NATIONAL RADIO ASTRONOMY OBSERVATORY

ngVLA Ref. Design for Front End and Cryogenics

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Next Generation Very Large Array

Introduction and General Requirements

- Proposed ngVLA has 244 18m antennas and 19 6m antennas, ~10 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 and reduced required maintenance
- “Reference” design concept for ngVLA receivers, feeds:
  - A feasible design with relatively low technical risk and well-defined costs
  - **Maximizing sensitivity is the primary goal; wide bandwidths are secondary**
  - Wide-angle feeds are highly compact, can be cooled => *lower overall Tsys*
  - Good aperture efficiency and low spillover noise, for optimum sensitivity

Reference Front End Subsystem

Specific Design Assumptions

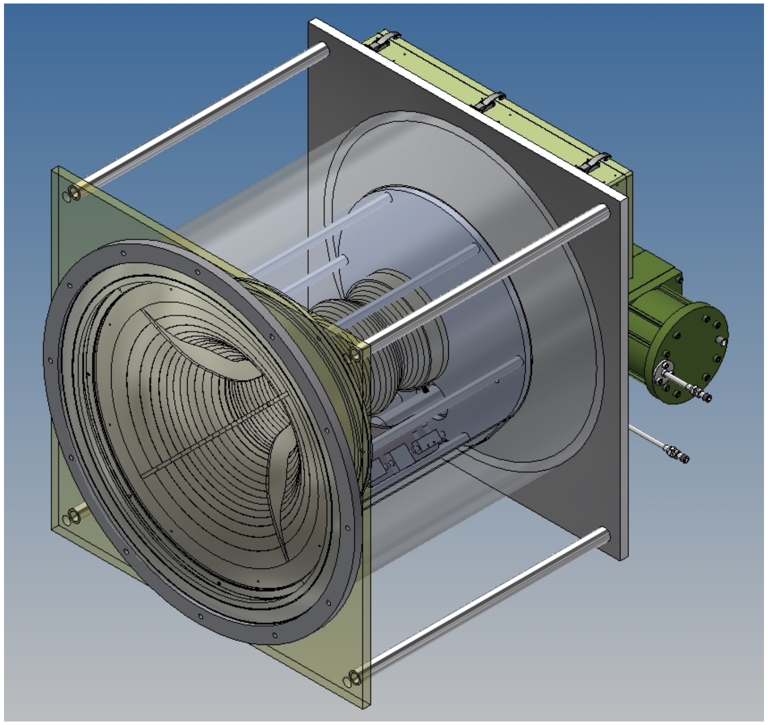
- Near-continuous frequency coverage from 1.2 – 116 GHz
  - Coverage gap from 50.5 - 70 GHz (O_2 absorption band)
- Feed horn has a beam half-angle of ~55 degrees.
- Receivers are single-pixel, with linearly-polarized outputs
- Feeds and LNAs in all bands are cryogenically cooled.
- Antenna is an unblocked, 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 Front End Configuration

- Six receivers (Bands 1-6), in a pair of compact cryogenic dewars
- Band 1 (1.2 – 3.5 GHz) in Dewar ‘A’:
  - Almost identical to the Caltech ngVLA receiver concept [1], but without the high-frequency bands and dewar extension. Feed cooled to 80K, LNAs to 20K.
  - ~3:1 bandwidth quad-ridged feed horn (QRFH) & LNAs, to cover L+S bands
- Bands 2-6 (3.5 – 116 GHz) in Dewar ‘B’:
  - Band 2 uses 3.5:1 QRFH & LNAs, to cover C+X bands
  - Bands 3-6 use ~1.67:1 bandwidth axially-corrugated feeds & LNAs, for more optimum aperture efficiency, spillover and noise performance.
  - Corrugated feed based on NRC DVA-1 octave-bandwidth design, scaled for ngVLA band frequencies [2].

Band 1 Receiver (Dewar 'A') Concept

- Based on design by S. Weinreb, H. Mani (Caltech/ASU)
- Cylindrical dewar houses cooled QRFH (80 K), coaxial LNAs (20 K)
- Challenges presented
  - Large vacuum window (Resistance to pressure, low RF attenuation)
  - RF connection between the feed and the RF tree (good thermal isolation with low insertion loss)



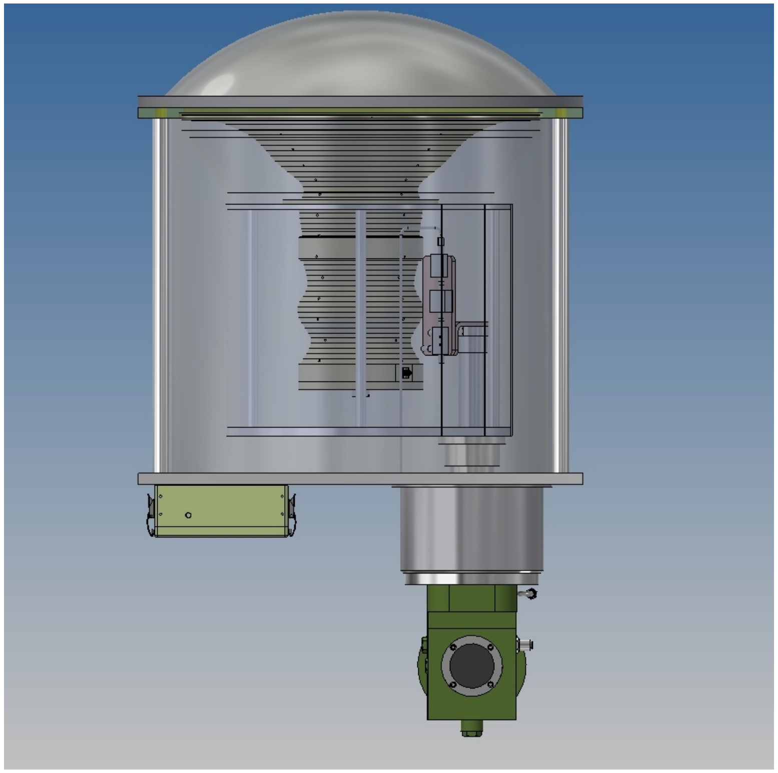
Thermal Analysis, Dewar 'A'

- Approximate Dewar dimensions & mass

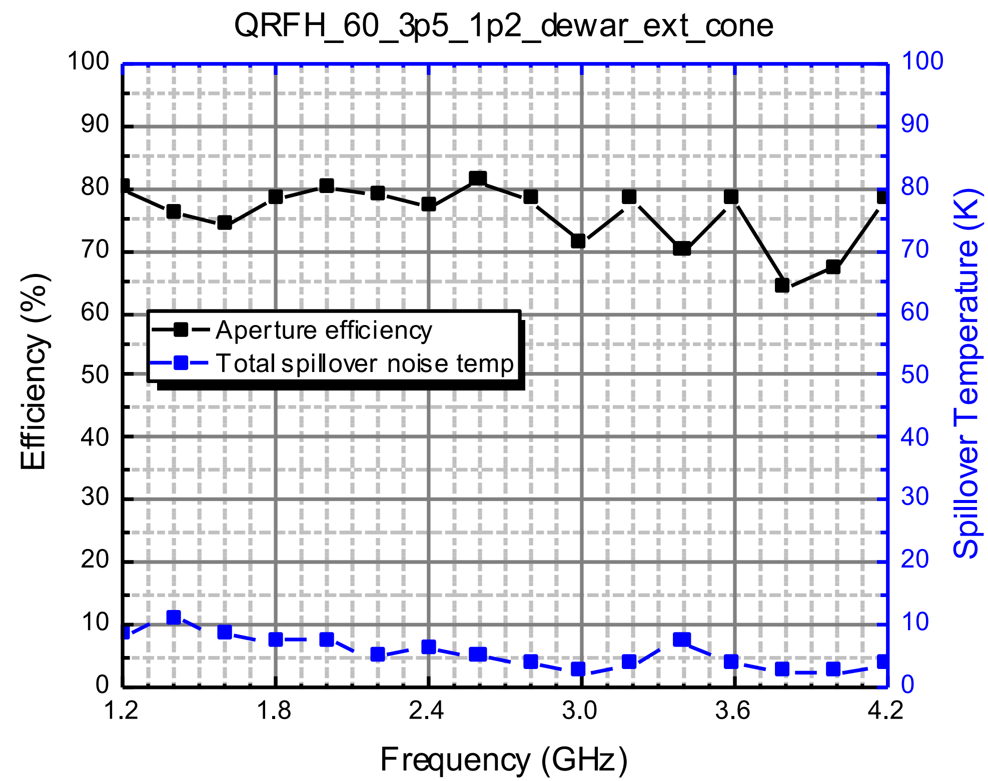
  458 x 406 mm (Dia. X H)

  67 liters and 60 kg
- Ambient Temperature 20°C, vacuum 10^{-6} mbar
  - 1^{st} stage 9.88W at 50°K
  - 2^{nd} stage 3.08W at 15°K
- Single GM cryocooler, variable speed

Note: Data from Callisto Thermal Study Analysis Report



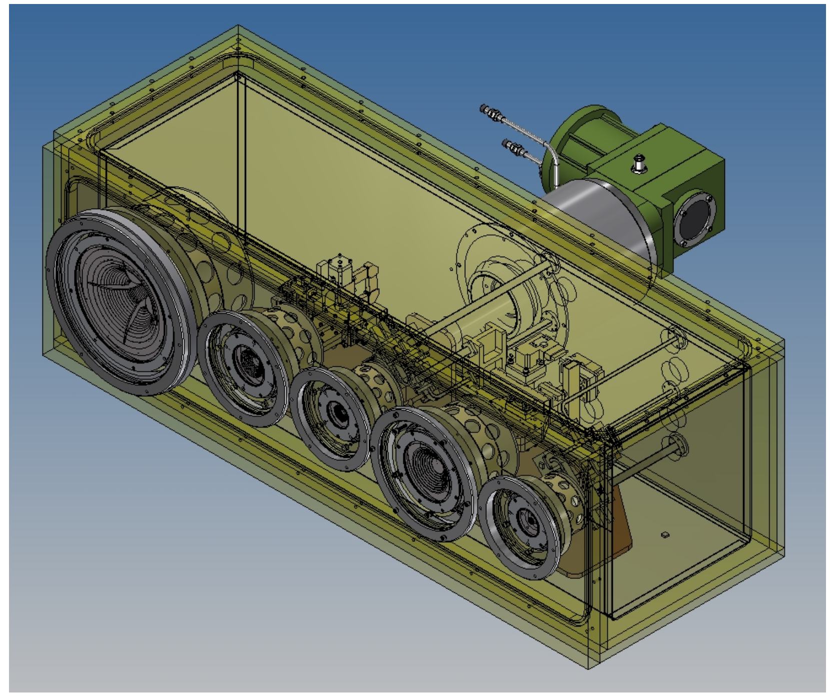
(photo courtesy S. Weinreb, Caltech, 2018)



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

Band 2-6 Receiver (Dewar 'B') Concept

- Rectangular dewar, inline bands
- Feed phase centers aligned on a lateral axis
- Modular receiver subassemblies
- Individual bands required minimal disassembly to be replaced, however operation can not be performed on the antenna
- Failure of any critical component will require a receiver swap



Thermal Analysis, Dewar ‘B’

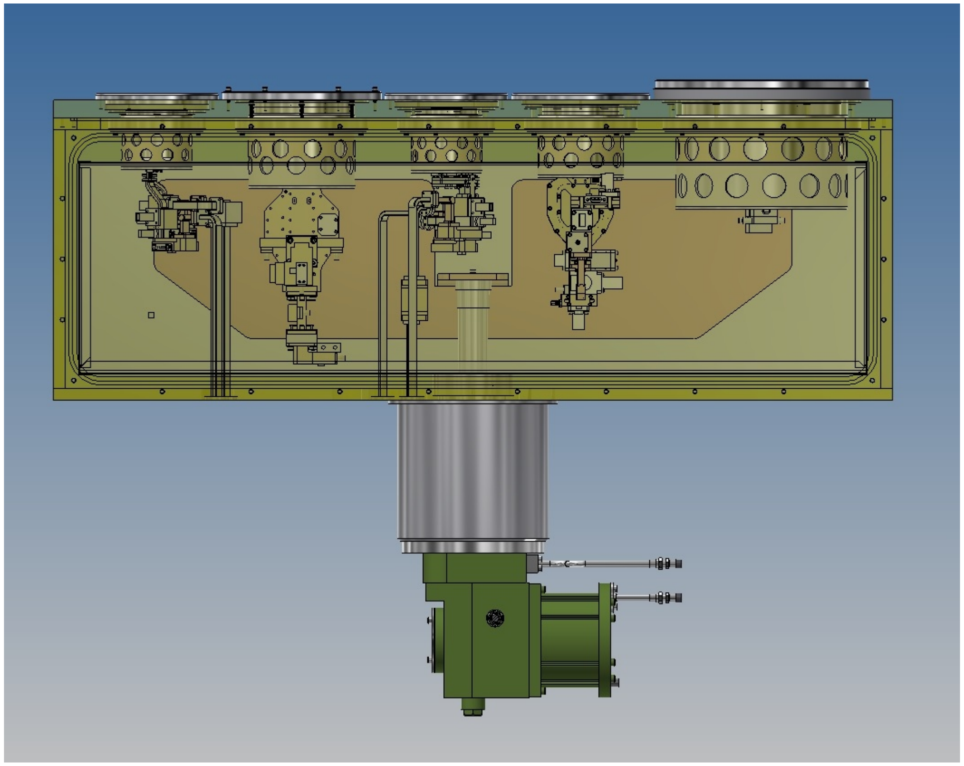
- Approximate Dewar size & mass

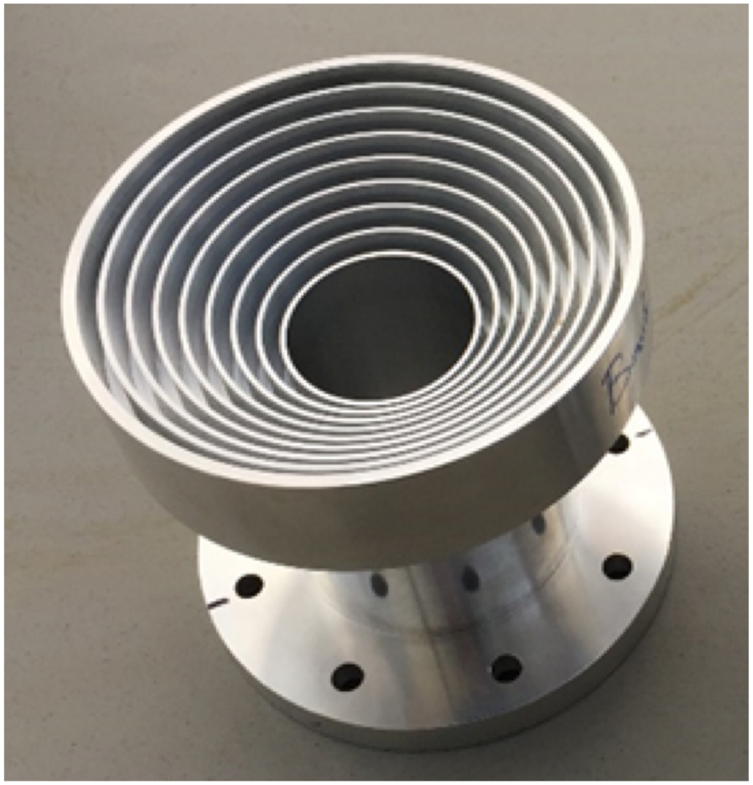
  725 x 260 x 300 mm (L x W x H)

  57 liters and 60 kg

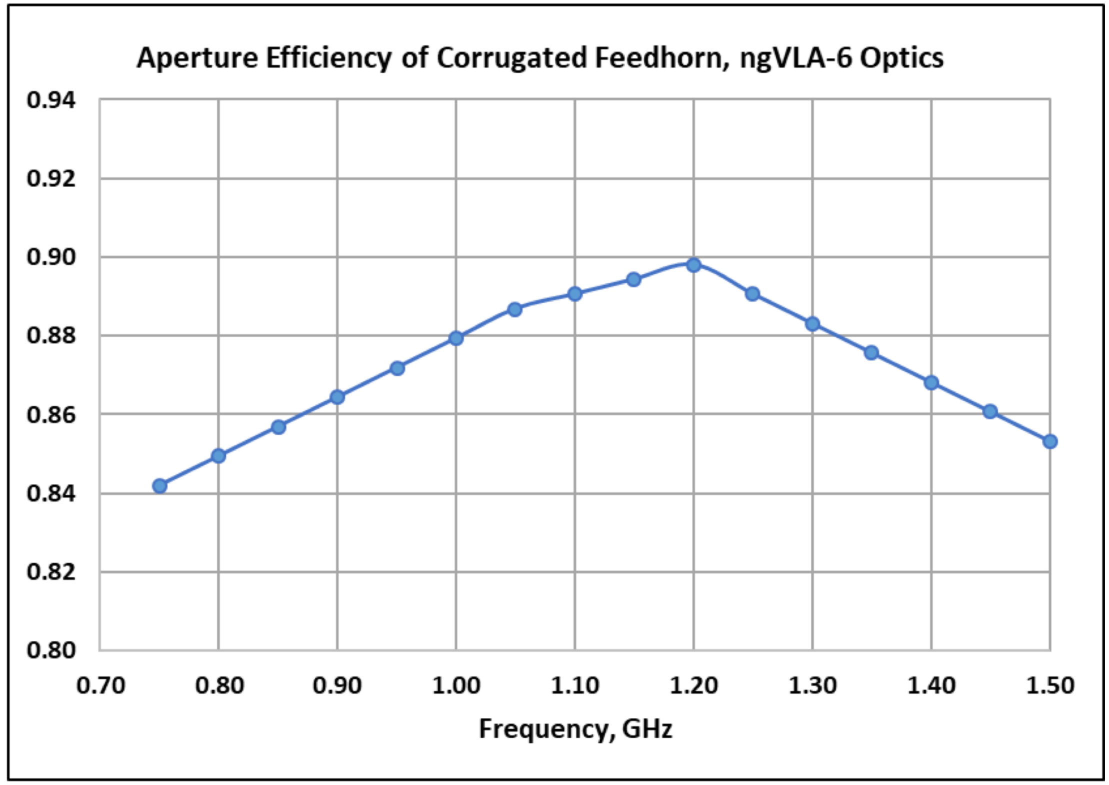
- Ambient Temperature 20°C, vacuum 10^{-6} mbar
  - 1^{st} stage 18.4W at 50°K
  - 2^{nd} stage 4.3W at 15°K
- Single GM Cryocooler , variable speed

Note: the thermal loads will go up with the outside temperature





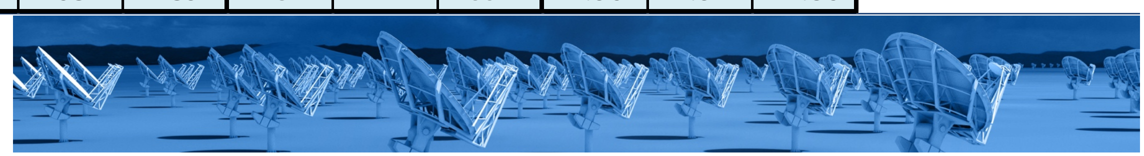
(photo courtesy S. Srikanth, NRAO, 2018)

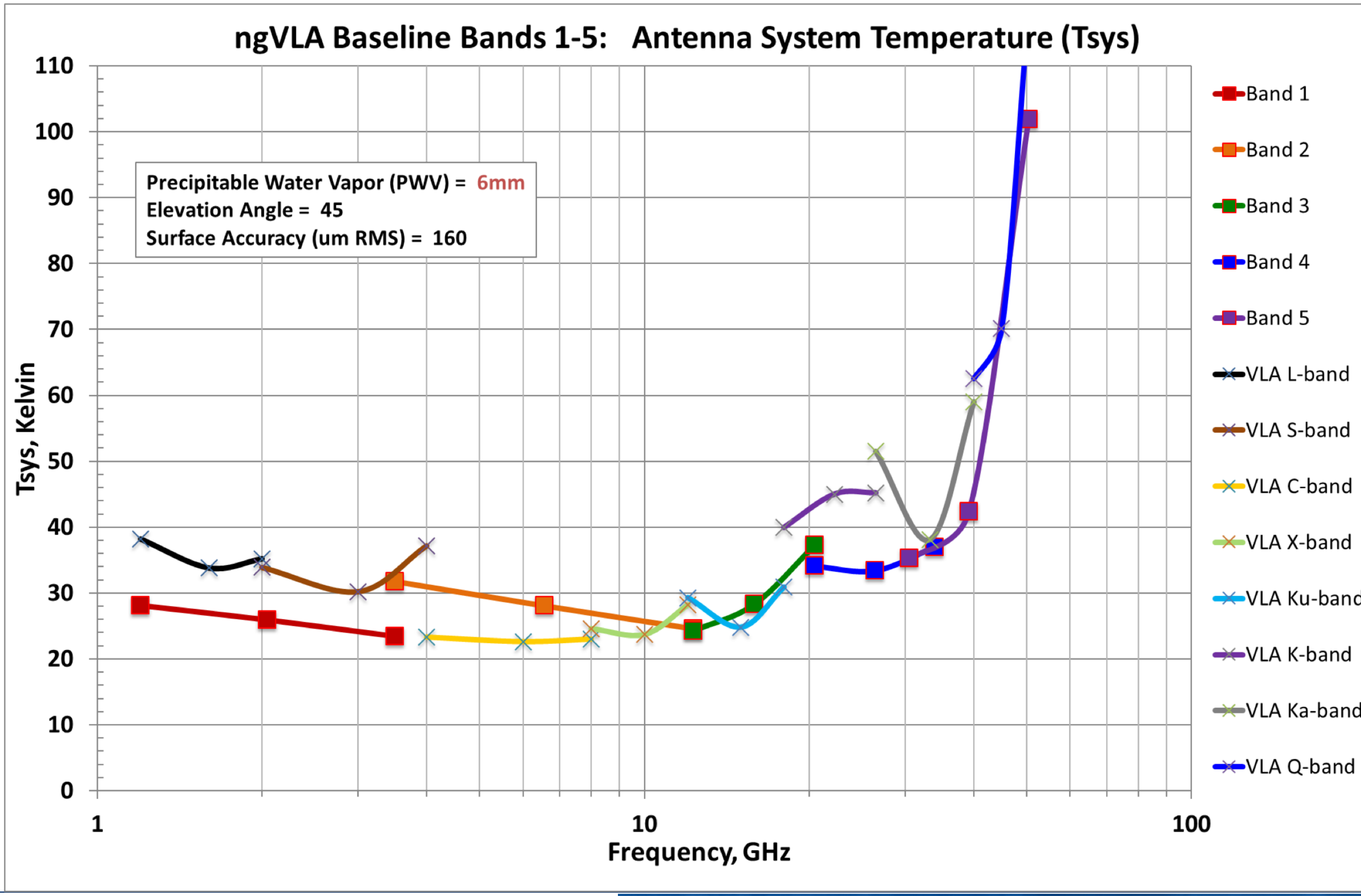


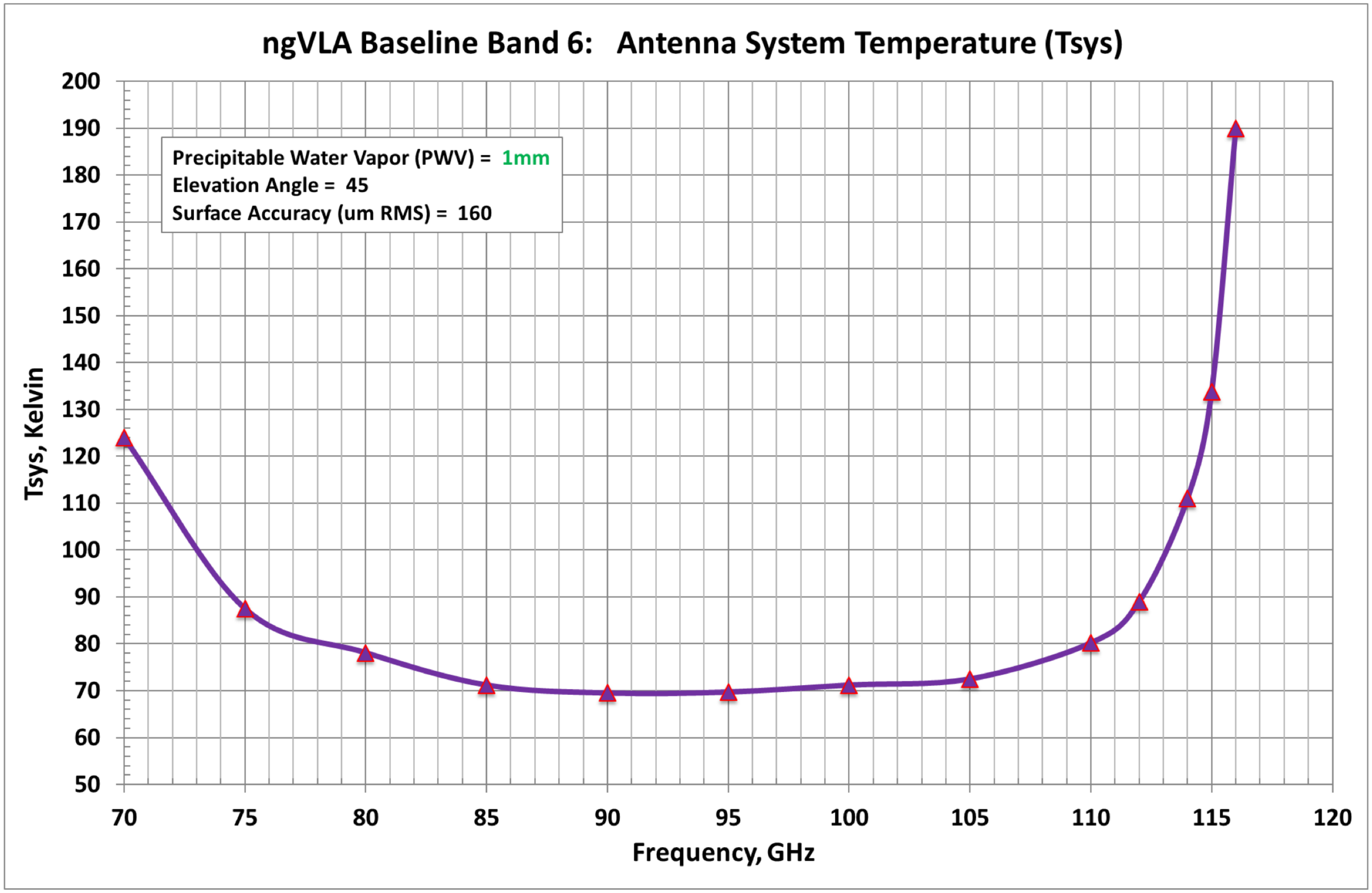
Front End + Optics Performance Estimates

Band #	f_L GHz	f_M GHz	f_H GHz	BW 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	2	0.80	0.79	0.74	13	10	4	9.9	10.3	13.8
2	3.5	6.6	12.3	8.8	0.80	0.78	0.76	13	7	4	13.4	15.4	14.4
3	12.3	15.9	20.5	8.2	0.84	0.87	0.86	4	4	4	13.9	16.9	18.6
4	20.5	26.4	34	13.5	0.83	0.86	0.83	4	4	4	15.4	16.2	19.5
5	30.5	39.2	50.5	20	0.81	0.82	0.78	4	4	4	19.1	20.4	26.5
6	70	90.1	116	46	0.68	0.61	0.48	4	4	4	50.6	49	72.6

Band #	T_{FEED} K	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	80	4.4	4.5	4.6	**28**	**26**	**23**	35	33	32	**1.55**	**1.44**	**1.39**
2	20	4.6	4.7	5.3	**32**	**28**	**25**	40	36	32	**1.75**	**1.59**	**1.42**
3	20	5.3	6.3	13.6	**24**	**28**	**37**	29	32	43	**1.27**	**1.43**	**1.91**
4	20	13.6	12.1	12.4	**34**	**33**	**37**	41	39	44	**1.80**	**1.72**	**1.95**
5	20	11.1	16.9	70.3	**35**	**42**	**102**	43	51	130	**1.91**	**2.27**	**5.73**
6	20	68	15	112	**123**	**68**	**189**	181	112	394	**7.96**	**4.92**	**17.36**

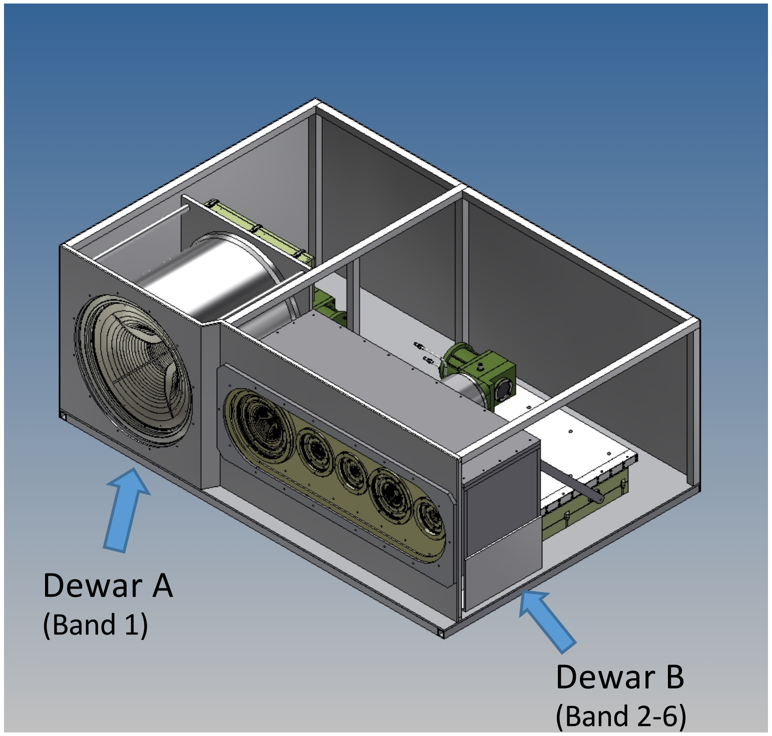


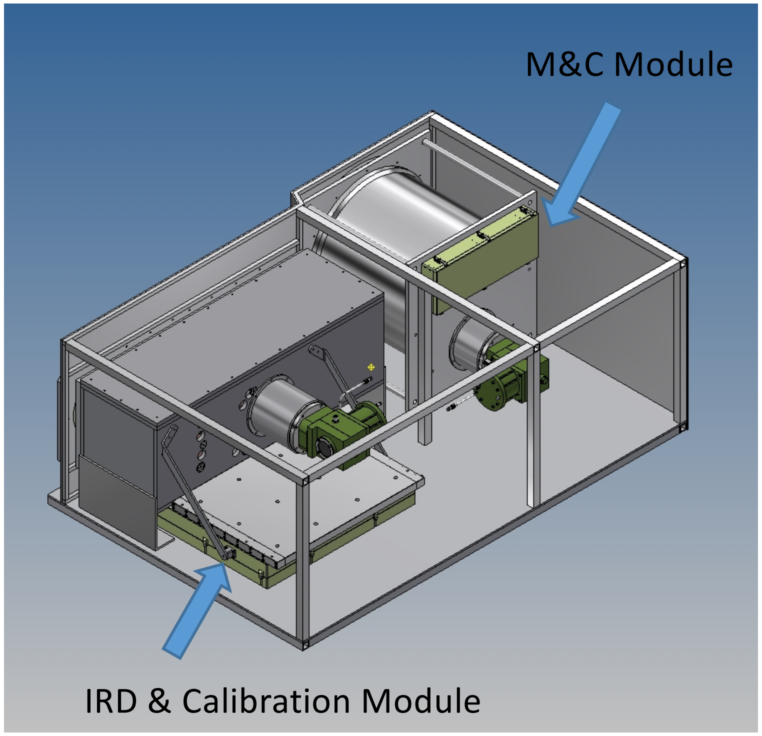

ngVLA Baseline Bands 1-5: Antenna System Temperature (Tsys)
Precipitable Water Vapor (PWV) = 6mm
Elevation Angle = 45
Surface Accuracy (um RMS) = 160
Tsys, Kelvin
Frequency, GHz
110
100
90
80
70
60
50
40
30
20
10
0
1
10
100
Band 1
Band 2
Band 3
Band 4
Band 5
VLA L-band
VLA S-band
VLA C-band
VLA X-band
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
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
70
75
80
85
90
95
100
105
110
115
120
Frequency, GHz

Antenna Receiver Platform Movable in X-Y for Band Selection and Focus Adjustment





IRD: Integrated Receiver/Downconverter and Digitizer

Future Work

- Feed horn development:
  - Optimize QRFH profile for reduced backlobe and flatter efficiency over a **3.25:1** bandwidth, for the opening angle of the ngVLA antenna.
  - Optimize corrugated feed horn efficiency over **1.67:1** bandwidth
  - Accurate pattern measurements of reference horns for both types
- Conceptual Designs for Dewars ‘A’ and ‘B’:
  - Improved Trx on Bands 1 & 2: eliminate noise cal coupler?
  - Detailed Band 3-6 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

Front End 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.

Reference Cryogenic Subsystem

Introduction

- The ngVLA may have up to **526** cryocoolers, versus **216** for the VLA.
- On the VLA, cryocoolers and compressors run at a **fixed-speed**
  - Oversized cryocooler: extra cooling capacity that is not needed to get the required performance out of the Front End. Compensation for a non optimized thermal design.
  - Oversized compressor: each compressor produces an excess of Helium flow to avoid starving the cryocooler.
  - 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 under development at NRAO (VLA Green Antenna initiative)

ngVLA GM Refrigerator

- Cryogenic Cold-head Model Trillium 350CS
  in use at the VLA with demonstrated good reliability
  (VLA data mtbm > 17000hrs including preventive maintenance)

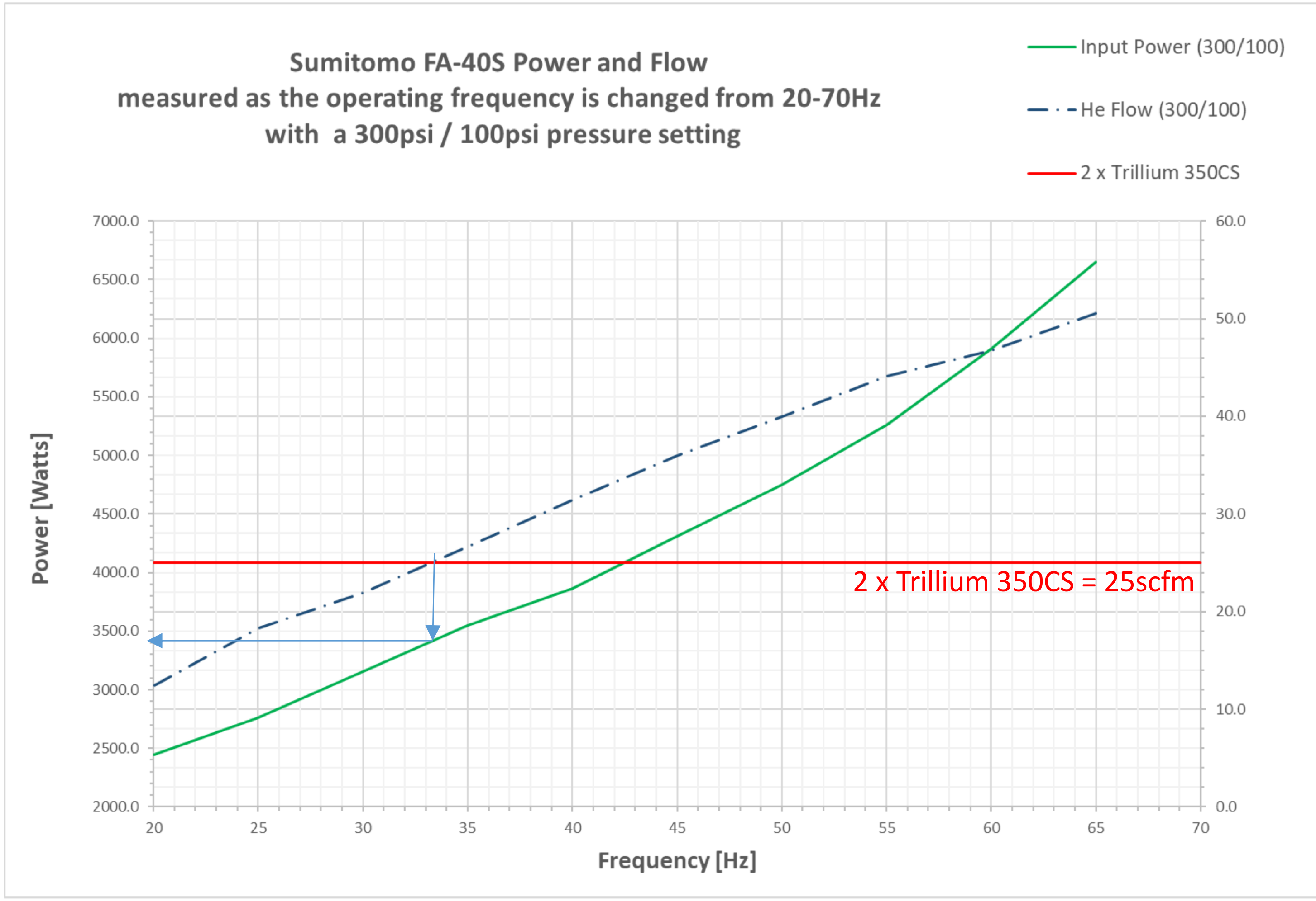
	Refrigeration capacity
First stage at 77°K	20 Watts
Second stage at 20°K	5 Watts

- Low maintenance/repair cost (parts $250, labor 5hours)
- In-house Designed Variable Frequency Drive 30-70Hz
- Estimated Flow at 60Hz **12.5scfm**

Compressor Development by Sumitomo SHI

FA40 Integration into
FA70 outdoor enclosure

- **Phase 1:**
  - Build FA40 prototype with VFD (completed)
  - Measure the performances: flow vs power (completed)
  - Measure RFI and design shielded enclosure for electronics (pending)
- **Phase 2** (pending available funding):
  - Integrate FA40 capsule into a FA70 outdoor enclosure
  - Relocate control/power electronics to an outdoor-rated RFI enclosure. (ngVLA prototype)



Delta P	300/100
Flow [scfm]	25
Power[kW]	3.4
Freq. [Hz]	34

VLA and ngVLA Cryogenics Comparison Table

	VLA	ngVLA	Rel. Cost
Antennas	27 x 25m	214 x 18m + 19 x 6m + 30 x 18m	n/a
He compressor	3 x 27 = 81	1 x 263 = 263	**3.25**
AC power consumption	81 x 6 = 486kW	263 x 3.4 = 895kW	**1.85**
Cryocooler Model(s)	1 x Model 22, 6 x Model 350, 1 x Model 1050	2 x Model 350	n/a
Cryocoolers	8 x 27 = 216	263 x 2 = 526	**2.43**
Estimated cryocooler maintenance index	27 x (1 x 3 + 6 x 1 + 1 x 1) = 270	263 x (2 x 0.66) = 350	**1.3**

ngvla

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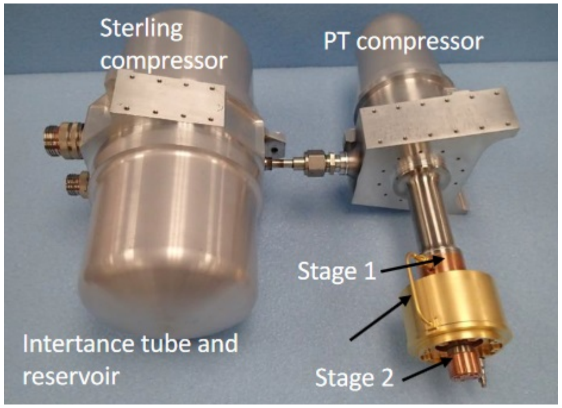
Advanced Cryocooler Study



- Collaboration with Northrop Grumman
- Dual cooler system
  - Single stage Stirling (110K stage)
  - Dual stage Stirling and pulse tube (50K and 15K stages)
- Maintenance free, flexure-bearing, non-wearing technology developed for space application
- Higher efficiency than the proposed reference design GM cooler
- Cost unknown at this time. Could this type of cryocooler be produced in large quantity and at a reasonable price?
- External liquid cooler required (already needed for other systems on the antenna)

ngVLA Front End Cryogenics Summary

- Cryogenic equipment selected for the reference design
  - Uses well-established technology, with proven reliability
  - Variable speed control to minimize power consumption and increase maintenance intervals
  - In-house expertise for service and repair => lower overall maintenance cost
  - Meet the operation budget set for the project
- More advanced type of cryocoolers under investigation for the design phase

References

[1] 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.

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

[3] Baker, L., "Analysis of ngVLA Design #6 With Ideal and Actual Feed", Internal ngVLA Doc. # 020.25.01.00.00-0001-REP, January 2018

[4] L. D'Addario, "Advanced Cryocoolers For Next Generation VLA" ngVLA Memo No. 24

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Reference Front End Band Frequencies

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