NA Development Cycle 2

ALMA Band 2plus Prototype Project

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plus represents 67-95 GHz
enhanced frequency coverage

NRAO NSF Associated Universities Inc

ALMA Band 2 Prototype Project

Outline / Overview

1. Why build a Band 2 prototype?
2. Configuration of the Band 2 prototype receiver.
3. Progress report / Status of the Band 2 prototype receiver.
4. Remaining work before a we can move to propose a full build out for Band 2.
5. Outline of future plan to get to implementation/construction phase.

ALMA Band 2 Prototype Project

Science Case

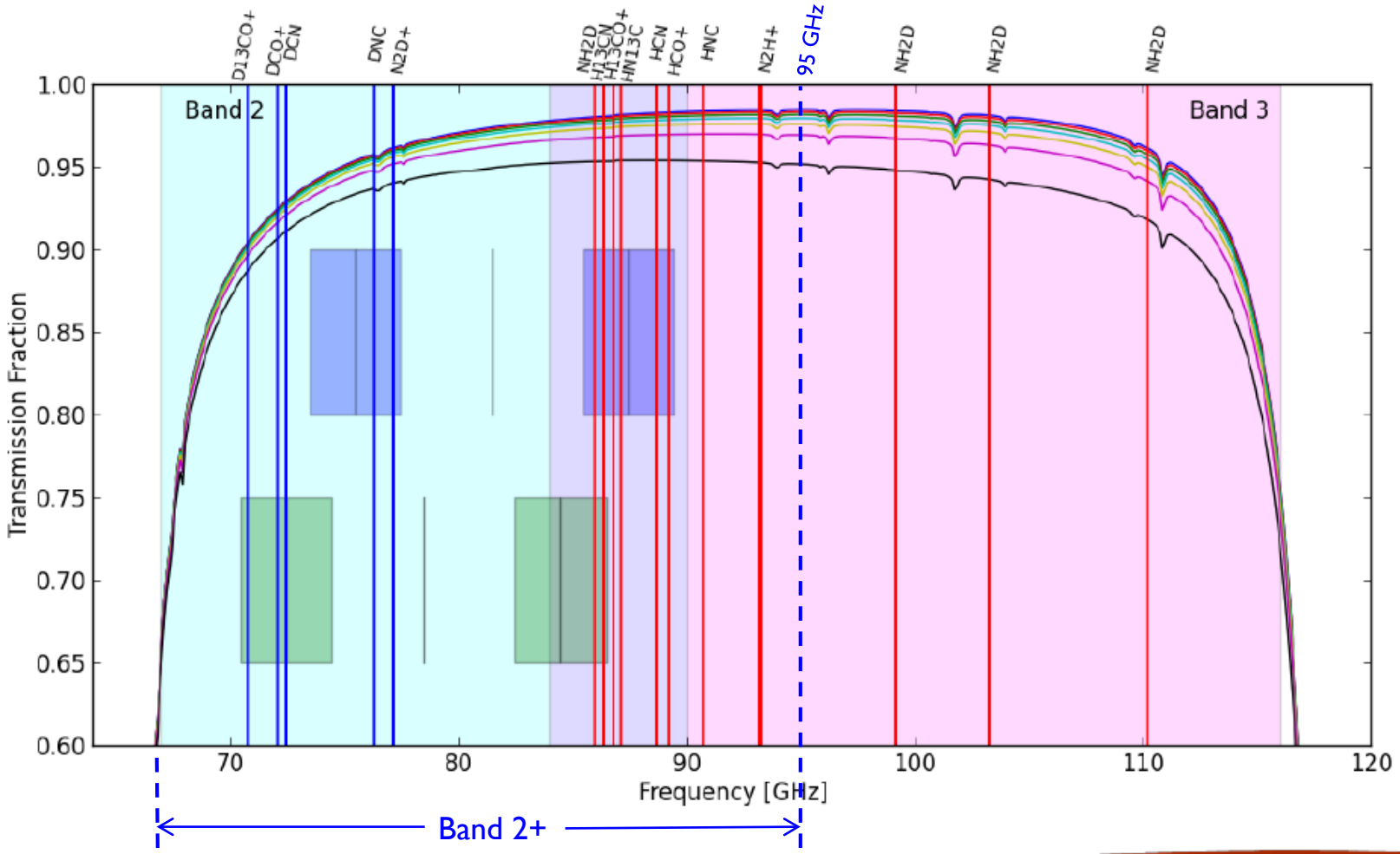
Band 2 is the one frequency band in the baseline ALMA design which remains to be completed. Primary objectives include:

- To cover the largely unexplored 4 mm band, previously available only on the 12 m Kitt Peak telescope (ARO) and very recently on the GBT (NRAO).
- Access the J = 1 → 0 transitions of the deuterium analogs of common, abundant interstellar molecules, including DCO^+, DCN, N_2D^+ & C_2D, as well as $H_2{}^{13}CO$, $^{13}C_2H$, $H^{13}CO^+$, $HC^{18}O$, $H^{13}CN$, $HC^{15}N$, H_2CO, $HCNH^+$ and C_2H.
- "Cold chemistry", using the lowest energy transitions of simple deuterated species to trace the coldest and densest areas of star-forming cores and proto-planetary disks.
- Study galaxies and clusters at low intermediate redshifts – this is currently unavailable with the present ALMA bands for the important CO(1 → 0), HCN(1 → 0), HCO^+(1 → 0), HNC(1 → 0), and SiO(2 → 1) transitions.

ALMA Band 2 Prototype Project

Band 2+
67-95 GHz

Valuable to cover spectral lines up to ~ 95 GHz. Band 2+ ?



ALMA Band 2 Prototype Project

Team Members / Contributors

- Low Noise Amplifiers:
  - Marian Pospieszalski (MIC)
  - Kieran Cleary & Team at CRAL (MMIC)
  - Matthew Morgan
- Optics:
  - Sri Srikanth
  - Alvaro Gonzalez
- Down Converter:
  - Dustin Vaselaar
  - Jim Muehlberg
  - Matthew Morgan
  - Kamaljeet Saini
- Local Oscillator:
  - Dustin Vaselaar
  - Jim Muehlberg
  - Kamaljeet Saini
- Cold Cartridge:
  - Kirk Crady
  - Greg Morris
  - Arthur Symmes
- Shop & Chemistry Lab:
  - Greg Morris
  - Gerry Petencin
- Evaluation / Metrology:
  - John Effland
  - Morgan McLeod
  - Kirk Crady
  - John Buchanan
  - Kamaljeet Saini
- Consultancy & Support:
  - Matthew Morgan
  - S K Pan
  - Robert Dickman

ALMA Band 2 Prototype Project

Project Summary - I

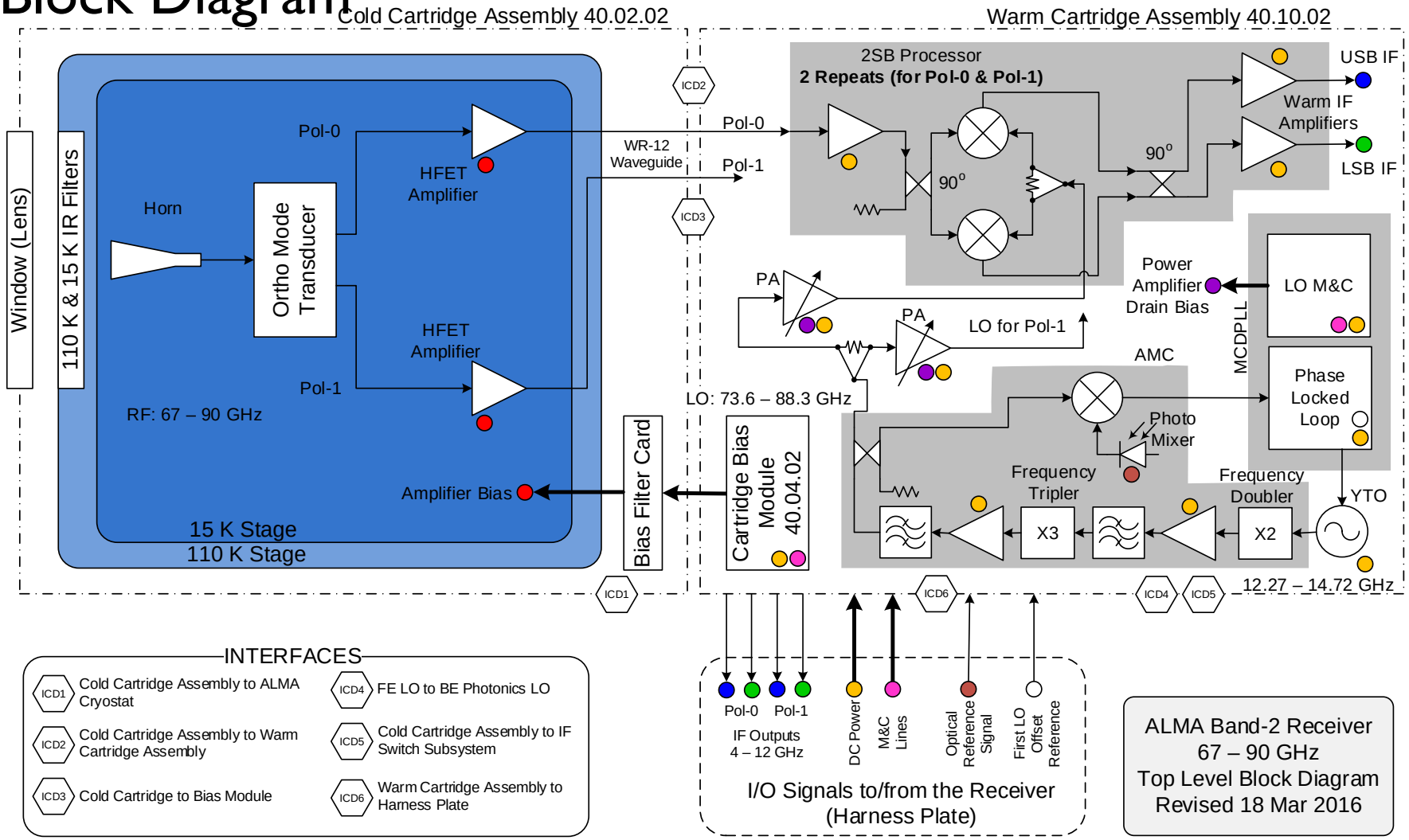
- The first ALMA Band 2 receiver (cold cartridge, local oscillator, as well as IF down converter) has been constructed.
- Even at the outset, the two year development project timeline was very tight to develop (design, fabricate and construct) MMIC based LNAs and then construct the receiver in a serial fashion.
- Consequently, we have constructed the receiver prototype around NRAO/CDL MIC (chip and wire) E-band LNAs in parallel with the CRAL MMIC effort, which is now beginning to produce results. Receiver will be upgraded with MMIC LNAs when they are delivered in September 2016.
- This presentation provides an overview of important cartridge component performances, cartridge (cold and warm) construction and alignment details, and significant receiver performance metrics (but not comprehensive compliance data, which has been taken and incorporated into the design report).

ALMA Band 2 Prototype Project

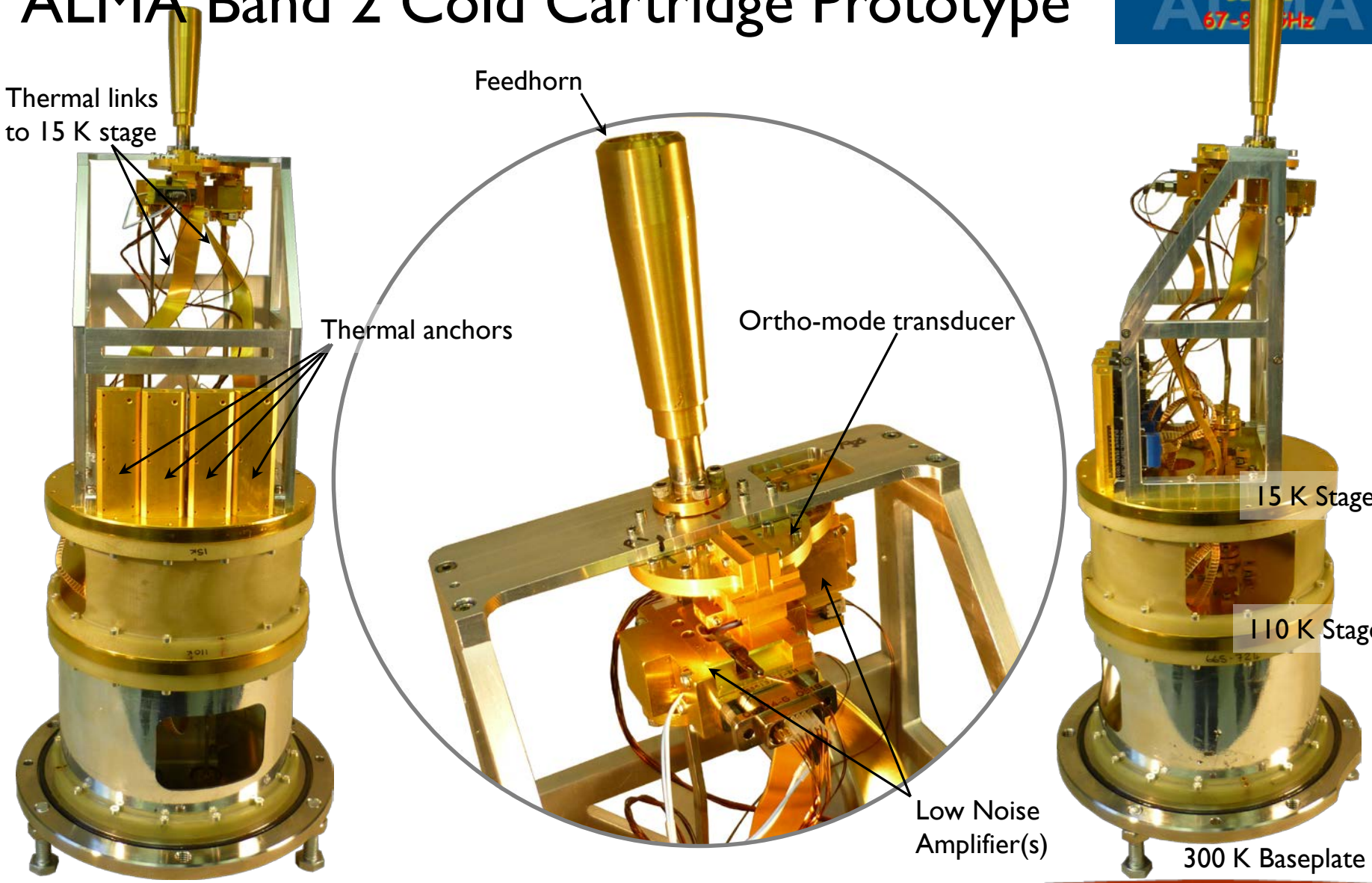
Project Summary - II

- Test results indicate that even the state-of-the-art E-band MIC LNAs barely meet the overall ALMA Band 2 noise specification by themselves. Allowing for additional noise degradation from the optics, it will be difficult to meet the existing ALMA noise specification by using them. Recent MMIC results appear promising (their noise temperature averaged over 67-90 GHz is ~10 K better compared to MIC amplifier average noise performance) and the receiver will be upgraded with MMIC LNAs when they are received in September 2016.
- The optics specifications are generally met with the exception that there are dips in polarization efficiency at specific frequencies that fall below the 99.5% specification value. These are attributed (both by measurements as well as by simulations) to an interaction of the 15 K IR filters with the horn aperture – an effect also seen on some other ALMA bands. (Discussing proposal to remove 15 K IR filters for both Band 1 and 2 to address this issue).

ALMA Band 2 Receiver Prototype Block Diagram

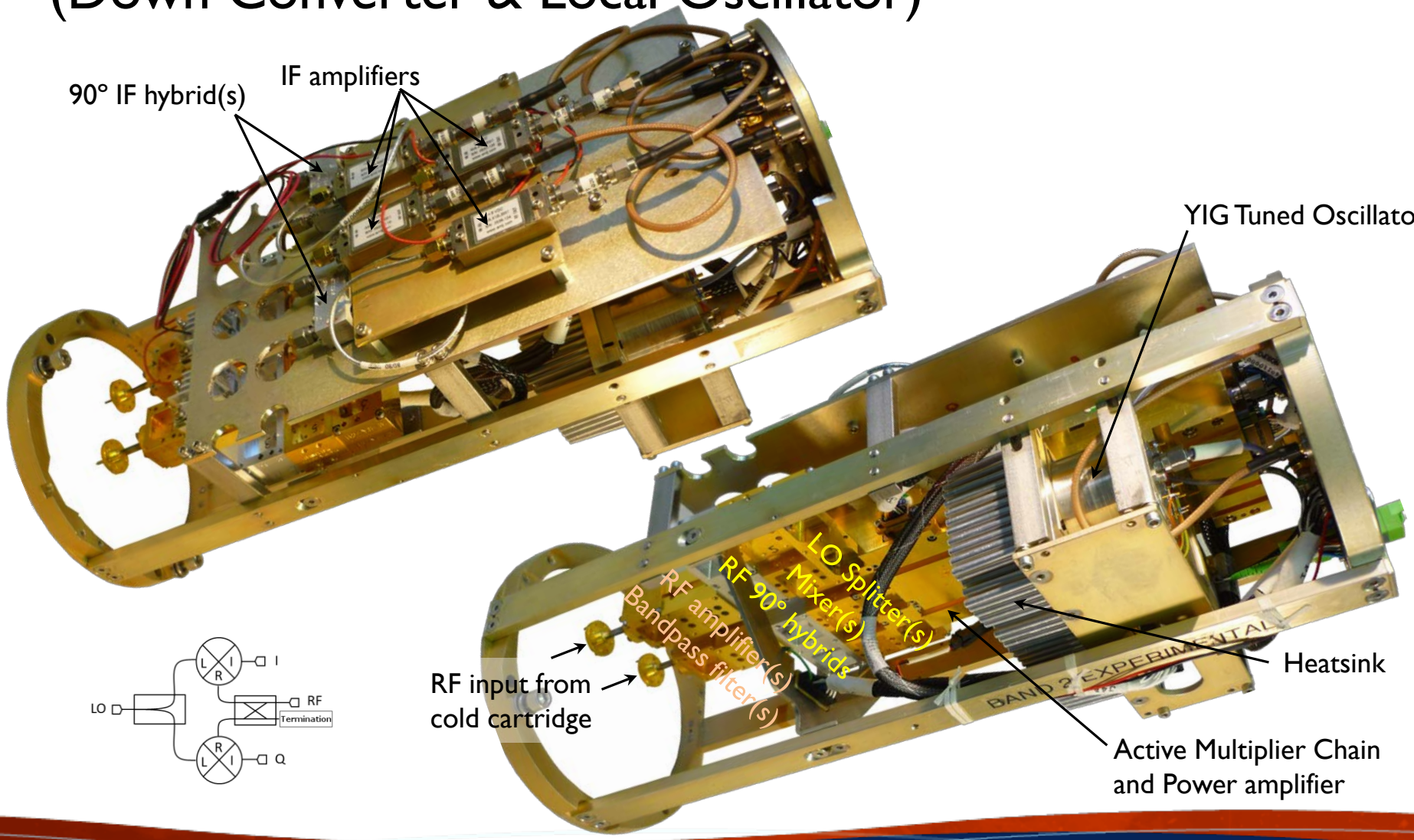


ALMA Band 2 Cold Cartridge Prototype



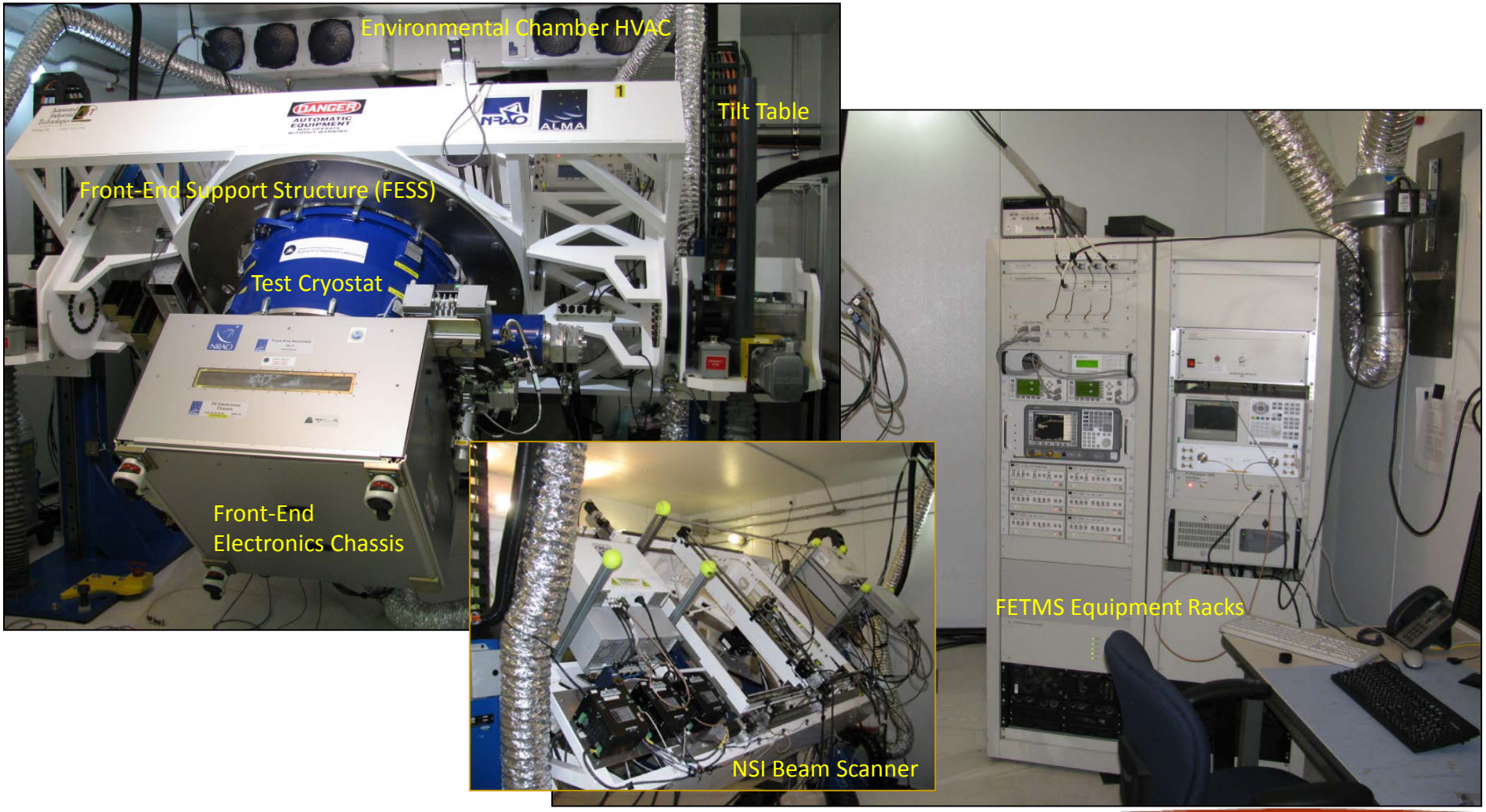
ALMA Band 2 Warm Cartridge Prototype

(Down Converter & Local Oscillator)



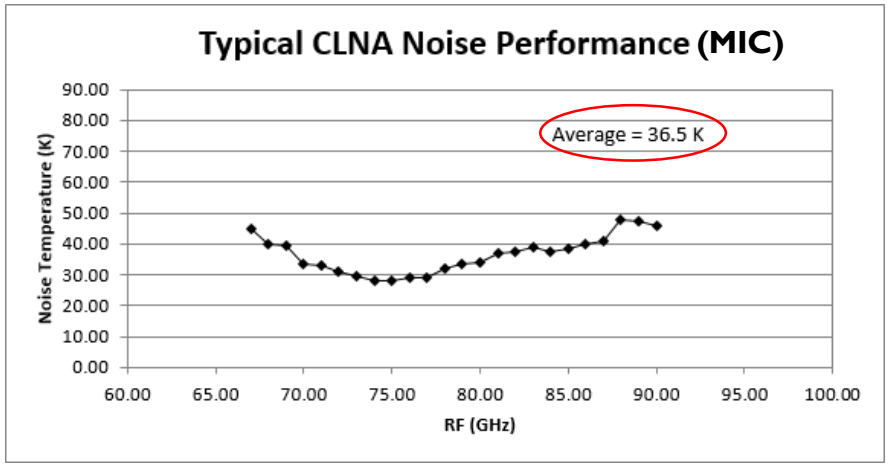
ALMA Band 2 Receiver Prototype

Evaluation in the ALMA Cryostat



ALMA Band 2 Receiver Prototype

System Noise Temperature Estimation



Band 2 Receiver stage	Gain	Cumulative Gain to preceding stage	Noise Figure	Noise Temperature	$T_{equivalent}$ (for MIC based)	$T_{equivalent}$ (for MMIC)
Lens/Window (room temperature)	-0.1 dB	0.0 dB	0.1 dB	8.9 K	8.9 K	8.9 K
IR Filters (15 K and 80 K)	-0.1 dB	-0.1 dB	0.1 dB	1.4 K	1.5 K	1.5 K
Feedhorn (15 K)	-0.1 dB	-0.3 dB	0.1 dB	0.3 K	0.4 K	0.4 K
OMT	-0.1 dB	-0.4 dB	0.1 dB	0.3 K	0.4 K	0.4 K
E-Band Amplifier (15 K)	35.0 dB	-0.5 dB		36.5 K	40.6 K	29.2 K
Waveguides, feed-thru and BPF	-4.0 dB	34.5 dB	4.0 dB	453.6 K	0.2 K	0.2 K
E-Band Amplifier (room temperature)	14.0 dB	30.5 dB	3.5 dB	371.6 K	0.3 K	0.3 K
2 SB Downconverter	-12.0 dB	44.5 dB	12.0 dB	4454.7 K	0.2 K	0.2 K
Warm IF Amplifier	30.0 dB	32.5 dB	2.0 dB	175.5 K	0.1 K	0.1 K
Total	**62.5 dB**				**52.4 K**	**41.1 K**

ALMA Band 2 Receiver Prototype

Thermal Budget(s)

From ALMA Front End Thermal Budget, FEND-40.00.00.00-050-B-GEN:

15 K Stage	Bands 1 - 2	Band 3	Bands 4 - 5, 8 - 10	Band 6	Band 7	Sum
Passive heat load	95 mW	95 mW	95 mW	75 mW	115 mW	950 mW
Active heat load	90 mW	20 mW	67 mW	67 mW	15 mW	200 mW
Total heat load	185 mW	115 mW	162 mW	162 mW	130 mW	1150 mW

110 K Stage	Bands 1 - 2	Band 3	Bands 4 - 8	Bands 9 - 10	Sum
Passive heat load	450 mW	350 mW	700 mW	600 mW	5950 mW
Active heat load	150 mW	50 mW	150 mW	250 mW	550 mW
Total heat load	600 mW	400 mW	850 mW	850 mW	6500 mW

- Requirements met comfortably for 15 K stage, CLNAs dissipate 15-30 mW each (article to article variation, depends on optimization).
- No active component on the 110 K stage.

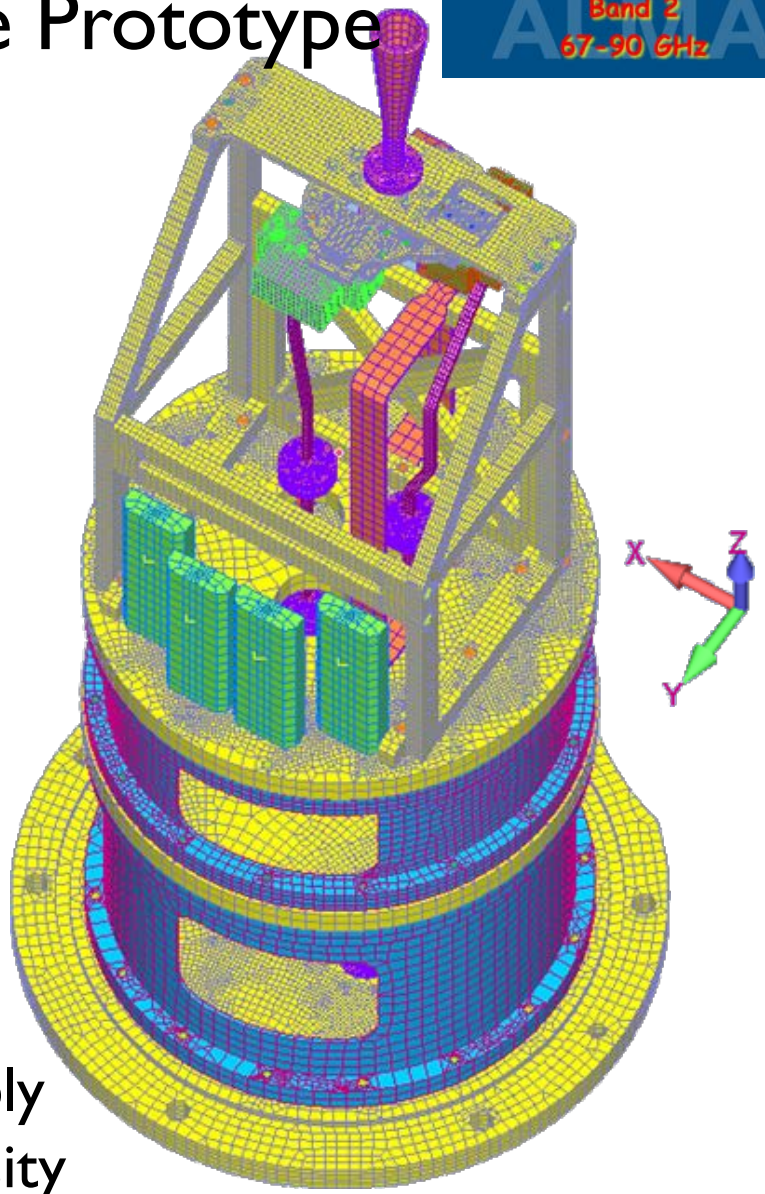
ALMA Band 2 Cold Cartridge Prototype

Band 2
67-90 GHz

Mechanical Analysis

A mechanical design analysis was performed by employing the Finite Element Analysis (FEA) technique using the NX NASTRAN version (with FEmap) provided by Siemens.

Temperature distributions, stresses, & deflections (both gravity and temperature induced), and vibrational modes and frequencies calculated.



Band 2 Cold Cartridge Assembly FEA Model showing mesh density

ALMA Band 2 Cold Cartridge Prototype

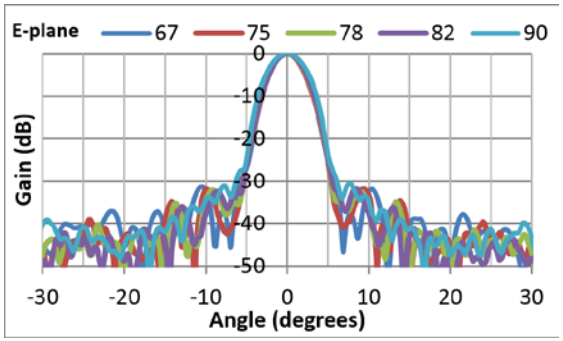
Optics Design

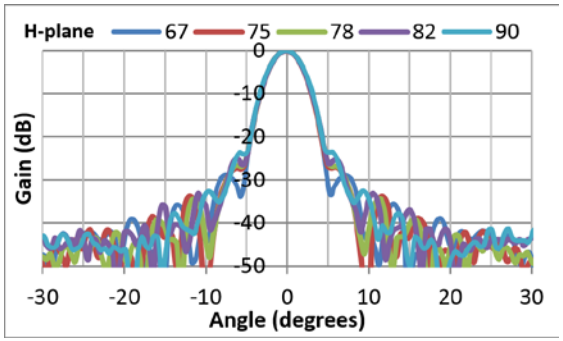
- Frequency independent illumination taper of -12 dB requires a 106 mm diameter, 785 mm long horn. Will result in beam truncation due to limited cryostat aperture – dictated by decisions made at the time of cryostat design. Similar truncation constraints apply to cooled lens.
- Reflective optics has to be placed outside the cartridge/cryostat (due to space constraints). Limited space outside due to calibration device, experimental design increased angle of incidence on the subreflector and yielded poorer polarization performance.
- Moderate beam waist horn with refractive optics (lens, which also serves as the vacuum window) design option was chosen.
- HDPE was selected for the lens material. Alternatives like high dielectric constant Si were studied (to save losses, since the lens would be thinner), but were not selected as the loss was found to be similar to a thicker HDPE lens. (Loss depends on electrical thickness, not the physical thickness) – some renewed interest in this regard and reviewing it again with help from NAOJ who have the expertise to fabricate matching layer on Si material. Relatively easy to substitute an alternate lens later to pick up improvement in noise temperature.

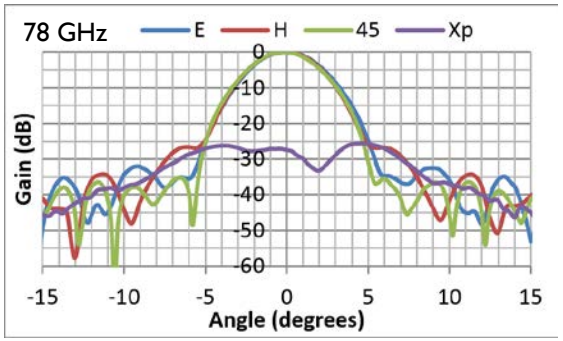
ALMA Band 2 Cold Cartridge Prototype

Horn & Lens

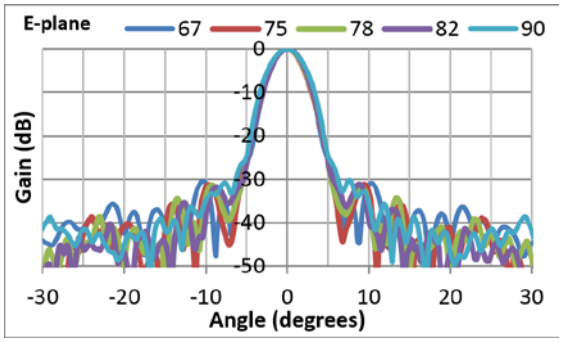
Lens #2

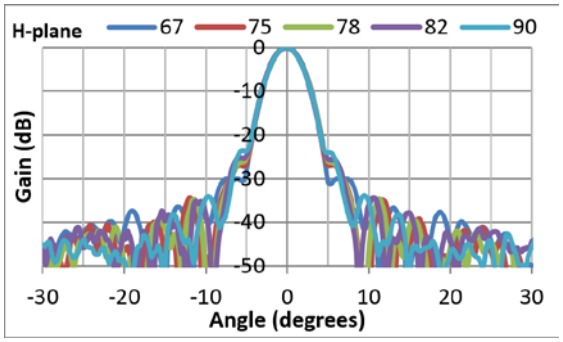


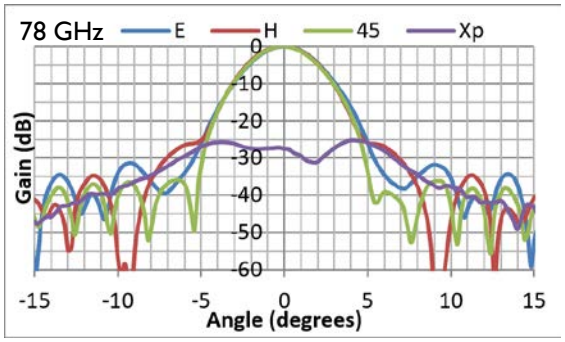




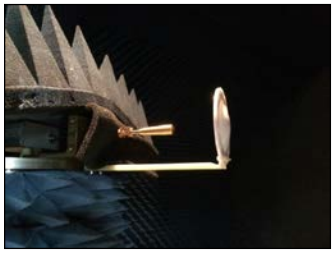
Lens #3





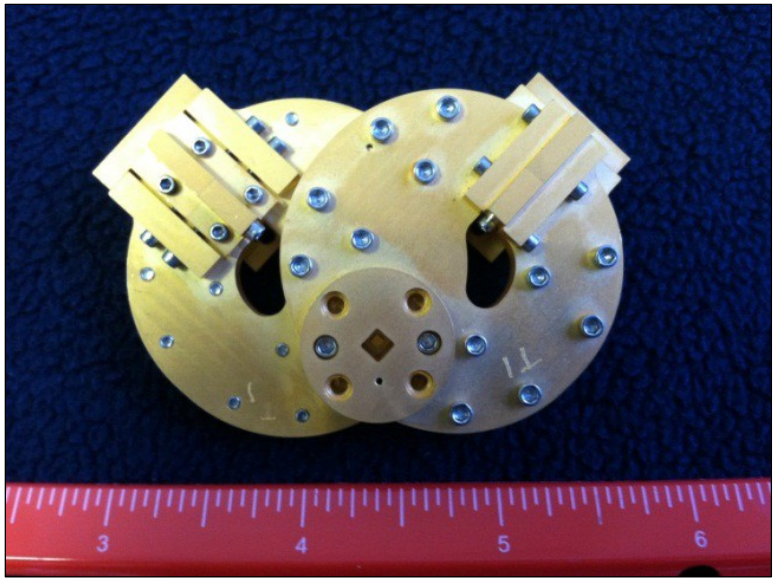


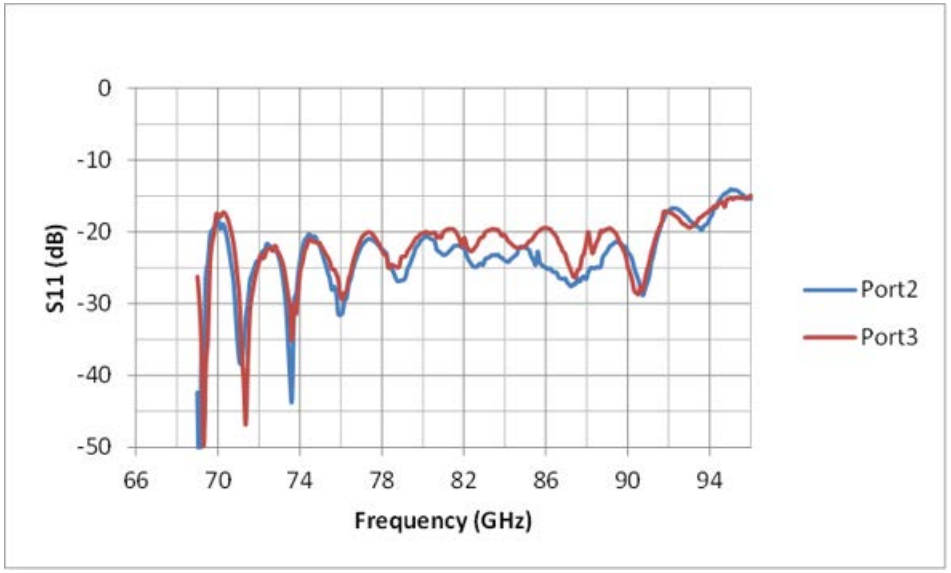
Lens #	Illumination taper at 3.6° (dB)		
	67 GHz	78 GHz	90 GHz
2	-13.44	-12.80	-11.33
3	-14.37	-14.03	-12.60
4 (Fresnel, 1-zone)	-10.88	-11.56	-11.36



ALMA Band 2 Cold Cartridge Prototype

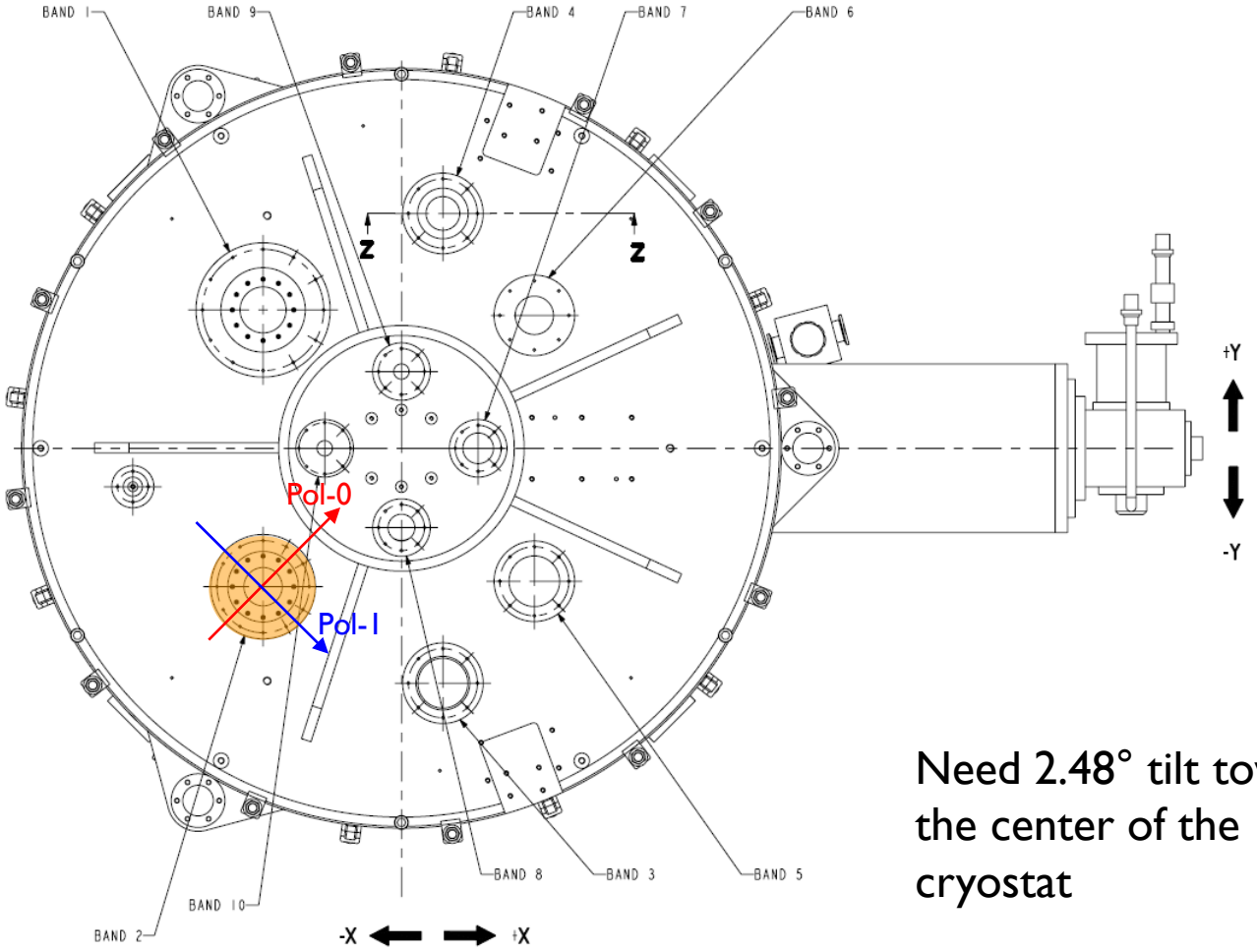
Orthomode Transducer





ALMA Band 2 Cold Cartridge Prototype

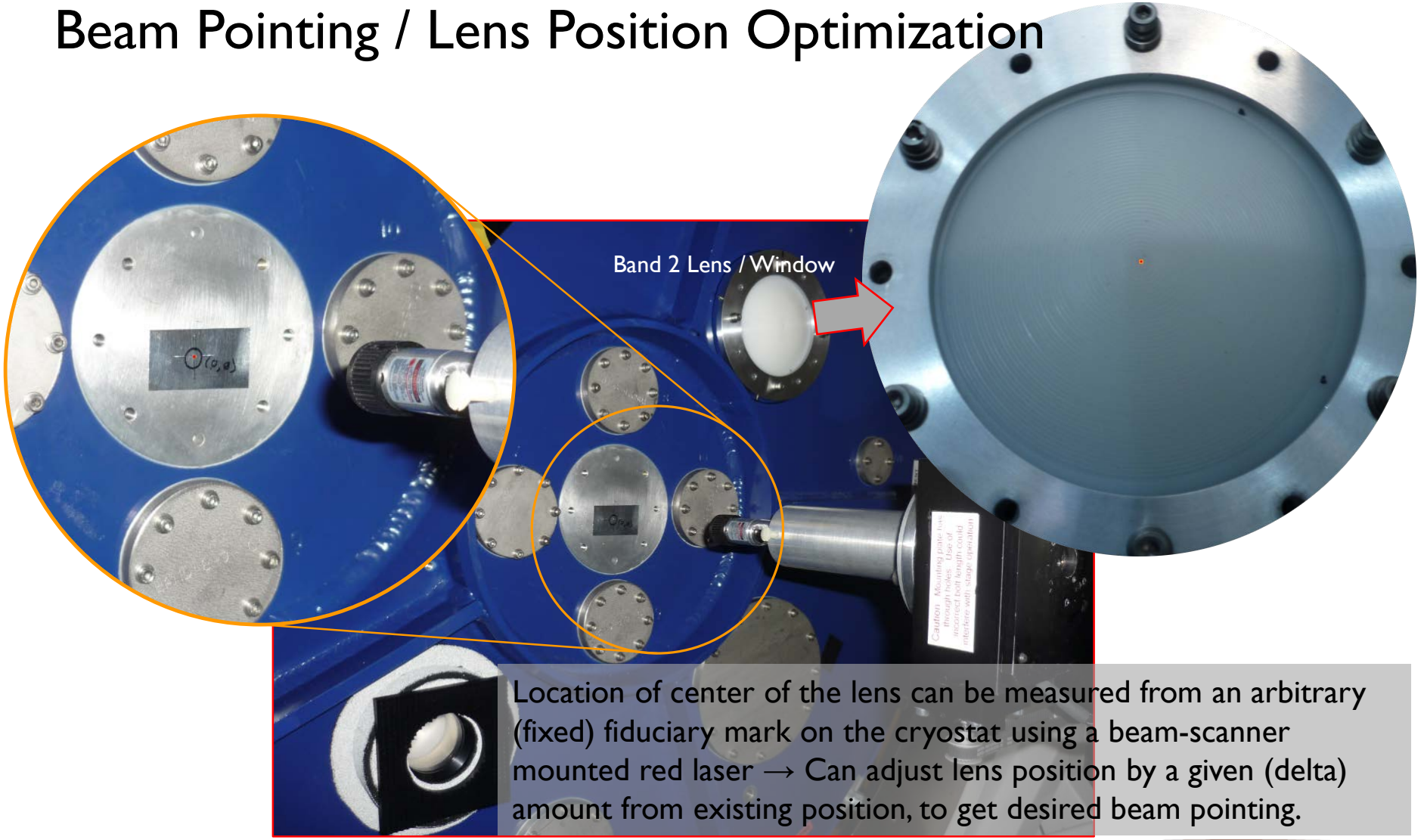
Location of the Band 2 window on the ALMA cryostat



Need 2.48° tilt towards the center of the cryostat

ALMA Band 2 Receiver Prototype

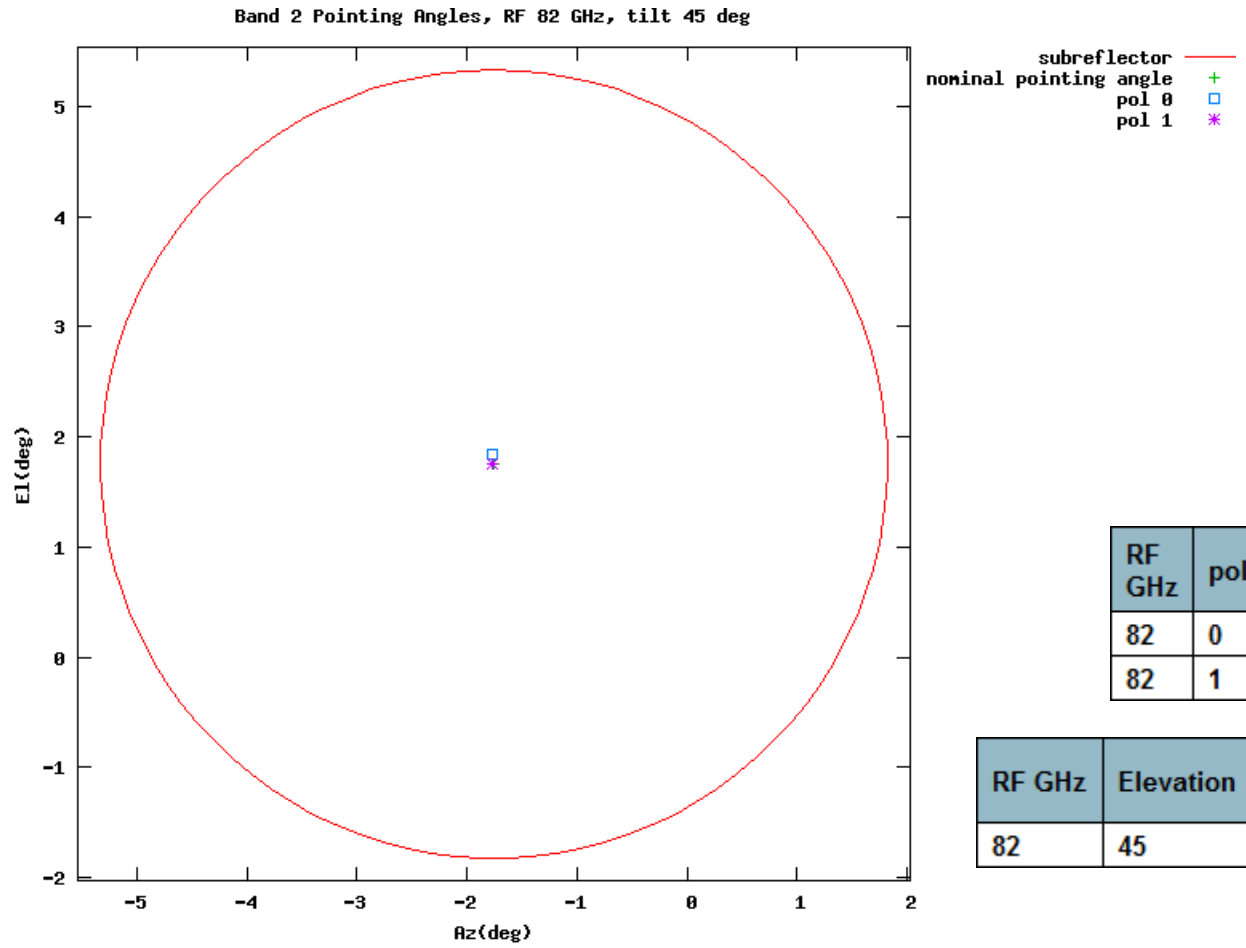
Beam Pointing / Lens Position Optimization



Location of center of the lens can be measured from an arbitrary (fixed) fiduciary mark on the cryostat using a beam-scanner mounted red laser → Can adjust lens position by a given (delta) amount from existing position, to get desired beam pointing.

ALMA Band 2 Receiver Prototype

Optics Performance / Beam Pointing

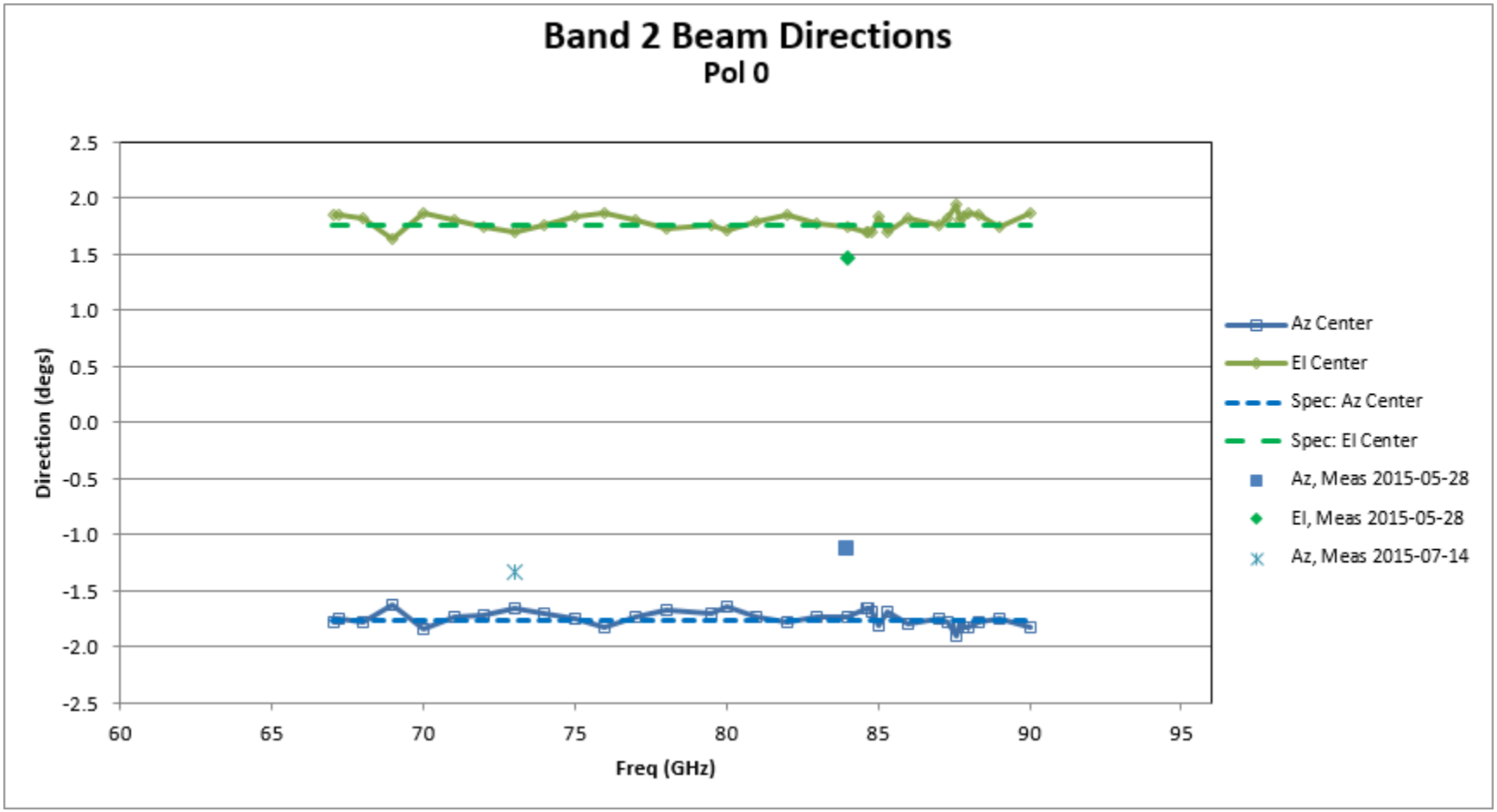


RF GHz	pol	Elevation	AZ Center	EL Center
82	0	45	-1.7718	1.8484
82	1	45	-1.7624	1.7619

RF GHz	Elevation	Squint (%FPBW)	squint (arc seconds)
82	45	1.37	0.99

ALMA Band 2 Receiver Prototype

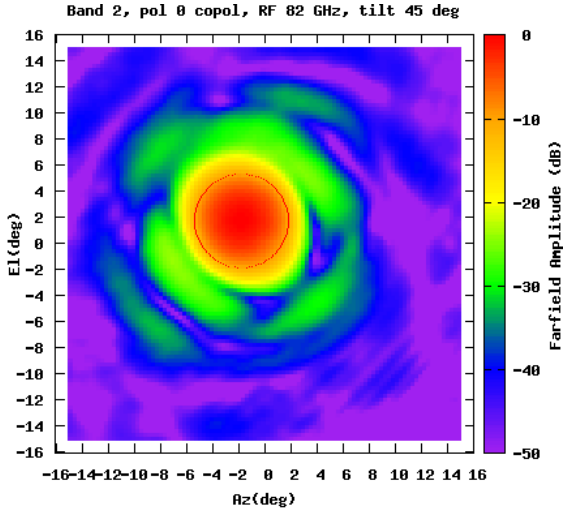
Optics Performance / Beam Pointing

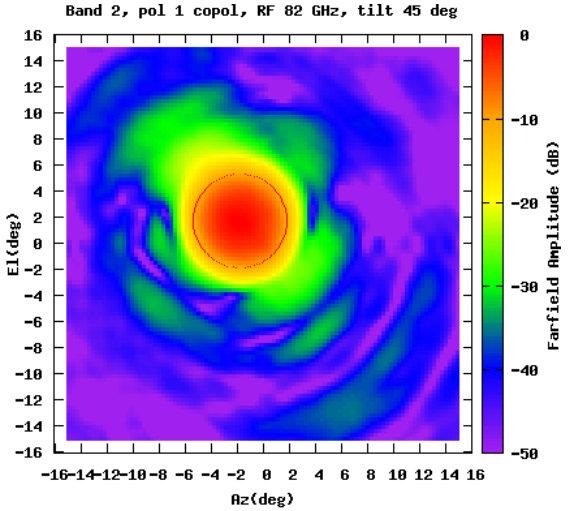


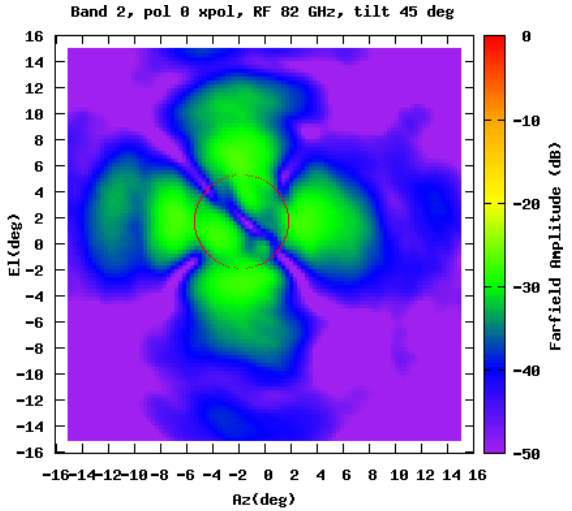
ALMA Band 2 Receiver Prototype

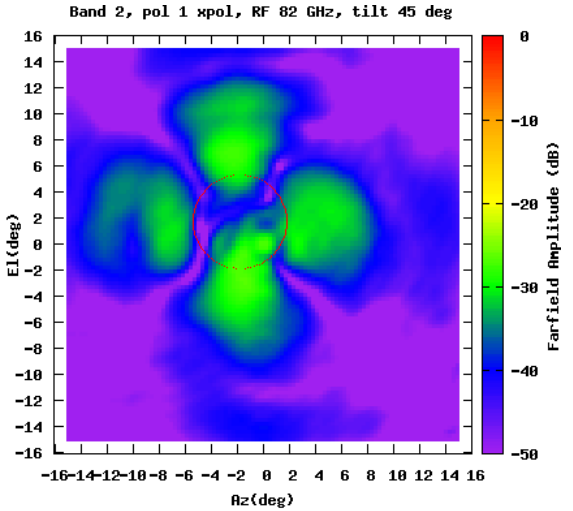
Band 2
67-90 GHz

Optics Performance / Beam Patterns



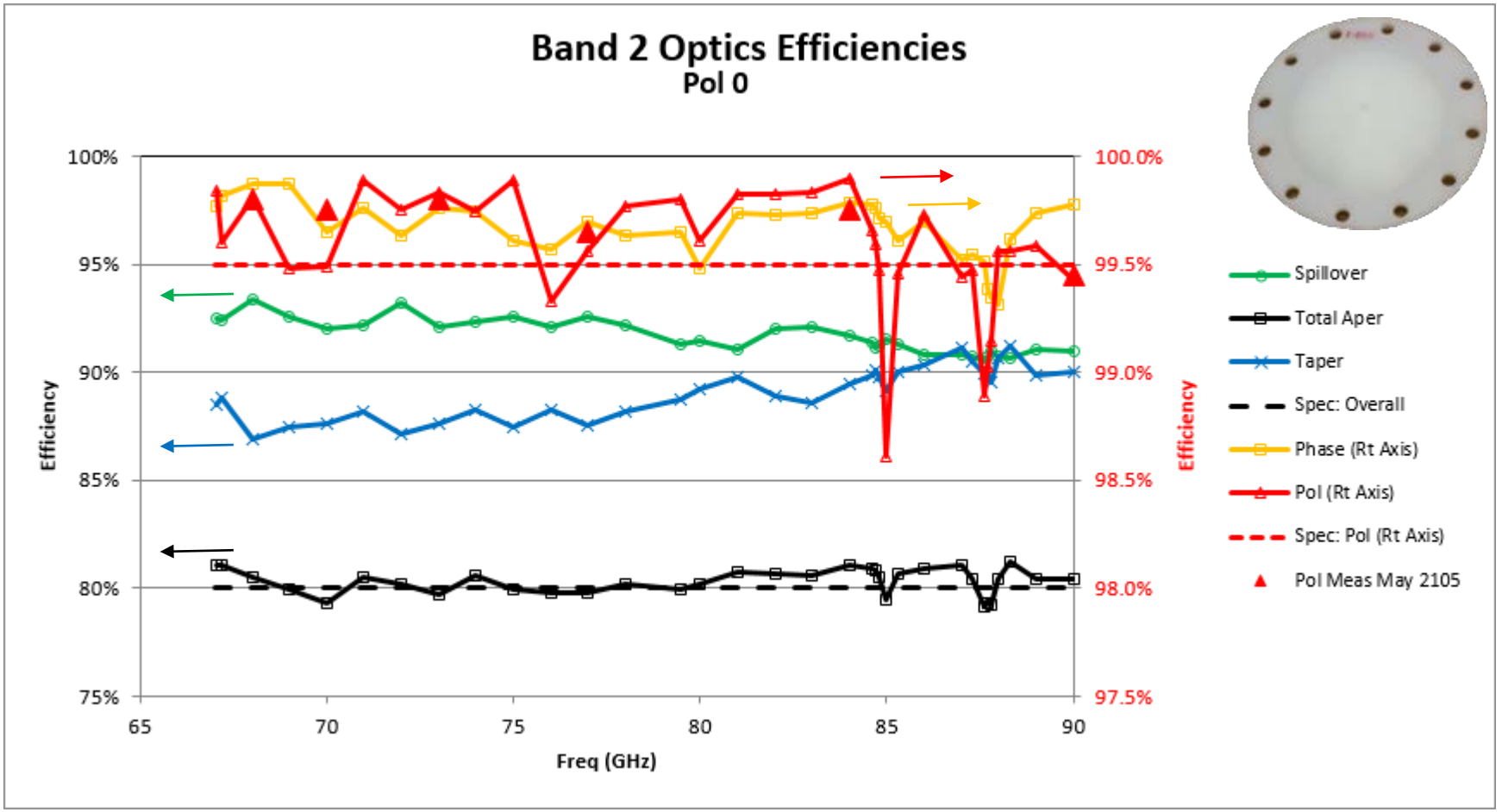






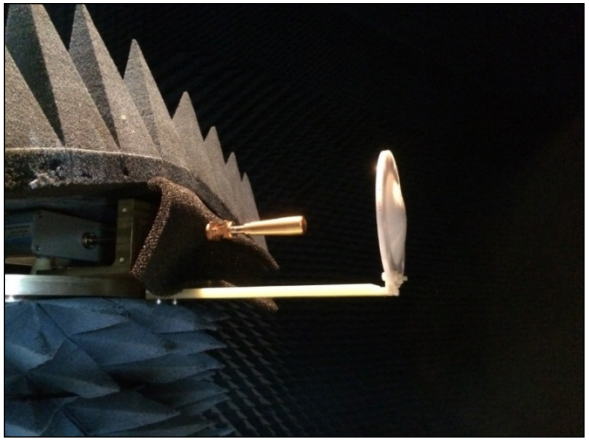
ALMA Band 2 Receiver Prototype

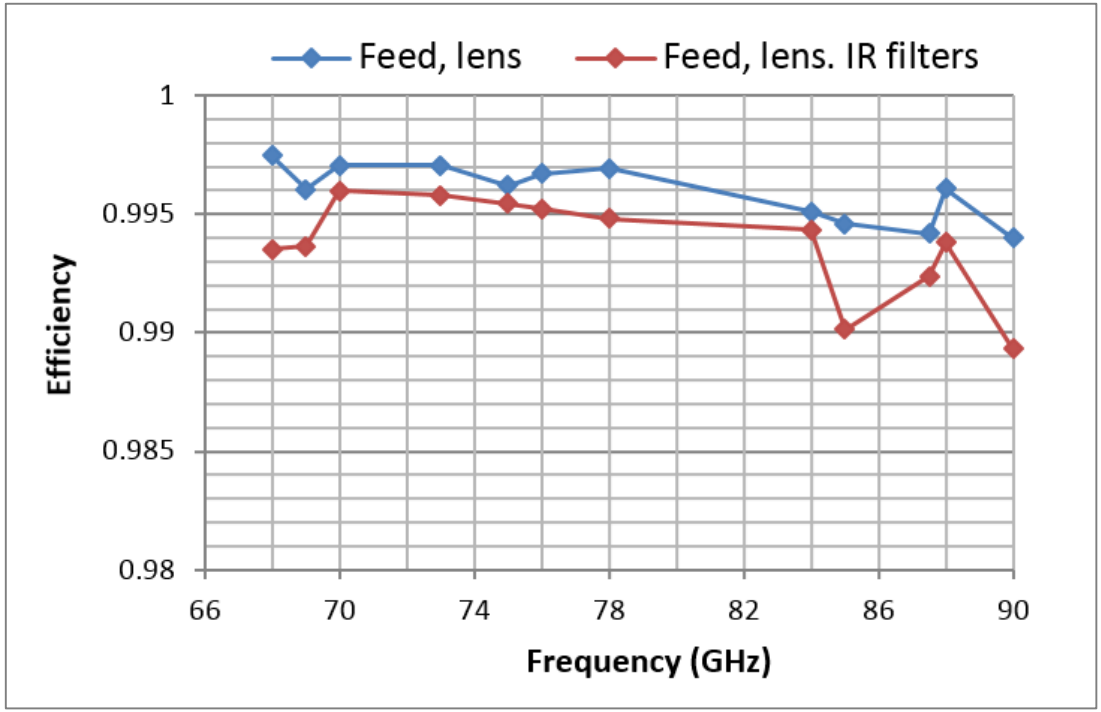
Optics Performance / Beam Efficiencies



ALMA Band 2 Receiver Prototype

Optics Performance / Beam Efficiencies

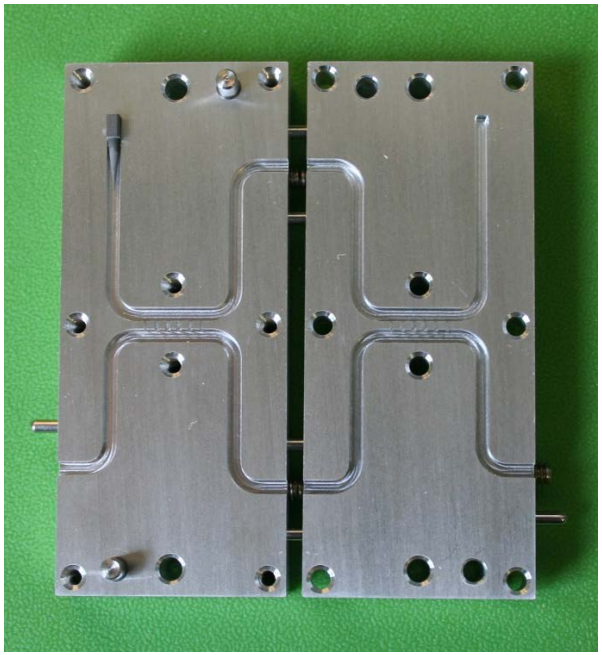


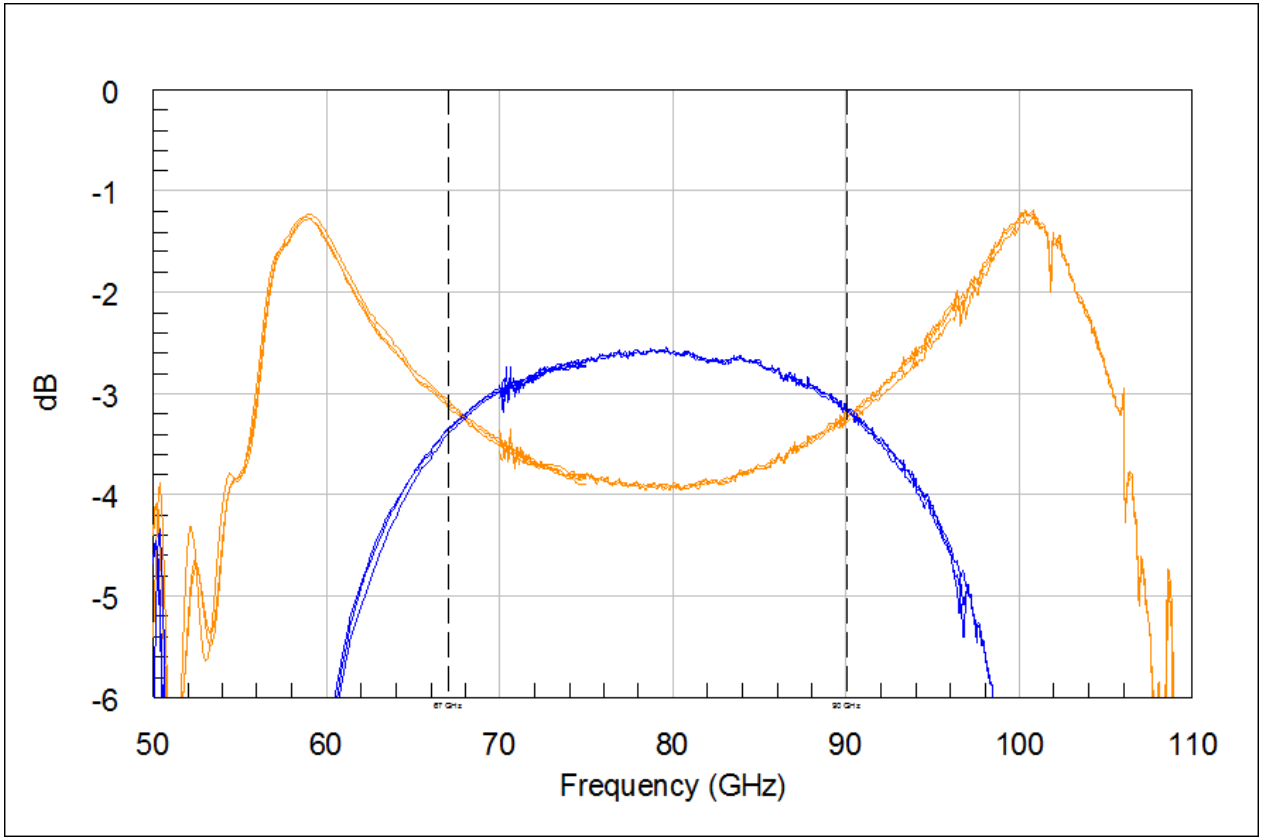


Measured polarization efficiency of feed horn & lens with and without the 15 K IR filter (anechoic chamber measurements).

ALMA Band 2 Warm Cartridge Prototype

RF 90° Hybrids





ALMA Band 2 Warm Cartridge Prototype

2SB Downconverter / Image Rejection

Polarization-0 Image Rejection Data

LO											IR RF	IR RF	IR RF	IR RF	IR RF	IR RF	IR RF	IR RF	IR RF	(USB)
	(LSB)	RF IR	RF IR	RF IR	RF IR	RF IR	RF IR	RF IR	RF IR	RF IR										
											14.5 dB	No meas								
72 GHz									67 GHz	68 GHz	76 GHz	77 GHz	78 GHz	79 GHz	80 GHz	81 GHz	82 GHz	83 GHz	84 GHz	
									No meas	28.1 dB										
											14.2 dB	17.5 dB	20.4 dB	No meas						
74 GHz							67 GHz	68 GHz	69 GHz	70 GHz	78 GHz	79 GHz	80 GHz	81 GHz	82 GHz	83 GHz	84 GHz	85 GHz	86 GHz	
							No meas	36.3 dB	16.6 dB	27.8 dB										
											10.6 dB	15.2 dB	19.5 dB	15.1 dB	19.7 dB	No meas				
76 GHz					67 GHz	68 GHz	69 GHz	70 GHz	71 GHz	72 GHz	80 GHz	81 GHz	82 GHz	83 GHz	84 GHz	85 GHz	86 GHz	87 GHz	88 GHz	
					No meas	19.8 dB	19.0 dB	22.1 dB	16.5 dB	29.0 dB										
											7.6 dB	10.0 dB	10.9 dB	11.4 dB	11.4 dB	17.0 dB	13.1 dB	No meas		
78 GHz			67 GHz	68 GHz	69 GHz	70 GHz	71 GHz	72 GHz	73 GHz	74 GHz	82 GHz	83 GHz	84 GHz	85 GHz	86 GHz	87 GHz	88 GHz	89 GHz	90 GHz	
			No meas	20.0 dB	20.8 dB	14.8 dB	19.6 dB	16.0 dB	14.2 dB	19.6 dB										
											11.4 dB	13.9 dB	23.4 dB	13.9 dB	15.1 dB	20.2 dB	24.1 dB	19.2 dB	20.6 dB	
80 GHz		68 GHz	69 GHz	70 GHz	71 GHz	72 GHz	73 GHz	74 GHz	75 GHz	76 GHz	84 GHz	85 GHz	86 GHz	87 GHz	88 GHz	89 GHz	90 GHz	91 GHz	92 GHz	
		23.1 dB	26.2 dB	28.4 dB	33.6 dB	23.2 dB	35.5 dB	24.0 dB	26.2 dB	34.0 dB										
											11.5 dB	12.7 dB	14.4 dB	12.5 dB	20.7 dB	15.3 dB	23.4 dB	No meas		
82 GHz		70 GHz	71 GHz	72 GHz	73 GHz	74 GHz	75 GHz	76 GHz	77 GHz	78 GHz	86 GHz	87 GHz	88 GHz	89 GHz	90 GHz	91 GHz	92 GHz	93 GHz	94 GHz	
			No meas	27.2 dB	36.0 dB	24.6 dB	33.7 dB	24.1 dB	18.8 dB	30.1 dB										
											10.0 dB	16.1 dB	16.0 dB	14.0 dB	19.2 dB	No meas				
84 GHz		72 GHz	73 GHz	74 GHz	75 GHz	76 GHz	77 GHz	78 GHz	79 GHz	80 GHz	88 GHz	89 GHz	90 GHz	91 GHz	92 GHz	93 GHz	94 GHz			
					No meas	23.6 dB	28.9 dB	23.9 dB	18.1 dB	35.9 dB										
											11.7 dB	17.1 dB	17.0 dB	No meas						
86 GHz		74 GHz	75 GHz	76 GHz	77 GHz	78 GHz	79 GHz	80 GHz	81 GHz	82 GHz	90 GHz	91 GHz	92 GHz	93 GHz	94 GHz					
							No meas	25.9 dB	20.5 dB	24.4 dB										
		12 GHz	11 GHz	10 GHz	9 GHz	8 GHz	7 GHz	6 GHz	5 GHz	4 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	9 GHz	10 GHz	11 GHz	12 GHz	
		IF (LSB)									IF (USB)									

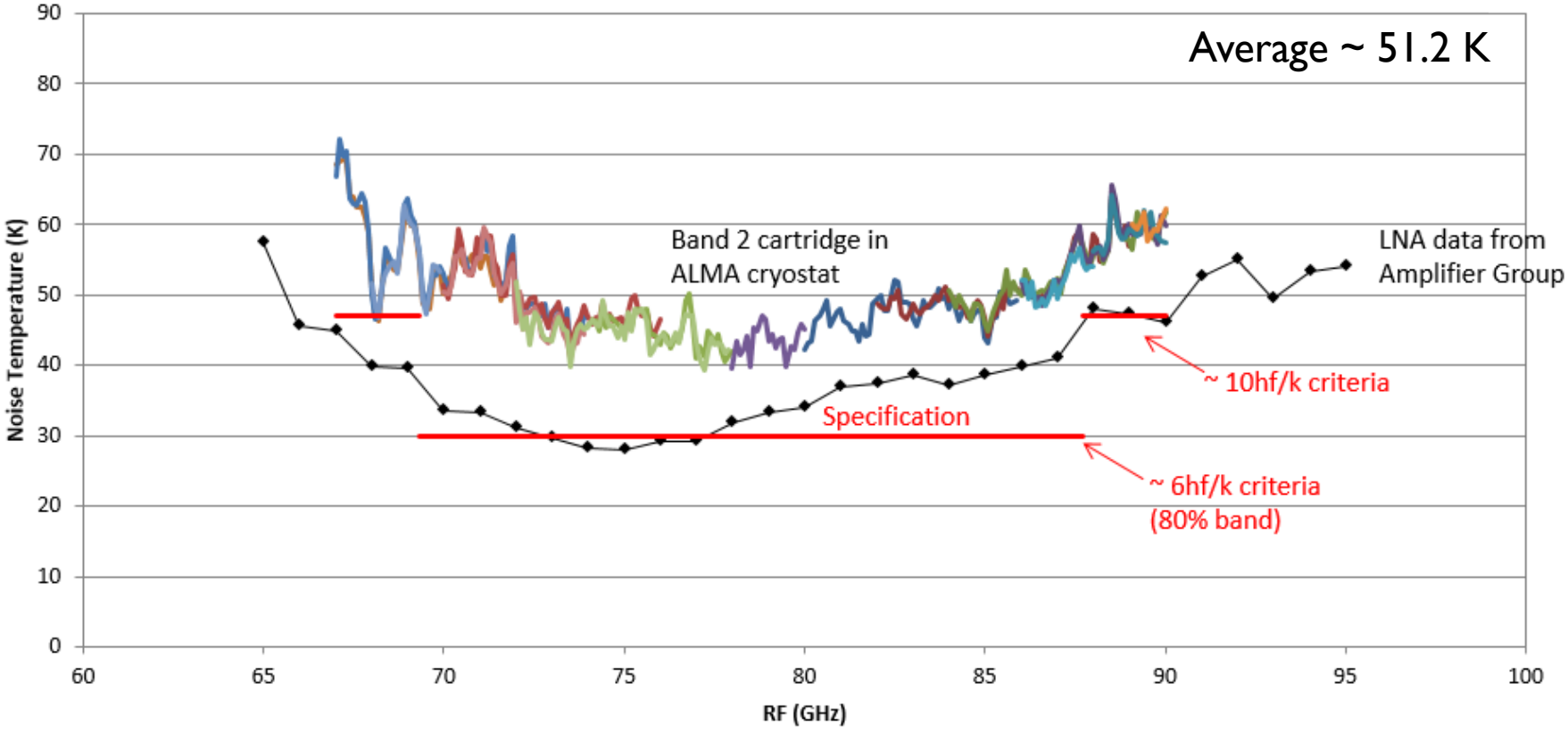
Number in green and blue font represent image rejection values corresponding to lower and upper sidebands respectively. Specification is better than 10 dB IR over 80% of the IF range, and better than 7 dB IR over the full range.
Intermediate frequencies outside of the contiguous diamond shaped area correspond to RFs that are "in-band" but have out-of-band image falling on it. "Out-of-band" RFs that are of interest are shown grayed out.

ALMA Band 2 Receiver Prototype

Noise Temperature (Polarization-0)

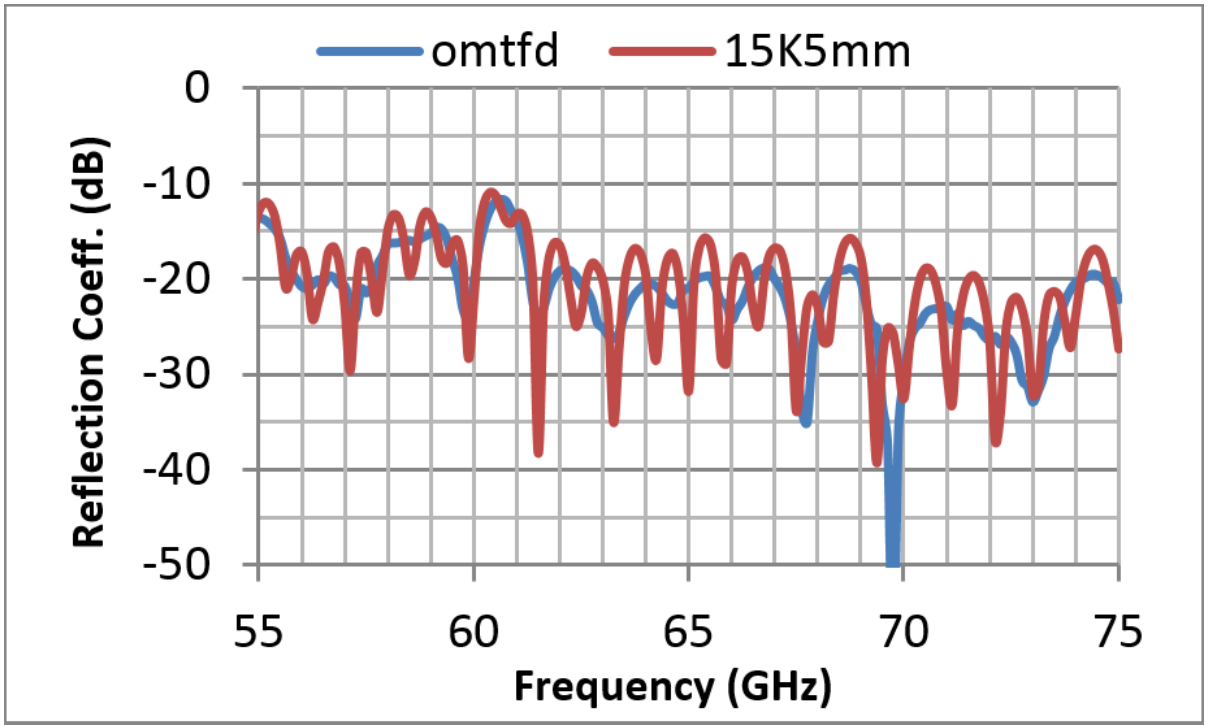
Band 2
67-90 GHz

Band 2 Receiver stage	Gain	Cumulative Gain to preceding stage	Noise Figure	Noise Temperature	$T_{equivalent}$ (for MIC based)
Lens/Window (room temperature)	-0.1 dB	0.0 dB	0.1 dB	8.9 K	8.9 K
IR Filters (15 K and 80 K)	-0.1 dB	-0.1 dB	0.1 dB	1.4 K	1.5 K
Feedhorn (15 K)	-0.1 dB	-0.3 dB	0.1 dB	0.3 K	0.4 K
OMT	-0.1 dB	-0.4 dB	0.1 dB	0.3 K	0.4 K
E-Band Amplifier (15 K)	35.0 dB	-0.5 dB		36.5 K	40.6 K
Waveguides, feed-thru and BPF	-4.0 dB	34.5 dB	4.0 dB	453.6 K	0.2 K
E-Band Amplifier (room temperature)	14.0 dB	30.5 dB	3.5 dB	371.6 K	0.3 K
2 SB Downconverter	-12.0 dB	44.5 dB	12.0 dB	4454.7 K	0.2 K
Warm IF Amplifier	30.0 dB	32.5 dB	2.0 dB	175.5 K	0.1 K
Total	62.5 dB				52.4 K



ALMA Band 2 Receiver Prototype

Interaction between 15 K IR filters and CLNA input



Measured reflection coefficient of the OMT plus feed horn without IR filter (trace labeled "omtfd") and that of the OMT plus feed horn with the 15 K IR filter placed 5 mm from the feed horn aperture (trace labeled "15K5mm")

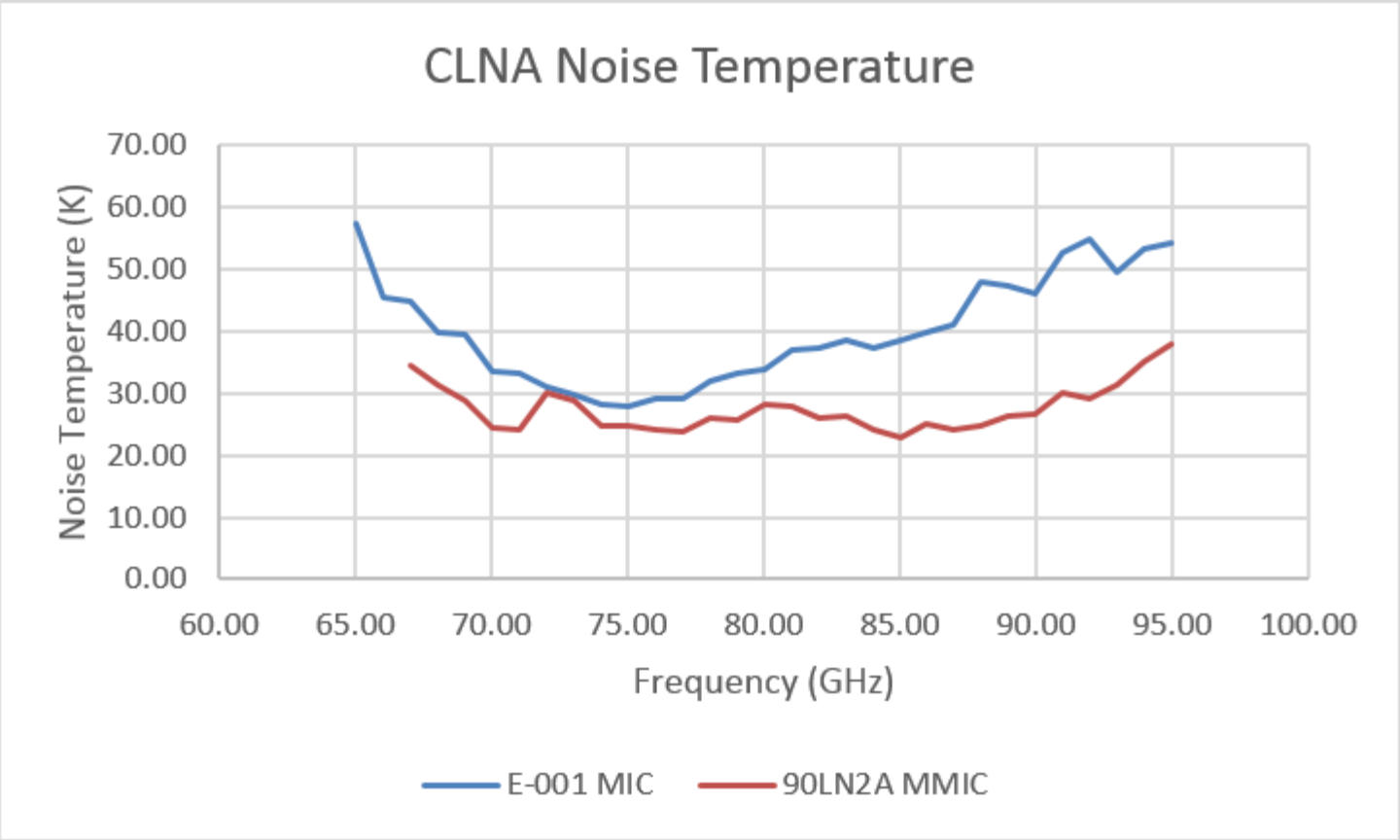
ALMA Band 2 Prototype Project

Status of the CRAL MMIC effort

- First wafer run (NGC) with multiple Band 2 LNA MMIC design variants completed in December 2015.
- All four wafers were successful, with good yields (room temperature testing completed on all wafers).
- Cryogenic probing of one wafer at CRAL indicates that there are several promising design variants for Band 2 application.
- Subsequently, these were packaged into test blocks to qualify their performance, and to identify designs that could be used for Band 2 multi-stage amplifier for integration into the prototype cartridge.
- Once the performance is confirmed, proceed to pick the corresponding chips from the NGC wafers and store for the full construction phase.

ALMA Band 2 Prototype Project

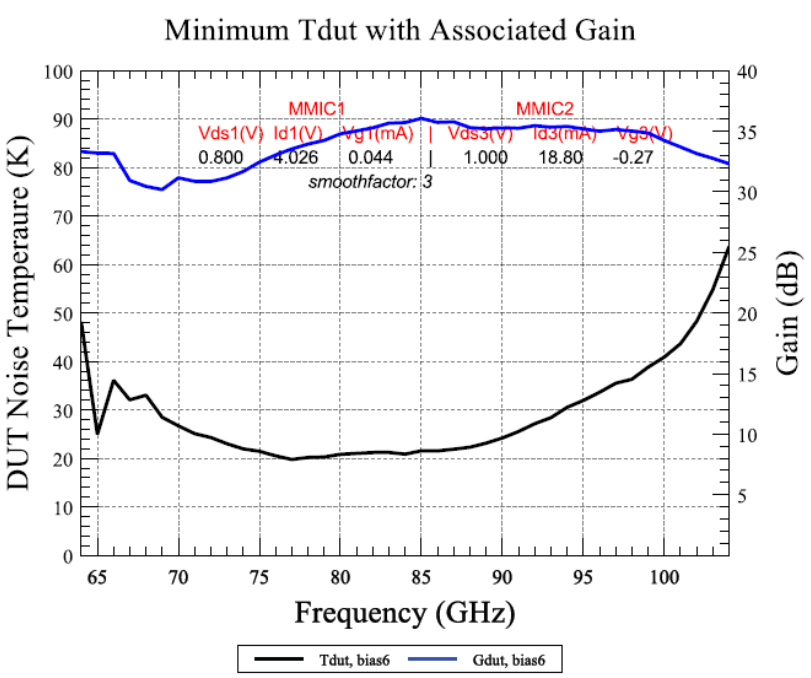
Preliminary packaged MMIC cryogenic performance



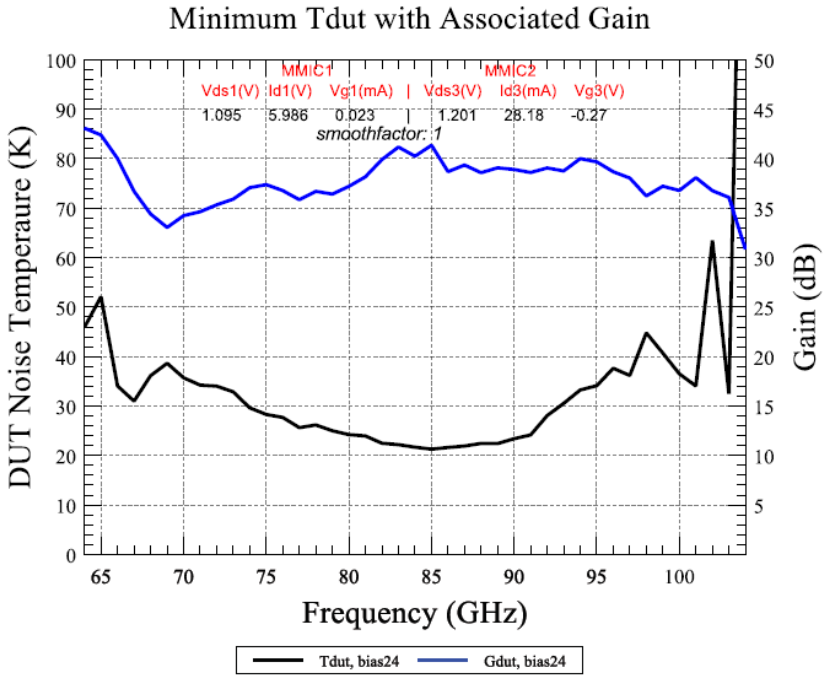
(Packaged amplifier data, single MMIC)

ALMA Band 2 Prototype Project

2-stage packaged MMIC LNA cryogenic performance



Bias optimized for lowest noise



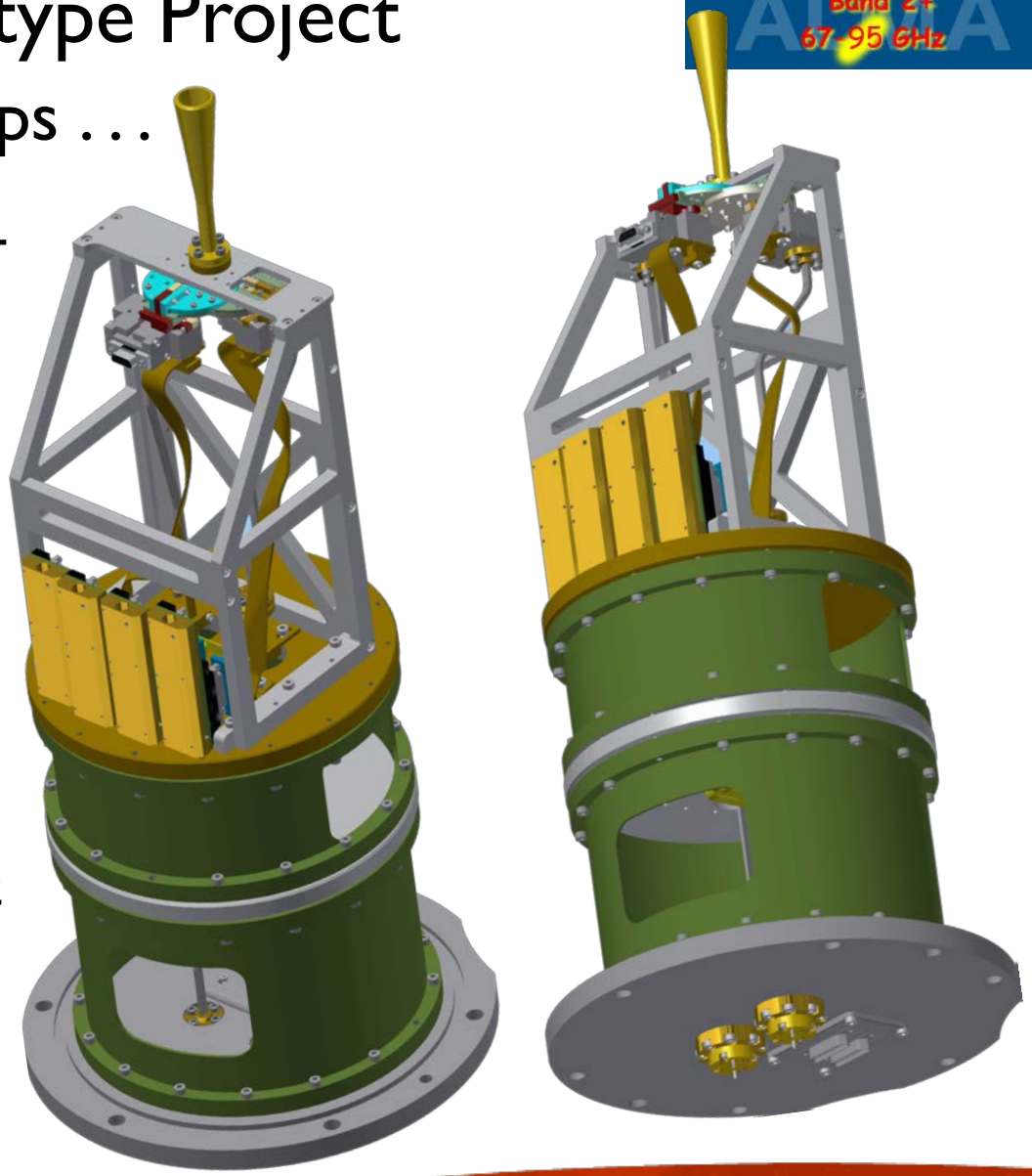
Bias optimized for lowest noise for gain >35 dB

(Packaged amplifier data)

ALMA Band 2plus Prototype Project

Final year plan. Next Steps …

- Finish evaluation with CRAL MMIC based amplifiers and update relevant project documentation as well as test reports.
- Review Band 2+ Noise Specifications.
- Preliminary Design Review.
- Propose a phased build-out for Band 2+ under the upcoming NA Development Project Call in October 2016.
- Questions.



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