NATIONAL RADIO ASTRONOMY OBSERVATORY

ngVLA Receiver Reference Design Concept

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ngVLA
The Next Generation Very Large Array

Introduction and General Requirements

- "Reference" design concept for ngVLA receivers, feeds:
  - A feasible design with relatively low technical risk and well-defined costs
  - **<u>Maximizing sensitivity is the primary goal; wide bandwidths are secondary</u>**
  - Wide-angle feeds => *compact enough to cool* => ***lower overall Tsys***
  - High aperture efficiency, low spillover noise from feeds, antenna optics
- Proposed ngVLA has 214 antennas, ~8 times that of the VLA
  - **Key requirement is to minimize operating cost to within 3 x VLA**
  - Reduce total number of dewars by consolidating receiver bands
  - Reduce total number of RXs by employing wideband feeds, where feasible
  - Efficient cryogenic system that optimizes power consumption

Specific Design Assumptions

- Near-continuous frequency coverage from 1.2 – 116 GHz
  - Coverage gap from 50.5 - 70 GHz (O_2 absorption band)
- Feed horn has a beam half-angle of ~55 degrees.
- Receivers are single-pixel, with linearly-polarized outputs
- Feeds and LNAs in all bands are cryogenically cooled.
- Antenna is an unblocked, offset Gregorian geometry, with shaped optics, low spillover by design, ~160um RMS surface accuracy
- Nominal VLA site conditions: 6mm PWV, 45° elevation angle (1 mm PWV assumed for W-band)

ngVLA Reference Receiver Configuration

- Six receivers (Bands 1-6), in a pair of compact cryogenic dewars
- Lowest-frequency receiver band (1.2 – 3.5 GHz) in dewar ‘A’
  - **Almost identical to the Caltech ngVLA receiver concept, but without the high-frequency band dewar ‘extension’ off to the side.**
  - Wideband (>3.0:1) feed and LNAs, covering L+S bands
  - Quad-ridged feed horn (QRFH), with **coaxial outputs**
- Five high-frequency bands (3.5 – 116 GHz) in dewar ‘B’
  - 3.5:1 b.w. QRFH used on Band 2 (3.5 - 12.3 GHz), to cover C+X bands
  - **Waveguide-bandwidth (~1.67:1) feeds & LNAs on Bands 3-6, for more optimum aperture efficiency and noise performance.**
  - Use axially-corrugated feed horns, with **circular waveguide output**

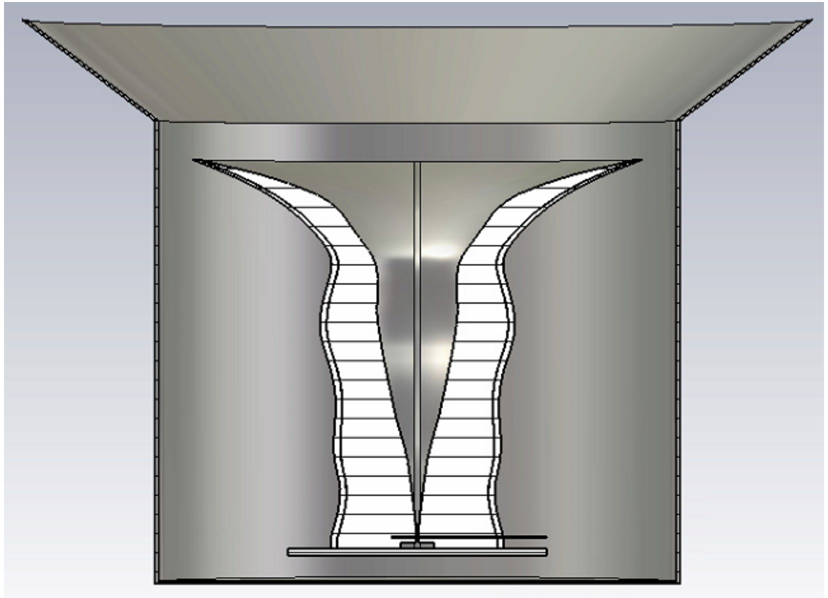
Reference Receiver Band Definitions

Band #	*Dewar #*	f_L *GHz*	f_M *GHz*	f_H *GHz*	$f_H : f_L$	*BW GHZ*
1	A	**1.2**	**2.0**	**3.5**	2.92	2.3
2	B	**3.5**	**6.6**	**12.3**	3.51	8.8
3	B	**12.3**	**15.9**	**20.5**	1.67	8.2
4	B	**20.5**	**26.4**	**34**	1.66	13.5
5	B	**30.5**	**39.2**	**50.5**	1.66	20
6	B	**70**	**90**	**116**	1.66	46

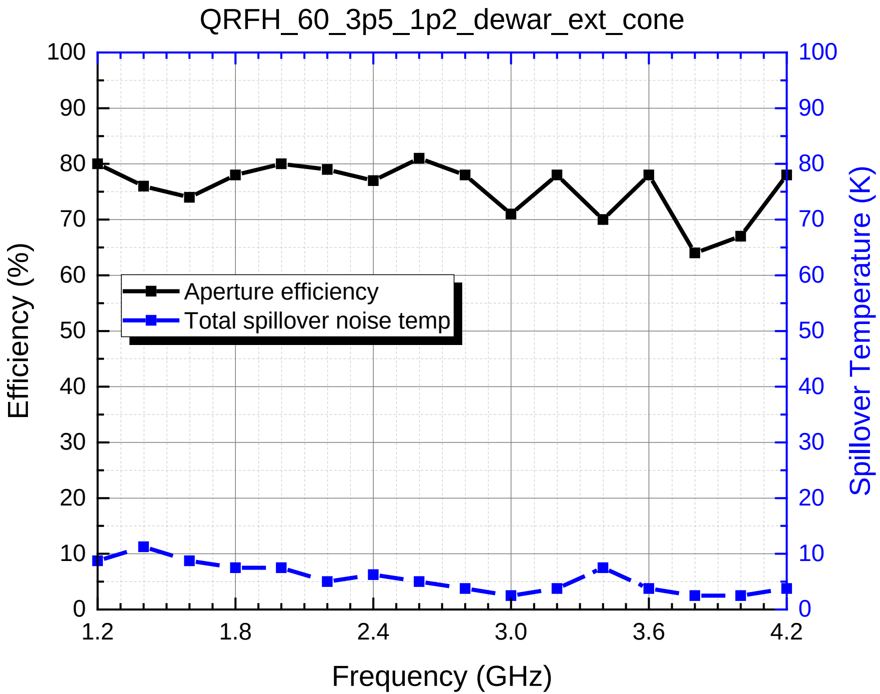
Feed Horn for Low-Frequency Bands (1-2)

- Based on the original 6:1 bandwidth quad-ridged feed horn design from Caltech (A. Akgiray and S. Weinreb, 2013)
- Refined and re-optimized for ~3.5:1 bandwidth (Mani/Weiye, 2017)
  - Better aperture efficiency, but high backlobe response -> higher Tspill
  - Needs an external feed cone to reduce spillover noise contribution to Tsys
- Current design has a subtended angle of 58 degrees
- Aperture efficiency ~65 - 80% over the band, assuming shaped optics
- Compact enough to cool to 80K (Band 1) and 20K (Band 2)
- Orthogonal linearly-polarized outputs in coax - no OMT needed.

(data and visuals courtesy S. Weinreb and H. Mani, Caltech, June 2017)



Feed cone is external to Dewar. Its main effect is on the back lobe

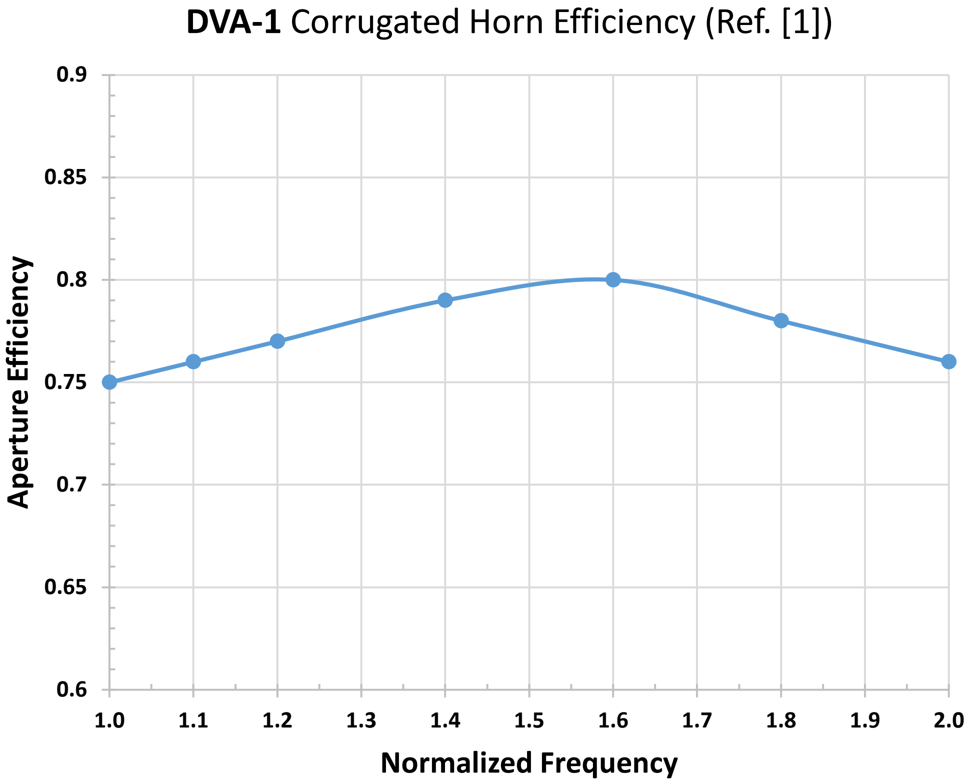


Spillover Noise is with conservative assumption that ½ the total spillover is at 250K

Feed Horn for High-Frequency Bands (3-6)

- Axially-corrugated feed design by G. Cortes and L. Baker [Ref. 2]
- Used on Canadian ‘DVA-1’ SKA antenna concept
- Half-beam subtended angle of 55 degrees
- Aperture efficiency ~75 - 80%, with DVA-1 shaped optics
- Excellent RF match, low loss, over octave- or waveguide-bandwidths
- Highly compact: can be integrated with the cold electronics
- Output is circular waveguide
  - Lower loss and Trx at high frequencies, versus with coax cable
  - Requires an external linear polarizer (OMT)

Ring-Loaded Feed

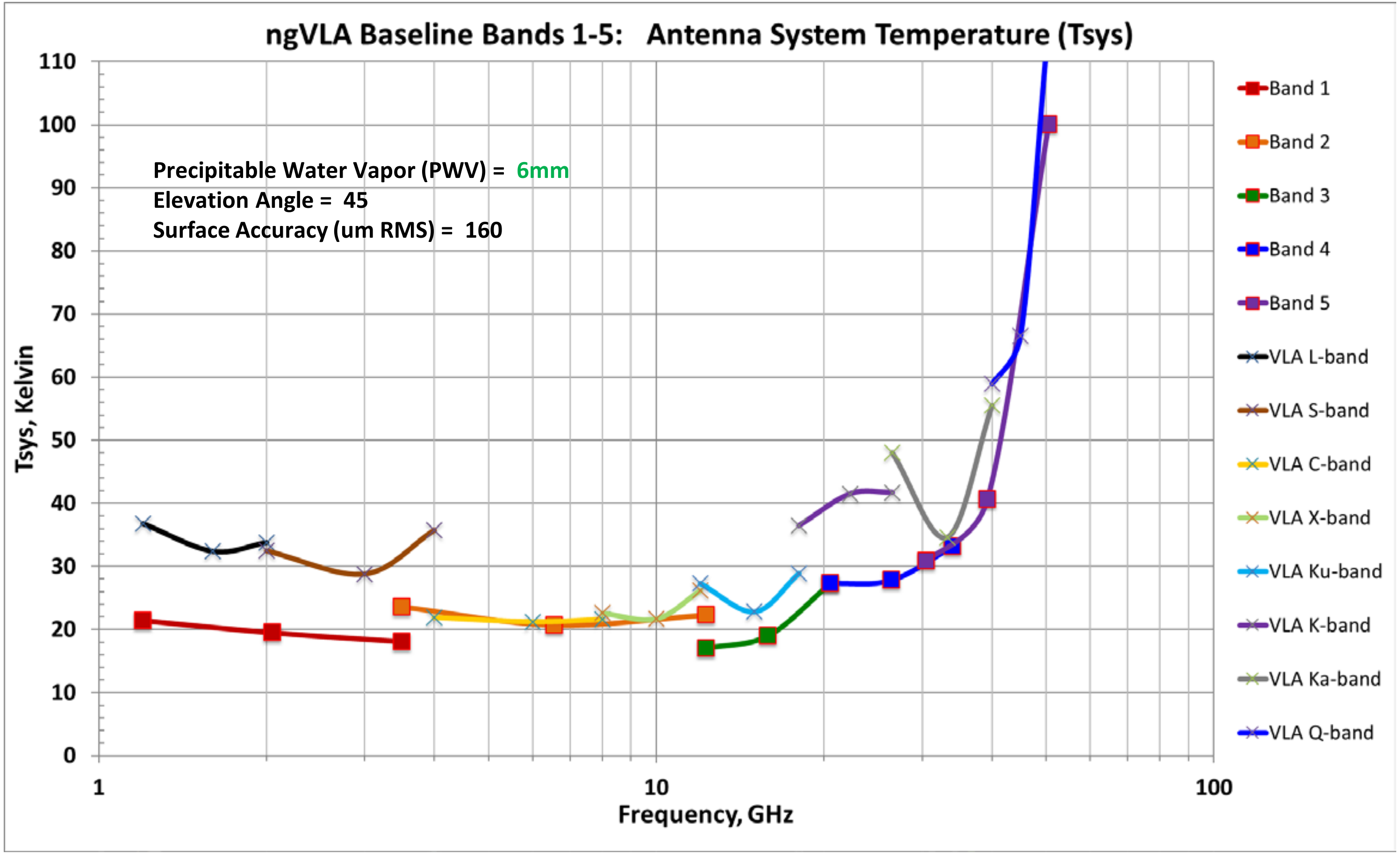


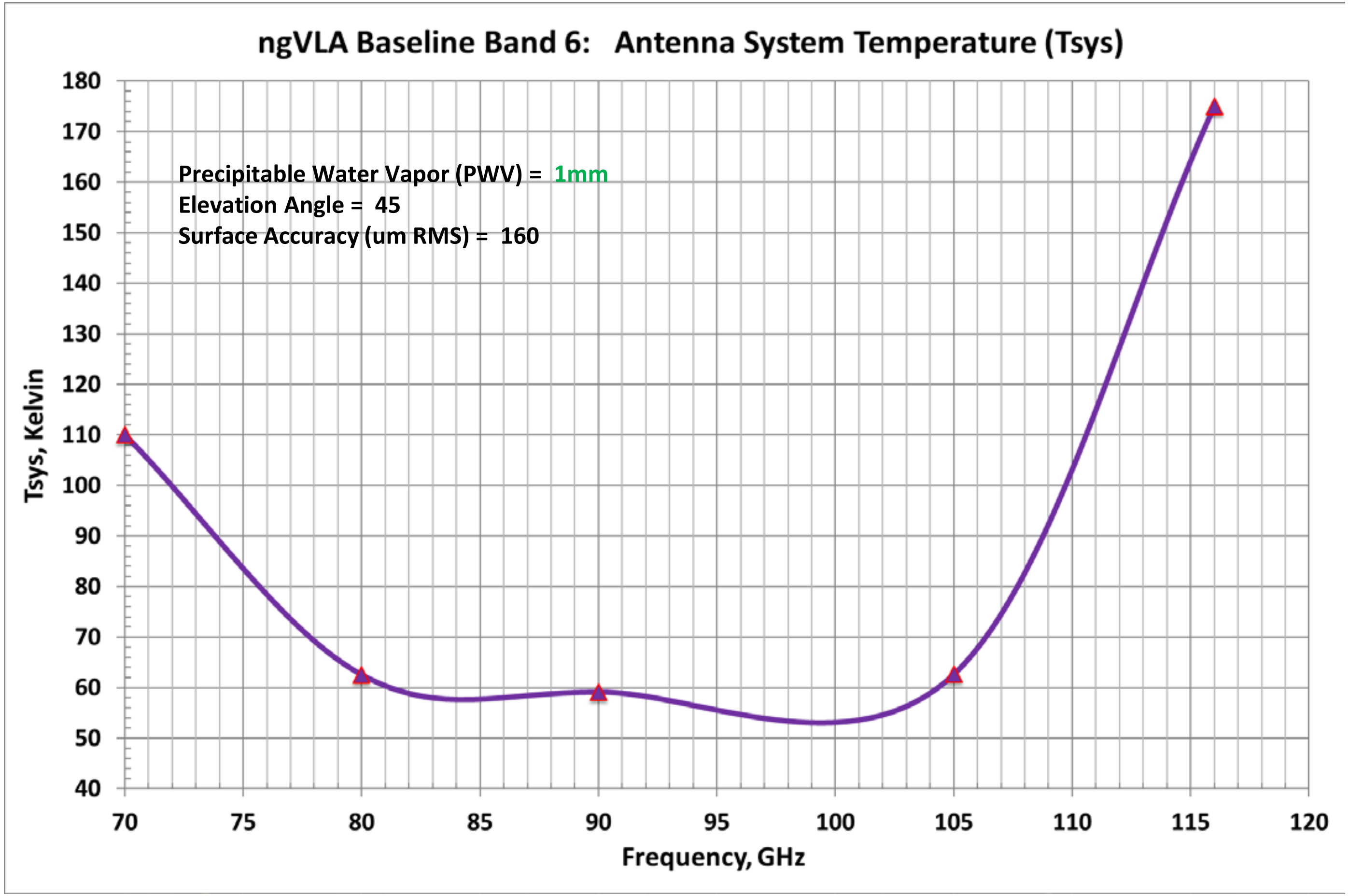
Performance Estimates

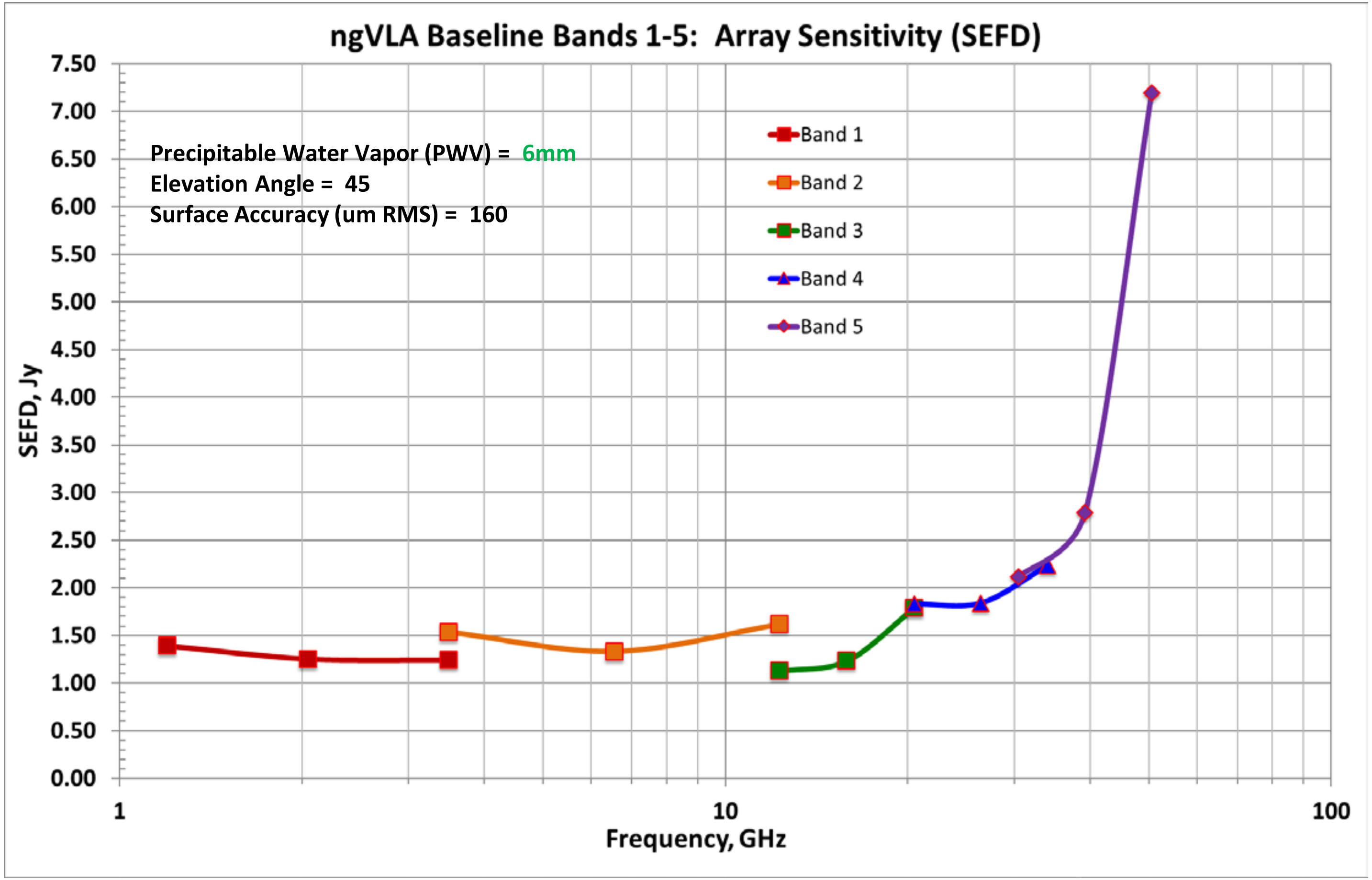
Reference Receiver Performance Summary

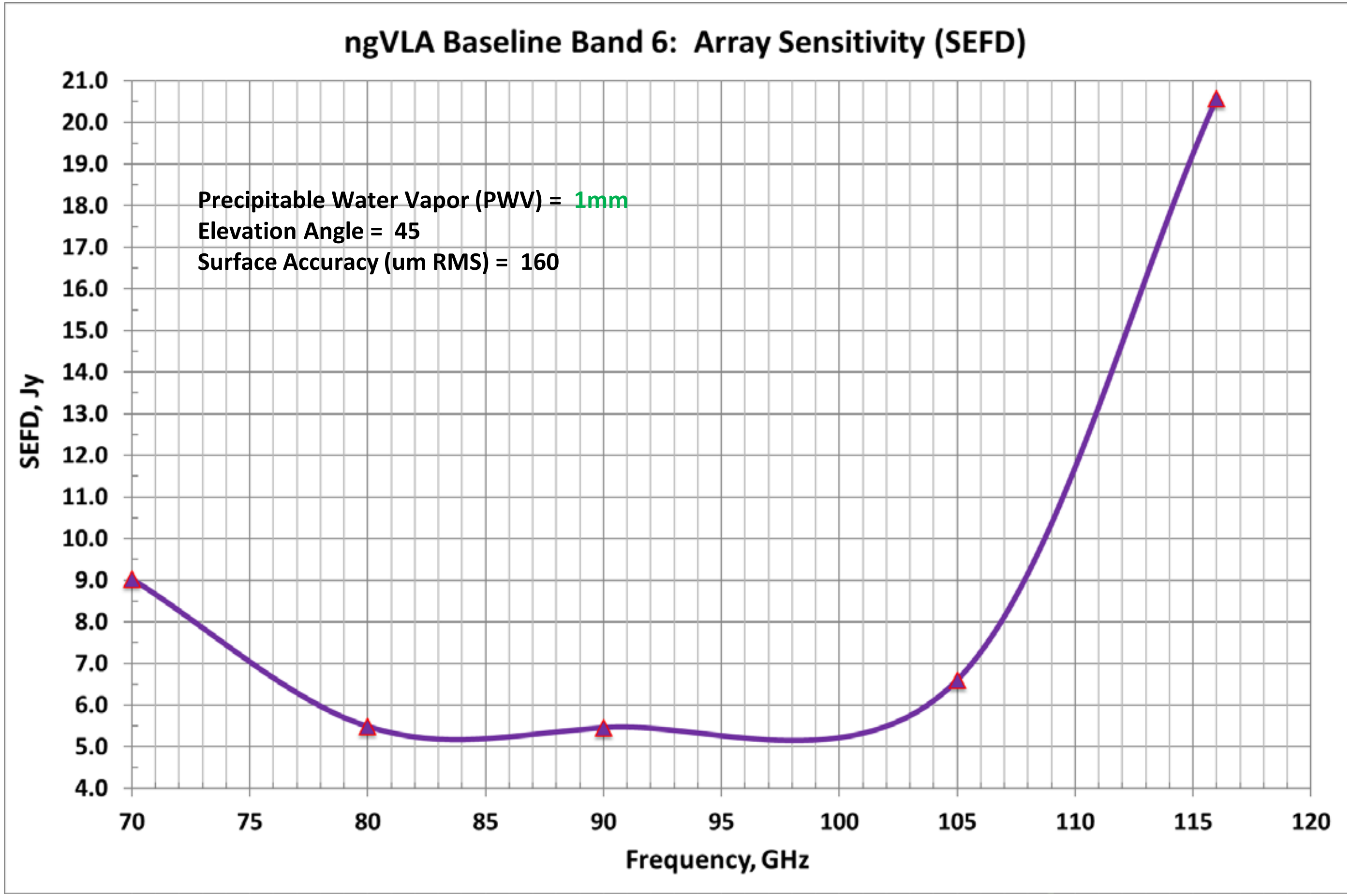
Band #	f_L GHz	f_M GHz	f_H GHz	Aperture Eff., η_A			Spillover, K			T_{RX}, K		
				@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H
1	1.2	2.0	3.5	0.78	0.79	0.74	10	7	5	7	8	8.5
2	3.5	6.6	12.3	0.78	0.79	0.70	10	6	4	9	10	13
3	12.3	15.9	20.5	0.76	0.78	0.78	3	3	3	9	10	11
4	20.5	26.4	34	0.76	0.77	0.75	3	3	3	11	13	18
5	30.5	39.2	50.5	0.74	0.74	0.70	3	3	3	17	21	27
6	70	90.1	116	0.62	0.55	0.43	3	3	3	39	41	60

Band #	T_{SKY}, K			**T_{SYS}, K**			(T_{SYS}/η_A), K			**Array SEFD, Jy**		
	@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H
1	4.4	4.5	4.6	**21**	**20**	**18**	27	25	24	**1.39**	**1.25**	**1.24**
2	4.6	4.7	5.3	**24**	**21**	**22**	30	26	32	**1.53**	**1.33**	**1.61**
3	5.3	6.3	13.6	**17**	**19**	**27**	22	24	35	**1.13**	**1.23**	**1.79**
4	13.6	12.1	12.4	**27**	**28**	**33**	36	36	44	**1.83**	**1.84**	**2.24**
5	11.1	16.9	70.3	**31**	**41**	**100**	42	55	142	**2.11**	**2.79**	**7.20**
6	68	15	112	**110**	**59**	**175**	178	108	406	**9.03**	**5.46**	**20.57**


ngVLA Baseline Bands 1-5: Antenna System Temperature (Tsys)
Precipitable Water Vapor (PWV) = 6mm
Elevation Angle = 45
Surface Accuracy (um RMS) = 160
Tsys, Kelvin
Frequency, GHz
110
100
90
80
70
60
50
40
30
20
10
0
1
10
100
Band 1
Band 2
Band 3
Band 4
Band 5
VLA L-band
VLA S-band
VLA C-band
VLA X-band
VLA Ku-band
VLA K-band
VLA Ka-band
VLA Q-band

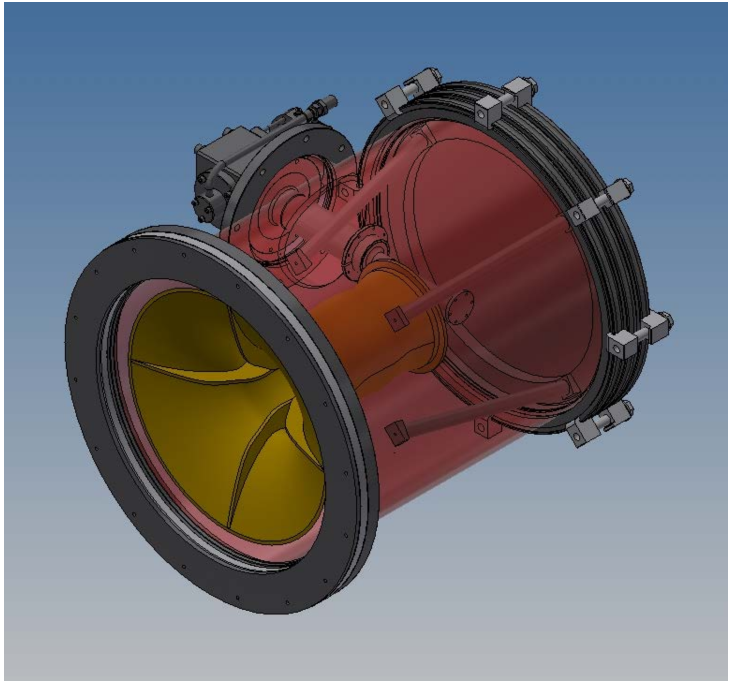

ngVLA Baseline Band 6: Antenna System Temperature (Tsys)
Precipitable Water Vapor (PWV) = 1mm
Elevation Angle = 45
Surface Accuracy (um RMS) = 160
Tsys, Kelvin
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
70
75
80
85
90
95
100
105
110
115
120
Frequency, GHz


ngVLA Baseline Bands 1-5: Array Sensitivity (SEFD)
Precipitable Water Vapor (PWV) = 6mm
Elevation Angle = 45
Surface Accuracy (um RMS) = 160
Band 1
Band 2
Band 3
Band 4
Band 5
SEFD, Jy
7.50
7.00
6.50
6.00
5.50
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1
10
100
Frequency, GHz


ngVLA Baseline Band 6: Array Sensitivity (SEFD)
Precipitable Water Vapor (PWV) = 1mm
Elevation Angle = 45
Surface Accuracy (um RMS) = 160
SEFD, Jy
Frequency, GHz
21.0
20.0
19.0
18.0
17.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
70
75
80
85
90
95
100
105
110
115
120

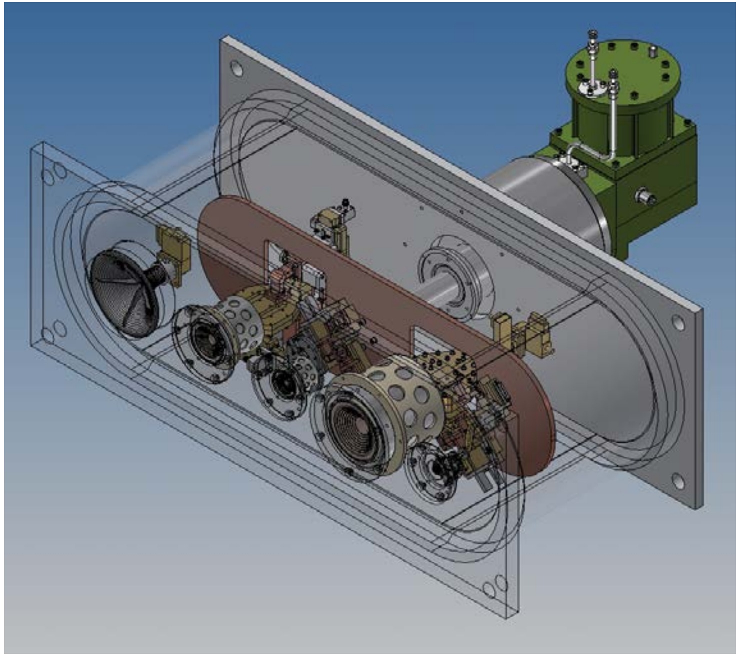
Band 1 Receiver Dewar Concept

- Based on design by S. Weinreb, H. Mani (Caltech/ASU)
- Cylindrical dewar houses cooled QRFH (80 K), coaxial LNAs (20 K)
- Single Sumitomo RDK-101D G-M cryocooler (1.2 kW)
- Approximate dewar dimensions: 510 x 580 mm (Dia. x H). Cryocooler protrudes ~150 mm.
- Approximate total mass: 60 kg



Band 2-6 Receiver Dewar Concept

- Rectangular dewar, with RX bands arranged inline
- Feed phase centers on a lateral axis
- Modular dewar, band subassemblies
- Single CTI 350 or 1050 G-M cryocooler, variable speed
- Two-axis translation stage (band select, focus)
- Dewar size w/o cryocooler: 725 x 260 x 300 mm (L x W x H)
- Approximate total mass: 55 kg



Cryogenic System Design

- ngVLA will have **418** cryocoolers, compared to **216** for the VLA.
- VLA crycoolers and compressors are a **fixed-speed** system
  - Sized for worst-case, maximum load conditions (warm startup on all dewars)
  - No provision to dial back helium flow for steady-state operation
  - As power consumption is proportional to available He flow => <u>*power is being wasted by delivering more flow capacity than needed for steady-state ops.*</u>
- ngVLA cryocoolers and compressors will be **variable-speed**
  - Cryocooler, compressor speeds adjustable to match cooling requirements.
  - Operating cost savings from **30-50%** possible, against a fixed-speed system
  - Prototype systems in testing at NRAO (VLA Green Antenna initiative)

Reference Design Summary

- Compact two-dewar solution to achieve full 1.2-116 GHz coverage
- Optimum sensitivity achieved with:
  - Compact, cooled feed horns with high aperture efficiency (>75%)
  - Waveguide-bandwidth receivers above X-band, for lower input losses and near-optimum LNA noise performance across the full band.
  - Two-stage G-M cryocoolers to get LNA temps < 20K.
- Reduction in relative operating costs through:
  - Employing wideband QRFHs below X-band, to cut # of RXs by half.
  - Use of modern variable-speed drives for cryocoolers and He compressors, and intelligent monitoring/control for optimizing their power usage.

Future Work / Next Steps

- Feed horn development:
  - Optimize QRFH profile for reduced backlobe and flatter efficiency over a **3.25:1** bandwidth, beam half angle of **55 degrees**.
  - Optimize corrugated feed horn for flatter efficiency over **1.67:1** bandwidth
  - Accurate pattern measurements of reference horns for both types
- Conceptual designs for Band 1 and Band 2-6 dewars:
  - Development of Band 1 concept by Caltech group.
  - Detailed Band 2-6 mechanical design/modeling, test dewar construction.
- Integration of receiver packages with back-end and support electronics, X-Y positioner at the antenna focus – mechanical design

References

[1] Baker, L. and Veidt, B., “DVA-1 Performance With An Octave Horn From CST & GRASP Simulations”, Internal Report, March 2014. Excerpted content used with permission from the authors.

[2] Weinreb, S. and Mani, H., “Low Cost 1.2 to 116 GHz Receiver System – a Benchmark for ngVLA”, ngVLA Science Workshop presentation, June 2017. Excerpted content used with permission from the authors.

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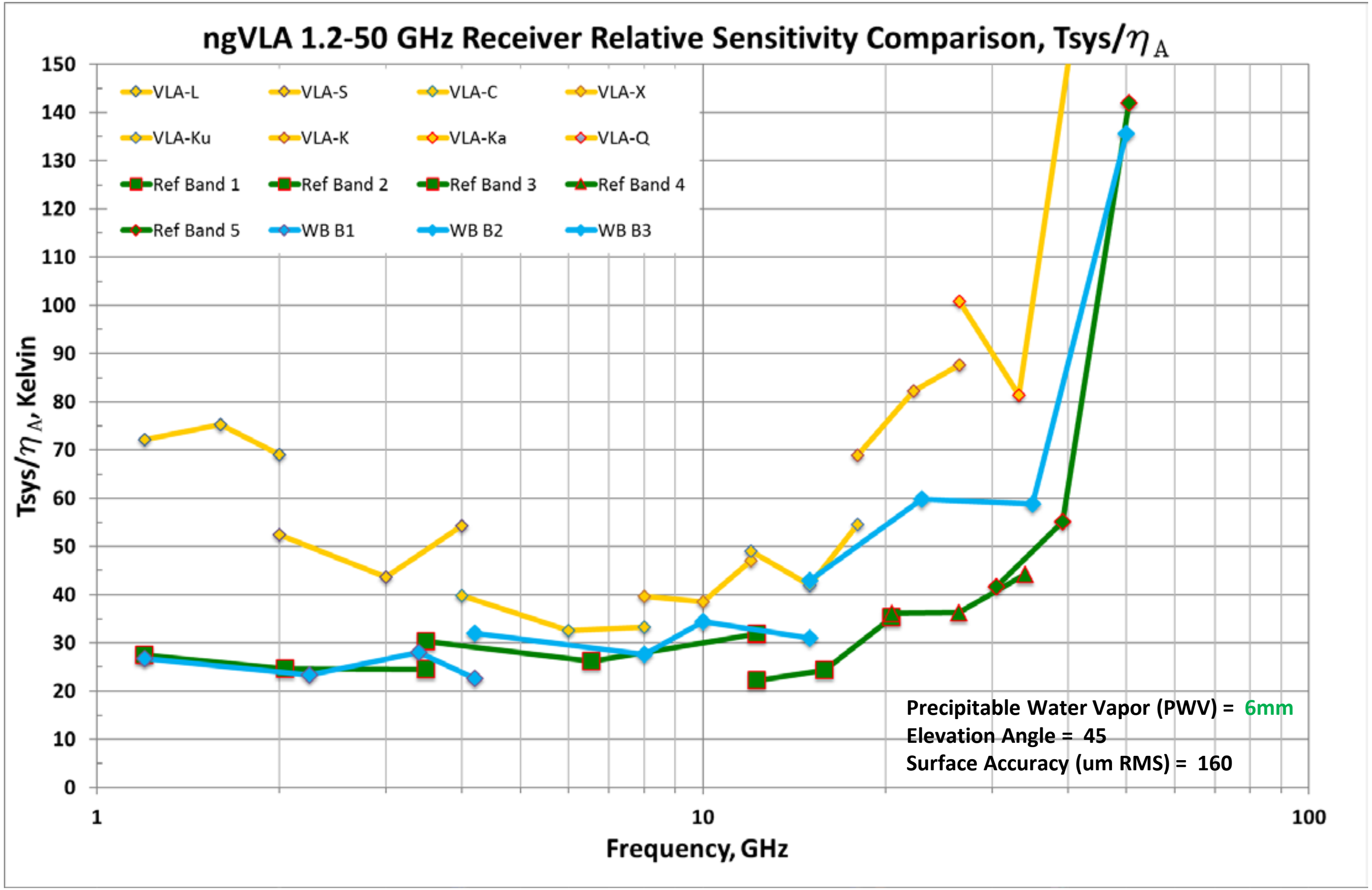
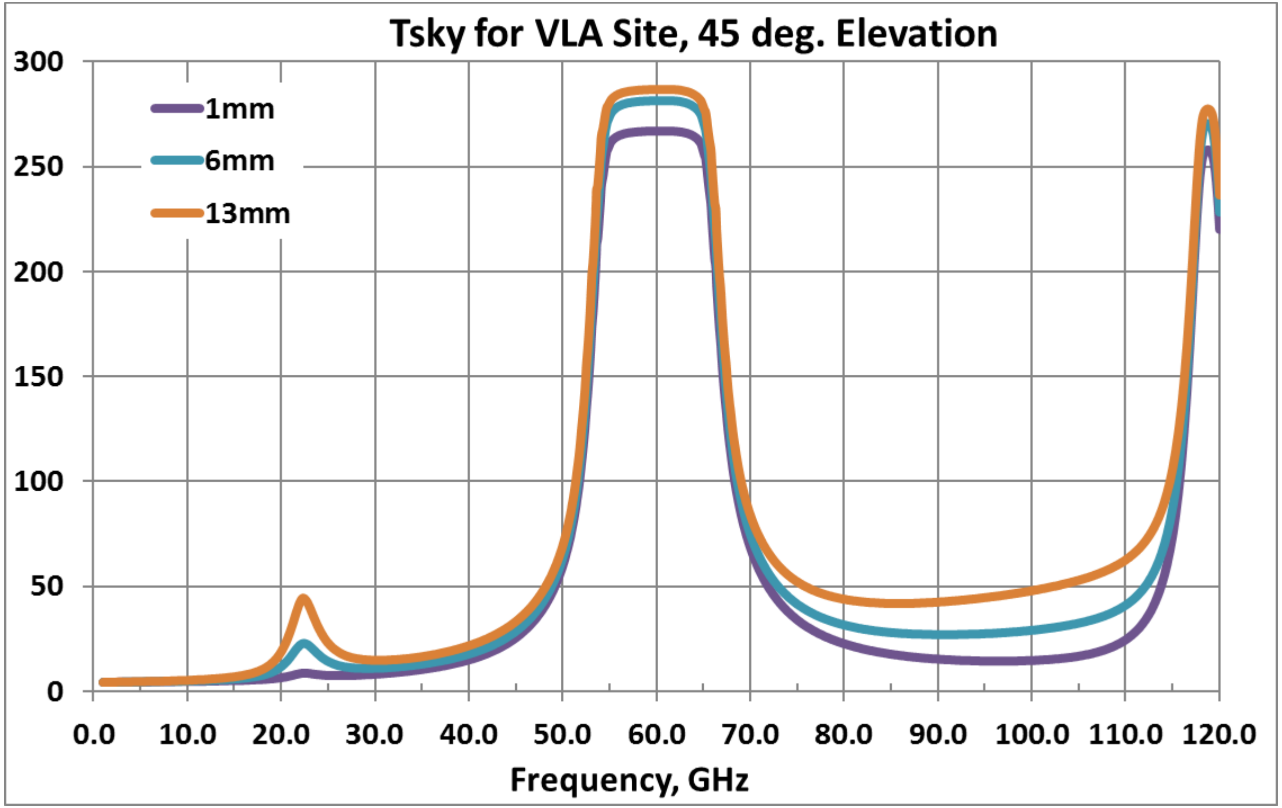
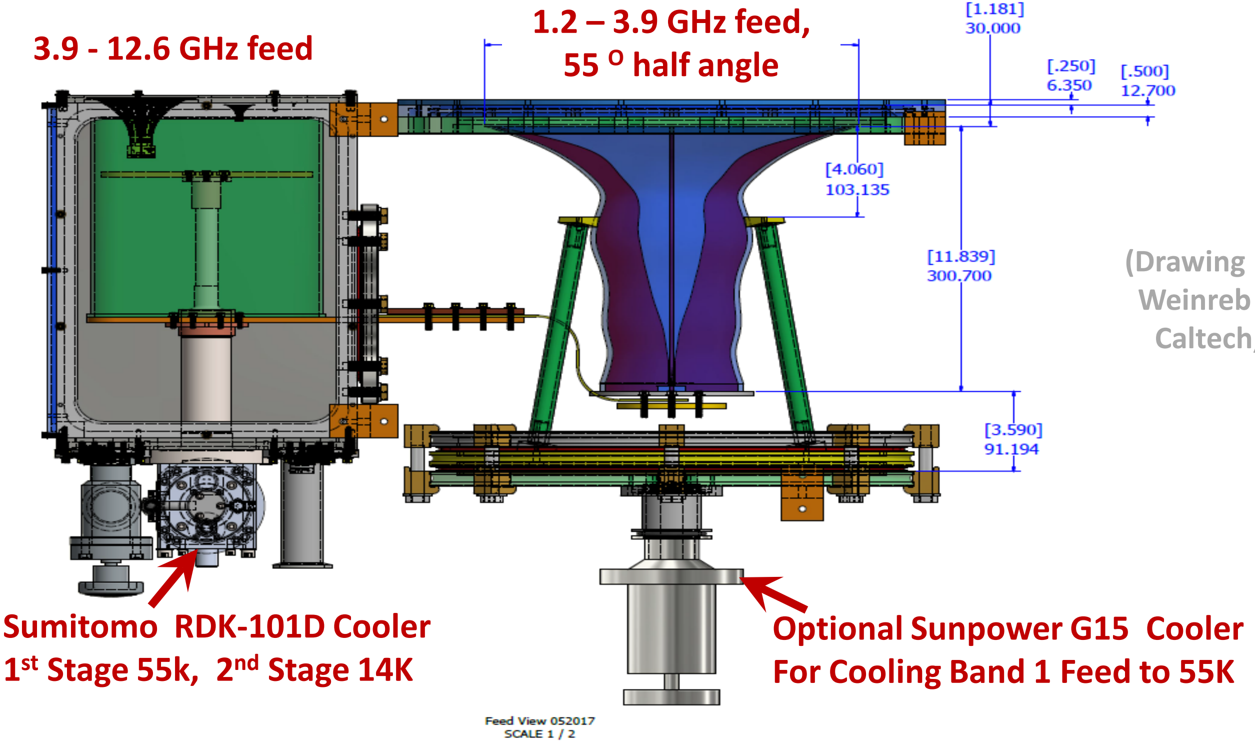
Additional Slides


ngVLA 1.2-50 GHz Receiver Relative Sensitivity Comparison, Tsys/η_A
VLA-L
VLA-S
VLA-C
VLA-X
VLA-Ku
VLA-K
VLA-Ka
VLA-Q
Ref Band 1
Ref Band 2
Ref Band 3
Ref Band 4
Ref Band 5
WB B1
WB B2
WB B3
Tsys/η_A, Kelvin
Frequency, GHz
Precipitable Water Vapor (PWV) = 6mm
Elevation Angle = 45
Surface Accuracy (um RMS) = 160

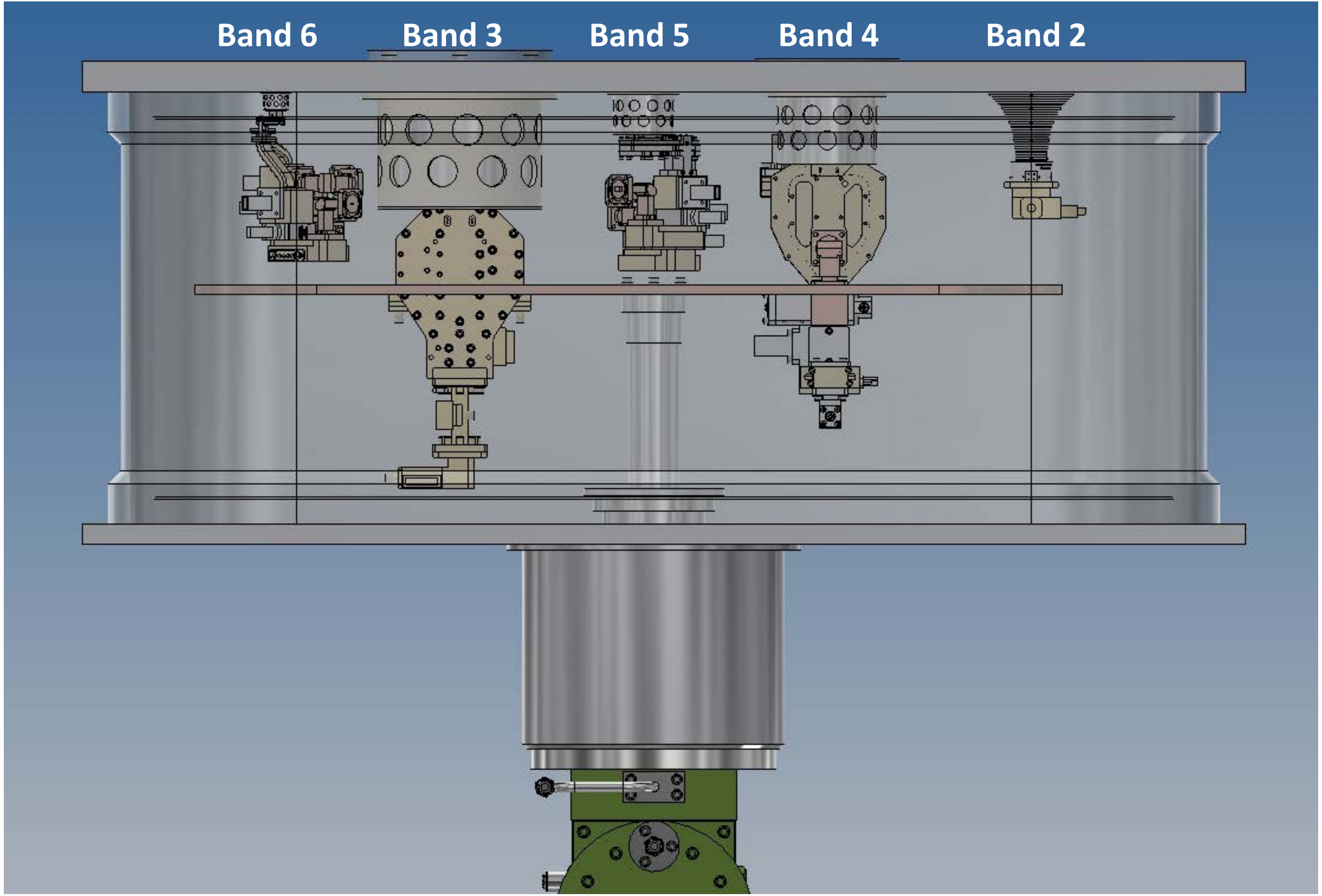


(Tsky data courtesy B. Butler, NRAO, July 2016)

Caltech Wideband Front end Concept: Cross-Sectional View



(Drawing provided by S. Weinreb and H. Mani, Caltech, June 2017)


Band 6
Band 3
Band 5
Band 4
Band 2