Low Cost 1.2 to 116 GHz Receiver System – a Benchmark for ngVLA

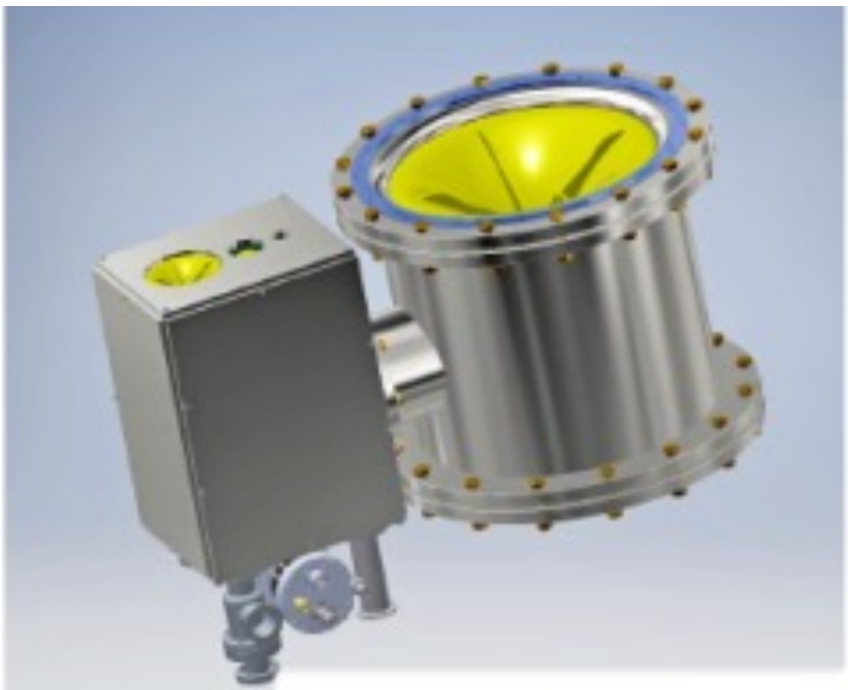
S. Weinreb and H. Mani

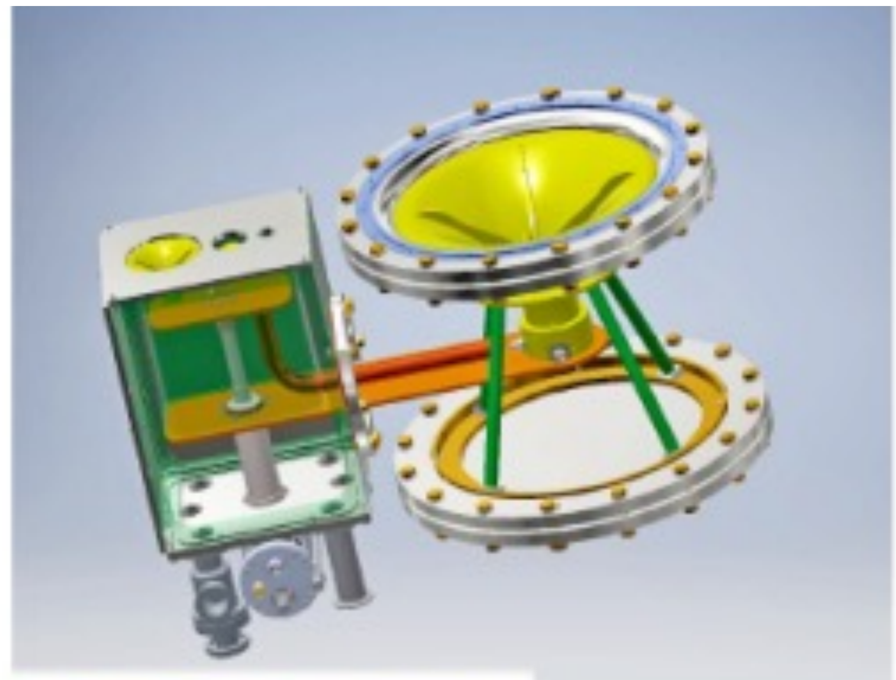
June 26, 2017, sweinreb@caltech.edu

1. Concept
2. Integration with Reflector
3. Wideband Feed Performance
4. Cost and Strategy
5. Current Hardware Status

Concept for 1.2 to 116 GHz Receiver

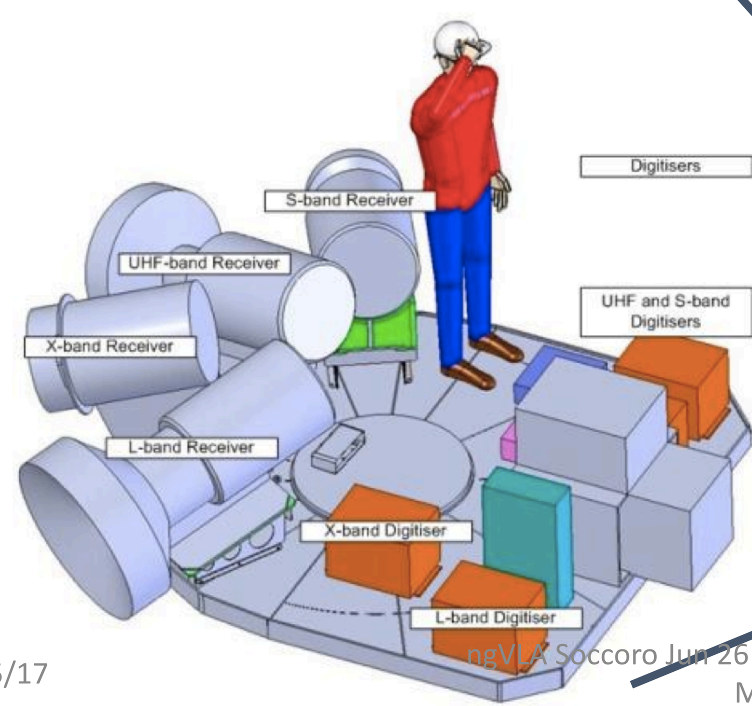
- Four dual-polarized receivers in one vacuum chamber and cryocooler
- Proposed bands are 1.2-4.2, 4-15, 15-50, and 70-116 GHz
- 1.2-4.2 GHz feed cooled to 80K, all other feeds and all LNA's cooled to 15K
- Receiver mounted on X-Y stage for band selection and focus
- Weight < 200 lbs and power consumption < 1500W





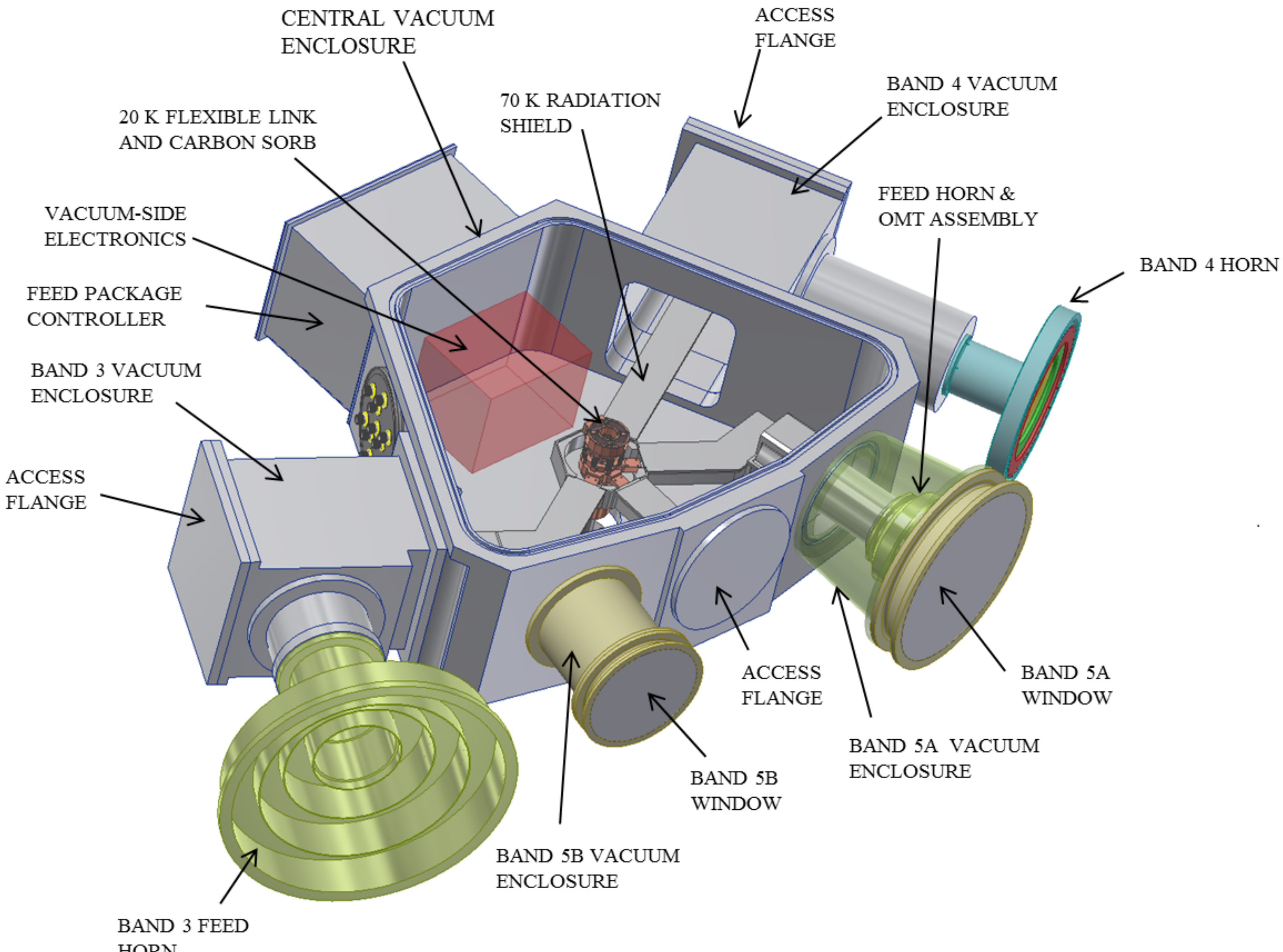
Offset Gregorian Reflector Design

- Provides unblocked reflector and easy access to receivers at secondary focus. Has been selected for SKA and recommended for ngVLA.
- Several feeds and dewars can be mounted on rotating platform as implemented on Meerkat 64 x 13.5m array and planned for SKA 133 x 15m.
- For the ngVLA 1.2 to 116 GHz receiver an X-Y stage rather than (or in addition to) the rotary platform is recommended to allow both frequency band selection and focus adjustment vs elevation.



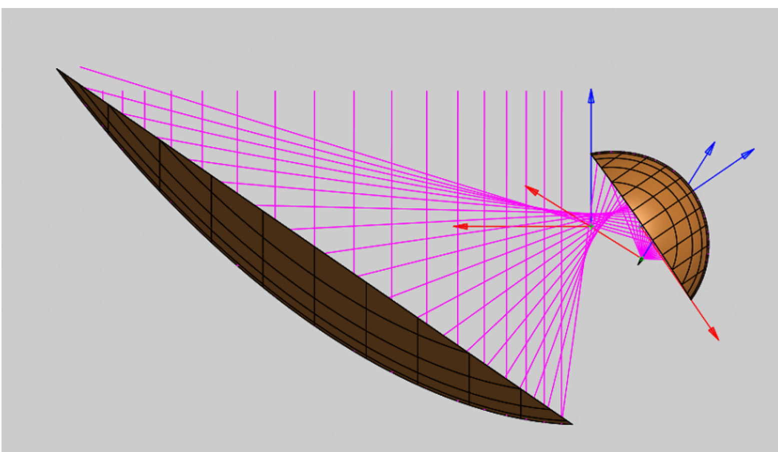
SKA Concept for Four Feeds for 1.6 to 15.3 GHz on One Cryocooler

Mike Jones, Jamie Leech, and Angela Taylor, U. of Oxford

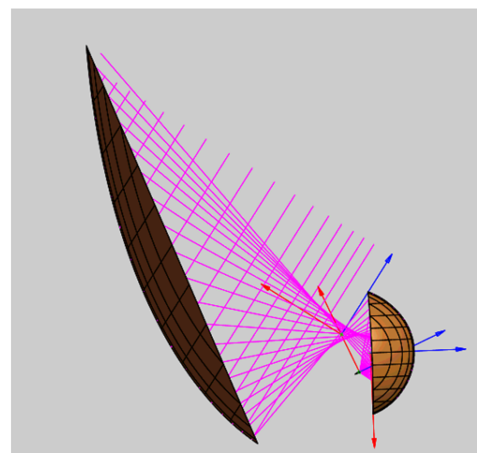


Offset Gregorian Ray Paths at El. 90º, 60º, and 15º

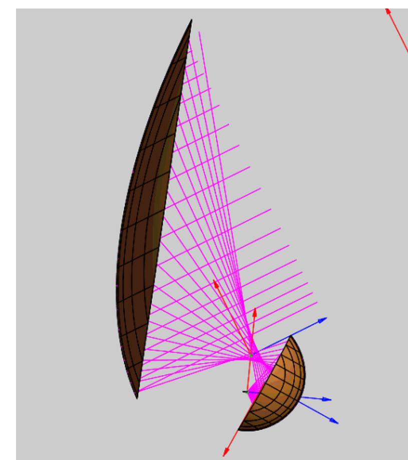
- The receiver system requires offset Gregorian optics such as that used on the Meerkat antennas and selected for the SKA dish array.
- No primary beam blockage with large subreflector and receiver platform
- Spillover is in cold sky for upper half of both subreflector and main reflector for all elevation angles



El. 90°



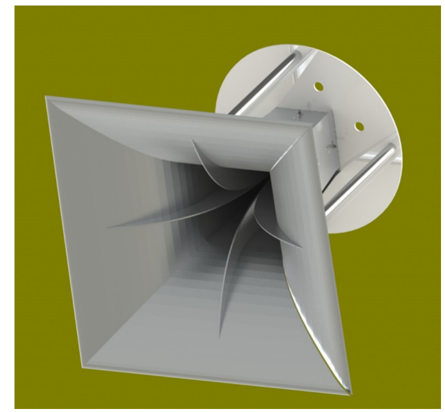
El. 60°

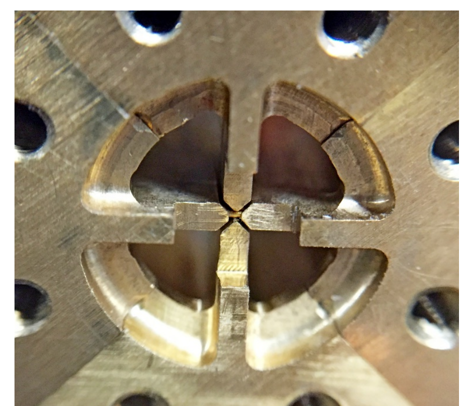


El. 15°

Quadridge Flared Horn (QRFH), Feeds

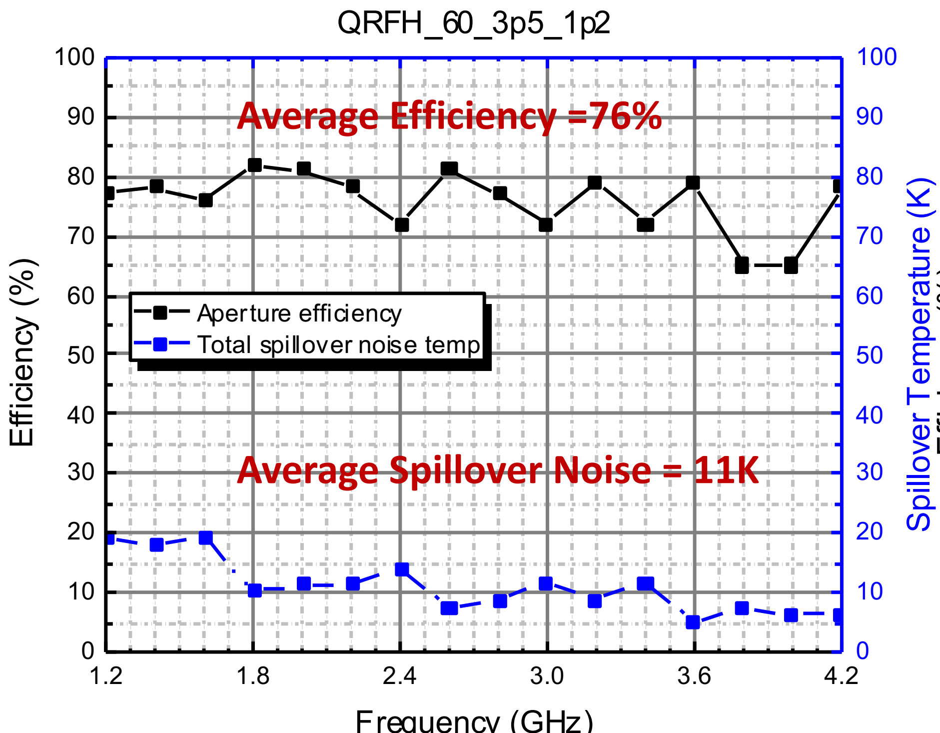
- Main attribute is beamwidth independent of frequency as required for antenna feeds.
- Based on Akgiray 2013 Caltech Ph.D. thesis, over 20 variations have been designed by several research organizations for a wide range of frequencies and dish optics.
- Efficiency and spillover noise vary somewhat with upper to lower frequency range
- Can be scaled proportional to wavelength. An 8-50 GHz version about 5cm in diameter, is shown below and a 0.26-1.6 GHz , 1.5m square, for the FAST telescope are shown below
- Easily machined in 5 pieces on numerically controlled mill.

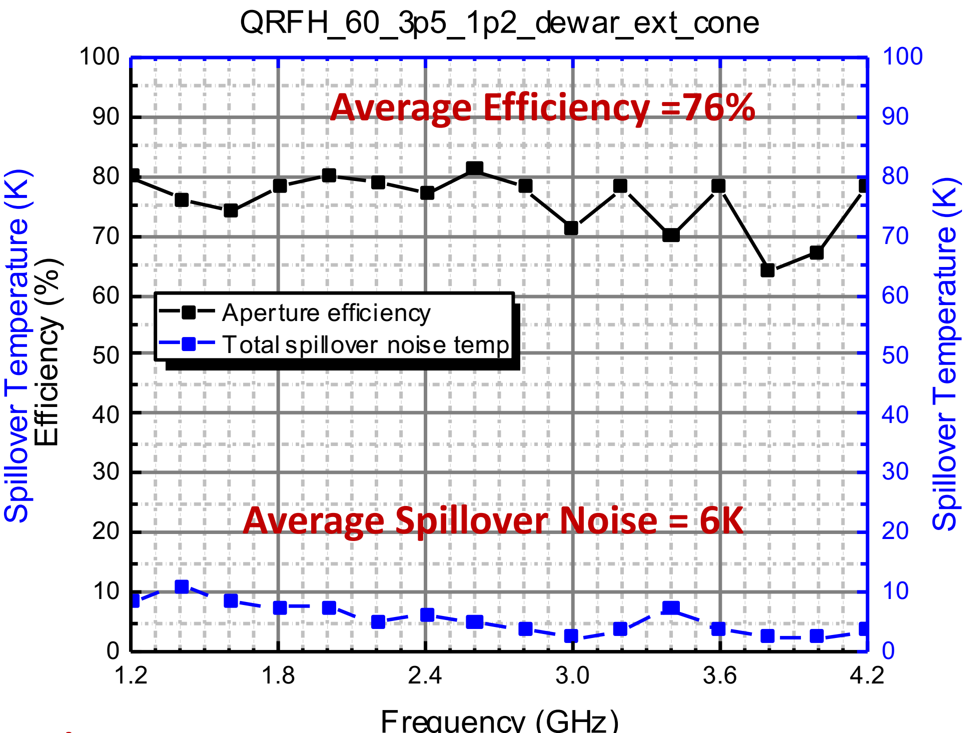


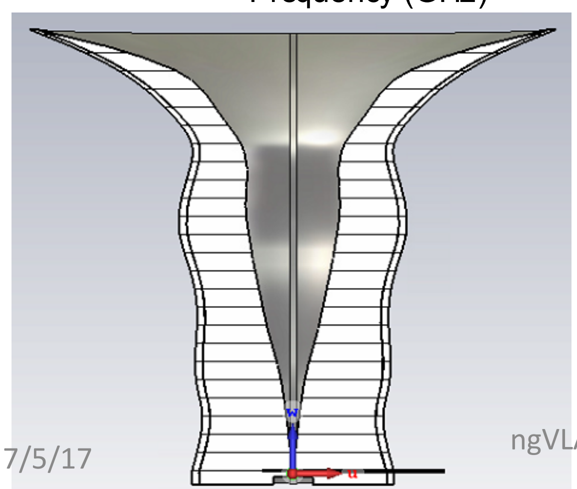


Total Feed Aperture Efficiency and Spillover Temperature

Current ngVLA demonstration design for 1.2 to 4.2 GHz with 58^{O} Half Angle

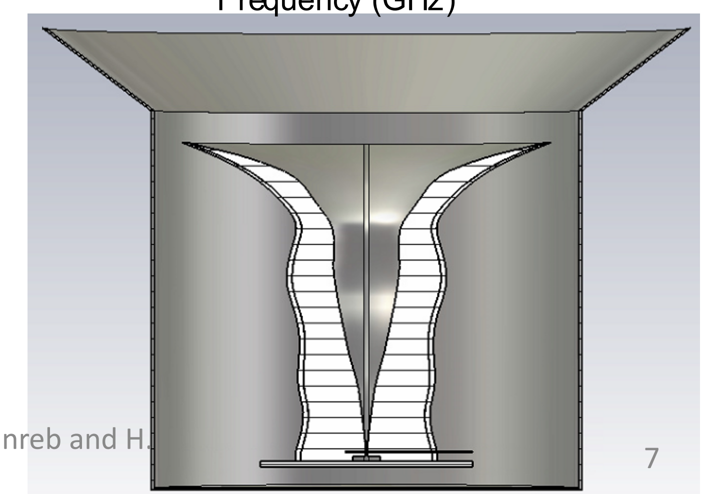






Feed cone is external to Dewar. Its main effect is on the back lobe

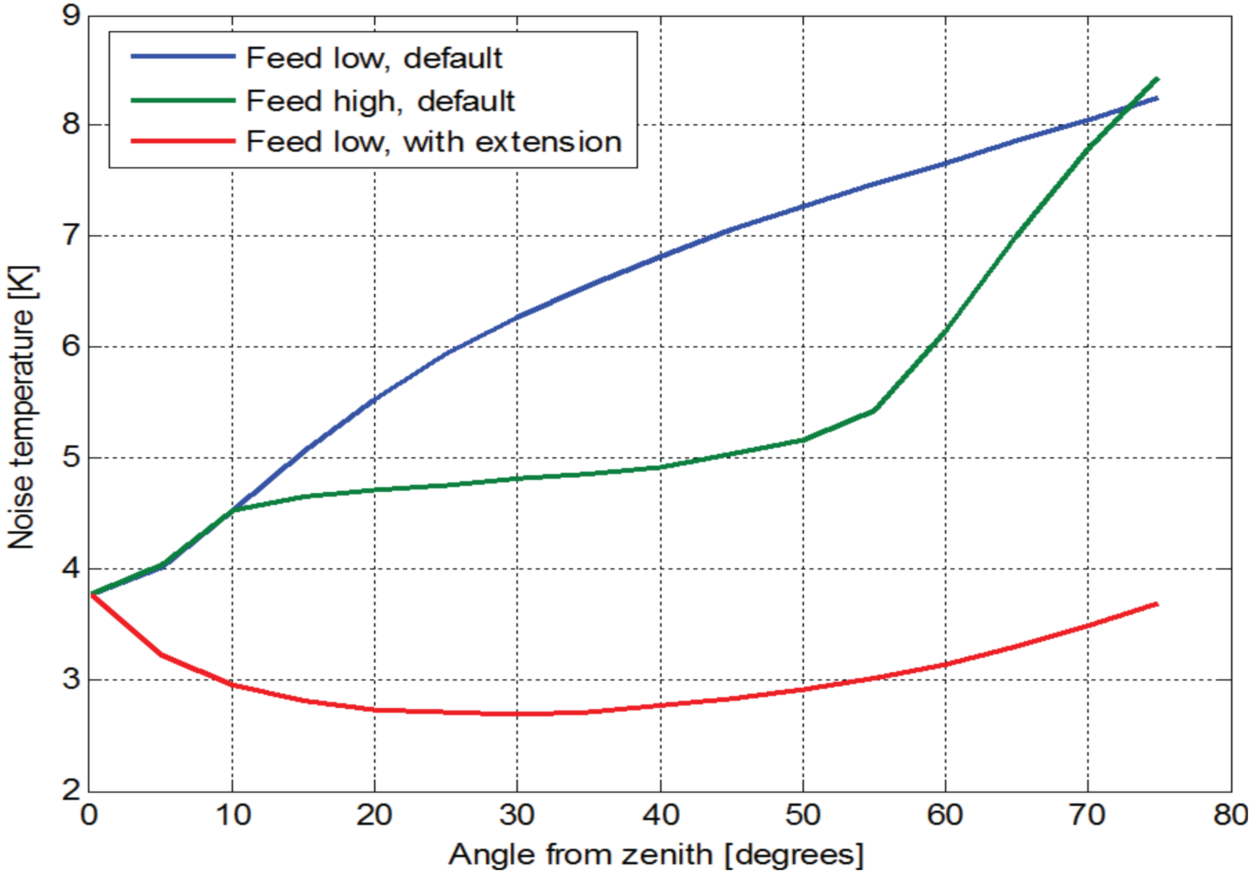
Spillover Noise is with conservative assumption that ½ the total spillover is at 250K



Sub Reflector Extension to Reduce Spillover

Isak Theron "The design of the MeerKAT dish optics", IEEE, 2012
Similar though larger shield used on Allen Telescope Array (ATA)

A small shield on lower edge of the subreflector lowers the spillover noise by ~4K over a wide range of zenith angle – A significant improvement to Tsys and allows the feed to be positioned near the ground for maintenance



Total System Noise Estimate at Center Frequencies of Primary Interest

Noise, K, due to component	**Remarks**	**Tsys 1.4 GHz**	**Tsys 8 GHz**	**Tsys 15 GHz**	**Tsys 35 GHz**	**Tsys 80 GHz**
Sky	Background + atmosphere, 45deg, 13mm	4	6	8	15	43
Spillover & Blockage	Reduce with offset antenna And ground shield	3	3	3	3	3
Feed loss	Computed 0.1 dB @60K for 1.4 GHz @20K for 8-116 GHz	1	1	1	2	4
Window and IR Filter	Mylar window; multilayer polymer blanket	2	3	3	3	3
Feed to LNA No Coupler	0.1 dB	1	1	2	2	2
LNA	Robust LNA measured at connector	4	5	8	12	25
Total	**Estimate, +/- 5K**	**15**	**19**	**25**	**37**	**80**

Rationale for Single Cryocooler Receivers

- **Operating Cost** in terms of power cost and cryogenics maintenance labor cost are major concerns for a new major array in the US. The ngVLA will have an order of magnitude more telescopes and distances from the control center and to reduce capital and operating costs it is imperative to reduce the number of cooled systems on each telescope

- **Number of Cryocoolers** Current VLA utilizes 8 cooled receivers on 27 telescopes – 216 vacuum dewars and cryocoolers. Our goal should be same operating cost for the future replacement with one dewar on ~256 antennas.

- **Single Dewar and** Cryocooler receiver is feasible but the questions are:

  - **Can a thermal design facilitate only 1.5 kW of AC power?**
  - **How many receivers are needed to cover the total frequency range?**
  - **What are the crossover frequencies?**
  - **How does sensitivity change for bandwidths of 6:1, 3:1, or octave?**
  - **What size cooler is needed and what is the operating cost?**
  - **How is reflector optics design impacted?**

Antenna Electronics Cost Estimate

- FY17 dollars and contingency not included
- $534K total per antenna. $187K for cold electronics and $347K for warm electronics

Item	Cost Estimate	# per Ant	$ per Antenna	$M per 117 Array	$M per 314 Array	Basis or Remarks
Antenna Electronics		**1**	**$534,277**	**62.51**	**167.76**	**$62.5M for an 117 antenna array of which $21.9M is for cold electronics (LNA, feed, dewar, cryogenics) and $40.6M is for warm electronics located on each antenna.**
Antenna Cold Electronics		**1**	**$187,000**	**21.88**	**58.72**	**Total cold electronics and cryogenics**
Antenna Warm Electronics		**1**	**$347,277**	**40.63**	**109.04**	**Total downconverters, A/D, and formaters**
Feeds	$8,000	4	$32,000	3.74	10.05	Based on QRFH designs fabricated by machine shops. Past history.
LNAs	$14,000	4	$56,000	6.55	17.58	Two LNA's per dual polarization receive with $7K per LNA based on current cryogenic LNA prices
Dewar Accessories	$3,000	4	$12,000	1.40	3.77	Vacuum pump, guage, valves, and temperature sensors
Calibration Components	$5,000	4	$20,000	2.34	6.28	Noise diodes and fiber receiver for phase cal if needed
Master PCB	$1,000	4	$4,000	0.47	1.26	Printed circuit board with voltage regulators, LNA bias, temperature and DC monitor, receiver control and interface to serial data link.
Cryo Dewar	$16,000	1	$16,000	1.87	5.02	Based upon cost for demonatration dewar of $16K but allowing for increases for testing and decease for quantity. No 2nd dewar and compressor is needed.
Cryo Compressior	$23,000	1	$23,000	2.69	7.22	Includes cryocooler and compressor. Cost based upon quote for single Sumitomp RDK-101D including flex lines.
Receiver Assembly and Test Labor	$24,000	1	$24,000	2.81	7.54	Based upon 6 person-weeks per antenna cryo package at $100/hour including burden. For 117 antennas this is a group of 5 working for 3 years
Downconverters	$3,000	32	$96,000	11.23	30.14	Based upon MMIC multi-chip modules including post amplifier, filter, mixer, IF amplifier, and LO mulitipler. Bandwidth dependent upon receiver center frequency but no greater than 5 GHz.
3-bit samplers	$2,000	48	$96,000	11.23	30.14	Two samplers per downconverter, 24 wideband downconverters
8-bit samplers	$1,000	16	$16,000	1.87	5.02	Two samplers per downconverter, 8 narrow band downconverters
LO System	$10,000	1	$10,000	1.17	3.14	One quartz standard, mutipliers, and fiber interface to round-trip phase correction system
Data Formatter [per Gbps]	$455	240	$109,277	12.79	34.31	2 Pol*20Gsps*2I/Q*3bits/sample = 240 Gbits/s for worst case W-band rcvr
M&C	$1,000	4	$4,000	0.47	1.26	One PCB with M&C and DC power per receiver
PSU	$1,000	1	$1,000	0.12	0.31	One bus +/-15V and +/-5V
Bins/modules/racks	$10,000	1	$10,000	1.17	3.14	Rack to house 48 plug-in modules
HVAC & Electrical	$5,000	1	$5,000	0.59	1.57	One heated to 45C weatherproof, RFI tight, box 24" x 24" x 48", 117VAC, 10amp

Strategy Recommendations

- Several person-years of conceptual design are needed to produce a supportable cost estimate for a 2019 proposal. Particular areas needed are antenna mechanical design, downconverters and formatters, systems for data and LO transmission, an AC power plan, and operations plan.

- Make use of SKA engineering where appropriate. Augment this with site and meeting visits and invitations to SKA engineers to visit NRAO.

- Produce a flexible, staged cost plan which can adjust as time goes on to best estimates of available funds as a function of time. The proposal to the decadal review committee could be posed as a question of “when” and not “yes or no”.

- A conservative ngVLA1 could be a 5 year, $80M/year cost capped program , which would utilize existing 25m antennas on fixed stations plus >100 new antennas on distant stations.

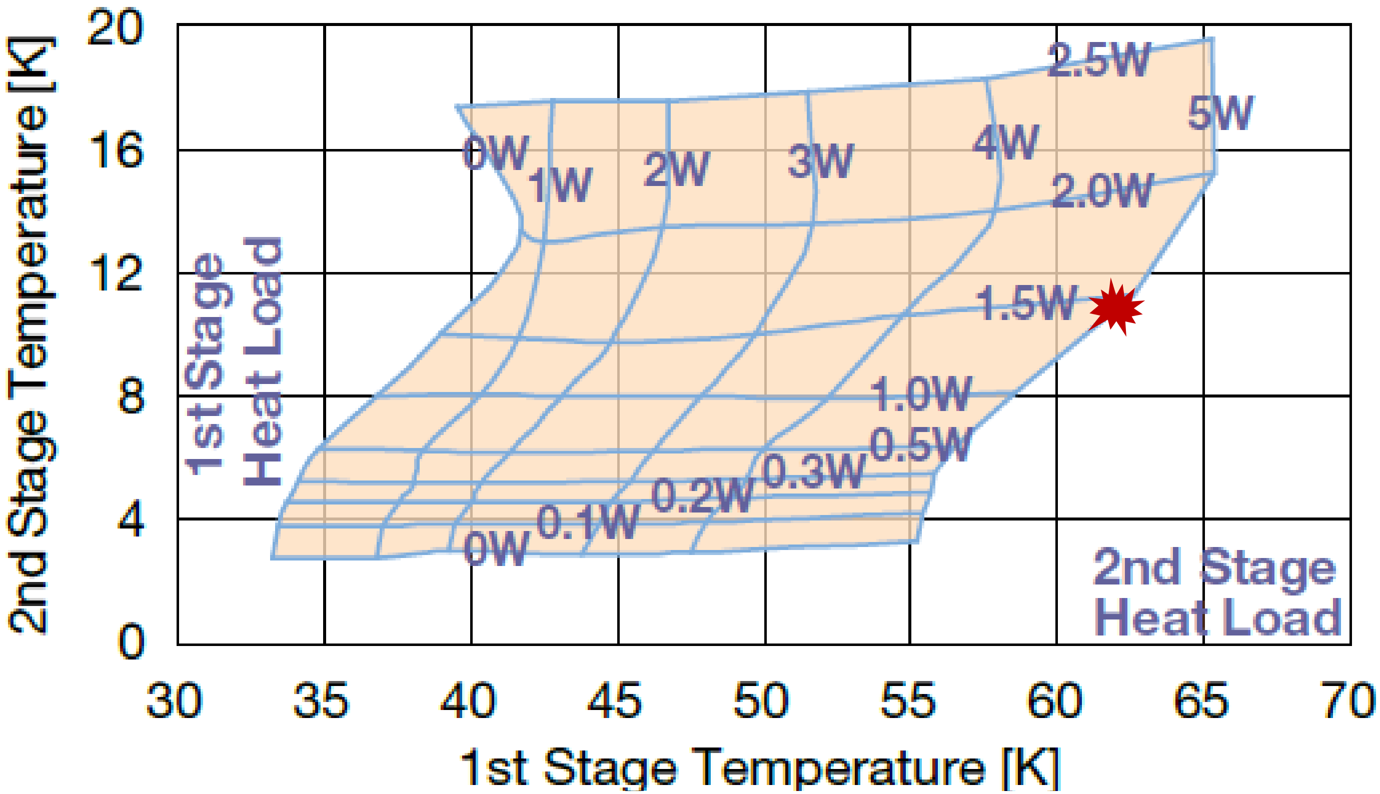
- Make budget decisions on judgements of science per dollar rather than a particular science driver which may change.

Switch to 5minute Hamdi Mani Presentation on Present Status

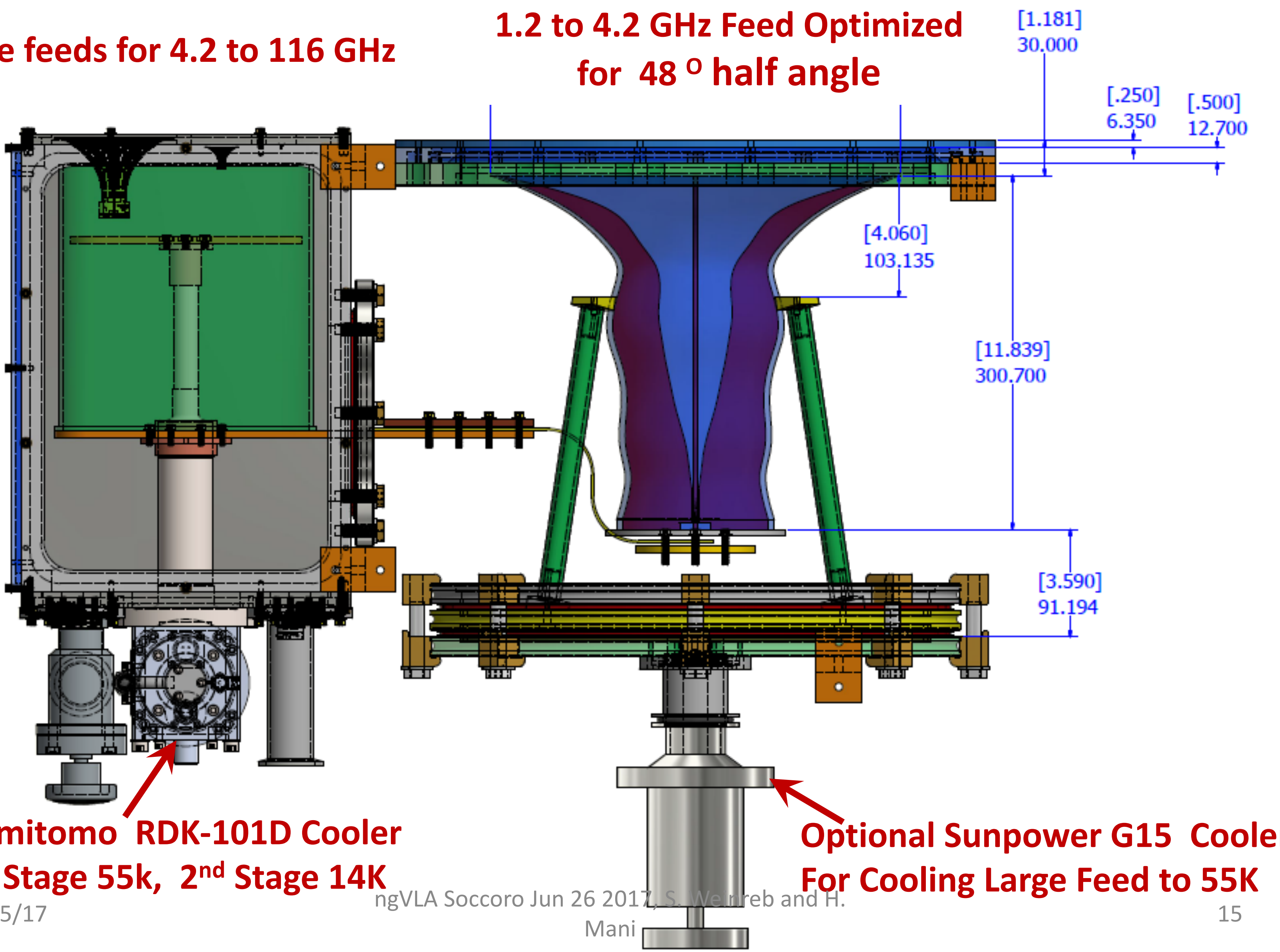
Cryocooler Operating Temperature

For Sumitomo RDK-101D with CNA-11 Compressor

- With careful thermal design a heat load of 5W on 1st stage and 1.5W on 2nd stages is expected
- This gives temperatures of 62K on 1st stage (1.2-4.2 GHz feed) and 11K on 2nd stage (all LNA's and feeds above 4.2 GHz.)
- Noise performance vs temperature will be measured with benchmark system



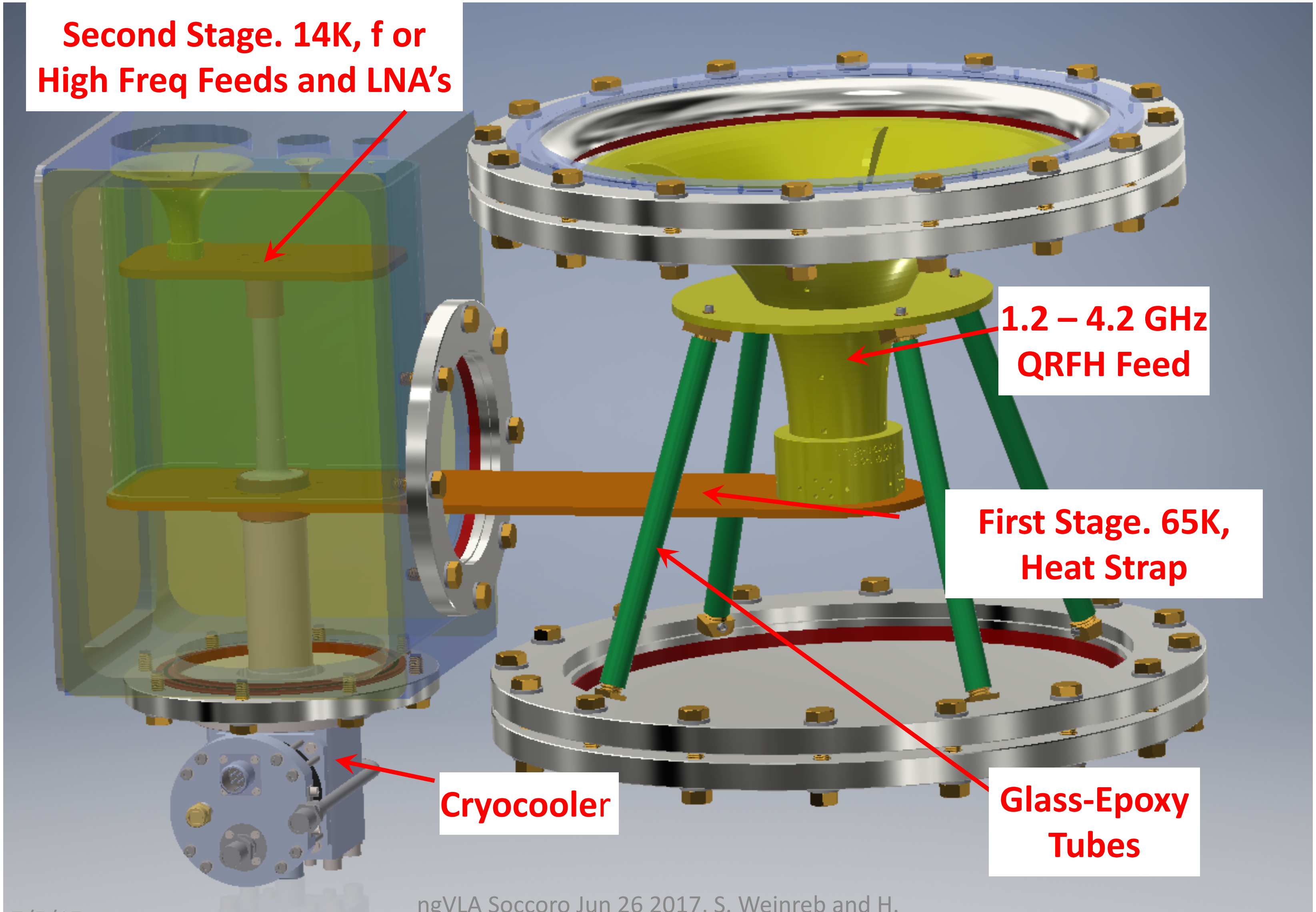
Cross Section View of Cryogenics Assembly



Backup Slides

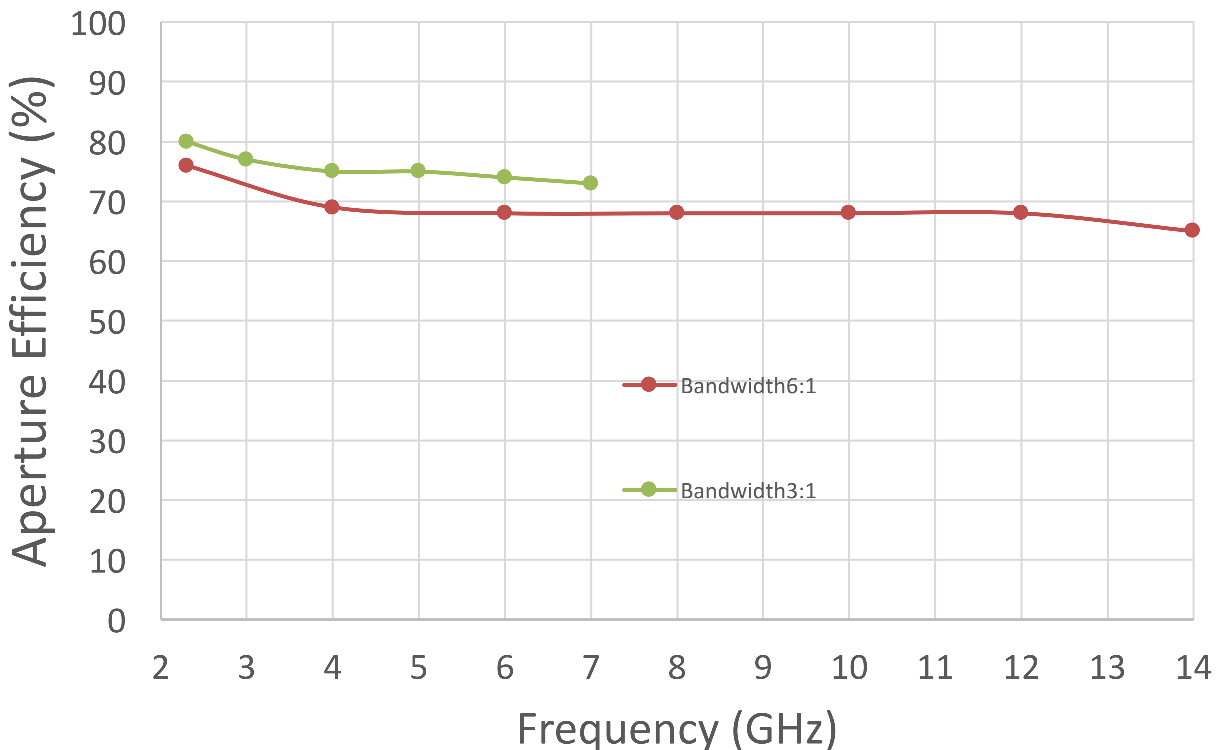
Interior View of Cooled Receiver Assembly

Close attention to heat conduction by windows, IR blankets, and heat straps to achieve <5W heat load at 65K and <1.5W at 14K



Feed Efficiency vs Bandwidth

- Feed efficiency is plotted below for a QRFH feed (in red) optimized for 6:1 bandwidth and one optimized for 3.5:1 bandwidth. Both are in a shaped reflector system which is recommended for ngVLA
- The 6:1 feed is typically 68% efficient while the 3.5:1 feed is typically 75% efficient – an advantage of 1.1 in sensitivity or 1.2 in observing time
- LNA's for narrower bandwidth are also somewhat lower noise
- Future development of feeds and LNA's will effect this decision



Comparison of ngVLA With Existing or Planned Radio Arrays

- The ngVLA fills the gap in frequency (13 to 116 GHz) between the SKA and ALMA
- The ngVLA will have an order of magnitude greater sensitivity and resolution compared with the current JVLA; survey speed is two orders greater

								Figures of Merit		Comparisons of Figures of Merit				
Array	N	D(m)	Total Area m^2	Tsys(K)	Freq Range, GHz	Comparison Frequency, Fo, GHz	BW (GHz)	Point Source PSFOM	Survey SSFOM at Fo	Point Source Sensitivity Comparison		Survey Speed Comparison		Flux Sens 1 hr uJ
MeerKat	64	13.5	9156.24	18	0.58-14	1.4	1	648	207.4		1.9		12.1	4.92
SKA1-Mid	190	14.5	31358.8	18	0.35-13.8	1.4	1	2219	2108.3		6.4		123.4	1.44
JVLA	27	25	13246.9	49	1-50	1.4	1	344	17.1		1.0		1.0	9.26
ngVLA	256	18	65111	18	1.2-116	1.4	1	4608	5898.2	x JVLA	13.4	x JVLA	345.4	0.7
SKA1-Mid	190	14.5	31358.8	22	0.35-13.8	10	5	4060	7056.8		3.7		41.3	0.79
JVLA	27	25	13246.9	31	1-50	10	4	1089	170.7		1.0		1.0	2.93
ngVLA	256	18	65111	22	1.2-116	10	8	10664	31587.3	x JVLA	9.8	x JVLA	185.1	0.3
ALMA	54	12	6104.16	80	31-950	80	8	275	47.2		1.0		1.0	11.60
ngVLA	256	18	65111	100	1.2-116	80	32	4692	6115.3	xALMA	17.1	xALMA	129.5	0.7

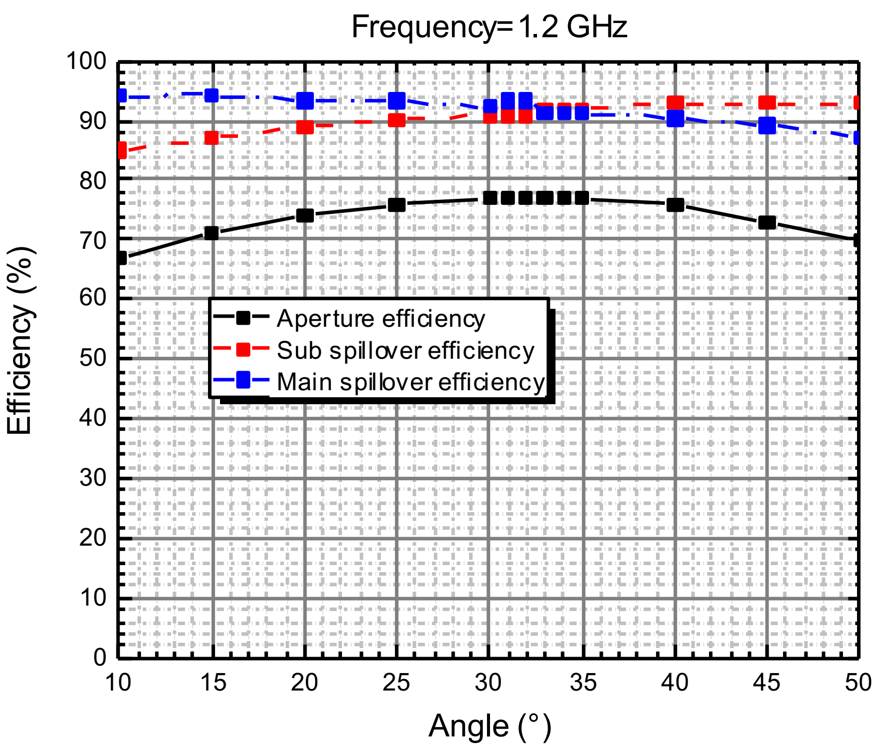
PSFOM = Point Source Figure of Merit = N*D^2/Tsys *BW^0.5

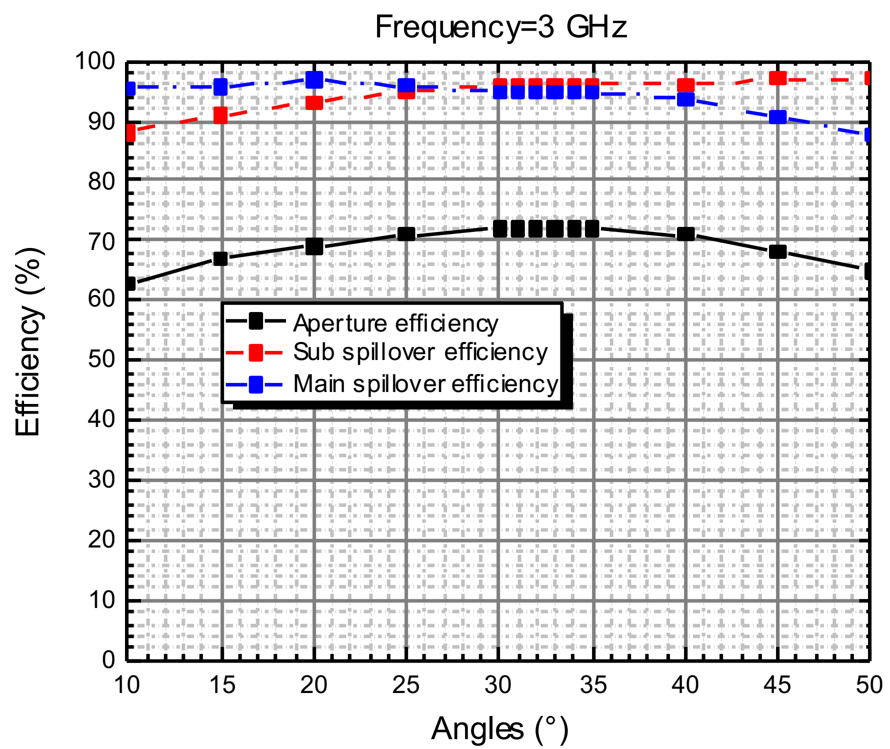
SSFOM = Survey Speed Figure of Merit = (λ/D)^2*Nb* (N*D^2/Tsys)^2*BW=((λ/D)^2*Nb*(PSFOM)^2

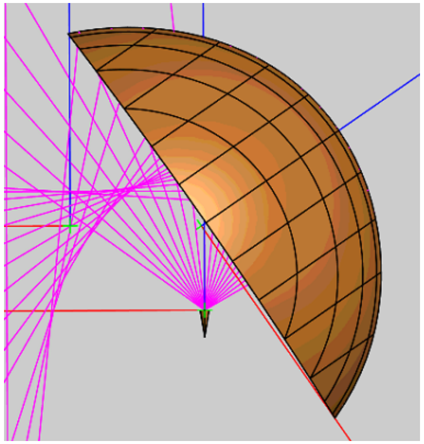
Fo is the frequency for evaluation of FOM's. which is proportional to Fo^-2

Ratio's to JVLA are for the same center frequency, Fo, at 1.4 and 10 GHz; ratio's to ALMA are at 80 GHz

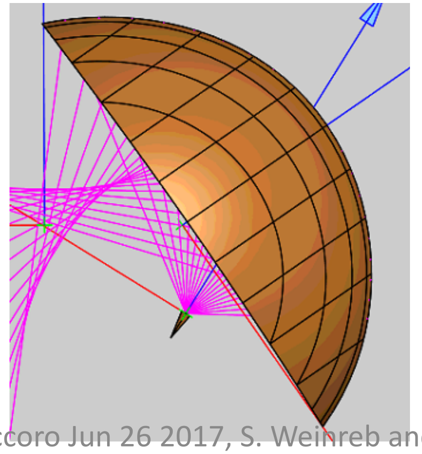
Aperture efficiency and spillover efficiency over different feed angles



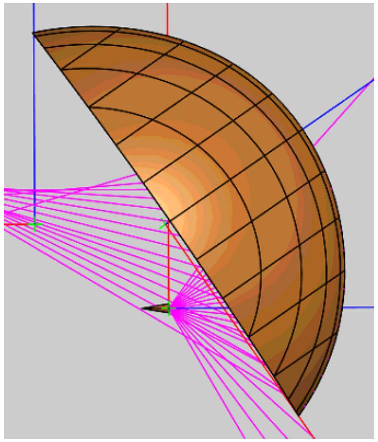




Angle=0°



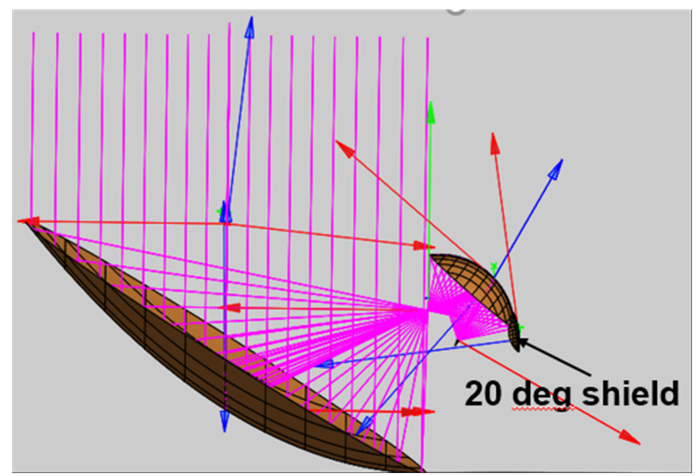
Angle=31.96º (SKA)



Angle=90°

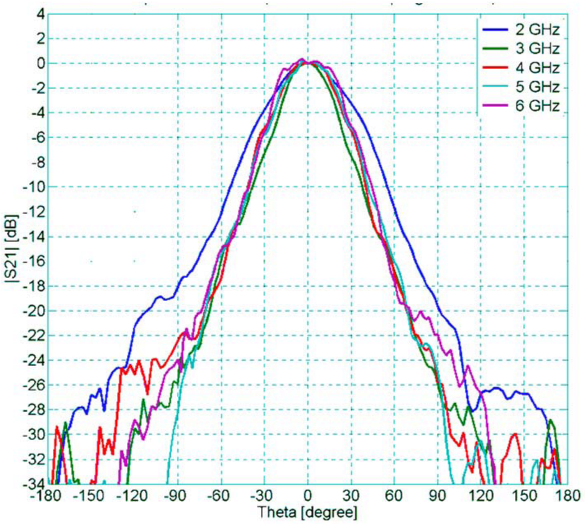
Synergistic Reflector Design

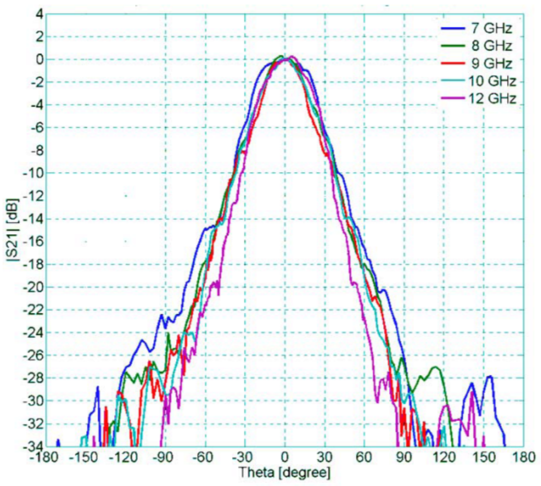
- Reflector optics has a major effect on the feed size and cooling requirements.
- Offset Gregorian optics with F/D=0.55 with 49 degree subreflector half-angle, close to what is used on Meerkat and SKA Mid, allows small feeds which can be completely cooled to reduce Tsys
- The offset Gregorian has additional advantages of allowing easy access to the receiver and of very low spillover noise with the addition of a small shield.

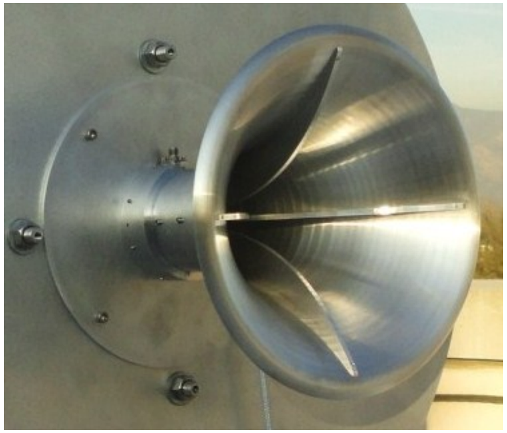


Wideband Antenna Feeds

- A 2 to 12 GHz feed has been designed, tested, and installed on a 12m antenna giving 60% efficiency
- Making this feed 4 times smaller, ~5cm diameter, would cover 8 to 48 GHz.
- Patterns are fairly constant from 8 to 50 GHz as required for an efficient feed for a parabolic reflector.
- Return loss is >15 dB over most of the frequency range.

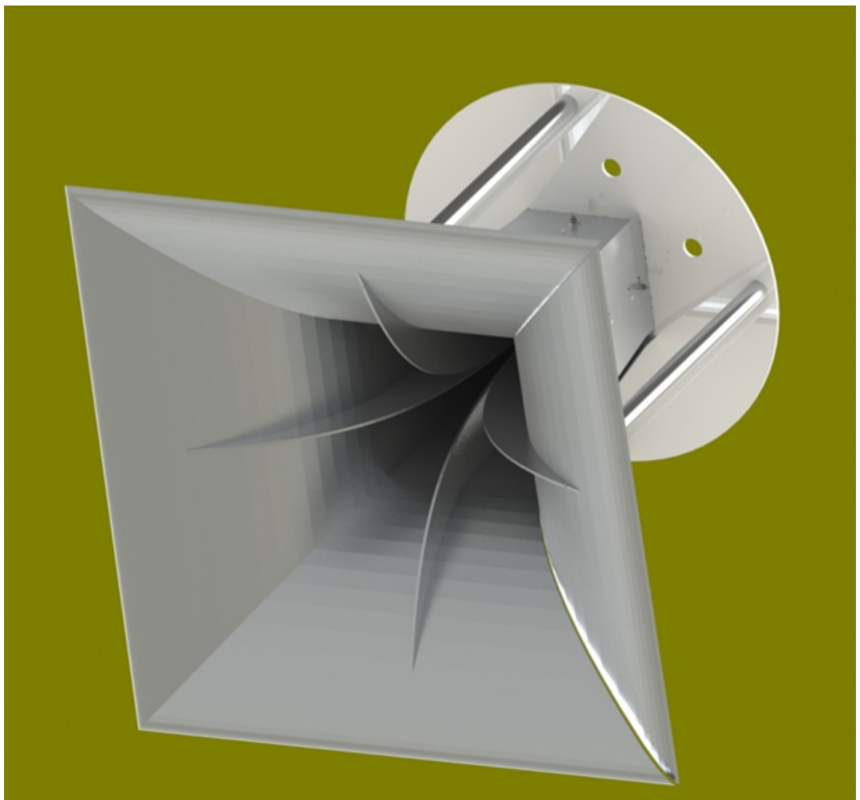


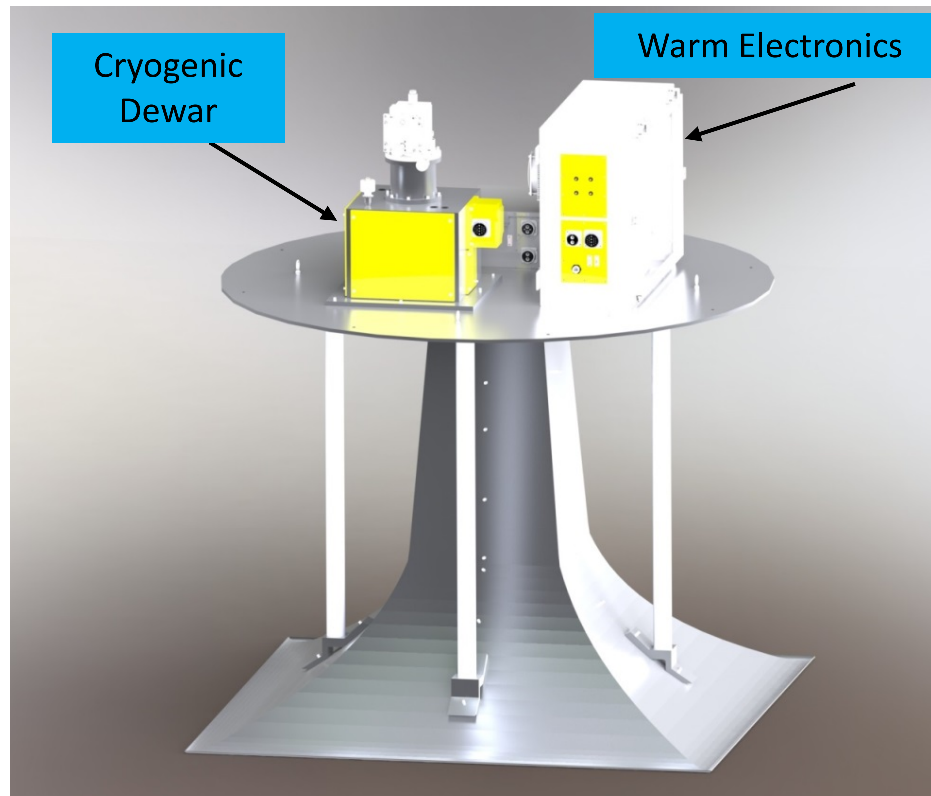




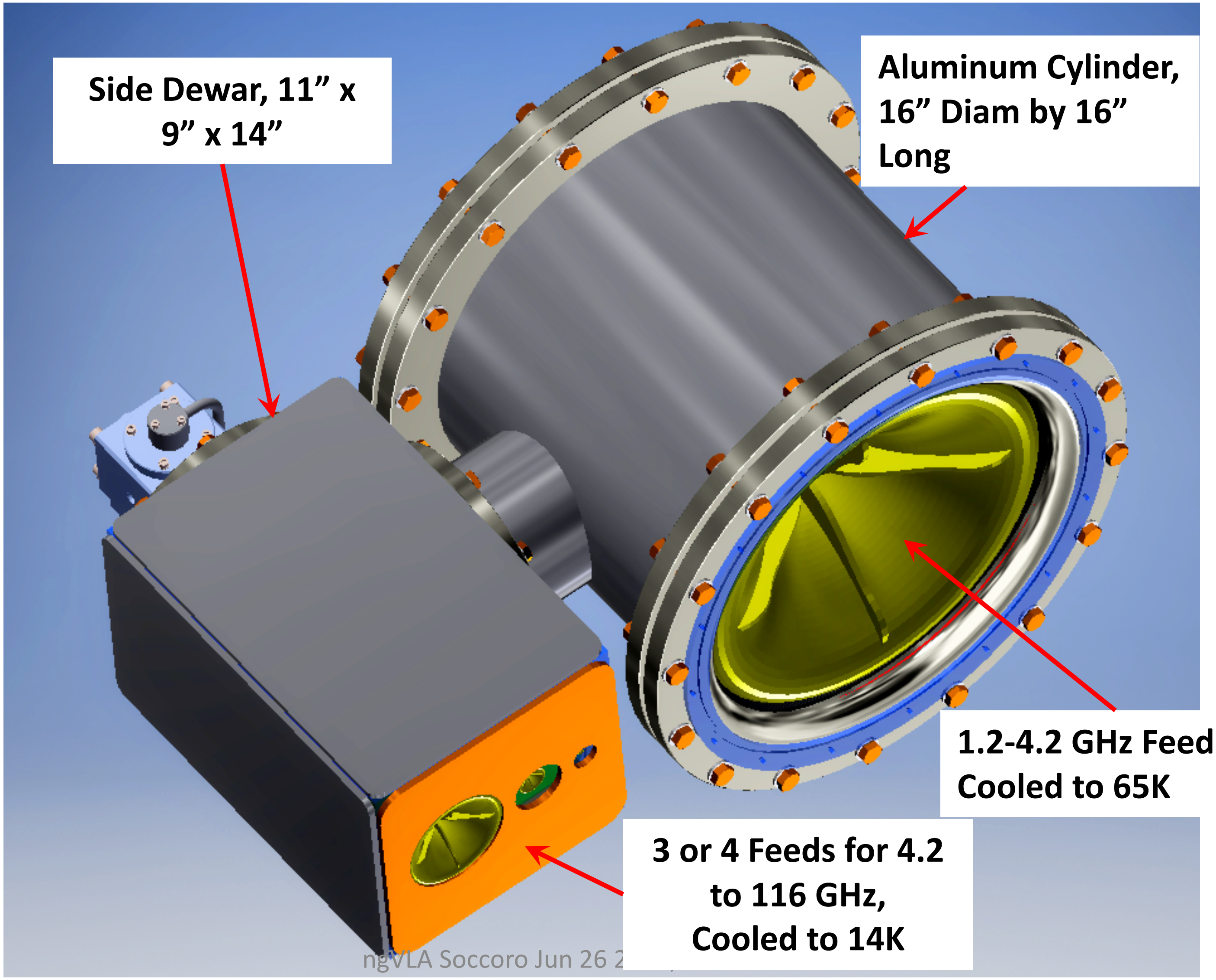
Caltech Receiver for FAST

0.26 to 1.62 GHz cryogenic receiver utilizes wideband feed and very low noise amplifier technology developed at Caltech.





Basic Concept – Multiple Cooled Feeds and LNAs With One Cryocooler In One Assembly Weighing 150 lbs and Consuming < 1.2kW Power



Cryocooler Power Cost Comparison

Existing Gifford-McMann Coolers – Others Can be Considered

Cooler	Heat Load at 14K	Typical Compressor	kW Power	256 Array Annual Power Cost
Sumitomo RDK-101D	1.5W	CNA-11	1.2	$0.54M
CTI 350	2W	8200	2	$0.90M
CTI 1020	7W	8500	5	$2.25M
Sumitomo RDK-4150	20W	CS-71	8	$3.6M

- At $0.20 per kWh and at full power[reduced power can be considered

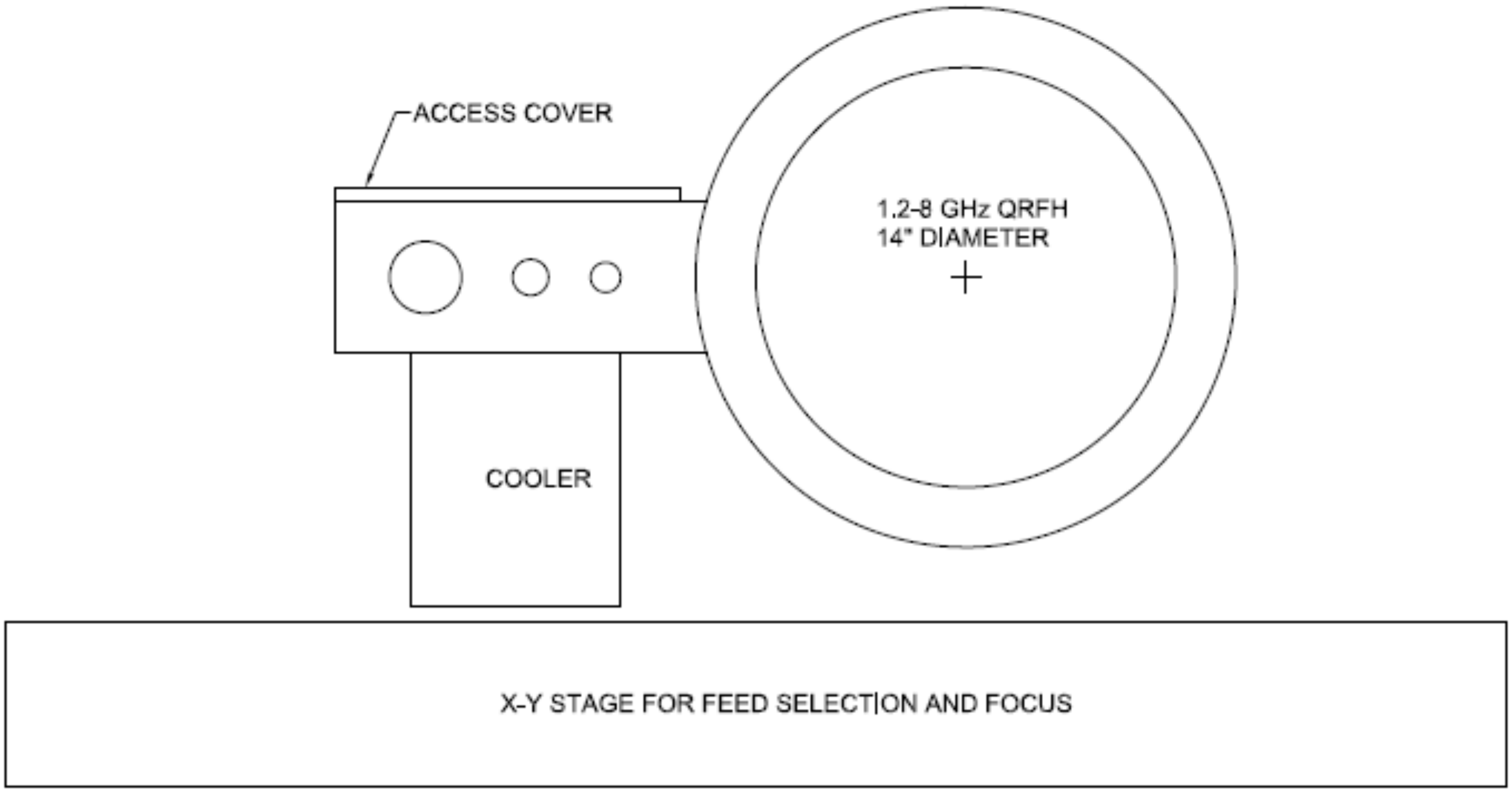
These figures show the importance of optimum thermal design involving windows, IR filters, metal finish, cable materials, heat straps, and insulator supports.

Cost Estimate for 1.2 to 116 GHz Antenna Electronics

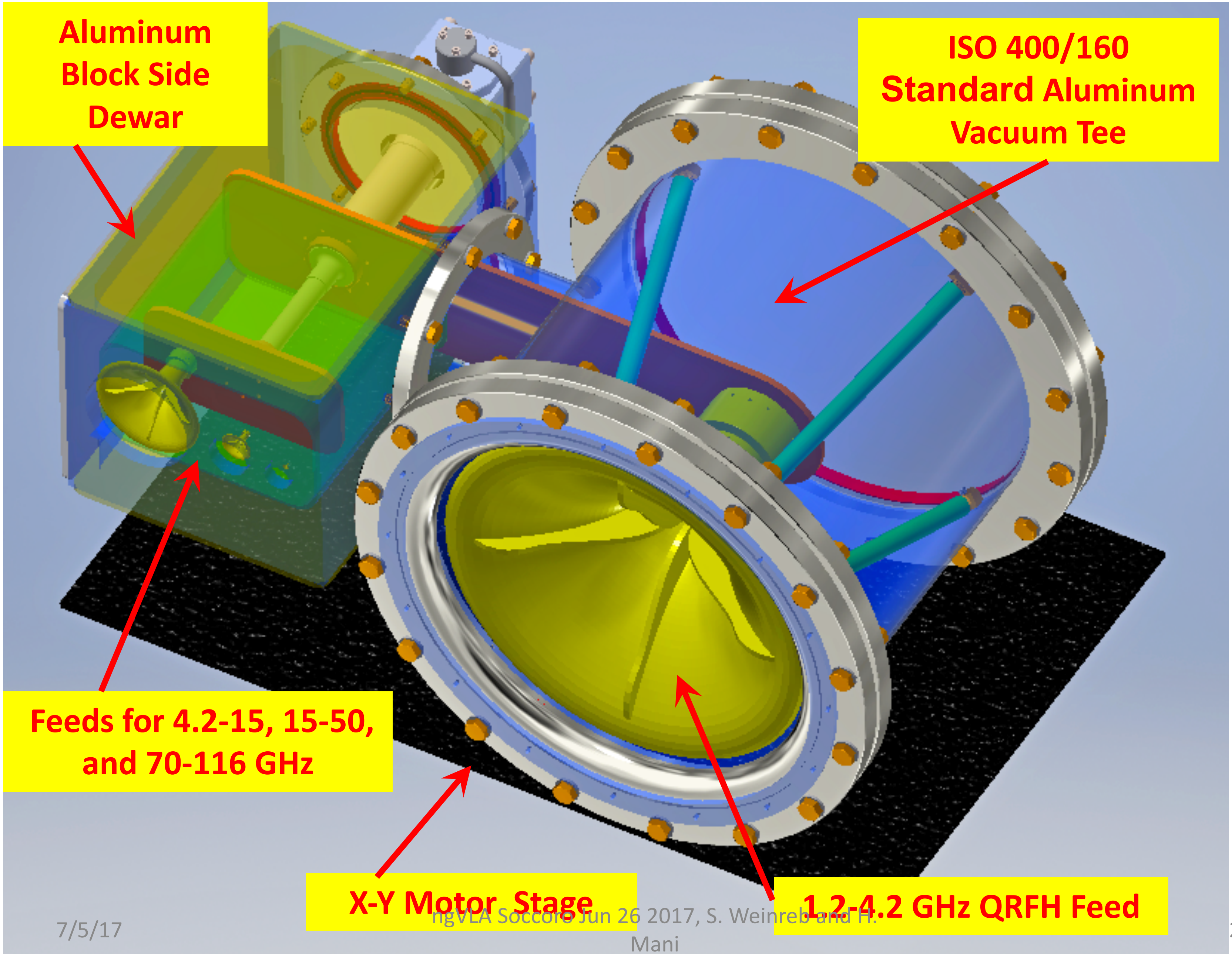
Item	Cost Estimate	# per Ant	$ per Antenna	$M per 117 Array	$M per 314 Array	Basis or Remarks
Antenna Electronics		**1**	**$534,277**	**62.51**	**167.76**	**$62.5M for an 117 antenna array of which $21.9M is for cold electronics and $40.6M is for warm electronics located on each antenna.**
Antenna Cold Electronics		**1**	**$187,000**	**21.88**	**58.72**	**Total cold electronics and cryogenics**
Antenna Warm Electronics		**1**	**$347,277**	**40.63**	**109.04**	**Total downconverters, A/D, and formaters**
Feeds	$8,000	4	$32,000	3.74	10.05	Based on QRFH designs fabricated by machine shops. Past history.
LNAs	$14,000	4	$56,000	6.55	17.58	Two LNA's per dual polarization receive with $7K per LNA based on current cryogenic LNA prices
Dewar Accessories	$3,000	4	$12,000	1.40	3.77	Vacuum pump, guage, valves, and temperature sensors
Calibration Components	$5,000	4	$20,000	2.34	6.28	Noise diodes and fiber receiver for phase cal if needed
Master PCB	$1,000	4	$4,000	0.47	1.26	Printed circuit board with voltage regulators, LNA bias, temperature and DC monitor, receiver control and interface to serial data link.
Cryo Dewar	$16,000	1	$16,000	1.87	5.02	Based upon cost for demonatration dewar of $16K but allowing for increases for testing and decease for quantity. No 2nd dewar and compressor is needed.
Cryo Compressior	$23,000	1	$23,000	2.69	7.22	Includes cryocooler and compressor. Cost based upon quote for single Sumitomp RDK-101D including flex lines.
Receiver Assembly and Test Labor	$24,000	1	$24,000	2.81	7.54	Based upon 6 person-weeks per antenna cryo package at $100/hour including burden. For 117 antennas this is a group of 5 working for 3 years
Downconverters	$3,000	32	$96,000	11.23	30.14	Based upon MMIC multi-chip modules including post amplifier, filter, mixer, IF amplifier, and LO mulitipler. Bandwidth no greater than 5 GHz.
3-bit samplers	$2,000	48	$96,000	11.23	30.14	Two samplers per downconverter, 24 wideband downconverters
8-bit samplers	$1,000	16	$16,000	1.87	5.02	Two samplers per downconverter, 8 narrow band downconverters
LO System	$10,000	1	$10,000	1.17	3.14	One quartz standard, mutipliers, and fiber interface to round-trip phase correction system
Data Formatter [per Gbps]	$455	240	$109,277	12.79	34.31	2 Pol*20Gsps*2I/Q*3bits/sample = 240 Gbits/s for worst case W-band rcvr
M&C	$1,000	4	$4,000	0.47	1.26	One PCB with M&C and DC power per receiver
PSU	$1,000	1	$1,000	0.12	0.31	One bus +/-15V and +/-5V
Bins/modules/racks	$10,000	1	$10,000	1.17	3.14	Rack to house 48 plug-in modules
HVAC & Electrical	$5,000	1	$5,000	0.59	1.57	One heated to 45C weatherproof, RFI tight, box 24" x 24" x 48", 117VAC, 10amp

Backup Slides

Concept Showing X-Y Positioner for Feed Selection and Focus



Interior View of Dewar



Comparison of System Sensitivity of 6.7:1 and 3.5:1 Feeds With and Without Shield on Gregorian Subreflector

Feed, Frequency Range, GHz	Comparison Frequency	Trcvr	Tsky	η Eff.	Tspo without Shield	Tspo with Shield	Tsys without Shield	Tsys with Shield	Tsys/η without Shield	Tsys/η with Shield
8 - 50	15	12	7	0.58	11	5	30	24	52	41
6 - 22	15	11	7	0.63	9	3	27	21	43	33
Trcvr values include LNA and cold losses due to feed, window, and IR filter										
Tsky values are from B. Butler, NRAO, 2016 and are for VLA site at zenith, with 13mm water vapor										
Tspo and η for 6.7:1 QRFH feeds designed by A. Akgiray, 2013; they are for 60 degree elevation.										
Tspo and η for 3.5:1 QRFH feeds optimized by A. Soliman, 2016, also for 60 degree elevation.										

Conclusions

For this representative example using current QRFH designs the 3.5:1 feed gives 41/33 = 1.24 greater sensitivity than a 6.7:1 feed.

The spillover shield increase sensitivity by 33/21 = 1.57.

This comparison is for two feeds for which we have computer files describing the patterns and can analyze efficiency and spillover using Grasp. The results are good but even better results may be obtained with future designs.

Current Suggestion for Receiver Bands for 1.2 to 50 GHz

Wide band feeds continue to be developed and will have improvements in the next 5 years but here are the ranges which give equal 3.5:1 frequency bands for 3 feeds to cover 1.2 to 50 GHz.

- **1.2 – 4.2 GHz** – L and S Band. An LNA for this range can be realized with <4K noise and a QRFH ;feed covering down to 1.2 GHz can be completely cooled to reduce system noise. Would a room temperature extension of the feed help the sensitivity at the low end of the band.

- **4.2 – 15 GHz** – C, X, and Ku Band. Excellent LNA available with < 6K noise in this range.

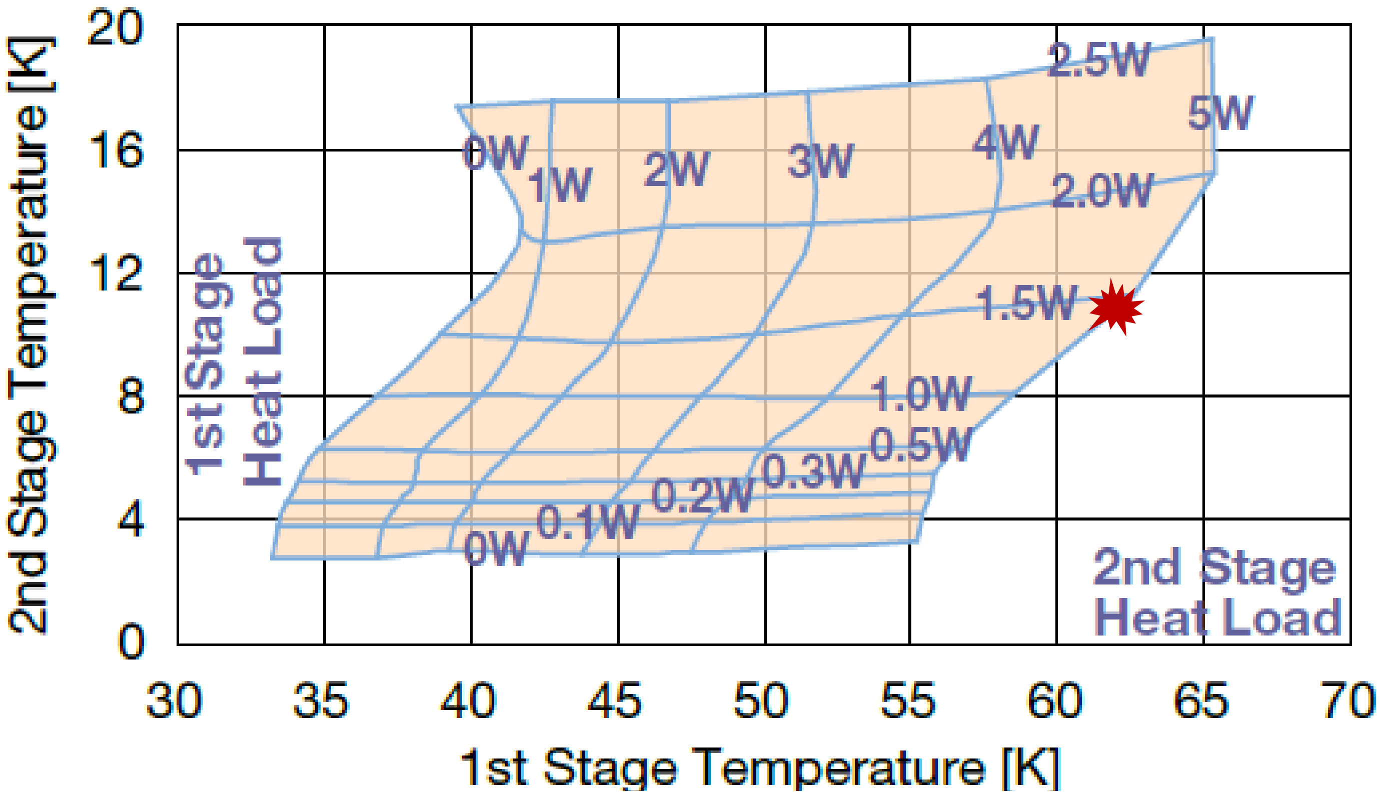
- **15 - 50 GHz** – K, Ka, and Q Band. LNA needs development but <15K appears feasible.

- **70-116 GHz** – A conventional high-efficiency corrugated horn would be used here. The LNAs are being developed for ALMA band 2/3 and 25K LNA noise is now achieved over most of this band.

Cryocooler Operating Temperature

For Sumitomo RDK-101D with CAN-11 Compressor

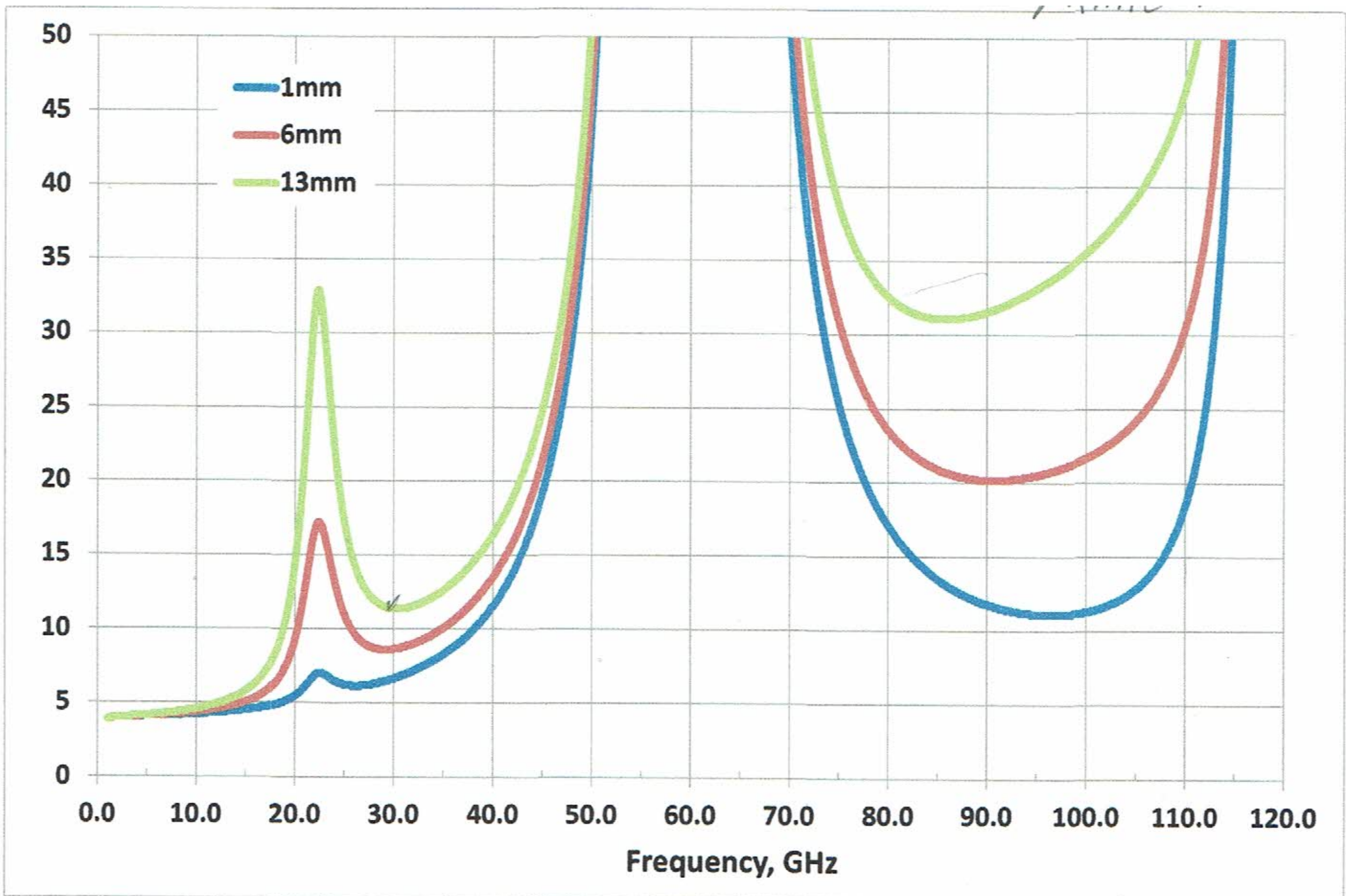
- With careful thermal design a heat load of 5W on 1st stage and 1.5W on 2nd stages is expected
- This gives temperatures of 62K on 1st stage (1.2-4.2 GHz feed) and 11K on 2nd stage (all LNA's and feeds above 4.2 GHz.)
- Noise performance vs temperature will be measured with benchmark system



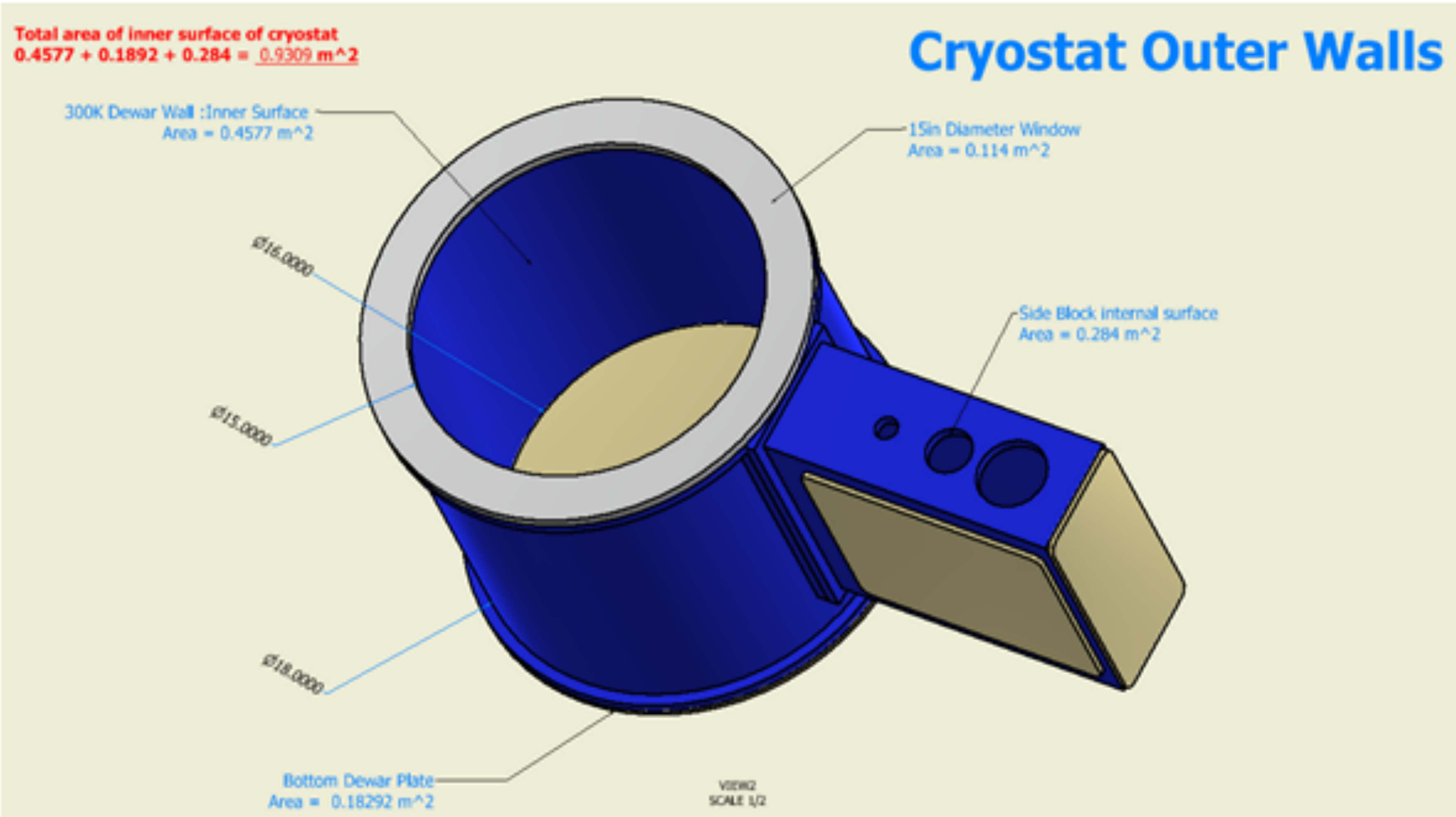
Meerkat 13.5m Offset Gregorian Antenna is Service Position

Sky Temperature vs Frequency and Water Vapor Content

JVLA Site, 2100m, at zenith. From B. Butler, NRAO

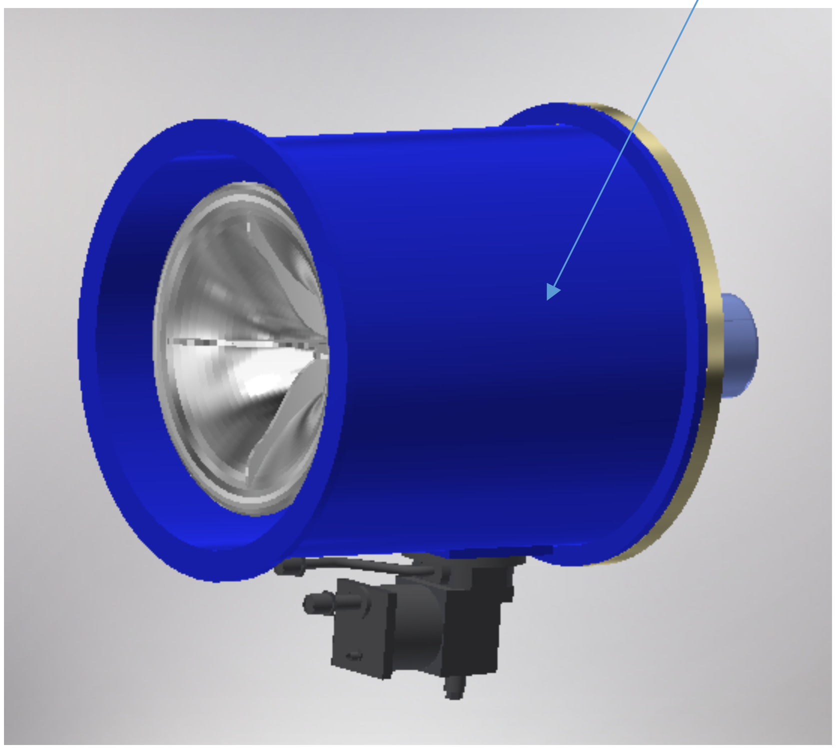


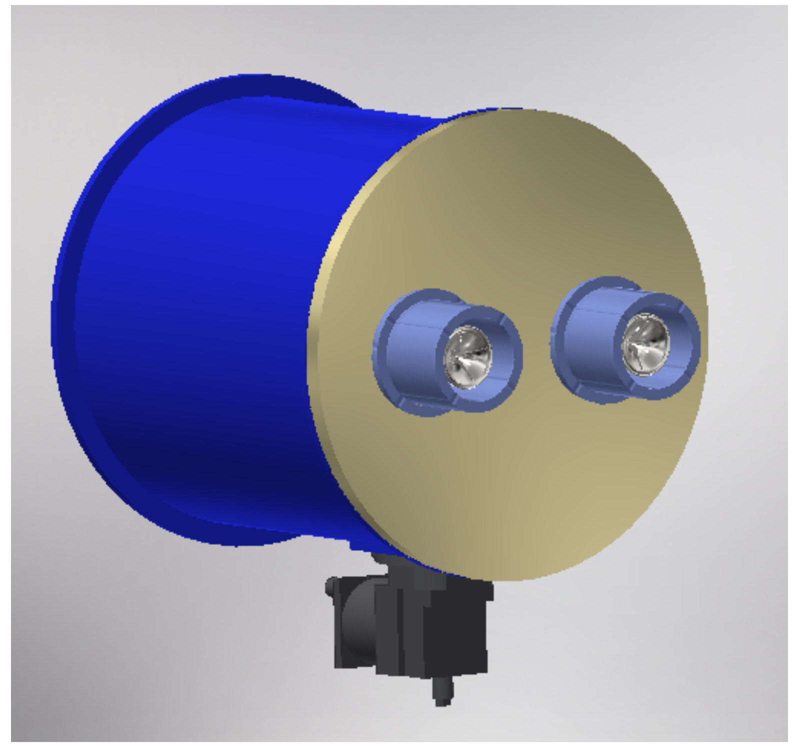
With diligent attention to heat shields and surface emissivity the cryogenics heat load can be reduced to <5W on the first stage of a GM cryocooler with low power requirements resulting in $millions of annual cost savings.



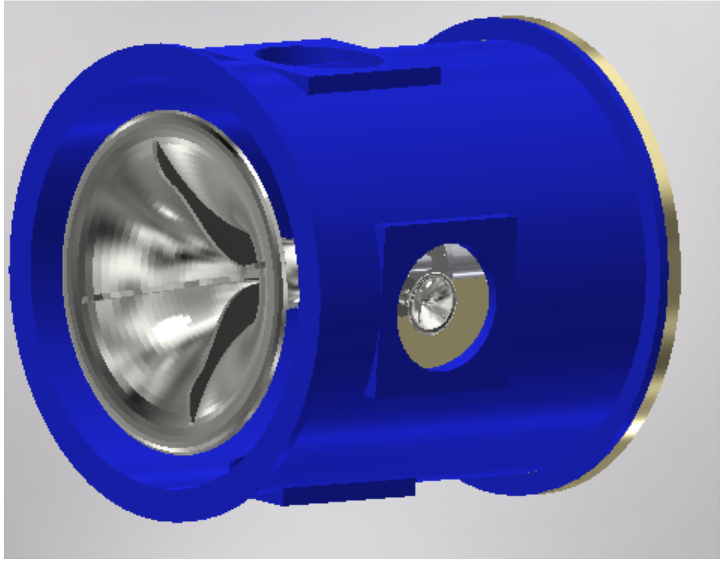
Concept # 1

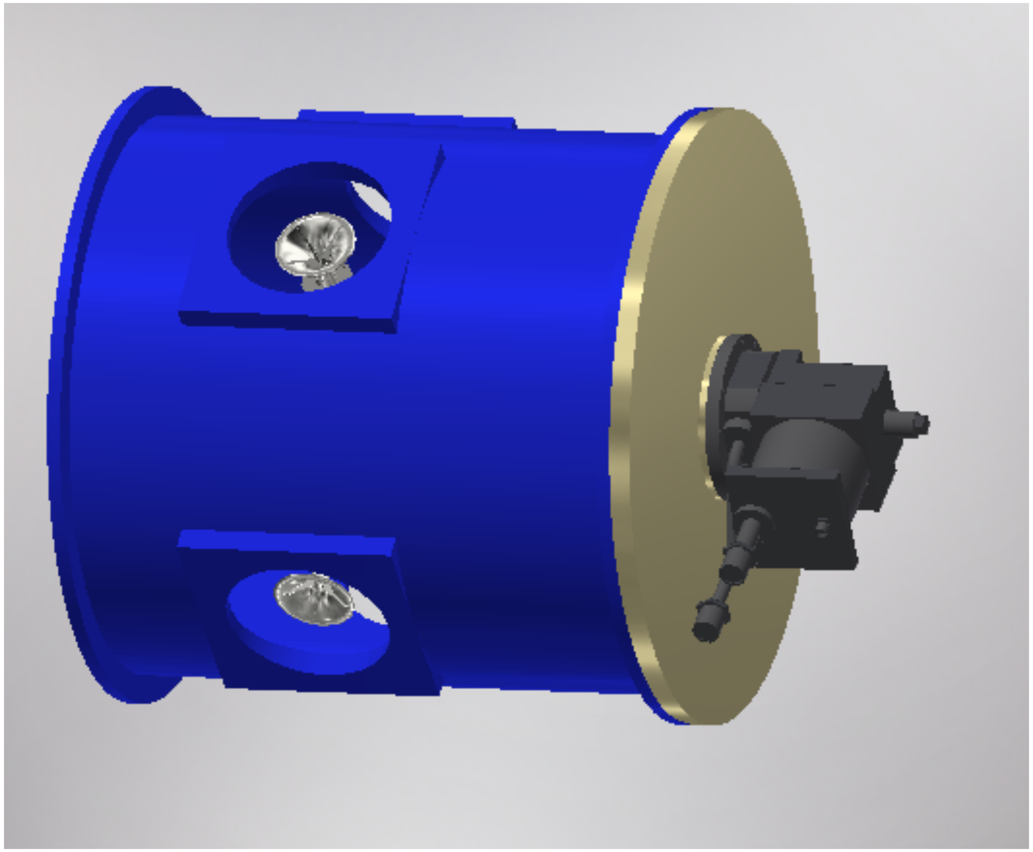
20 in diameter cylinder made of a rolled and welded Aluminum Sheet



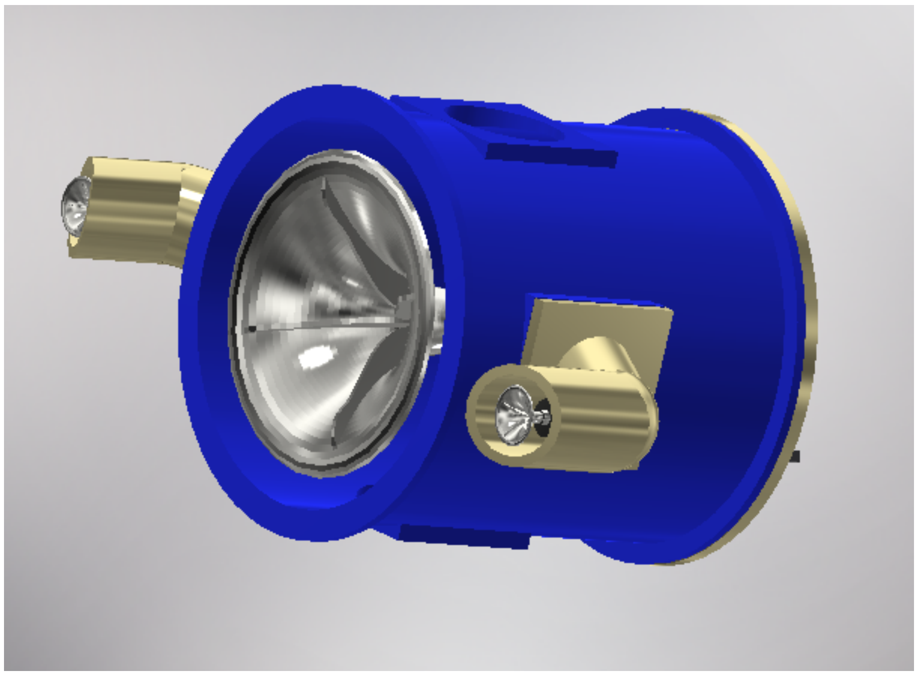


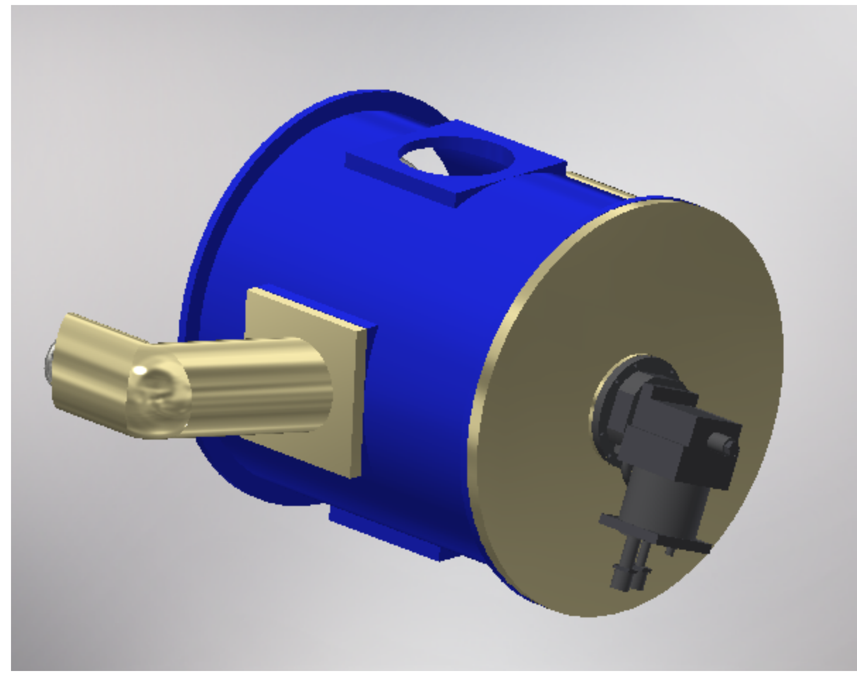
Concept # 2





Concept # 3





Dewar Requirements

- 1 x Vacuum vessel to host 3 feeds + electronics (LNAs, filters, couplers, Noise sources
- 1 x Cryogenic cooler to cool 3 feeds
- Easy and cheap to manufacture: build 256 systems
- Easy to assemble and maintain
- Individual feeds must be selected with one translation motion or one rotation motion
- Minimum package size: minimize blockage
- Minimize weight

A Four Receiver Solution with Different Crossover Frequencies

:

Feed and LNA improvements in the next several ;years could push this in the direction of 3 or 5 receivers but prototyping and testing a 4 receiver system will answer many questions with hard facts. Suggested bands are:

- **1.2 – 8 GHz** – An LNA for this range can be realized with <4K noise and a QRFH ;feed covering down to 1.2 GHz can be completely cooled to reduce system noise.

- **8-22 GHz** – The 8 to 50 GHz range could be accommodated with one feed but the LNA as 8 GHz would have higher noise than desired. The efficiency is also improved by lowering the frequency ratio

- **22-50 GHz** – Same comment as above.but also note that an 8-50 GHz receiver would allow simultaneous observations over the entire range

- **70-116 GHz** – A conventional high-efficiency corrugated horn would be used here. The LNAs are being developed for ALMA band 2/3 and 25K LNA noise is now achieved over most of this band.