Enabling Technologies for the ngVLA:

Quadruple-Ridged Flared Horn

Ahmed H. Akgiray

ngVLA Workshop, 9 April 2015, Caltech

Why decade-bandwidth radio astronomy?

Enabling new science

- ✓ Observations of pulsed (pulsar) and transient radio sources over many octaves of frequency, as well as accurate timing of pulsar echoes
- ✓ Search for spectral lines with unknown, large red-shifts
- ✓ Measurements of spectral shape (spectral index) of continuum radio sources
- ✓ Increased timing accuracy in very-long baseline interferometry while reducing fringe ambiguity

Why decade-bandwidth radio astronomy?

Reducing cost of new arrays

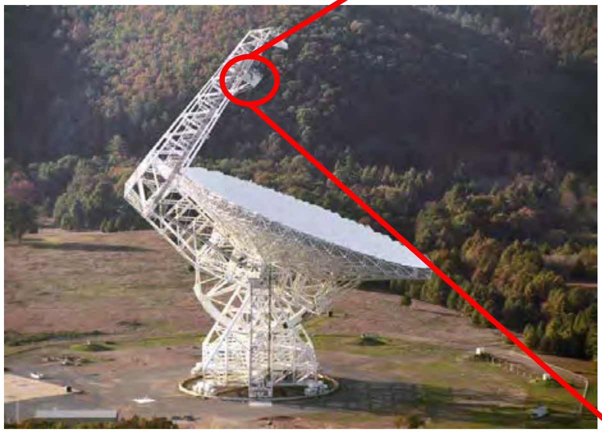
Replacing

~3 octave bandwidth horns and associated cryogenic Rx electronics

With

one decade bandwidth feed and one cryogenic receiver

translates to tremendous savings in up-front and maintenance costs



Prior State of the Art

Corrugated horns satisfy all except *bandwidth*

Type	Radiation pattern features	Typical aperture efficiency	Input Impedance	BW	Cost Estimate
Corrugated horn	Almost Gaussian beam, constant with freq; low sidelobes, excellent x-pol; const phase ctr; **can be designed for different beamwidths**	75-85%	50 Ohm single-ended	**2:1**	Low to medium
Eleven feed	Const beamwidth w/ reasonably circular beam; mediocre x-pol; const phase ctr; **tough to change beamwidth**	60-65%	**200 Ohm differential**	7:1	High
ATA feed	Const beamwidth w/ reasonably circular beam; mediocre x-pol; **large phase ctr variation**; **tough to change beamwidth**	50%	**200 Ohm differential**	>= 10:1	Medium to high
QSC feed	Const beamwidth w/ reasonably circular beam; **mediocre to poor x-pol**; **??? phase ctr variation**; **tough to change beamwidth**	60%	**200 Ohm differential**	10:1	???
Sinuous feed	Mediocre beamwidth stability w/ **elliptical beam;** mediocre x-pol; const phase ctr; **tough to change beamwidth**	60%???	**260 Ohm differential**	4:1	Medium

Prior State of the Art

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Type		Typical		W	Cost Estimate
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Eleven feed	Co be			:1	High
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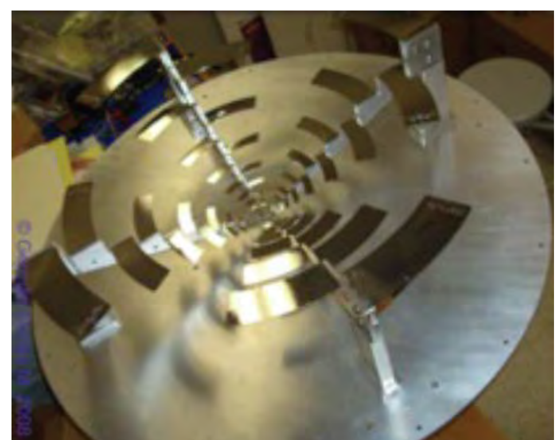
QSC feed	Co I p			0:1	???
Sinuous feed	el phase ctr; **tough to change beamwidth**		differential	:1	Medium

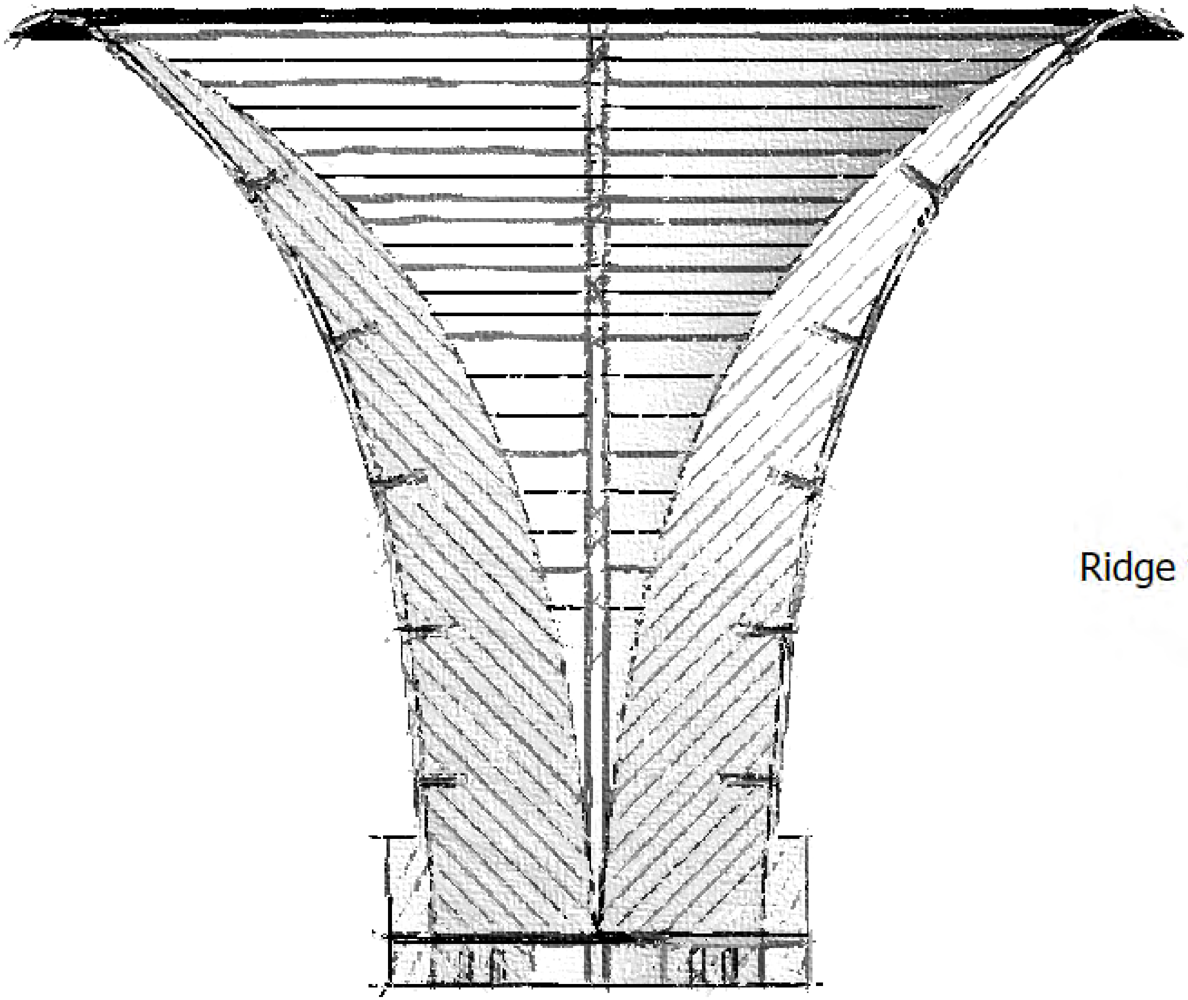
Eleven Feed (Chalmers)

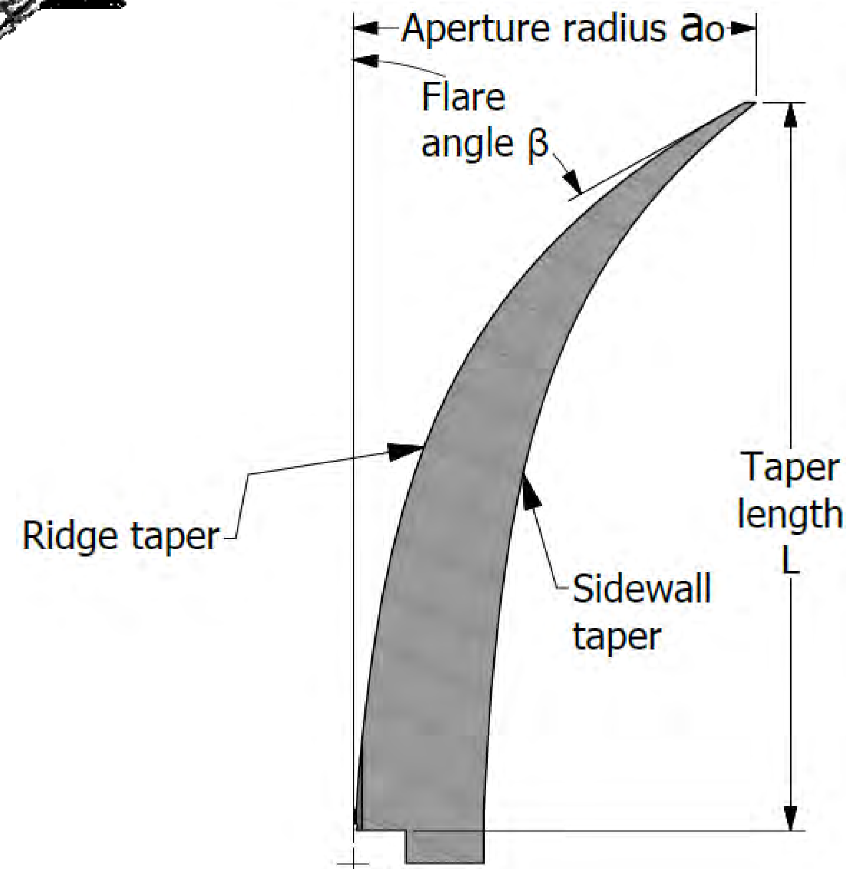
ATA Feed (UCB)

Sinuous Feed (UVa)

QSC Feed (Cornell)







Several ideas coming together:

CIT QUADRUPLE-RIDGED FLARED HORN

Timeline of QRFH development

2007-2010, G. Cohn, Z. Zhang

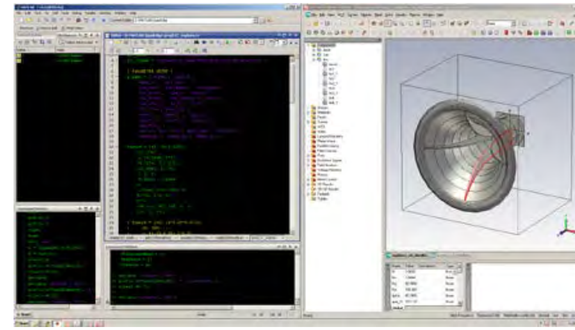
ETS-Lindgren 3164-05
- Open-boundary
- 2-18 GHz
- Max 6 dB RL in band
- 10 dB beamwidth varies btw 60-130 deg (E-plane)

2007-2009, G. Jones

3164-05 in dewar
- RL perf similar
- Slightly smaller beamwidth variation
- More ripples on both patterns and RL

2010-2013, A. Akgiray

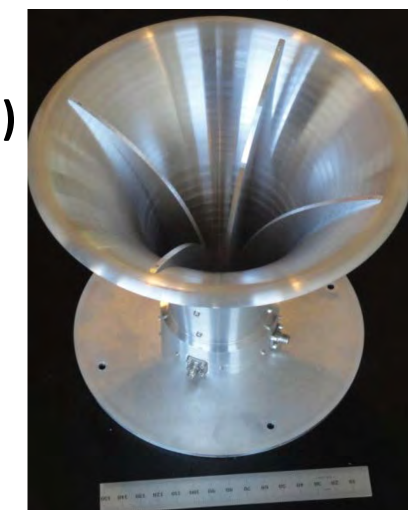
MATLAB controls and operates CST



Almost fully automated software setup combined with a Tesla GPU workstation

Accumulated > 15000 simulation runs

CIT Quad-ridge Flared Horn (QRFH)

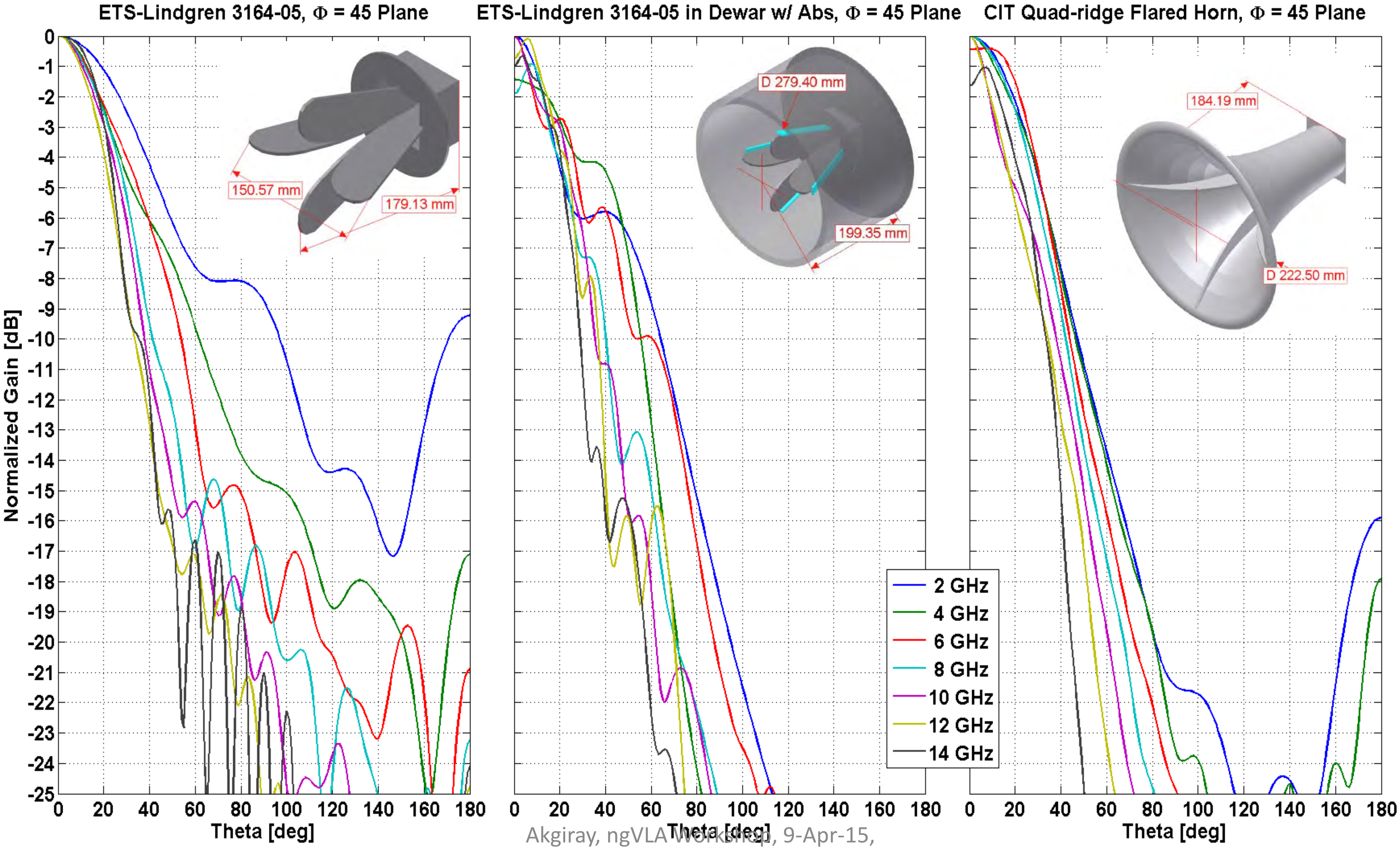


Obtained bandwidth: 4:1 to 7:1 depending on beamwidth

Return loss: > 15 dB over most of freq range

A more quantitative look:

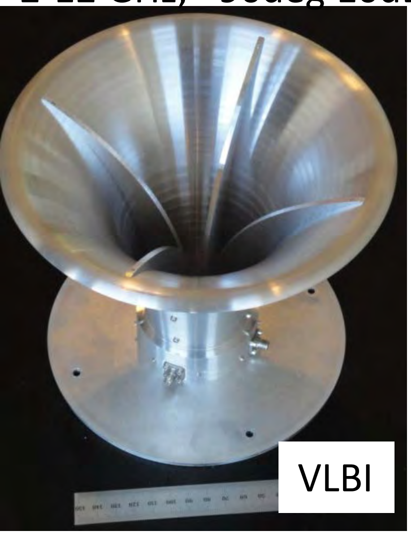
ETS-Lindgren vs. an early QRFH design



Timeline of QRFH development

Flexible design enables multitude of applications

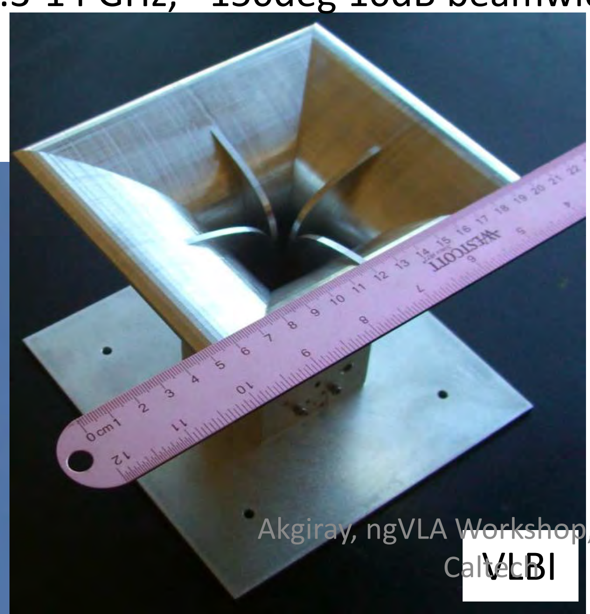
MIT Haystack Observatory
2-12 GHz, ~90deg 10dB beamwidth



MIT Haystack Observatory, Shanghai Astronomical Observatory, Geospatial Information Authority of Japan
2.3-14 GHz, ~120deg 10dB beamwidth

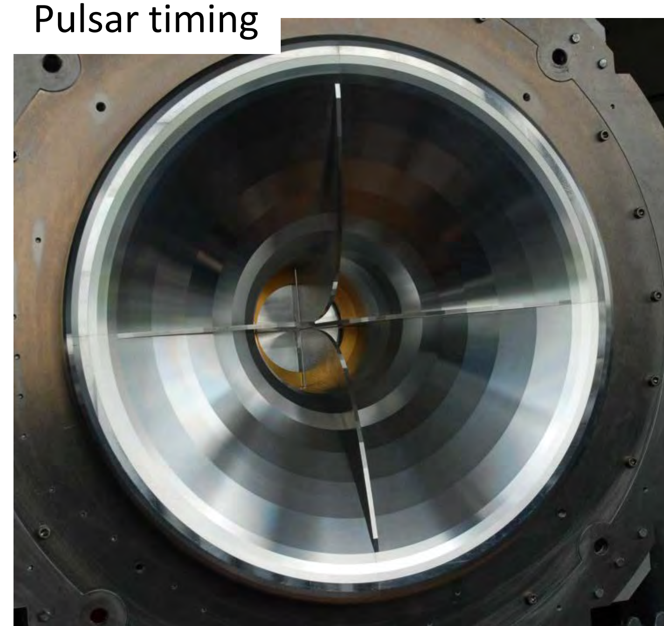
Caltech 6m
0.6-3 GHz, ~150deg 10dB beamwidth

MIT Haystack Observatory
2.3-14 GHz, ~150deg 10dB beamwidth



Max Planck Institute for Radio Astronomy
0.6-2.5 GHz, ~150deg 10dB beamwidth

Pulsar timing



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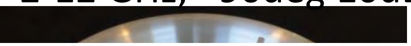

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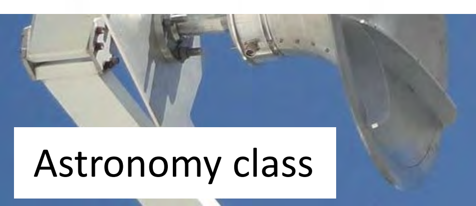
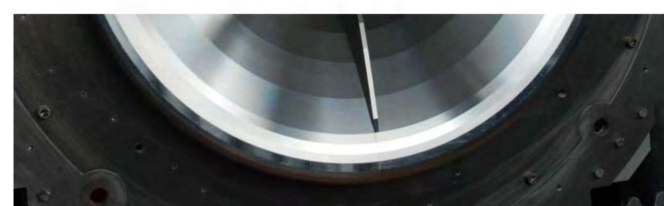
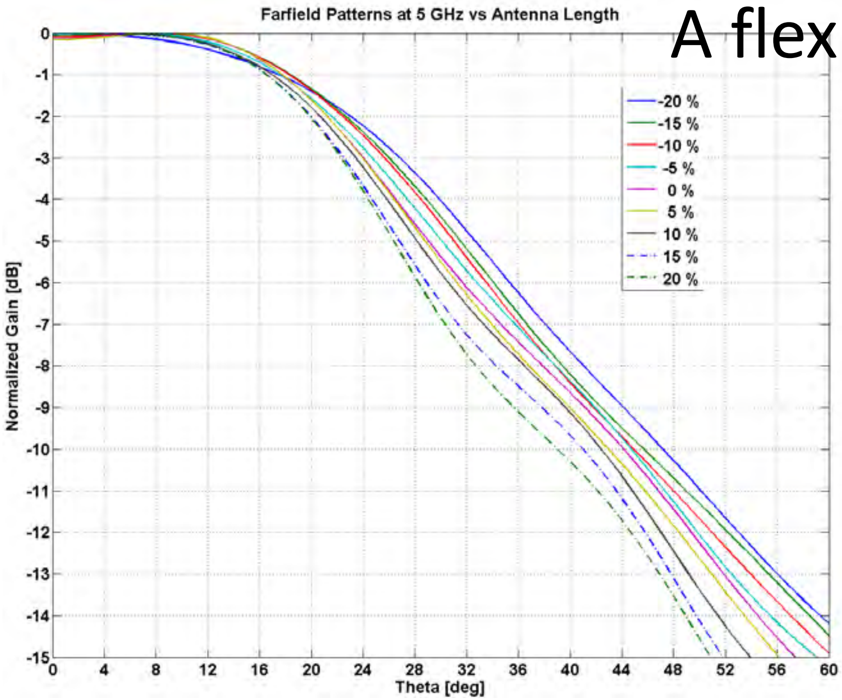
Telescope	Primary Diam. [m]	QRFH 10 dB beamwidth [deg]	Frequency range [GHz]	Feed Diam & Length [cm]	Operated by	Status
NASA Goddard	**12**	**90**	**2-12**	**18 x 16.4**	**MIT Haystack Observatory**	**On telescop**
Westford	**18.3**	**140**	**2.3-14**	**14.3 x 11.9**	**MIT Haystack Observatory**	**On telescop**
Effelsberg	100	140	0.6-2.5	74.6 x 35	Max Planck Institute for Radio Astronomy	On telescope
Caltech	6	150	0.6-3	72.6 x 32	Caltech	On telescope
Japanese VLBI	**13.2**	**120**	**2.3-14**	**20 x 13.4**	**Geospatial Information Authority of Japan**	**Shipped**
Caltech OVRO	27	120	1-6 and 3-18	12.4 x 5.7 (3-18)	Caltech OVRO	In fabricatio
Haystack VLBI	N/A	120	2.3-14	20 x 13.4	MIT Haystack Observatory	Under test
Shanghai VLBI	N/A	120	2.3-14	20 x 13.4	Shanghai Astronomical Observatory	Under test
Deep Space Network	**70**	**30**	**0.5-3.5**	**230 x 401**	**NASA/JPL**	**In discussio**
Shanghai	65	30	4-28?	TBD	Shanghai Astronomical Observatory	In discussion
Australian VLBI	N/A	90	2.3-14	TBD	CSIRO	In discussion
GAVRT	**34**	**65**	**0.7-4.9**	**82 x 73.2**	**Lewis Center for Educational Research/Caltech**	**On hold**

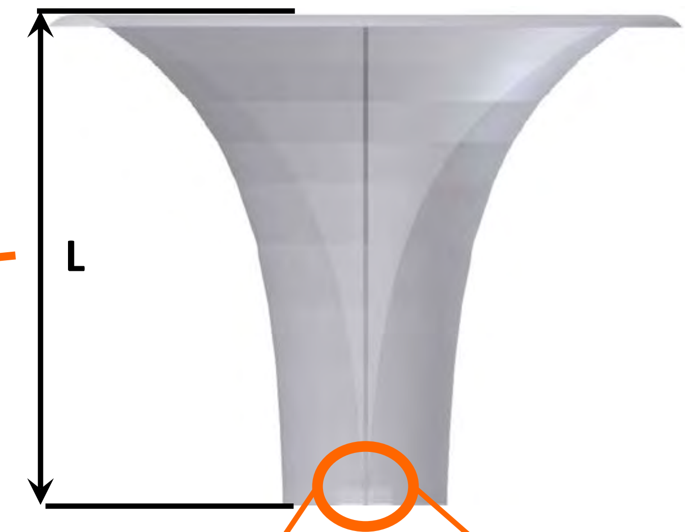


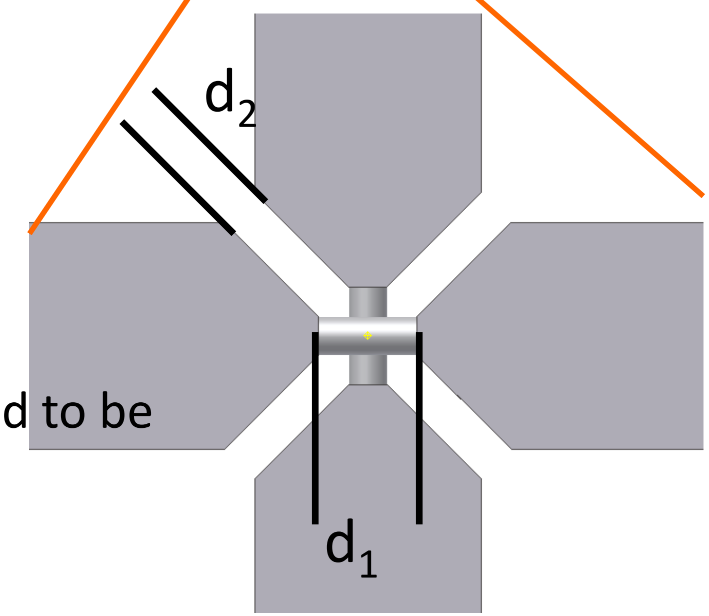


Unique Features of the QRFH

A flexible antenna







First horn design to achieve bandwidths ≥ 4:1 with:

1. Nearly constant beamwidth with freq for 10 dB beamwidths between 30-130 deg

   BW = 60 deg => Bandwidth = 7:1

   BW = 140 deg => Bandwidth = 4:1

2. Nominal input impedance of 50 Ohm (can be tuned to be anywhere between 50 and 100 Ohms)

3. One single-ended 50 Ohm LNA per polarization

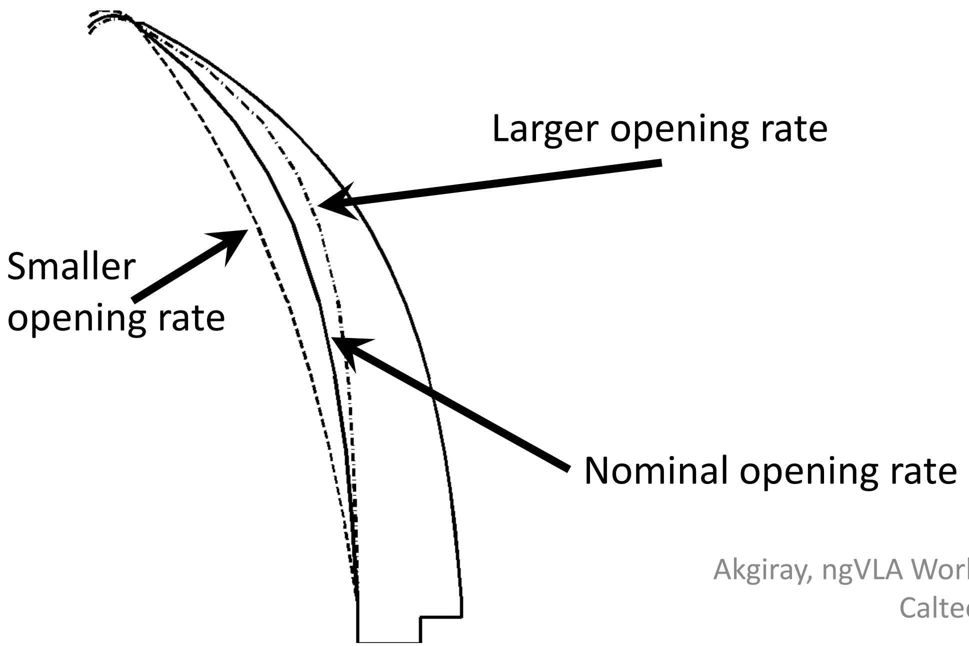
Sidewall and Ridge Profiles

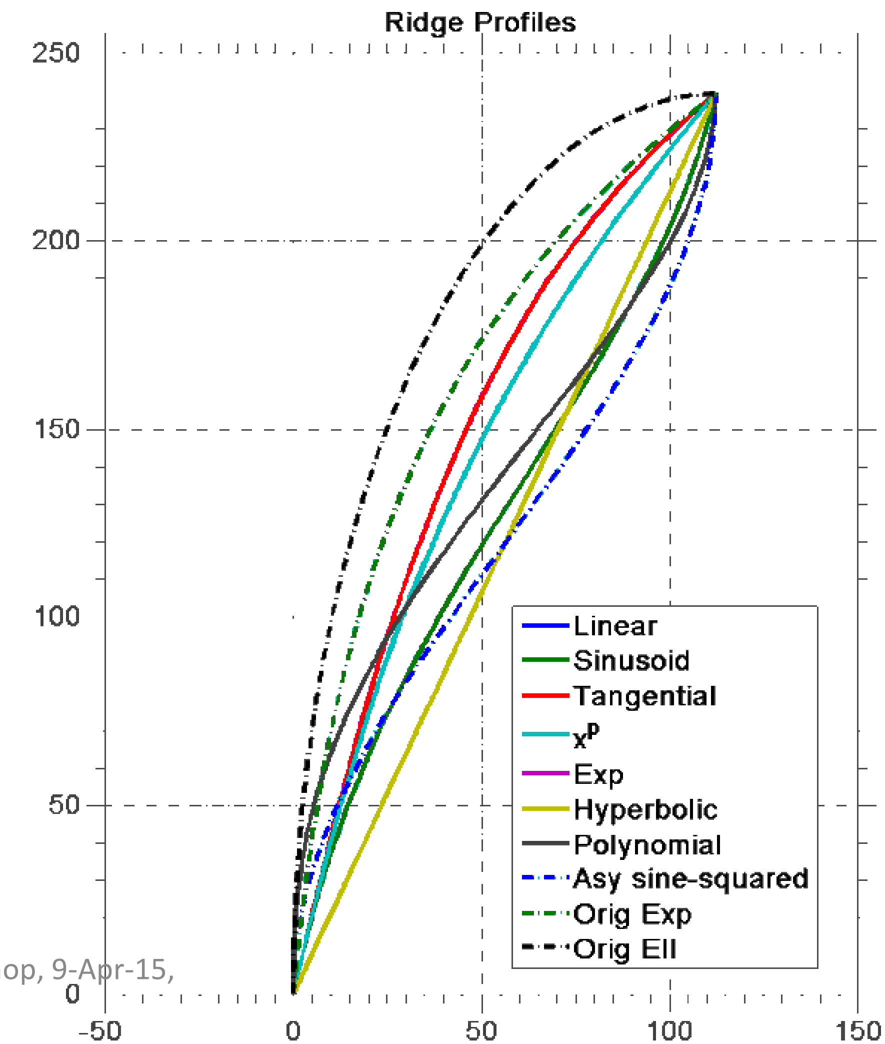
Critical for desired performance

Infinitely many possibilities in choice of profile shape (derived from profiled horn literature):

Ridge and sidewall profiles determine:

1. Bandwidth
2. Beamwidth
3. Return loss





Impact of ridges

A qualitative perspective

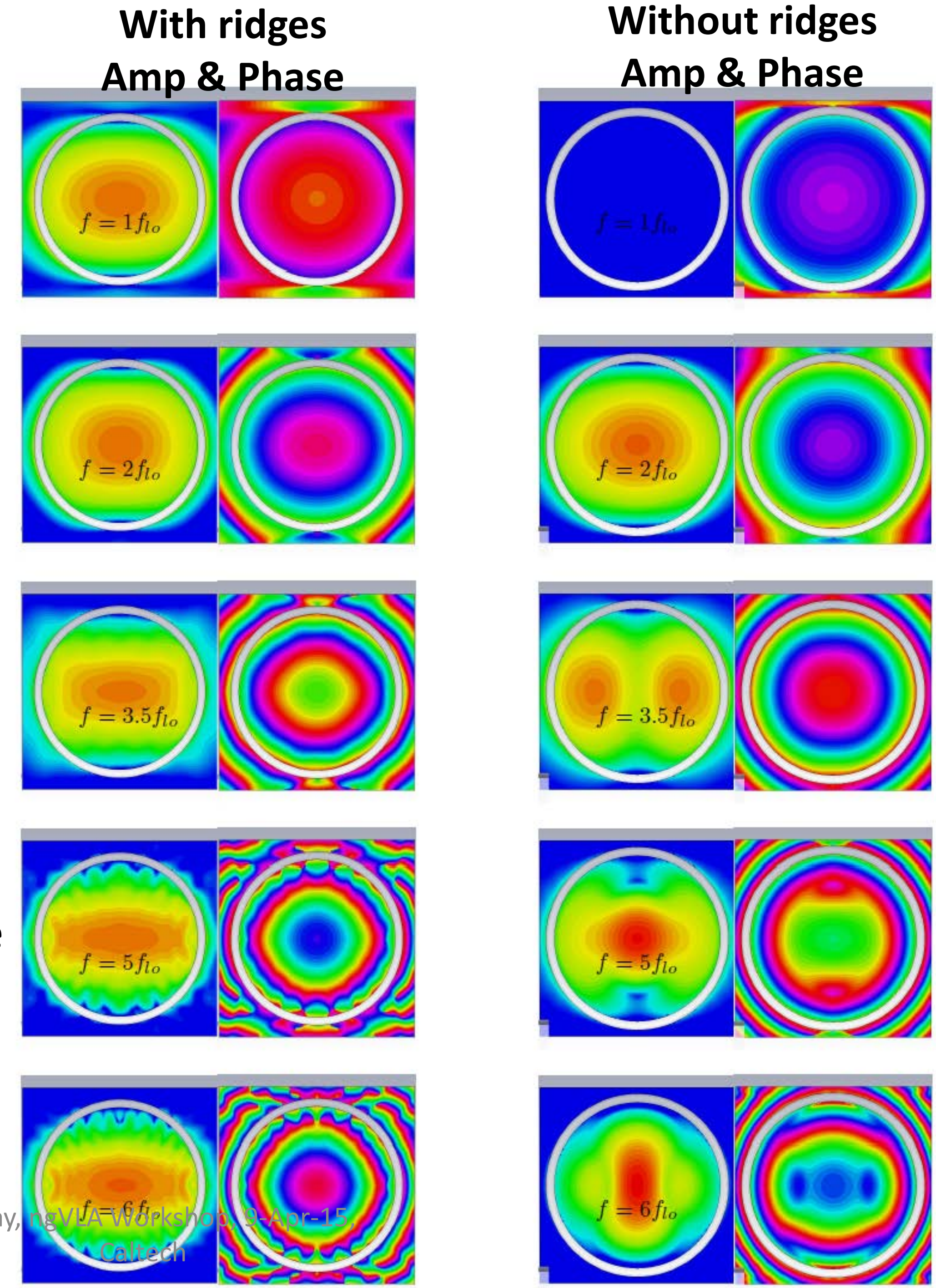
Ideally one needs the fractional aperture area with *uniform phase and amplitude* to reduce with frequency to achieve constant beamwidth.

In the QRFH:

1. area with uniform amplitude is fairly constant in the plane of the excited polarization

2. It's the area with uniform phase that shrinks considerably

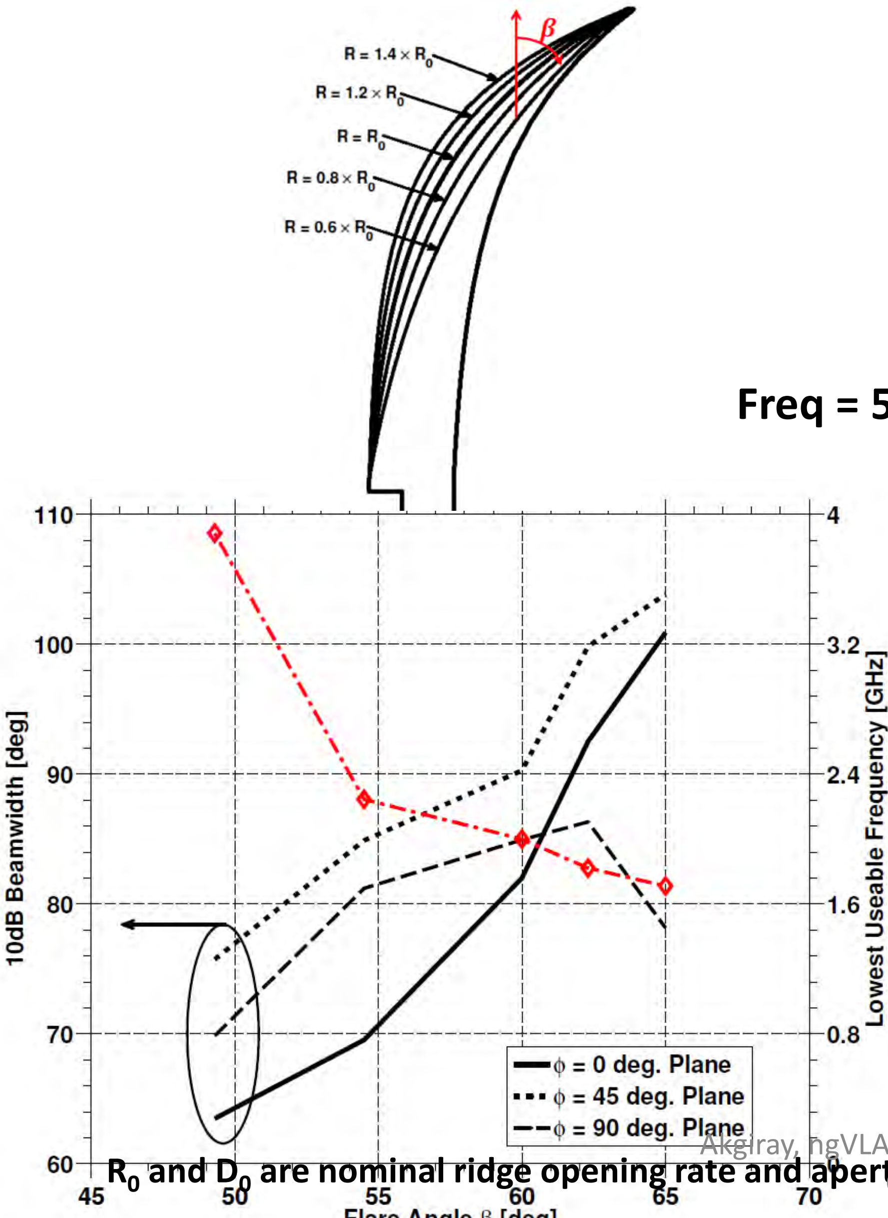
This suggests that the QRFH is a flare-angle limited horn…



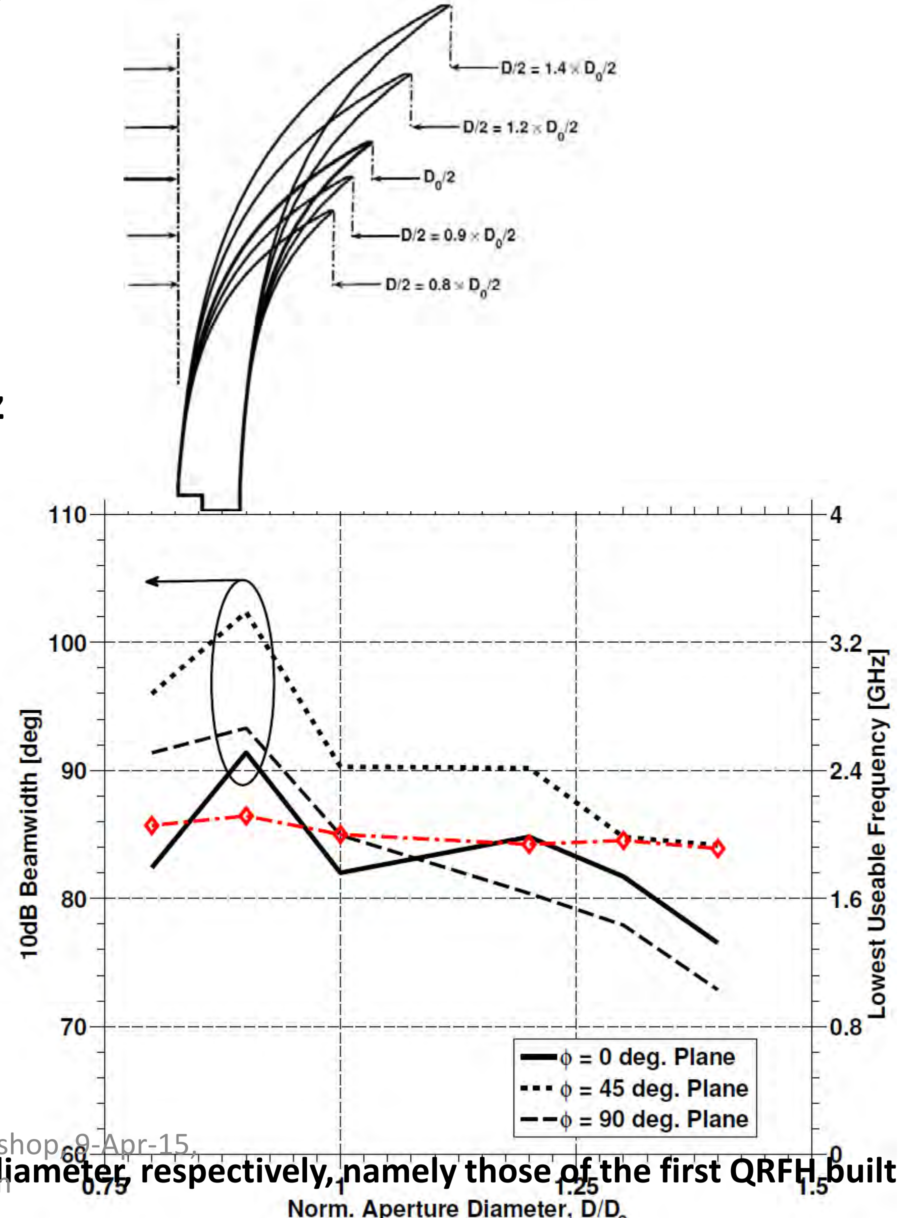
only x-directed aperture fields plotted

Ridge Profile Opening Rate vs. Aperture Diameter

QRFH: a flare-angle limited horn



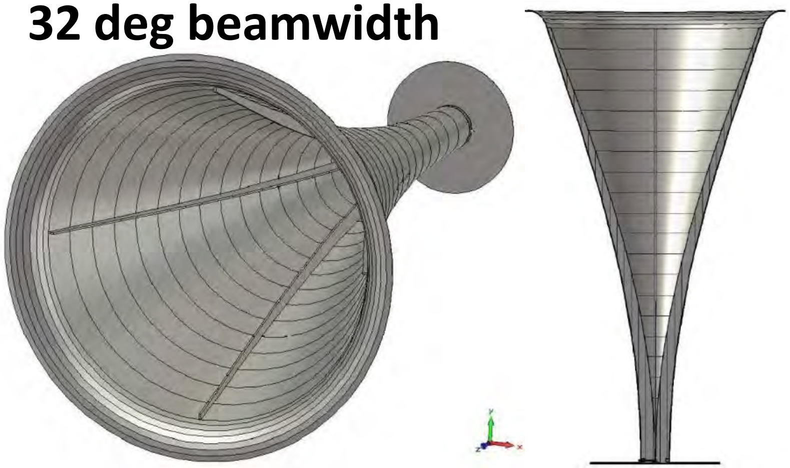
Freq = 5GHz



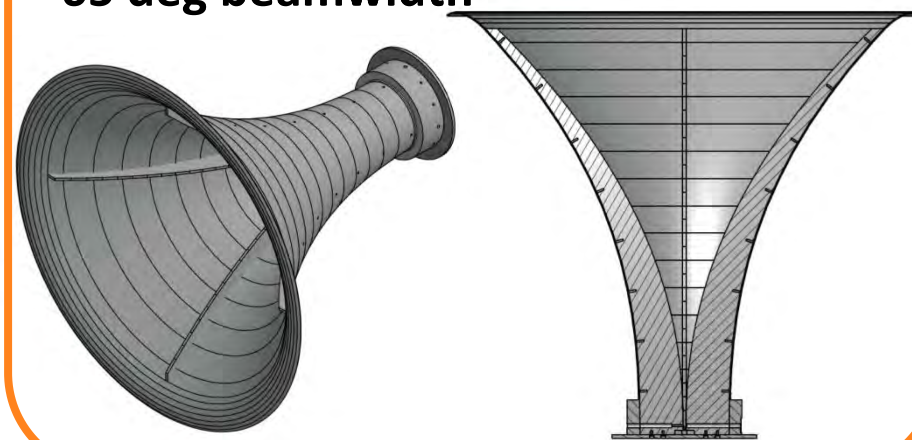
R_0 and D_0 are nominal ridge opening rate and aperture diameter, respectively, namely those of the first QRFH built

Geometries of Four QRFH Designs

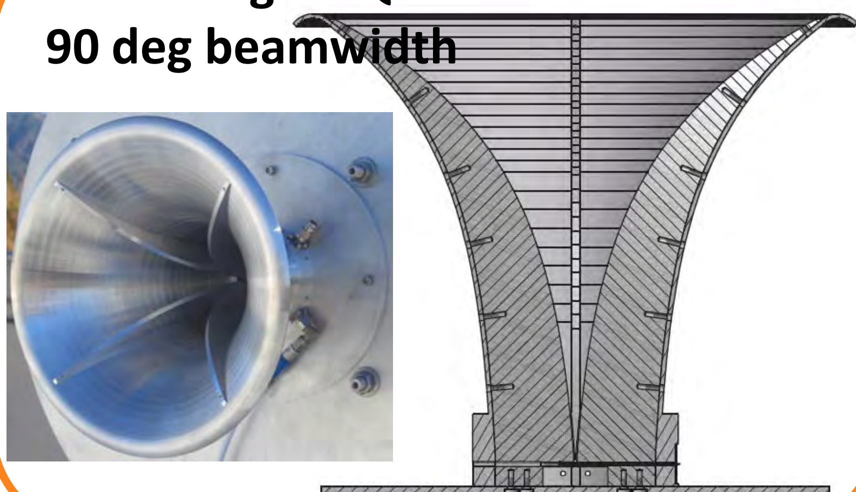
Very high gain QRFH
32 deg beamwidth



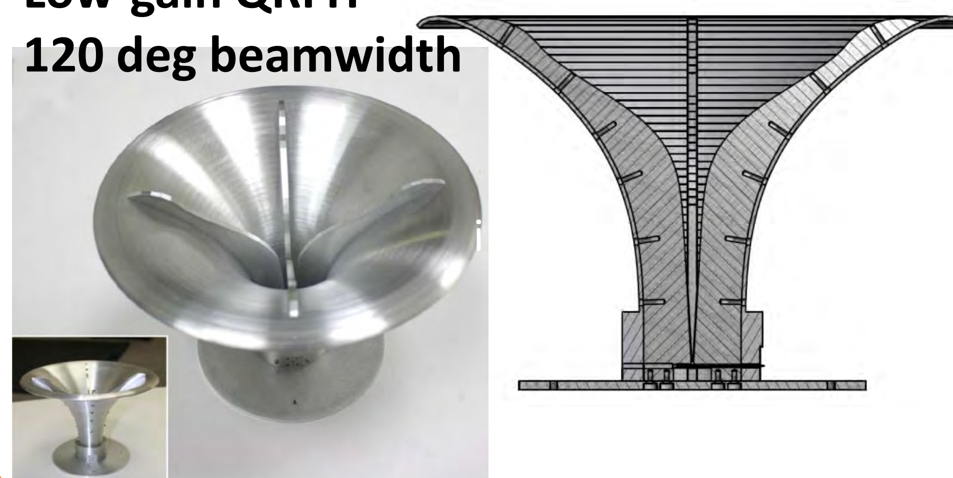
High-gain QRFH
65 deg beamwidth



Medium-gain QRFH
90 deg beamwidth



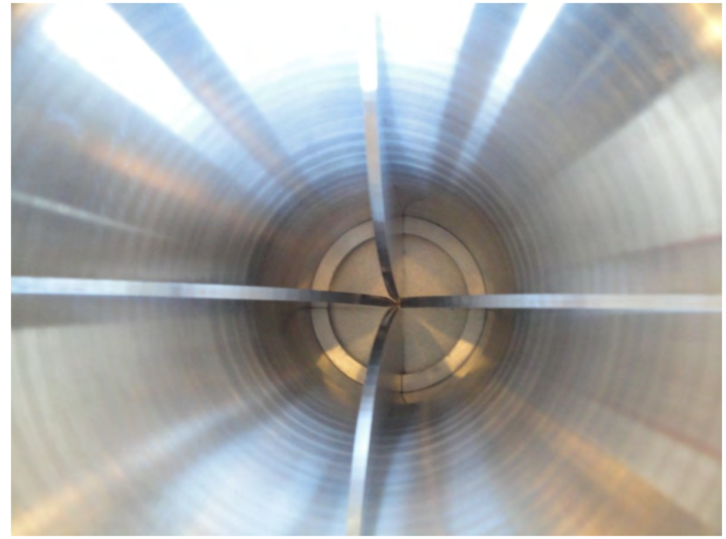
Low-gain QRFH
120 deg beamwidth

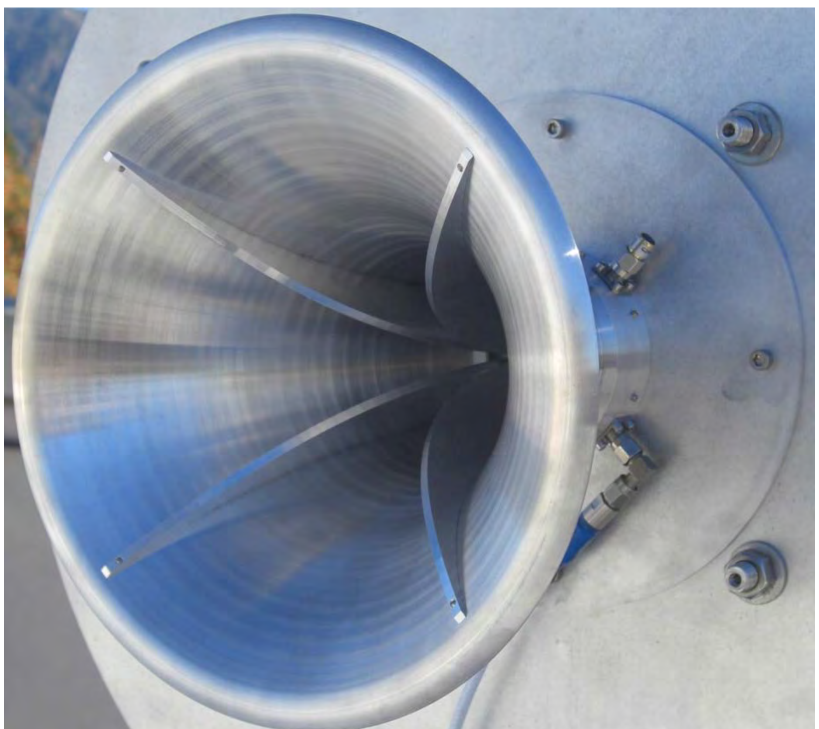


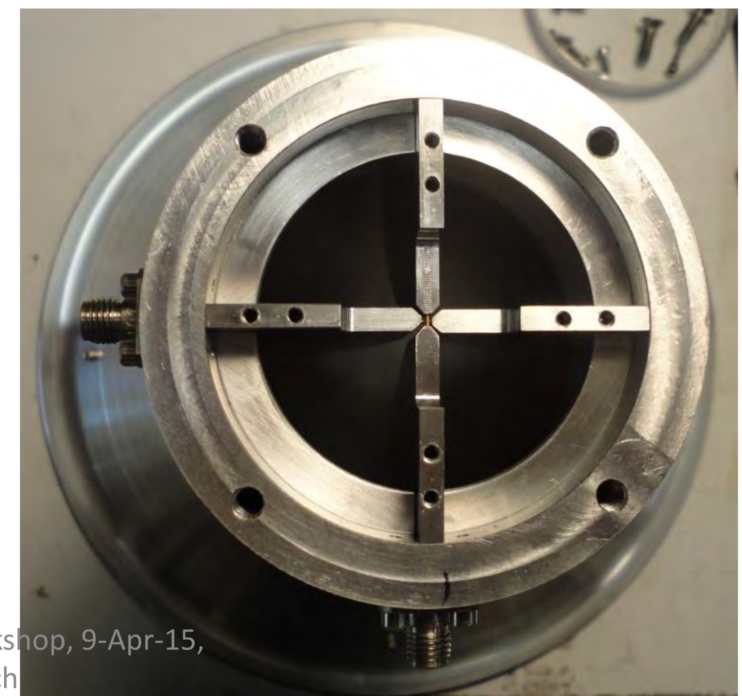
Drawings are on different scales

The First QRFH

Application:
Secondary focus operation on 12m Patriot/Cobham symmetric, shaped, dual reflector antennas of geodetic VLBI community
Target 10 dB beamwidth = ~ 85-90 deg
Target bandwidth = 2 – 12 GHz
Size = 18cm x 18cm x 17cm

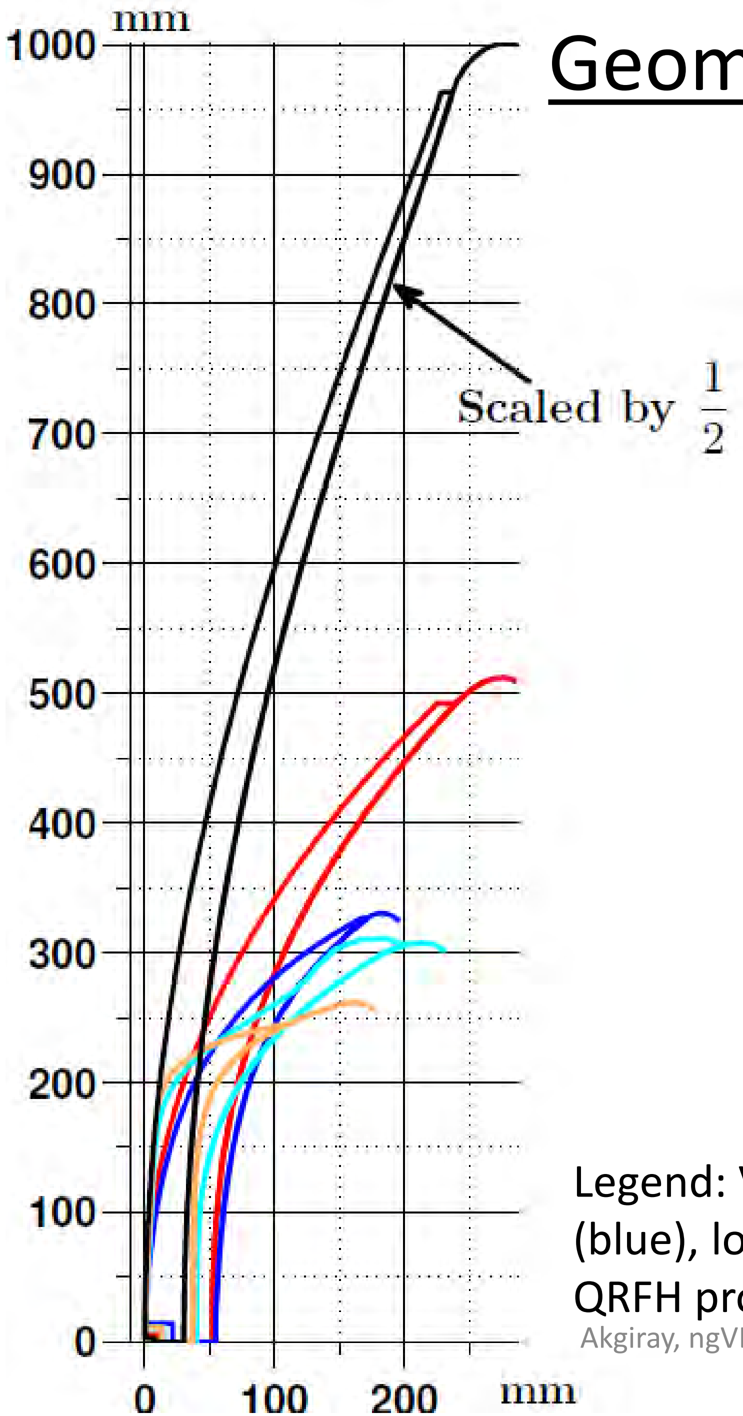






Geometries of Four QRFH Designs

Ridge Profiles



All horns are scaled such that their lowest frequency of operation is 1 GHz

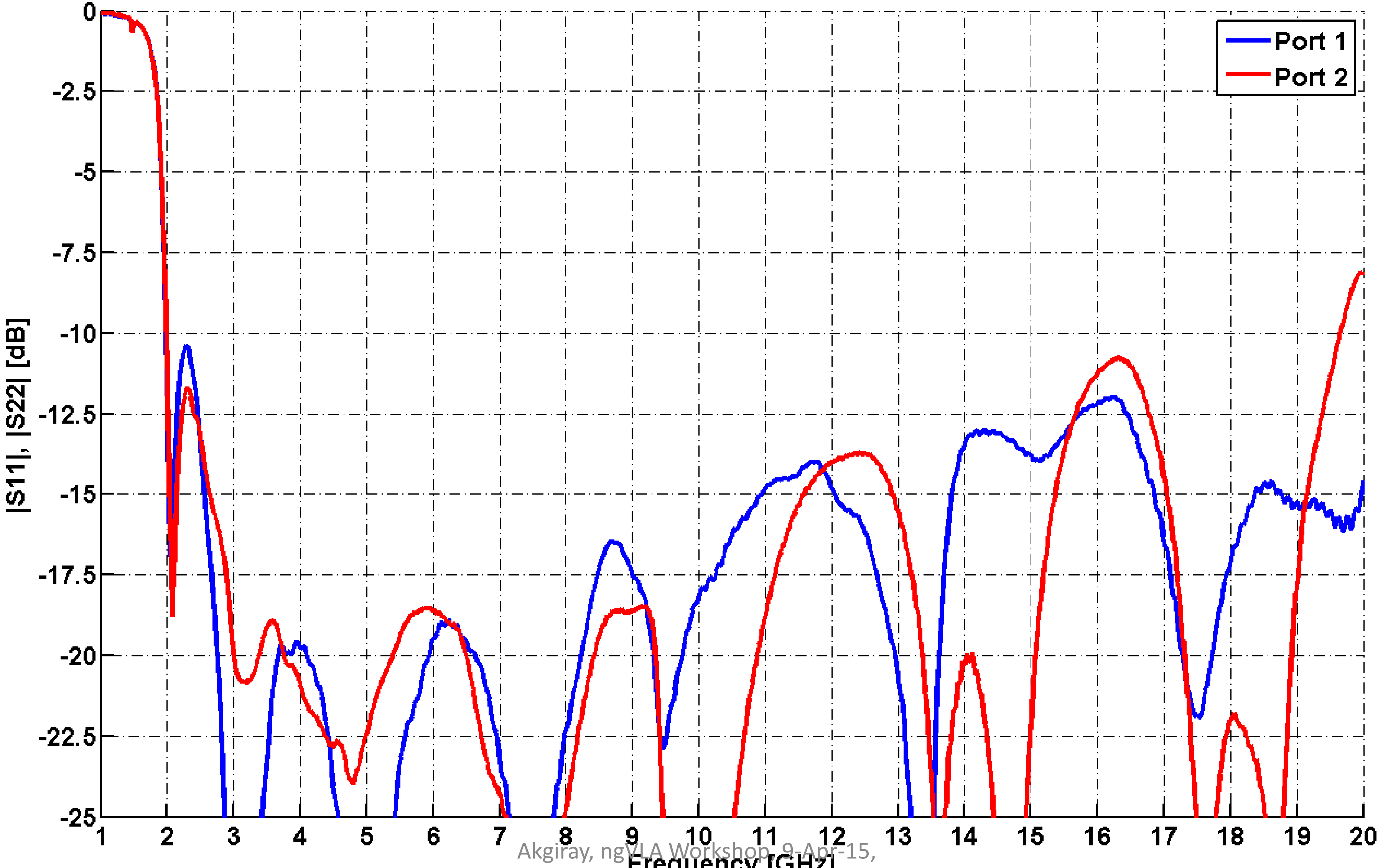
Note the enormous size of the very-high gain QRFH

These plots further underline importance of the flare angle

Legend: Very-high (black), high (red), medium (blue), low (turquoise), very-low (orange) gain QRFH profiles

Measurements

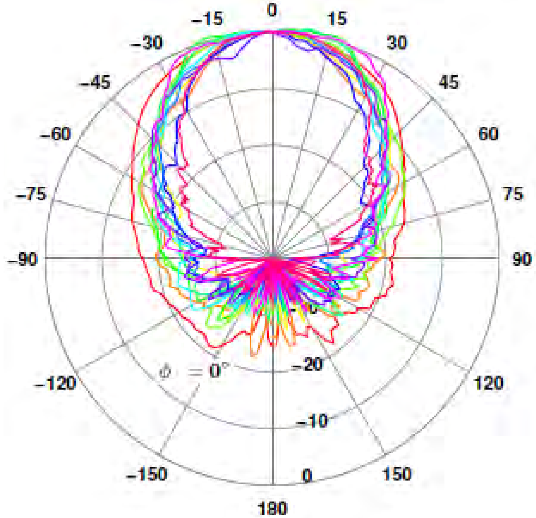
Return loss (Z_0 = 50 Ohm)

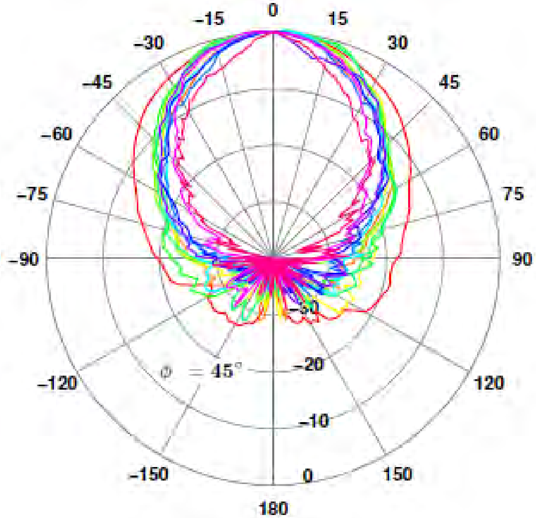


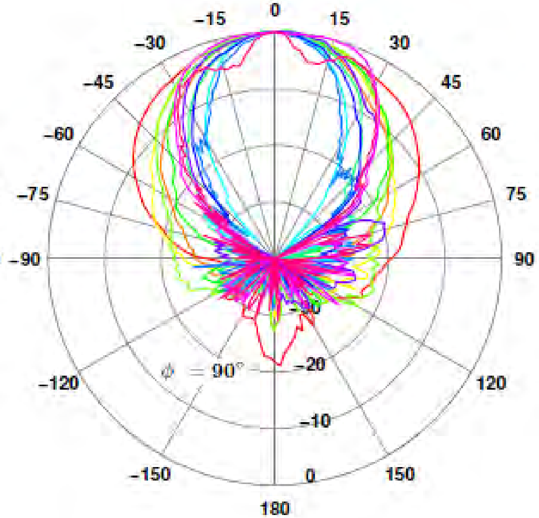
Far-field Patterns

Medium-gain QRFH, ***Measured***

Co-pol

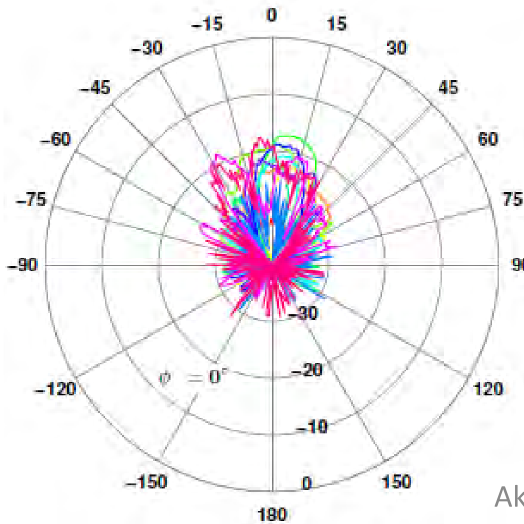


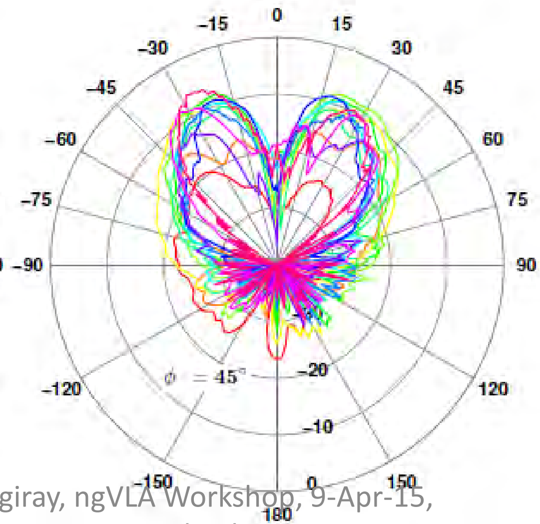


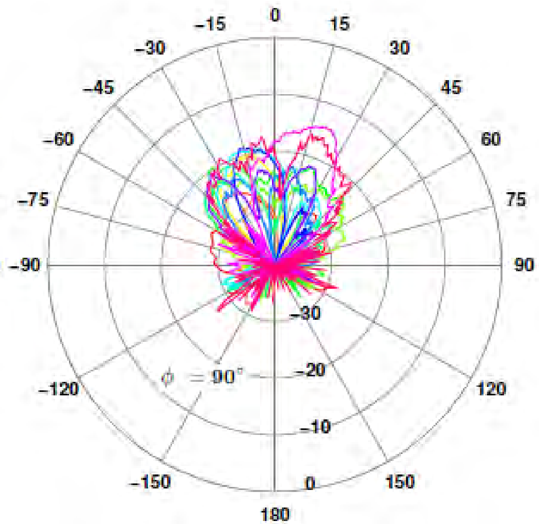


E-plane (ϕ=0 deg) **D-plane (ϕ=45 deg)** **H-plane (ϕ=90 deg)**

X-pol





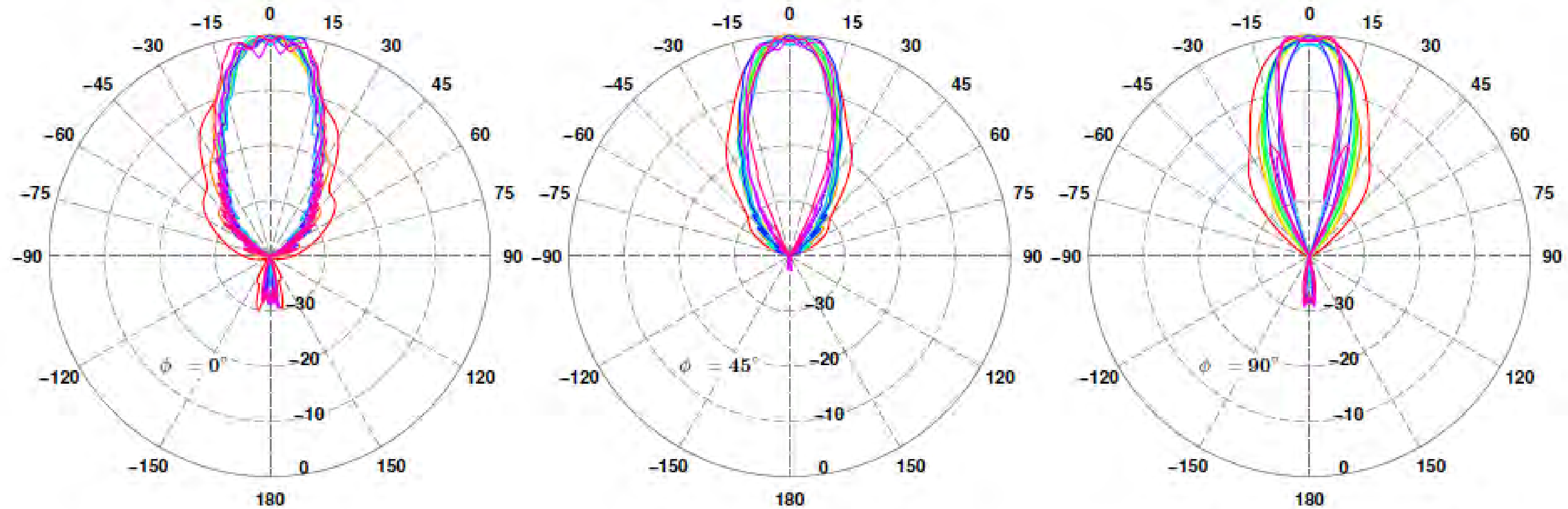


Normalized to boresight gain

Far-field Patterns

Very-high gain QRFH, Simulated

Co-pol



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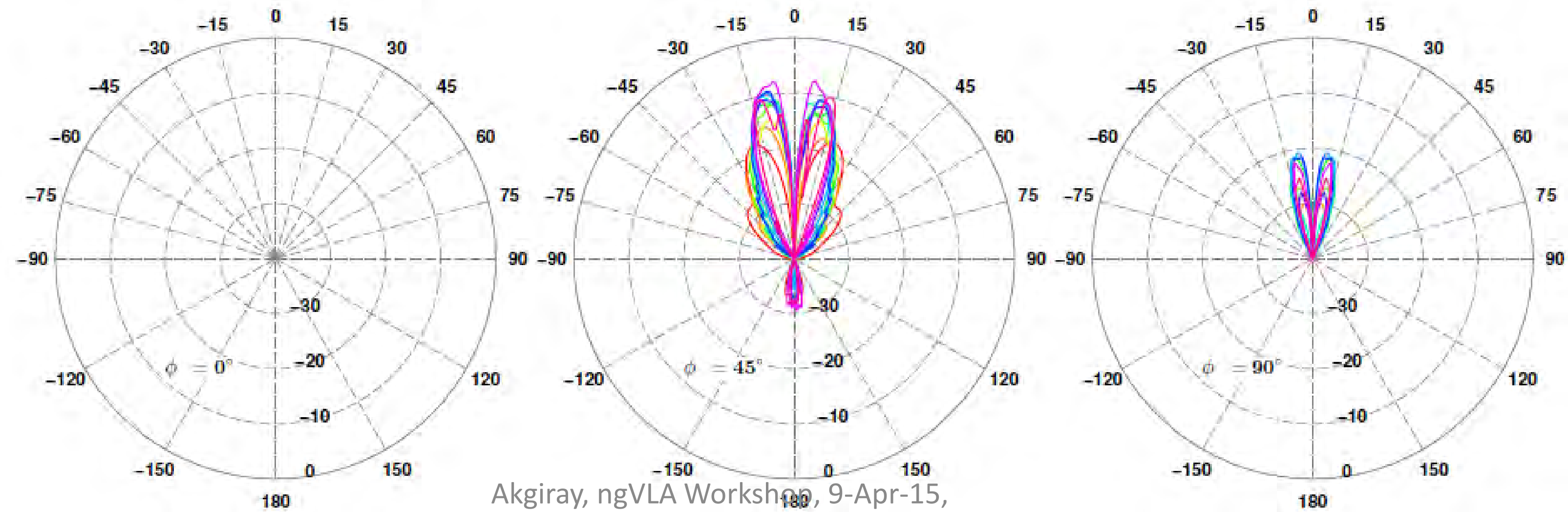
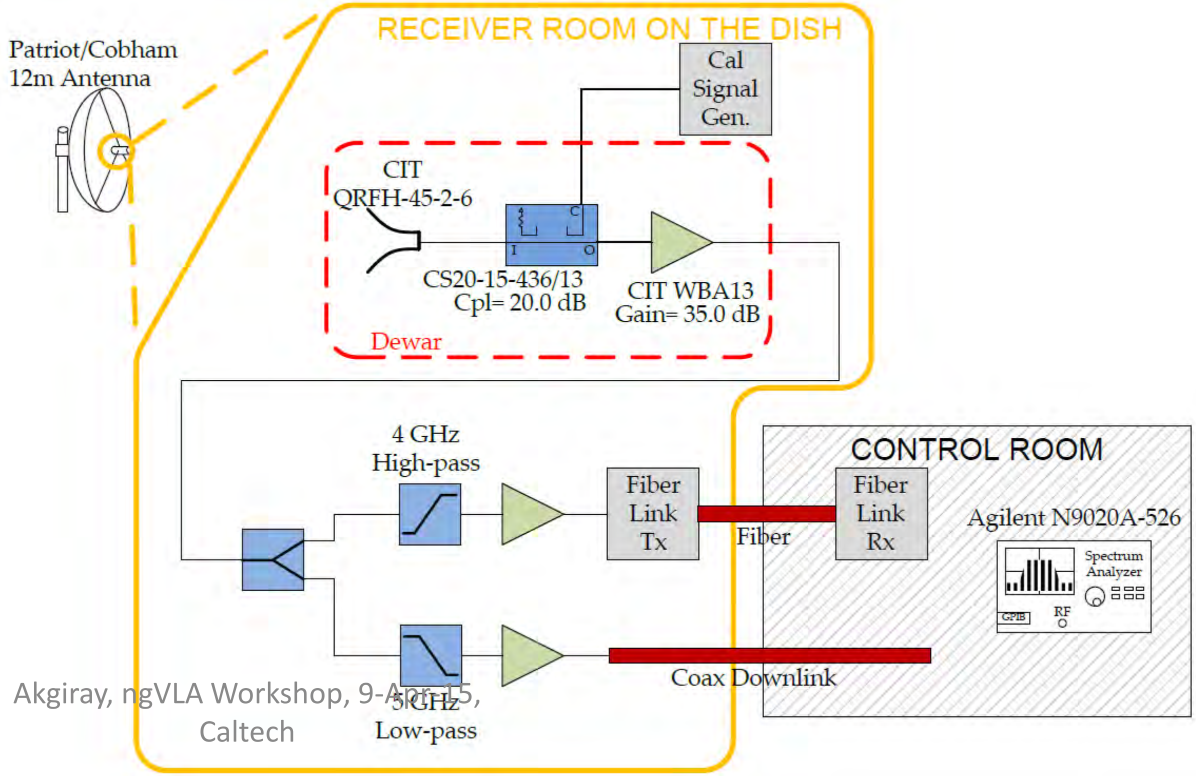


Normalized to boresight gain

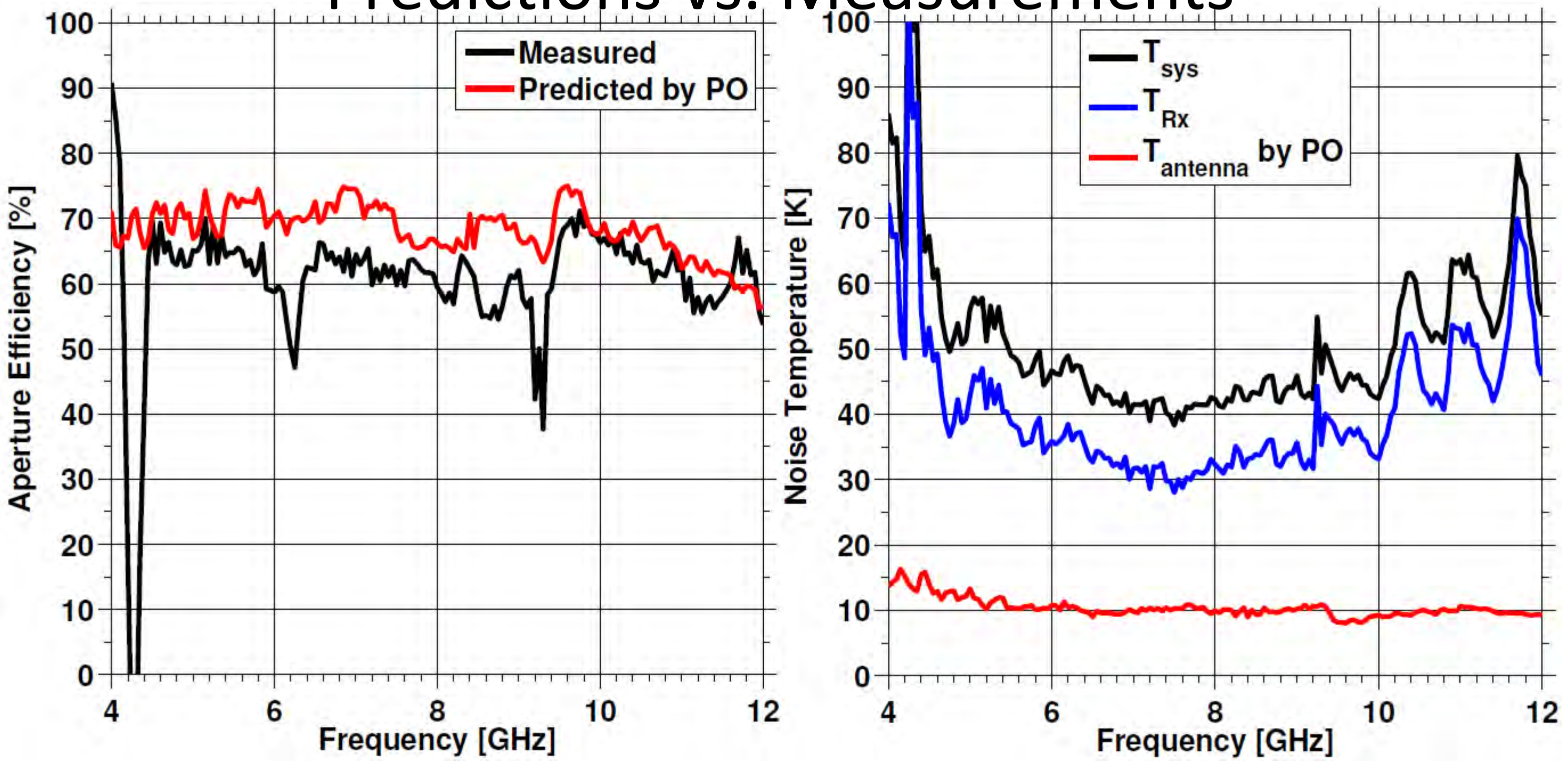
System Measurements with Medium-Gain QRFH

Block Diagram



System Measurements with Medium-Gain QRFH

Predictions vs. Measurements



Very good agreement for A_{eff}

Noise rise due to S-band filter roll-off Measured Tsys is >= 10 K higher. Difference is likely due to:

1. Strut scattering
2. Cryogenic losses unaccounted for in the analysis

T_{ant} calculated at 48deg elevation angle, measurements performed at 60 deg; feed position fixed for both measurements and simulations

Predicted aperture efficiency and antenna temperature are computed by W. Imbriale using physical optics. They don't include blockage, RMS surface error, mismatch, strut losses. G. C. Medellin, "Antenna noise temperature calculation," SKA Memo 95, 2007.

Current State of the Art

QRFH is a very attractive option

Type	Radiation pattern features	Typical aperture efficiency	Input Impedance	BW	Cost Estimate
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Sinuous feed	Mediocre beamwidth stability w/ **elliptical beam;** mediocre x-pol; const phase ctr; **tough to change beamwidth**	60%???	**260 Ohm differential**	4:1	Medium
QRFH	Good beamwidth stability in E&D planes; mediocre x-pol; small phase ctr variation; **can be designed for different beamwidths**	50-65%	**50 Ohm single-ended**	6:1-7:1	Low

Pros and Cons of QRFH for ngVLA

- ✓ Flexible feed that doesn't restrict dish f/D
- ✓ Good 10 dB beamwidth stability in two of three principal planes
- ✓ Good return loss performance and polarization iso
- ✓ Cheap and easy to fabricate and very low maintenance
- ✓ Requires 2 single-ended LNAs

— Scaling QRFH flo to > 4 GHz => new excitation mechanism needed => a challenge but also an opportunity to integrate feed + LNA?

Future work:

1. Unlike freq-independent antennas, constant beamwidth is achieved by waveguide modes (like a corrug horn) => better understanding of these will yield better designs
2. Some effort ongoing on dielectric-filled QRFH, even better beamwidth stability perhaps?

P A

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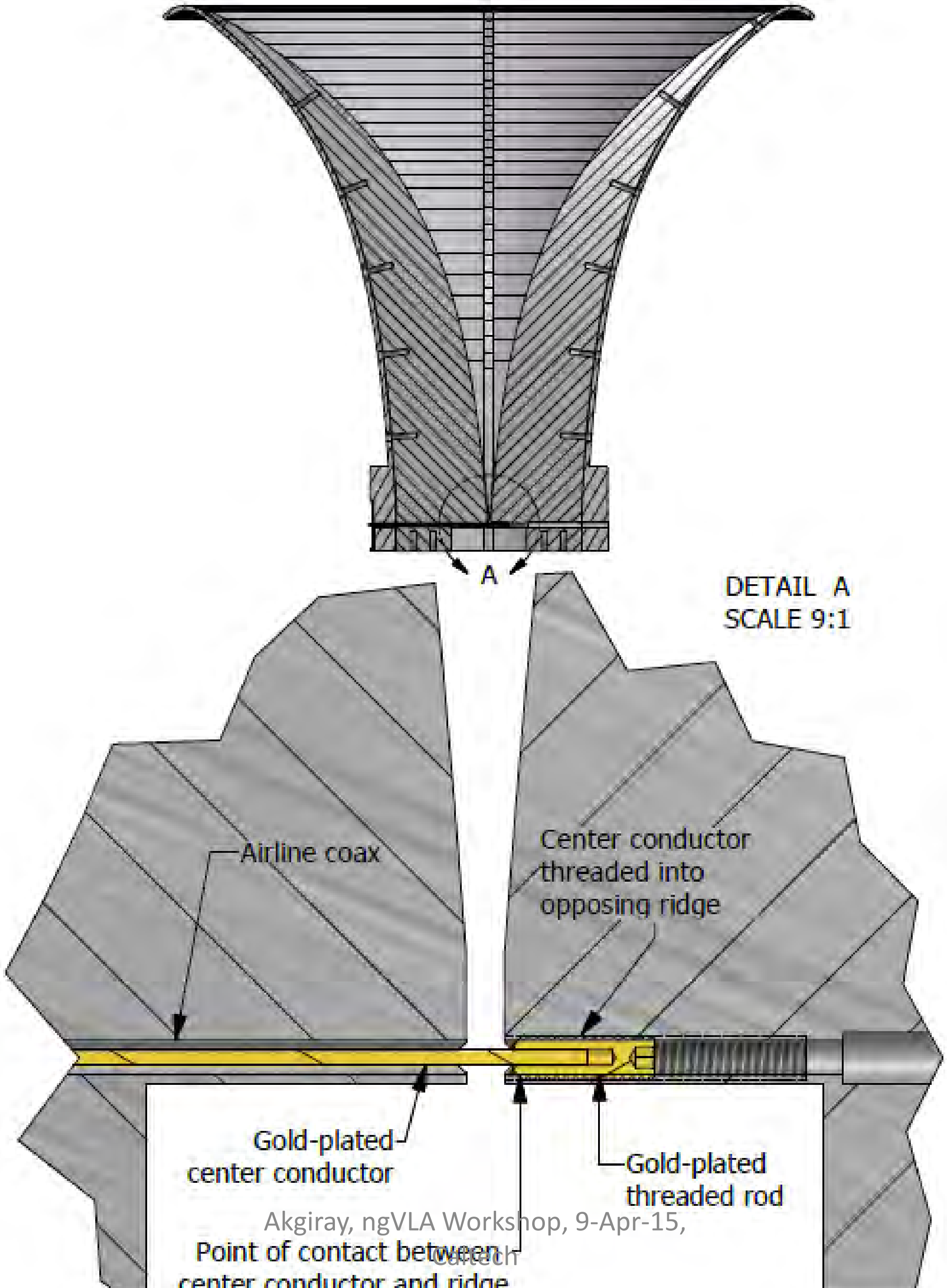

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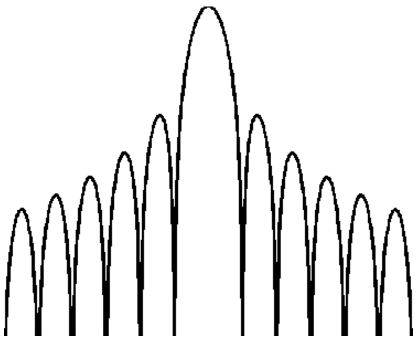
BACKUP MATERIAL

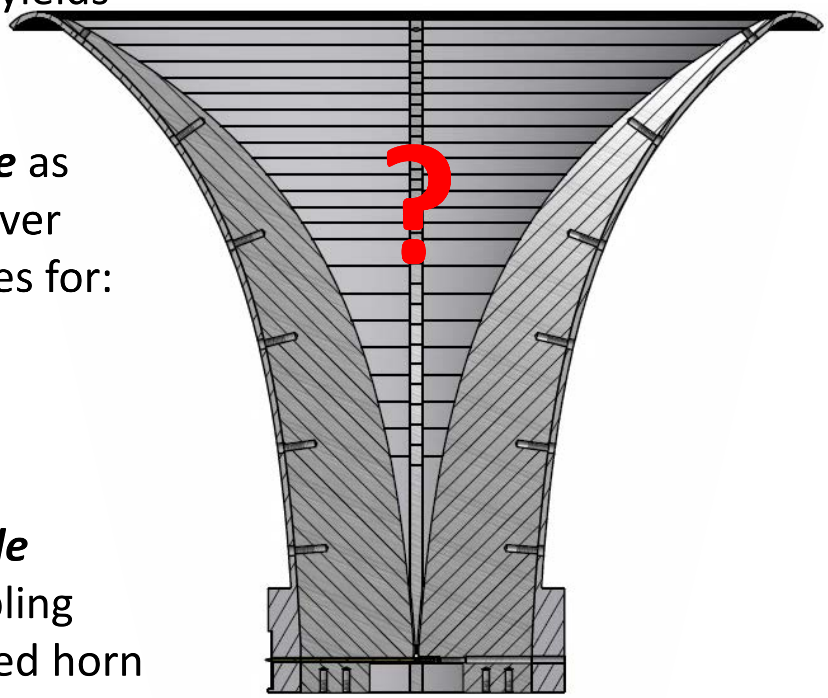
QRFH Modal Analysis

Missing link between far-fields and excitation

Having established confidence in our simulations, still no idea what exactly goes on in the horn. To pursue this, we take two *parallel* approaches:



1. ***Express far-field patterns in terms of radiation patterns of circular waveguide modes***. QRFH aperture is circular with no ridges; hence, radiated field can be written in terms of circular WG mode patterns. This method yields the mode content at the aperture of the horn;



2. ***Calculate modes of quad-ridge circular waveguide*** as ridge thickness and ridge-to-ridge gap are varied over parameter range of interest. Use these eigenmodes for:
   a. mode matching
   b. expressing simulated total electric field along z=constant planes

Goal: empirical relation btw. ridge slope and mode coupling (closed form eqns exist giving mode coupling coeff as a function of smooth-walled and corrugated horn profile slope)

QRFH Modal Analysis

Modes at the aperture

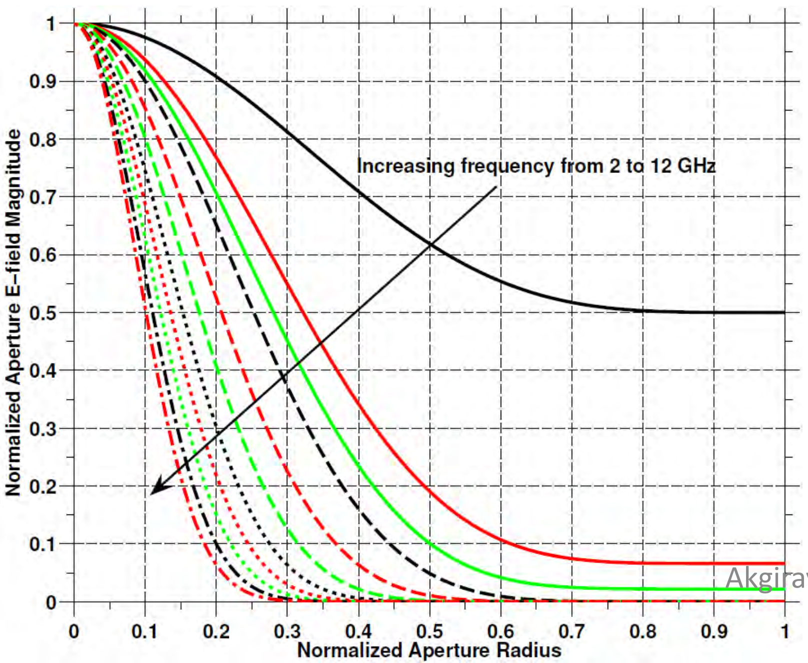
Idea: Express far-fields of QRFH as a superposition of radiation patterns of circular waveguide modes.

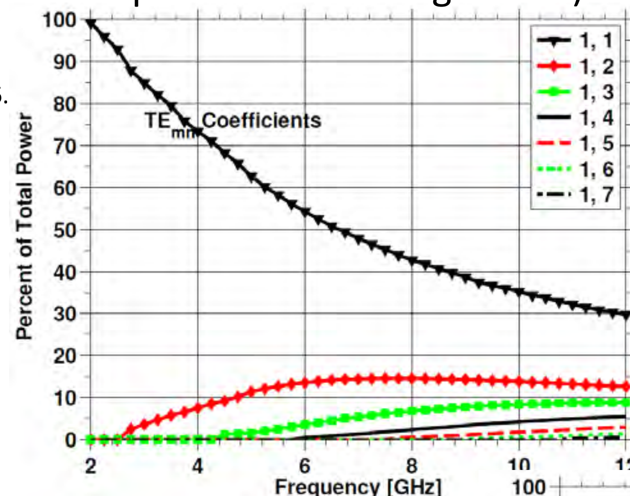
Theory: Far-zone radiation patterns of all modes that can propagate in a circular waveguide are expressed in close-form equations [1,2]

Assumptions in theory: Large circular aperture compared to wavelength => 1) uniform phase front is planar; 2) reflections are ignored

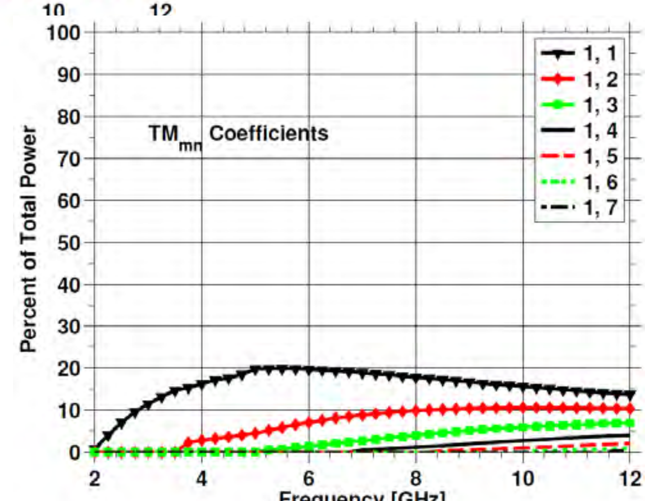
[1] A. C. Ludwig, IEEE Trans. Antennas Propag., vol. AP-14, no. 4, Jul. 1966.
[2] Waveguide Handbook, MIT Rad Lab Series

Normalized aperture field distribution to achieve constant 90deg 10dB beamwidth & circular beam; uniform phase assumed





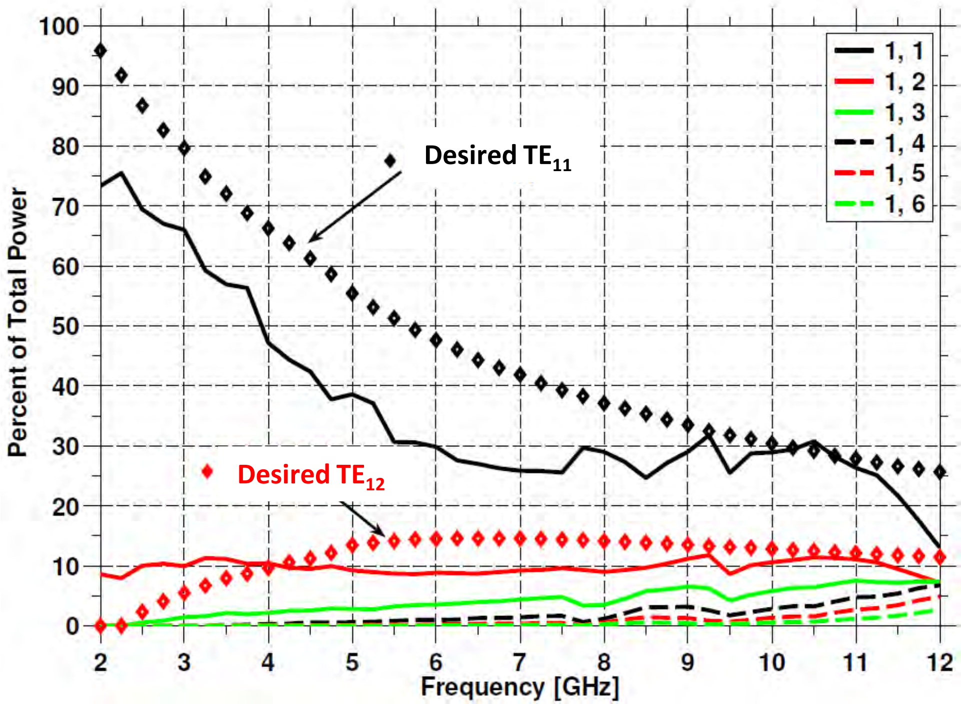
Req'd modes



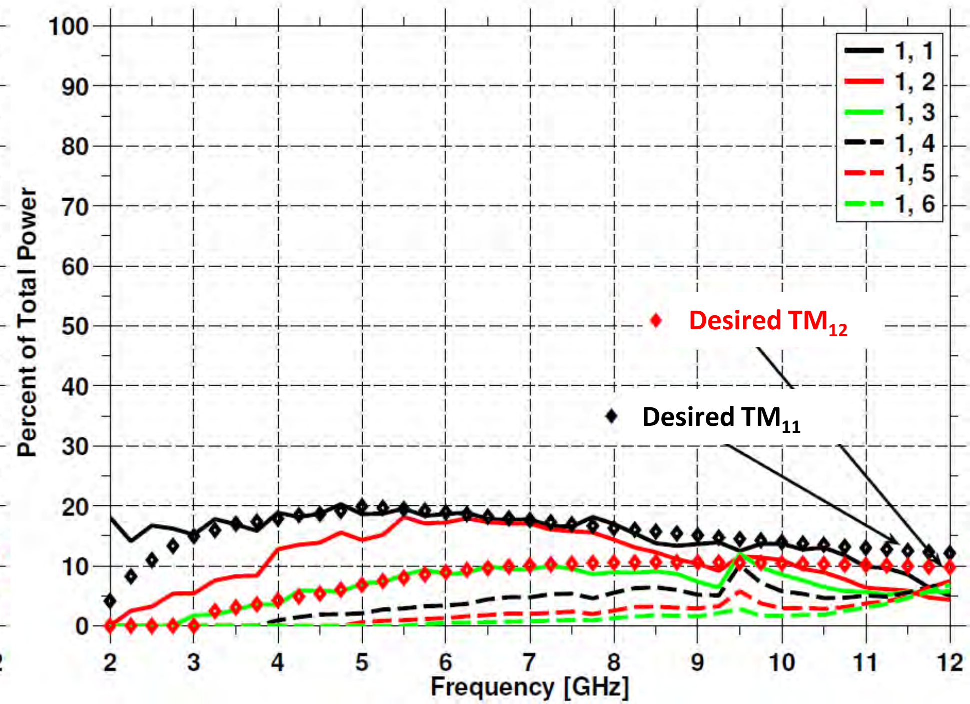
QRFH Modal Analysis

Modes at the aperture of 1st QRFH

Realized TE modes



Realized TM modes



- QRFH comes close to achieving desired mode distribution.
- Note the lack of even-order modes
- TE12 present at aperture below 7 GHz=> generated thru ridge/sidewall profile

Plots use simulated patterns due to higher azimuthal resolution

QRFH Modal Analysis

Mode coupling in the horn

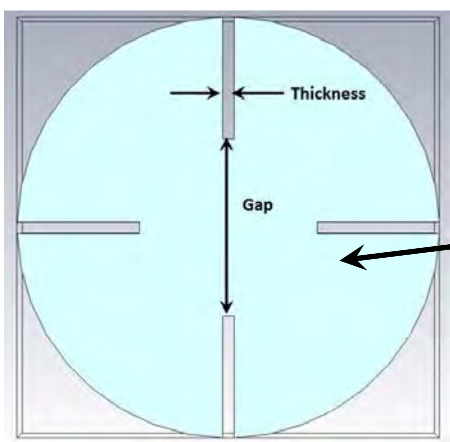
Procedure: Numerically calculate modes of quad-ridge circular waveguide as ridge thickness and ridge-to-ridge gap are swept from 0.02 to 0.25 and 0.02 to 2, respectively (normalized to waveguide radius => gap = 2 means hollow circ WG)

Primarily interested in TE_{1x} and TM_{1x} modes with x = 1, 2, 3, 4.

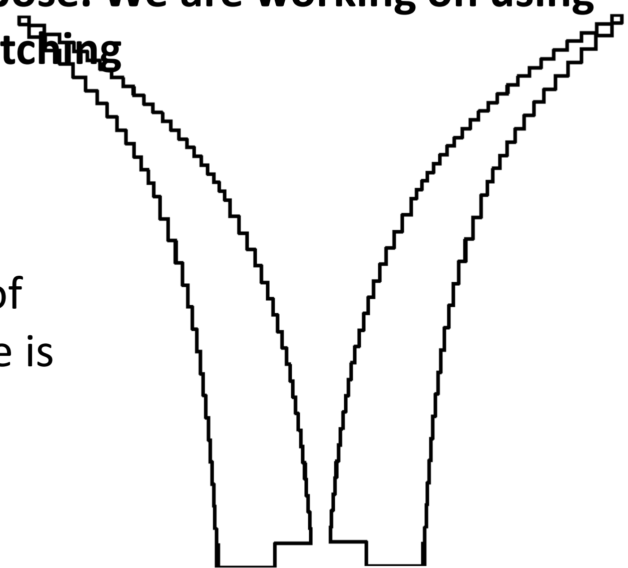
Goal: mode matching, or an equivalent, to obtain relationship between ridge/sidewall profile and mode conversion in horn

Calculating eigenmodes of structure easier said than done, even with commercial EM packages!!

=> I have been collaborating with Prof. Bruno and E. Akhmetgaliyev of Applied Math @ Caltech; a special mode solver has been written for this purpose. We are working on using that to understand mode coupling and implement mode matching

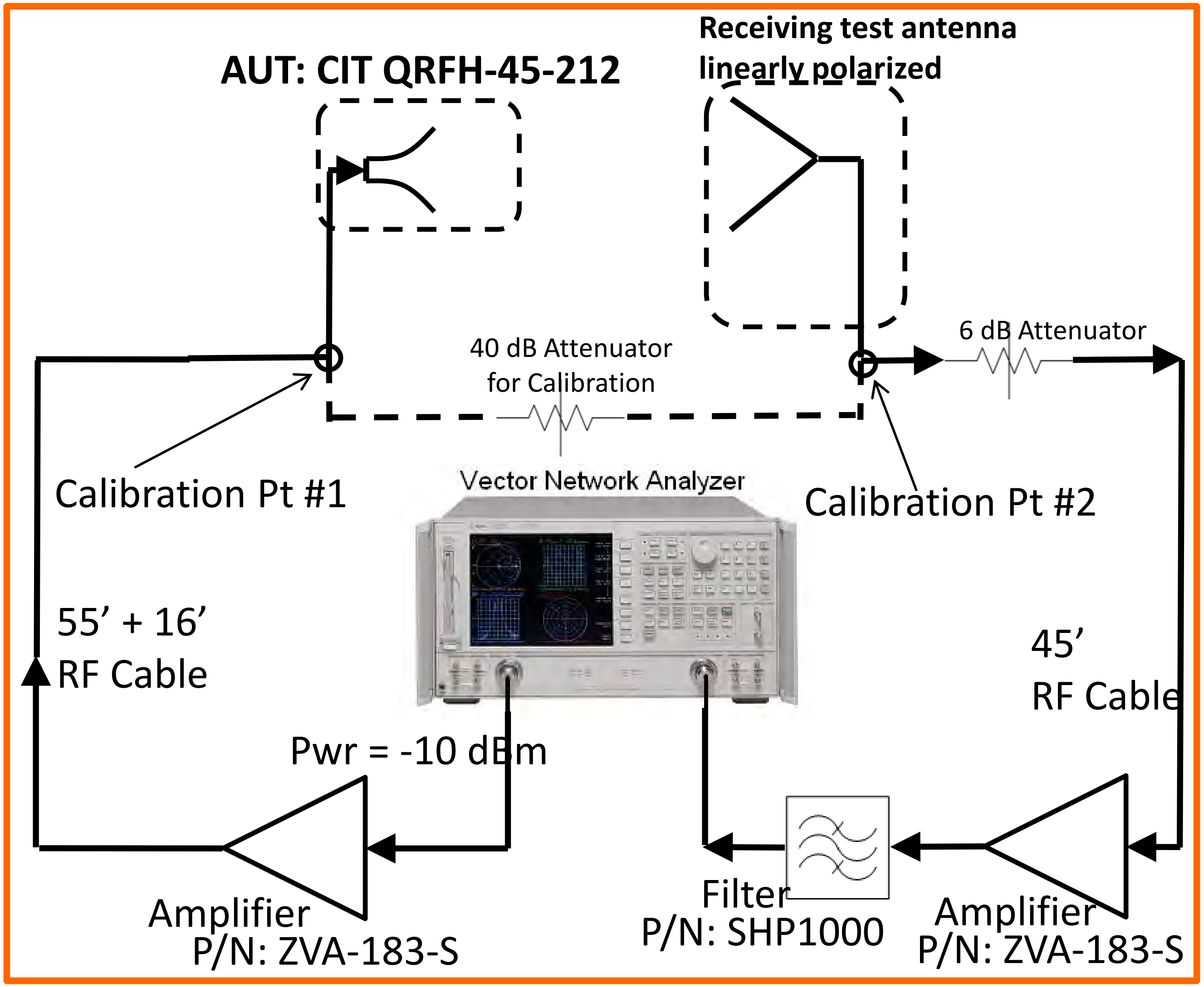


Light green region is interior of waveguide, surrounding space is filled with PEC



Measurements

Pattern Setup (I)



Patterns measured -180 to +180 degrees in 1 degree step (in the main beam) from 1 to 17 GHz in 40 MHz steps

Both co- and cross-polarized patterns collected in E-, D-, and H- planes (ϕ = 0, 45, 90 degrees, respectively)

Measurement repeated on both ports (Port 1 closer to back of feed)

VNA configuration:

Start Freq: 1 GHz

Stop Freq: 17 GHz

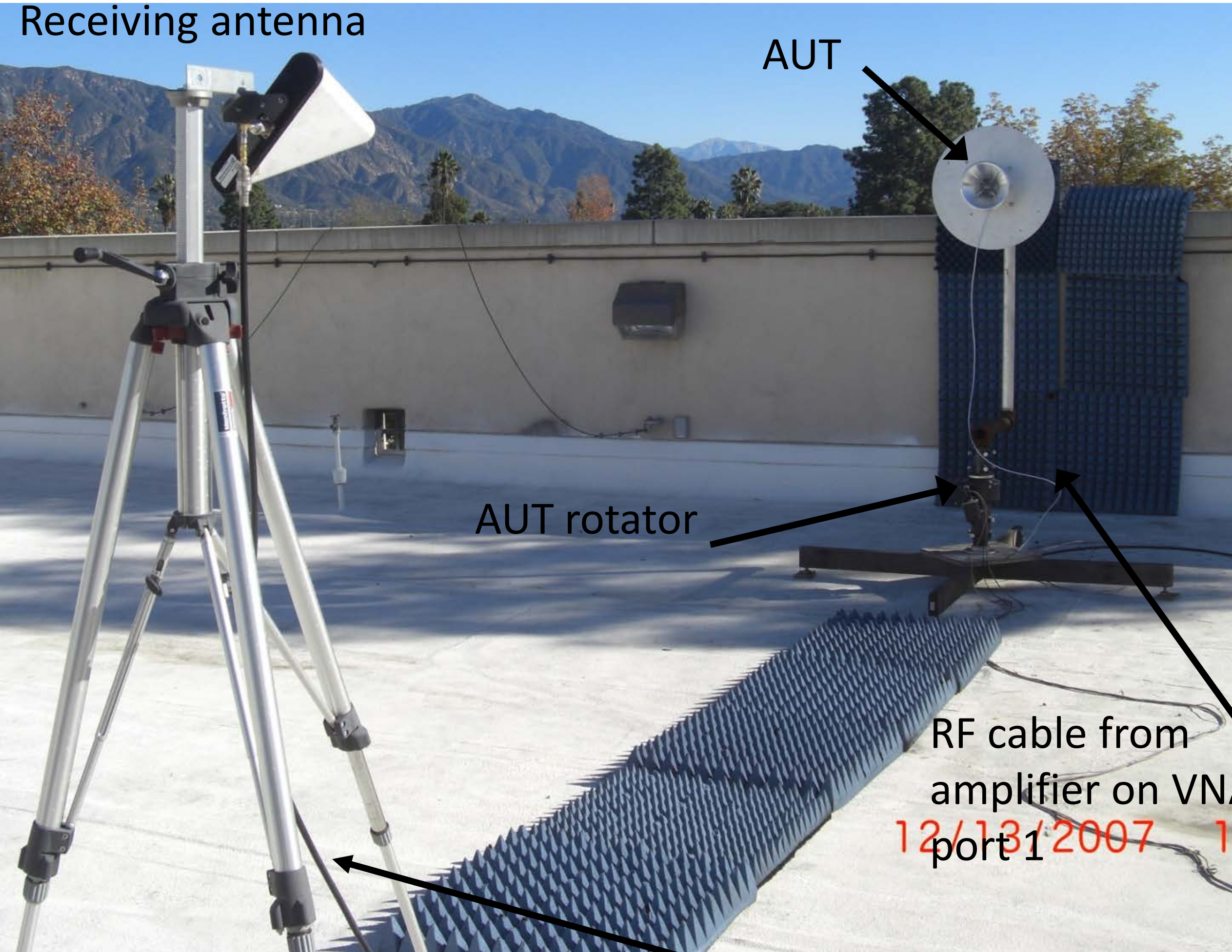
Number of points: 401

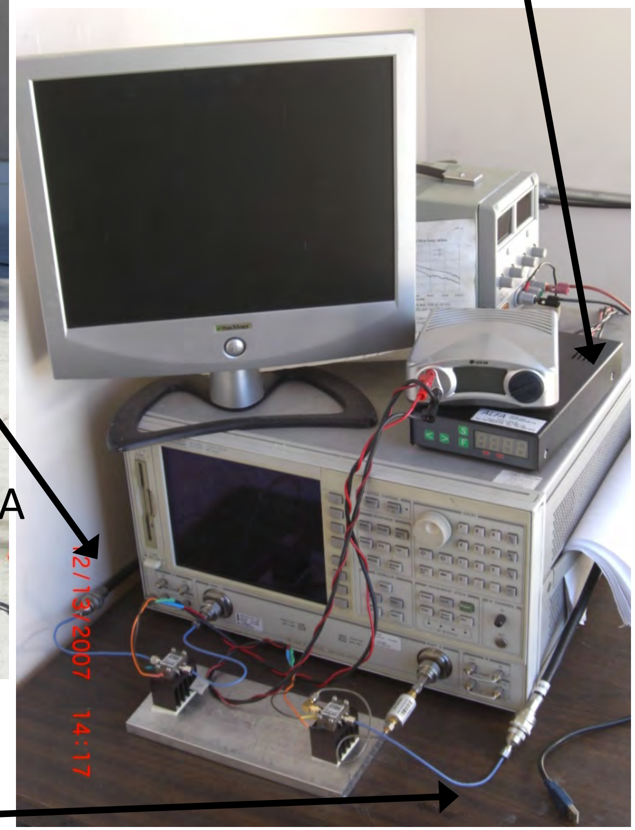
IF BW: 100 Hz

Output power = -10 dBm

Measurements

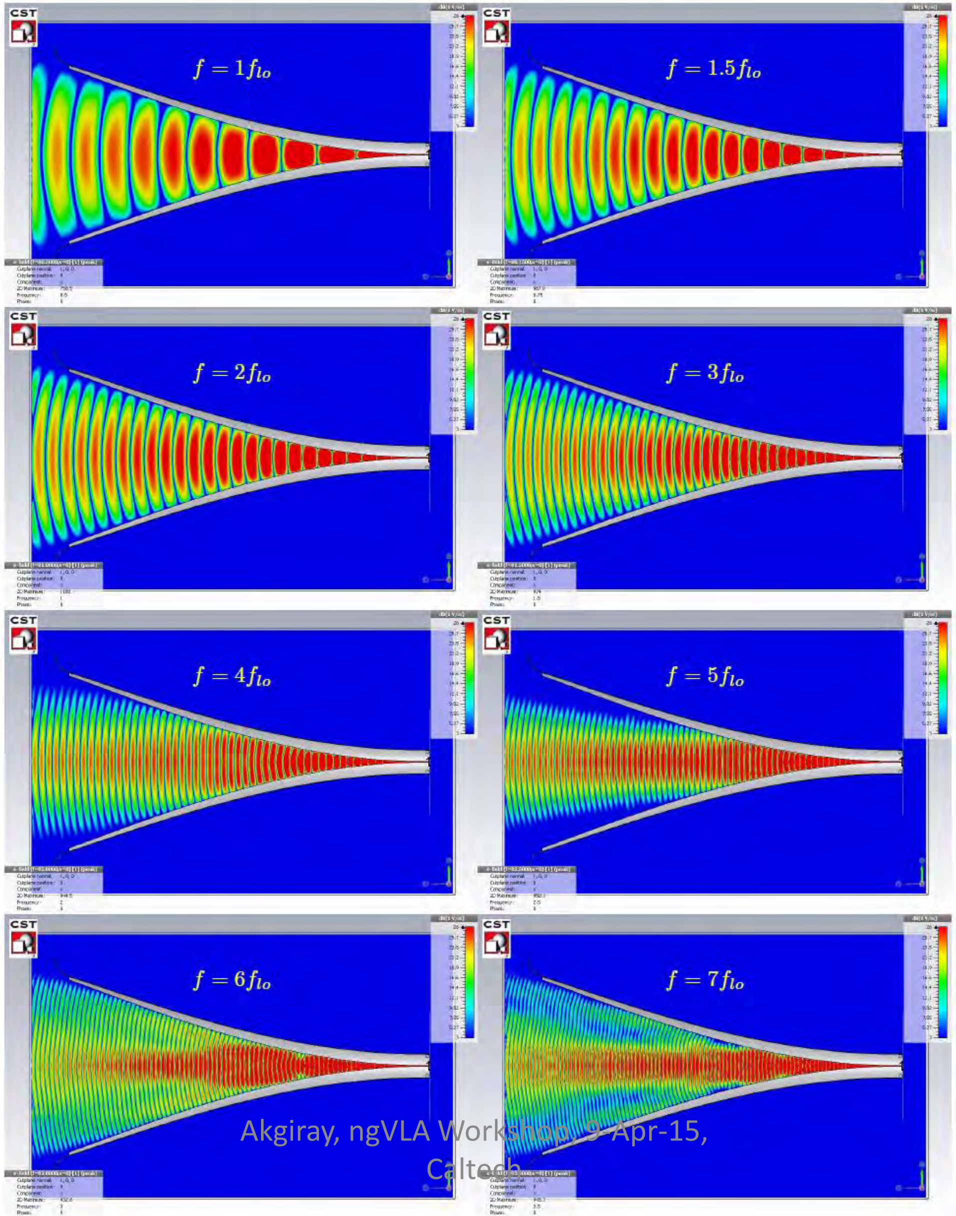
Pattern Setup (II)





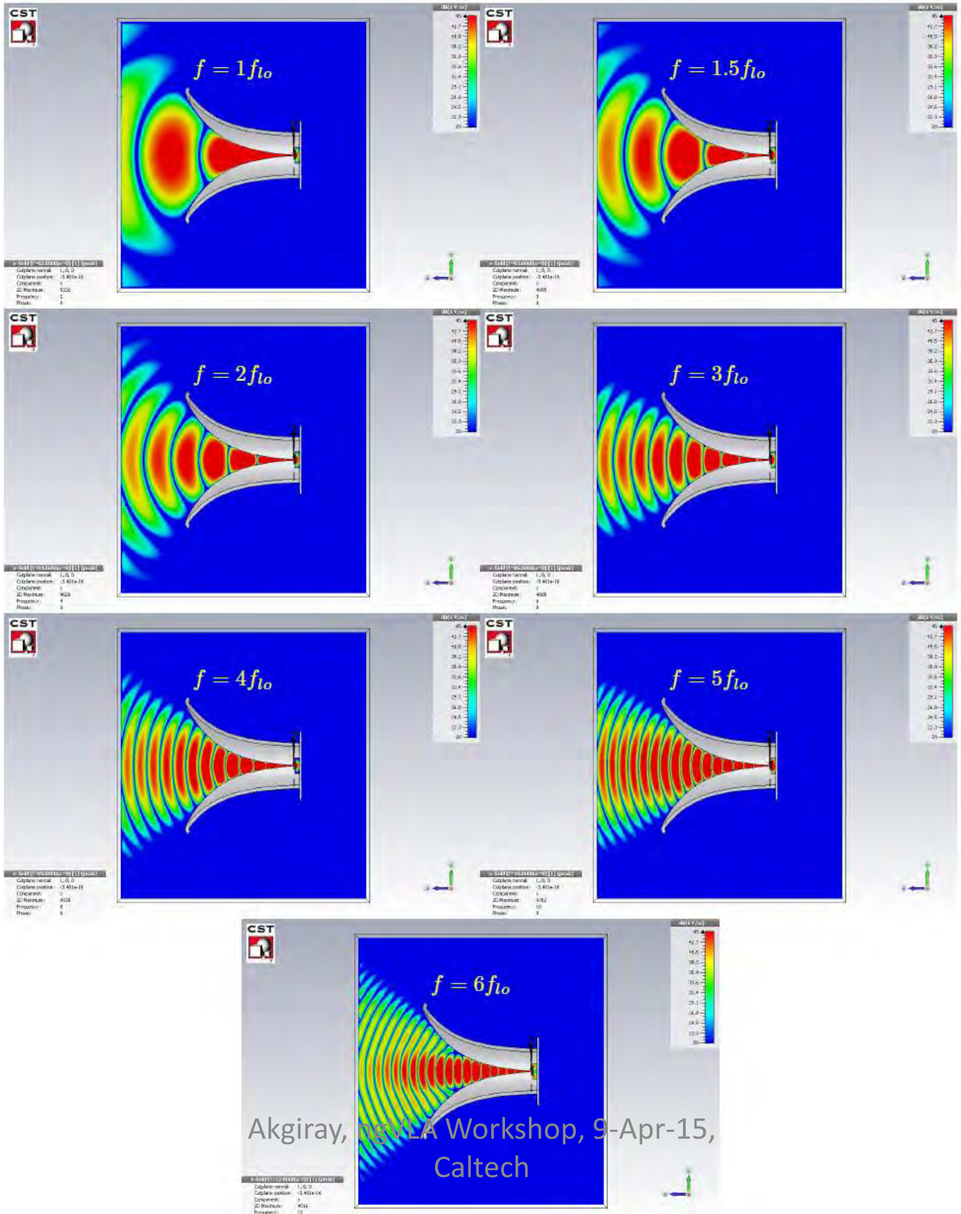
Field Propagation Through the QRFH

Very-high gain QRFH



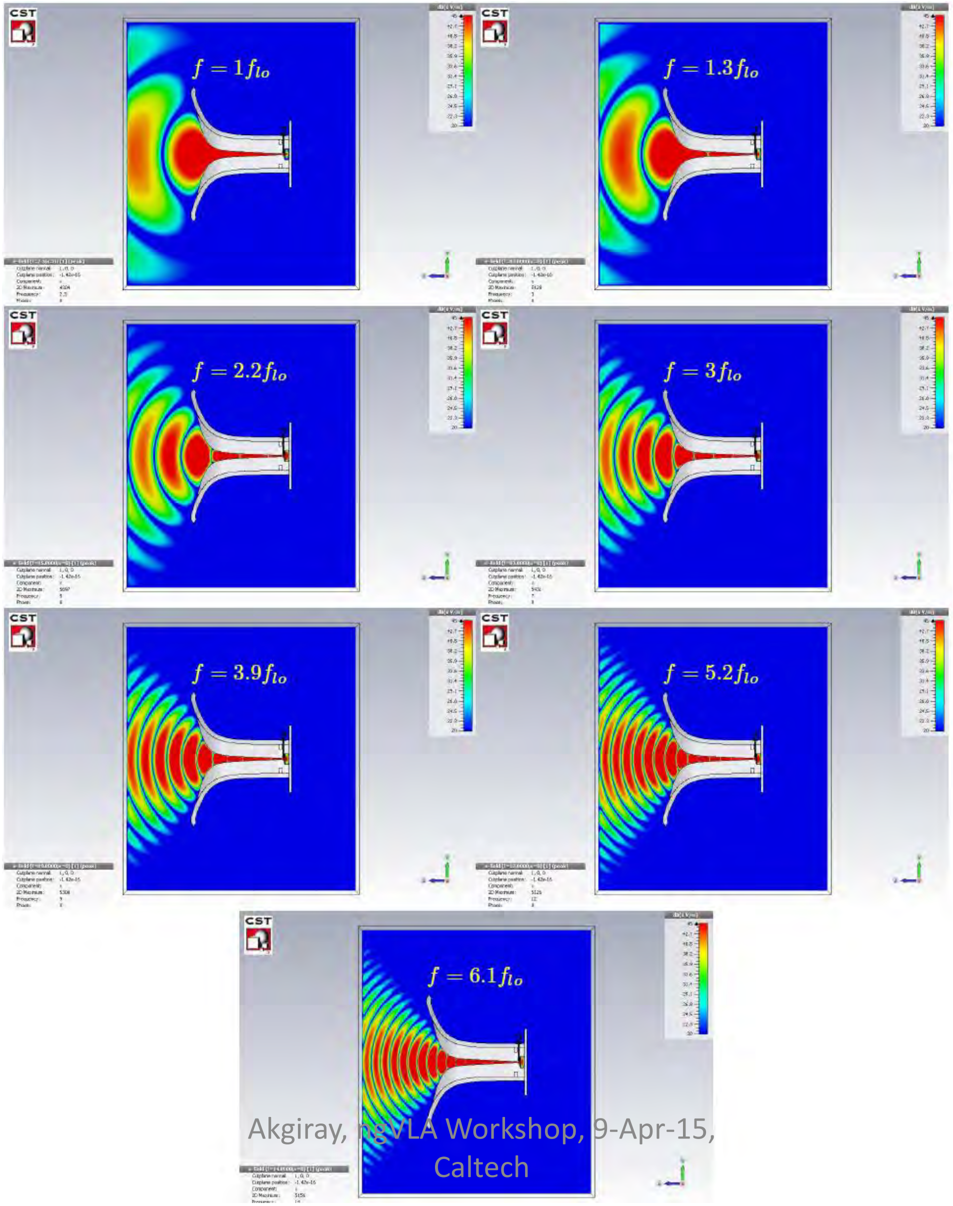
Field Propagation Through the QRFH

Medium gain QRFH (first one to be built)



Field Propagation Through the QRFH

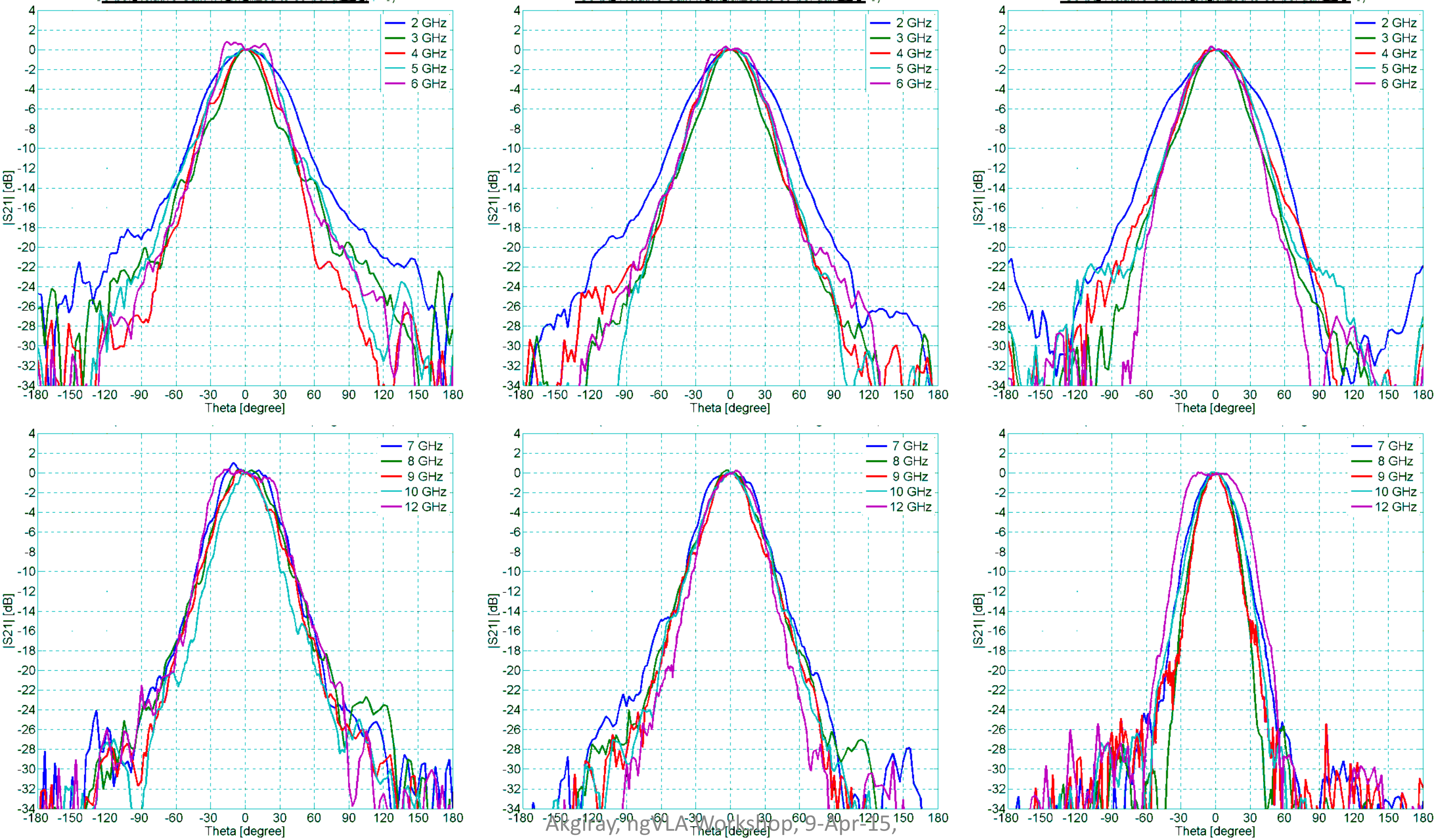
Very-low gain QRFH (square)



Measurements

Radiation Patterns, Co-pol

E-plane (ϕ=0 deg) **D-plane (ϕ=45 deg)** **H-plane (ϕ=90 deg)**

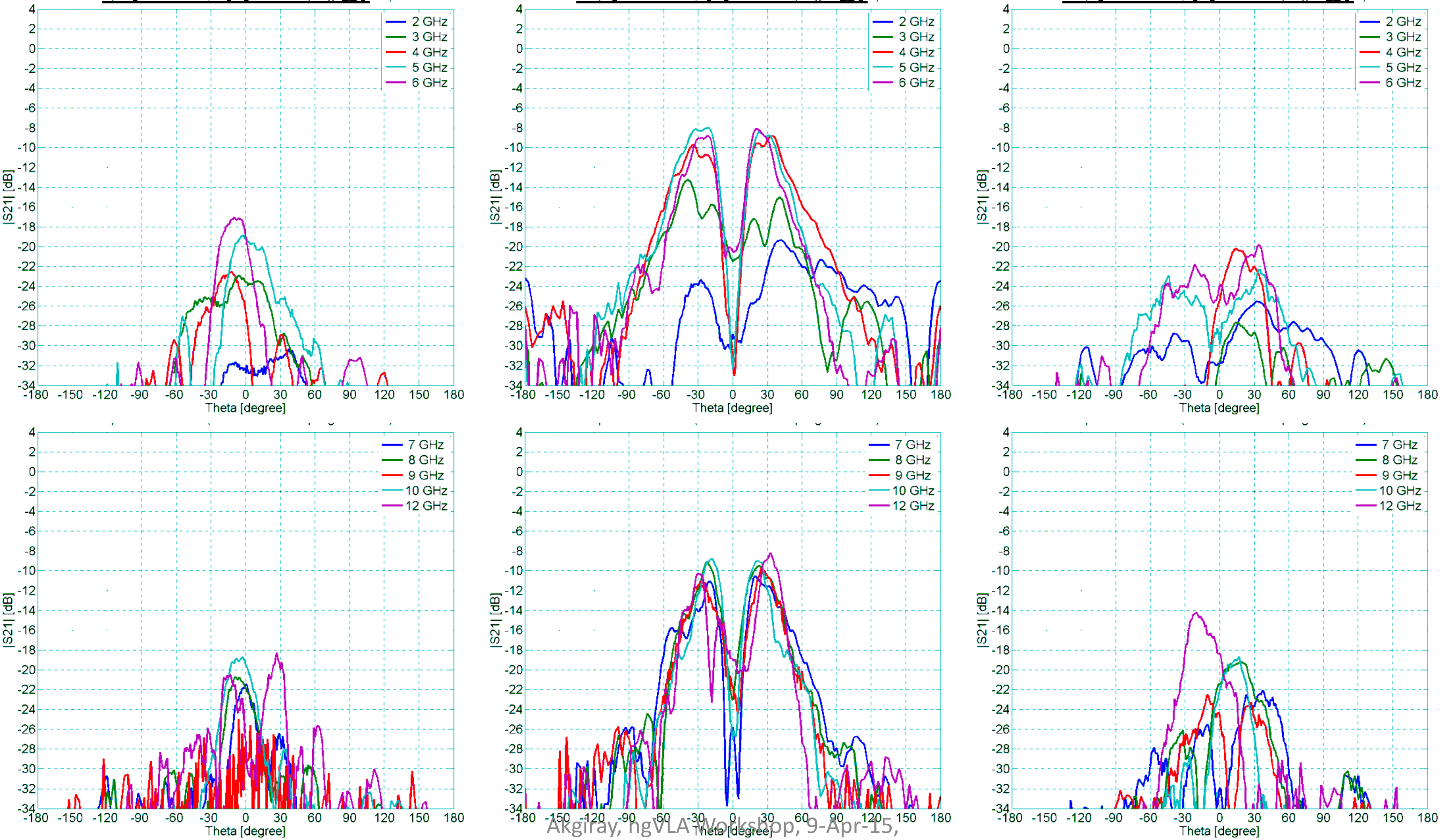


Normalized to boresight gain

Measurements

Radiation Patterns, X-pol

E-plane (ϕ=0 deg) **D-plane (ϕ=45 deg)** **H-plane (ϕ=90 deg)**



Normalized to co-pol boresight gain

Design approach
Small-signal models dictate

Common themes:

- All amplifiers employ either three or four common-source stages
- Both shunt and series inductive peaking used
- Large first-stage device, with inductive degeneration, required for “better” match but limits bandwidth
- First stage optimized for noise and match with fairly aggressive shunt peaking to increase gain at high frequencies
- Subsequent stages smaller to achieve desired bandwidth (still need series peaking)
- Main goal was to achieve as low noise and as flat gain as possible from the MMIC; in hindsight, should have co-designed the input matching network

NGC designs:

- Amplifiers designed “blindly” because the SSM provided by NGC:
  - Specified at a high current density incompatible with low-noise operation at cm wavelengths
  - No information about impact of bias on device parameters
  - May not even be accurate due to continuously changing process
- I made two rookie errors that didn’t help:
  1. Drain resistors limit available bias range
  2. Inter-stage AC coupling caps too small in value (used them to curb the very high low-frequency gain predicted by the SSM)

OMMIC designs:

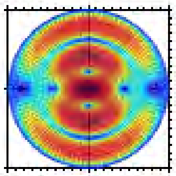
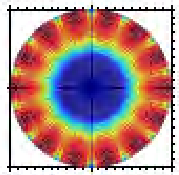
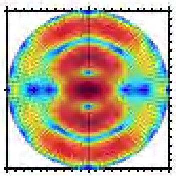
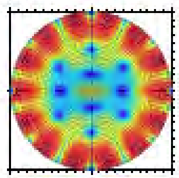
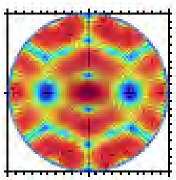
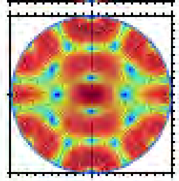
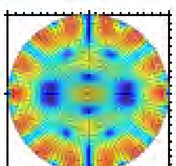
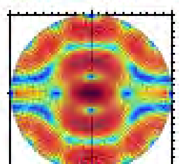
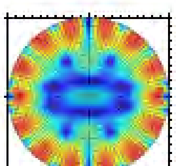
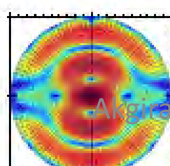
- Lack of temperature dependence on device parameters => all design work performed at 290K

QRFH Modal Analysis

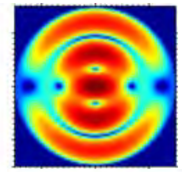
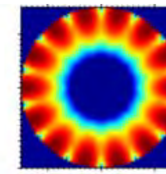
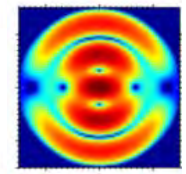
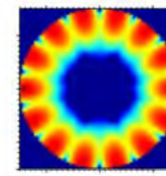
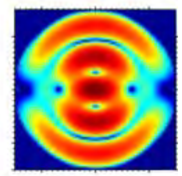
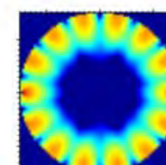
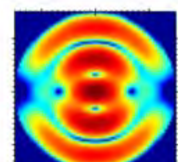
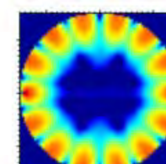
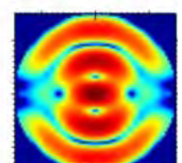
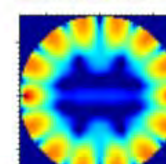
Difficulties in obtaining eigenmodes

When *two modes of same type* have *very close cutoff* frequencies, the eigenmode calculation yields *superposition* of the two mode patterns

What the EM solver produces

Mode 9		Mode 10	
Gap = 2; fc = 8.1458		Gap = 2; fc = 8.1854	
Gap = 1.95; fc = 8.1468		Gap = 1.95; fc = 8.1743	
Gap = 1.92; fc = 8.1385		Gap = 1.92; fc = 8.1596	
Gap = 1.9; fc = 8.1231		Gap = 1.9; fc = 8.1569	
Gap = 1.85; fc = 8.0474		Gap = 1.85; fc = 8.1555	

What the modes should really look like

Mode 9		Mode 10	
Gap = 2 fc= 8.1456		Gap = 2 fc= 8.1849	
Gap = 1.95 fc= 8.14494		Gap = 1.95 fc= 8.1658	
Gap = 1.92 fc= 8.1291		Gap = 1.92 fc= 8.1552	
Gap = 1.89 fc= 8.0951		Gap = 1.89 fc= 8.1541	
Gap = 1.86 fc= 8.0434		Gap = 1.86 fc= 8.1527	

QRFH Modal Analysis

Custom code

- Given these challenges, decided to write my own finite element analysis (FEA) code in Matlab

- ***First attempt:*** edge- and node-based FEA, not yet working. Not quite sure but problem may be with enforcing continuity over element edges

- ***Second attempt:*** node-based FEA, working well with no spurious modes or field singularities (not yet at least). Faster than CST and lets me calculate only the modes I'm interested in.

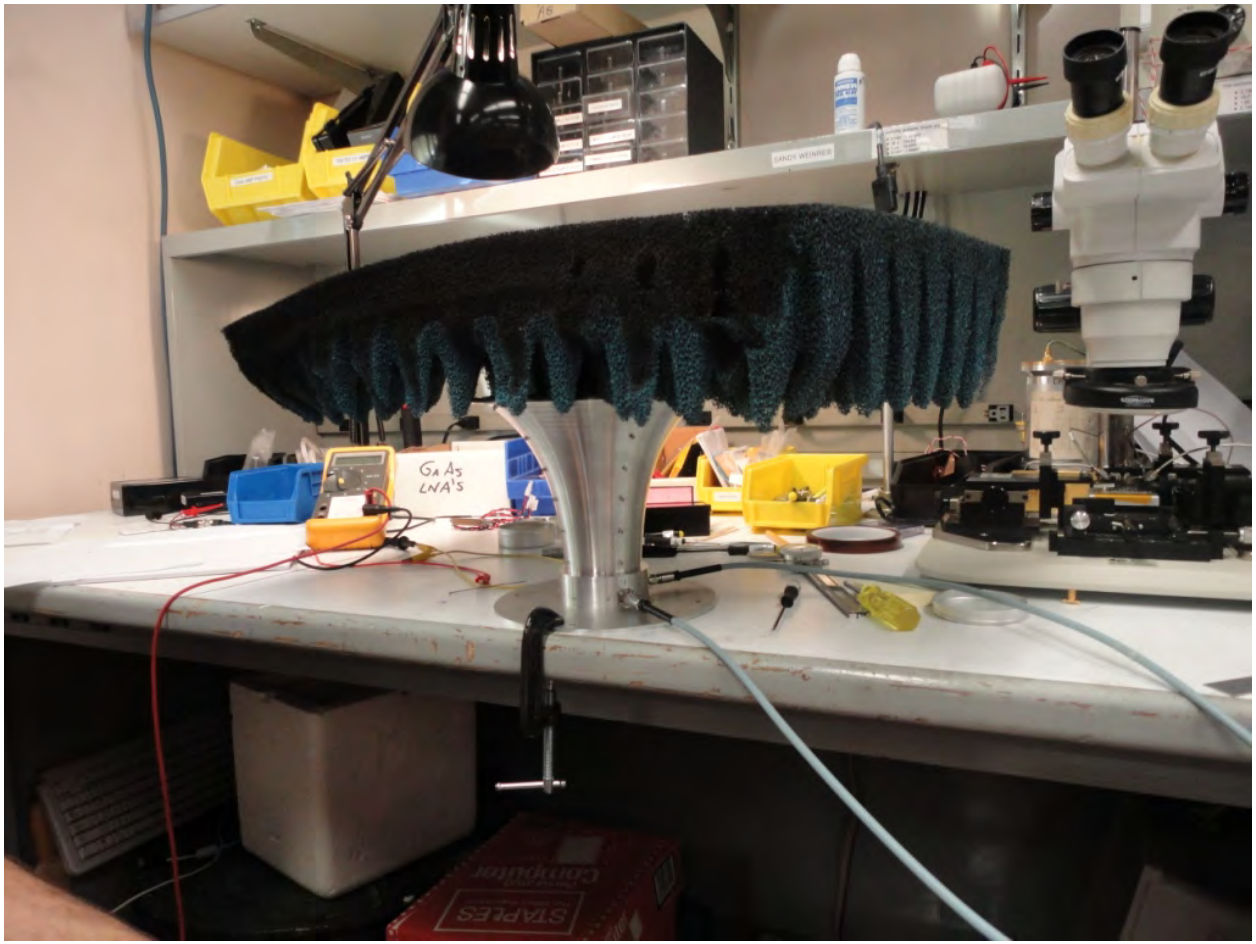
  The only problem: mode superposition of close-by modes!!

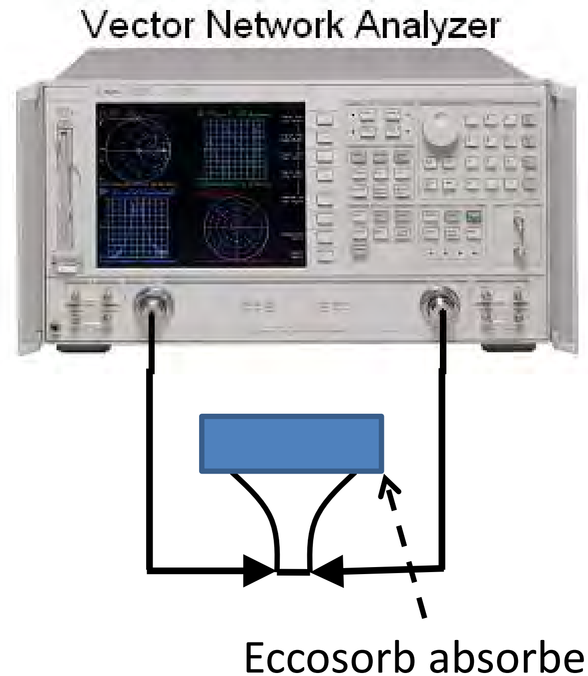
  This confirms the problem is with eigenvalue solver.

- Recently started collaborating with Prof. Oscar Bruno of Caltech. My feeling is that since we are slowly "perturbing" the waveguide, the eigenmodes of previous (larger) gap should be excellent initial values for the next (smaller) gap.

Measurements

S-parameter setup





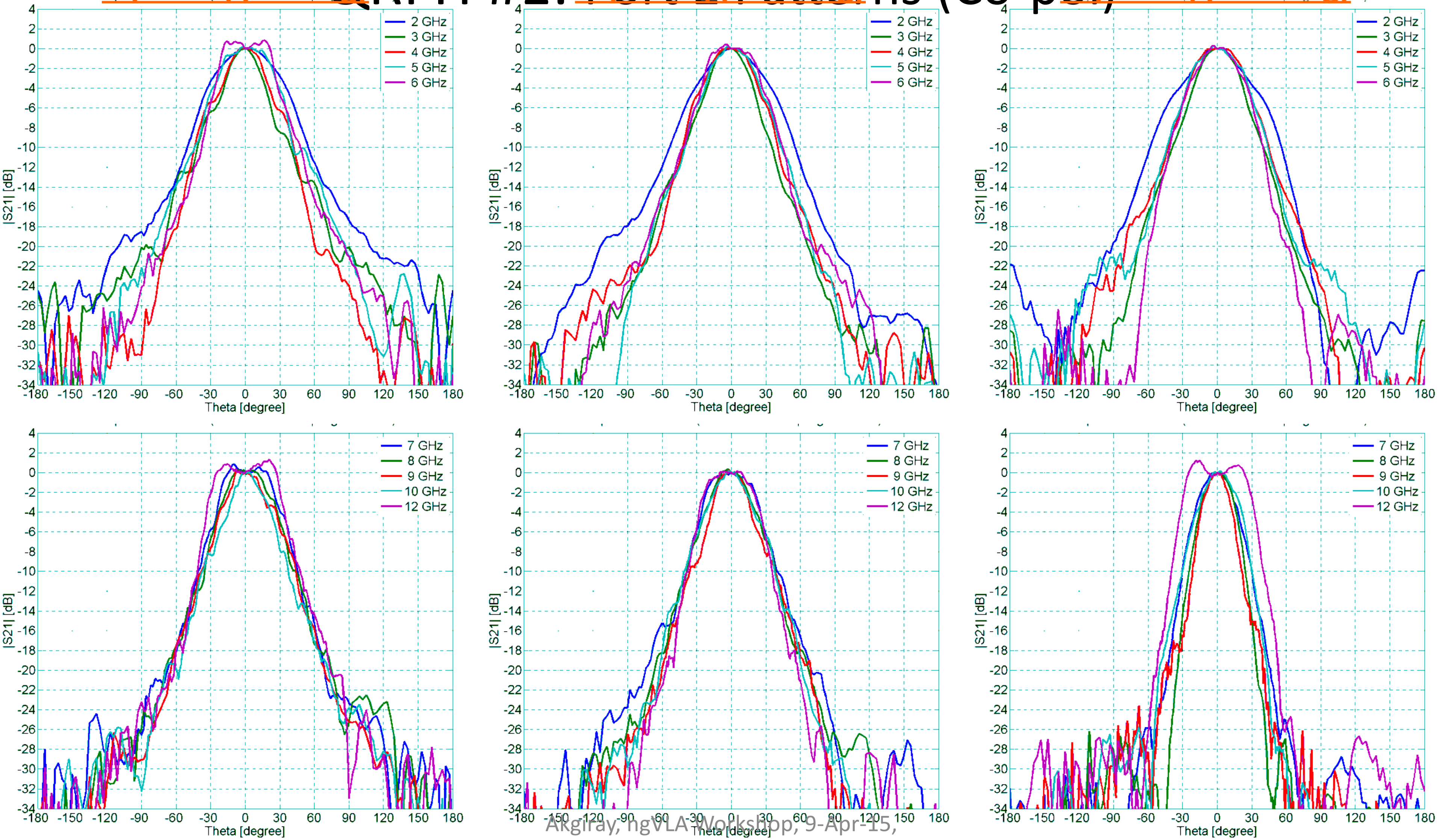
VNA Settings:

Output power = -10 dBm
IF BW = 1 kHz
Freq Span = [1, 20] GHz
# of Points = 801

Measurements

QRFH #1: Port 2 Patterns (Co-pol)

E-plane (ϕ=0 deg) **D-plane (ϕ=45 deg)** **H-plane (ϕ=90 deg)**

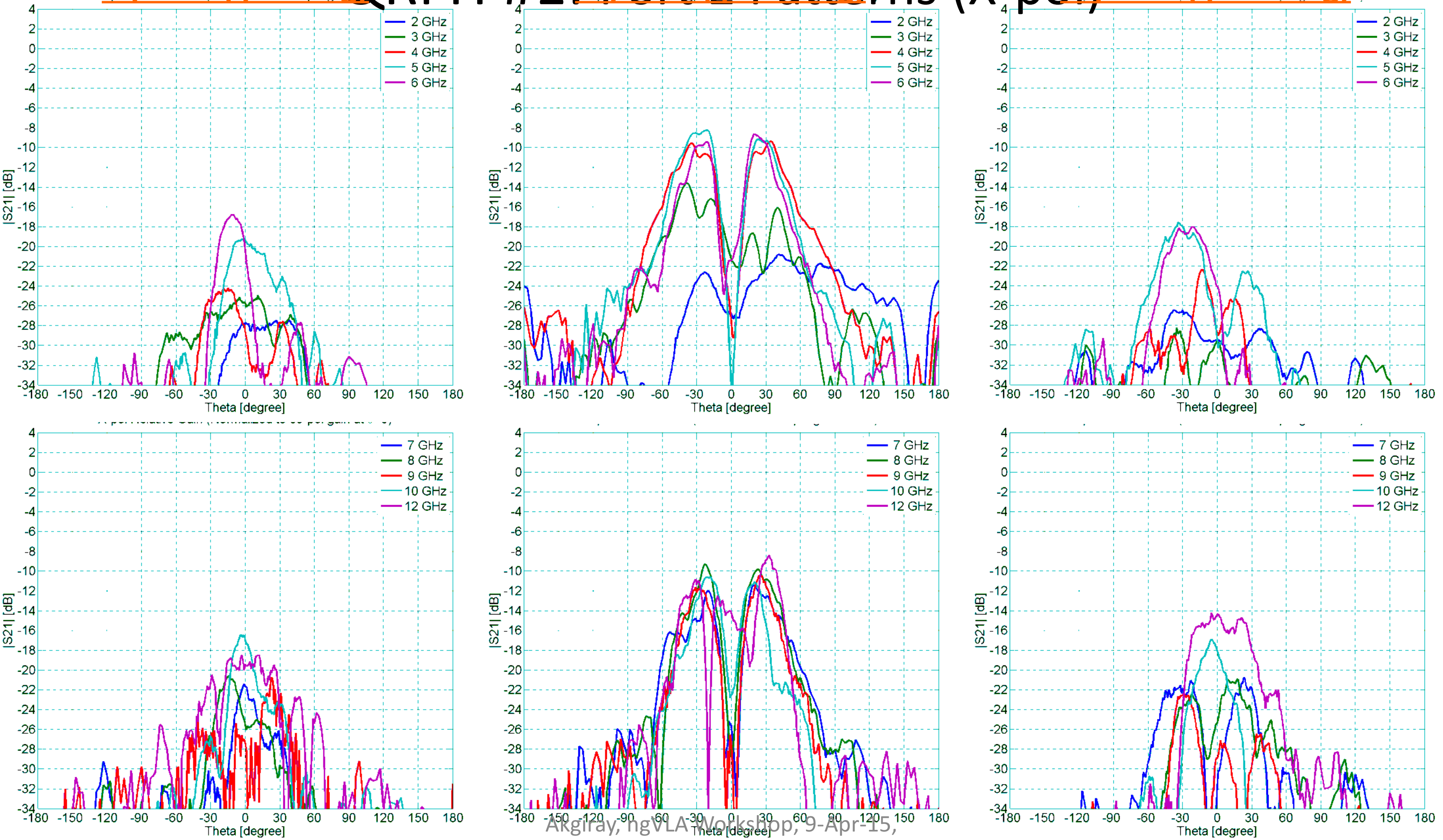


Normalized to boresight gain

Measurements

QRFH #1: Port 2 Patterns (X-pol)

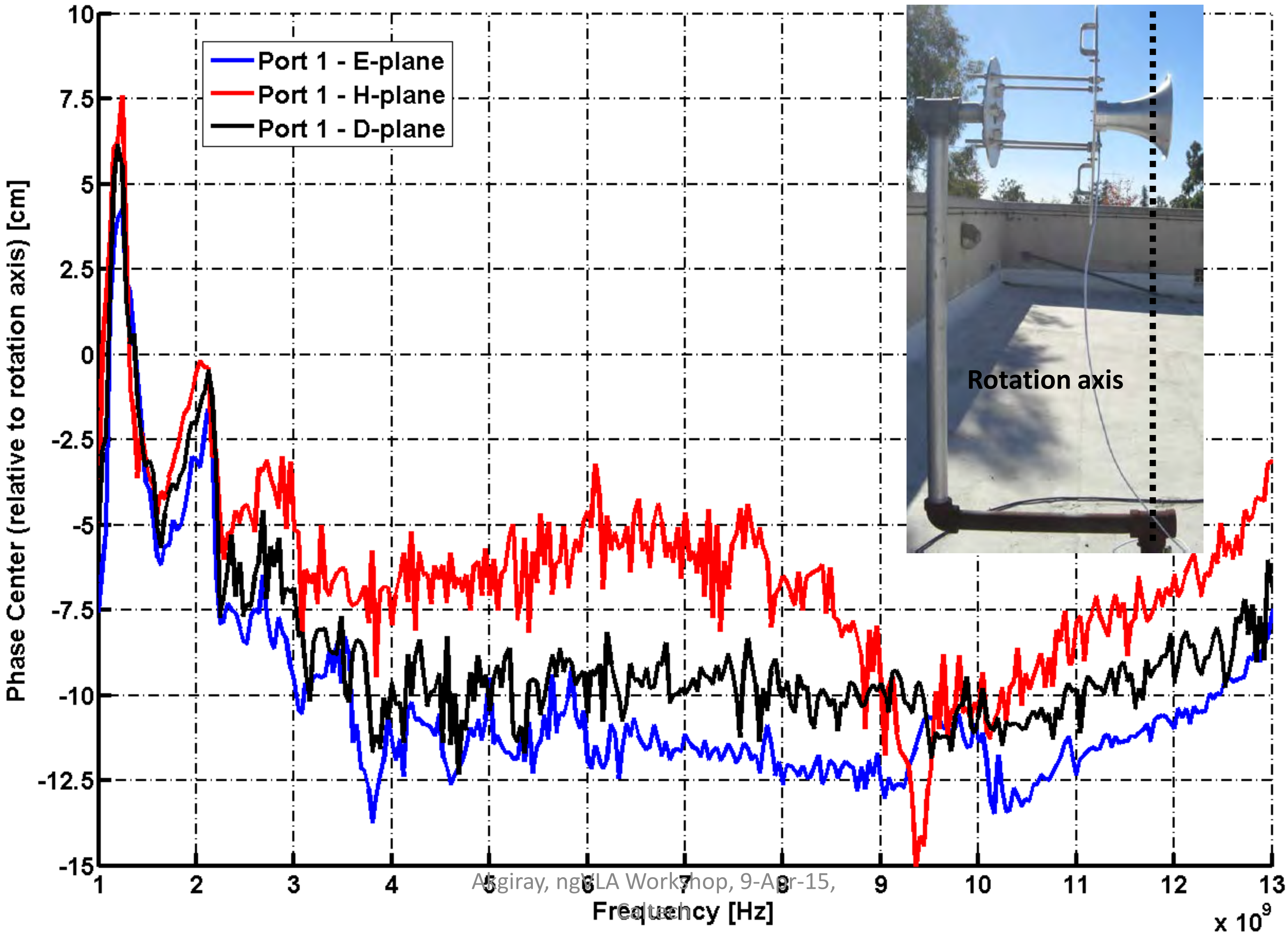
E-plane (ϕ=0 deg) | D-plane (ϕ=45 deg) | H-plane (ϕ=90 deg)



Normalized to co-pol boresight gain

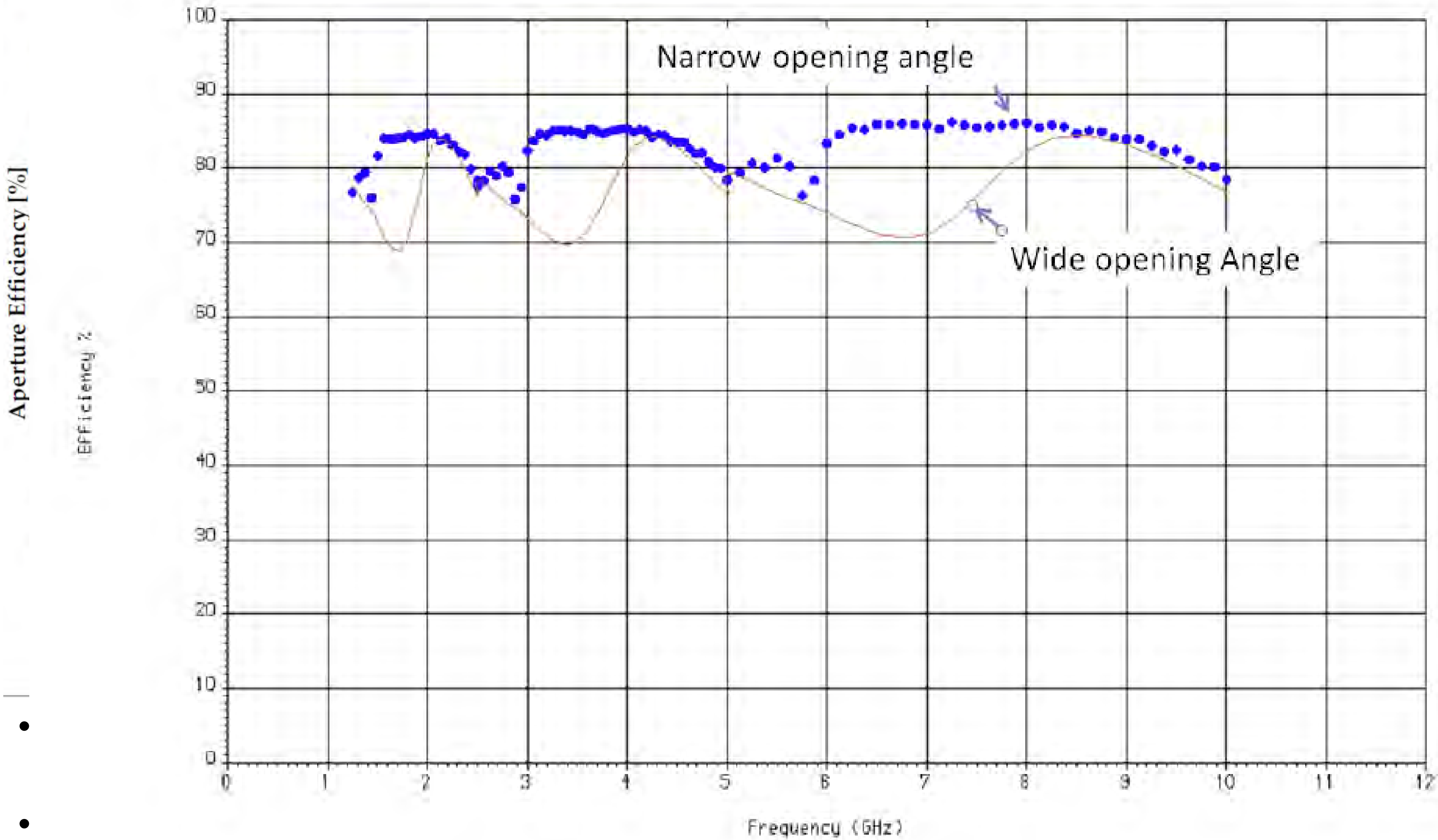
Measurements

QRFH #1: Port 1 Phase Center (50 deg half angle)



System Measurements

Corrugated horn performance on a different reflector



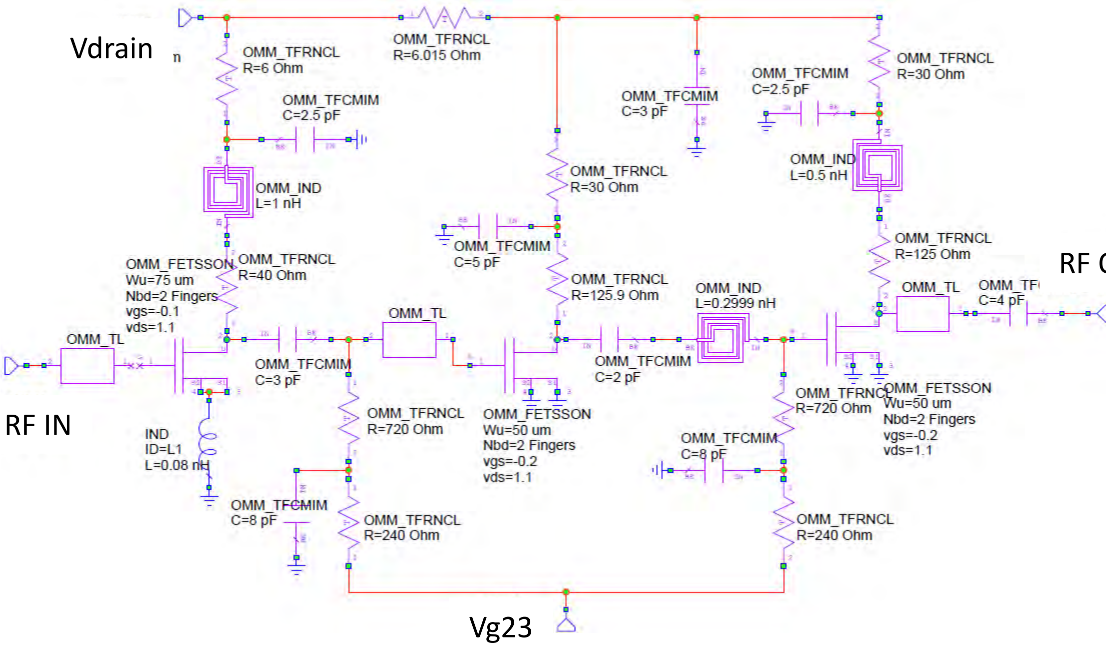
Cortes, Imbriale, Baker, Ivashina, "DVA-1 Optics and Feed Performance, July 2011

Figure 1.12: Octave Band Horns Efficiency

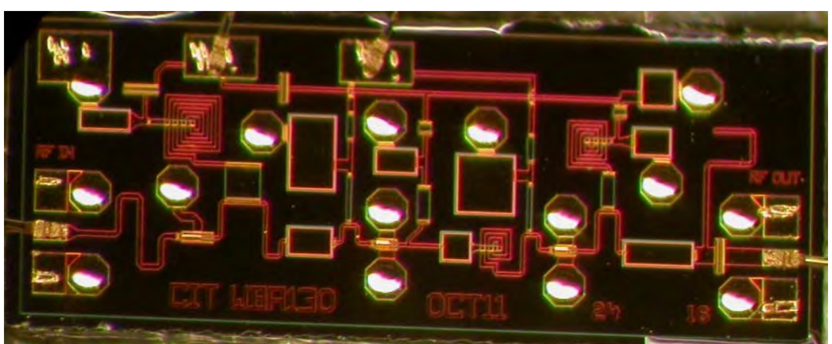
Antenna noise temperature calculation," SKA Memo 95, 2007.

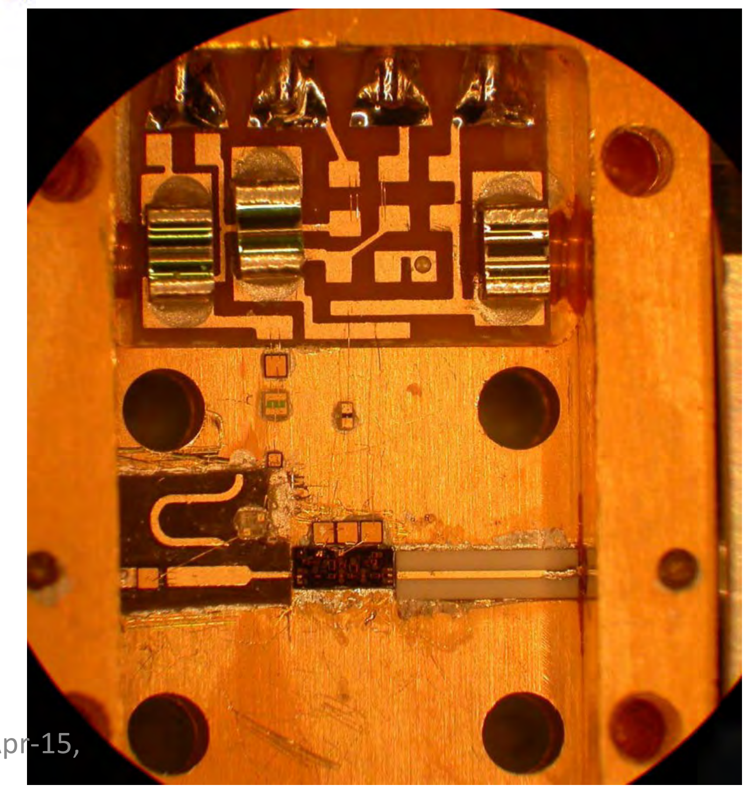
OMMIC 1-20 GHz Amplifier v2

Schematic



- Three stages: 2f150um, 2f100um, 2f100um
- Installed in Ka-band chassis with modified 6-18 amplifier input matching network



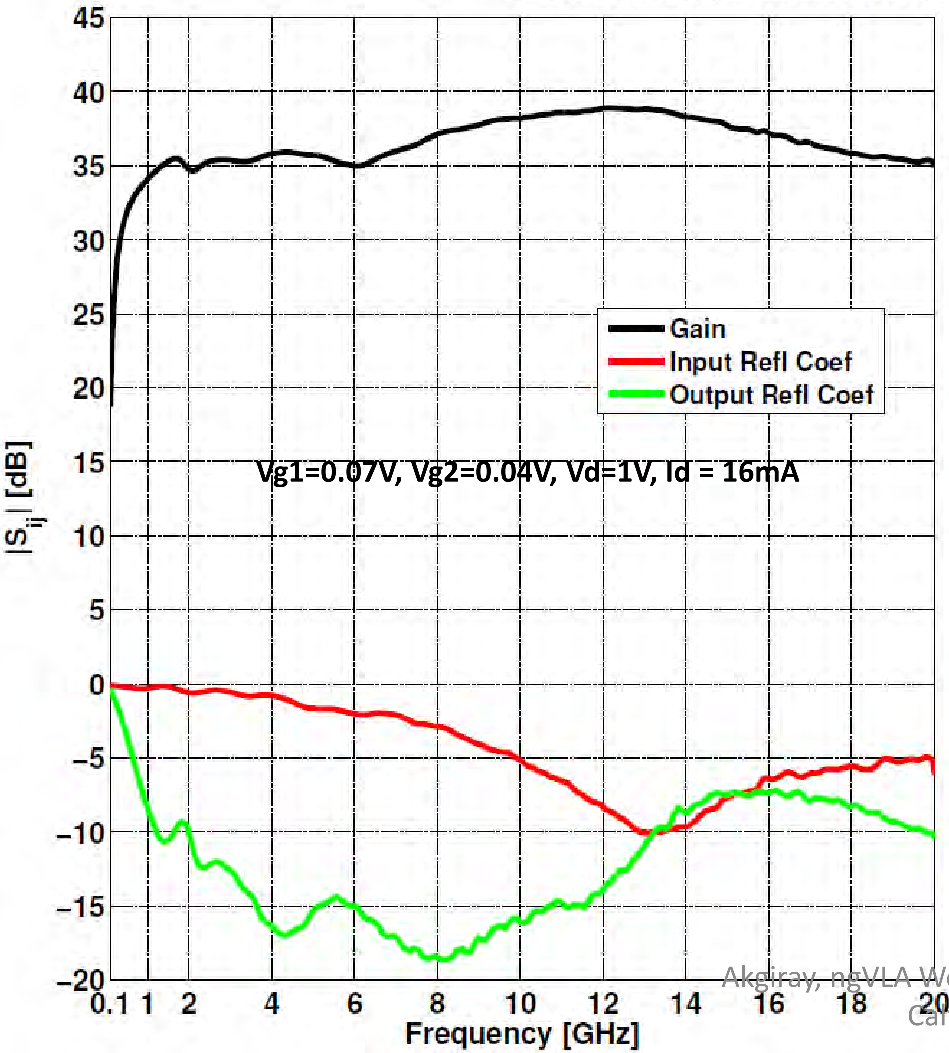


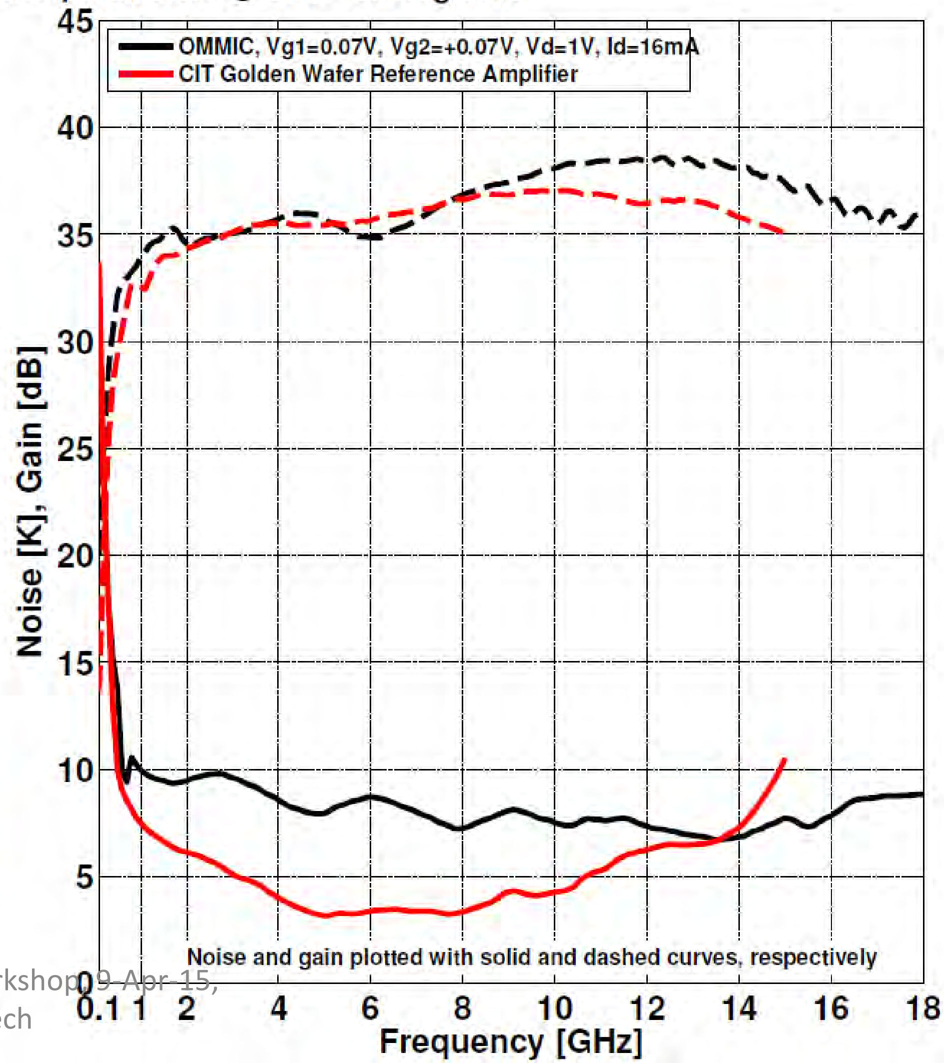
OMMIC 1-20 GHz Amplifier v2 @ 20K

A new amplifier for radio astronomy

Slightly better match, noise is < 10 K up to > 18 GHz. At the top of the band, other components start to play a role (more on this little later)

CIT 3–18 in Chassis 40A166 Noise/S–parameters @ 21K – 27 Aug 2012





Discrete devices tested and tests conducted

- All transistors are from FETCAL35 chips on the 4493-107A (100% In content in the channel)
  - total of 11 FETCAL35 chips made with 8 different transistors on each
  - all transistors are wafer-probed for DC and S2P (up to 50 GHz) at room temperature

- Four transistor sizes are installed in fixtures and cooled to 20K for cryogenic DC and S2P measurements

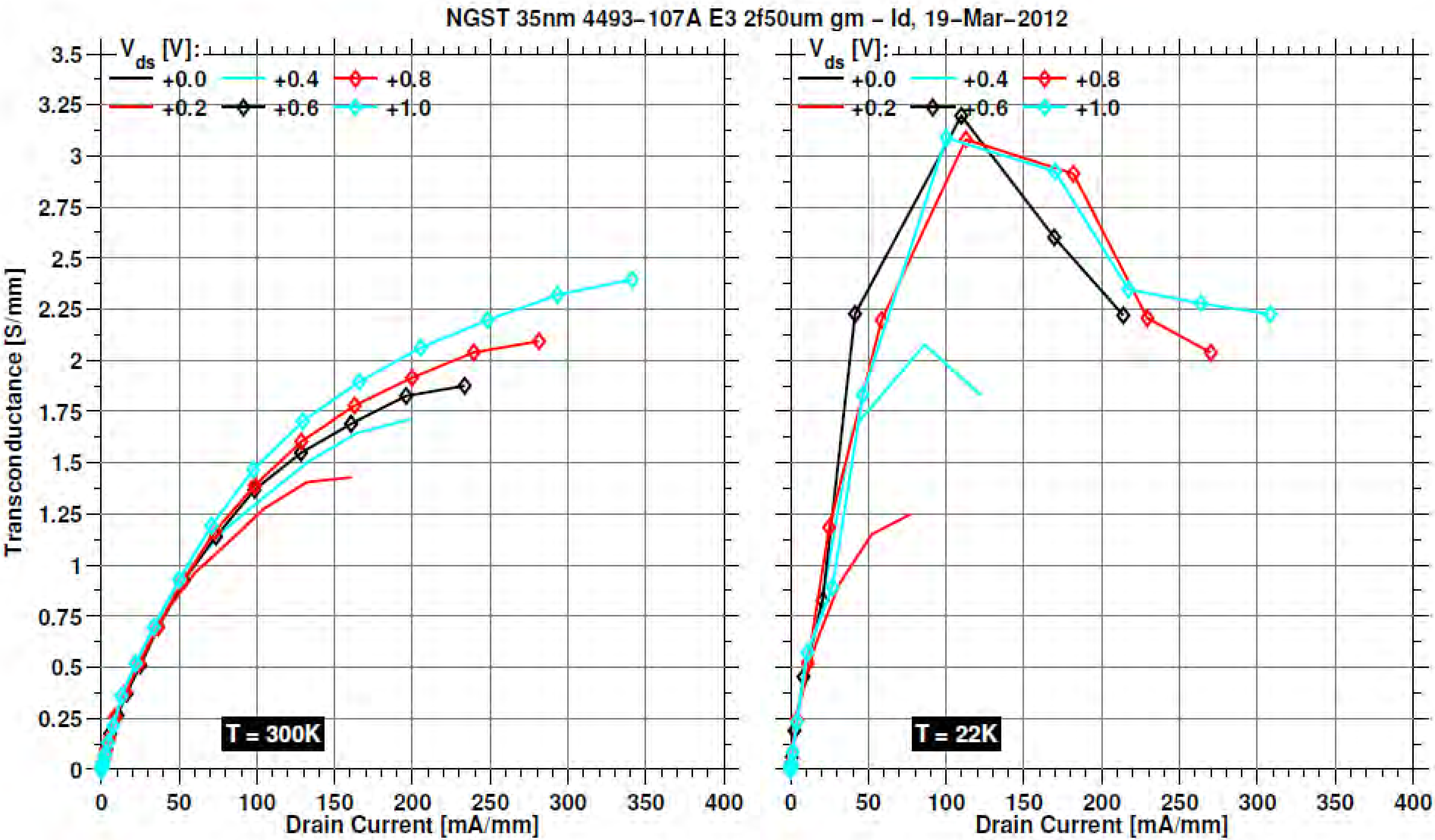
- Device sizes cryogenically tested: 2f200um, 2f130um, 2f80um and 2f50um
  - # of devices tested for each size:

    1) 2x 2f200um; 2) 3x 2f130um; 3) 2x 2f80um; 4) 1x 2f50um

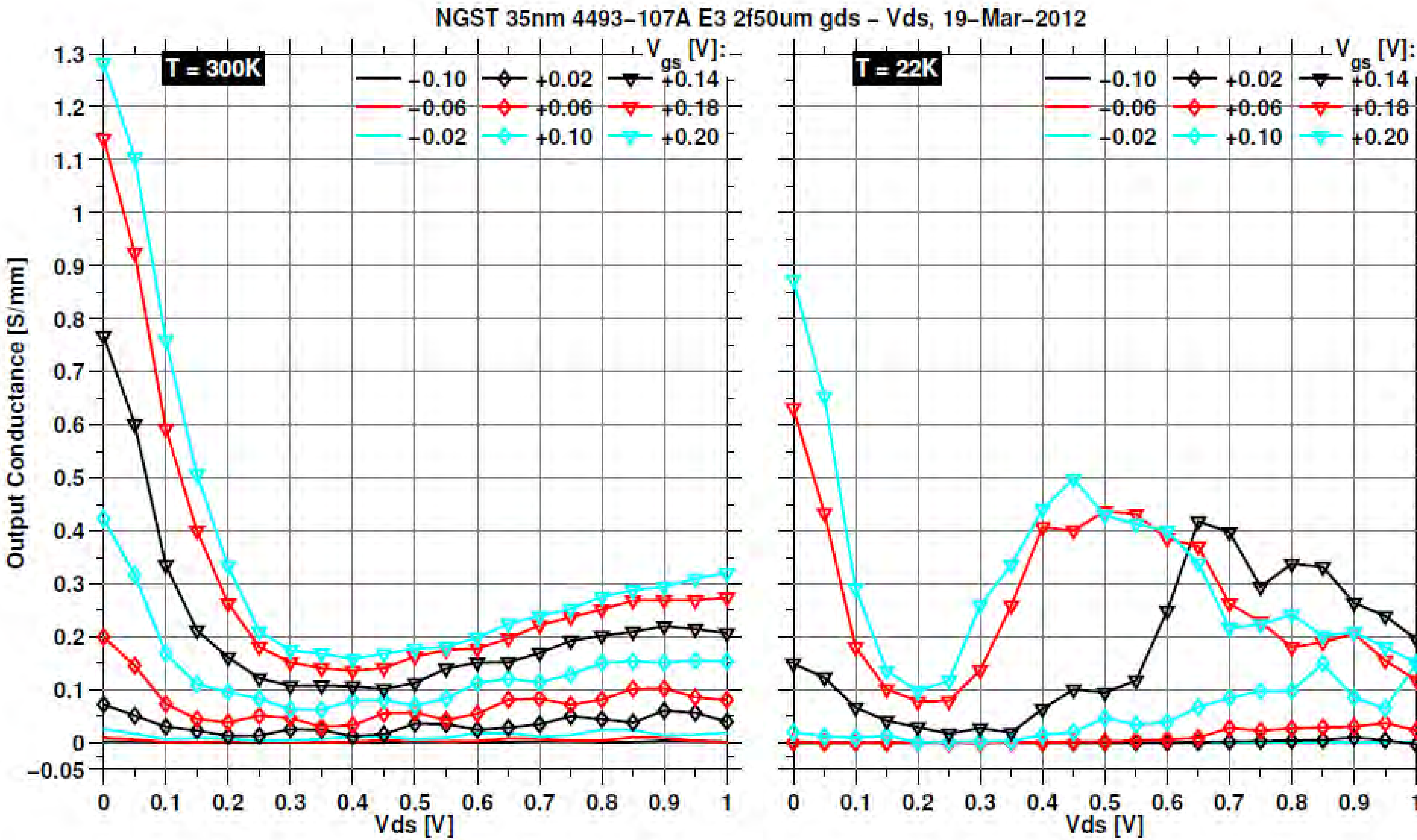
- Test details (conducted both at 300K and 20K):

DC: Vgs swept from -0.6V to approx +0.2V in at most 0.02V steps (usually 0.01V)
Vds swept from 0 to 1V in at most 0.1V steps (usually 0.05V)

S2P: S-parameters recorded for Vgs = [-0.2, 0.2] and Vds = [0, 1] from 0.01 to 20 GHz

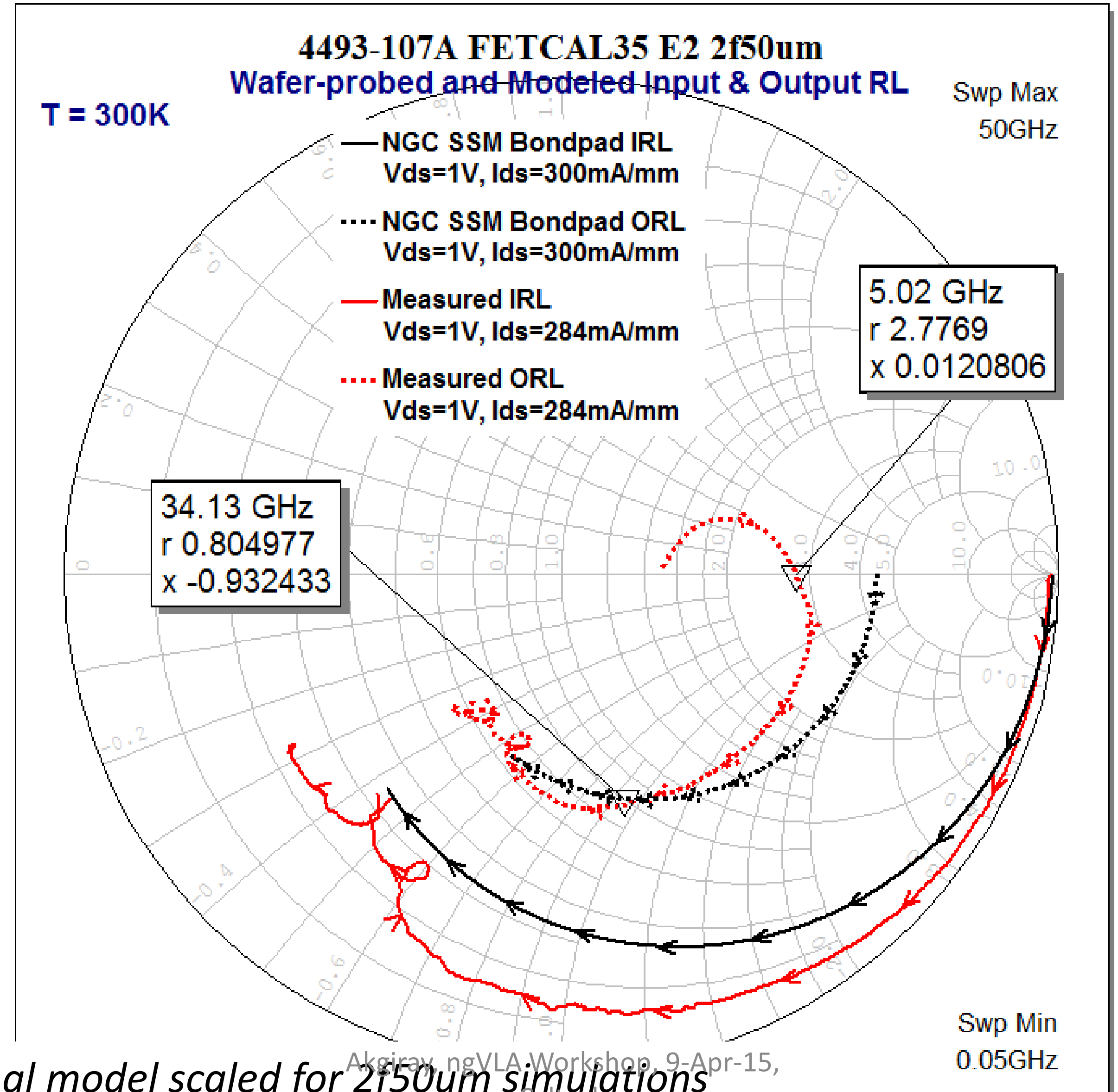


NGST 35nm 4493-107A E3 2f50um gm - Id, 19-Mar-2012
Vds [V]:
+0.0
+0.4
+0.8
+0.2
+0.6
+1.0
Transconductance [S/mm]
Drain Current [mA/mm]
T = 300K
T = 22K


NGST 35nm 4493-107A E3 2f50um gds - Vds, 19-Mar-2012
T = 300K
T = 22K
V_{gs} [V]:
-0.10
-0.06
-0.02
+0.02
+0.06
+0.10
+0.14
+0.18
+0.20
Output Conductance [S/mm]
Vds [V]

Predicted and Measured Return Loss

Prediction of impact ionization needed for low-freq designs



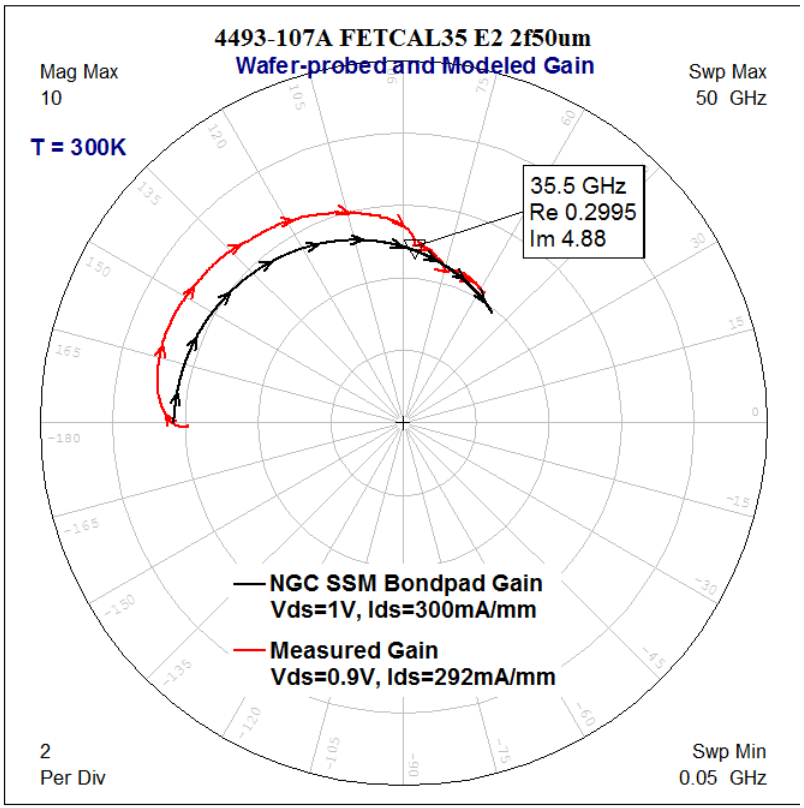
NGST small-signal model scaled for 2f50um simulations

Predicted and Measured Gain – 2f50um

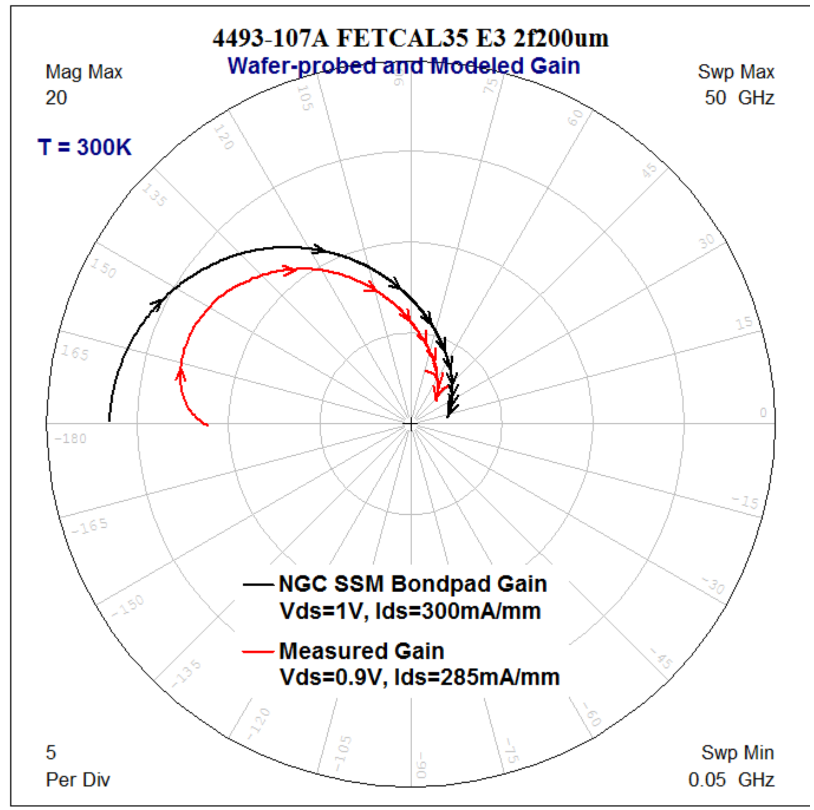
Impact ionization decreases low-freq gain

Scaled SSM overestimates gain considerably for large devices, underestimates it for smaller transistors

2f50um



2f200um

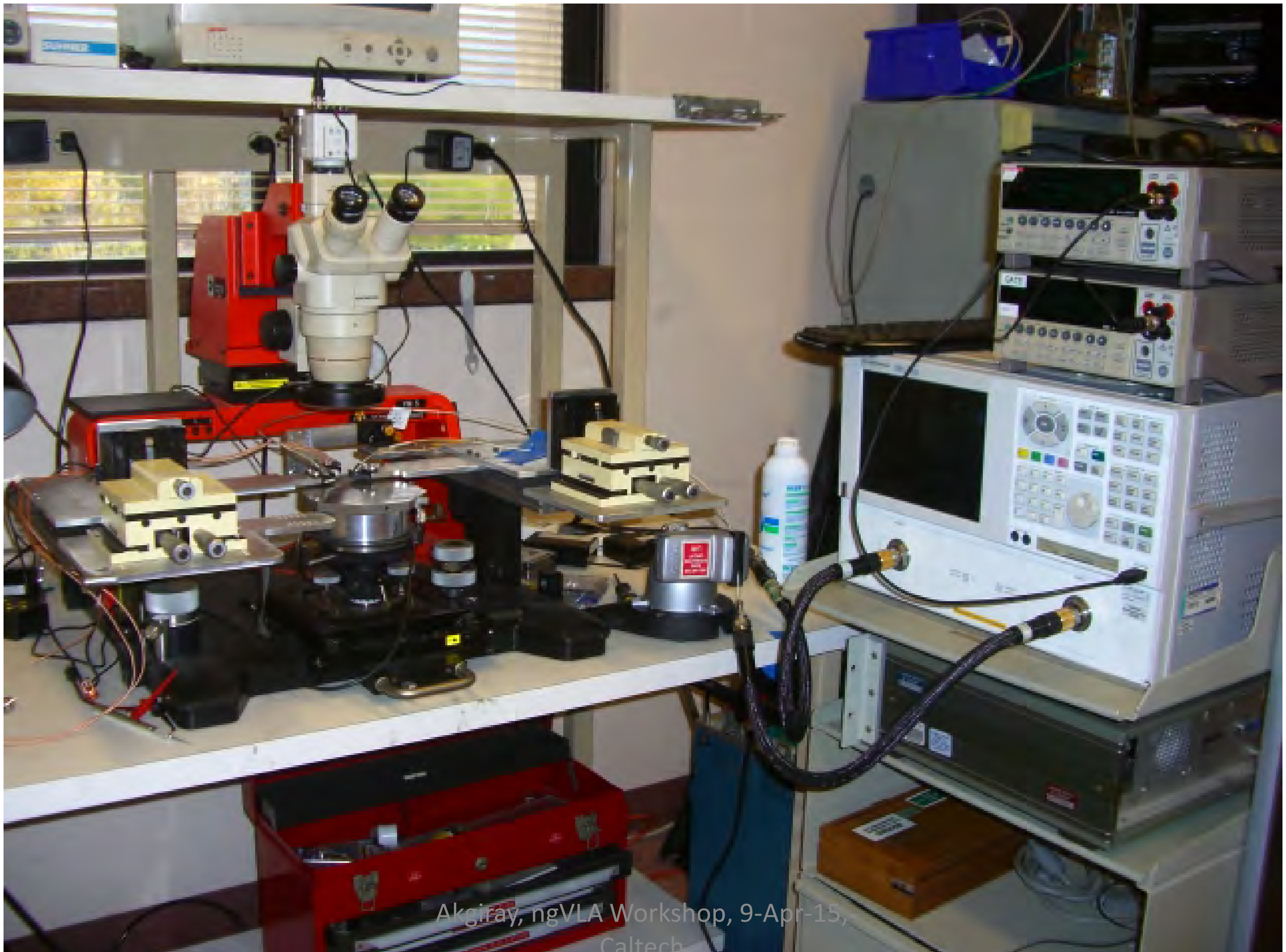


Black: Simulated, **Red: Measured**

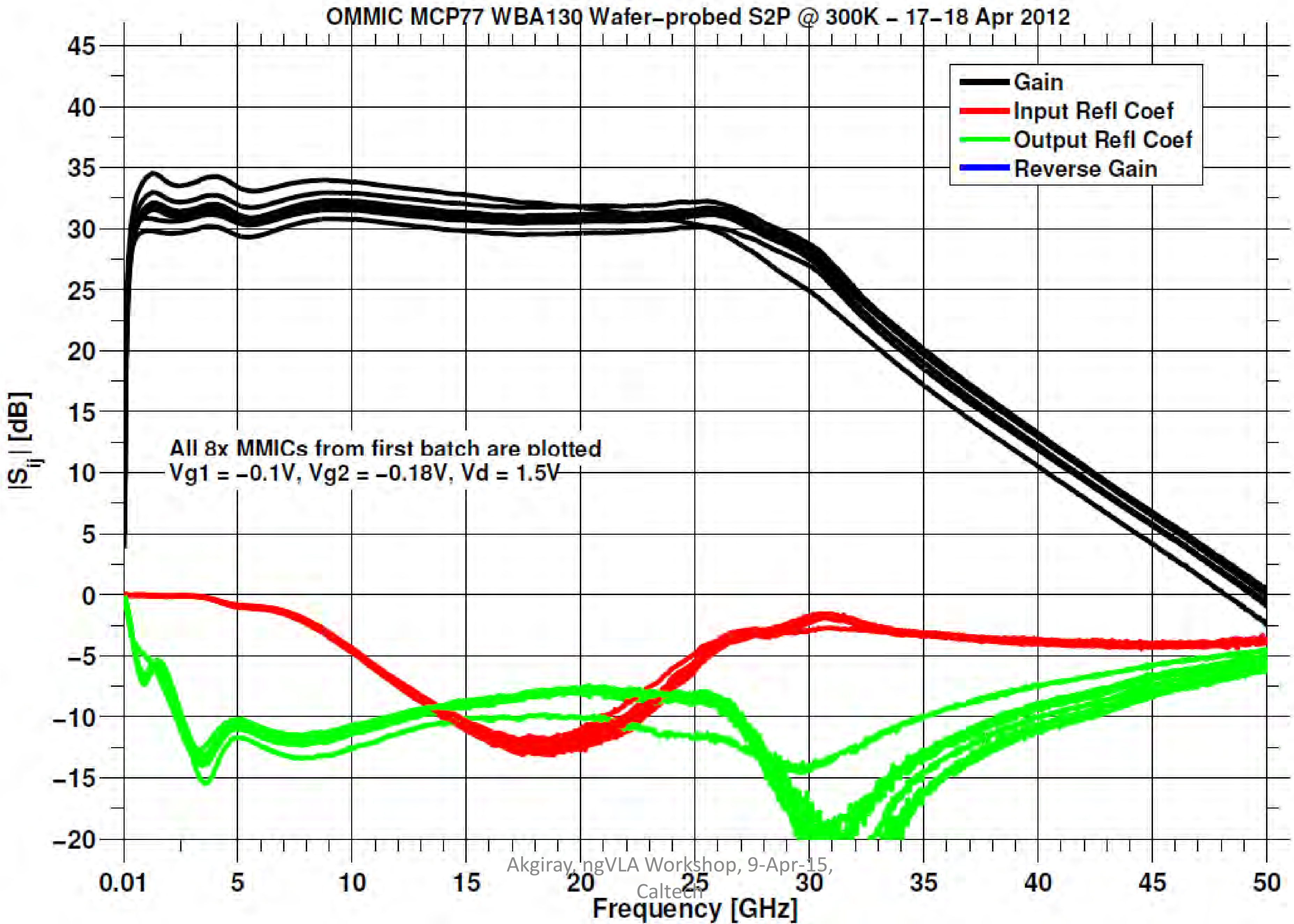
NGST small-signal model scaled for 2f50um and 2f200um device sizes

Wafer-probe test station

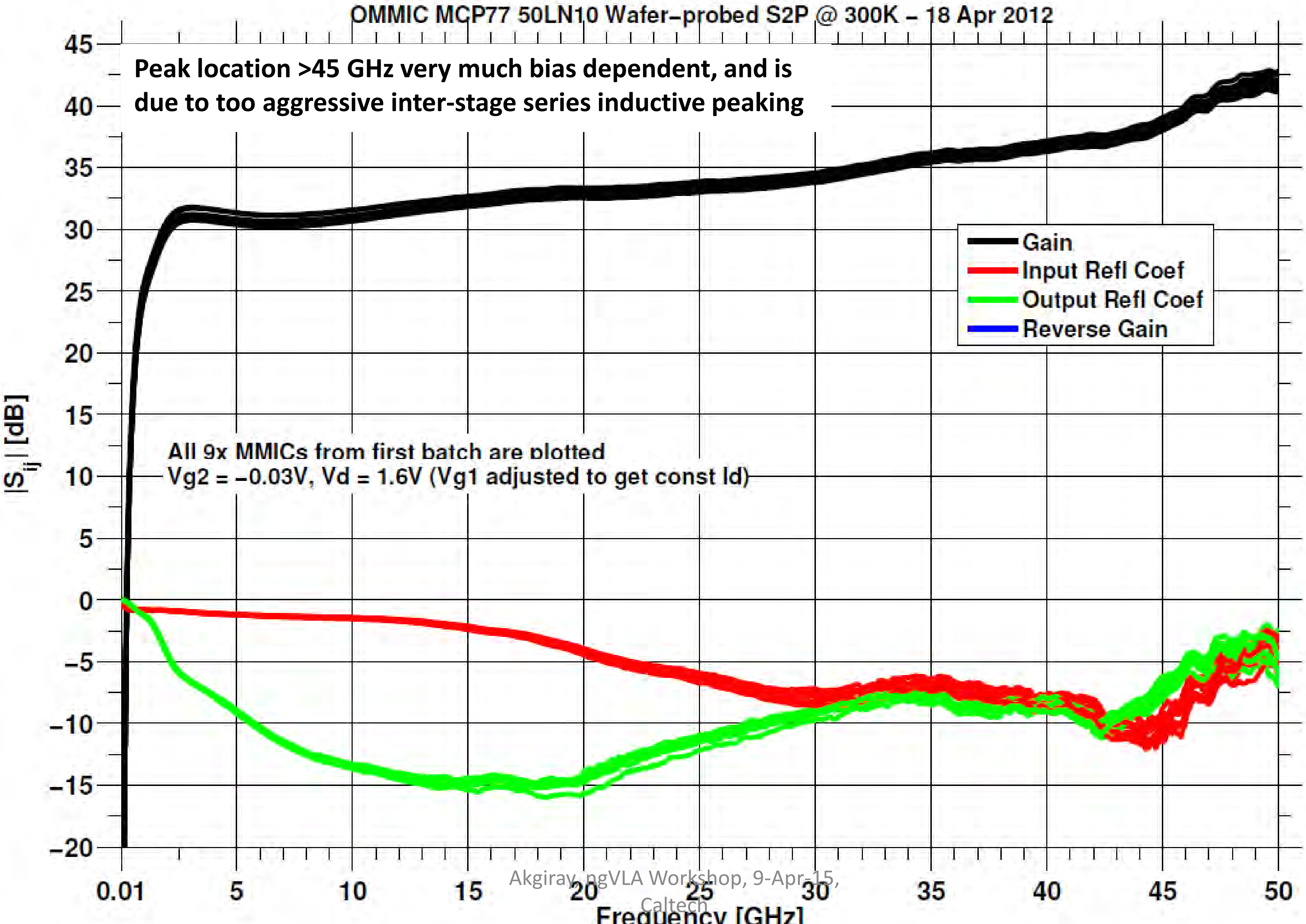
Agilent 50GHz PNA is calibrated using CS-5 cal substrate from GGB Industries, S-parameters are measured up to 50GHz at a range of bias values



WBA130 Probed S-parameters @ 300K



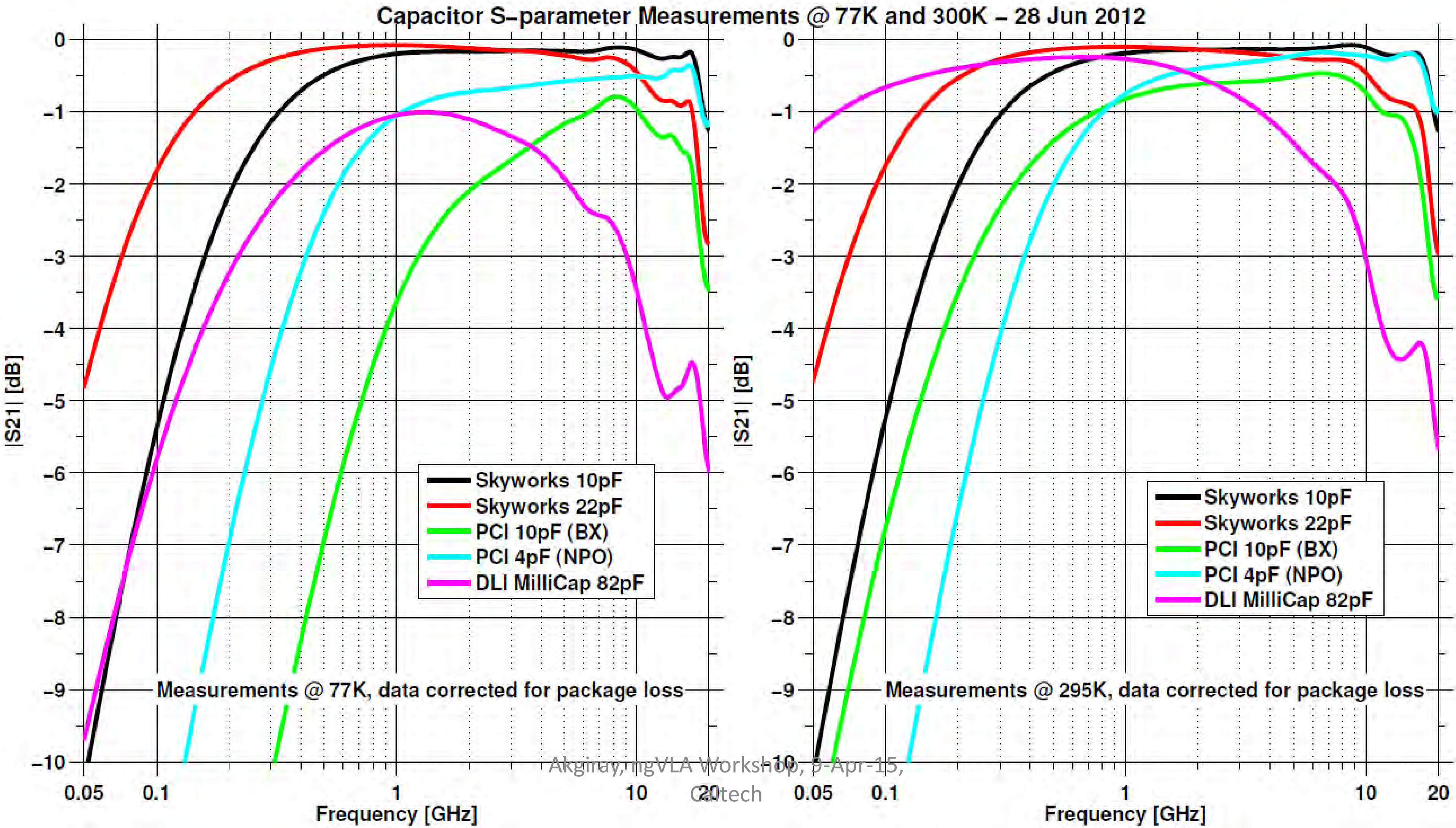
50LN10 Probed S-parameters @ 300K



Measured Loss of Several Capacitors

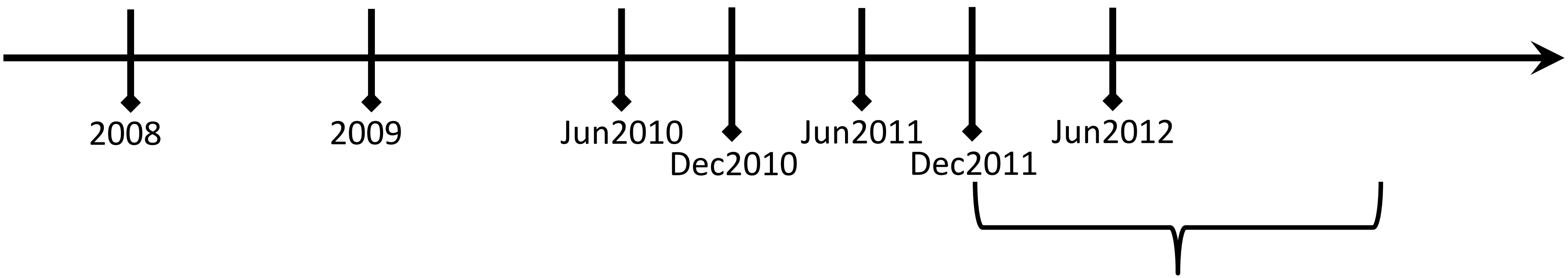
Skyworks the most stable over temperature

Looking for a capacitor that is resonant-free up to 20 GHz and low-loss with stable temperature response



Timeline of QRFH development

Ongoing work



QRFHs on the way

2-4 more QRFH designs are being finalized for radio telescopes in US, Japan, Aus

Emphasis is on square horns for low-frequency designs due to easier fabrication

Modal Analysis

Ongoing effort since mid 2011

Presently trying to catalog up to 10 modes of interest as a function of ridged waveguide cross-section

Will enable mode-matching for better understanding of the EM as well as easier design process

Never done before

Outline

I. Quad-ridge flared horn (QRFH):

- *Early history*
- ***Initial approach:*** automated simulation setup facilitating rapid computation of S-parameters and far-fields
- ***Converging on a 6:1 antenna:*** combining new and existing ideas with our optimization codes yields "optimum" geometries
- ***Closer look at unique features***
- ***Examples:*** Four designs; stand-alone & system measurements
- ***Modal analysis:*** analytical investigation of modes needed to yield optimum performance vs. frequency

II. Compound-semiconductor HEMTs and LNAs:

- ***Performance of HEMTs from two processes: 35nm InP and 70nm GaAs***
- ***NGC LNA measurements: First-iteration MMICs plagued by oscillations***
- ***OMMIC LNA measurements:*** excellent noise, gain and yield; poor match
- ***Cryogenic measurements of single-layer capacitors:*** MMICs are not the only components limiting bandwidth

Capacitor S-parameter tests @ 77K

- 1-20 GHz MMICs don't have an AC coupling capacitor before 1^{st} stage
- Instead, an external single-layer capacitor is used. The new MMICs working up to 20 GHz raised the question of capacitor behavior with frequency
- Several capacitors identified as microwave components are installed in the V-band chassis and S-parameters tested up to 50 GHz.
- Capacitor noise contribution estimated per:

$$L_{eff} = \frac{(1 - |s22|^2)}{|s21|^2}$$

$$T_{cap} = (T_{LNA} + T_{phys})(L_{eff} - 1)$$

Noise Contribution of the Capacitors
Skyworks best of the bunch

Even Skyworks capacitors a little questionable beyond 15 GHz (10 pF is a little better in this respect)
Packaging resonances affect the results beyond 13 GHz