441	0.961	1.84
	Cal Coupler (thru path)	16		-0.25	0.9441	1.018	2.86
	Cal Coupler (coupled path)	300	-30	0	1.0000	0.300	3.16
	WG to Coax	16		-0.5	0.8913	2.221	5.38
	LNA	12		30	1000.0000	15.317	20.69
	Stainless Steel Coax	159		-2	0.6310	0.119	20.81
Post-Amp Module	Filter (35-50 GHz)	300		-2	0.6310	0.355	21.17
	RF Post-Amp	300	4.5	20	100.0000	1.926	23.09
Downconverter	Downconvert* (to 1.5-2.5 GHz)	300		-9	0.1259	0.067	23.16
	Amplifier	300	3	25	316.2278	0.076	23.24
	Filter (1.5 - 2.5 GHz)	300		-2	0.6310	0.045	23.28
Fibre Trx	Fiber Optic Tx/Rx	300	23	0	1.0000	0.000	23.28
	*estimated						

Figure 13: Cascaded noise estimation for Q-band receiver. Phys. Temp is the physical temperature of the component (K), NF/C is the noise figure/coupling of the component (dB), Gain is the power gain (+) or loss (-) of the component (dB or linear), Tcomp is the calculated noise temperature of the component (K), and Trx is the cumulative receiver noise temperature from the dewar window as the first component to the output of the component (K)

9 Cascaded Noise Analysis

The estimated cascaded receiver noise temperature referenced to the cryostat window is shown in Figure 13. This incorporates contributions from the cryostat (dewar) components, post-amplifier module, downconverter, and fibre transmitter/receiver. The noise contribution from the cryostat alone is 20.81 K, and from the entire receiver including cryostat, post-amplifier module, downconverter and fibre transmitter is 23.28 K. The contribution from sky noise, spillover, and contributions of added noise as a function of elevation angle are not included, but will be addressed in a future analysis that incorporates the telescope optics.

10 Outlook

At this point in the project, we are well advanced on a conceptual design and have some critical receiver components available. The priority is to move on to a preliminary design suitable for deployment on the DVA2 telescope. Among the critical components requiring significant development work is the cryogenic LNA, but past experience with LNA development for ALMA Band 1 and the expertise of the NRC Herzberg LNA group indicates this is low-risk. The current schedule for the future of this project is

Date	Item
2017Q1	Functional and performance requirements established, scheduling - complete
2017Q4	Conceptual design - complete
2018Q1	Preliminary design including full mechanical details
2018Q2	Construction

Table 5: Future project milestones and delivery dates

shown in Table 5. The preliminary design phase which is now beginning will include the full mechanical design and thermal analysis (planned for completion by early 2018), with construction set to commence in the summer of 2018.

Acknowledgements

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