OPTICS OF SINGLE BEAM, DUAL BEAM & ARRAY RECEIVERS ON LARGE TELESCOPES

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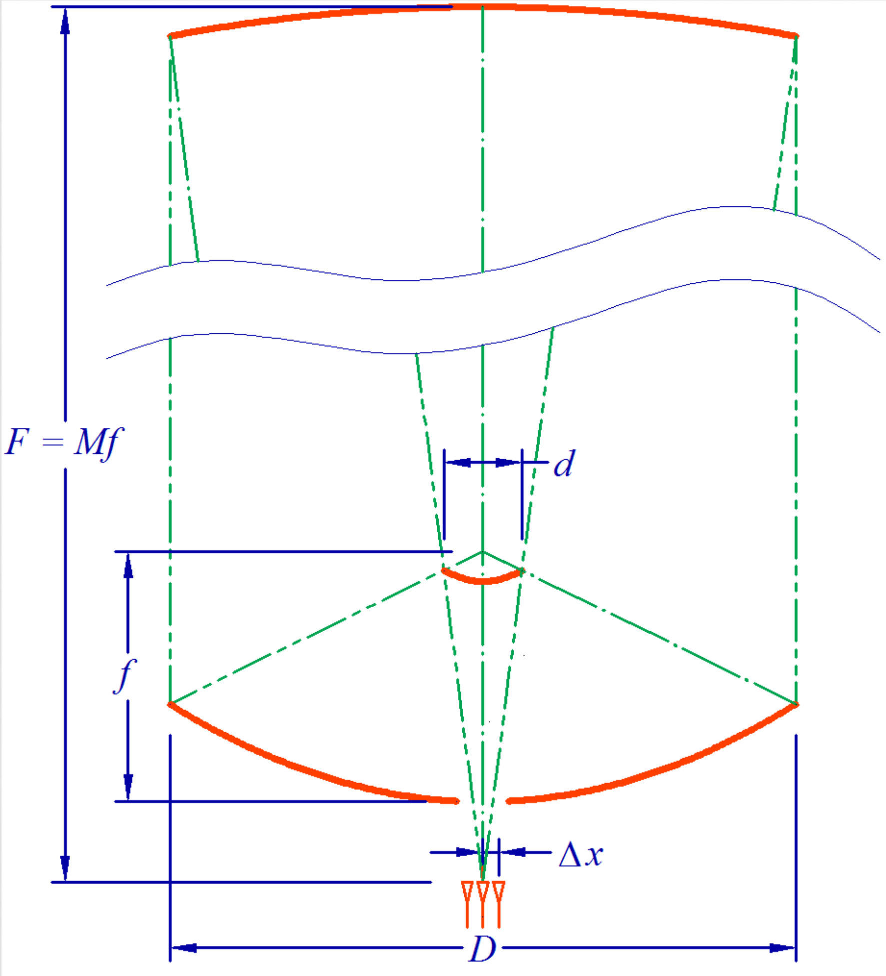
OUTLINE

- Antenna optics
  - Aberrations
  - Diffraction
- Single feeds
  - Types of feed
  - Bandwidth
  - Imaging feeds
- Dual feeds
  - Beam switching
  - Nutating secondary
- Focal plane arrays
- Aperture plane arrays
- Conclusion

ANTENNA ABERRATIONS



Numerical aperture: $N = F/D$

RMS path error

Astigmatism: $p_{rms} = 2\frac{\Delta x^2}{d}\frac{1}{(4N)^3}$

Coma: $p_{rms} = \frac{\sqrt{2}}{6}\Delta x\frac{1}{(4N)^3}$

Efficiency loss: $\left(\frac{2\pi}{\lambda}p_{rms}\right)^2$

COMA VS. ASTIGMATISM

ALMA antenna

D = 12 m

f = 4.8 m

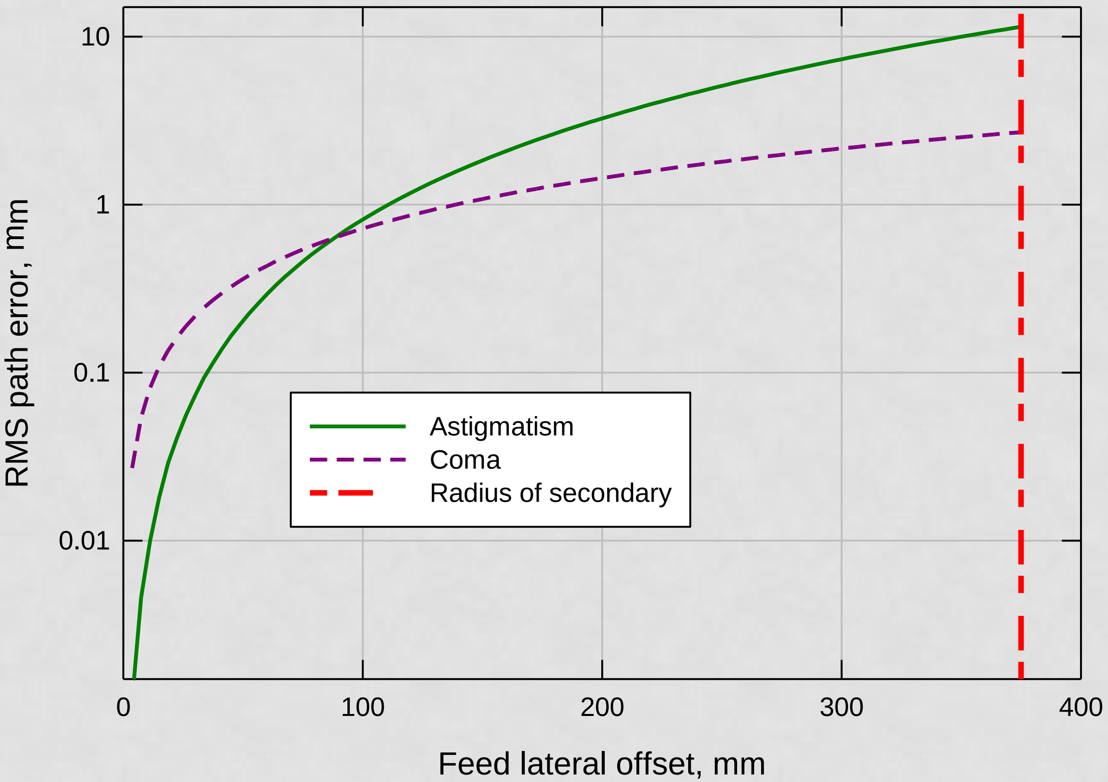
d = 750 mm

M = 20

$F = Mf$ = 96 m

$N = F/D$ = 8

surface error: 20 μm



Note

Ritchey–Chrétien

telescopes designed to reduce ***coma***, but they degrade ***astigmatism***

ANTENNA PATTERN

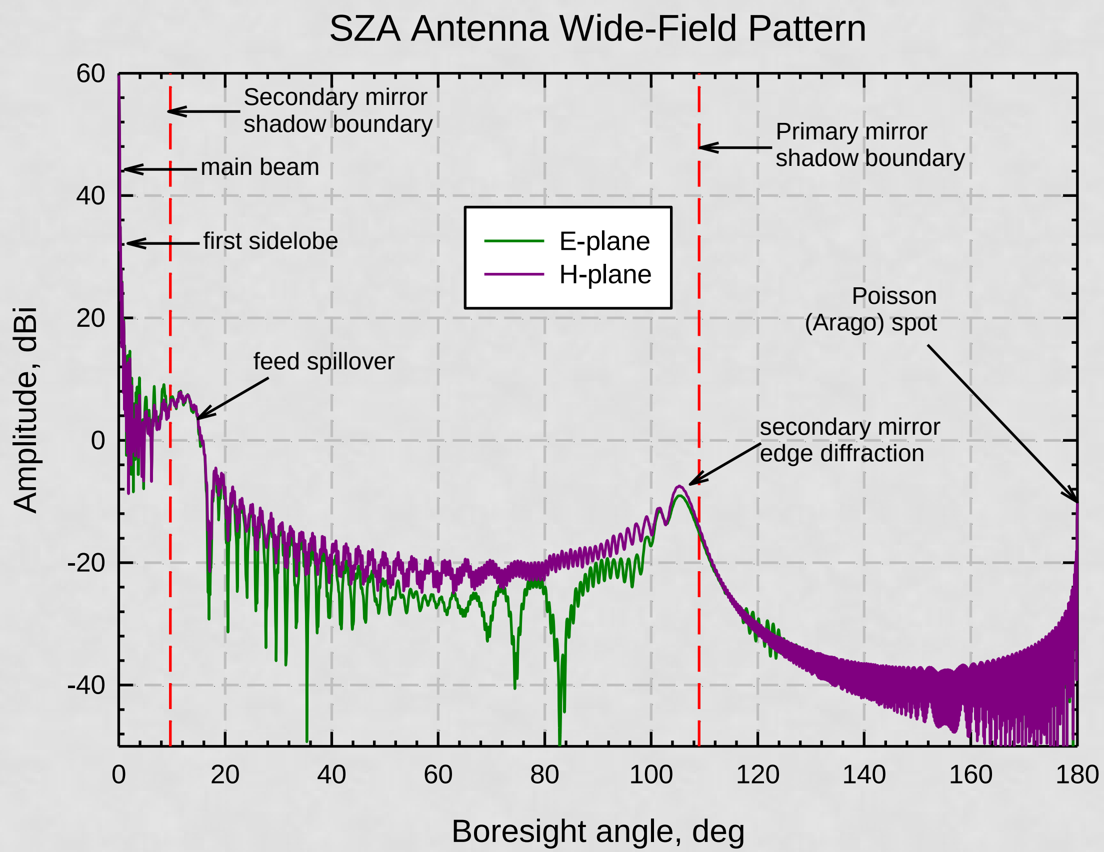
SZA antenna

$D = 3.5$ m

$f = 1.4$ m

$d = 350$ mm

$\lambda = 1$ cm



Note

Diffraction spillover proportional to $\lambda^{1/2}$

OTHER ANTENNA PERFORMANCE ISSUES

- Focal surface
  - Petzval surface
  - Half sum of optical element curvatures
  - Surface has radius of curvature ~2 x secondary radius of curvature
  - Single offset pixel — refocus secondary (e.g., ALMA)
  - Pixel array — place on Petzval surface

- Polarization
  - Offset feeds have beam separation between LCP and RCP

PLANAR FEEDS

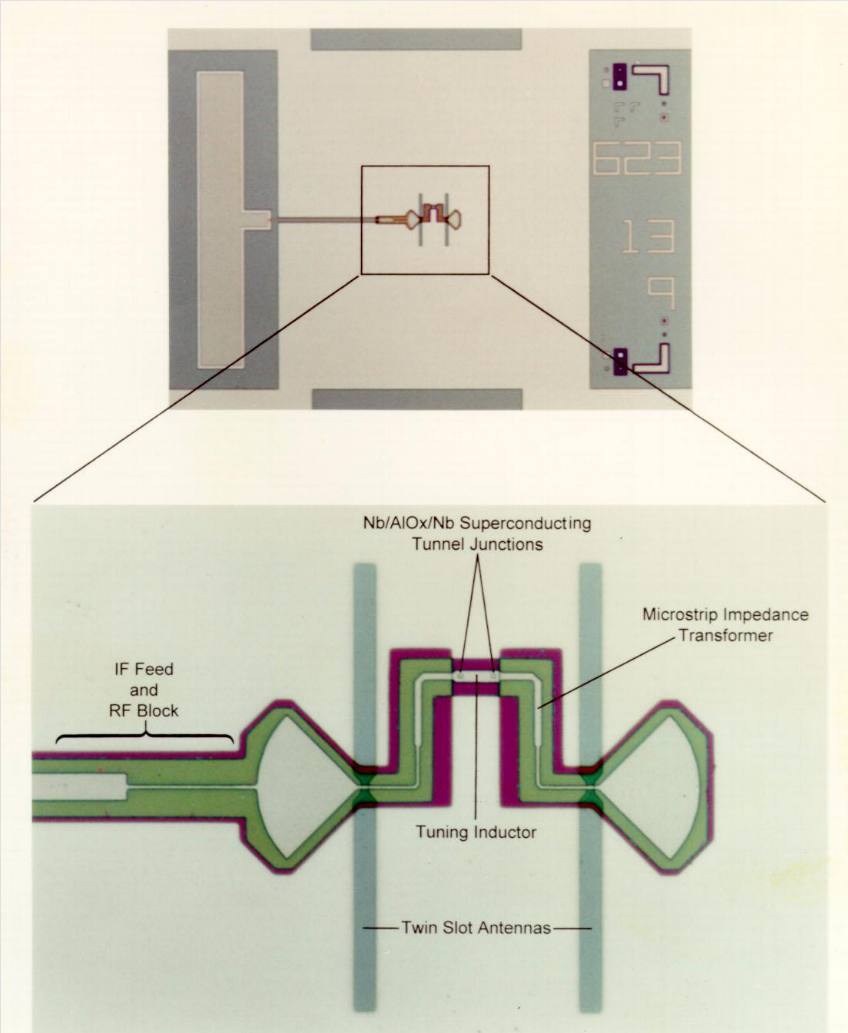
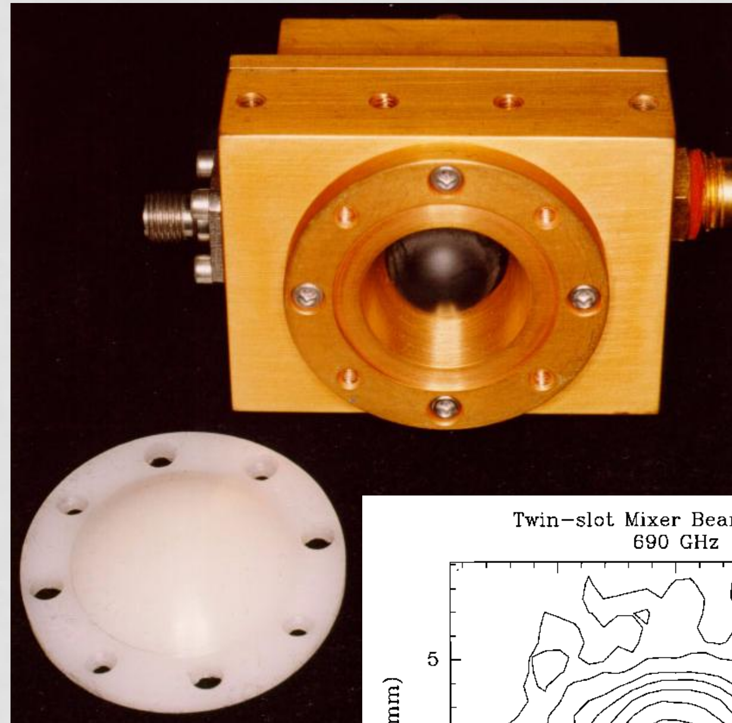
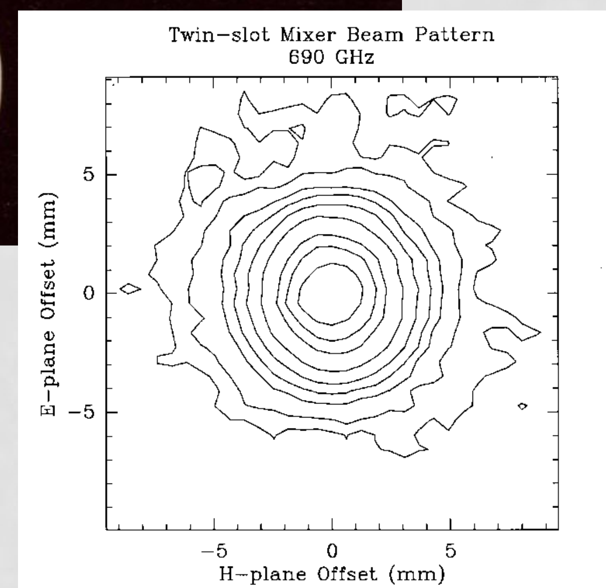


Figure 4: A microscope photograph of our SIS mixer chip. Note the microstrip radial stubs, quarter-wave transformers, and the two-junction tuning circuit.



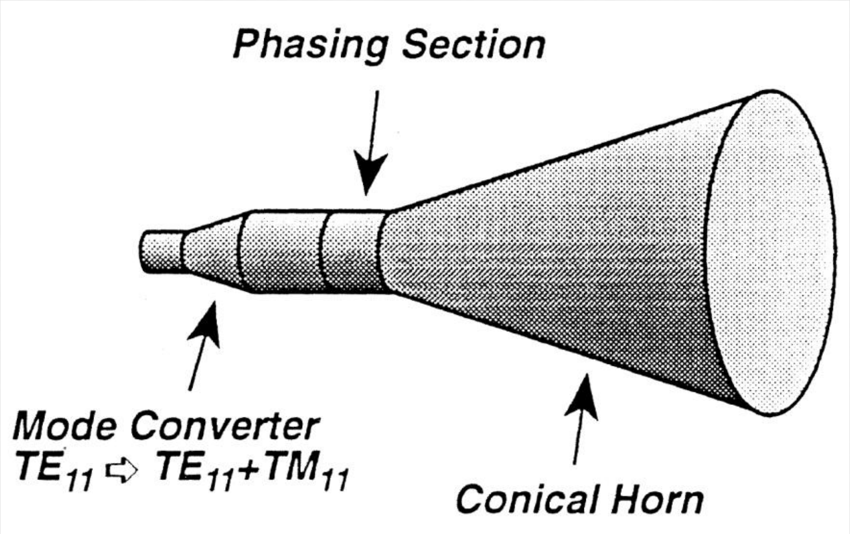
J. Zmuidzinas,
Caltech



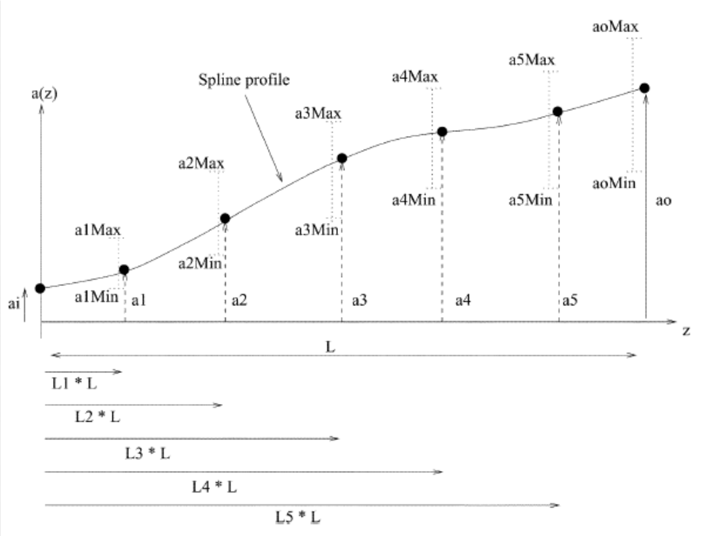
WAVEGUIDE FEEDS

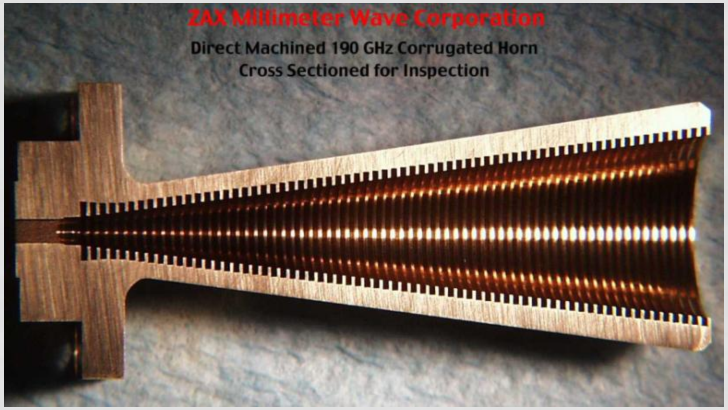
- Rectangular
- Conical
- Diagonal
- Potter (dual-mode)
- Dielectric loaded
- Quad-ridge
- Corrugated (‘scalar’)
- Smooth-wall
- …

Potter horn (picture J.F. Johansson)



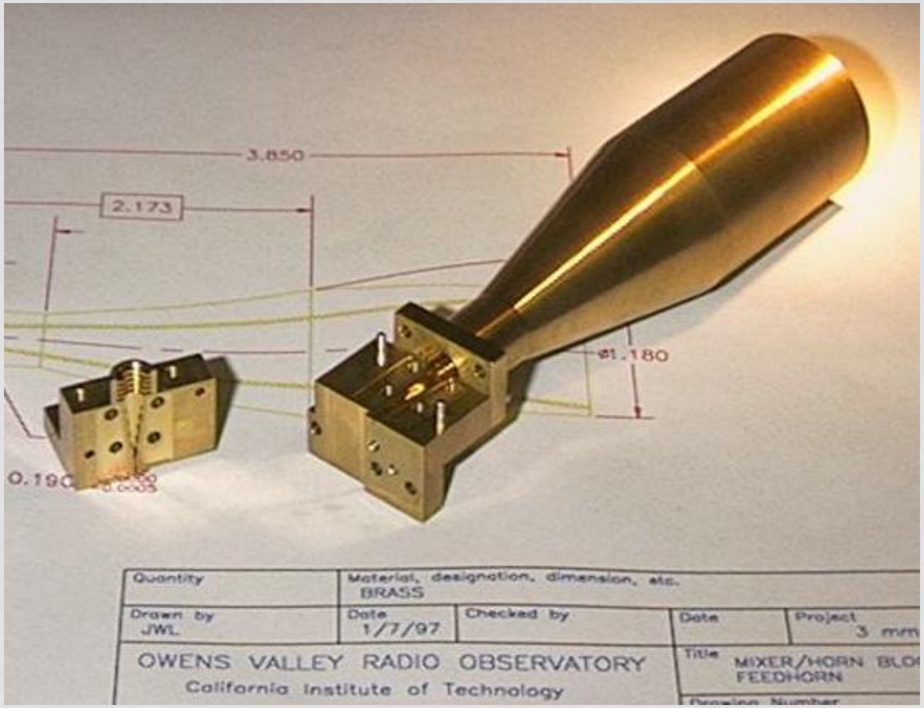
CSIRO, Aust





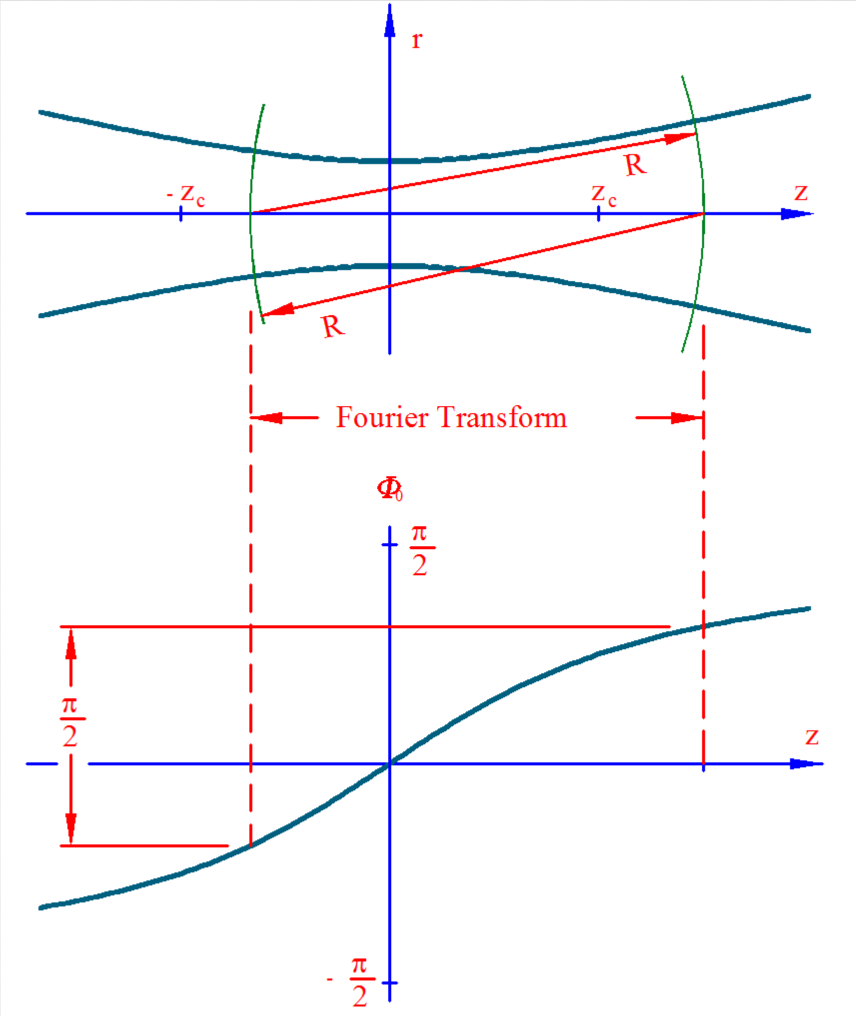
CORRUGATED HORN

- ‘Gold Standard’
- Properties
  - Circularly symmetric pattern
  - Low sidelobes
  - Low cross-pol
  - ~40 % bandwidth
  - Low VSWR
- Variants
  - Diffraction limited
  - Wideband
  - Profiled
  - Dual-band
  - Ring-loaded slots
  - …

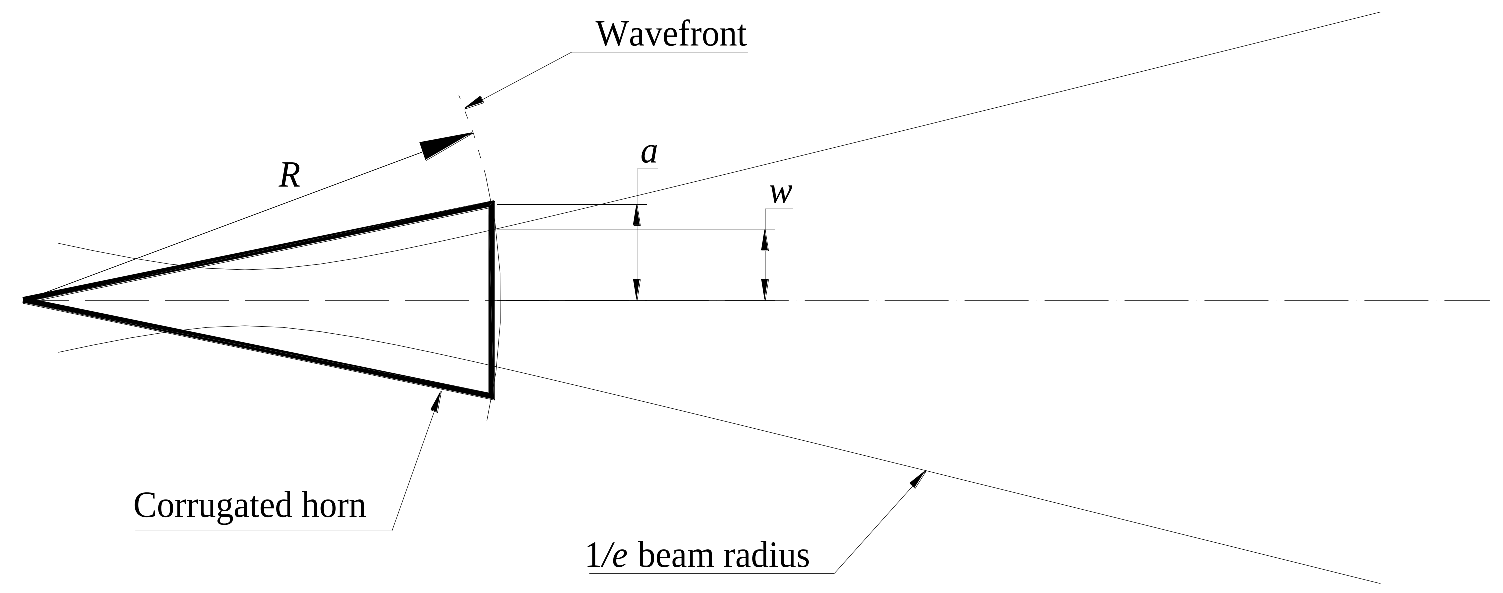


GAUSSIAN BEAM PARAMETERS

- Fundamental mode captures propagation properties of ***all*** modes
- Changing structure with propagation due to ***only*** phase slippage between modes
- Waist to far-field, $\phi_0 = \pi/2$: Fourier transform
- Between confocal planes: Fourier Transform
- $\phi_o = \pi$: two FTs -> image (inverted)

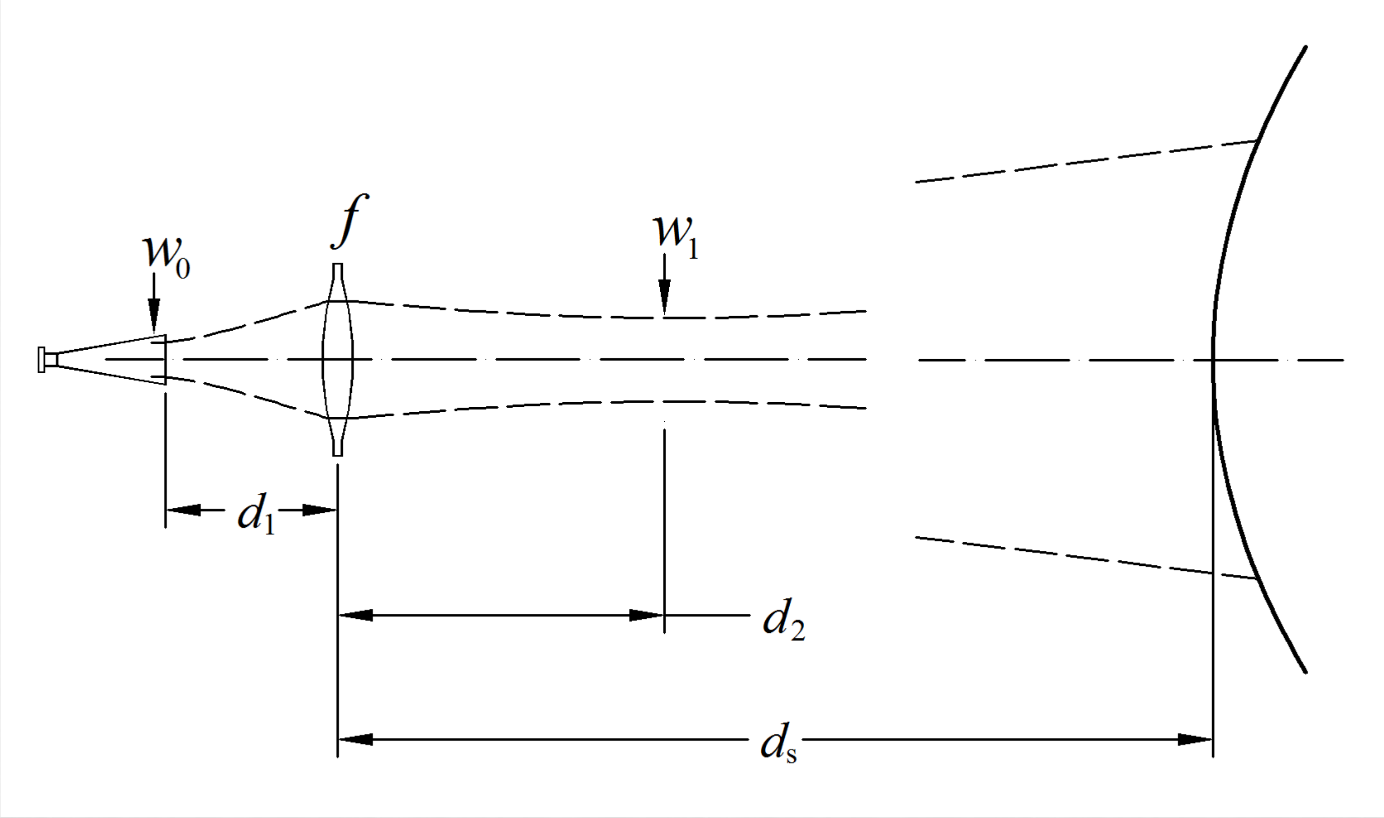


CORRUGATED HORN AND GAUSSIAN BEAM



- Aperture phase error -> ‘diffraction limited’ or ‘wideband’
- Aperture close to waist, or in far-field of GB
- Aperture at confocal surface -> optimum gain horn

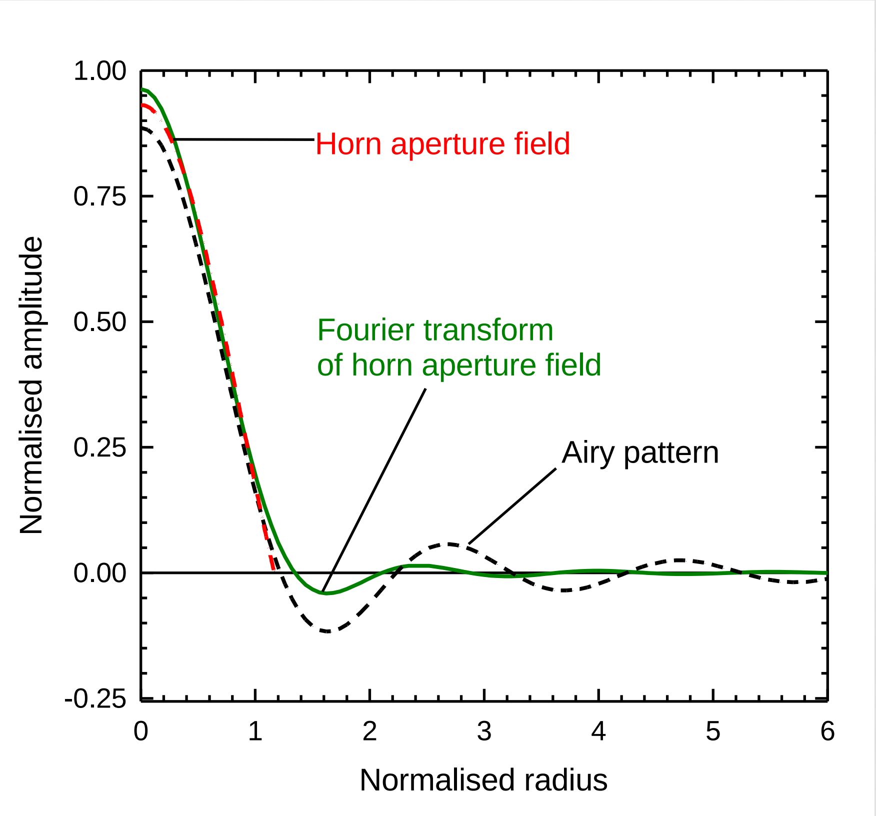
IMAGE FEED APERTURE ON TO SECONDARY



T.-S. Chu, "An imaging beam waveguide feed," *IEEE Trans Antennas and Propagat.*, vol. AP-31, no. 4, pp. 614–619, July 1983.

FOCAL PLANE FIELDS: COUPLING

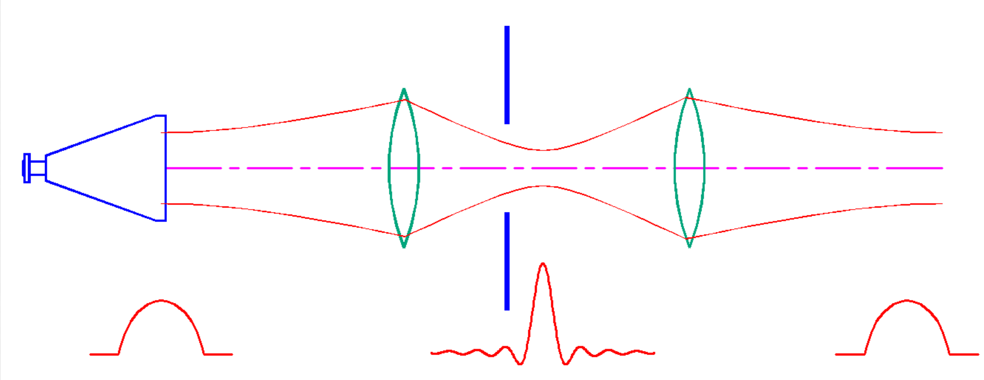
- Integrate over source and horn beams to obtain coupling
- Diffraction limited horn
  - Matches central Airy lobe well
- Imaged horn
  - Matches central and first sidelobe of Airy pattern well

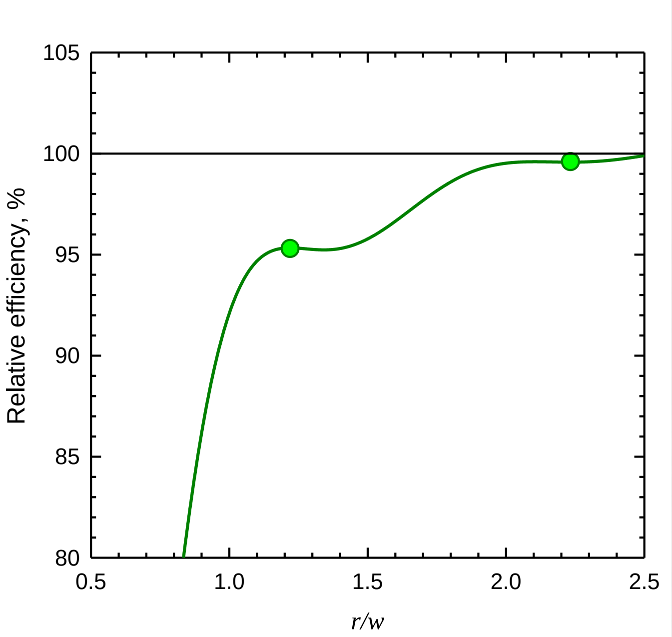


FOCAL PLANE FIELDS: TRUNCATION

- Effect of truncation depends on location
  - effect worst near (image of) focal plane
  - effect least near (image of) aperture plane

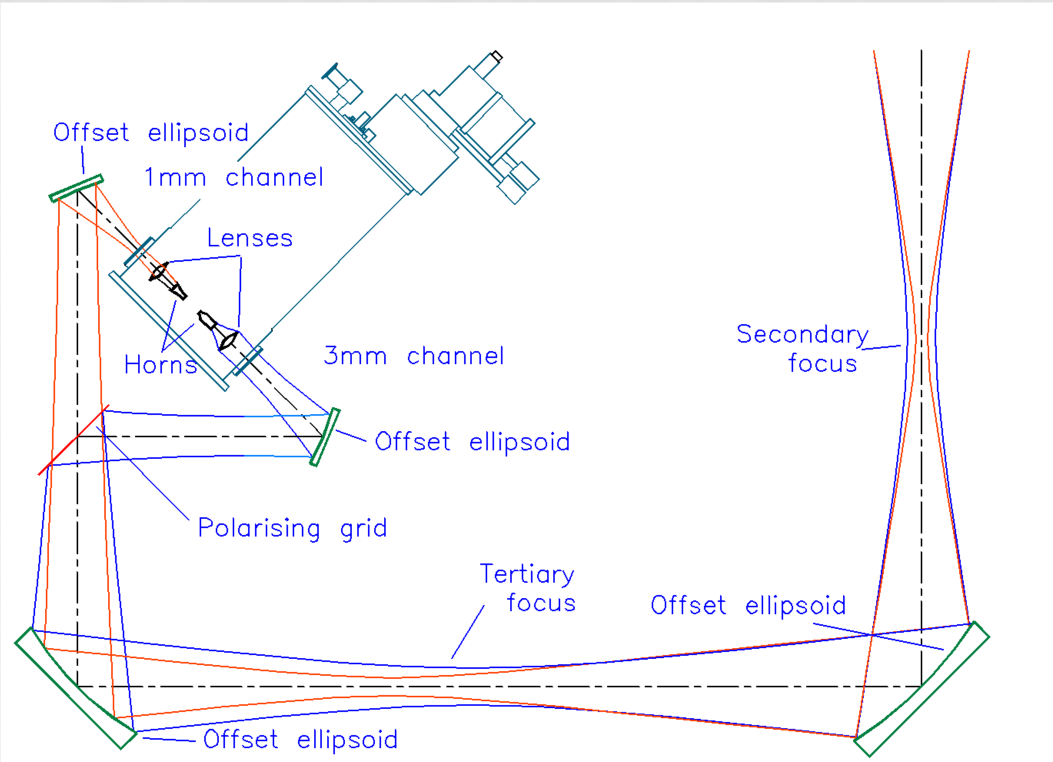
- Clear ***diameter*** of 5 beam ***radii*** is conservative

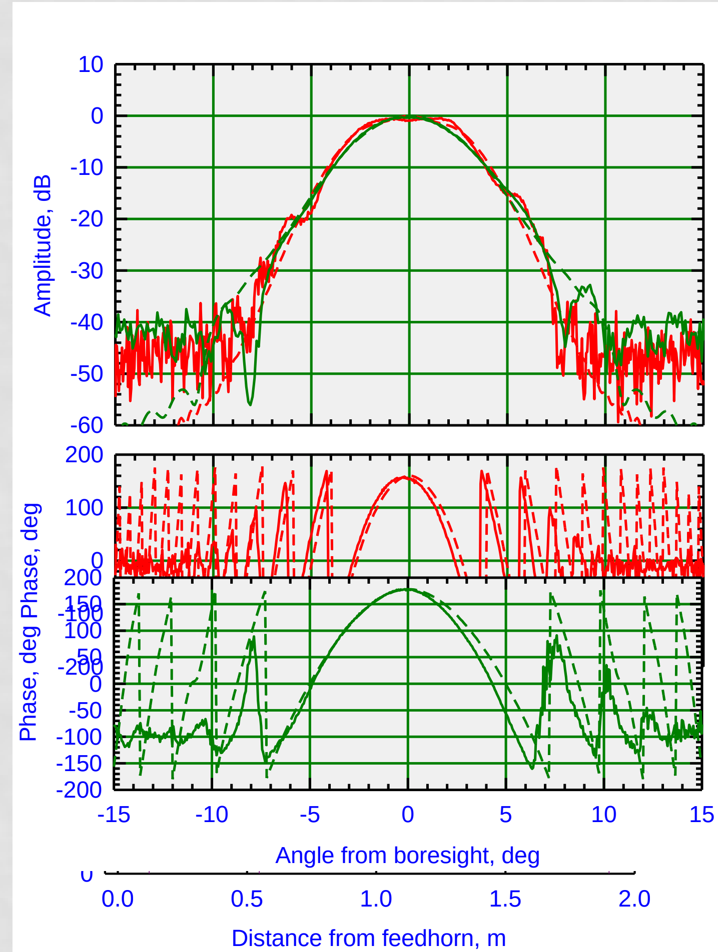




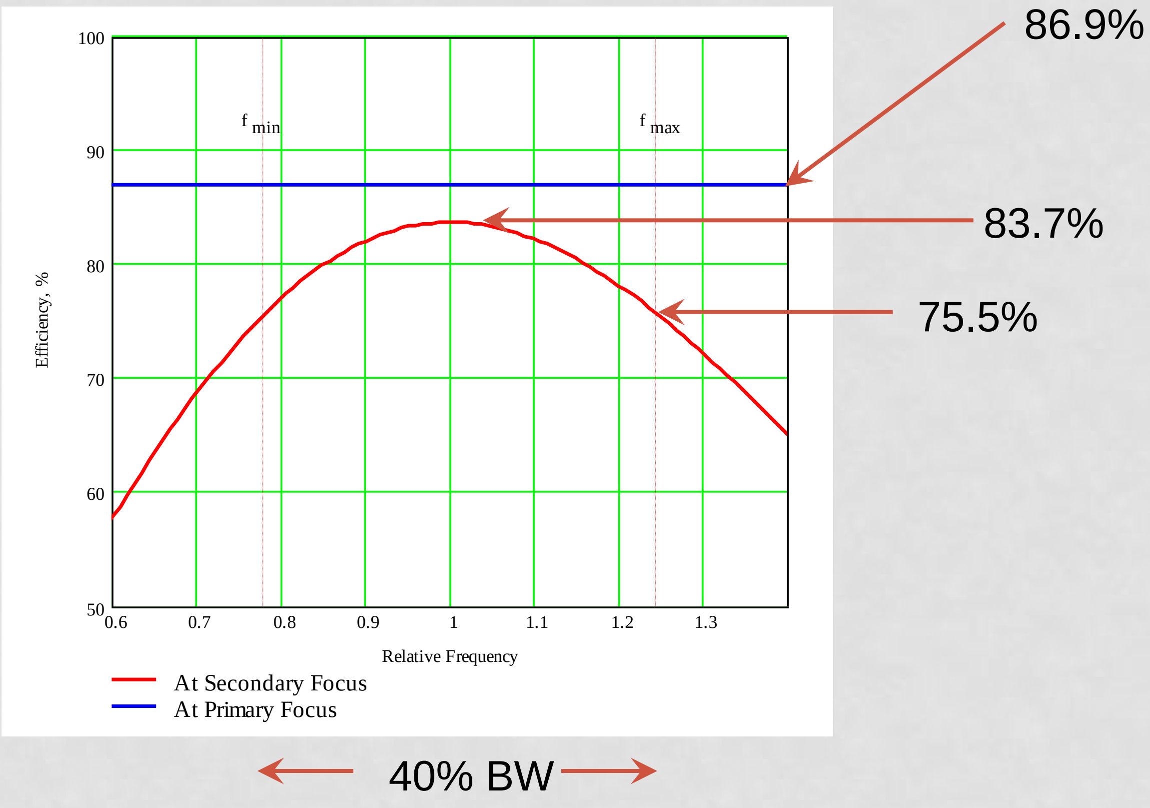
EXAMPLE OF FREQUENCY-INDEPENDENT OPTICS

- SEST frequency-independent optics





IMAGED VS. NON-IMAGED HORN

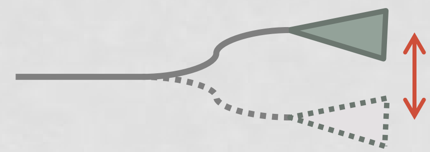


DUAL-BEAM SYSTEMS

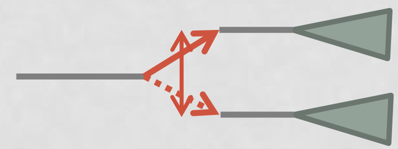
- Principle
  - Rapidly switch between two close positions on sky
  - Difference removes
    - atmospheric fluctuations
      - beams overlap in atmosphere (near field)
      - v. important for (sub-)millimeter
    - Rx gain fluctuations
      - Dicke switching
- Considerations
  - Frequency
    - atmosphere: 1-10 Hz
    - receiver: 1 Hz – 10 kHz
  - Beam throw: < 1 deg
  - Single dish—not required for interferometry

IMPLEMENTATION: WITH FEEDS

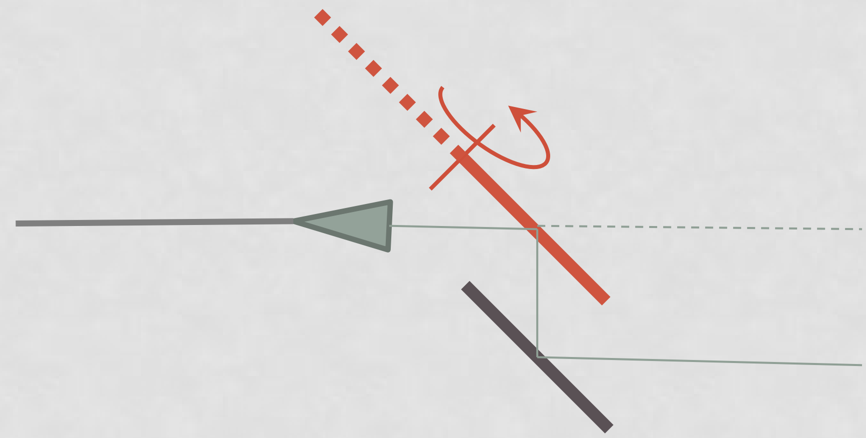
Move feed mechanically



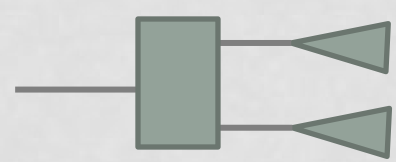
Switch between feeds (mechanical or electrical)



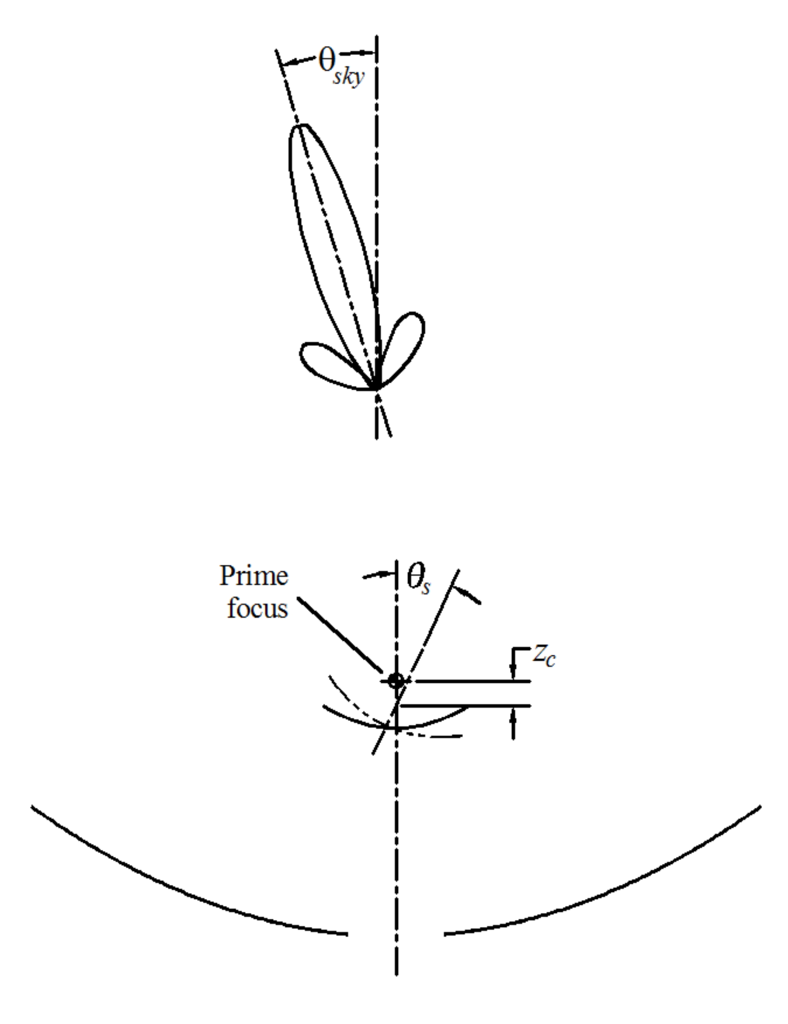
Optical chopper

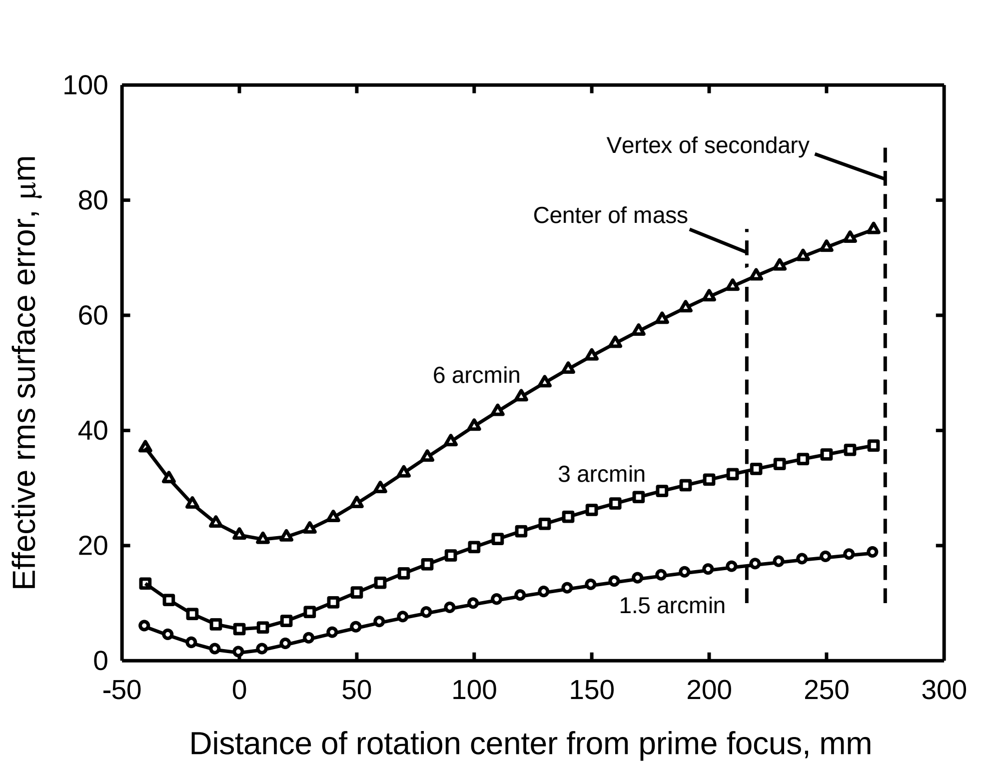


Correlation radiometer



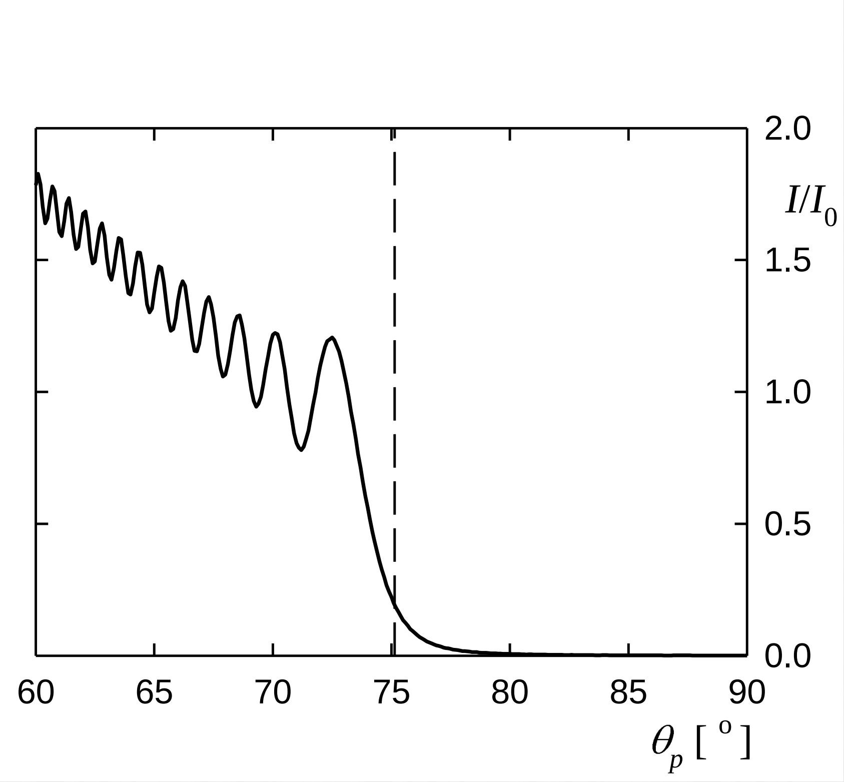
IMPLEMENTATION: USING SECONDARY





DIFFRACTION AT SECONDARY

- Adds ground spillover noise
- Increases with
  - feed offset
  - secondary motion
- Cancels for symmetrical beam switching
- Nutating secondary and focal plane array
  - combine offset and switching effects
  - large imbalance
  - reduce with shield
    - primary
    - secondary

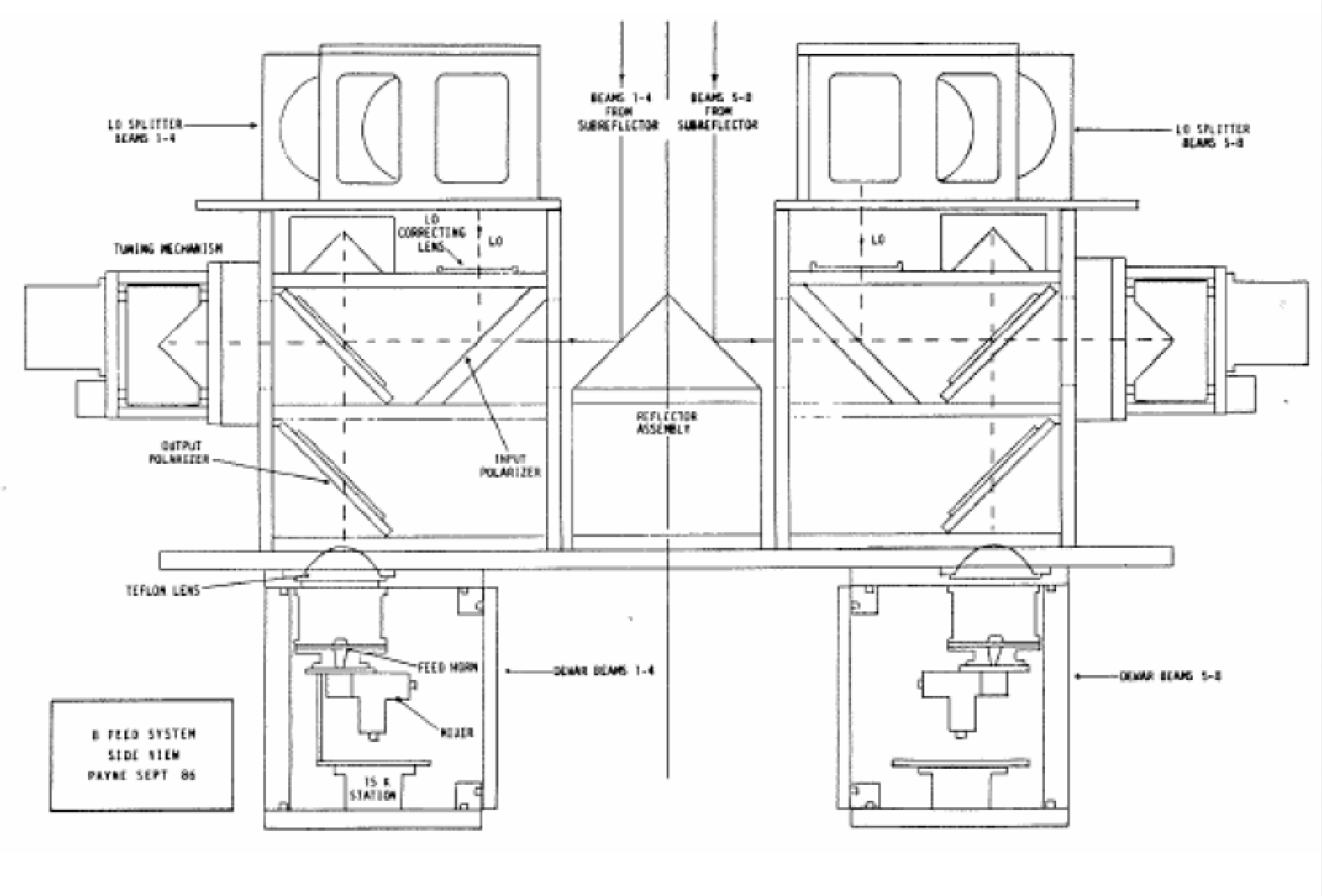


FOCAL PLANE ARRAY CONSIDERATIONS

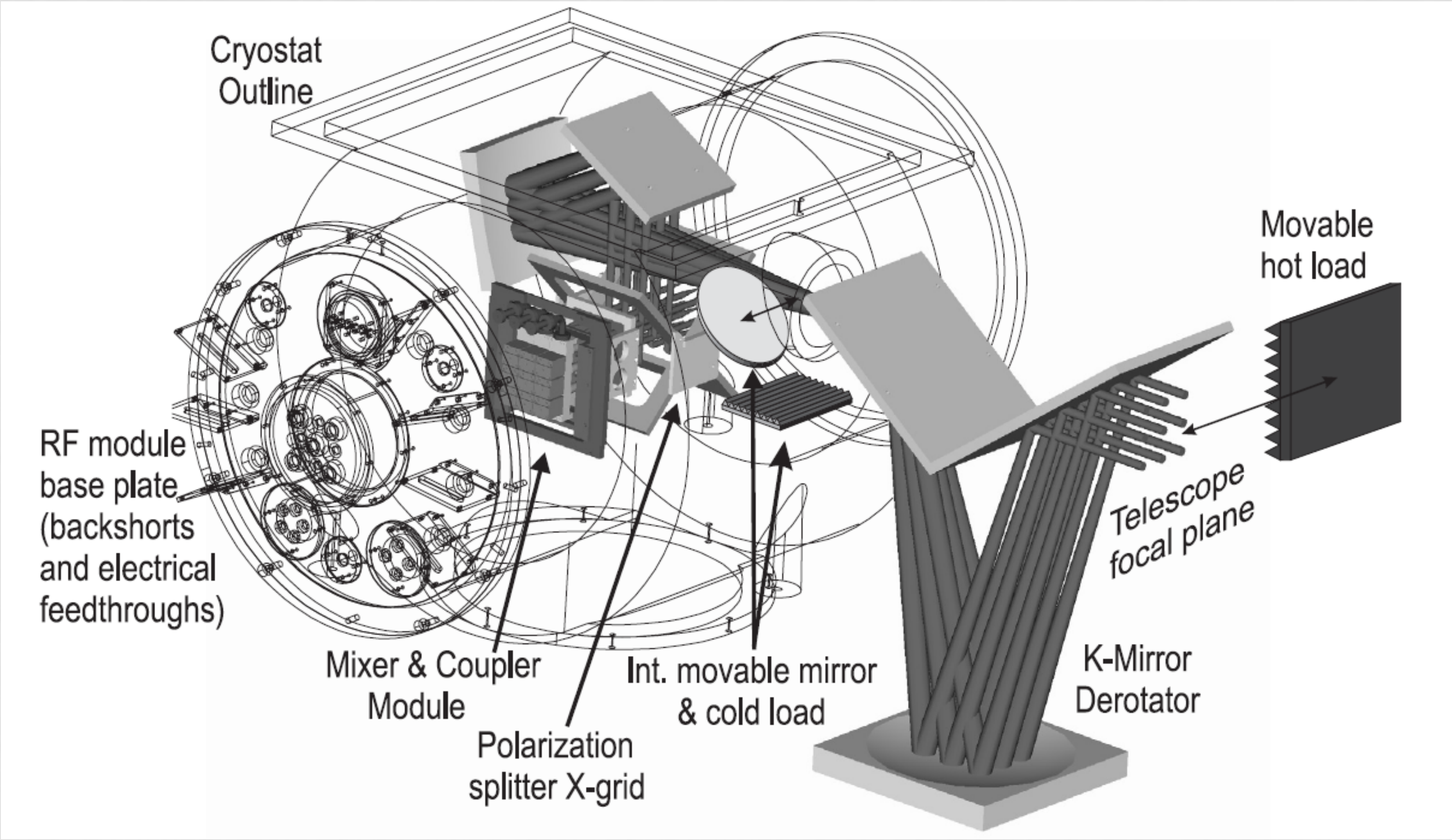
- Number of pixels
  - Cost
  - Backends
  - Focal plane size
  - Aberrations
- Beam spacing
  - ~2.5 beams minimum horn spacing
  - Heterogeneous interferometer arrays?
- Diffraction limited or imaged feeds?
- Image de-rotation (Az/El antennas)
  - Rotate in optics
  - Rotate receiver
  - Rotate in software

NRAO 8-BEAM 1-MM RX

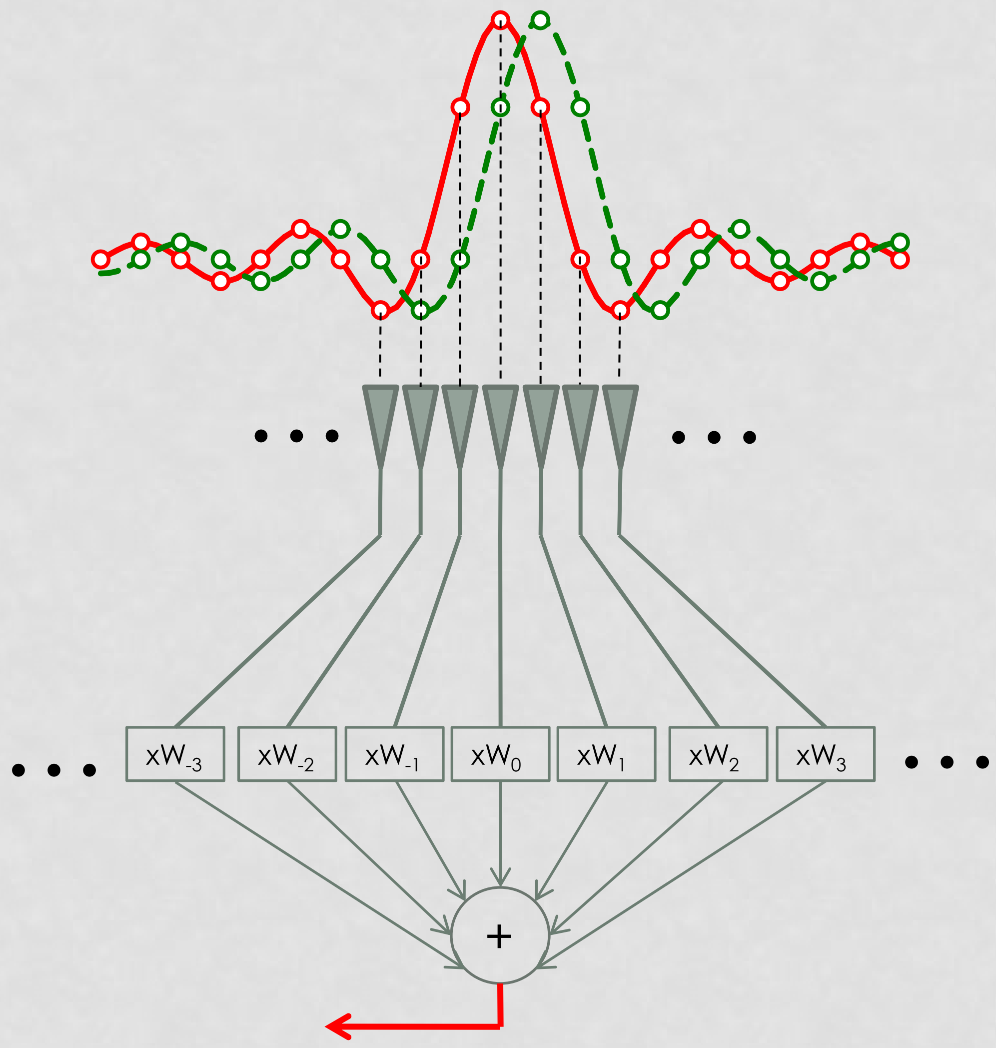
- Originally Schottky
- Retrofitted with SIS



IRAM 9-BEAM SIS RECEIVER

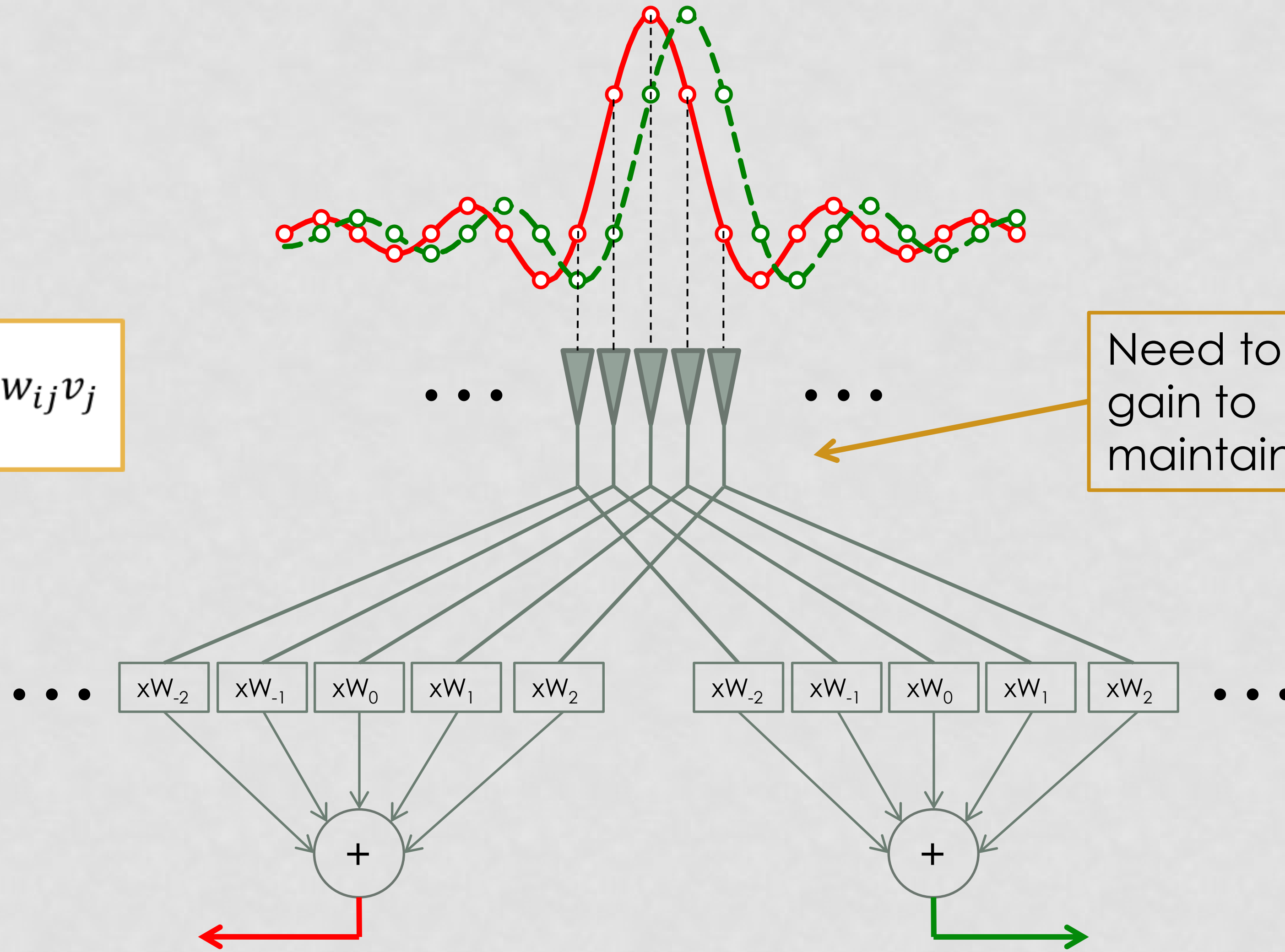


PHASED ARRAY FEEDS



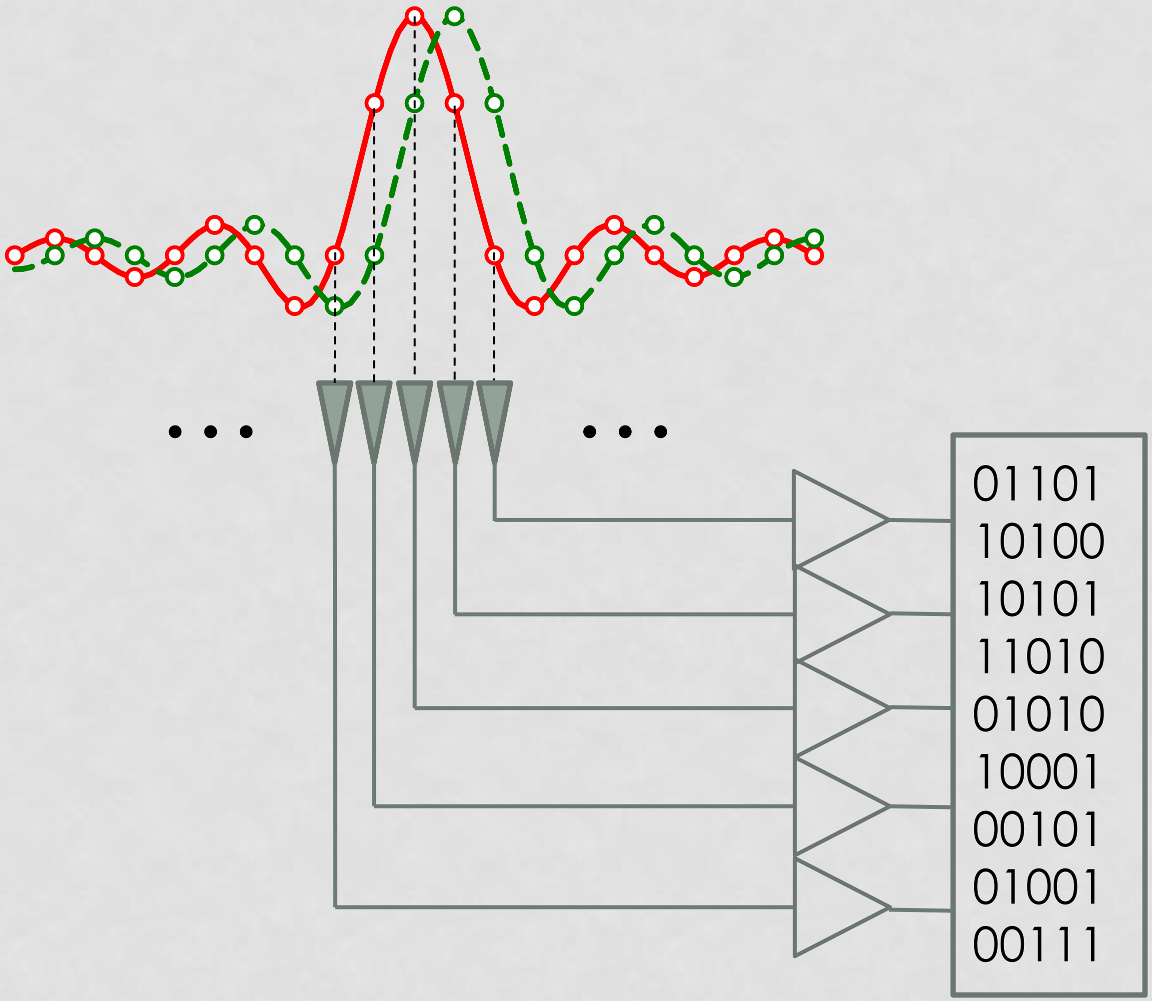
PHASED ARRAY FEEDS

$$b_i = \sum_j w_{ij} v_j$$



Need to add gain to maintain S/N

PHASED ARRAY FEEDS



APERTURE PLANE FEEDS

- Phased array feeds sample complex field
  - Can be placed anywhere along beam
  - In aperture plane amplitude uniform, phase varied
- Can place individual feeds in aperture plane
  - Use: e.g., CARMA correlate subapertures on 10-m antennas with 3.5-m antennas

CONCLUSIONS

- Radio antennas capable of wide field imaging
- Imaging often limited by focal plane size
- Many feed designs to choose from
  - corrugated horn is probably still the best
- Large arrays may compromise single pixel performance
- Synthesized feed arrays may become practical
  - large digital back-ends will help