Design and physical optics evaluation of LiteBIRD optical system

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B-mode from Space, 5 Dec. 2017

Outline

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2. Requirements of beam patterns
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3. Factors to determine beam patterns
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   - Feeds and optical elements (dependent on a specific system)
4. LiteBIRD LFT design study
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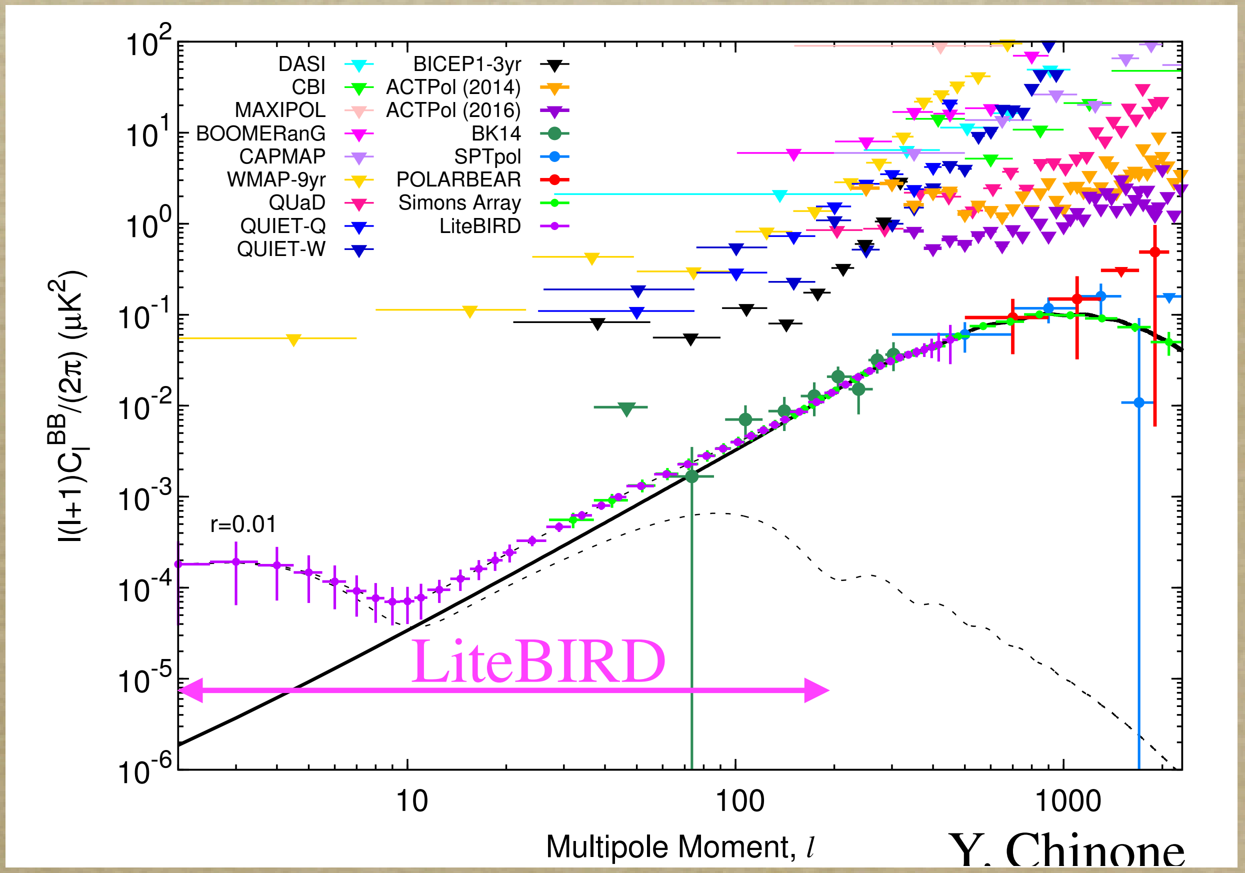
   - Arrangement of bands on focal plane
5. Beam patterns in the lowest bands
   - Lens-let diameter
   - Arrangement of bands on focal plane
6. Conclusion

1. Introduction

- **Lite** (Light) Satellite for the studies of **B**-mode polarization and **I**nflation from cosmic background **R**adiation **D**etection
  - aiming at measuring CMB B-mode polarization originated from the primordial gravitational wave
- Mission goal
  - the uncertainty of the tensor-to-scalar ratio δr is less than 0.001
- Mission requirements
  - angular multipole: $2 \leq l \leq 200$
  - observing frequency: 34 - 448 GHz
  - mission lifespan: > 3 years
  - operation: at the 2nd Lagrange point



Telescope overview

- ❖ Two telescopes are needed
  - to cover the wide range of frequency (15 bands)
    - ➡ Low Frequency Telescope (LFT), High Frequency Telescope (HFT)
- ❖ Requirements (relating to optical system)
  - beam size: ~ 1 deg.
    - ✓ multipole range of $2 \leq l \leq 200$
  - aperture diameter: 400 mm for LFT, 200 mm for HFT
    - ✓ the beam size and the lowest frequencies
  - FoV: 20 x 10 deg^2 for LFT, 10 x 10 deg^2 for HFT
    - ✓ sensitivity
  - beam pattern: the details in next page
    - ✓ contamination to CMB B-mode signal

2. Requirements of beam patterns

- Contamination of false B-mode signal should be less than 1% of the lensing B-mode (R. Nagata)
  - the values in the following table correspond to 1% lensing
  - if some values exceed, make an effort into data analysis

main lobe	w/ rotating HWP[1]	w/o rotating HWP[2]	note
FWHM	~ 1 deg.	~ 1 deg.	$2 \leq l \leq 200$
ellipticity	~ 10%	~ 7%	CMB E to B leakage
diff. gain	—	2×10^{-5}	CMB T to B leakage
diff. pointing	—	2”	CMB T to B leakage
diff. FWHM	—	2×10^{-3}	CMB T to B leakage
diff. ellipticity	—	4×10^{-4}	CMB T to B leakage

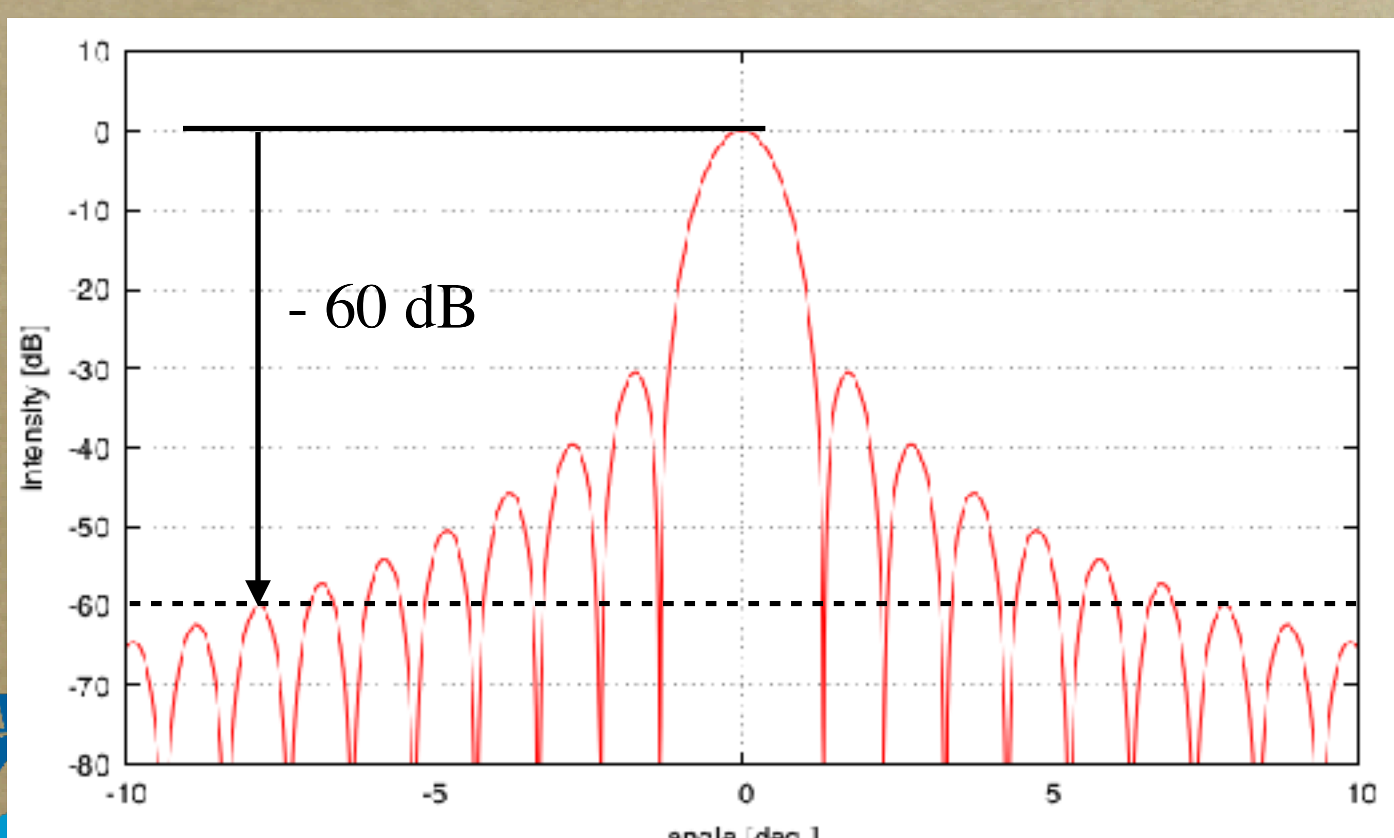
[1]corresponding to the case one polarized detector is used

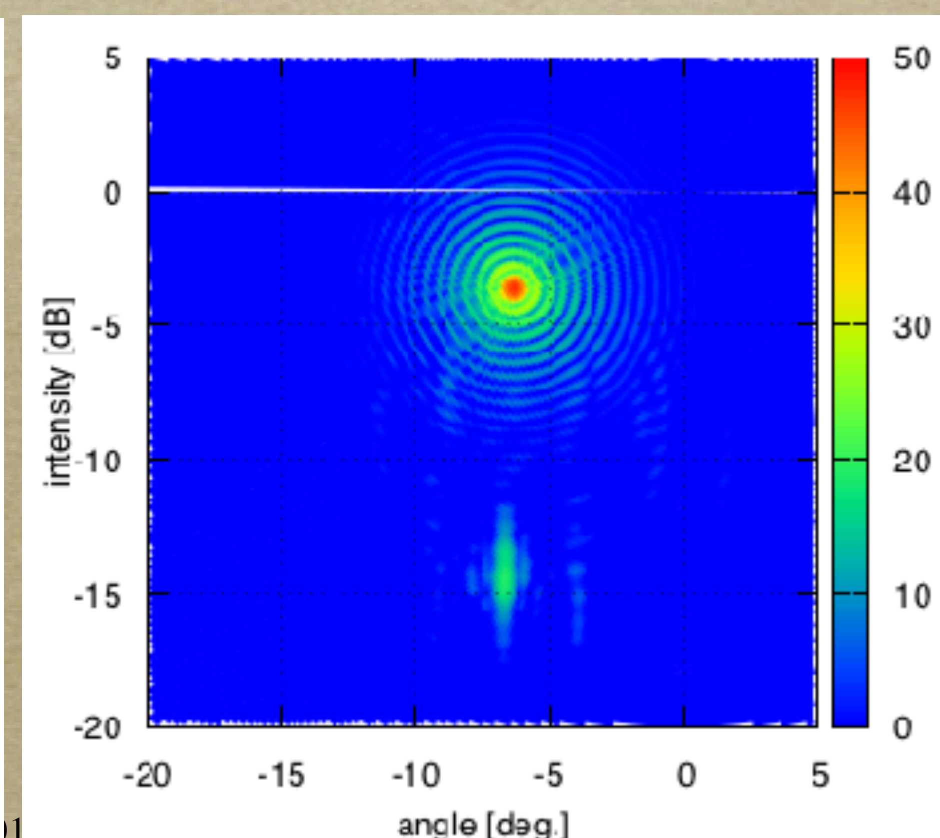
[2]corresponding to the case two polarized detectors are used

2. Requirements of beam patterns

❖ Contamination of false B-mode signal should be less than 1% of the lensing B-mode (R. Nagata)

side lobe	w/ rHWP	w/o rHWP	note
ring/diffuse	-15 dB	-50 dB	CMB T to B leakage
	-10 dB	-45 dB	foreground I to B
	-60 dB	-60 dB	polarized foreground
point-like	(r/7 deg)*(intensity/3%)*(d/30’) ≤ 1	(r/7 deg)*(intensity/3%)*(d/30’) ≤ 1	CMB E to B leakage
	(intensity/0.1%)*(d/30’) ≤ 1	(intensity/0.1%)*(d/30’) ≤ 1	polarized foreground





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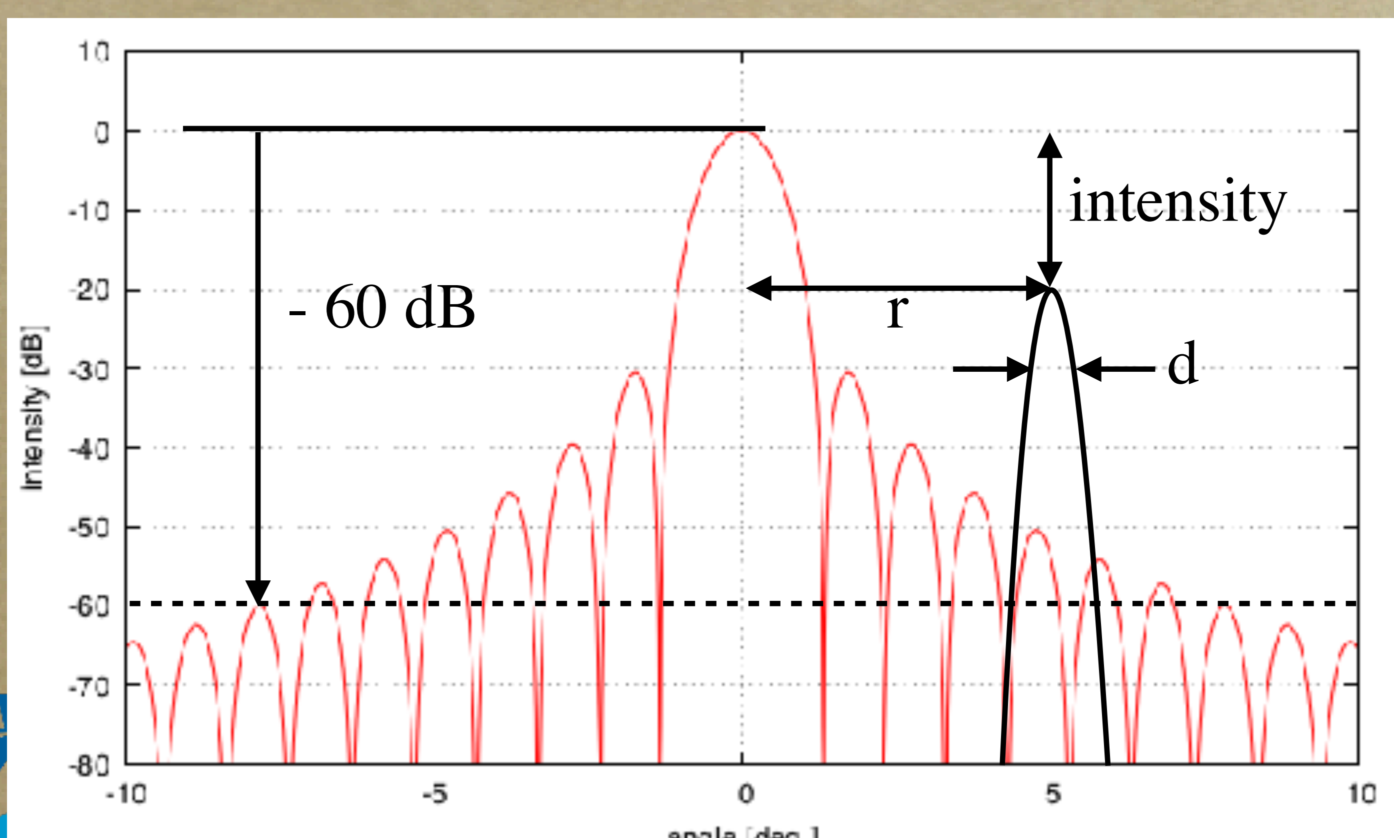
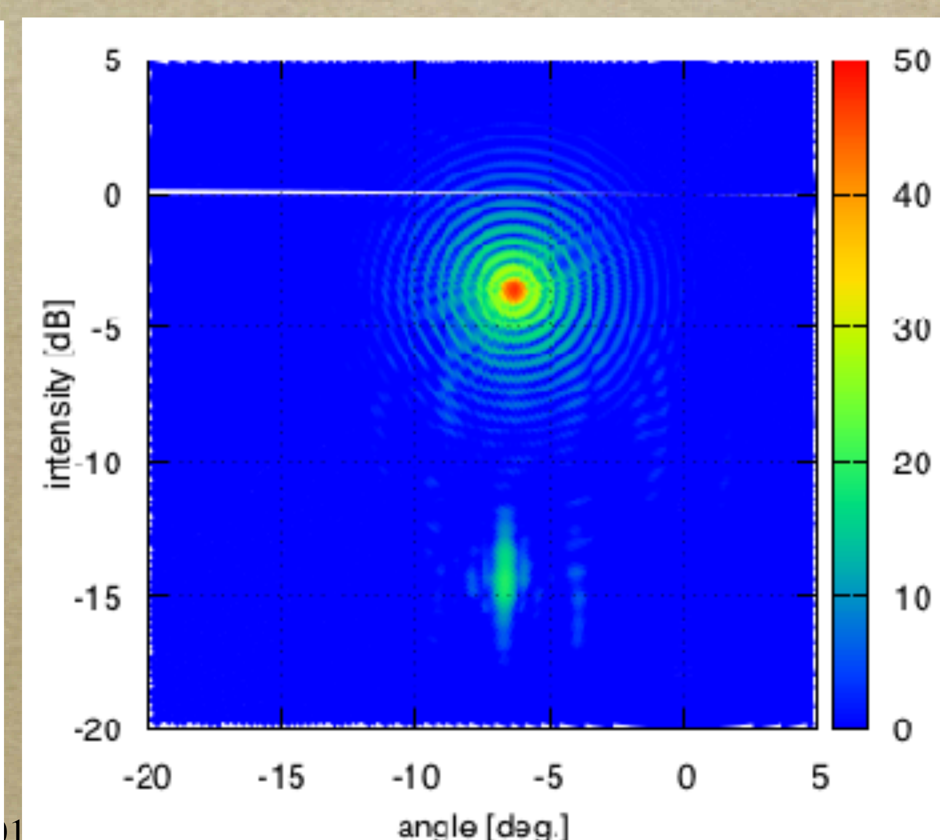
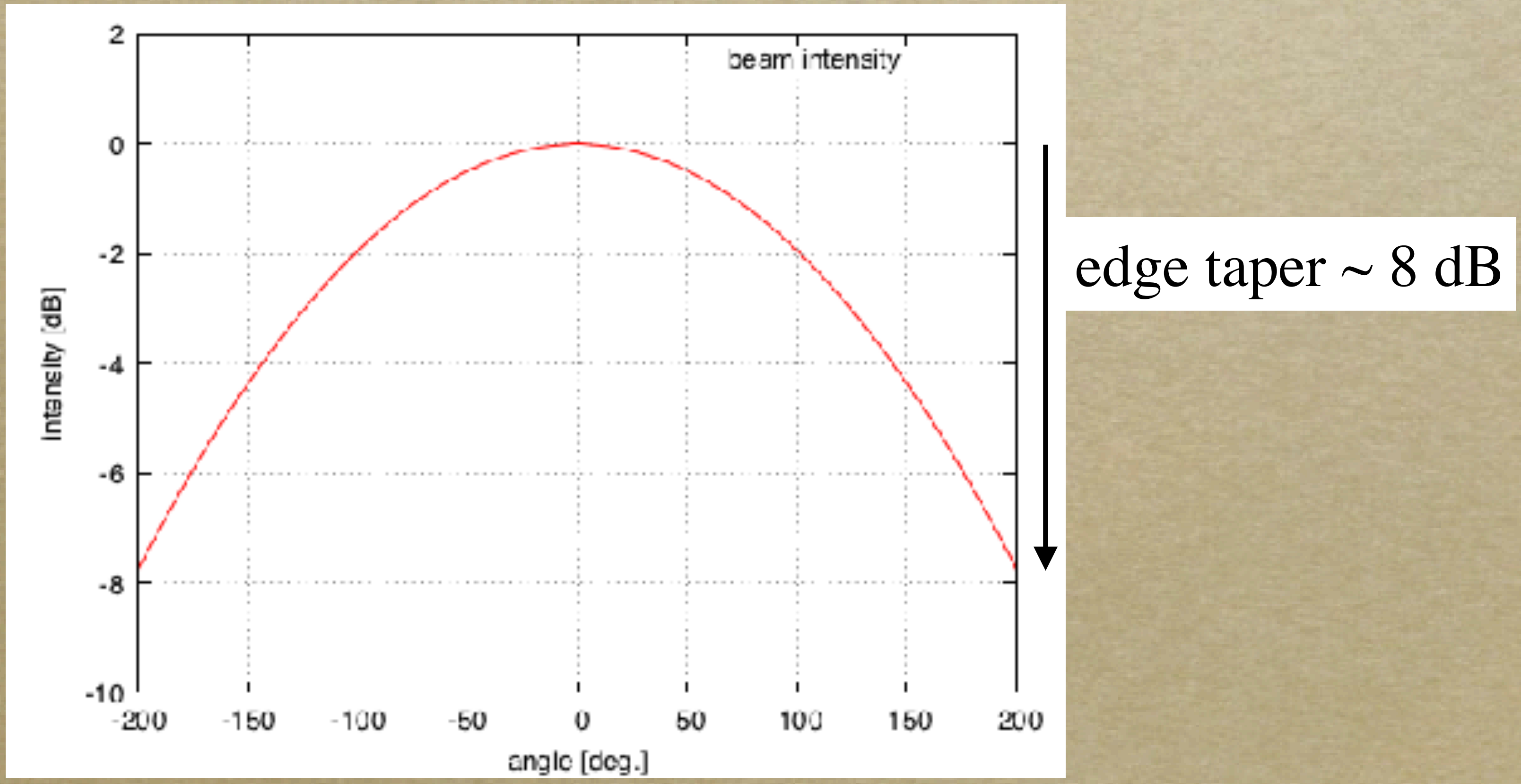




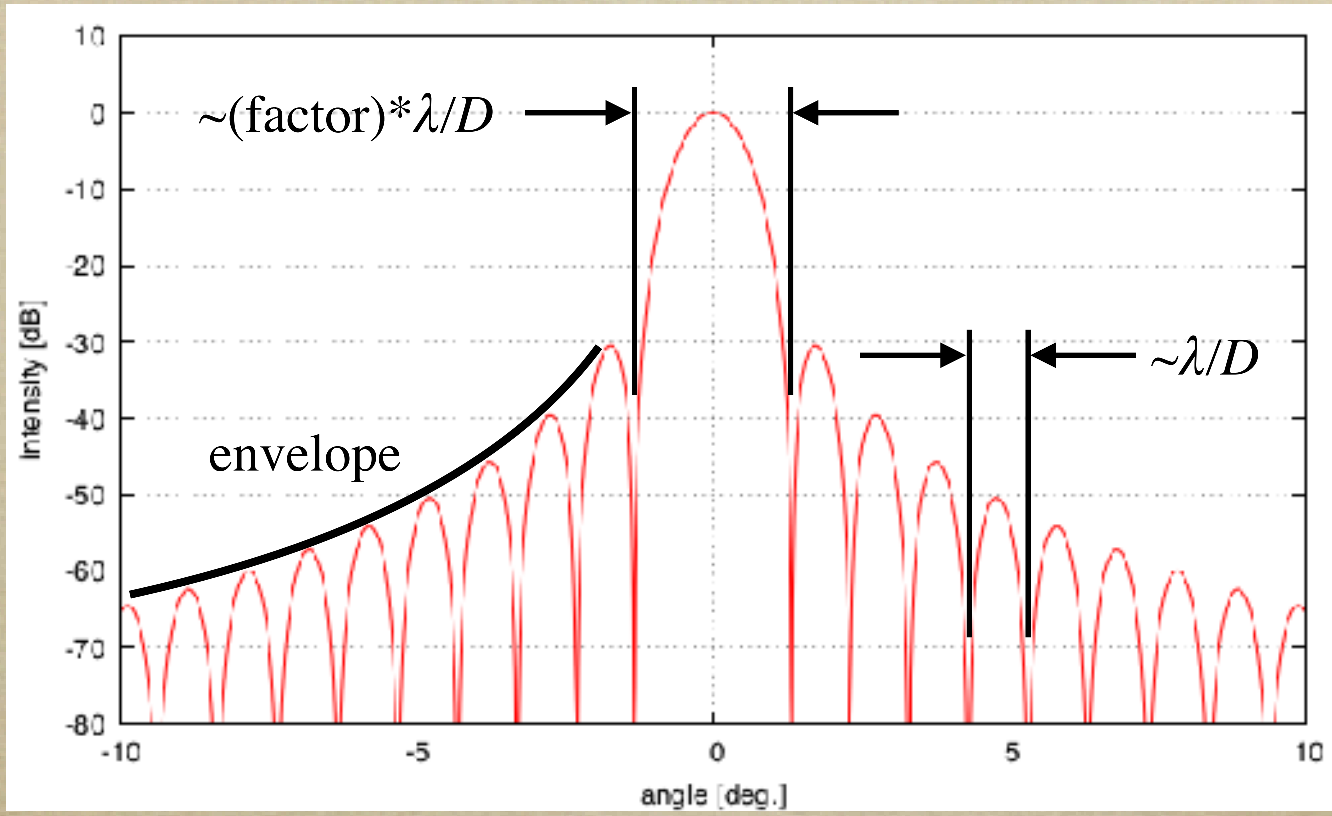
3. Factors to determine beam patterns

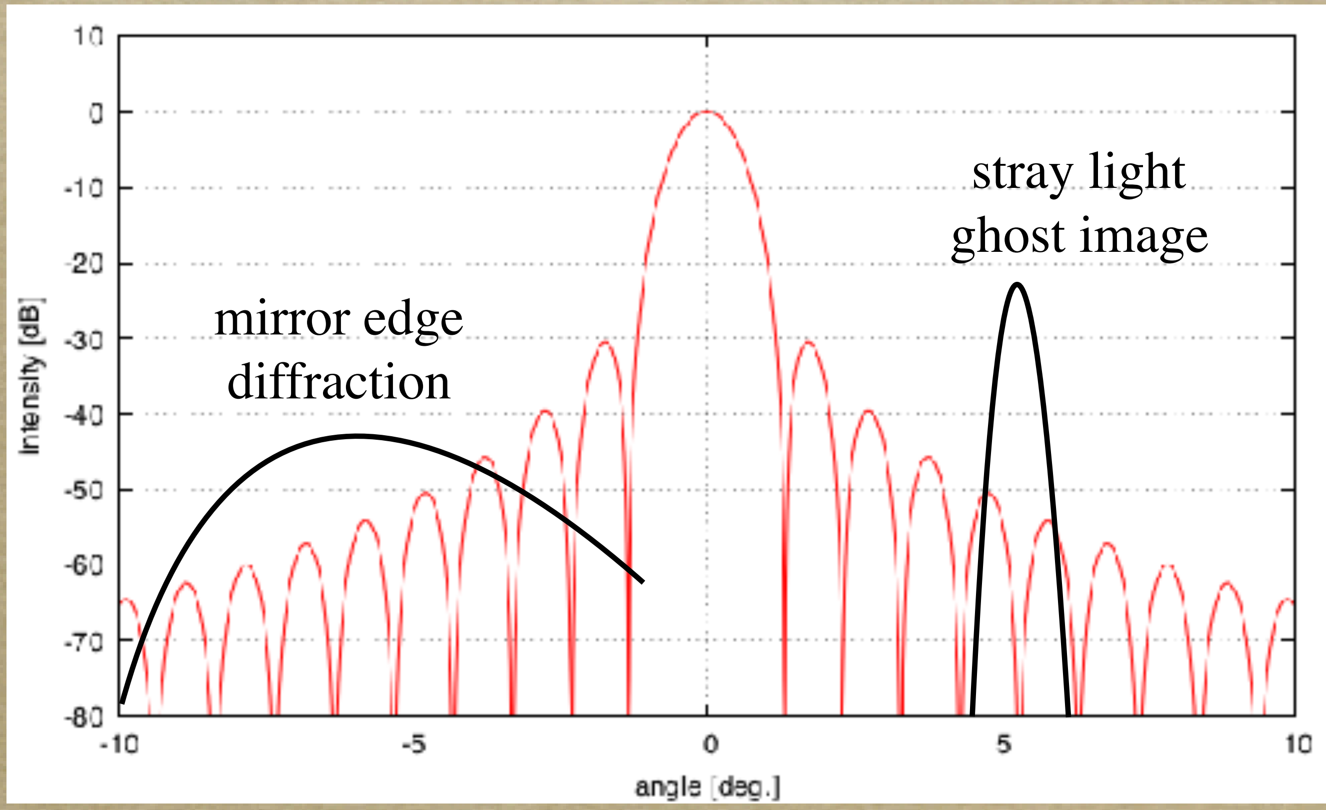
- ❖ two types
  - independent of a specific system
    - ✓ edge taper
  - dependent on a specific system
    - ✓ feeds, optical elements, and configuration
- ❖ Just a reminder
  - edge taper: relative intensity at a point apart from maximum



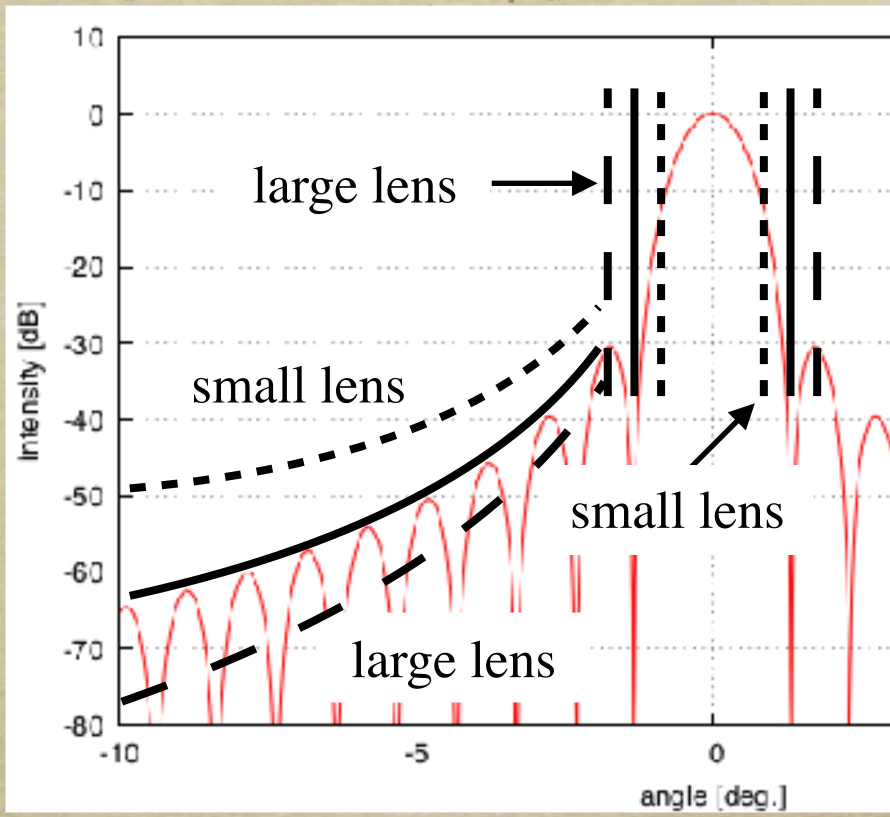
3. Factors to determine beam patterns

- ❖ Common factor
  - Edge Taper
    - ✓ envelope level
    - ✓ main lobe size
- ❖ Specific factors for LiteBIRD
  - feed
    - ✓ main lobe ellipticity
    - ✓ side lobes
  - diffraction at mirror edges
    - ✓ relatively diffuse structure
  - configuration
    - ✓ point-like structure
  - these are additional components, so ideally, they should be suppressed





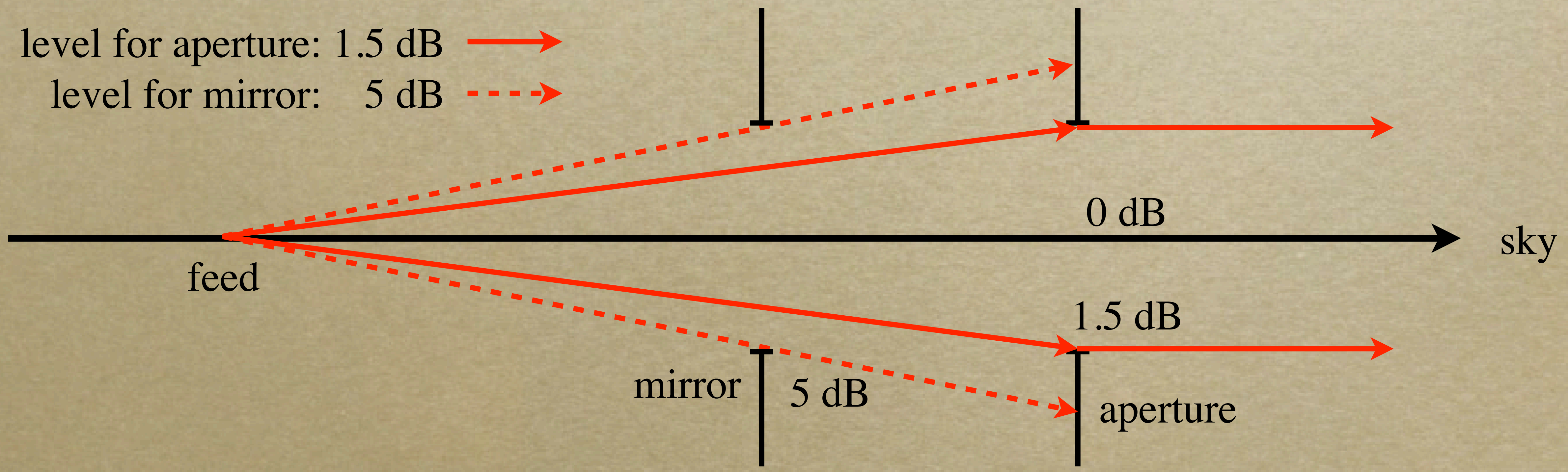
3. Factors to determine beam patterns



- ❖ Edge taper
  - determined by the lens-let diameter
  - the lens-let diameter is given by sensitivity
    - ✓ cf. for -60 dB envelope, the edge taper of 30 dB and lens-let size of 90 mm
      - ➡ cannot satisfy, so make an effort in analysis
- ❖ Diffraction at mirror edges
  - once we choose edge taper, the beam size in a system is determined
    - ✓ the requirement of mirror size to avoid additional side lobe
- ❖ Feed and baffling (configuration)
  - a beam pattern with a realistic feed can be calculated
  - then, adjusting configuration and considering baffling structures

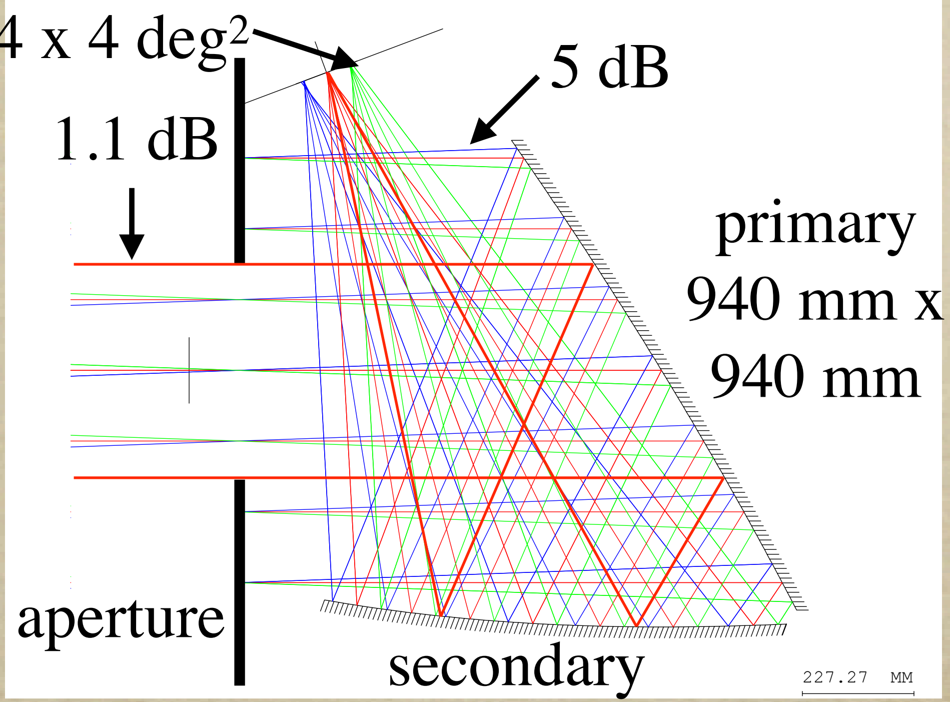
3. Factors to determine beam patterns

- Requirement of mirror size
  - serration or rolled edge at mirror edges is assumed
  - mirror size is set large in order that the beam intensity at edges is less than
    - ✓ 5 dB for the edge taper of 1.5 dB at aperture
    - ✓ 7 dB for the edge taper of 3 dB at aperture



4. LiteBIRD LFT design study

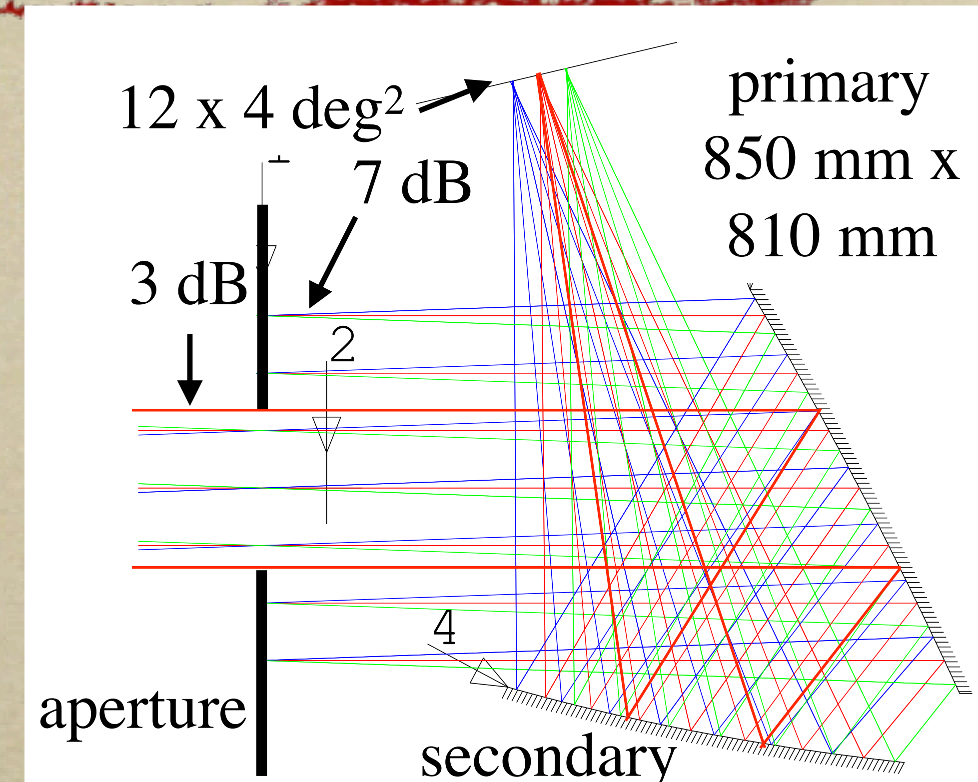
❖ Current design
- cross-Dragonian telescope
  - ✓ extremely wide field of view



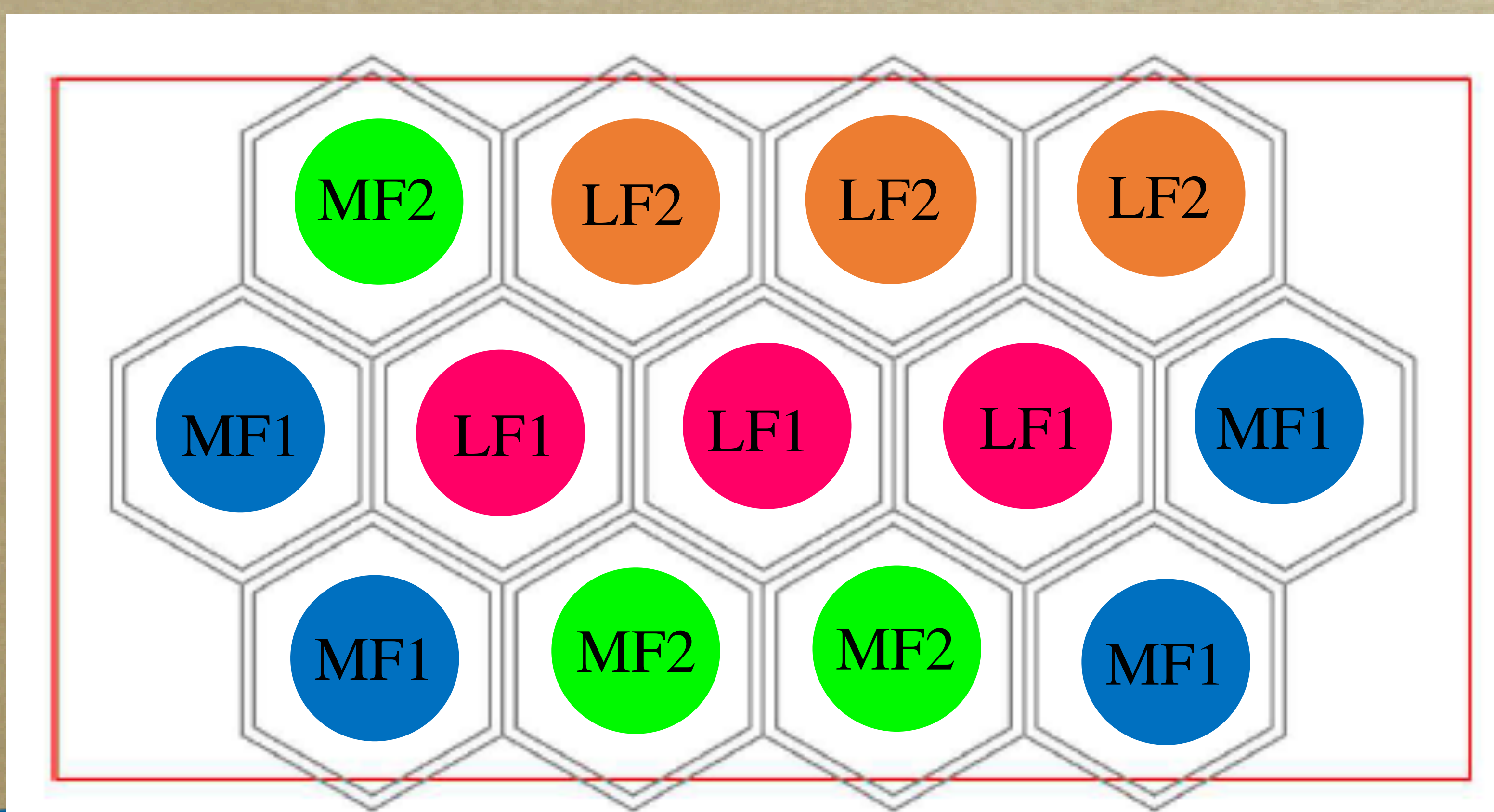
❖ If the lens-let diameter is assumed to be 18 mm
- edge taper: 1.1 dB at 34 GHz
- mirror size:
  - ✓ ~ 900 mm x 900 mm for a FoV of 4 x 4 deg^2
  - ✓ ~ 1250 mm x 1050 mm for a FoV of 20 x 10 deg^2 (mechanical conflict)
    - ➡ lowest bands should be put at the center of the focal plane
- disadvantage
  - ✓ hard to put a baffle at the focal plane
  - ✓ stray light: feed -> primary -> secondary -> primary -> aperture
  - ✓ large loading from 2 K cold stop (at aperture) at lower frequencies
    - ➡ reducing sensitivity (23% comes from the sky, 77% from the stop)

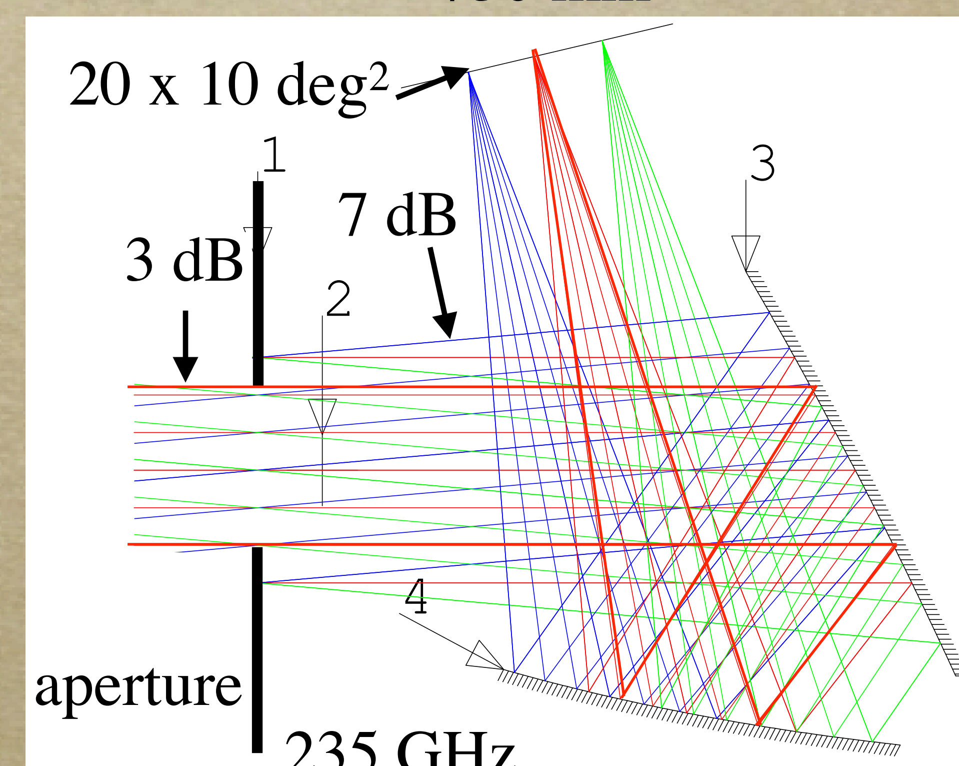
4. LiteBIRD LFT design study

❖ If the lens-let diameter is assumed to be 30 mm
- edge taper: 3.0 dB at 34 GHz
- mirror size:
  - ✓ ~ 800 mm x 800 mm (FoV of 12 x 4 deg^2)
  - ✓ sufficient for higher bands (20 x 10 deg^2)
- band arrangement



830 mm x
730 mm

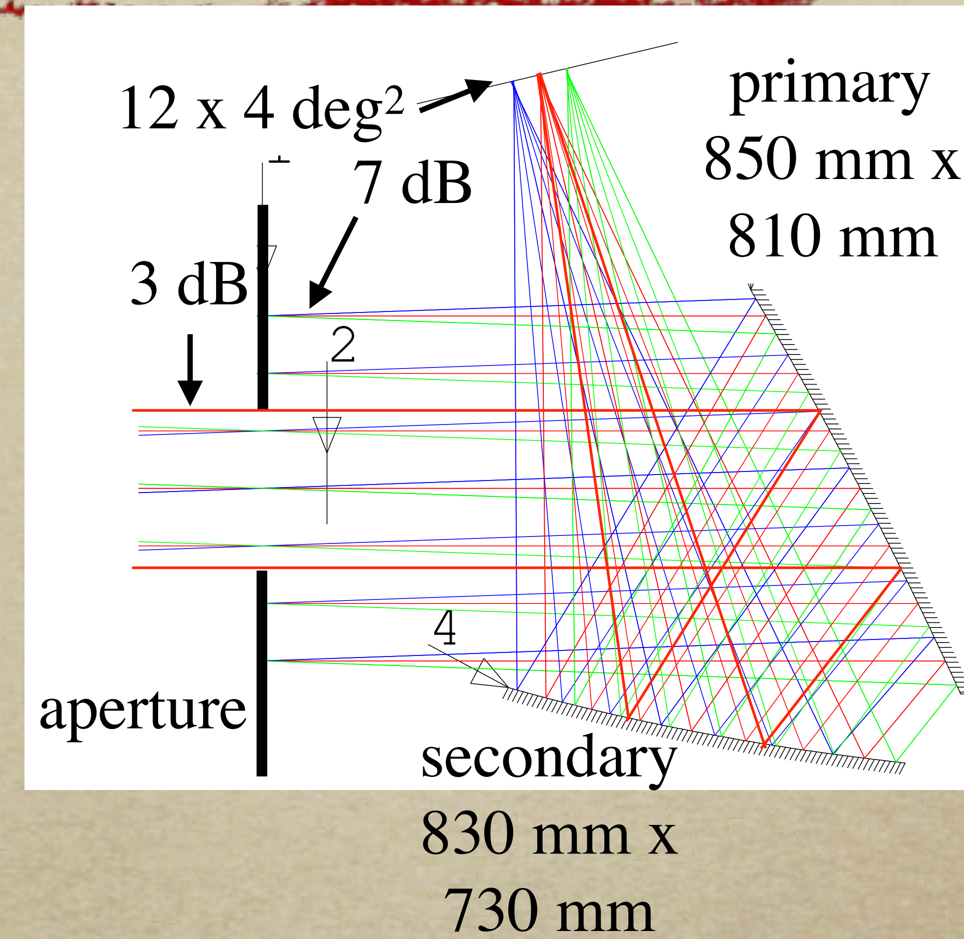


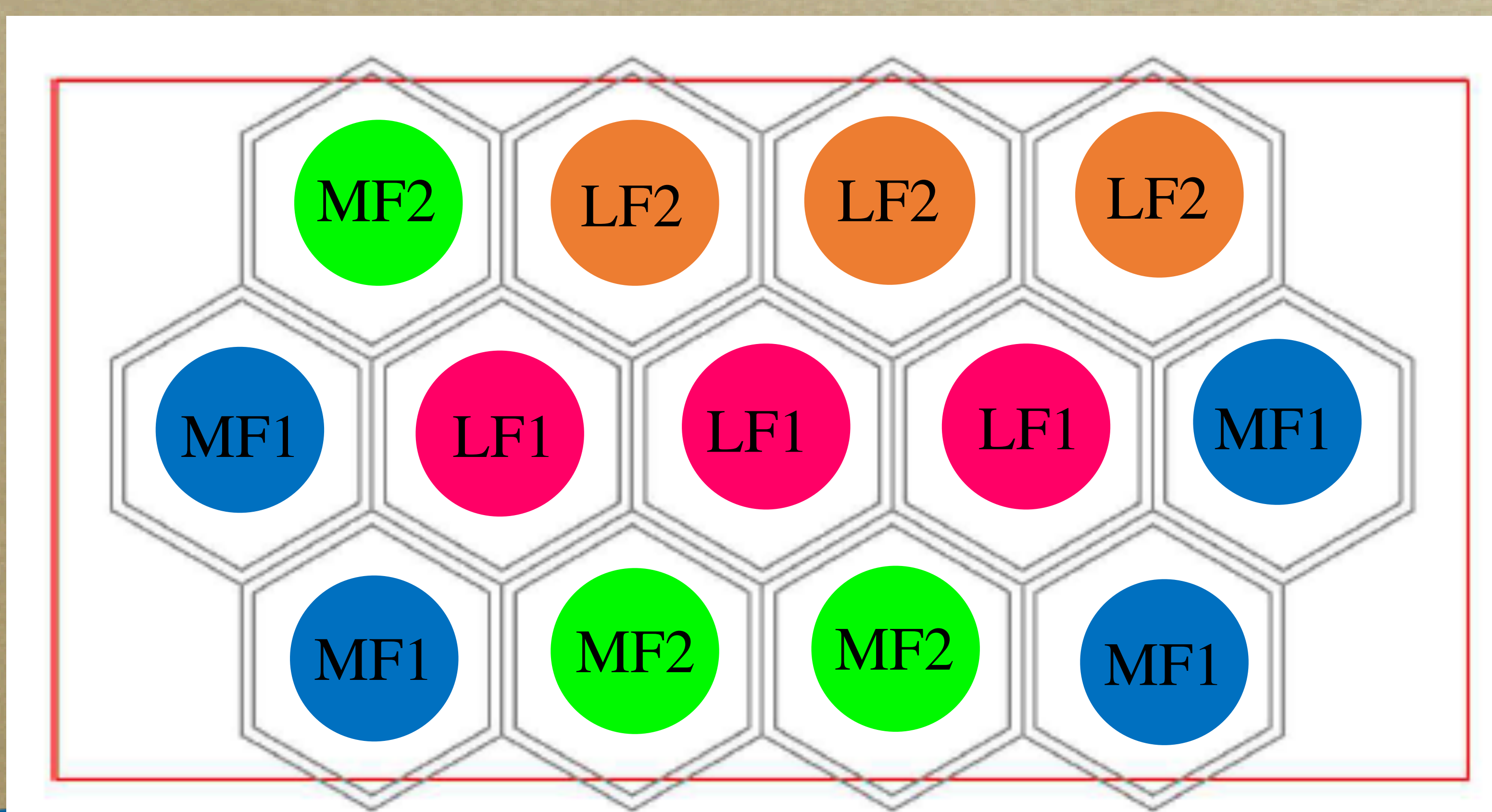


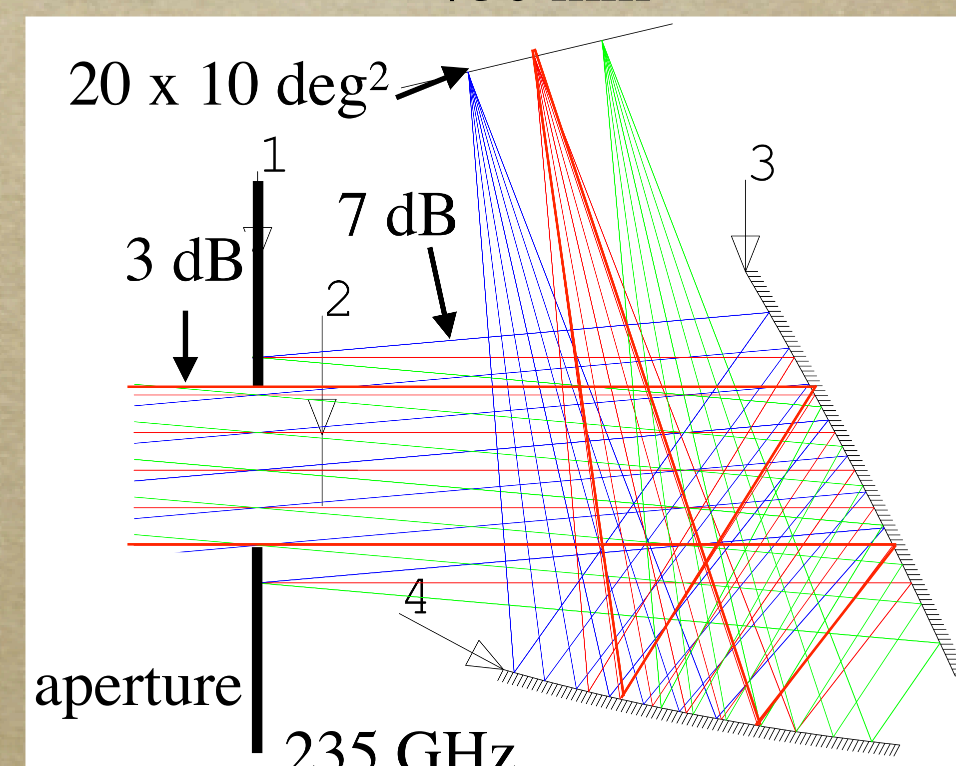
S.Kashima

4. LiteBIRD LFT design study

- ❖ How about LF2 at focal plane edge?
  - the lowest is 42.5 GHz
  - edge taper: 1.7 dB (18 mm), 4.7 dB (30 mm)
- ❖ LF1 occupies the center
  - LF2 has to be at the edge but beams are too broad for 18 mm lens-let
    - ➡ the same case as 34 GHz







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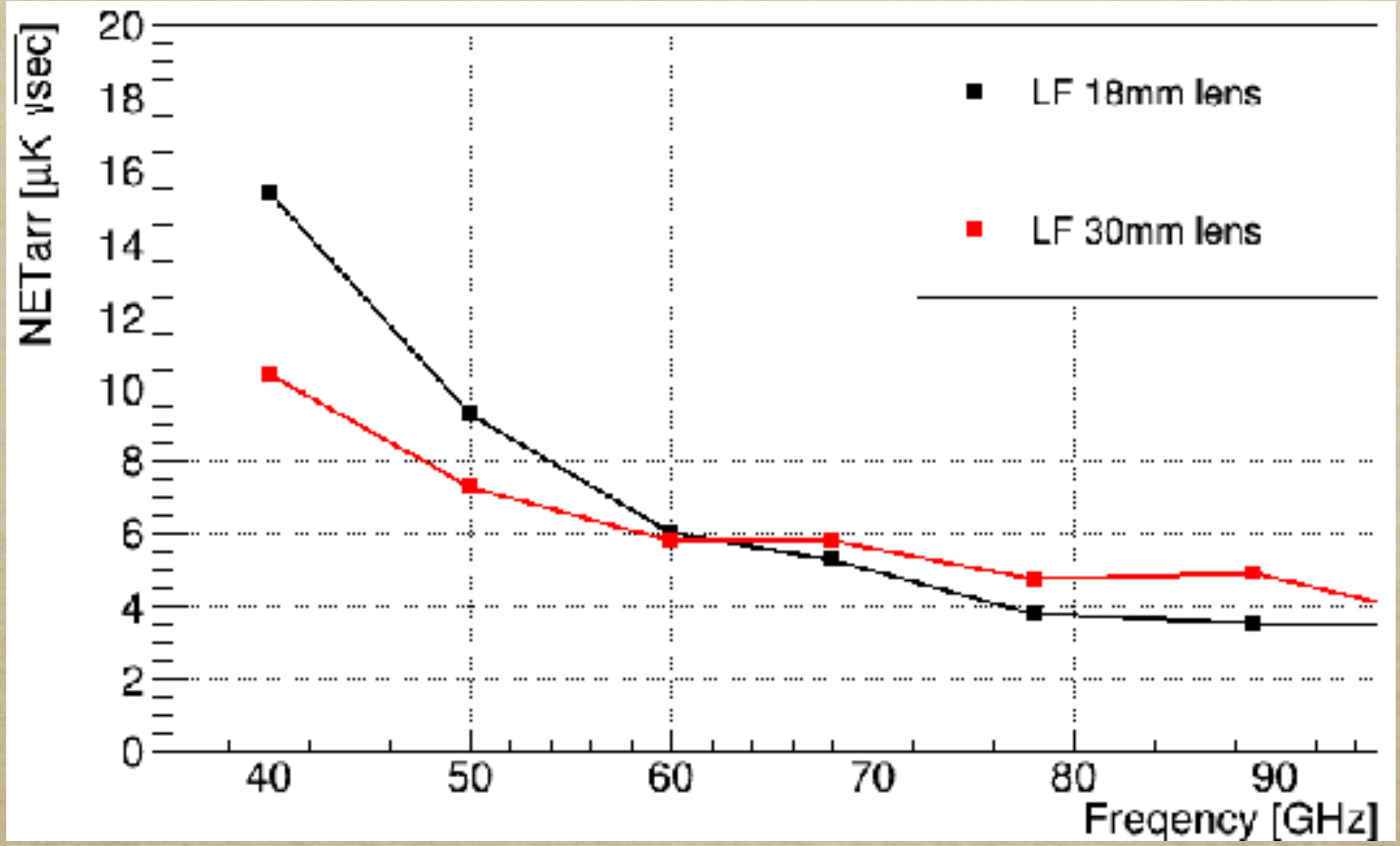
4. LiteBIRD LFT design study

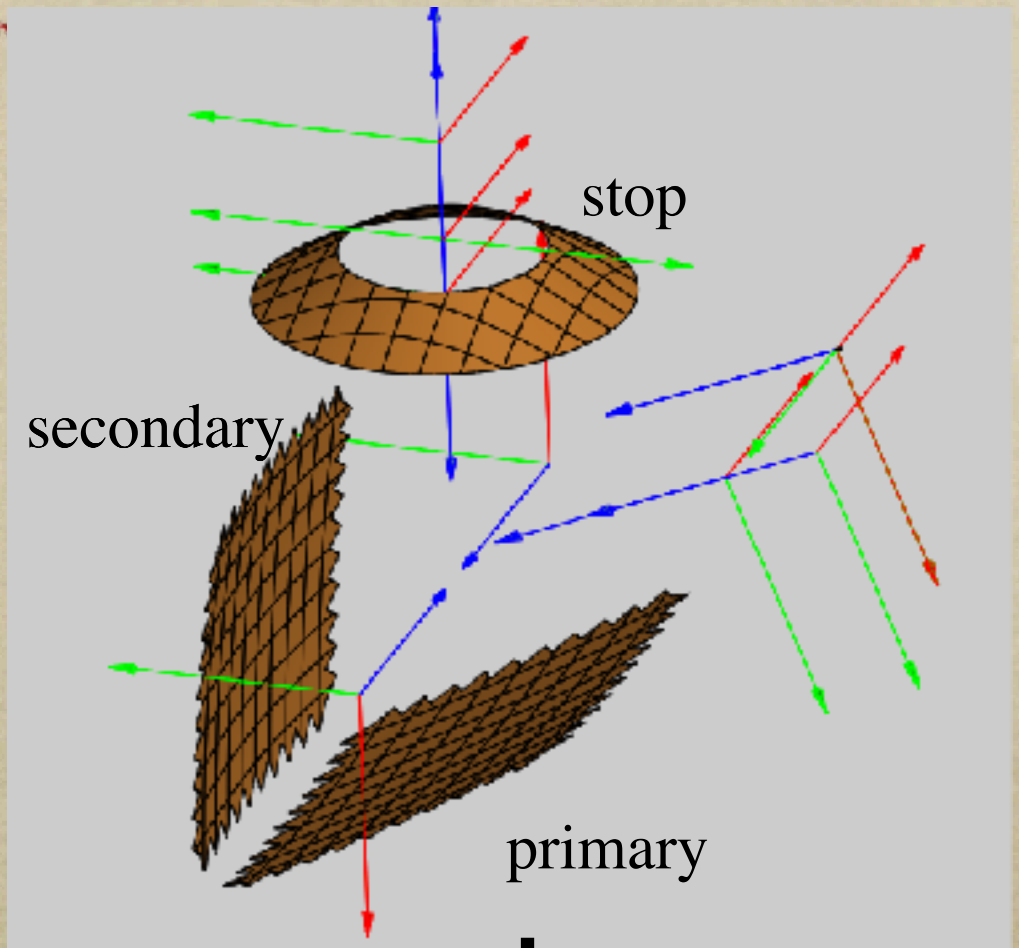


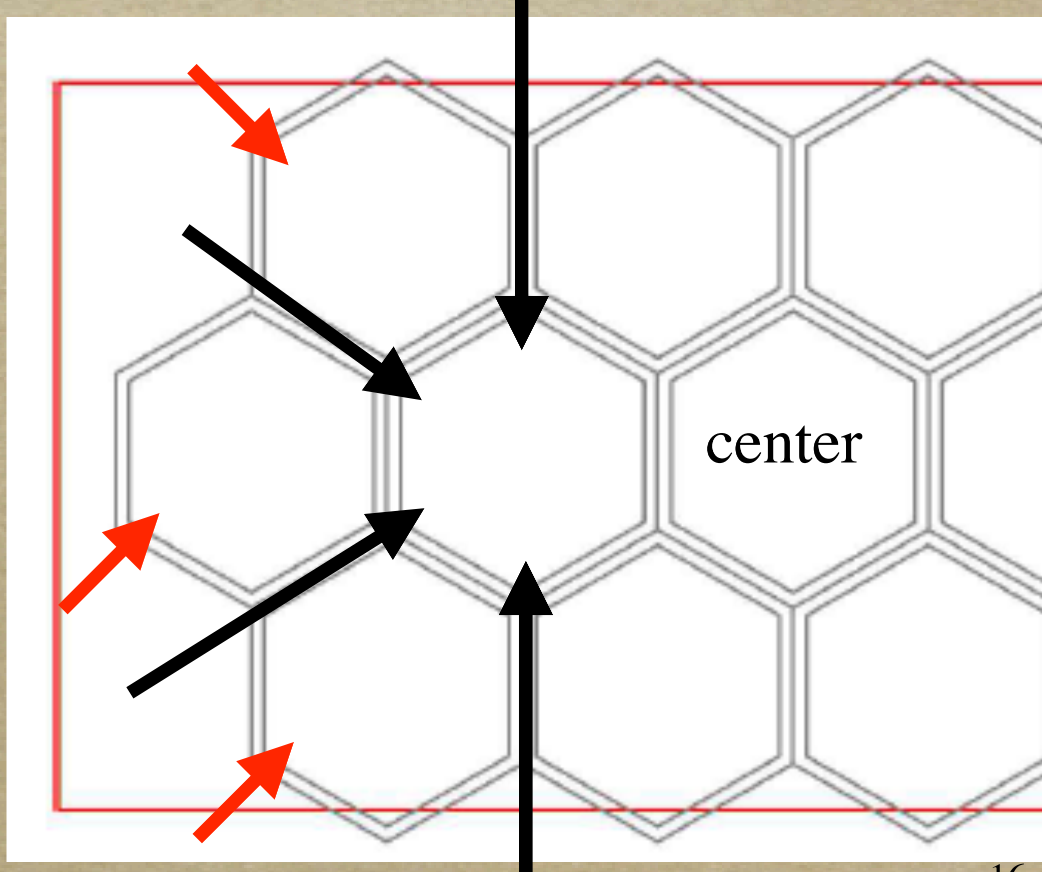
T. Hasebe

- ❖ Sensitivity (enhanced LFT)
  - black:
    - ✓ 5 * 18 mm lens for LF1
    - ✓ 4 * 18 mm lens for LF2
  - red:
    - ✓ 5 * 30 mm lens for LF1
    - ✓ 4 * 30 mm lens for LF2
- ❖ Results
  - improvement at the lowest frequencies
    - ✓ loading from stop decreases
  - reducing sensitivity at 68, 78, and 89 GHz
    - ✓ the number of detectors decreases
  - there is room to adjust a combination
    - ✓ e.g. 3 * 18 mm + 2 * 30 mm (LF1), 2 * 18 mm + 2 * 30 mm (LF2)

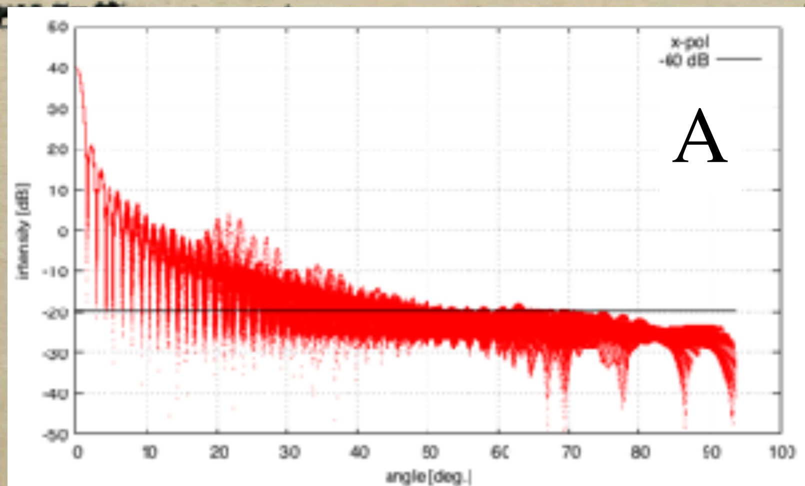
5. Beam patterns in the lowest bands

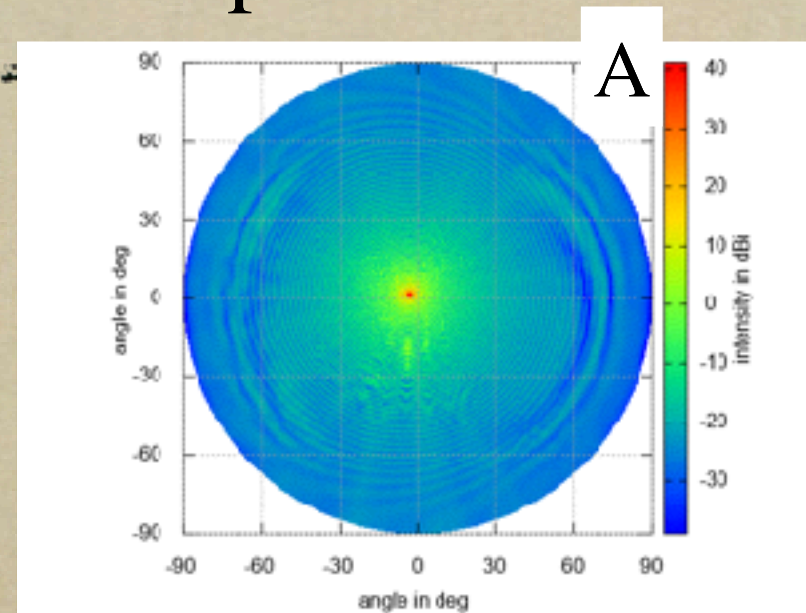
- ❖ Model
  - 400-mm aperture, F/3.5
  - three elements
    - ✓ two anamorphic aspherical mirrors w/ serration
    - ✓ a cold aperture stop
  - 34 and 42.5 GHz
  - elliptical Gaussian beam
    - ✓ corresponding to a 30-mm lens-let beam
    - ✓ 34 GHz at the black arrows
    - ✓ 42.5 GHz at the red arrows
- ❖ Stray light is included
  - up to triple bounces
    - ✓ e.g. feed -> secondary -> primary -> secondary -> aperture -> sky

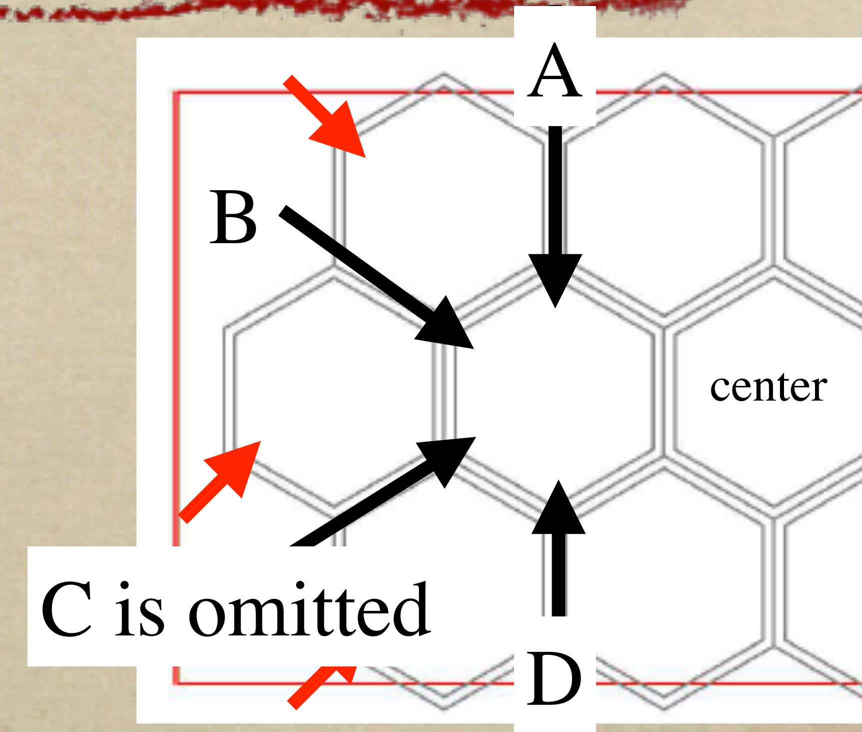


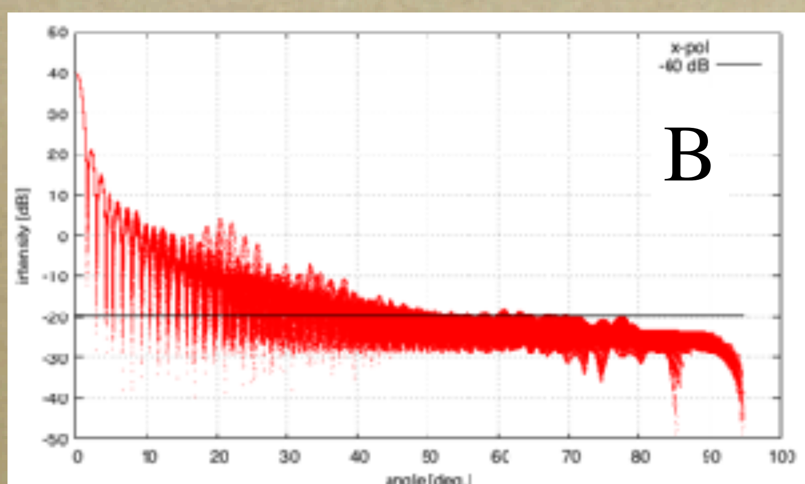


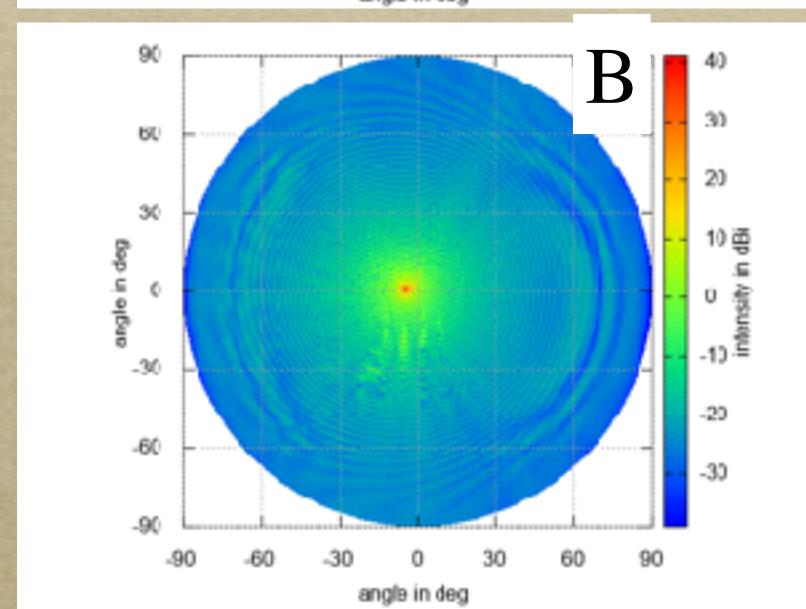
5. Beam patterns at 34 GHz

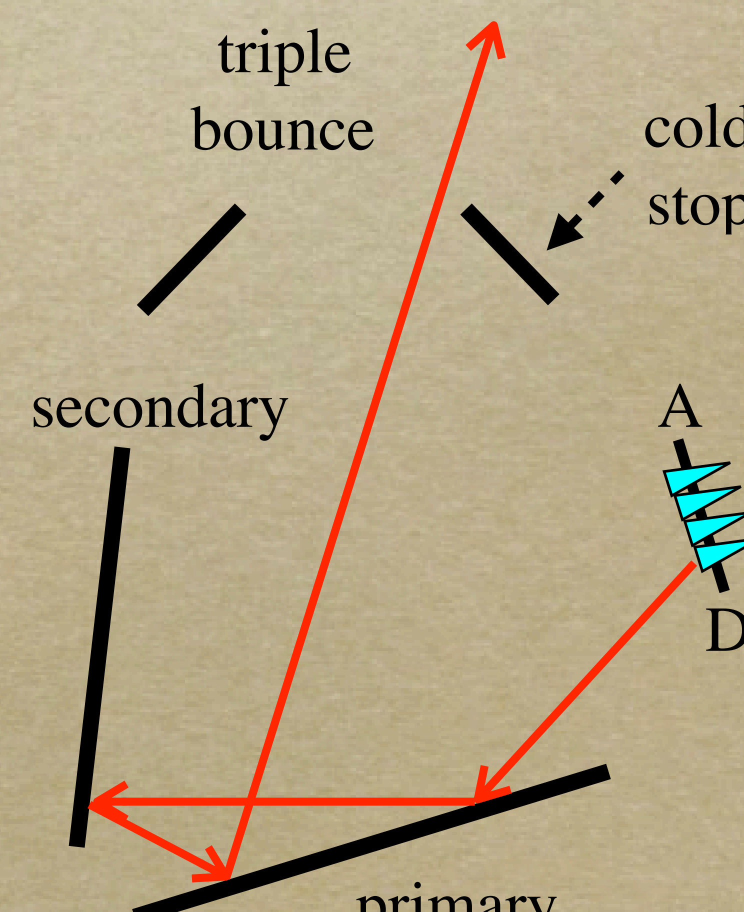


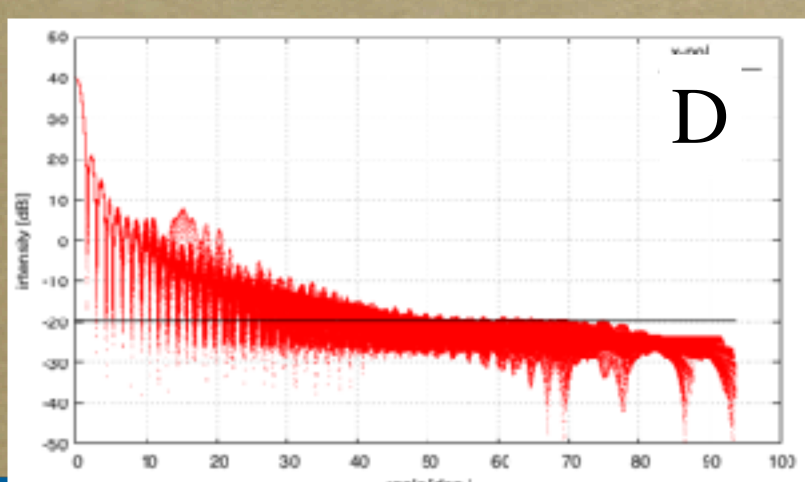


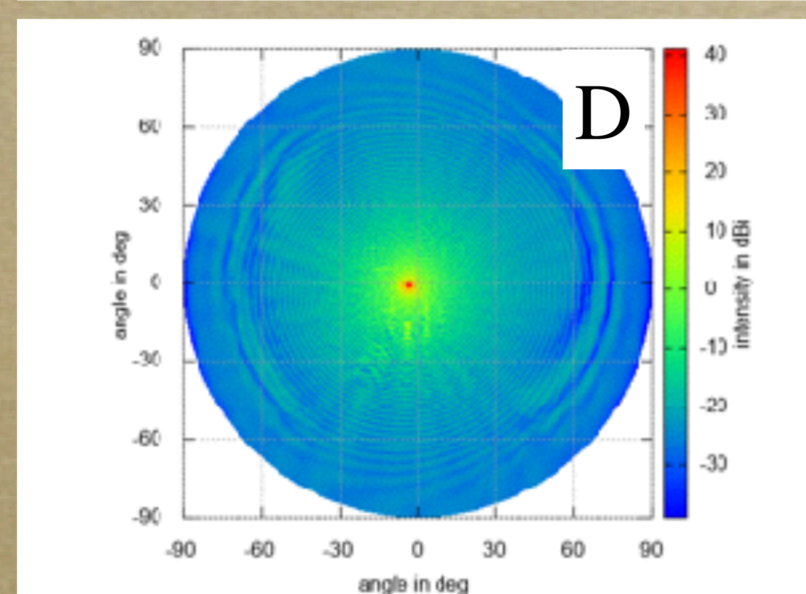




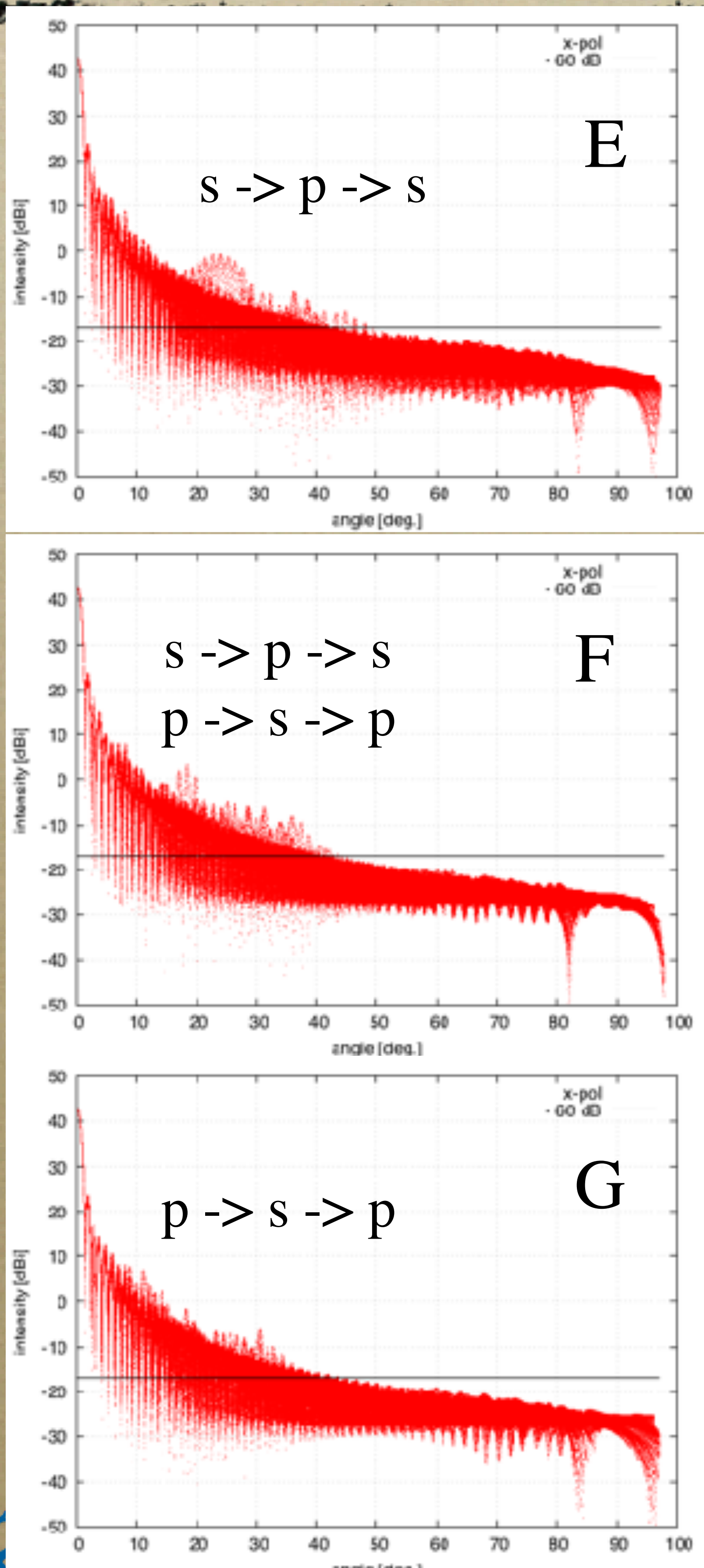


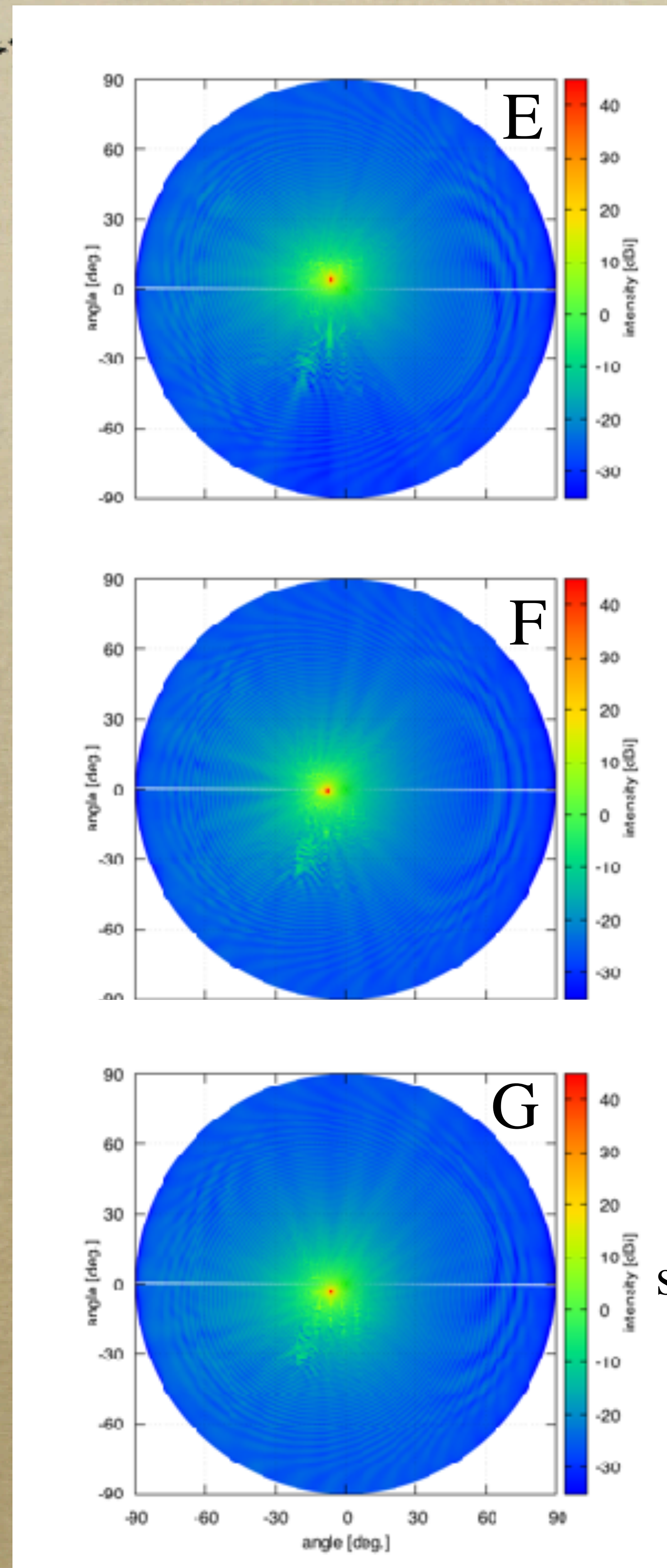


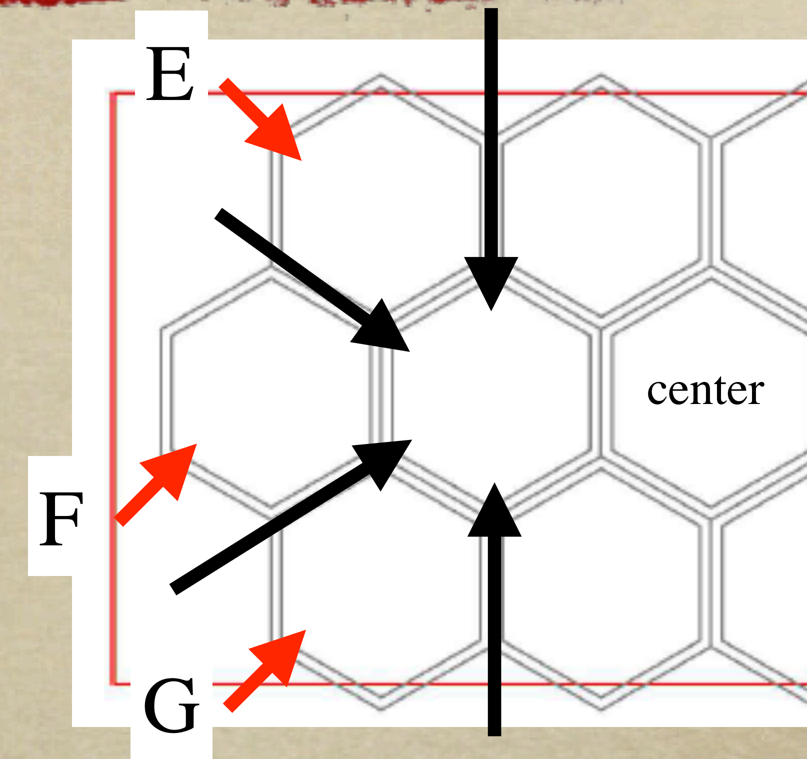


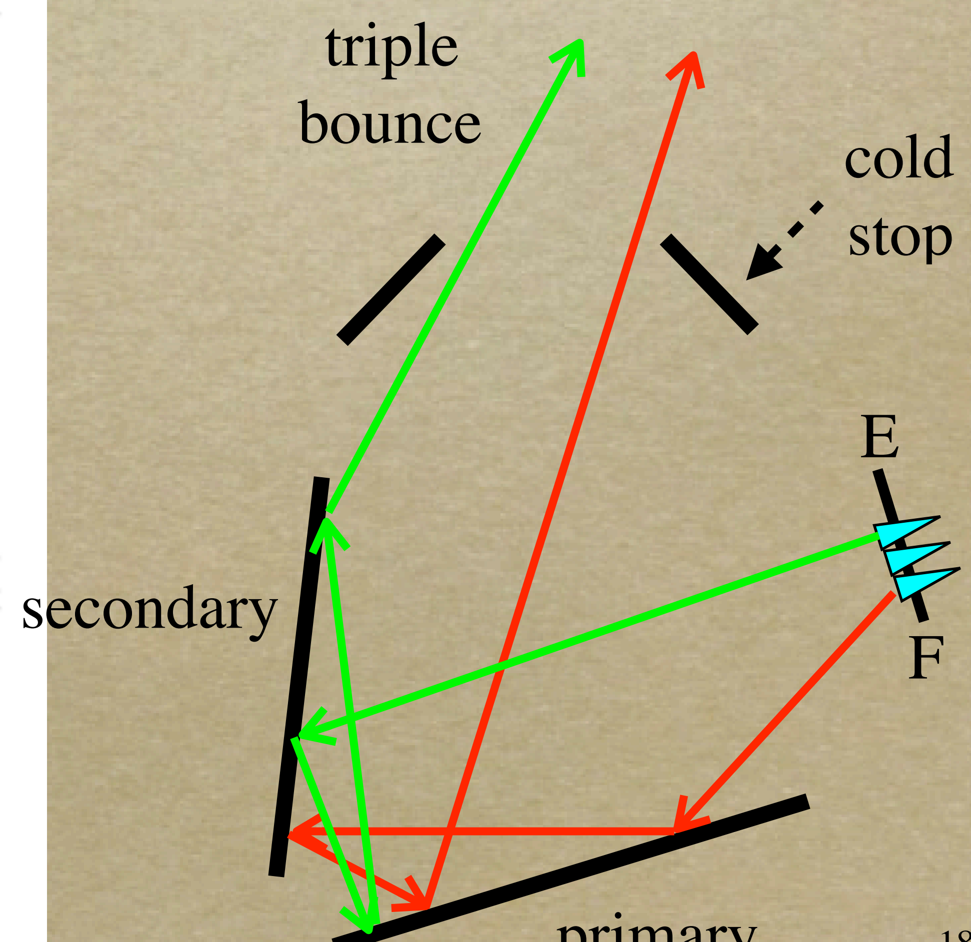


5. Beam patterns at 42.5 GHz









6. Conclusion

- ❖ The requirements of a beam pattern are introduced
  - main lobe: not so strict
  - side lobes: -60 dB (ring/diffuse), inequalities (point-like)
- ❖ What determines beam shape
  - edge taper, feed, diffraction at edges, and configuration
- ❖ To avoid additional side lobe originated from diffraction at mirror edges
  - 30 mm lens-let is better for the lowest bands
    - ✓ sensitivity is also improved
  - LF1 is located at the center of focal plane
  - there is room to discuss how many modules are changed to 30-mm
- ❖ PO simulation at 34 GHz and 42.5 GHz
  - triple bounce stray light can be seen
  - next steps: lens-let pattern, then baffling