Progress Towards Coherent Multibeam Arrays

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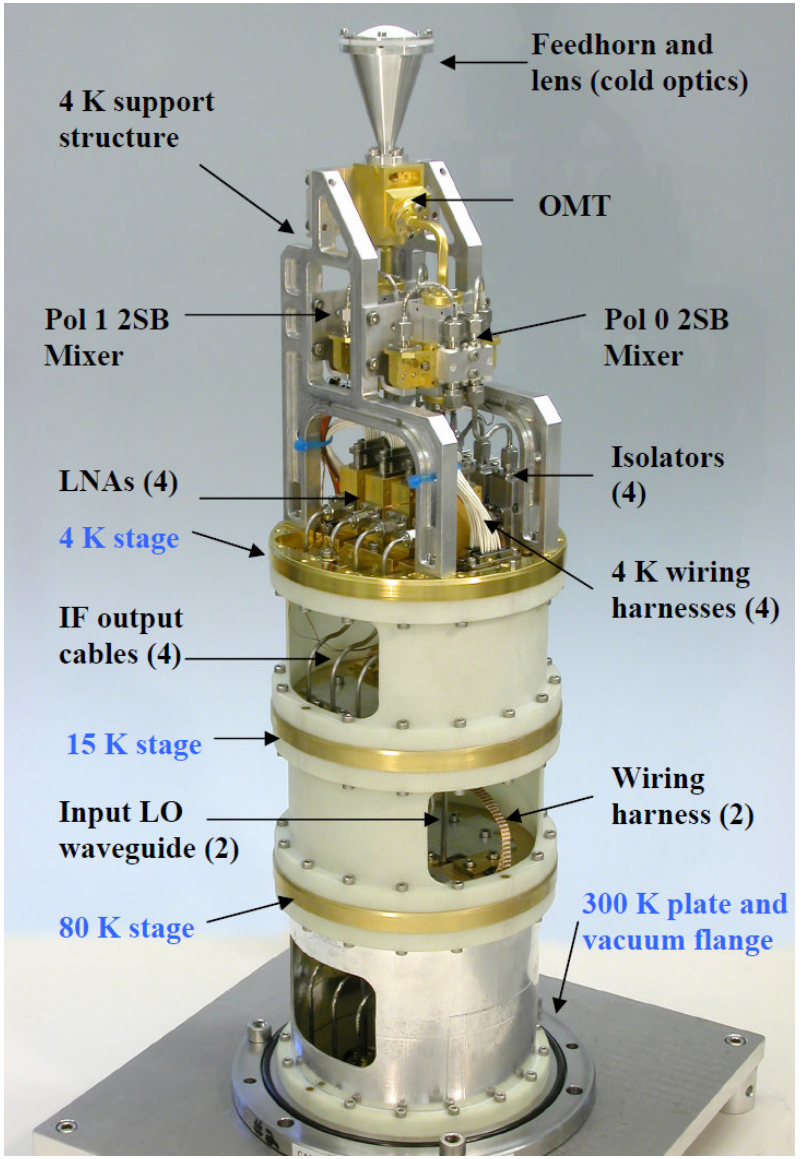
Canada

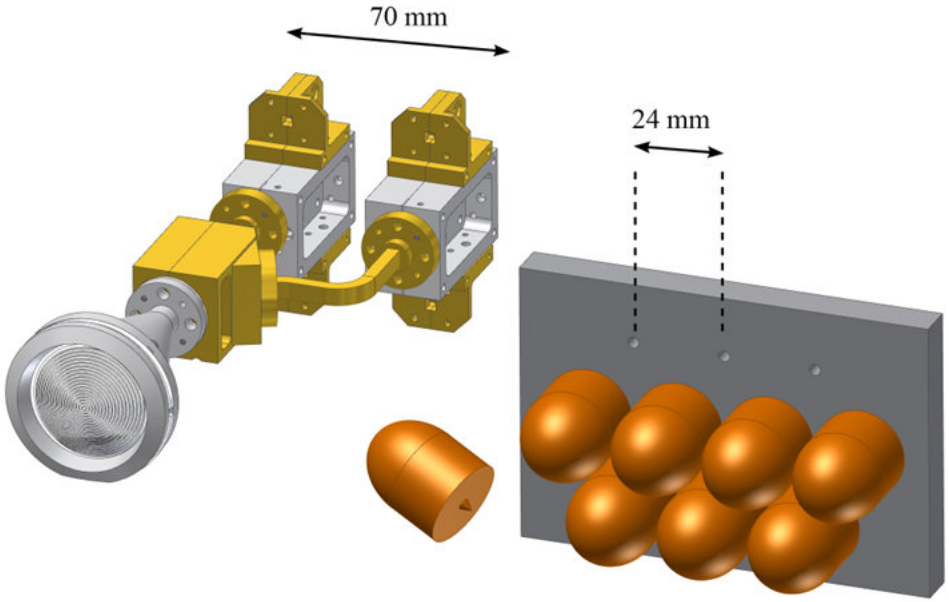
ALMA Band 3 Receiver (84–116 GHz)

- Dual linear, 2SB
- Feed horn
- OMT (two linear polarisations)
- Each polarisation has upper and lower sideband
- Four mixers + IF outputs
- Two LO sources

Multibeam?

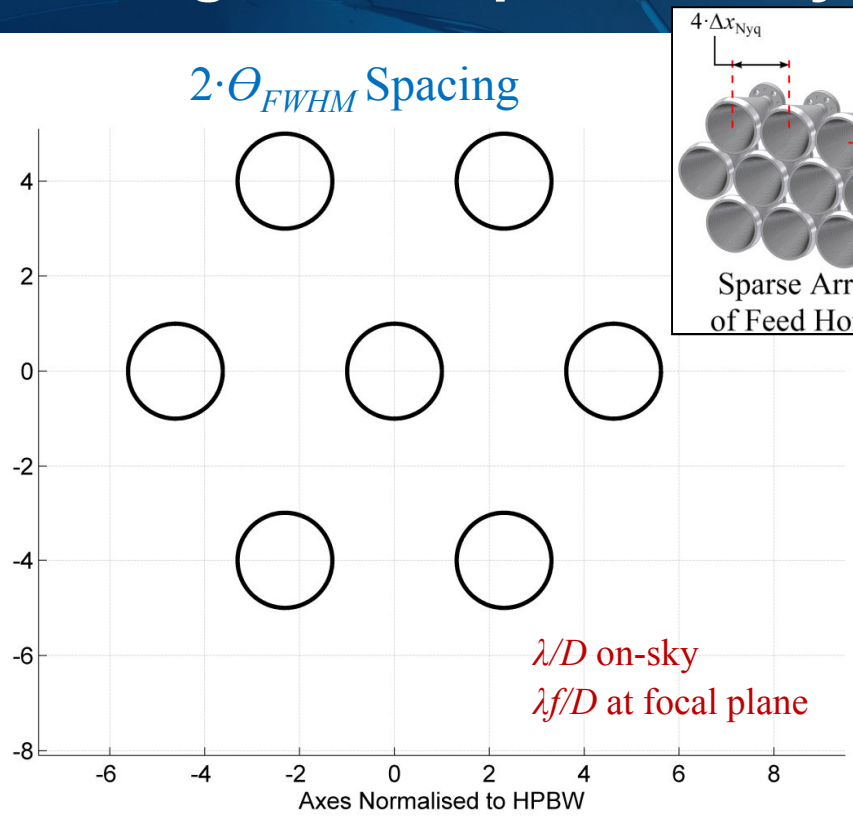


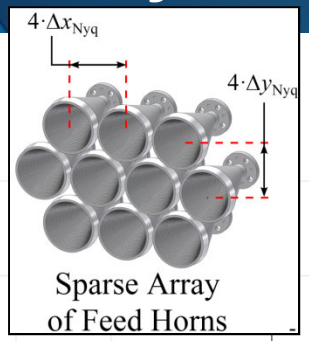
Why Dense Arrays?

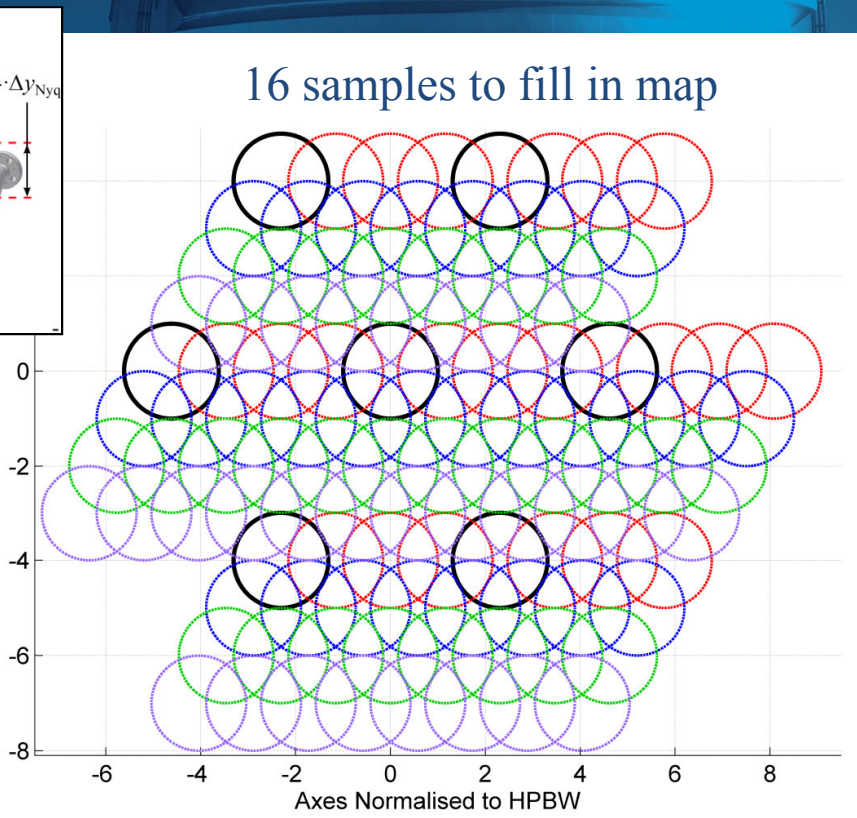


- Each lenslet (right) corresponds to the placement of an entire 2SB feed (left)
- Sparse arrays are essentially limited by feed horn diameter (~$2 \cdot \Theta_{FWHM}$)
- Move towards a *camera* type implementation
- Increase density of detectors within focal plane
- Consider the trade-off in terms of noise and aperture efficiency
- Will it improve overall mapping speed?
  - Depends on dominance of sky/background noise and number of pixels

Background: Sparse Arrays





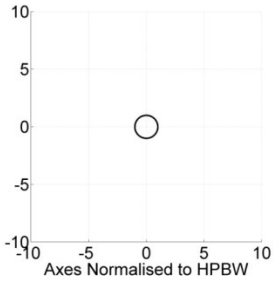


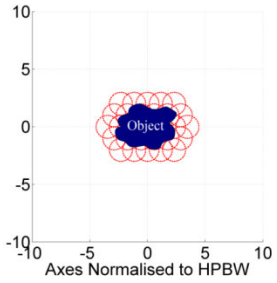
- To improve mapping efficiency, arrays are used
- Heterodyne arrays are typically sparse and limited by:
  - Feed horn diameter
  - Aperture efficiency
- Hexagonal spacing

- Can do on-the-fly techniques: “raster” or “daisy” modes
- Or, discrete pointings aka “jiggle” mode.
- On-the-fly is continuous, but is slower since angular steps are very small

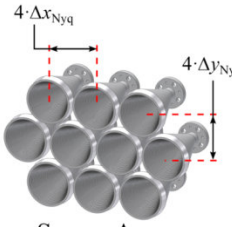
Detector | Footprint on Sky | Number of Pointings

Single-Pixel Receiver

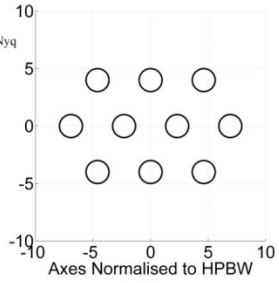


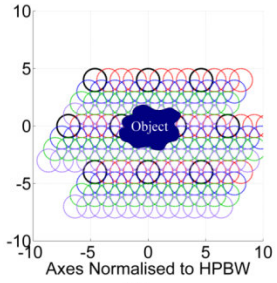


Just point as many times as necessary
Tailored to size of object
Best noise and aperture efficiency

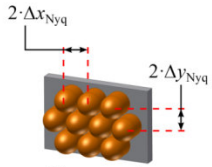


Sparse Array of Feed Horns

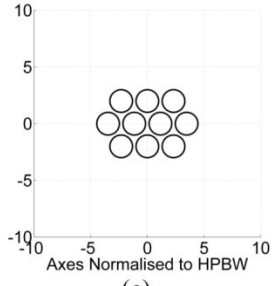


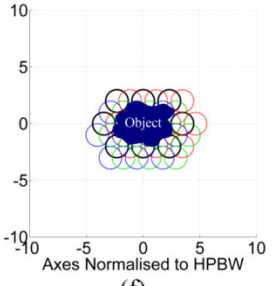


If frequency is at $2\cdot\Theta_{FWHM}$ …16 pointings
Some degradation, but here assume same as single-pixel

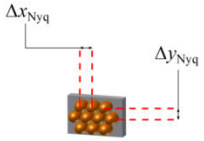


Compact "Twice-Nyquist" Array

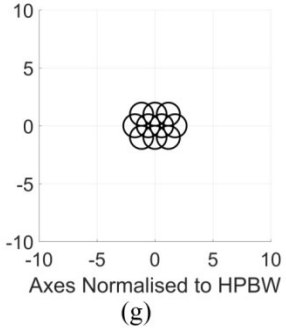


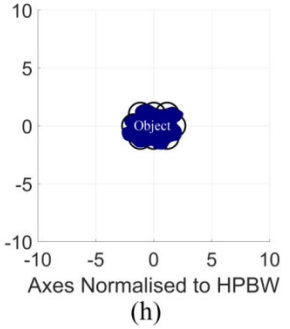


4 pointings
Compromise on signal-to-noise
(T_{oRec} gets ~2.5–5 times worse)



Nyquist-Spaced Array

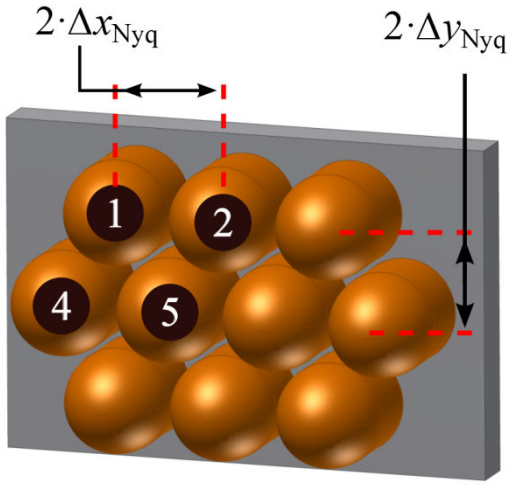


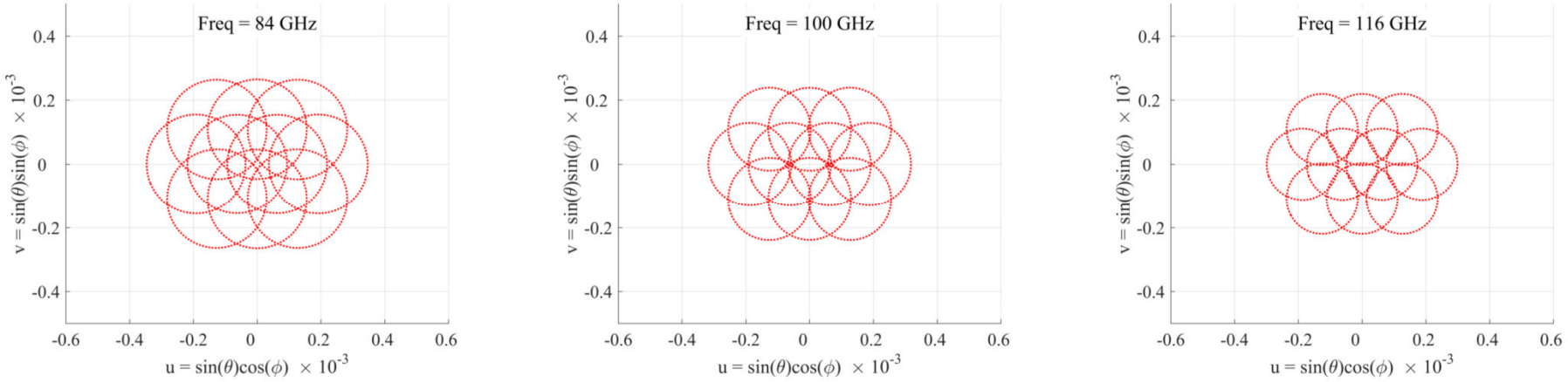


Fully sampled "camera"
Huge degradation in signal-to-noise
(T_{oRec} gets ~6–11 times worse)

➡ τ_{int} depends on T_{sys}

Spacing for Array…only perfect for one frequency



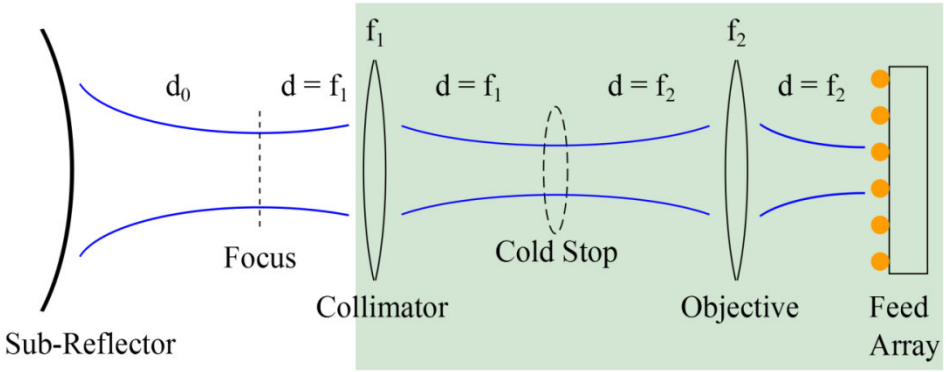


(a) Nyquist, Δx_{Nyq} = 11.94 mm

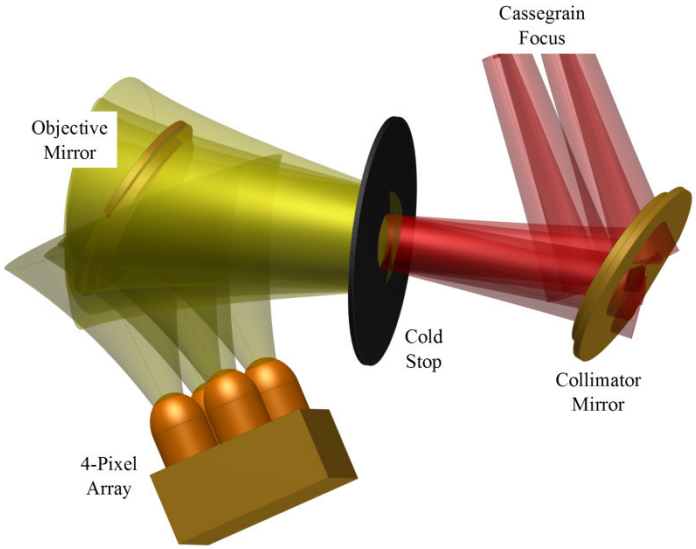
Cold Aperture Stop

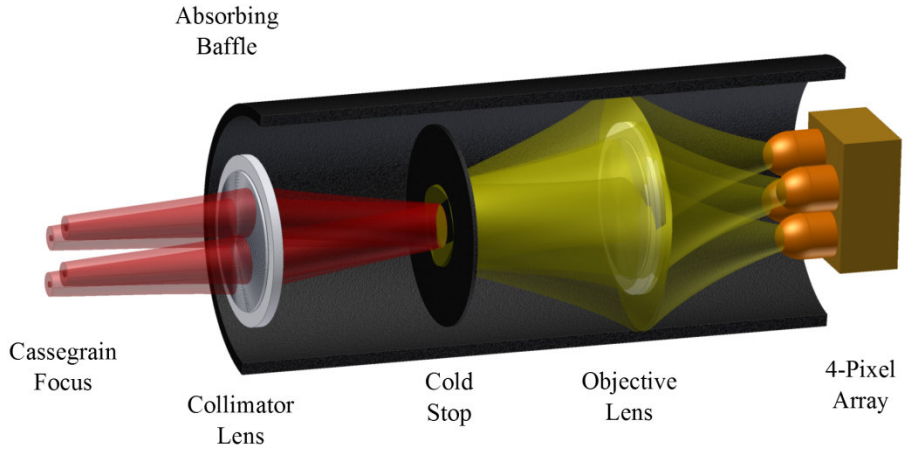
Closer spacing is possible if the optical system uses more uniform aperture illumination with the detector beam truncated by a cold Lyot stop. This is a typical method for incoherent THz instruments but has not yet been implemented in a coherent array receiver.

C. E. Groppi and J. H. Kawamura, "Coherent Detector Arrays for Terahertz Astrophysics Applications," *IEEE Trans. THz Sci. Technol.*, vol.1, no.1, pp. 85–96, Sept. 2011.



- Cold stop aperture is adjusted for maximum aperture efficiency
- Arbitrary detector feed spacing

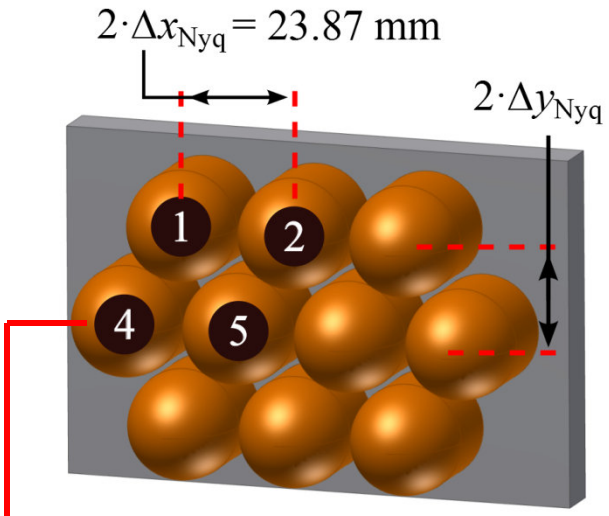




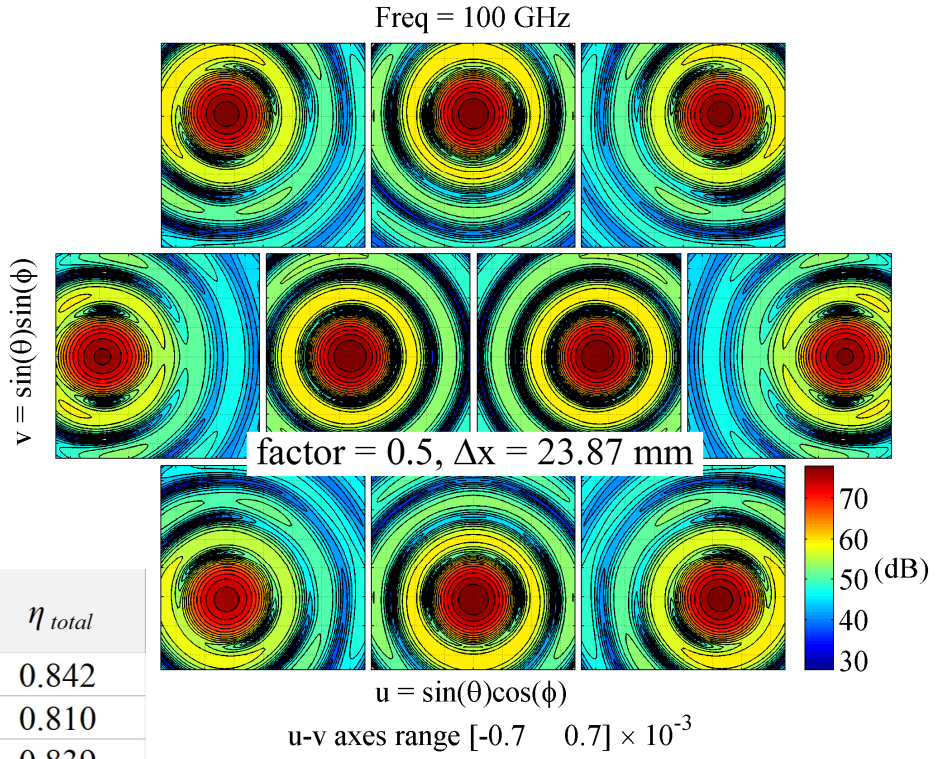
~150 mm separates each element

What Aperture Efficiency can be Expected for Each Beam?

- Neglect power truncated within reimager and by absorber baffling (this will be accounted for by sensitivity degradation)
- I.e., only consider signal exiting reimaging optics for aperture efficiency calculation
- f/D = 1 for reimager, and I choose ~150 mm for diameter & focal length (a bit small)
- Overlap integral for calculation (assume equivalent paraboloid)
- Using GRASP, ideal absorbing surface with aperture cut out



Frequency (GHz)	Feed Element	η_{spill}	η_{amp}	η_{pol}	η_{phase}	η_{total}
84	4^{th} (2·Nyq)	0.894	0.949	1.000	0.992	0.842
100		0.895	0.912	1.000	0.993	0.810
116		0.908	0.935	1.000	0.989	0.839



Simulated Far-Field Beams on Sky

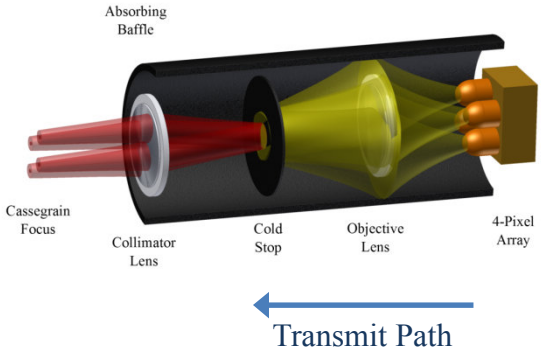
Amount of Terminated Power

- Use GRASP to calculate the amount of spill-over at each reflector within the cryostat (WRT feed)
- Reciprocally, we must consider as noise input and as a loss → cold attenuator

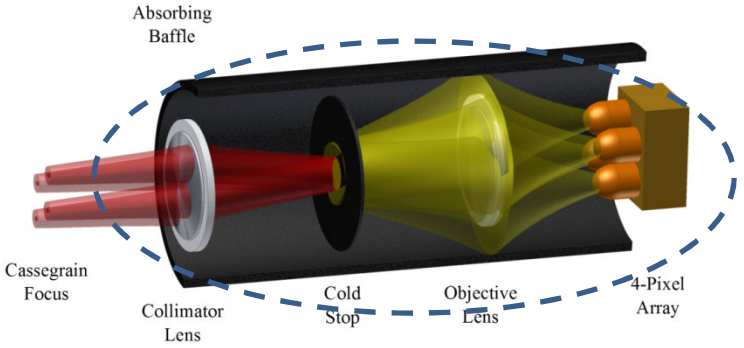
Cumulative Fractional Power
Lenslet Diameter = 22.88 mm, $2 \cdot \Delta x_{Nyq}$ = 23.88 mm

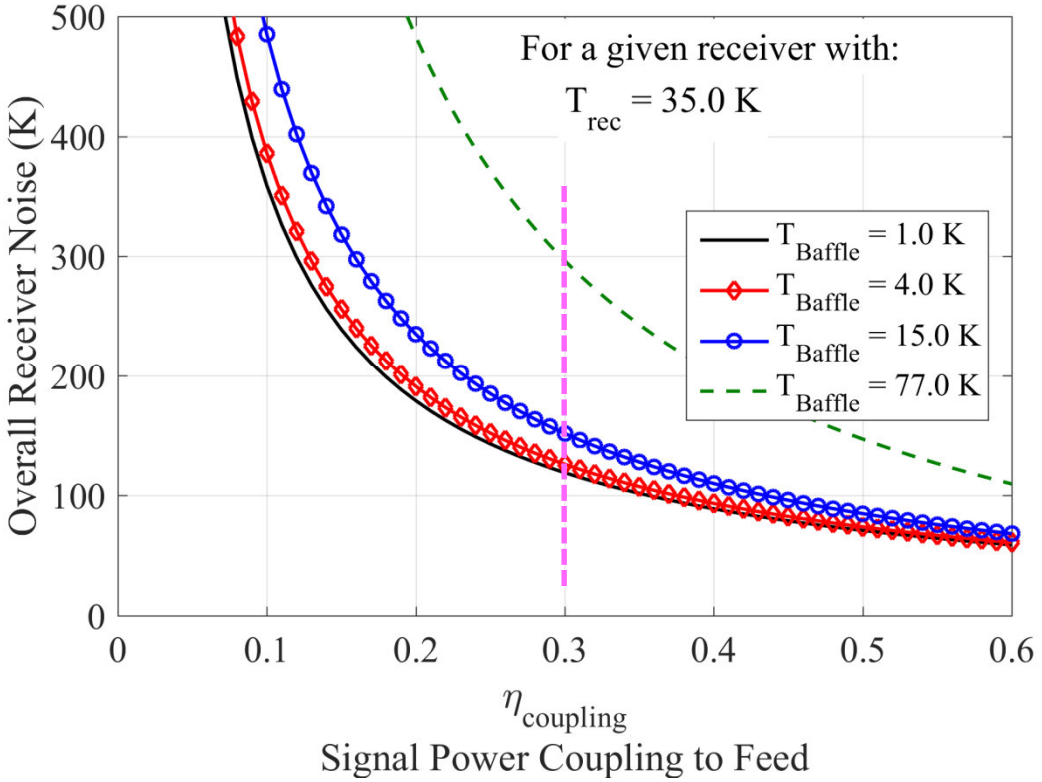
Frequency	Feed Element	Objective	Stop	Collimator	$\eta_{coupling}$
84 GHz	1	70.4%	39.7%	28.7%	26.4%
	2	68.8%	36.3%	30.6%	28.3%
	4	70.0%	40.6%	27.3%	25.0%
	5	67.6%	35.2%	30.6%	28.3%
100 GHz	1	77.3%	39.2%	36.3%	33.7%
	2	77.7%	35.8%	40.2%	37.4%
	4	77.2%	43.0%	32.1%	29.7%
	5	75.8%	32.2%	42.1%	39.3%
116 GHz	1	82.2%	34.6%	45.7%	42.8%
	2	81.5%	29.8%	50.1%	47.0%
	4	83.0%	37.2%	43.6%	40.6%
	5	81.8%	27.6%	52.7%	49.6%

Objective mirror | Cold Stop | Collimator | Signal Coupling



Signal Lost within Reimager: Receiver Noise Degradation

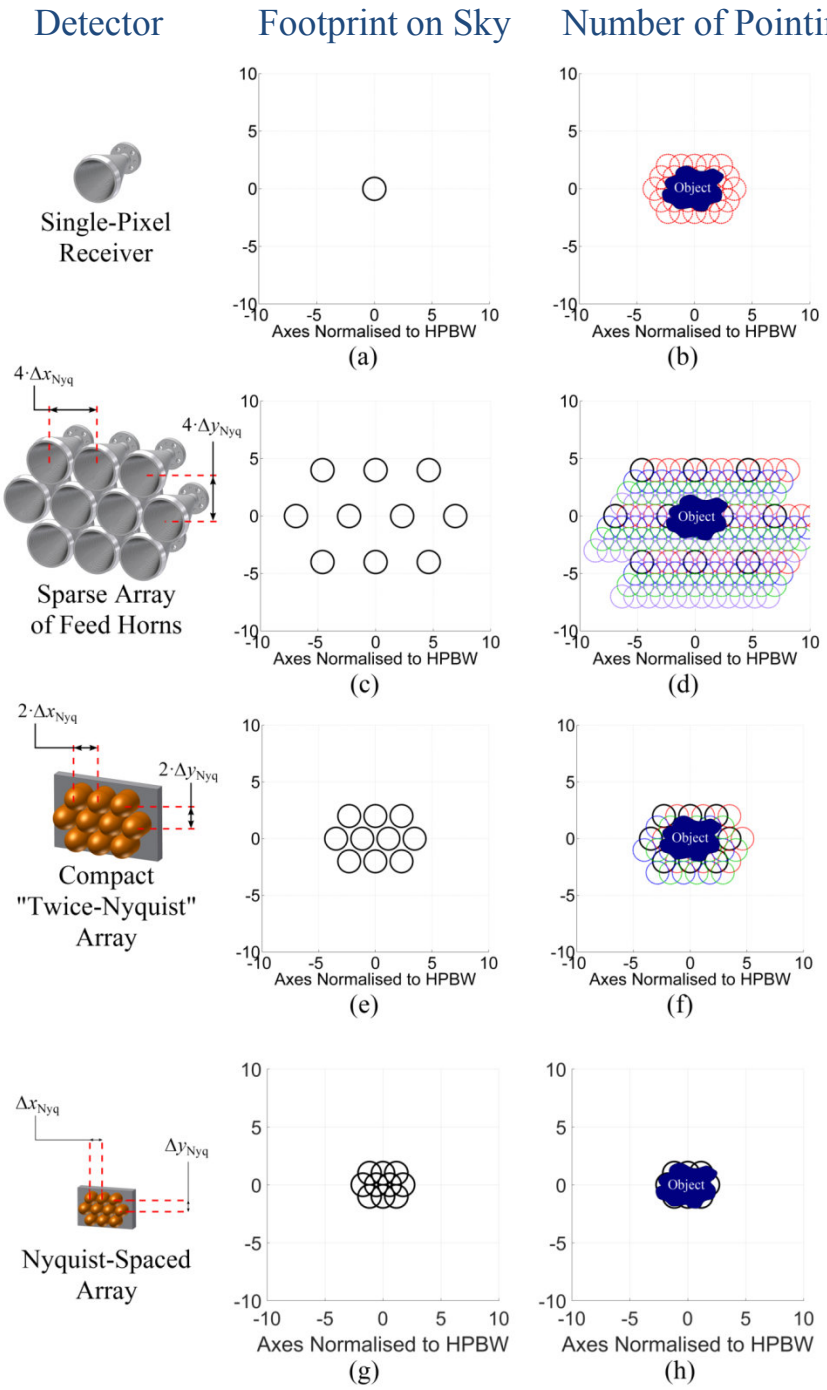


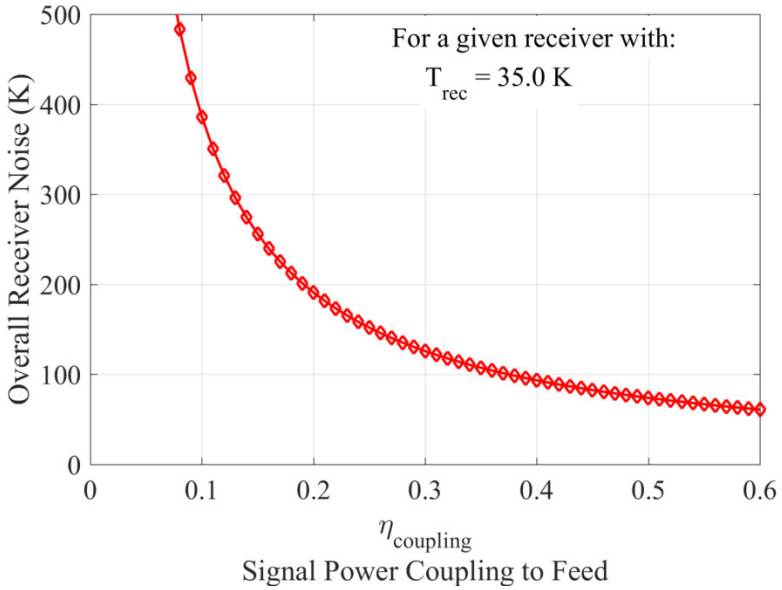


- Signal power that is intercepted within the stop and baffle constitute a noise input to the receiver

$$T_{oRec} = \frac{T_h - YT_c}{Y-1} = \frac{T_{rec} + T_{baffle}\left(1-\eta_{coupling}\right)}{\eta_{coupling}}$$

- Less dense detector layouts allow for more directivity (i.e., larger lenslets)

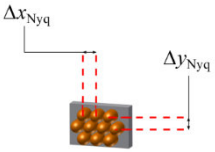




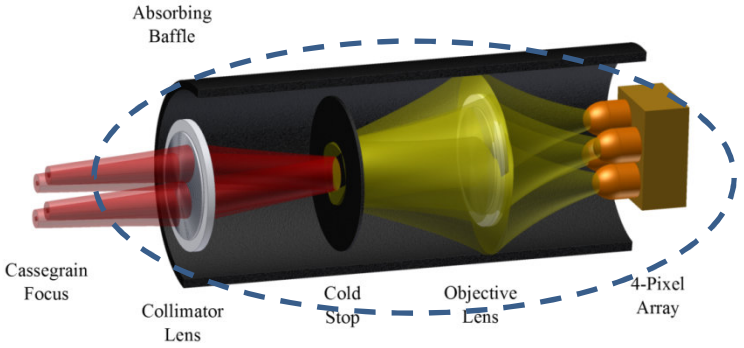
4 pointings
Compromise on sensitivity

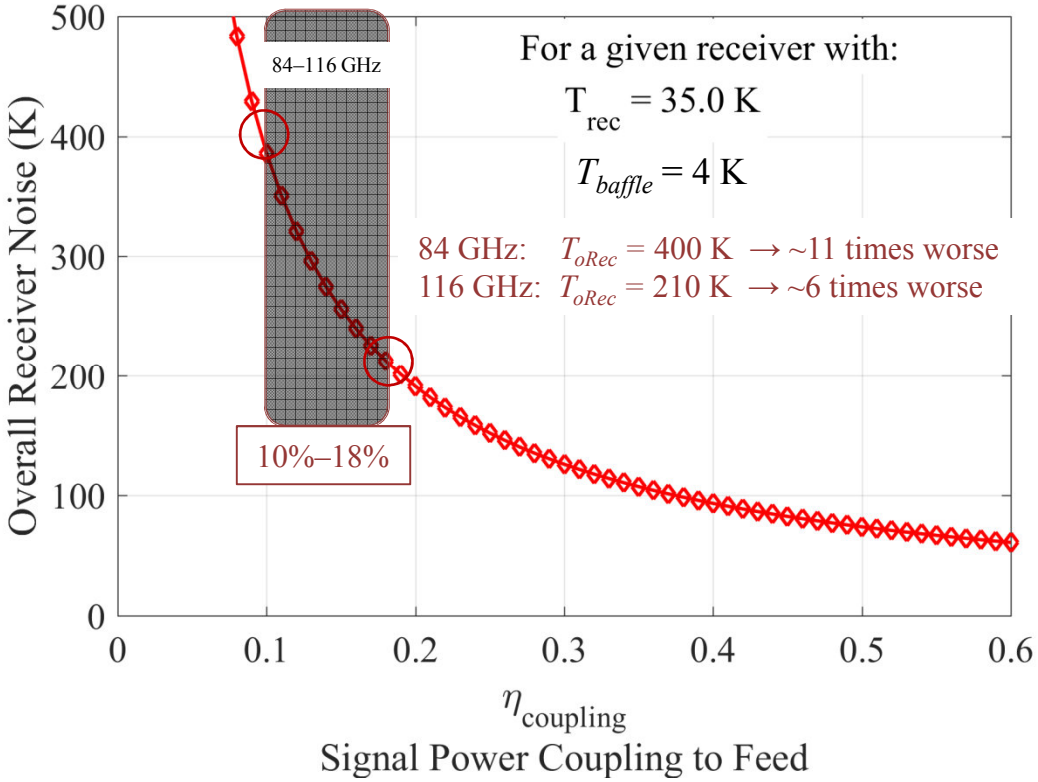
Fully sampled “camera”
Huge degradation in sensitivity

Signal Lost within Reimager: Receiver Noise Degradation



Nyquist-Spaced Array





- Signal power that is intercepted within the stop and baffle constitute a noise input to the receiver

$$T_{oRec} = \frac{T_h - YT_c}{Y-1} = \frac{T_{rec} + T_{baffle}\left(1-\eta_{coupling}\right)}{\eta_{coupling}}$$

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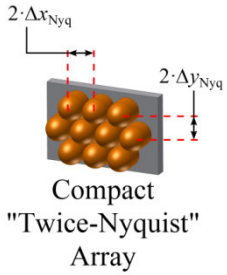
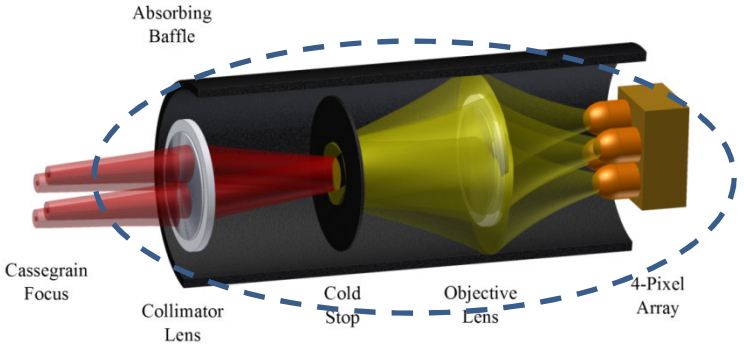
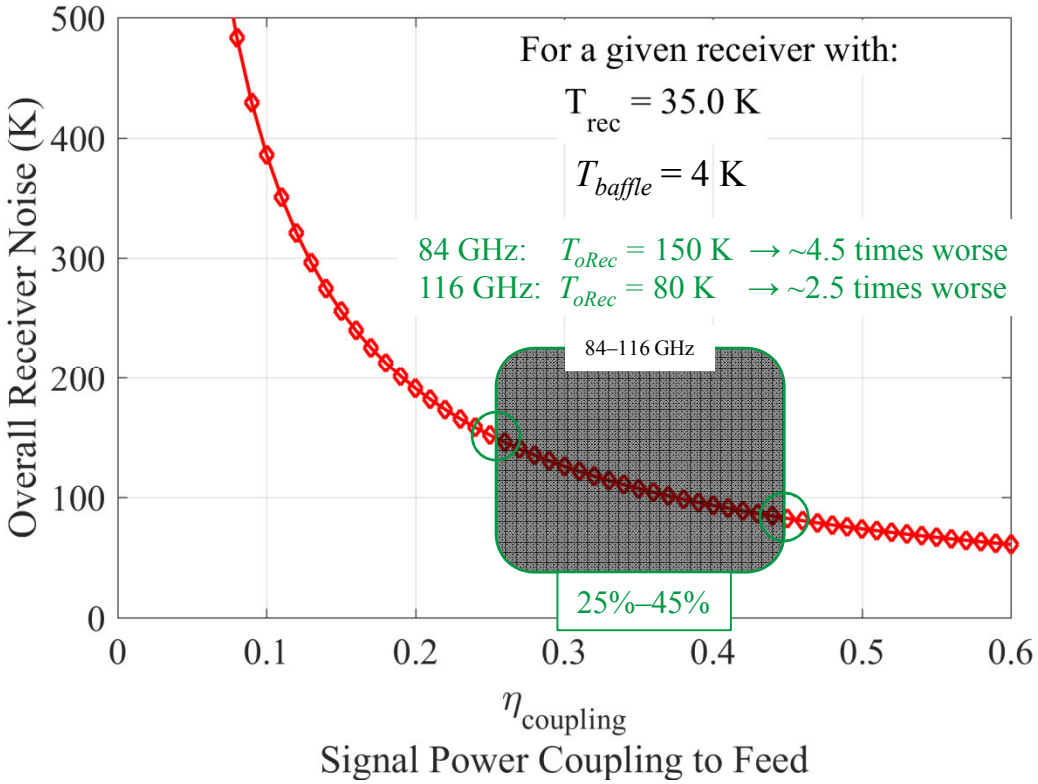
Signal Lost within Reimager: Receiver Noise Degradation







- Signal power that is intercepted within the stop and baffle constitute a noise input to the receiver

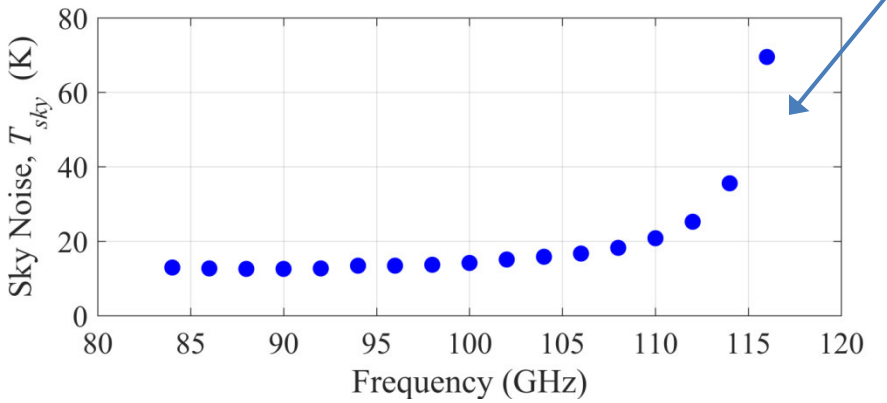
$$T_{oRec} = \frac{T_h - YT_c}{Y-1} = \frac{T_{rec} + T_{baffle}\left(1-\eta_{coupling}\right)}{\eta_{coupling}}$$

- Less dense detector layouts allow for more directivity (i.e., larger lenslets)

System Noise Temperature, T_{sys}

- The primary goal of a feed array is to improve mapping speed ~$(A_e/T_{sys})^2$

$$T_{sys} = \frac{1}{\eta_{eff} e^{-\tau_0}} \left(T_{oRec} + \eta_{eff} T_{sky} + \left(1 - \eta_{eff}\right) T_{amb} \right)$$

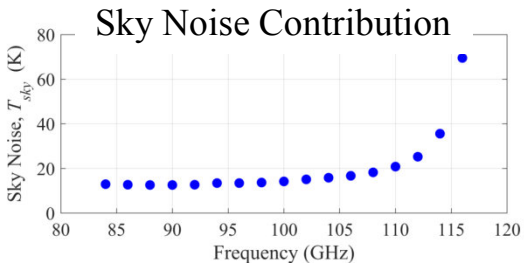


Freq. (GHz)	Single-Pixel or Sparse Array Element		Twice-Nyquist Element	
	T_{oRec}	T_{sys}	T_{oRec}	T_{sys}
84	35	67	130	172
100	35	69	94	134
116	35	169	74	226

From ALMA Sensitivity Calculator

System Noise Temperature, T_{sys}

- System noise temperature of each array element
  - depends dominance of T_{oRec} within T_{sys}
  - ALMA B3 is an interesting example b/c of the large change in sky noise
  - Across the band, B3 goes from “detector-limited” towards “background-limited”

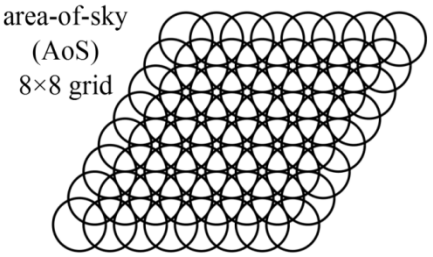


Freq. (GHz)	Single-Pixel or Sparse Array Element	Twice-Nyquist Element	Factor Difference
	T_{sys} (K)		
84	67	172	~2.5
100	69	134	~2.0
116	169	226	~1.3

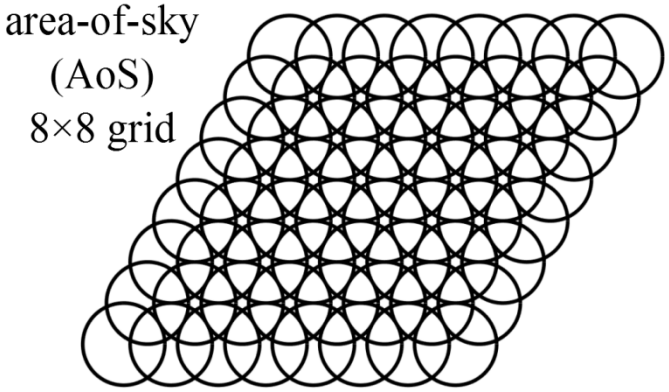
Mapping Speed

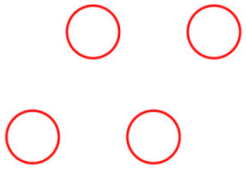
- Mapping speed ~$(A_e/T_{sys})^2$ / N_p for a given Area-of-Sky
- One way to compare mapping speed WRT a single-pixel receiver:
  - Fix the size of AoS
  - Choose size of array to fit AoS
  - Determine total number of pointings to sample AoS

Single Pixel Beam Spot

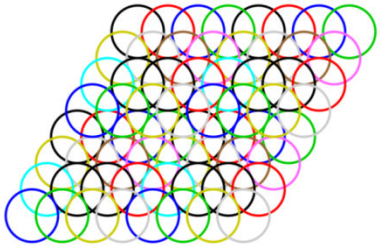


64 pointings

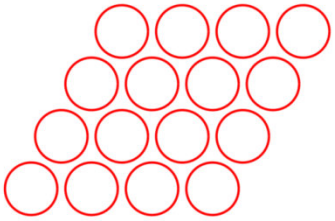




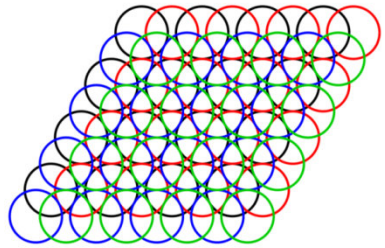
2×2 Sparse Array



16 pointings



4×4 Twice-Nyquist Array

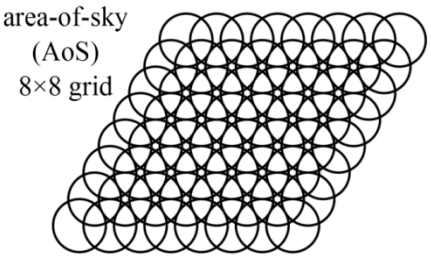


4 pointings

Normalized (Point Source) Mapping Speed

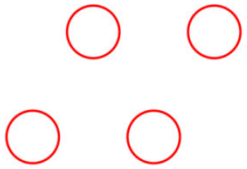
- point-source mapping speed ~$(A_e/T_{sys})^2$ / N_p

Single Pixel Beam Spot

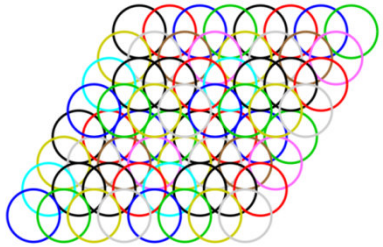


64 pointings

	Array Size		
AoS Grid of Points	Single-Pixel Receiver	Sparse Array	Twice-Nyquist Array
8×8	**1**	**2×2**	**4×4**

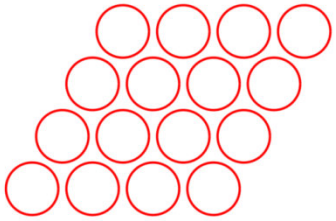


2×2 Sparse Array

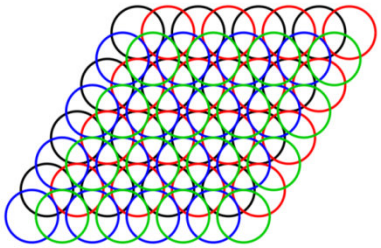


16 pointings

	Minimum Number of Pointings, N_p		
AoS Grid of Points	Single-Pixel Receiver	Sparse Array	Twice-Nyquist Array
8×8	**64**	**16**	**4**



4×4 Twice-Nyquist Array



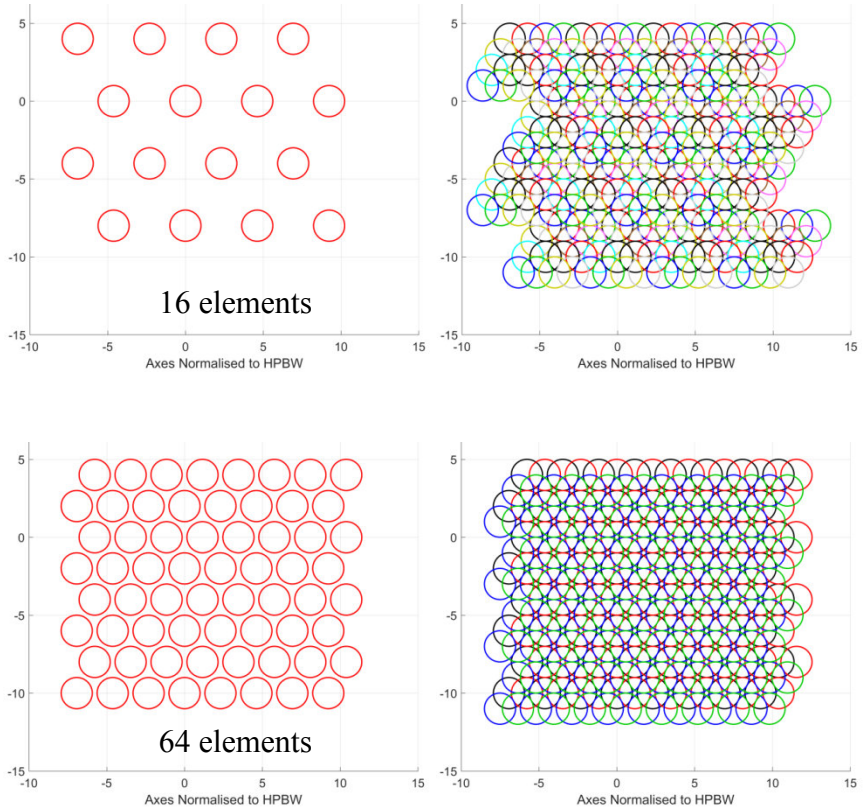
4 pointings

(Array Mapping ÷ Single-Pixel Mapping)

	Normalized Point Source Mapping Speed				
			Twice-Nyquist Array		
AoS Grid of Points	Single-Pixel Receiver	Sparse Array	84 GHz	100 GHz	116 GHz
8×8	**1**	**4.0**	**2.4**	**4.2**	**8.9**

Normalized (Point Source) Mapping Speed

- point-source mapping speed ~$(A_e/T_{sys})^2 / N_p$



AoS Grid of Points	Array Size: Single-Pixel Receiver	Sparse Array	Twice-Nyquist Array
8×8	**1**	**2×2**	**4×4**
→ 16×16	**1**	**4×4**	**8×8**

AoS Grid of Points	Minimum Number of Pointings, N_p: Single-Pixel Receiver	Sparse Array	Twice-Nyquist Array
8×8	**64**	**16**	**4**
→ 16×16	**256**	**16**	**4**

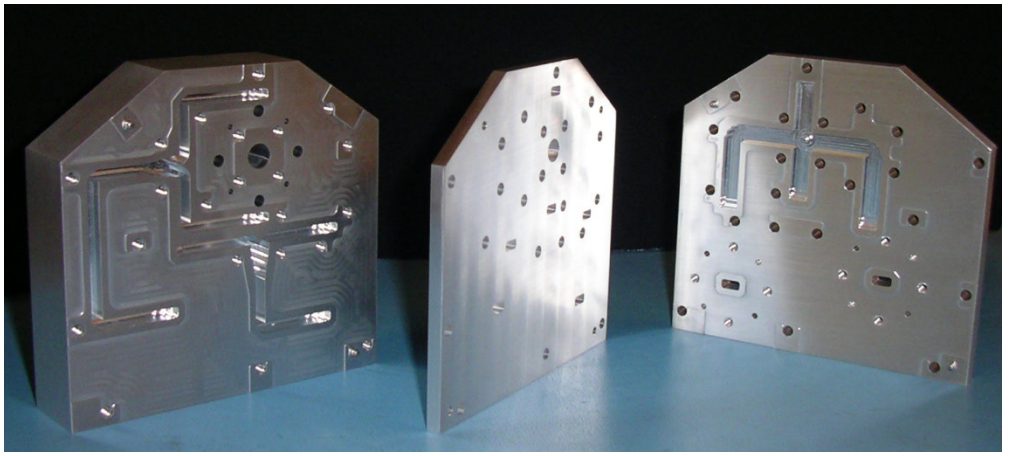
(Array Mapping ÷ Single-Pixel Mapping)

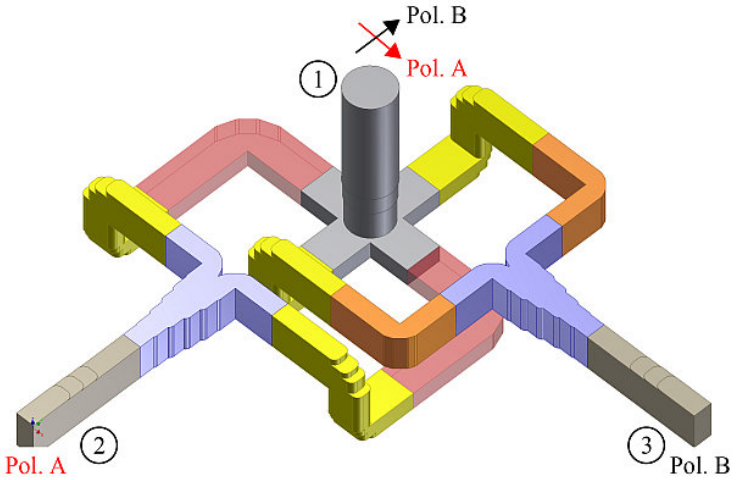
AoS Grid of Points	Normalized Point Source Mapping Speed: Single-Pixel Receiver	Sparse Array	Twice-Nyquist Array: 84 GHz	100 GHz	116 GHz
8×8	**1**	**4.0**	**2.4**	**4.2**	**8.9**
→ 16×16	**1**	**16.0**	**9.7**	**16.8**	**35.6**

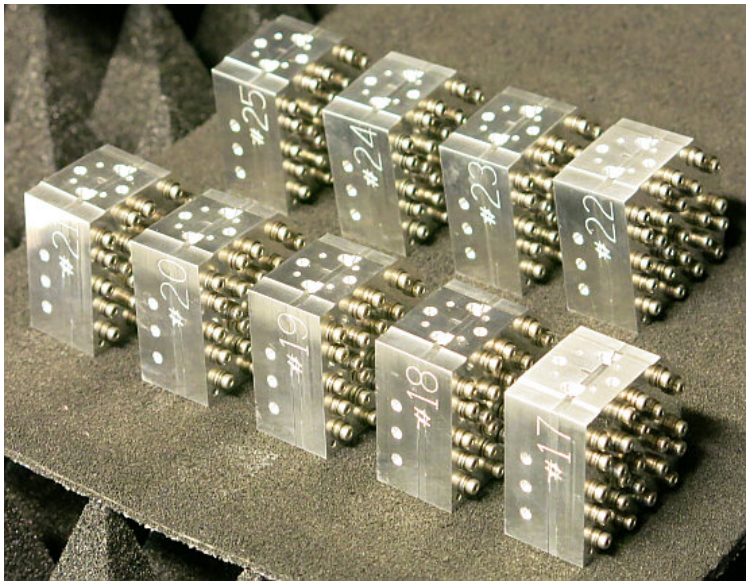
Wideband OMT

Turnstile based OMTs:

- 33–52 GHz
- 70–116 GHz



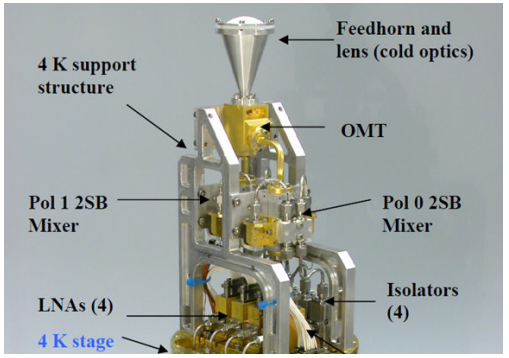


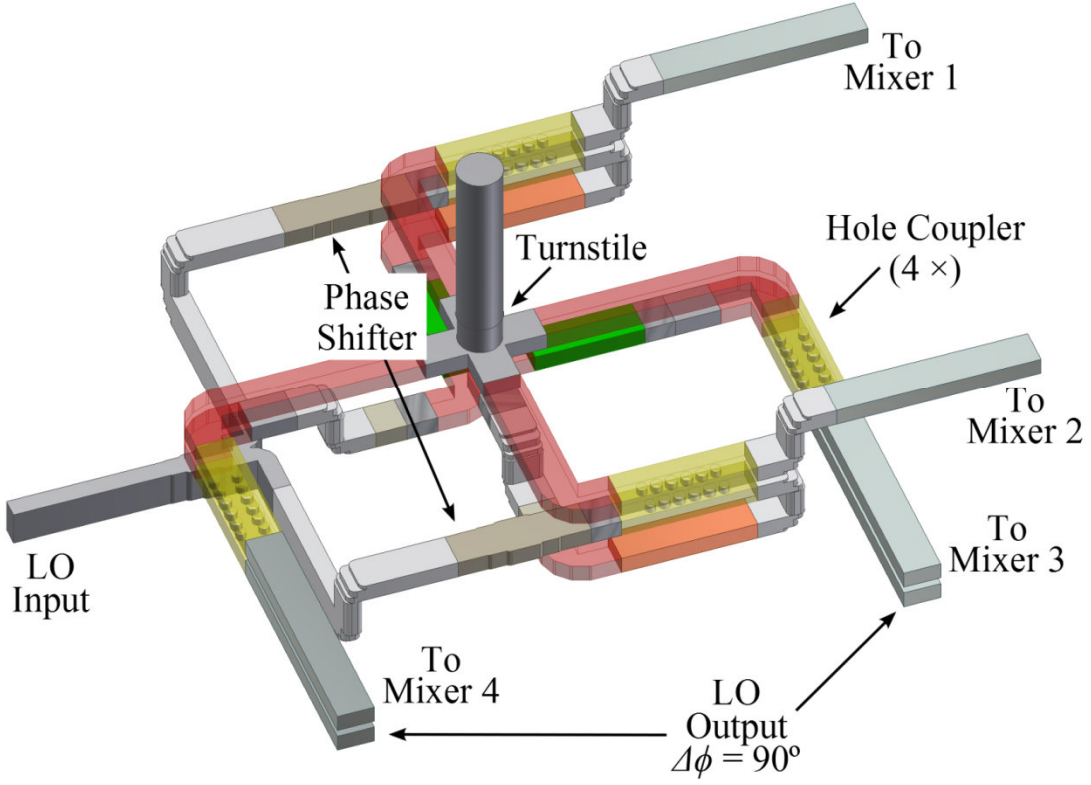


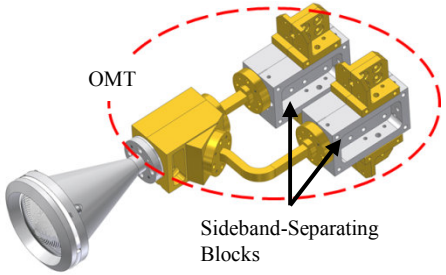
- Turnstile discriminates polarisation + evenly divides signal in-phase
- Part of the challenge of the OMT is to recombine the outputs
- If using 2SB…use turnstile as in-phase splitter

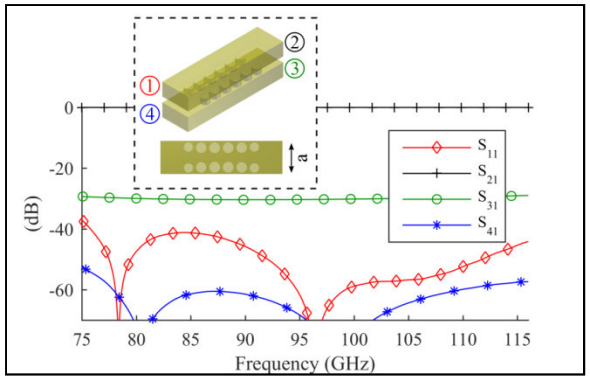
Integration of a Hole Coupler with a Turnstile for 2SB

- Integrate OMT + 2SB block
- Hole coupler for LO coupling (broadband, machinable, high isolation)

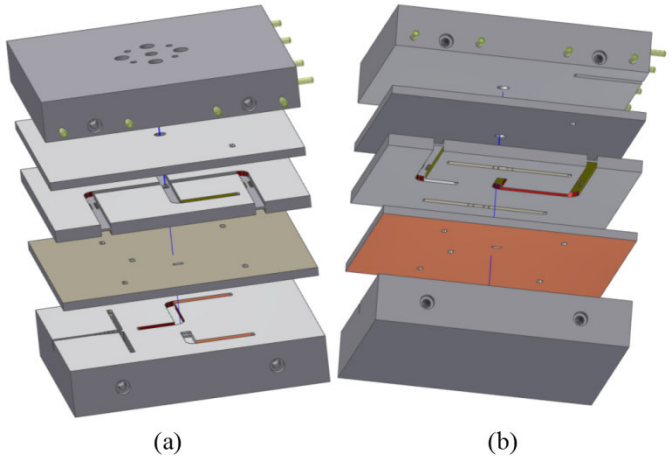


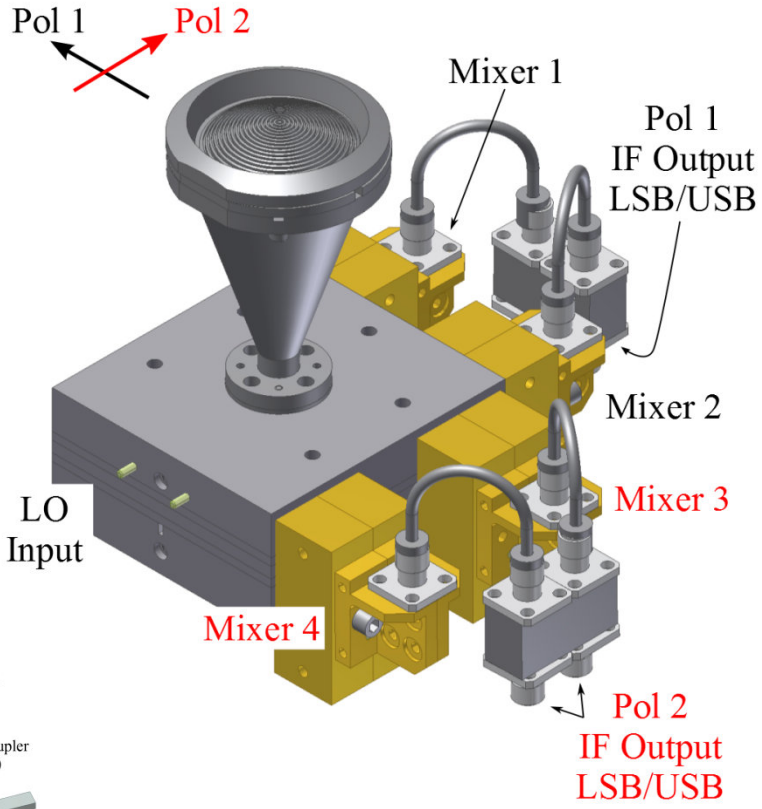


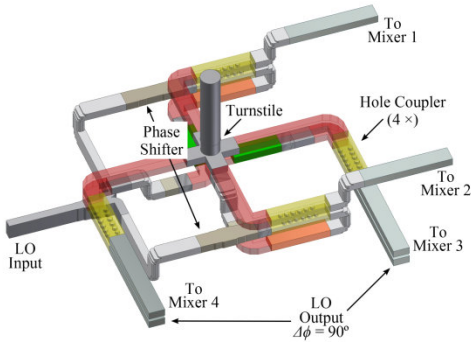




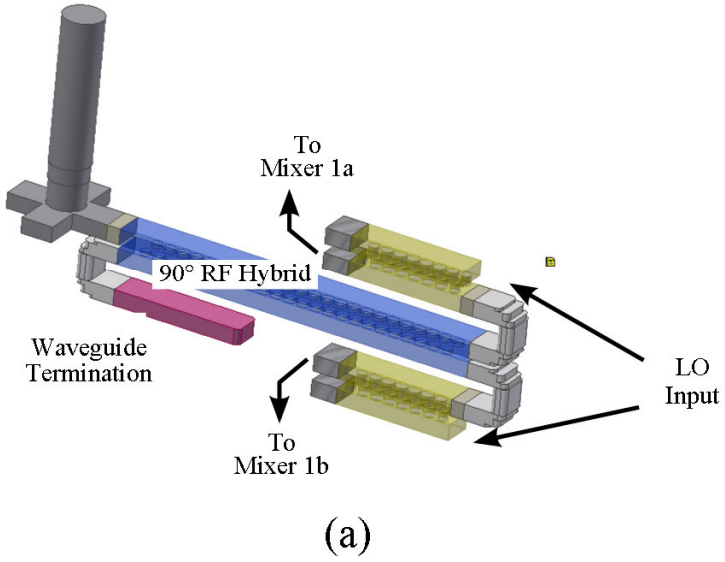
OMT + 2SB Block

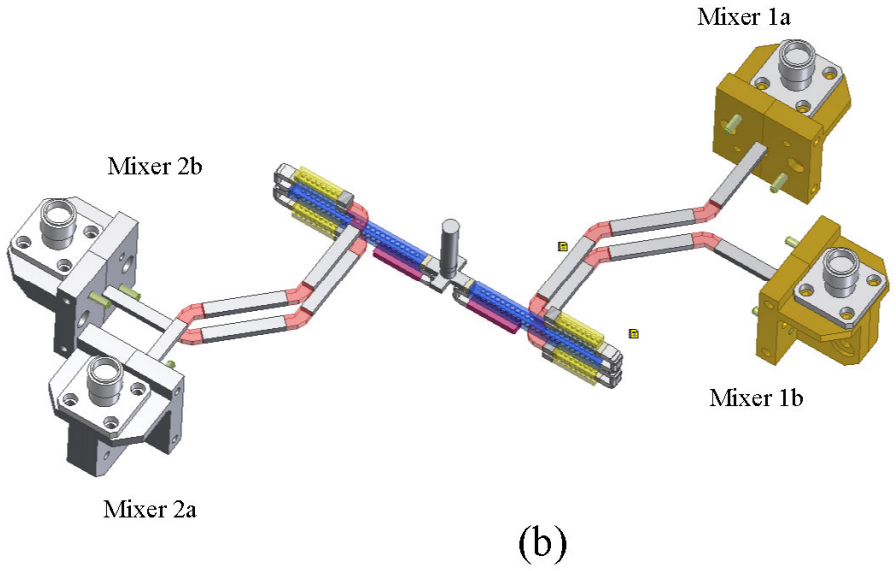


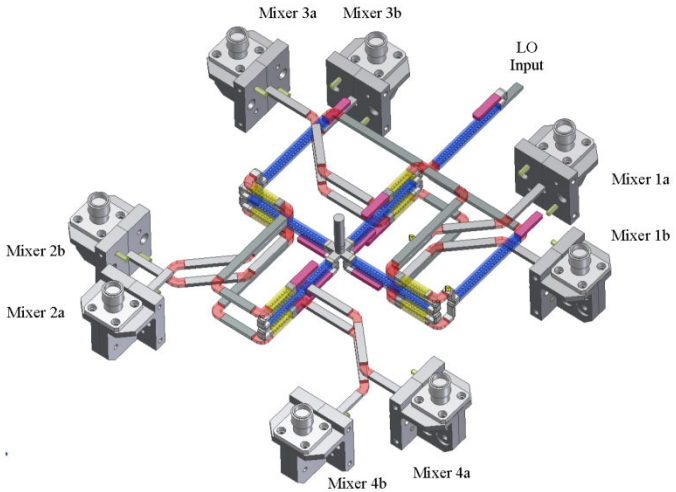




Balanced, Dual-Linear, 2SB?







Frequency of Feed Arrays

- Scientific interest? What frequency should we concentrate on for arrays? (~100 GHz, ~350 GHz?)

Thank you

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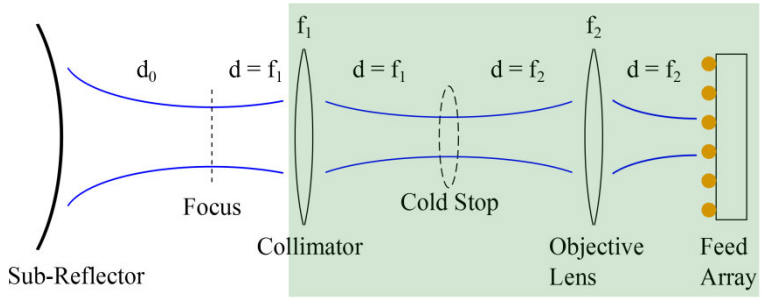
Acknowledgements:

Stéphane Claude
James Di Francesco
Pat Niranjanan
Lewis Knee

Extra Slides

Optical Path for Array: GRASP

- Quasioptics: work backwards from secondary
- Simplified GRASP analysis



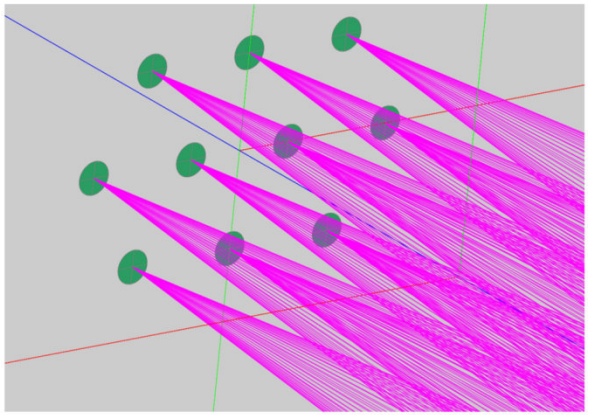
In this example,
$f_1 = f_2 = 158$ mm & $f/D = 1$

(a) hexagonal layout of feeds

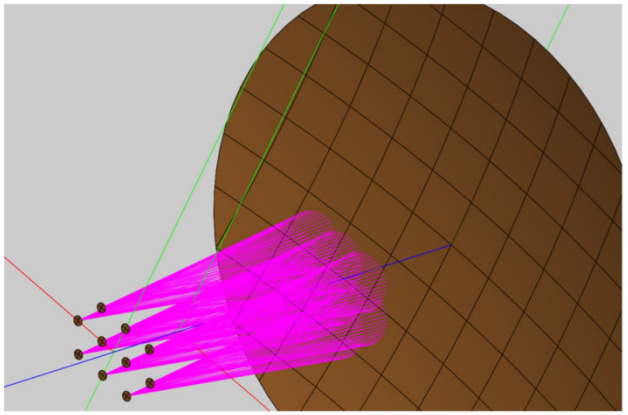
(b) off-axis beams illuminating the objective mirror

(c) beams converge to "optical waist" (location of stop) (truncation not shown)

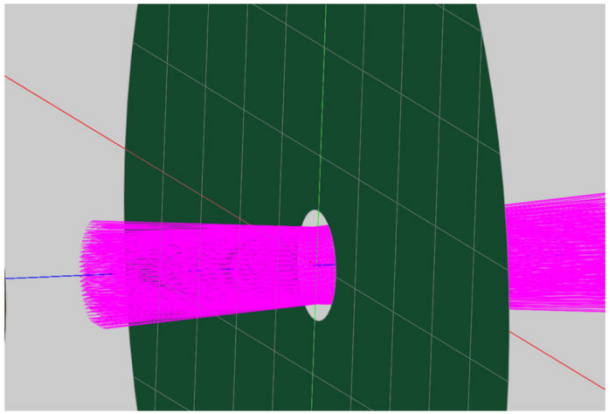
(d) output of collimator…shows reimaging onto the focal plane.



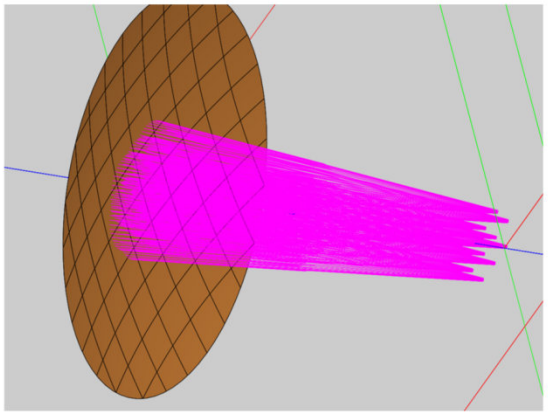
(a)



(b)

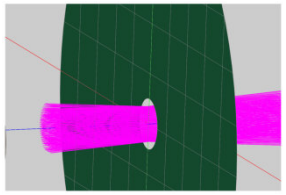


(c)

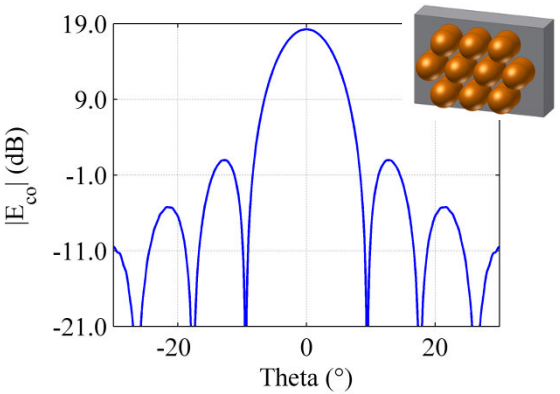


(d)

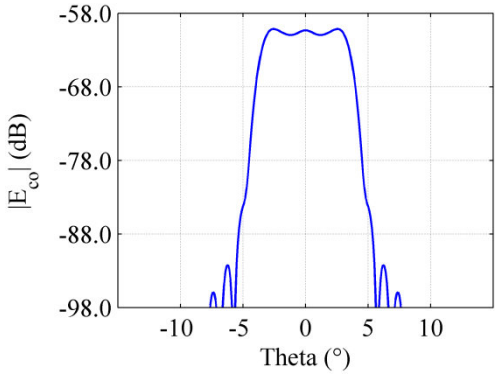
Radiation Patterns along the Optical Path



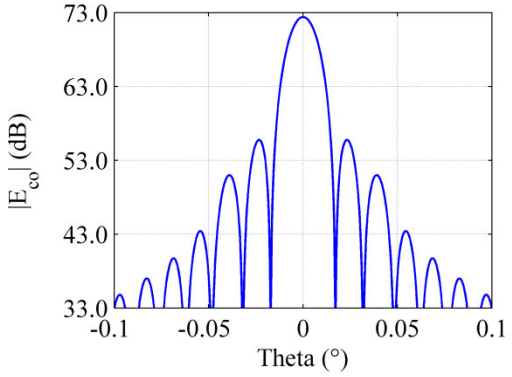
Far-field output of aperture stop



Near-field output of collimator at secondary

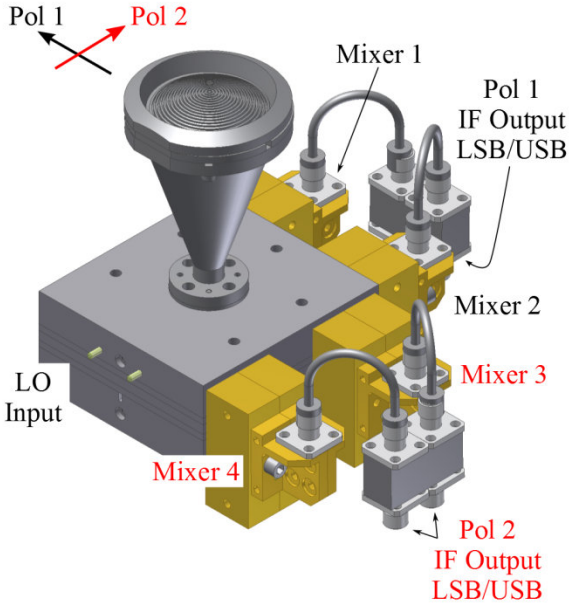


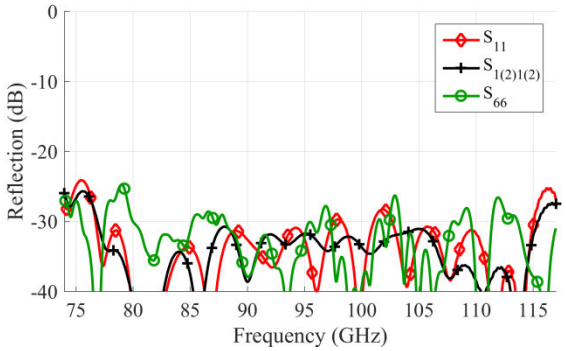
Far-field of telescope

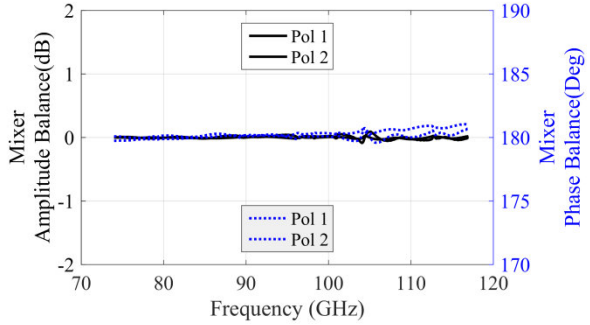


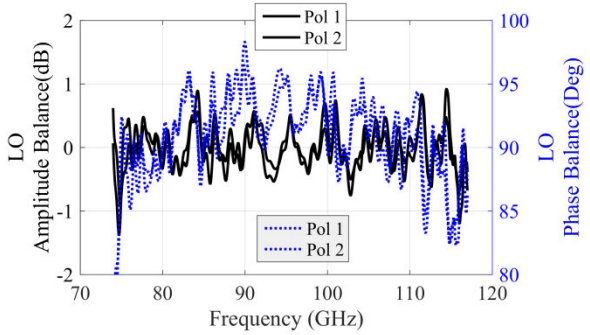
DL-2SB Block Simulation

- Mixer path imbalances of ±0.2 dB and ±2º
- LO coupled path imbalances of ±1.0 dB and ±10º
- Indicate that 15–20 dB of image rejection may be achieved
- Drawbacks: Does not have input RF Hybrid, so reflected power from mixers or LNA can leak into other polarization or be reflected out the feed horn

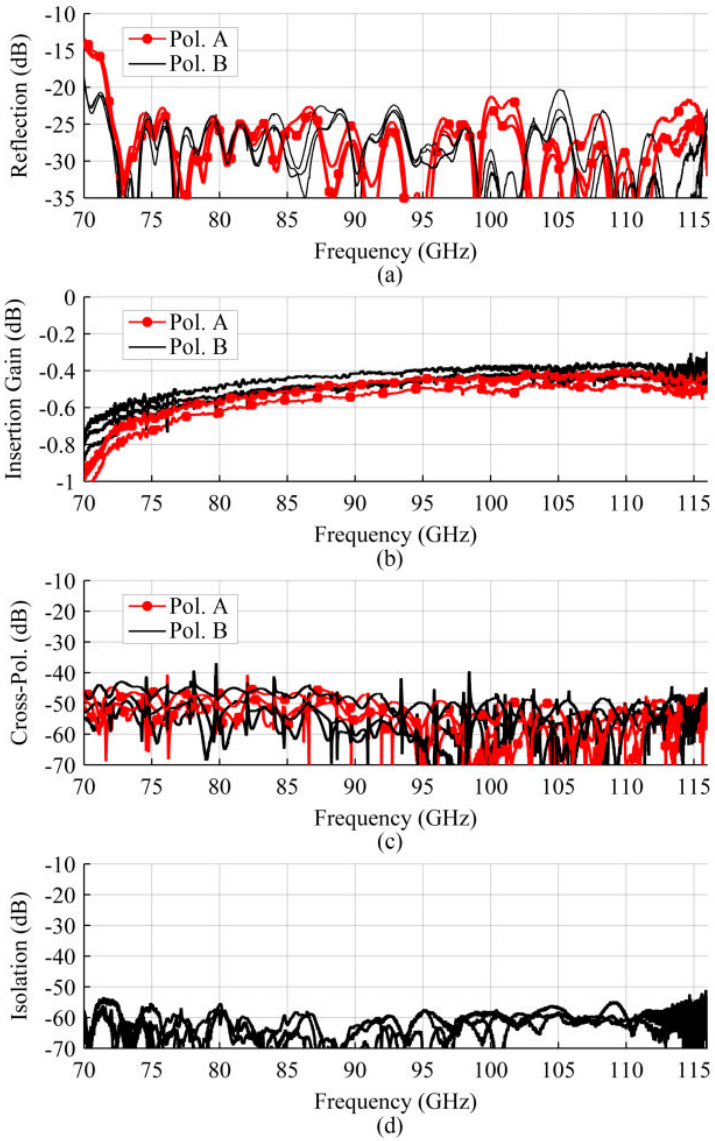


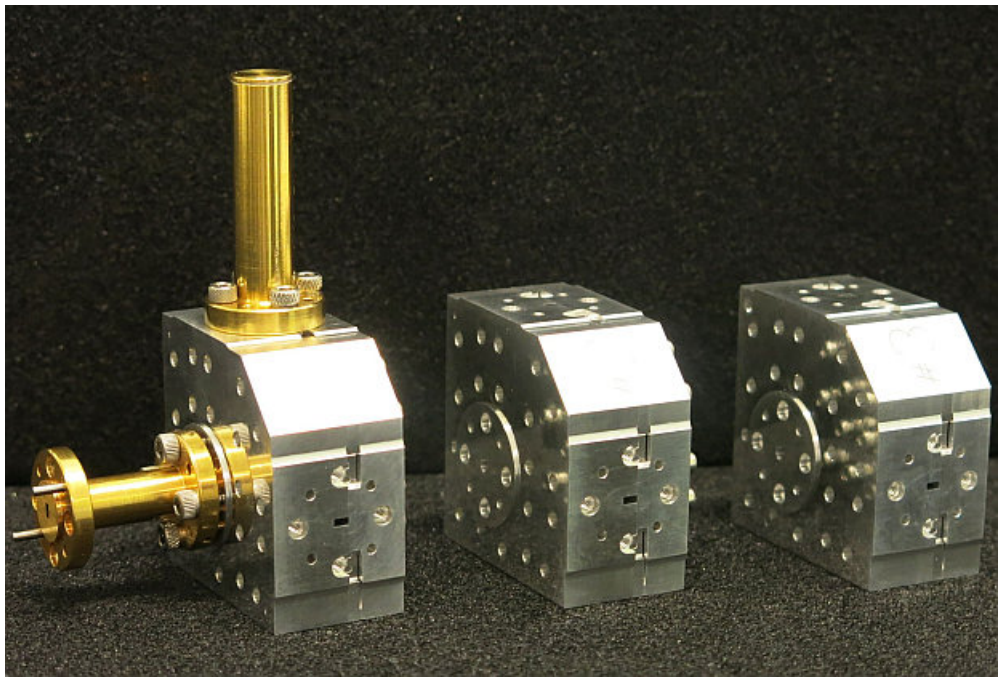






70–116 GHz OMTs





D. Henke and S. Claude, "Design of a 70–116 GHz W-band turnstile OMT," in *44th Eur. Microw. Conf.*, Rome, Italy, Oct. 6–9, 2014, pp. 456–459.