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CryoPAF4 -
a cryogenic phased array feed design

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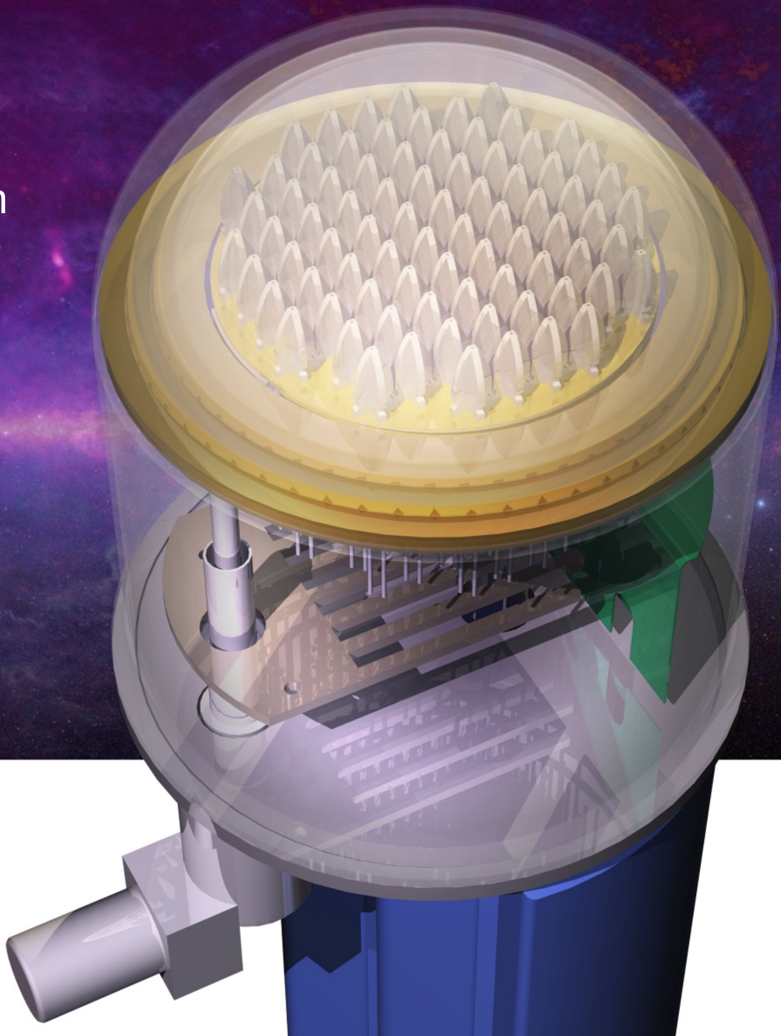

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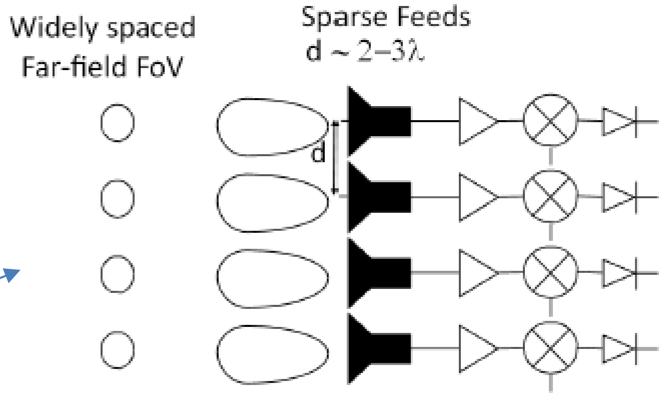
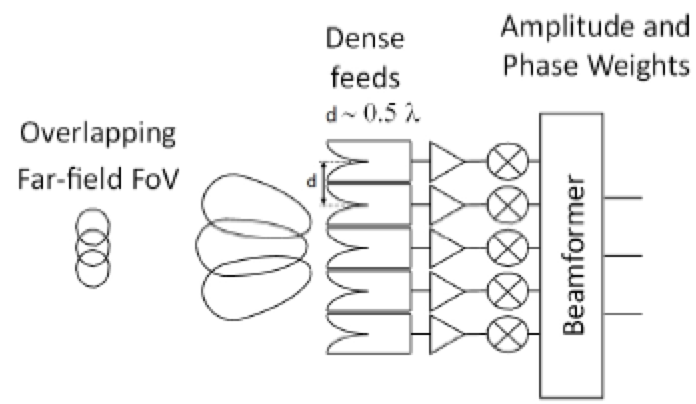
1. Introduction

- Microwave (1-10 GHz), millimeter wave (10-300 GHz) has unique astronomical information.
- Currently single pixel receivers, but more more more … field of view, without compromising sensitivity
- Use image plane of radio telescope to increase the area that can be imaged at once.



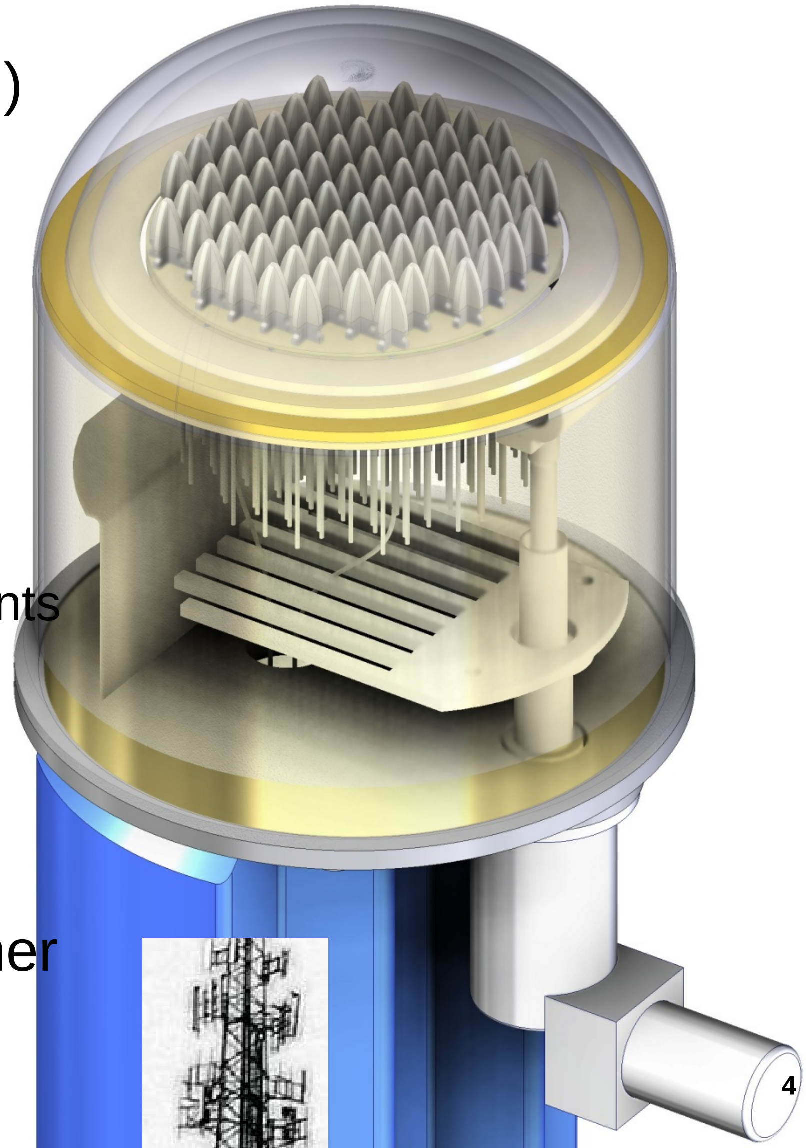
* Multibeam receivers – multiple horn feeds, multiple receivers, multiple detectors -> requires multiple passes

* <u>Phased array feeds</u> – closely spaced feeds, multiple receivers, sum with complex weights in beamformer. -> single pass



2. CRYOGENIC PHASED ARRAY FEED SYSTEM DESIGN

- 2.80 – 5.18 GHz (10.7 cm – 5.8 cm)
- 48 cm diameter cryostat
- Composite laminate radome
- Multi-layered RF transparent IR shields
- Array (16 K physical)
  - 31 cm diameter
  - 140 all metal dual-linear Vivaldi elements
  - 2.8 cm square grid spacing
- 3.5 K Low noise amplifier (16 K physical)
- Sampling and 18 beam dual-polarization time domain beamformer



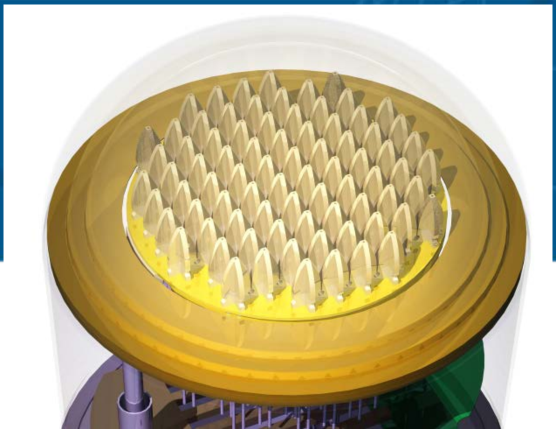
2.1 Cascaded Noise – single active element

- Based on single active element receiver
- Cascaded Gain/Loss, cumulative noise temperature and physical temperature
  - Radome: ~1.5K
  - 5 K mutual coupling* between elements
  - Low Noise Amplifer: 3.5 K
  - Post Amp (PA) is 3 dB noise (290 K noise)
- Recevier temperature is 10.82 K => 11 K

	Radome	Blade + coupling*	connector	LNA	Filter	PA	Coax	DBE
Gain/Loss (dB)	-0.02	-0.10	-0.10	40.00	-1.00	35.00	-2.00	-1.00
Cumulative Noise Temp (K)	1.34	6.69	7.05	10.73	10.74	10.82	10.82	10.82
Physical Temperature (K)	290	15	15	15	290	290	290	290
		cryogenic			room temperature			

2. CRYOGENIC PHASED ARRAY FEED SYSTEM DESIGN

2.2 Laminate Radome



- DRAO Penticton, BC, Canada
- Dimensions: 48 cm diameter, 1 mm thick
- TenCate EX-1515 composition:
  - quartz glass fiber (ε_r=4.5) layers
  - Cyanate ester resin ($\varepsilon_r = 3.7, \tan\delta = .005$)
  - Low dielectric constant and dissipation
- Mechanically strong, holds a vacuum
- Low moisture absorption, low outgassing
- Used in other radome & space/satellite applications
- Create mold, fabricate on site

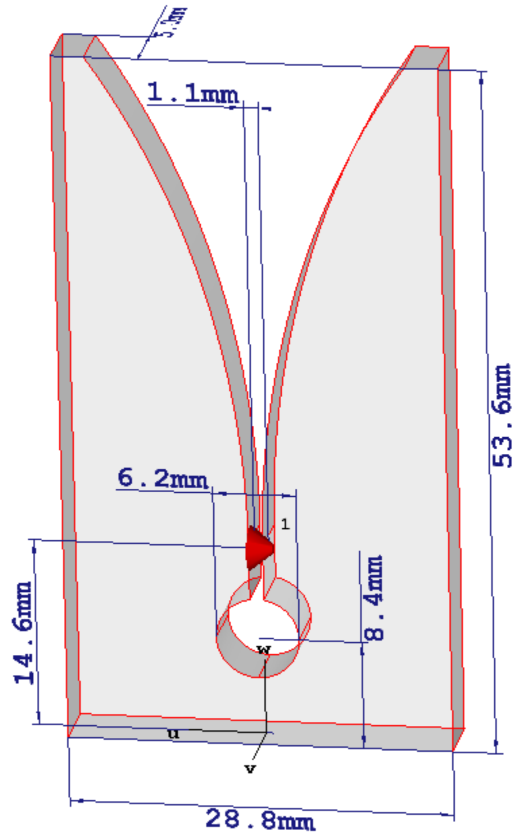
The Dish Verification Antenna, DVA-1

2.3 Backend Electronics / Digital Beamformer

- Digitization
  - Inputs from 96 active antenna elements, 10 Gsps, 4-bit
  - U of Calgary: Xu, Y., Belostotski, L. and Haslett, J.W., "A 65-nm CMOS 10-GS/s 4-bit background-calibrated noninterleaved flash ADC for radio astronomy," IEEE Transactions on Very Large Scale Integration (VLSI) Systems, 22, 2316-2325 (2014).
  - put on fibre
- Frequency band selection
  - 6 DRAO Kermode boards with FPGAs selects and bandlimits signal with programmable bandwidth
  - Channelized to 1 MHz with polyphase filter bank
- Freq Domain Beamforming & array covariance matrix calib.
  - FPGAs compute 18 polarized beams (36 beams total)
  - In single dish mode the beamformer FPGAs compute the integrated auto-power spectrum for the PAF

3 SINGLE ANTENNA ELEMENT

- Vivaldi element simulated with full-wave solver CST Microwave Studio 2016
- Vivaldis ☺:
  - large bandwidths
  - narrow physical width
  - can be made all-metal for cryogenic cooling
  - Symmetric radiation patterns in E- & H-planes
  - Low side lobes
  - Good cross-polarization properties

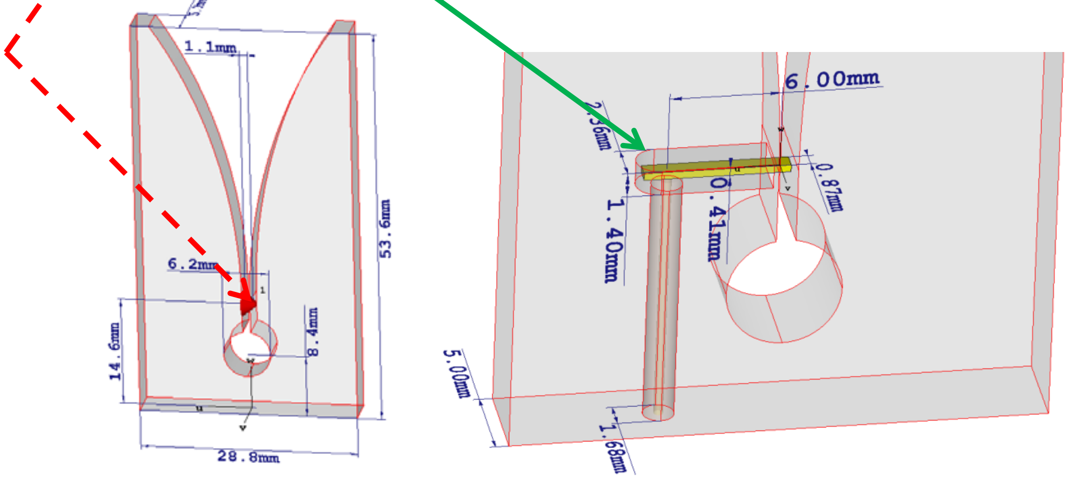


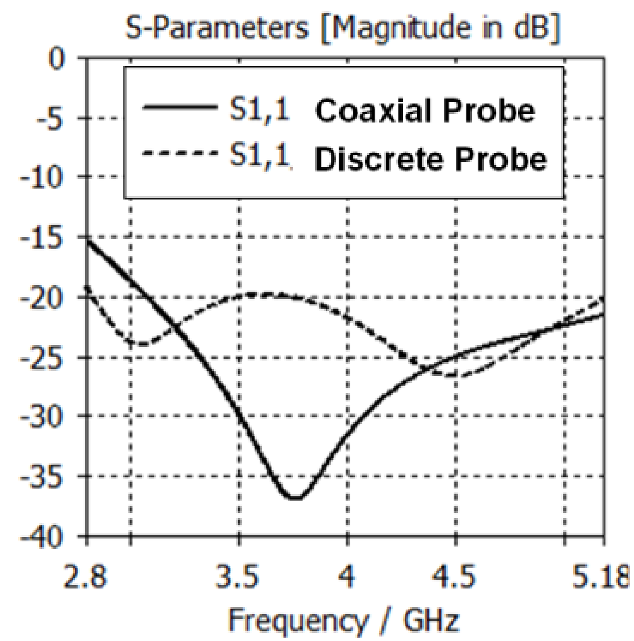
3 SINGLE ANTENNA ELEMENT

3.1 Coaxial Feed Design

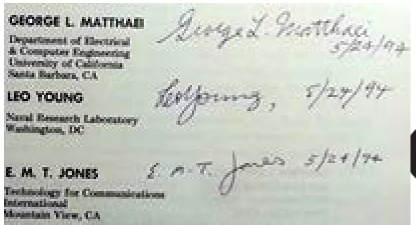
- Antenna: electric field in slot line – need to pick up to transmission line
- Discrete Probe: ideal: first approx
- Coaxial Feed: realistic 2-section coax

Element width (u)	28.8 mm
Element length (w)	53.6 mm
Element thickness (v)	5.0 mm
Slot termination diameter (u,w plane)	6.2 mm
Slot offset from backplane to center	8.4 mm
Slot width	1.1 mm



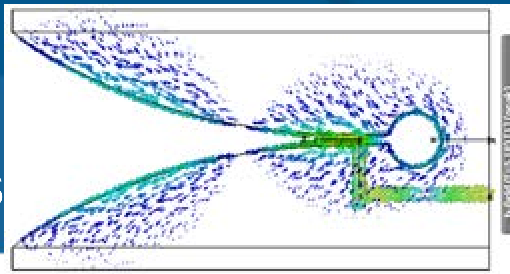


Validated: 50 ohm impedance, input reflection coefficient, S11 low, single mode TEM propagation

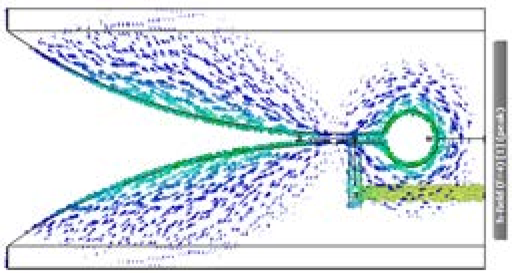


3 SINGLE ANTENNA
3.2 Surface Currents

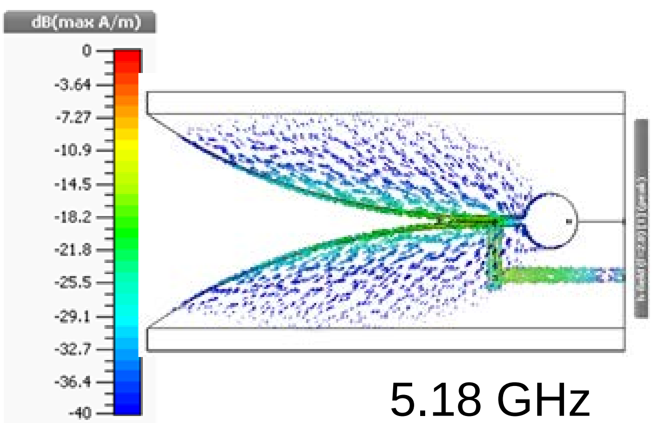
- During the design, currents on metal surface and in the feed is informative:
  - Clear physical picture
  - radiation process
  - travelling waves
  - mutual coupling
  - Unwanted reflections
- Surface current plots (dB), normalized to max.



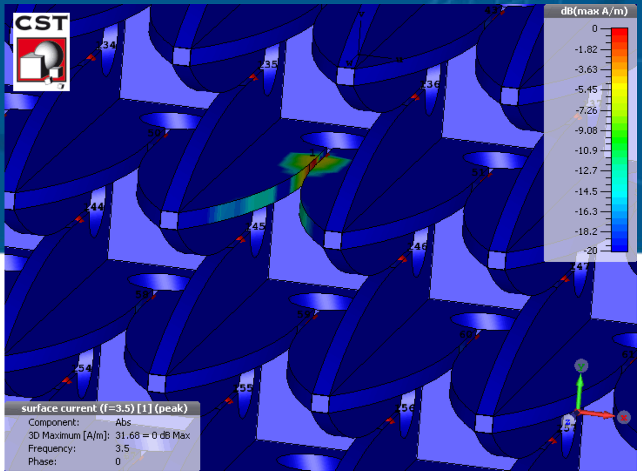
2.8 GHz

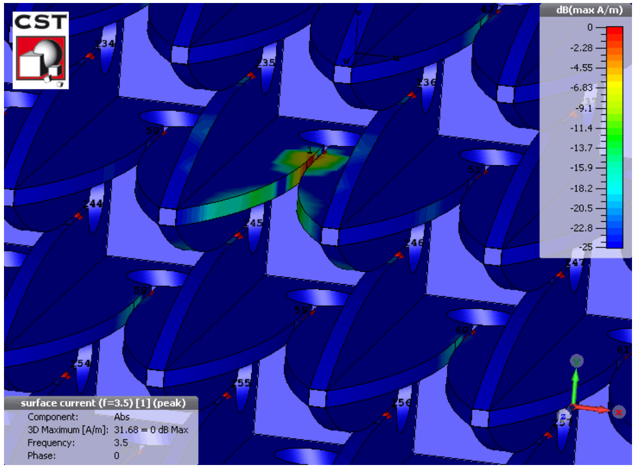


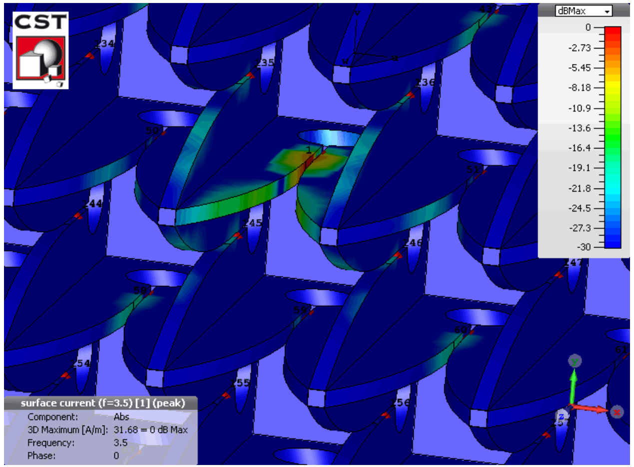
4.0 GHz



5.18 GHz







3 SINGLE ANTENNA ELEMENT

3.3 Radiation Patterns

- Far field normalized gain for L to R: 2.8, 4.0, 5.18 GHz
- Spherical coordinates: φ cut planes E (φ = 90°), D (φ = 45°) H (φ = 0°) vs elevation angle, θ
- Co-pol and cross-pol, Ludwig 3rd.
- -> Expected results: very broad, ~ constant with frequency

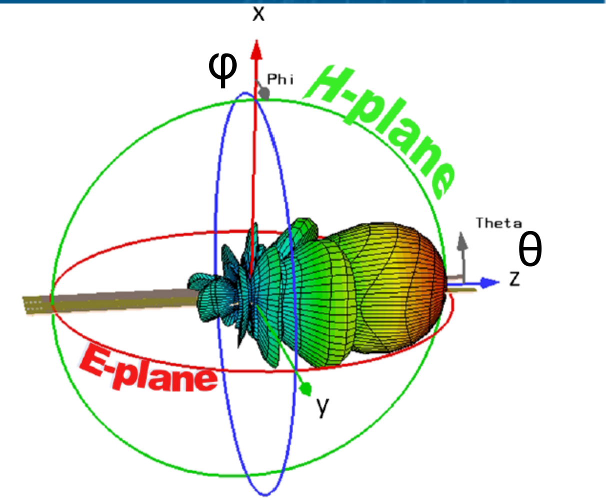
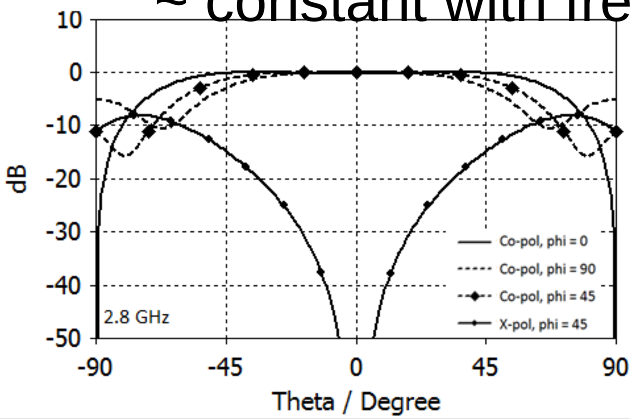
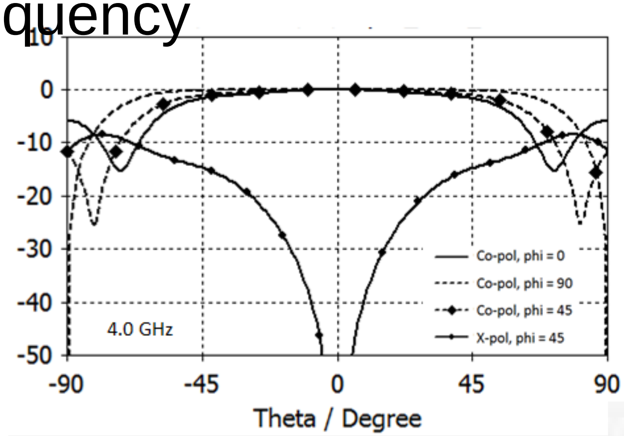
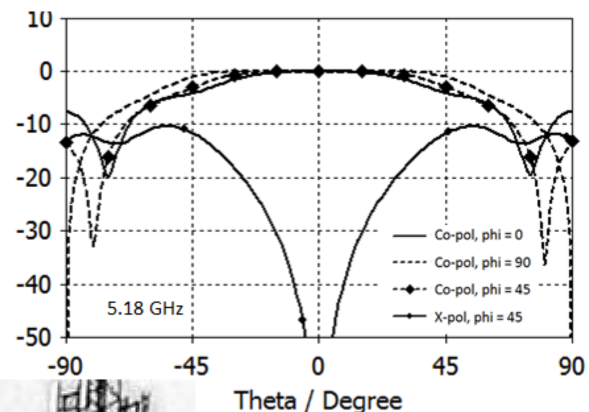
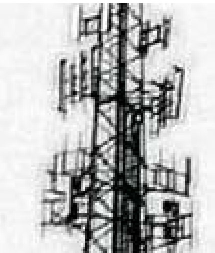


Figure 3.4: TSA geometry cartestian coordinate system and far-field spherical coordinates (ϕ, θ) including E-plane $(\phi = 90°)$ and H-plane $(\phi = 0°)$ definitions.



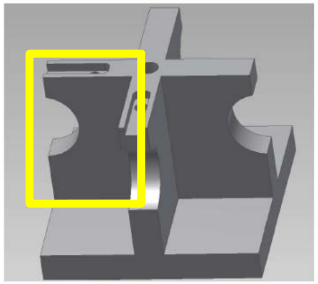






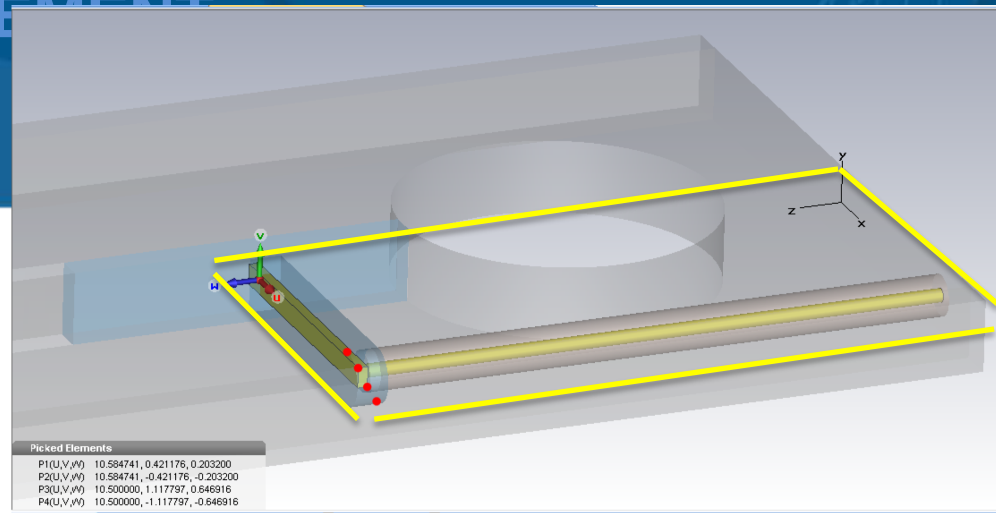
3 SINGLE ANTENNA ELEMENT

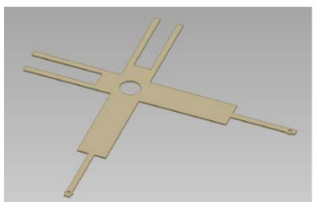
3.4 Manufacturing
- 3 Piece Dart



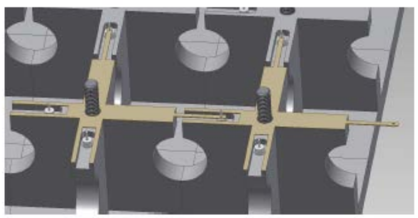
bottom

Coax with dielectric + pin

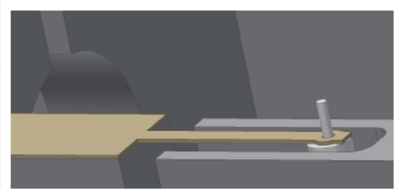




Strip

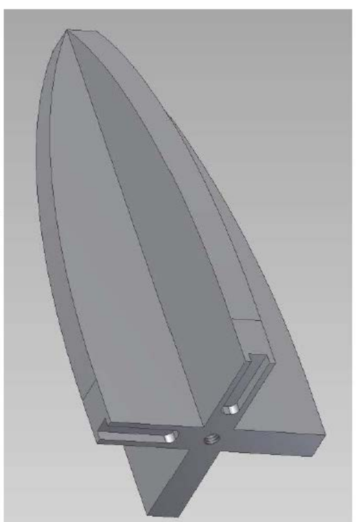


Placing strips down



metal strip

- 2D electric model -> 3D manuf model
  - Better suited for small antenna elements (28.8mm) than previous 2D manuf methods



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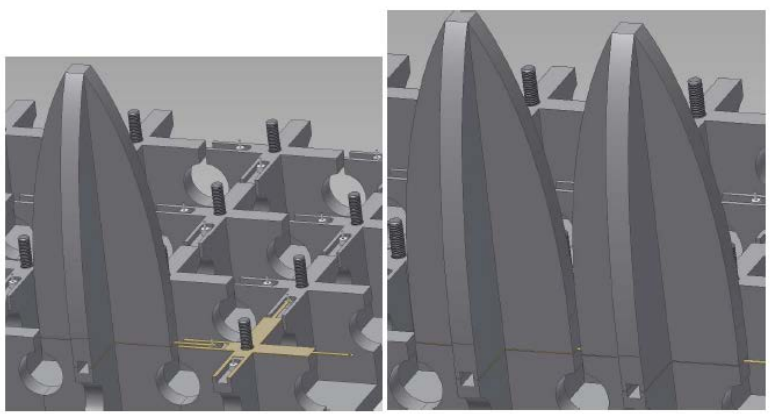
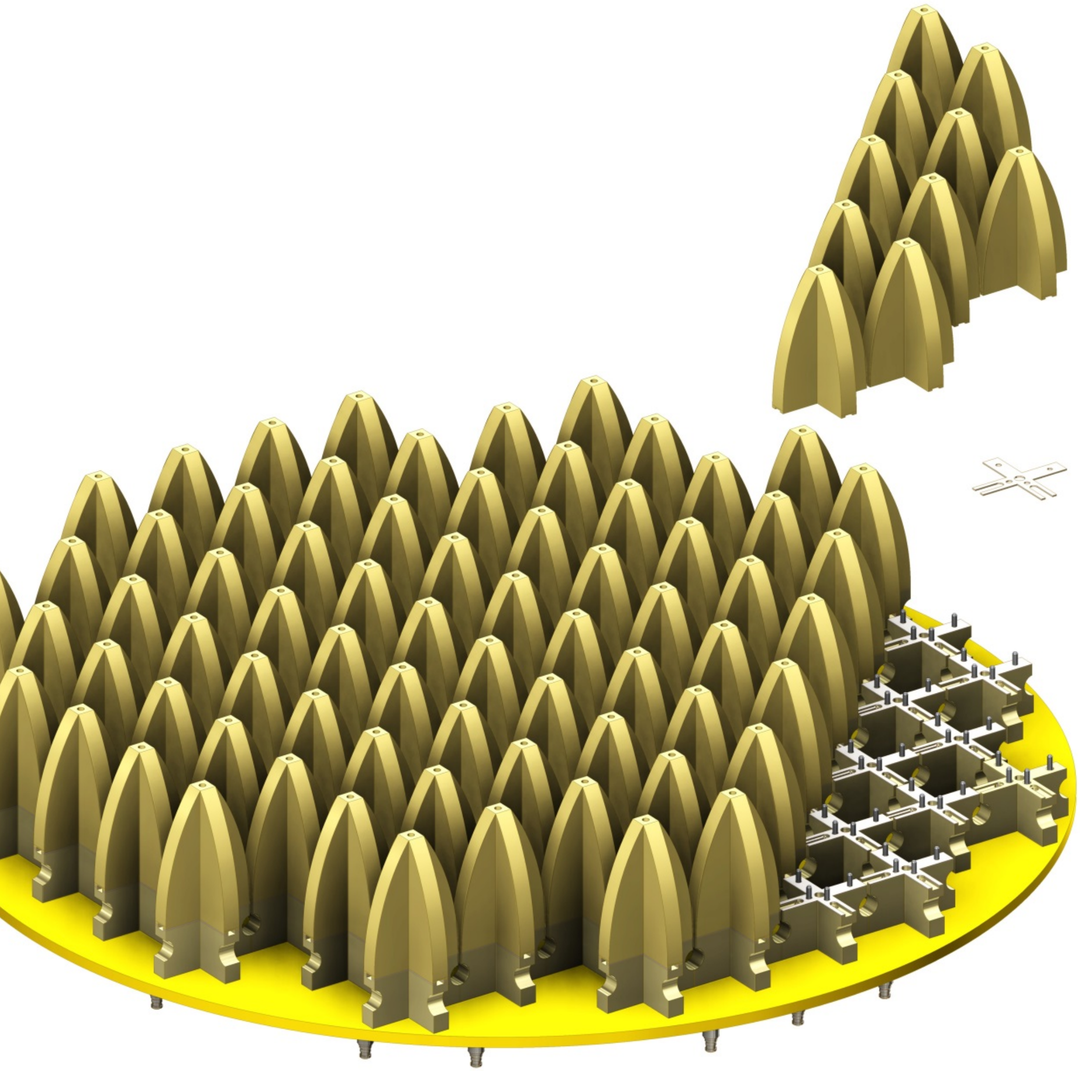
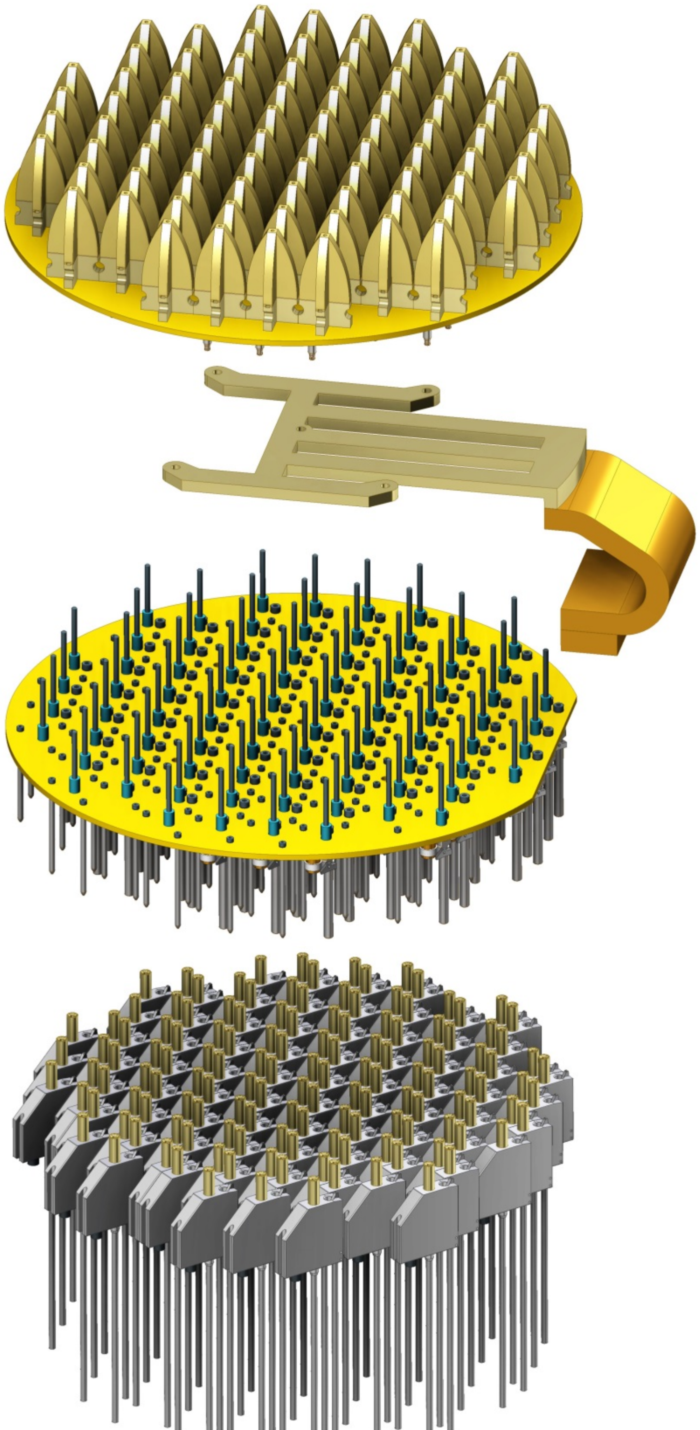


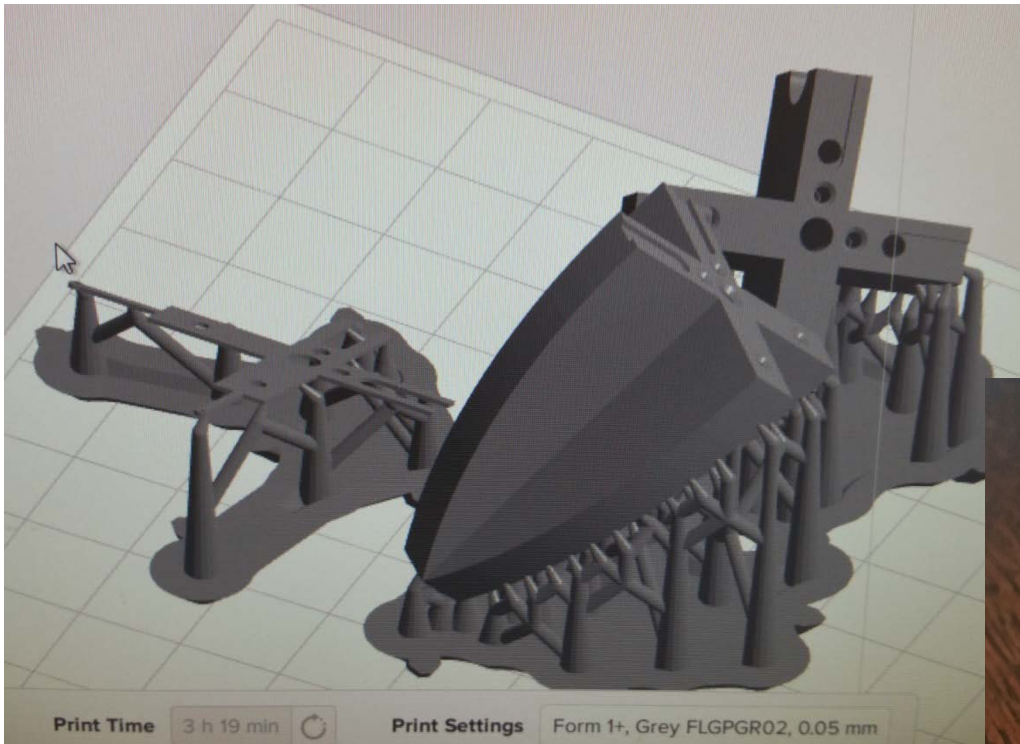
3 SINGLE ANTENNA ELEMENT

3.4 Manufacturing & Thermal
- 3 Piece Dart – pg 2

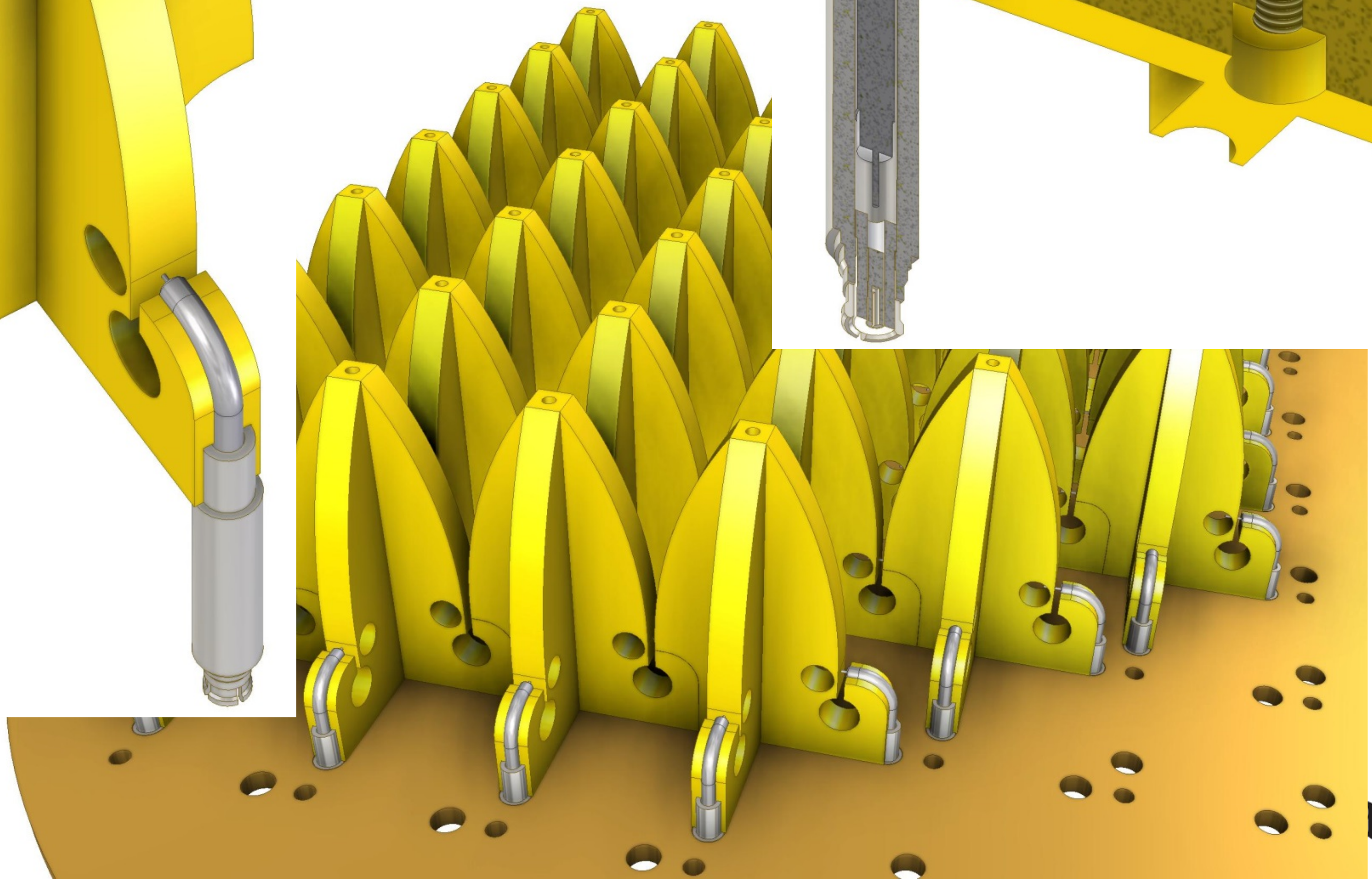


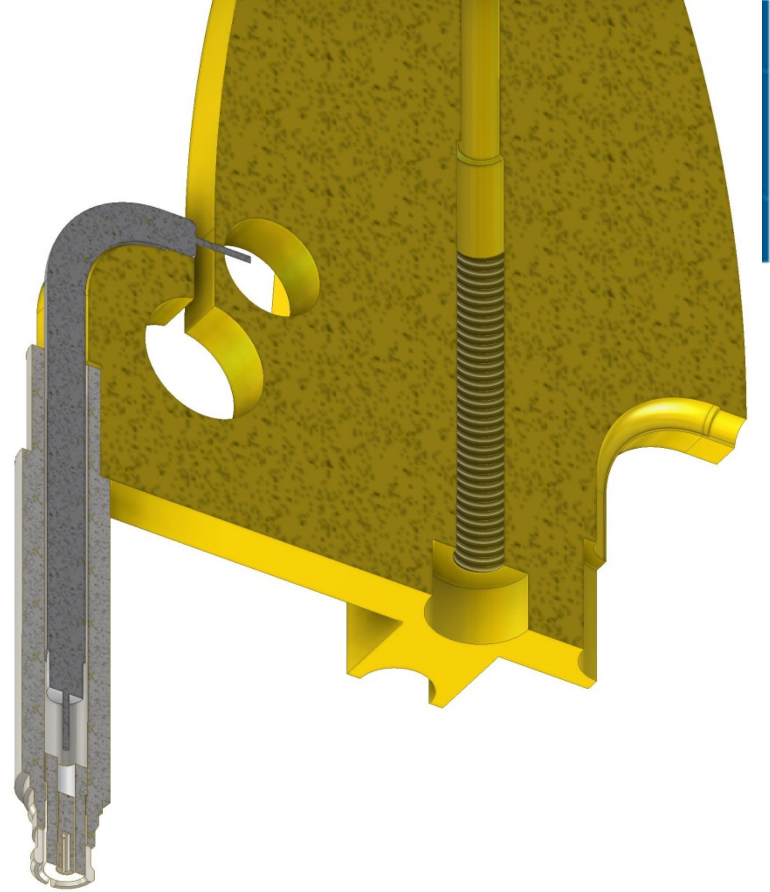


3 SINGLE ANTENNA ELEMENT
3.4 Manufacturing
- 3 Piece Dart – pg 3



3.4 Manufacturing
- 2 Piece “Arabesque”

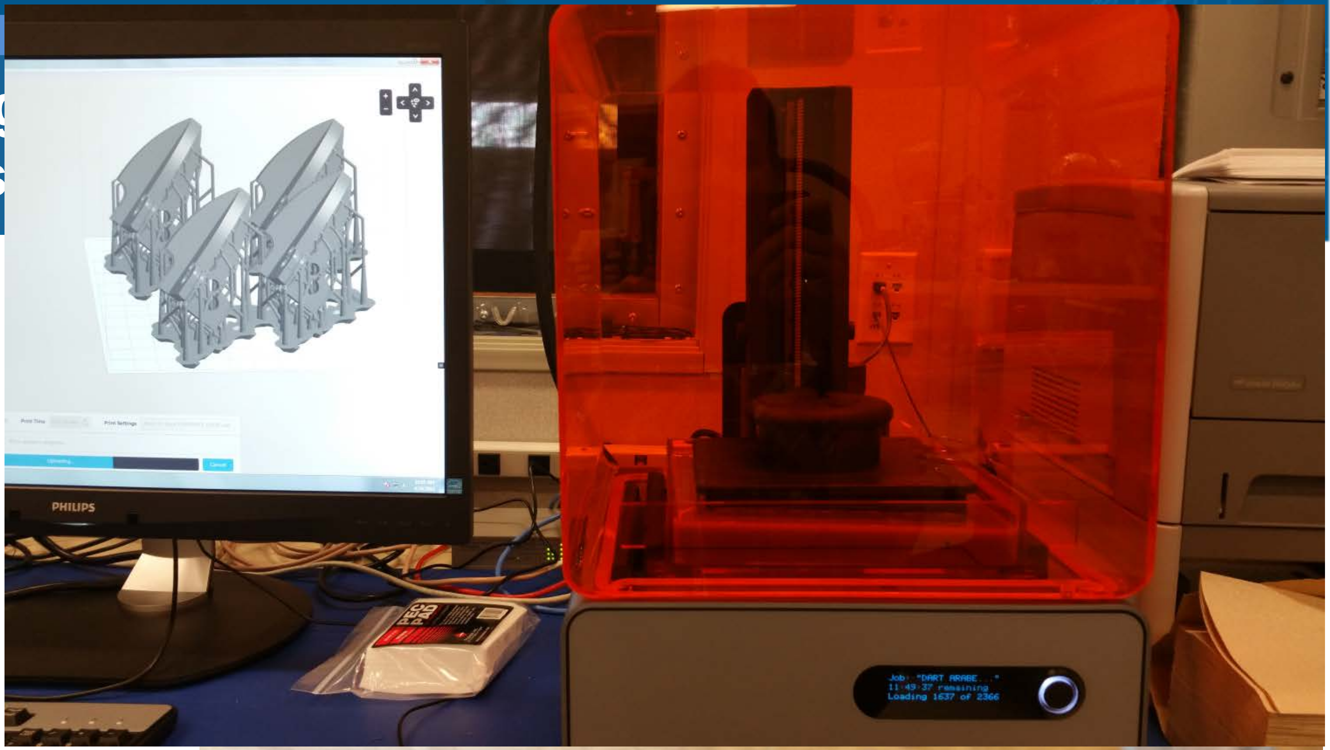




3 SINGLE ANTEN

3.4 Manufacturing

- 2 Piece “Arabes



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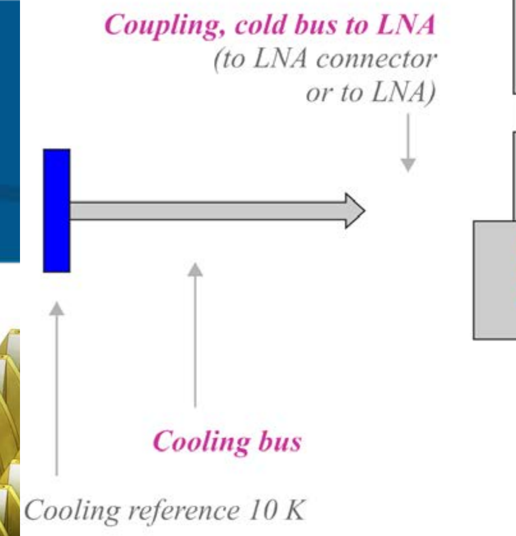
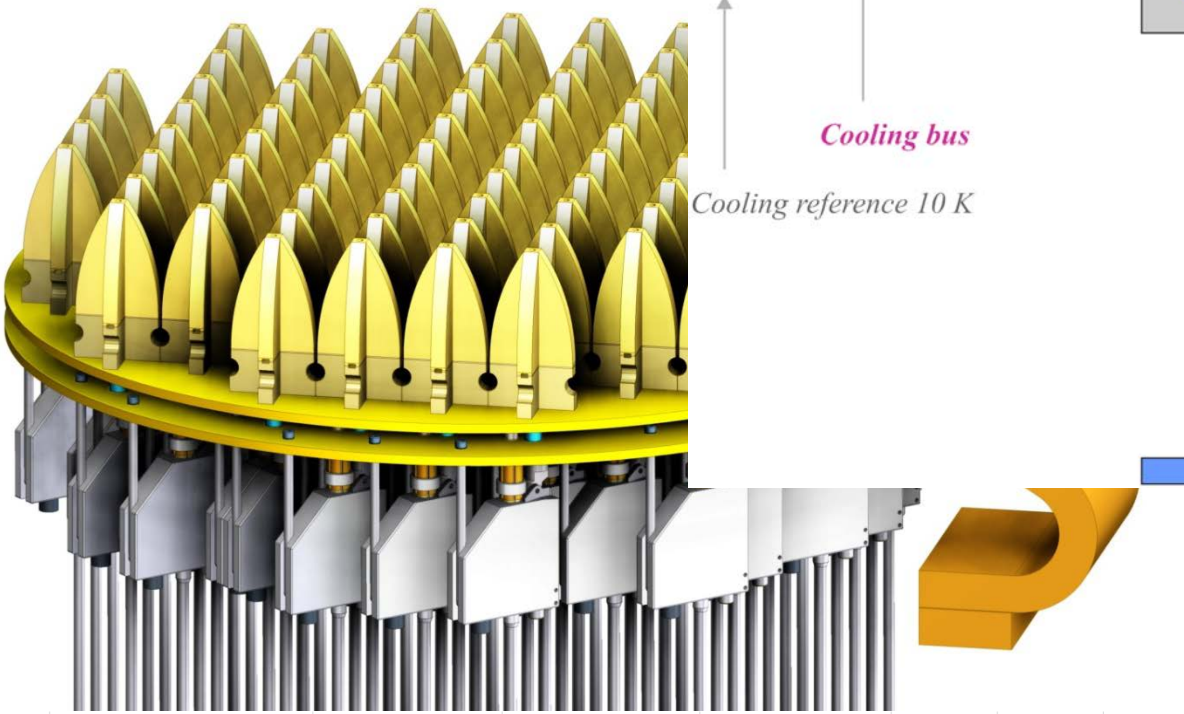
3 SINGLE ANTENNA ELEMENT

3.4 Thermal

- 300K heat load
- 10K to plate
- 70K to LNA output cables
- Vary: cross sectional diameter of
  - Cooling bus-LNA connection cross section
  - Cooling bus copper cross section
  - LNA-Vivaldi connection cross section
- Result: <15K on antennas & LNAs

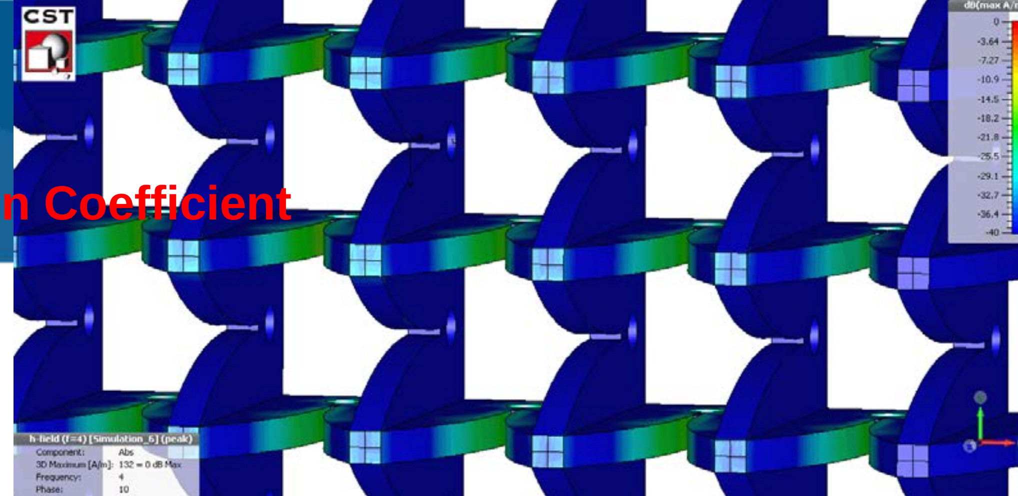




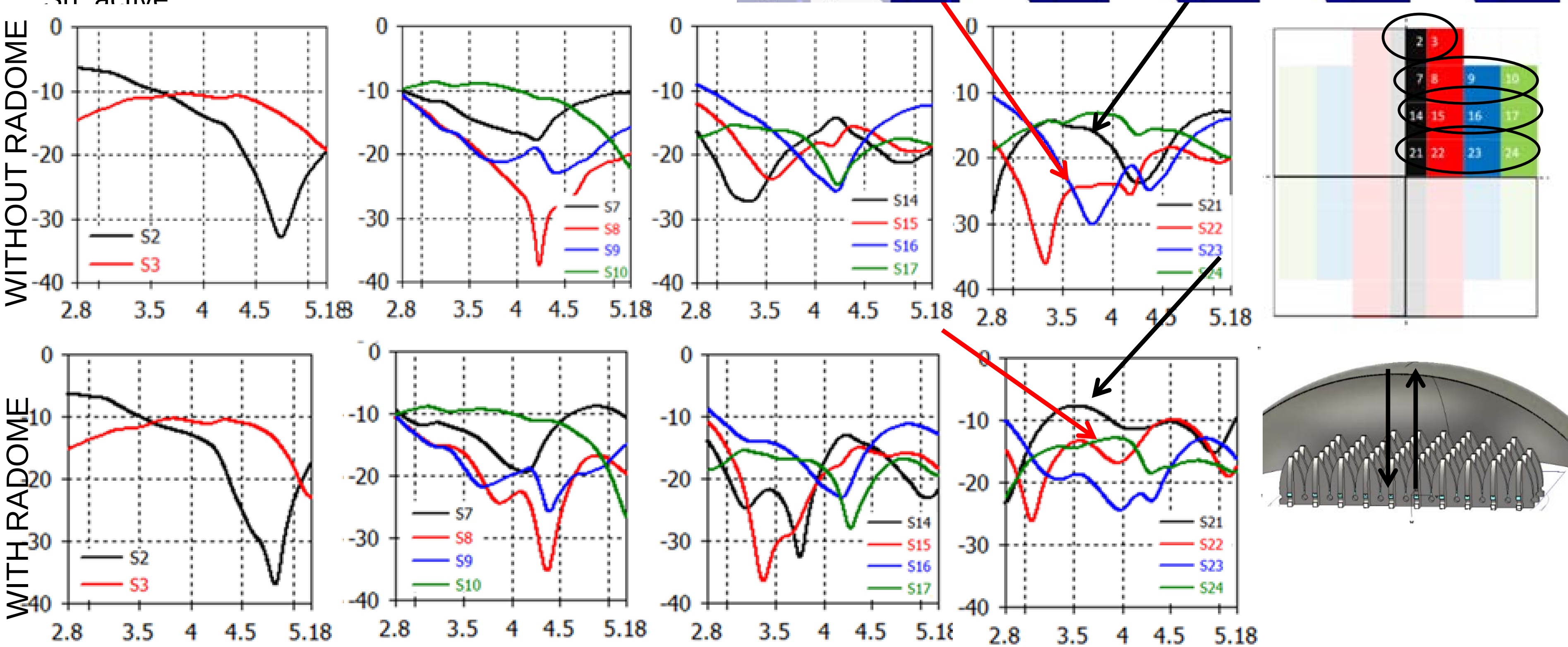
	element sections, sq mm			temperatures, K	
design	*coupling cold bus to LNA*	*cooling bus*	*coupling LNA to Vivaldi*	*Vivaldi*	*T1*
compression coupling	22.7	150	4	**14.2**	**11.1**
tabs+screws	113.4	150	4	**14**	**11**
tabs+screws	113.4	25	4	**18.8**	**15.7**
tabs+screws	113.4	25	12.6	**17.4**	**15.8**

4.0 ARRAY PERFORMANCE

S_active: Simultaneous Excitation – Active Input Reflection Coefficient

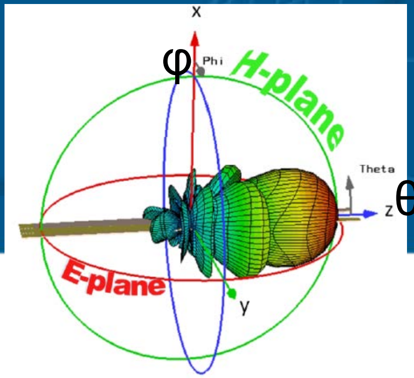


- Horizontal elements, one quadrant
- Effect of radome, modeled as a homogeneous dielectric, $\varepsilon_r = 4.0$, $\tan\delta = .005$
- Even complex excitation: 1, 0°
- Active Input reflection (dB) measurements: Sn => Sn_active

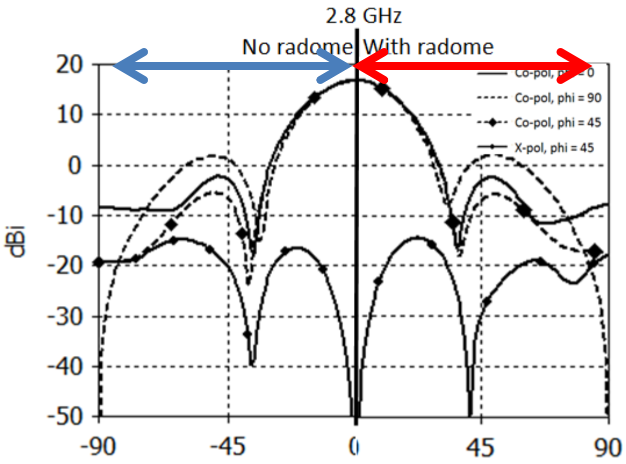


4.0 ARRAY PERFORMANCE

4.4 Radiation Patterns

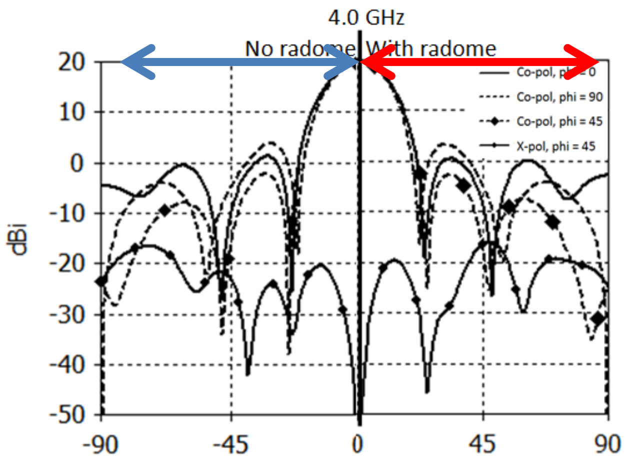


- Active radiation patterns for 2.8 GHz / 4.0 GHz / 5.18 GHz
- All 48 horizontal elements stimulated, with amplitude = 1, phase = 0°
- Directivity patterns vs elevation angle θ (°)
- Co-pol H-, E-, D-planes (φ = 0°, 90°, 45°), cross-pol D-plane
- No radome (left), With radome (right)
- Results:
  - Radome barely affects beam patterns
  - HPBW reduces with frequency as expected.



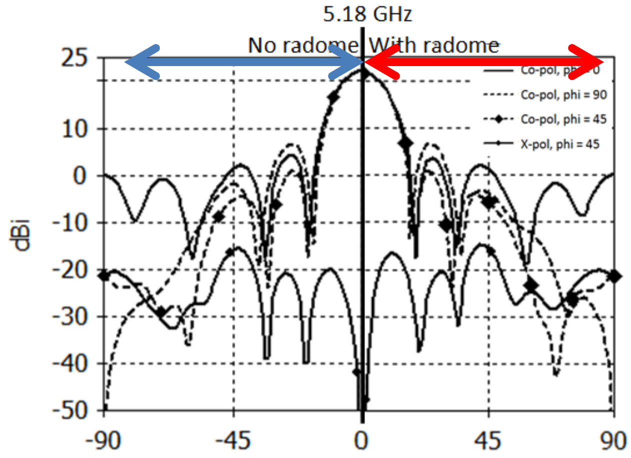
28.3°/27.1°, 27.0°/26.4°, 27.7°/26.7°

Co-pol FWHM (0, 90, 45 degrees) No Radome/With Radome



20.2°/19.3°, 18.6°/18.5°, 19.5°/19.0°

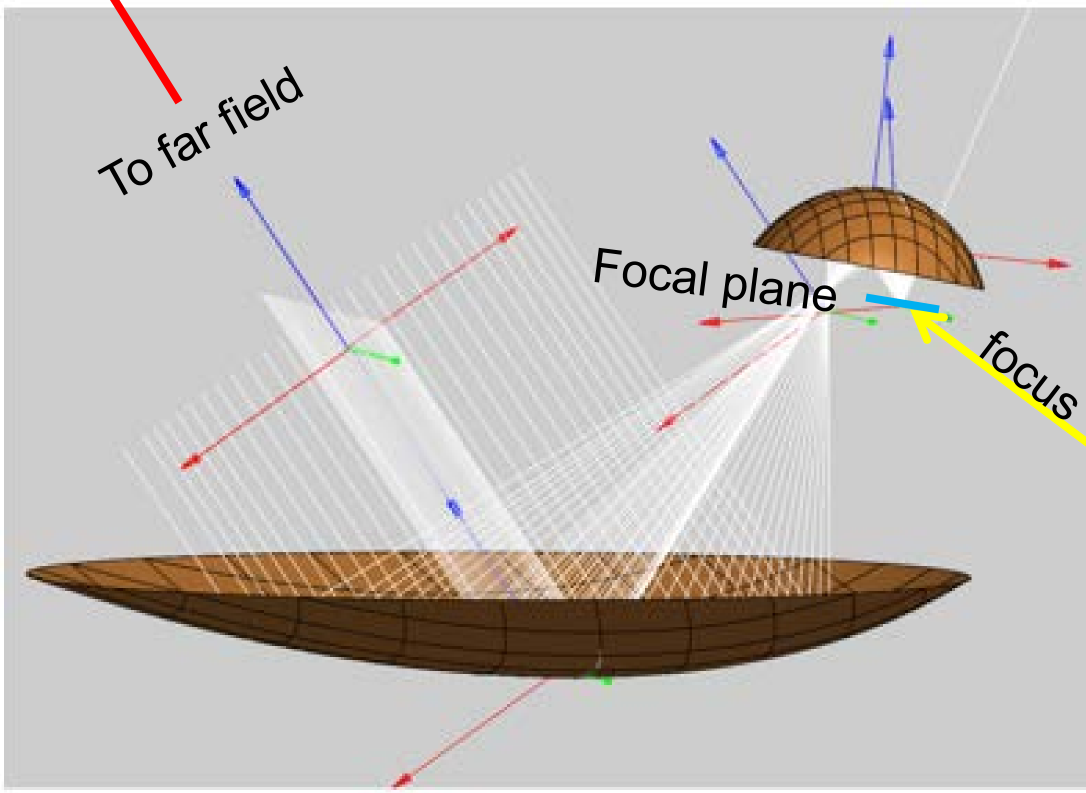
Co-pol FWHM (0, 90, 45 degrees) No Radome/With Radome



15.3°/15.6°, 14.5°/15.4°, 14.9°/15.5°

Co-pol FWHM (0, 90, 45 degrees) No Radome/With Radome

4.5 Optical Coupling with Reflector



Offset Gregorian optics of DVA-1 telescope at DRAO Penticton, with white ray-traces from focus to far field computed with GRASP (PO, PTD, GO).

- Primary reflector: *D*=15 m diameter
- Half-opening angle: 55°
- Feed edge taper: -16 dB
- The antenna array will be placed at the focus of the subreflector.
- When coupled with reflector:
  - λ/D in the far field
  - $\lambda f/D$ in the focal plane

  where *f: focal length*

4 ARRAY PERFORMANCE

4.6 Focal Plane Beams

- Overlaid on antenna elements in focal plane:
- 3dB width of beam: FWHM (3 dB circles)
- Spacing of beams: Nyquist spacing λ/2, Δ
- Signal processing power of beamformer-limited

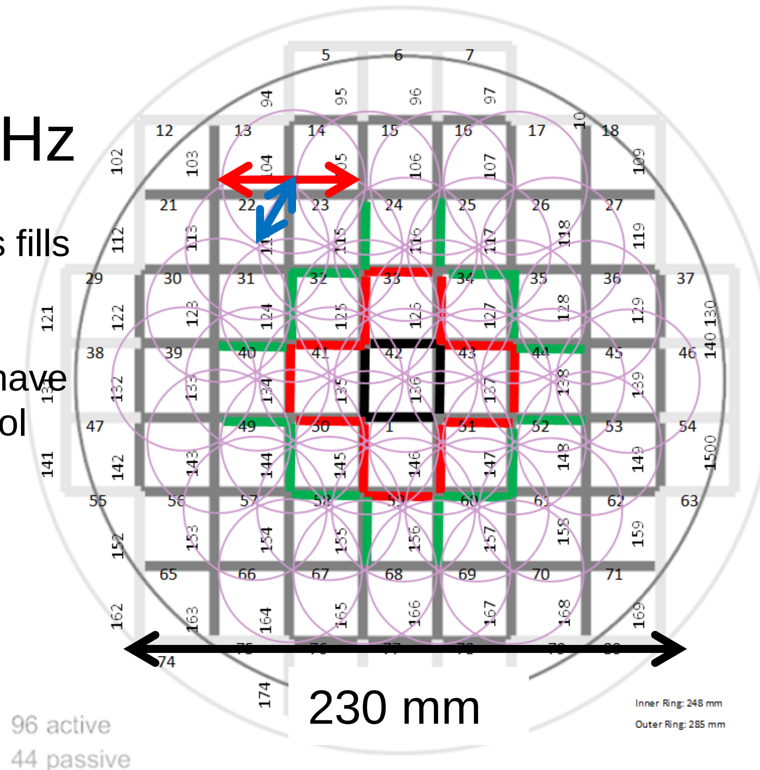
FWHM　　　Δ

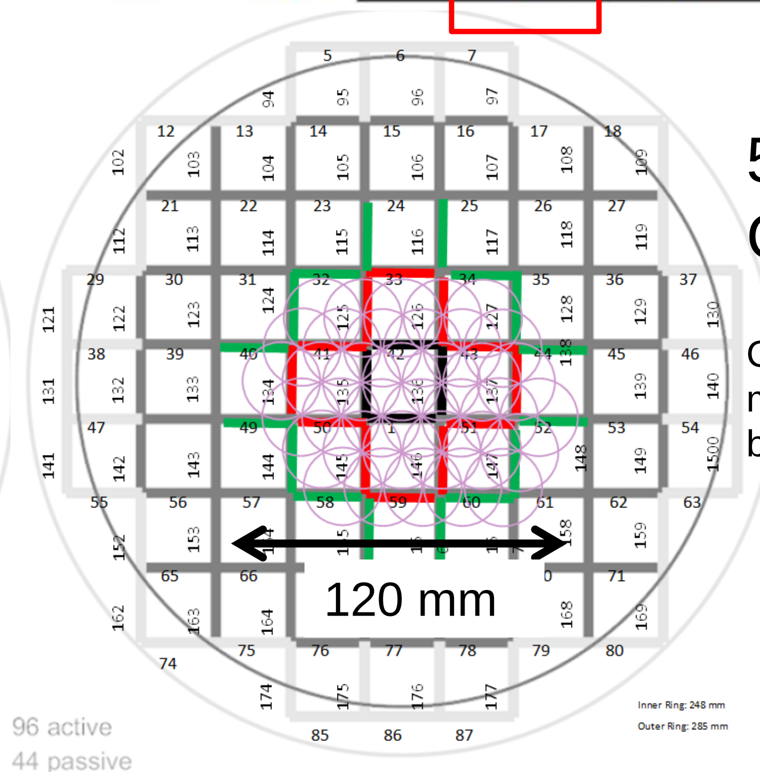
		FWHM		Beam spacing - hexagonal	
Freq (GHz)	λ (mm)	λ/D (°)	λf/D (mm)	λ/(√3D) (°)	λf/(√3D) (mm)
2.80	107.14	0.41	55.71	0.24	32.17
5.18	57.92	0.22	30.12	0.13	17.39

2.8 GHz

36 beams fills array.

But only have 18 dual-pol available.

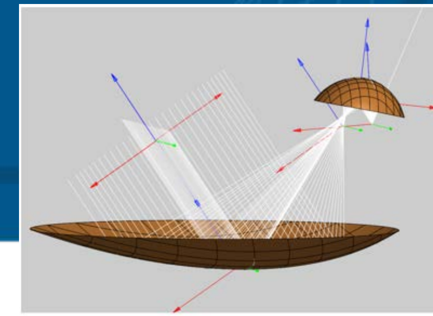


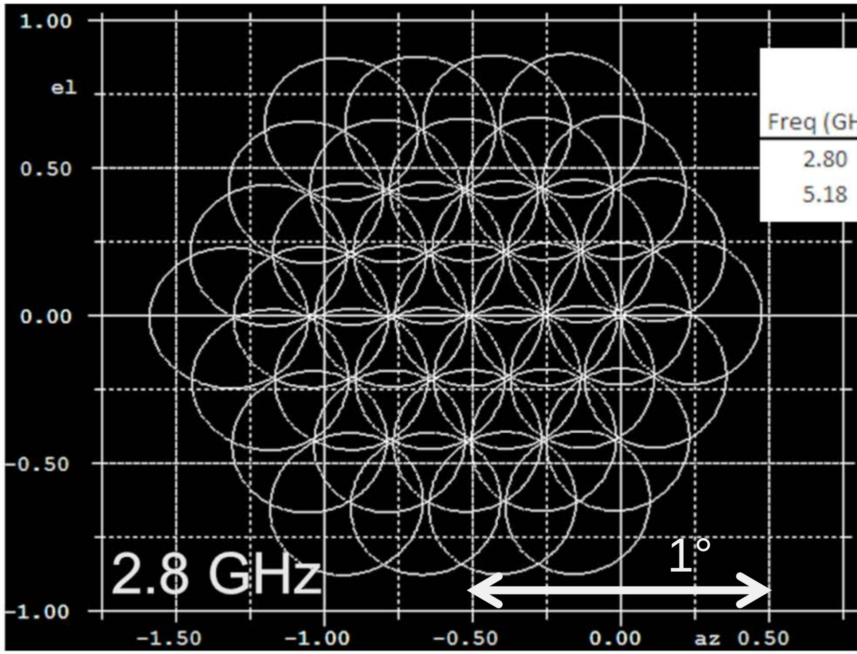


5.18 GHz

Could use many more beams

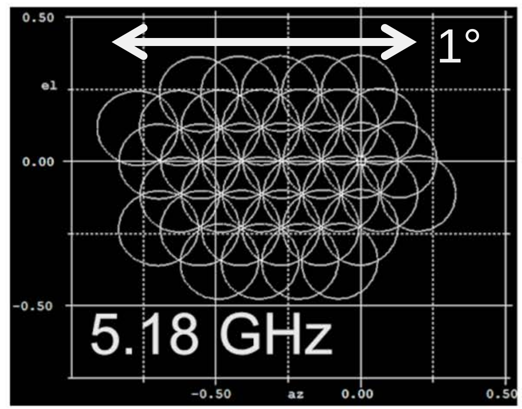
4.7 Far-field Beams





FWHM | Δ

Freq (GHz)	λ (mm)	FWHM λ/D (°)	FWHM λf/D (mm)	Beam spacing - hexagonal λ/(√3D) (°)	Beam spacing - hexagonal λf/(√3D) (mm)
2.80	107.14	0.41	55.71	0.24	32.17
5.18	57.92	0.22	30.12	0.13	17.39



- Using D=15m offset Gregorian reflector, far-field beam simulation

	2.8 GHz	5.18 GHz
Single beam	0.41° x 0.41° = 0.17(°)^2	0.22° x 0.22° = 0.048(°)^2
18 beams	1.6° x 0.8° = 1.28 (°)^2 (7.5x)	1.0° x 0.4° = 0.4 (°)^2 (8.3x)
36 beams	1.6° x 1.6° = 2.56 (°)^2 (15x)	1.0° x 0.8° = 0.8 (°)^2 (16.6x)

5 CONCLUSIONS

- Cryogenic (16 K) PAF for 2.8 – 5.18 GHz designed
- Trx = 11 K
- Composite laminate radome
- 140 metal Vivaldi antenna elements
- 96 low noise (T = 3.5 K) amplifiers
- Post amplification, filtering
- FD Digital beamformer – 18 beams for now
- Can attain ~8x FoV of SPF for 18 beams and ~16x FoV for 36 beams assuming overlap well within 3 dB Airy circles.
- Construction starting Summer 2016

NRC·CNRC

Thank you

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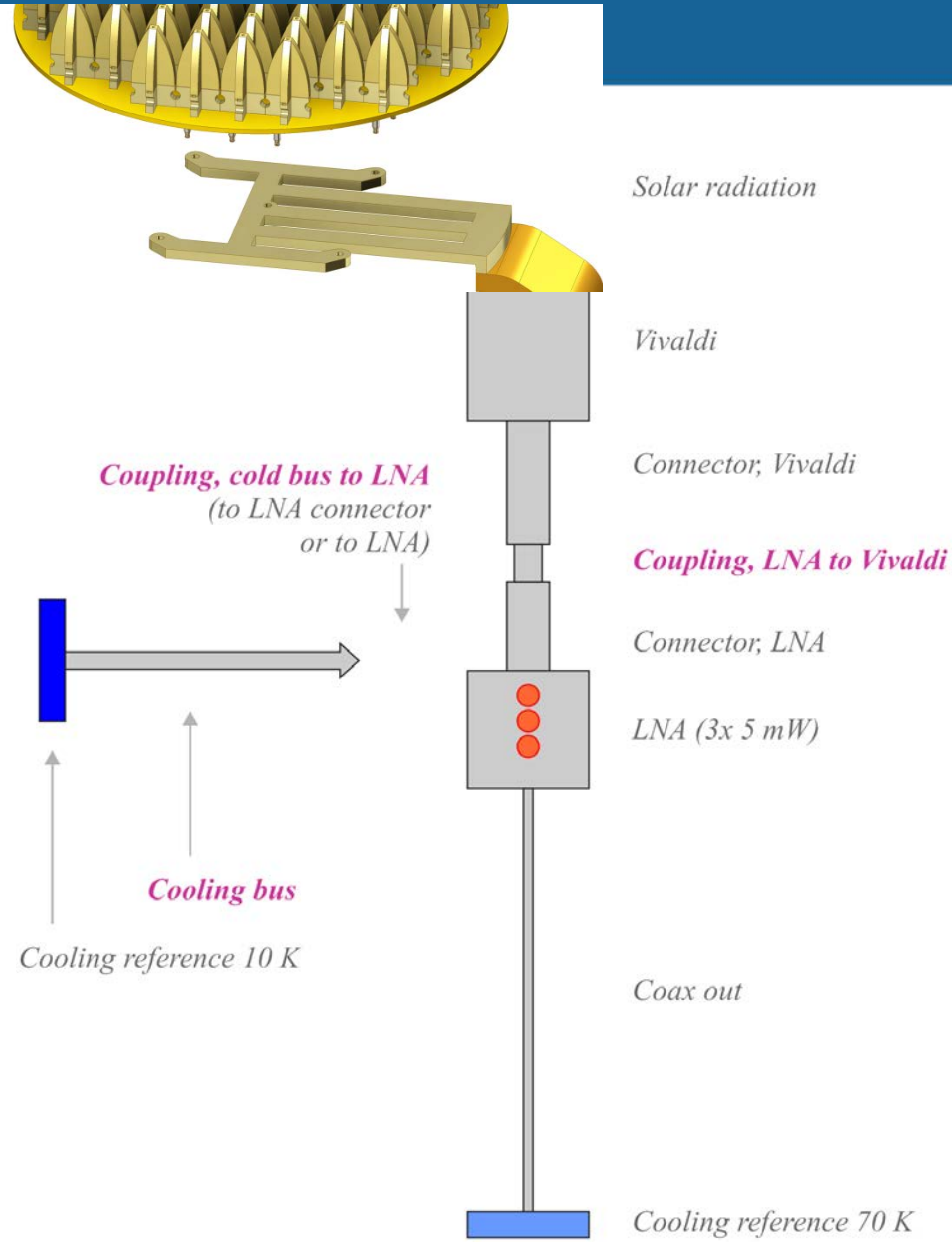
Mechanical Array Design
Thermal Analysis - Simulink



- Impact of
  - Cooling bus-LNA connection cross section
  - Cooling bus copper cross section
  - LNA-Vivaldi connection cross section

Can attain <20K on LNA and Vivaldi

	element sections, sq mm			temperatures, K	
design	*coupling cold bus to LNA*	*cooling bus*	*coupling LNA to Vivaldi*	*Vivaldi*	*T1*
compression coupling	22.7	150	4	14.2	11.1
tabs+screws	113.4	150	4	14	11
tabs+screws	113.4	25	4	18.8	15.7
tabs+screws	113.4	25	12.6	17.4	15.8