SKA Reflector Design

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Background

XDM: 2005 - 2007

EMSS ANTENNAS

- 15 m prime focus cluster feed
- Single antenna, Haartebeeshoek
- Subtended half-angle: ~ 53°
- 1414 – 1670 MHz

R. Lehmensiek and I. P. Theron, “On the design of the feed horns for the Karoo Array Telescope dish antennas,” in *Proc. IEEE Africon Conf.*, Windhoek, Namibia, Sep. 2007, pp. 1-5.

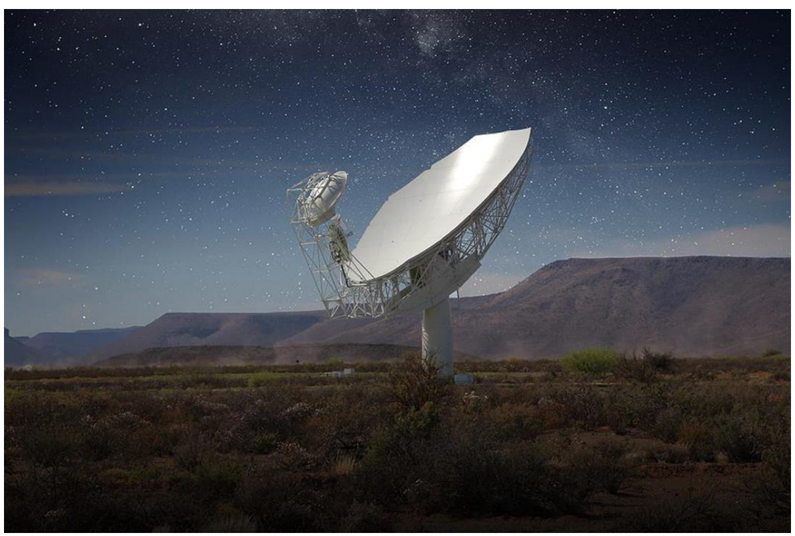
KAT-7: 2008 - 2012

- 12 m prime focus
- 7 antennas,
  SKA core site
- Subtended half-angle: ~ 67°
- 1200 – 1950 MHz

A. R. Foley, et al., "Engineering and science highlights of the KAT-7 radio telescope," *Mon. Not. R. Astron. Soc.*, vol. 460, no. 2, pp. 1664-1679, Aug. 2016.

MeerKAT: 2011 - 2018

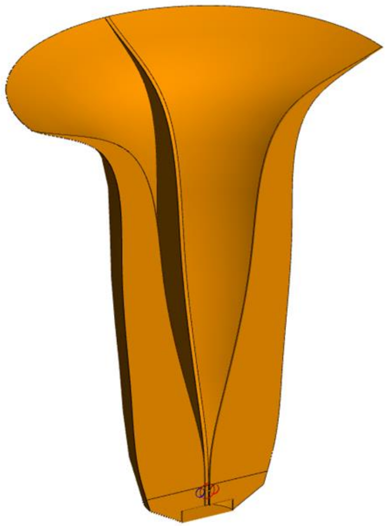
- **13.8 m offset Gregorian**
- **64 antennas,**
  SKA core site
- **Subtended half-angle: ~ 49°**
- **UHF: 580 – 1050 MHz**
  L-band: 900 – 1670 MHz
  S-band: 1750 – 3440 MHz
  X-band: planned

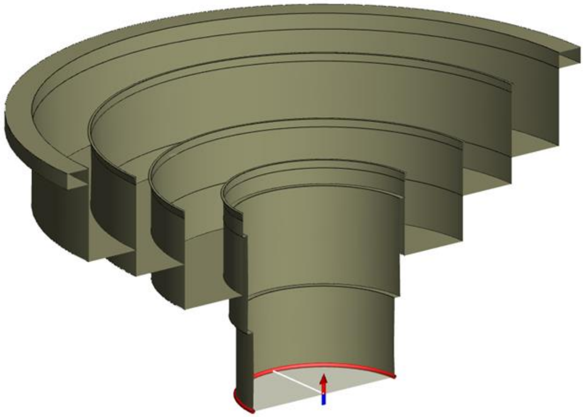


F. Camilo, *et al.*, "Revival of the magnetar PSR J1622-4950: Observations with MeerKAT, Parkes, XMM-Newton, Swift, Chandra, and NuSTAR," *The Astrophysical Journal*, vol. 856, no. 2, article id. 180, pp. 1-11, Apr. 2018.

SKA

- SKA – Square Kilometre Array
  - 1 km^2 receiving aperture
  - SKA1-mid (~10% of full SKA)
    - 64 x 13.5 m MeerKAT (precursor) & 133 x 15 m SKA1 shaped dishes
    - Six single pixel feeds:
      - Band 1: 350 – 1050 MHz (3:1)
      - Band 2: 950 – 1760 MHz (1.85:1)
      - Band 3: 1.65 – 3.05 GHz (1.85:1)
      - Band 4: 2.8 – 5.18 GHz (1.85:1)
      - Band 5a: 4.6 – 8.5 GHz (1.85:1)
      - Band 5b: 8.3 – 15.4 GHz (1.86:1)
  - SKA1-low (Log-Periodic)
  - Advanced program on PAFs

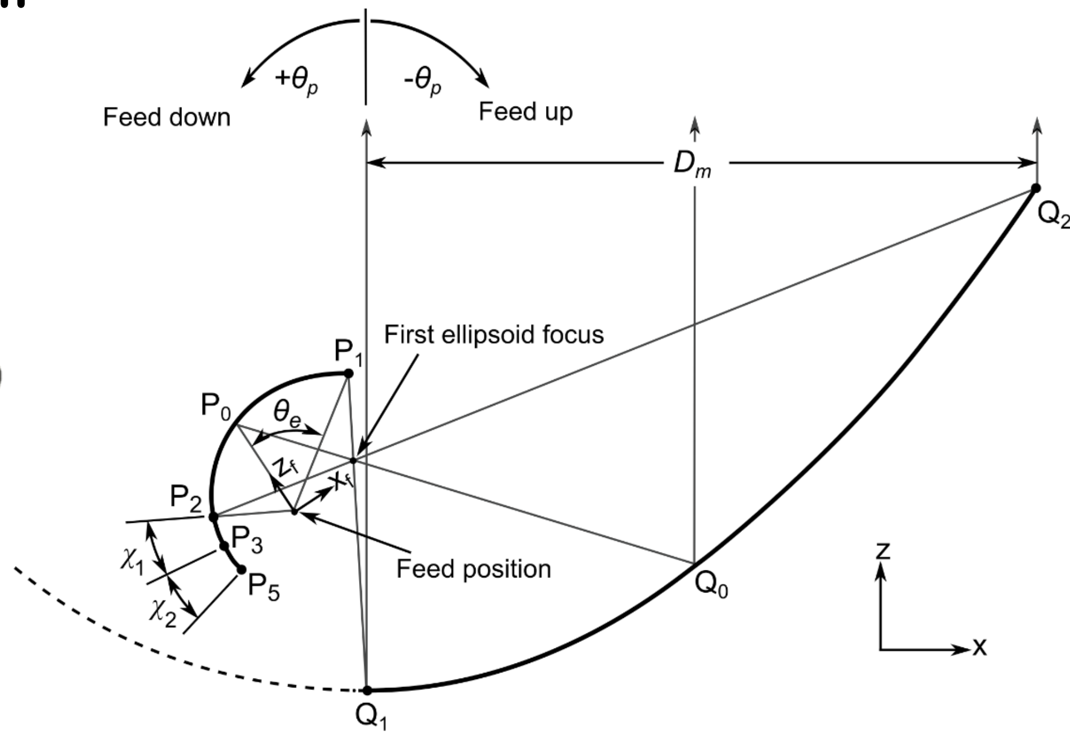




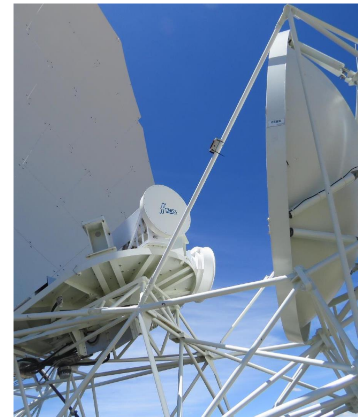
G. H. Tan, R. Lehmensiek, B. Billade, K. Caputa, S. Gauffre, I. P. Theron, M. Pantaleev, Z. Ljusic, B. Quertier and A. Peens-Hough, "An innovative, highly sensitive receiver system for the Square Kilometre Array Mid Radio Telescope," in *Proc. SPIE Astronomical Telescopes and Instrumentation*, Edinburgh, United Kingdom, Jun. 2016, vol. 9906.

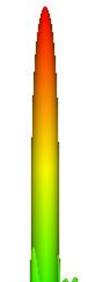
Reflector system

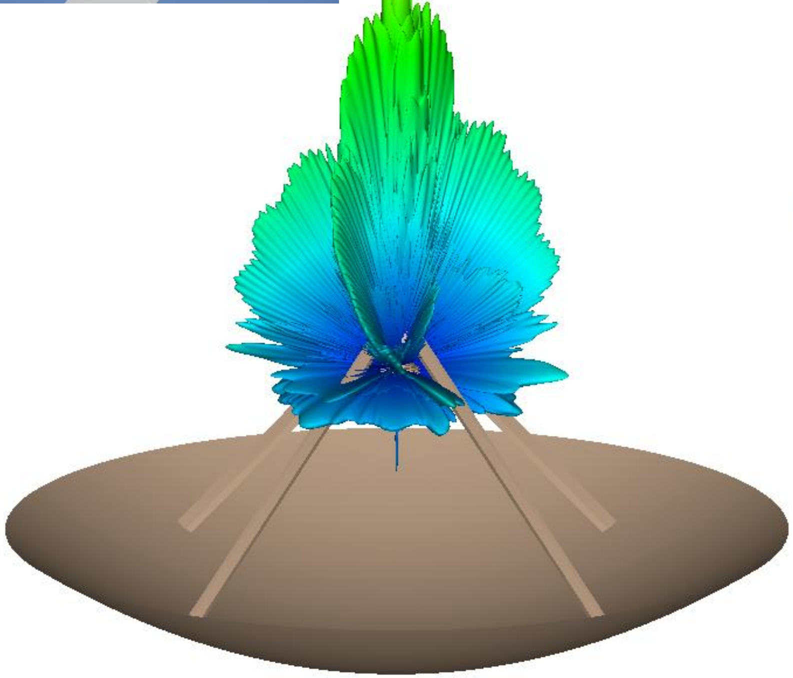
- **Offset Gregorian reflector system**
  - **Main:** ➢ D_m = 15 m
    ➢ $\|Q_1Q_2\| \approx$ 18.2 m
  - **Sub:** ➢ $\|x_{P1}x_{Q1}\| \approx$ 0.5 m
    ➢ $\|P_1P_3\|$ = 5 m
    ➢ θ_e = 58°
  - **Extension:** ➢ $\chi_{1,2}$ = 40°
  - **Tipping: Feed down**

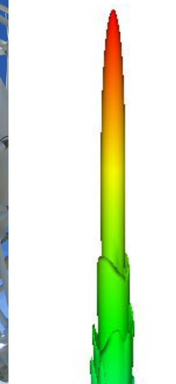


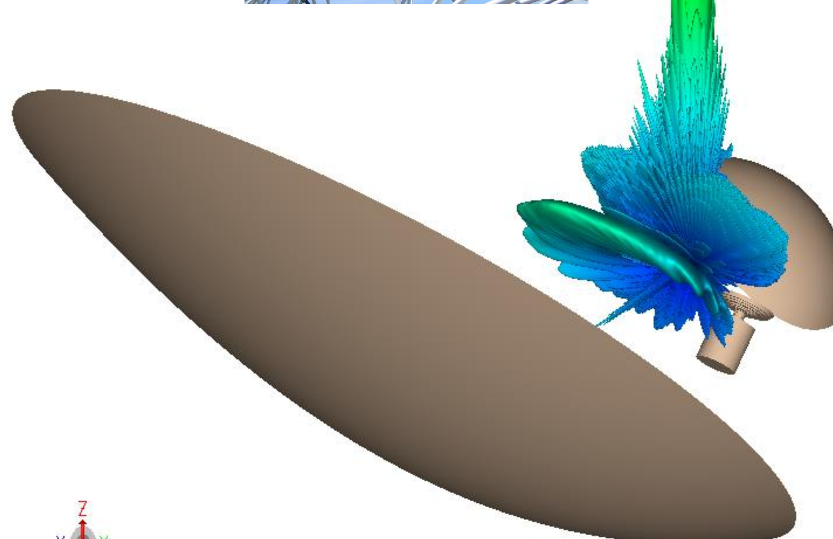
Prime Focus vs Offset Gregorian

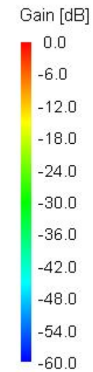






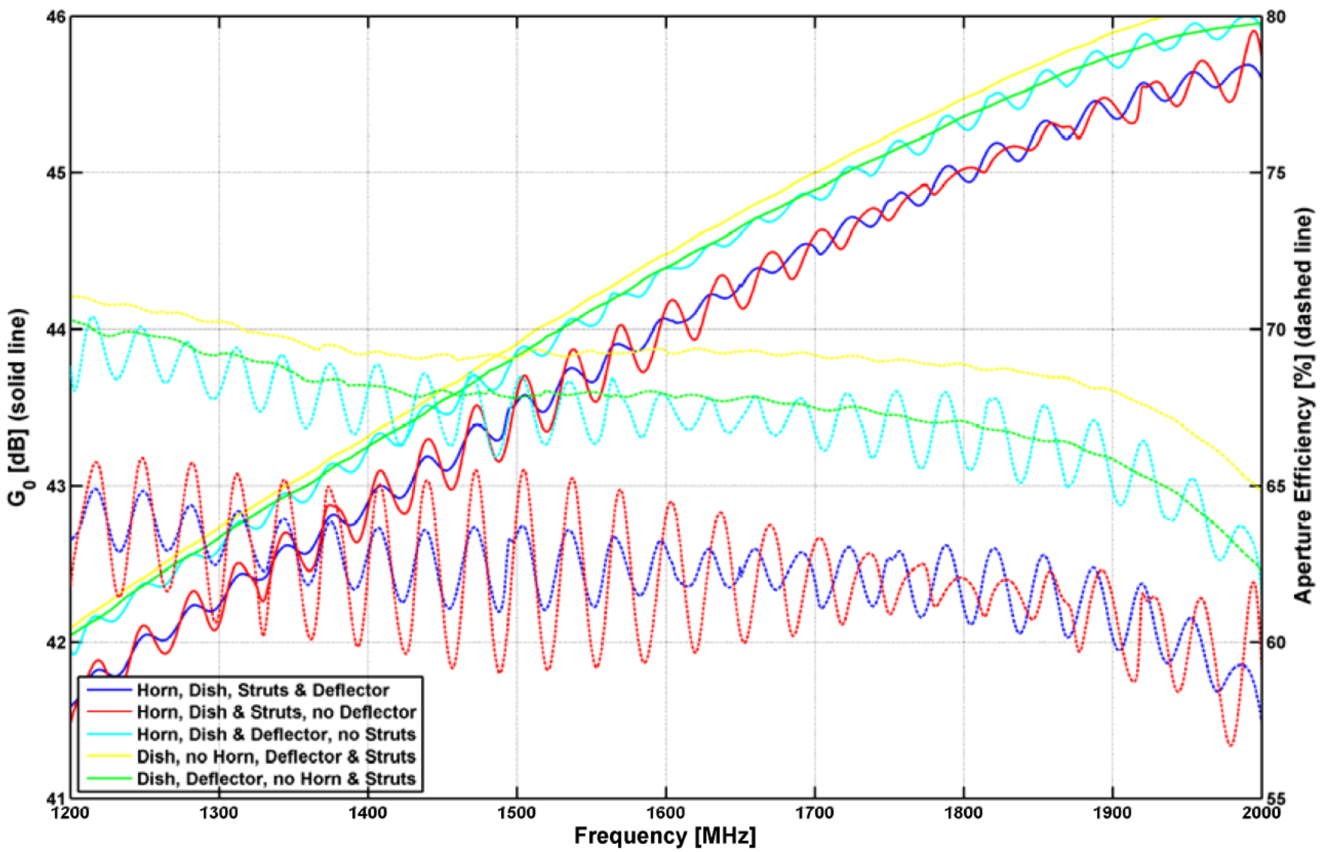






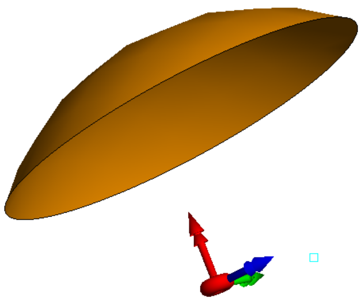
I. P. Theron, R. Lehmensiek and D. I. L. de Villiers, "The design of the MeerKAT dish optics," in *Proc. Int. Conf. Electromagn. Adv. Appl. (ICEAA)*, Cape Town, South Africa, Sep. 2012, pp. 539-542.

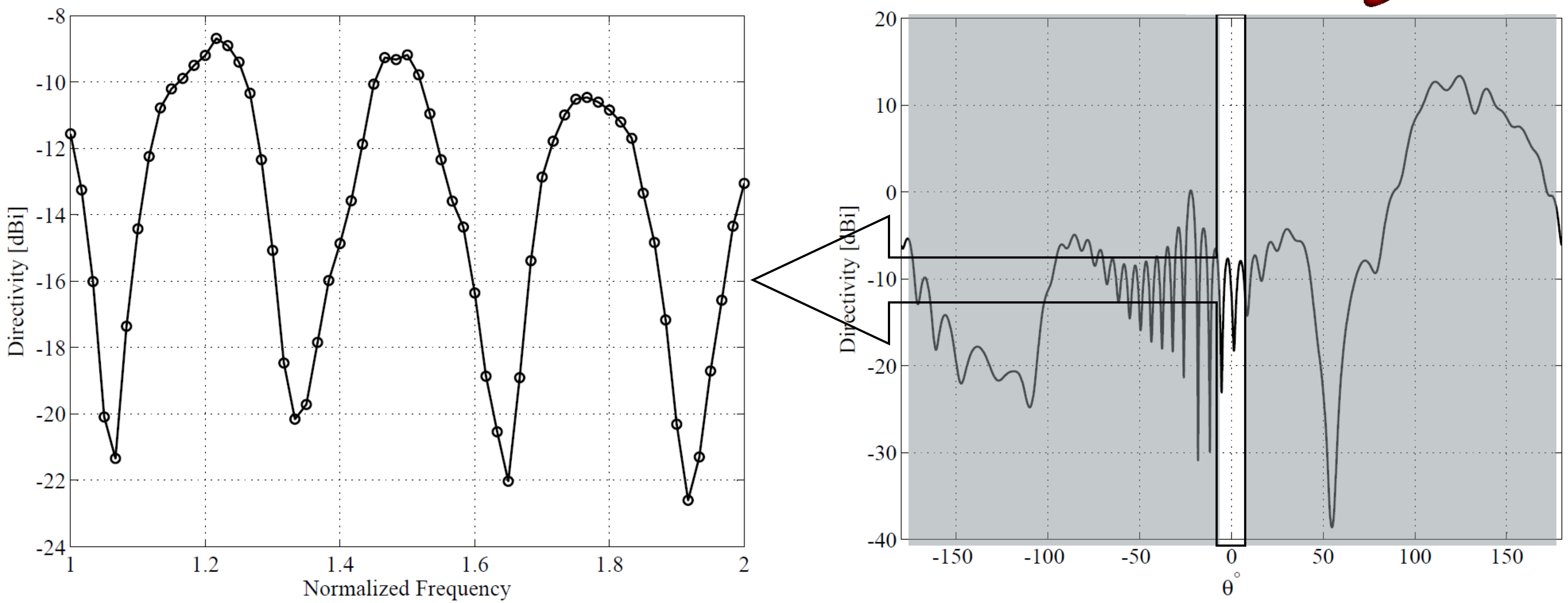
Frequency ripple: KAT-7



Frequency ripple: Offset Gregorian

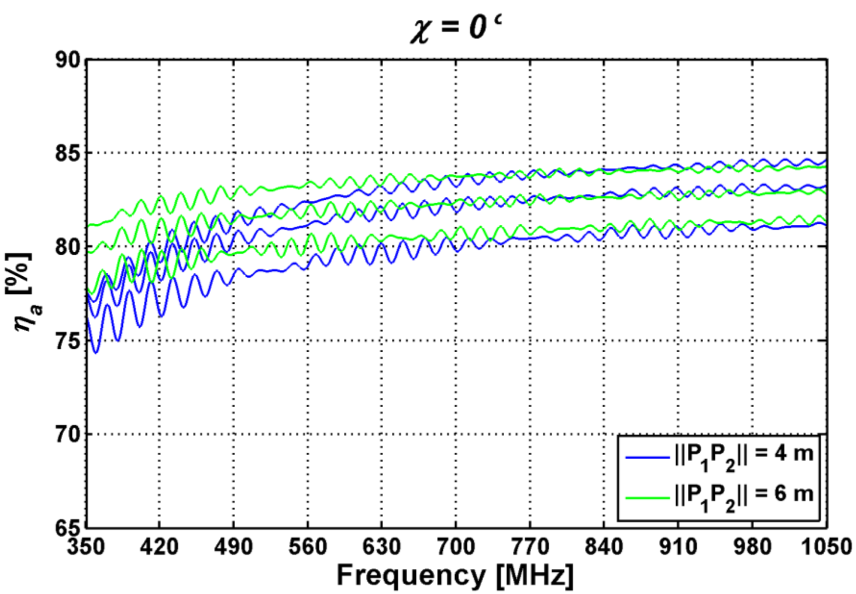
- **Diffraction from the sub-reflector can be significant in small to medium sized systems (tens of wavelengths SR size – result below for 10 λ case)**

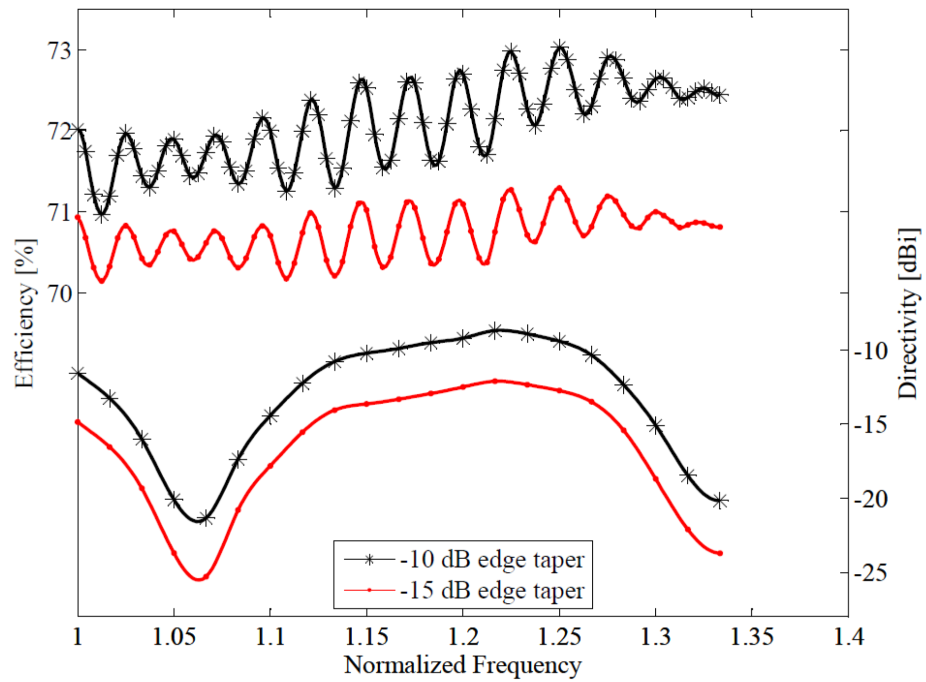




D.I.L. de Villiers, "Prediction of aperture efficiency ripple in clear aperture offset Gregorian antennas", *IEEE Trans. Antennas Propag.*, vol. 61, no. 5, pp. 2457 – 2465, May, 2013.

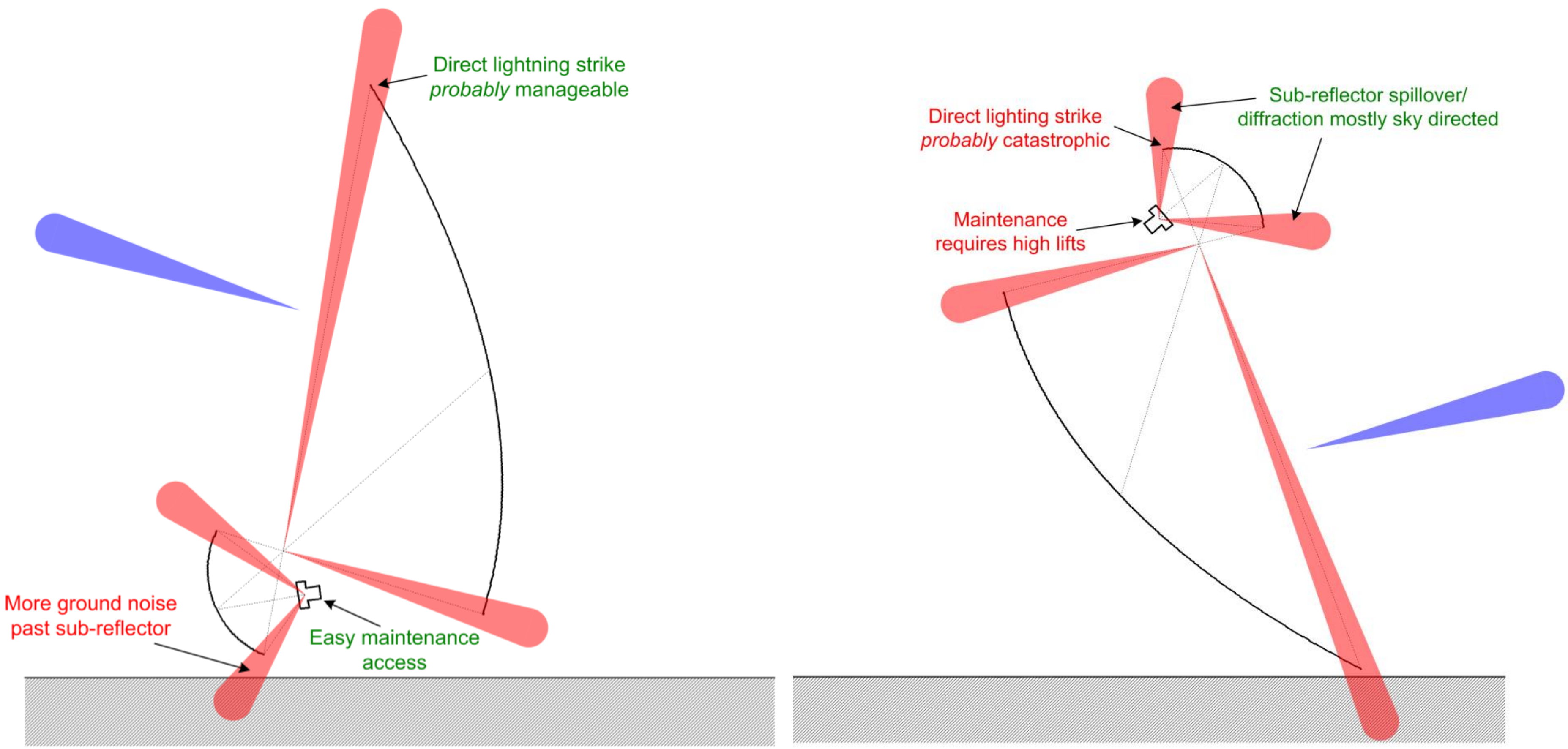
Frequency ripple: Offset Gregorian



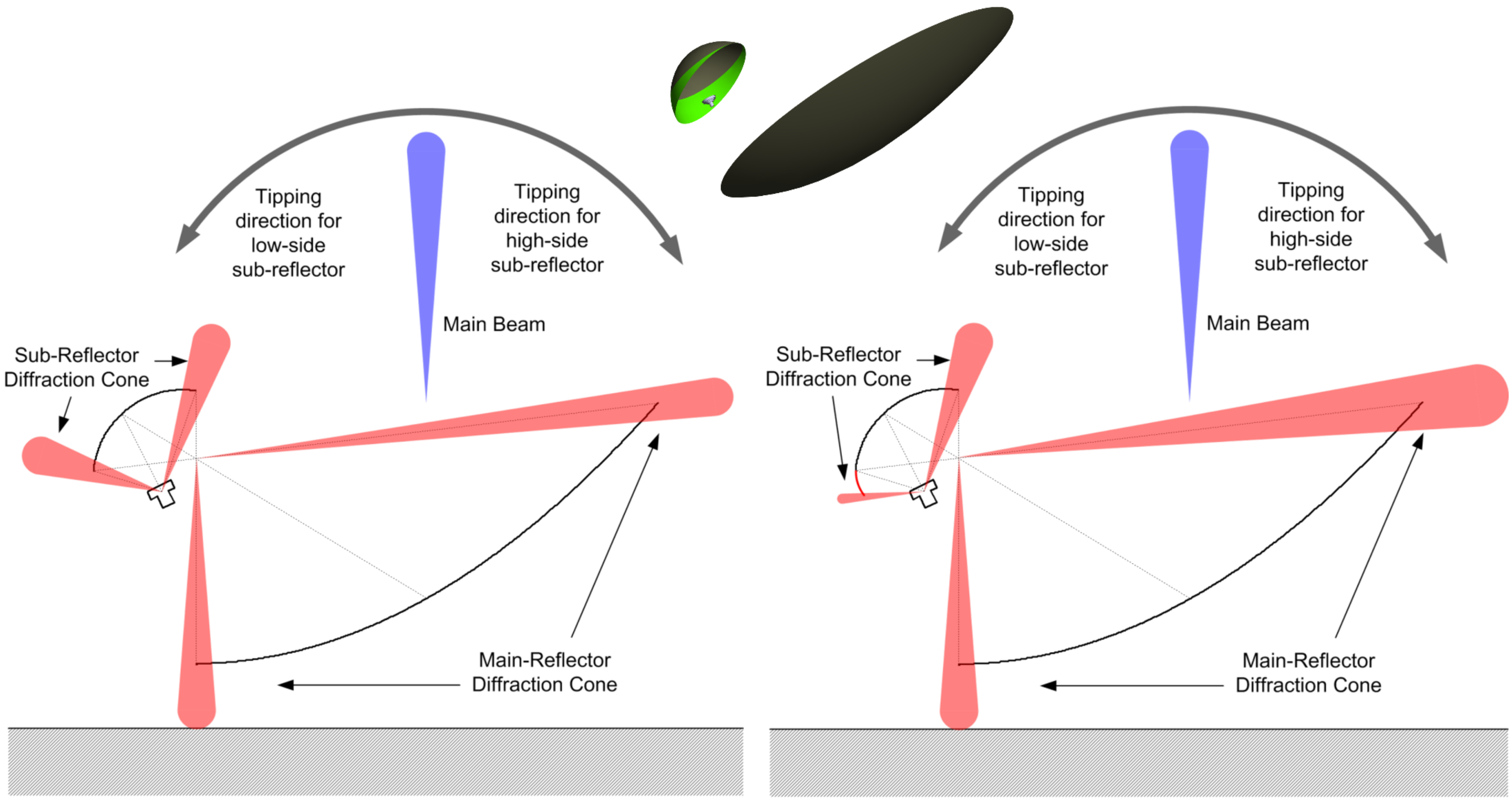


D. I. L. de Villiers, R. Lehmensiek and M. V. Ivashina, "Effects of diffraction and feed pattern variation in shaped offset Gregorian reflectors," *IEICE Trans. Commun.*, vol. E101-B, no. 2, pp. 316-323, Feb. 2018.

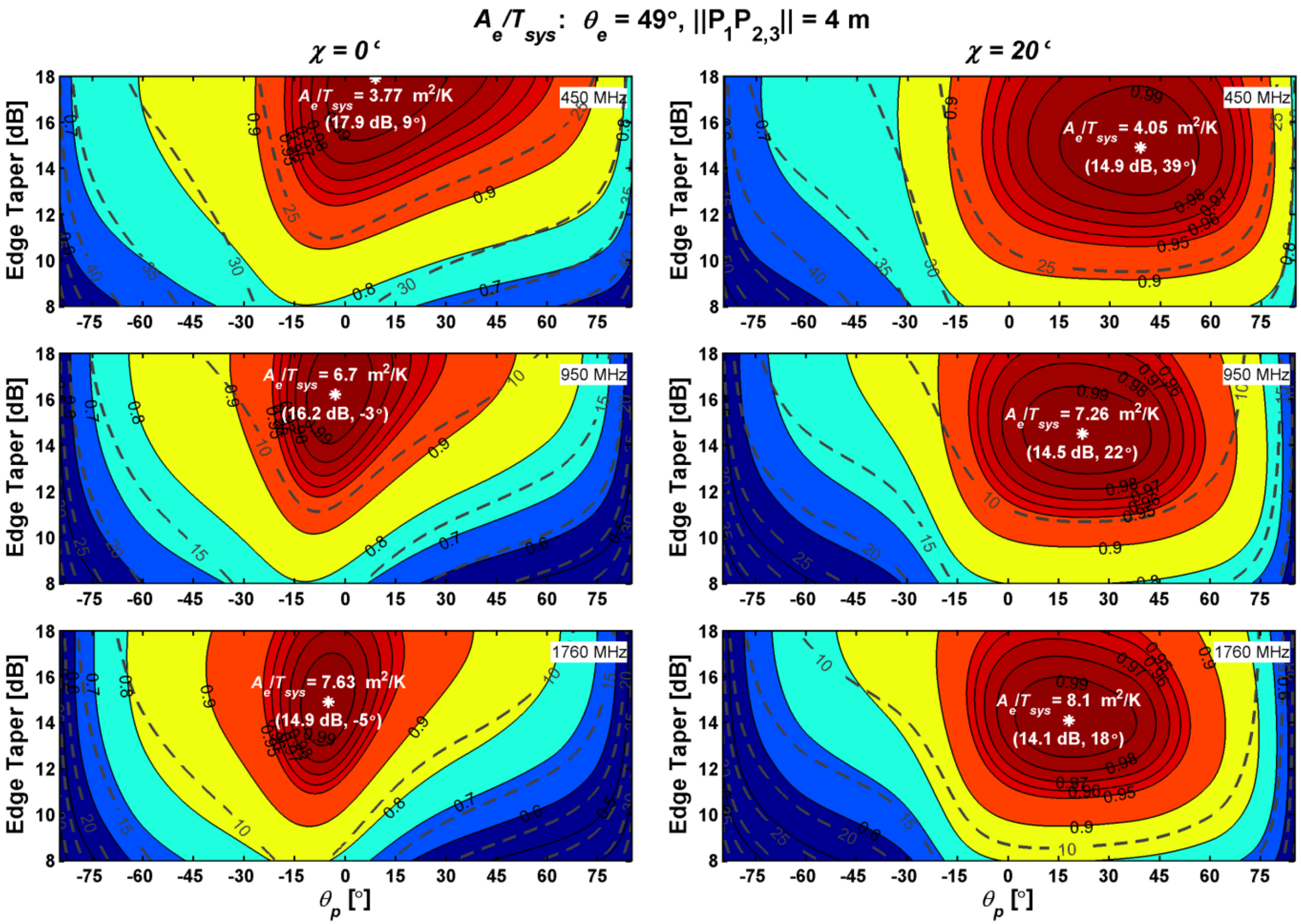
Feed up vs Feed down



Feed up vs Feed down



Feed up vs Feed down



- D.I.L. de Villiers and R. Lehmensiek, "Sub-Reflector Extensions in Shaped Dual Reflector Systems", *IEEE AP-S International Symposium on Antennas and Propagation,* Memphis, TN, USA, pp. 1481-1482, July, 2014.
- D.I.L. de Villiers and R. Lehmensiek, 'Sub-reflector extension shapes for reduced far-out sidelobes in offset Gregorian antennas', *International Symposium on Antennas, Propagation and Electromagnetic Theory (ISAPE)*, Xi'An, China, pp. 55 – 58, October, 2012.

Dish optics design

- **Dish and Feed Design Methodology**
  - **Parametric study of unshaped dishes with Gaussian feeds**
    - Reflector dimensions, θ_e
  - **Designed feeds for a subset of unshaped dish**
  - **Shaped dish given the optimised (for unshaped) feeds**
    - Exhaustive search of a parameterised mapping function, $\rho(\theta_f)$
  - **Re-optimised the feeds on the optimum shaped dish**
  - **Full-wave analyses to determine system performance**
    - Take into account diffraction effects

I. P. Theron, R. Lehmensiek and D. I. L de Villiers, "Towards an optics design for the SKA," in *Proc. IEEE Africon/URSI Conf.*, Mauritius, Sep. 2013, pp. 1313-1317.

Metric

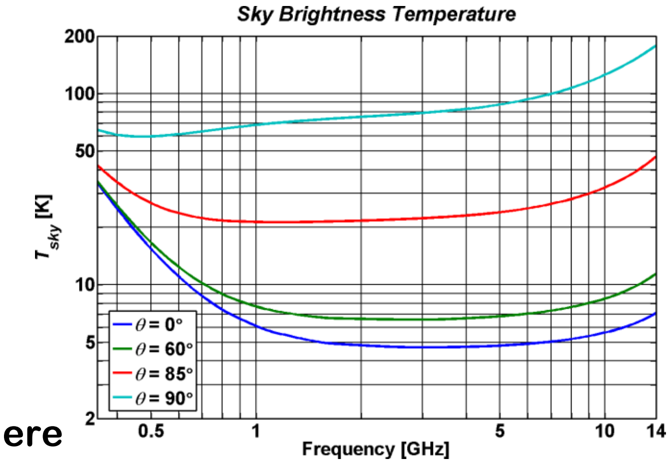
- **Receiving sensitivity, A_e / T_{sys} (m²/K)**

  $$T_{sys} = T_A + T_{rec}$$

  $$T_A(f\,|\,\hat{\mathbf{r}}_0) = \frac{\iint_{4\pi} T_b(f,\theta,\phi) P_n(f,\theta,\phi) \sin\theta \, d\theta \, d\phi}{\iint_{4\pi} P_n(f,\theta,\phi) \sin\theta \, d\theta \, d\phi}$$

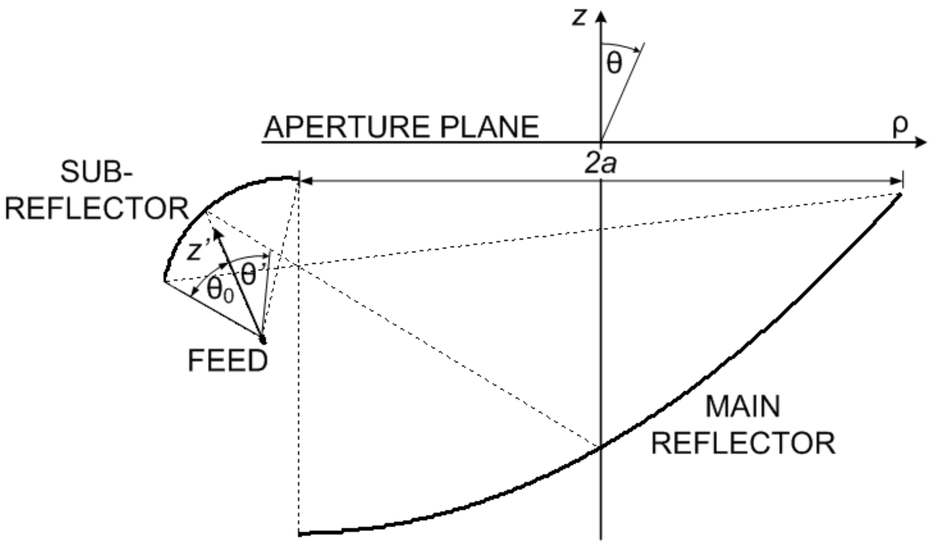
  $P_n(f, \theta, \phi)$ - **antenna radiation pattern**

  $T_b(f, \theta, \phi)$ - **scene brightness temperature**
  - emission from water vapour and oxygen in atmosphere
  - cosmic microwave background and galactic emission (average parameter values) as observed through the atmosphere
  - ground emission includes the sky radiation reflected from the ground and the ground emission



- **Sidelobe levels, 2nd and higher**
  - SLL_1 – imaged as part of the main beam
  - SLL_2 – typically highest
- **Cross-polarisation levels (IXR), -1dB and -3dB contour**
- **For optimisation purposes**
  - Average over frequency and tipping angles (0° - 70°)

Shaping



Shaped offset Gregorian system:

1. Conservation of energy
2. Equal path length
3. Snell's law reflection
4. Specified Θ-ρ mapping

$$\rho(\theta_f)\rho'(\theta_f) = \frac{|G(\theta_f)|^2 \sin\theta_f}{V_c|E(\rho)|^2}$$

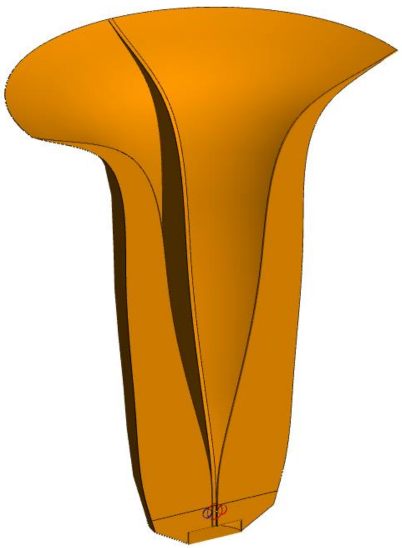
- **Maps feed pattern to a desired aperture field distribution**
- **Assumes:**
  - **Axially symmetric feed pattern**
  - **Frequency invariance**
  - **No diffraction effects**

Feeds

Band 1

350 – 1050 MHz

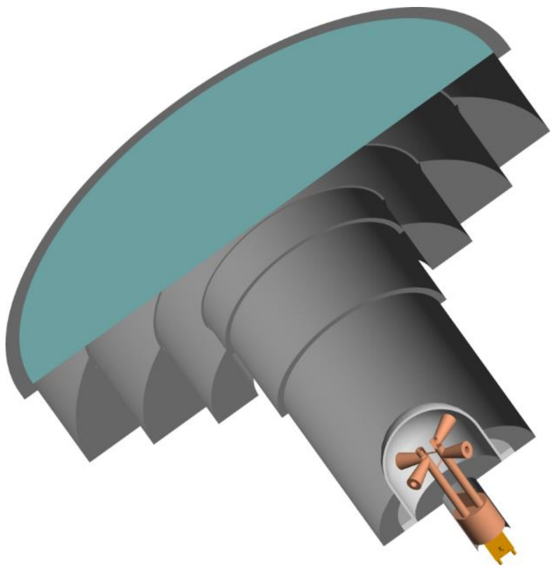
Quad-ridge flared horn



Band 2

950 – 1760 MHz

Corrugated conical horn (OMT & Coupler)



R. Lehmensiek and I. P. Theron, "The design of the MeerKAT UHF band feed," in *Proc. 8th Eur. Conf. Antennas and Propag. (EuCAP)*, The Hague, Netherlands, Apr. 2014, pp. 880-884.

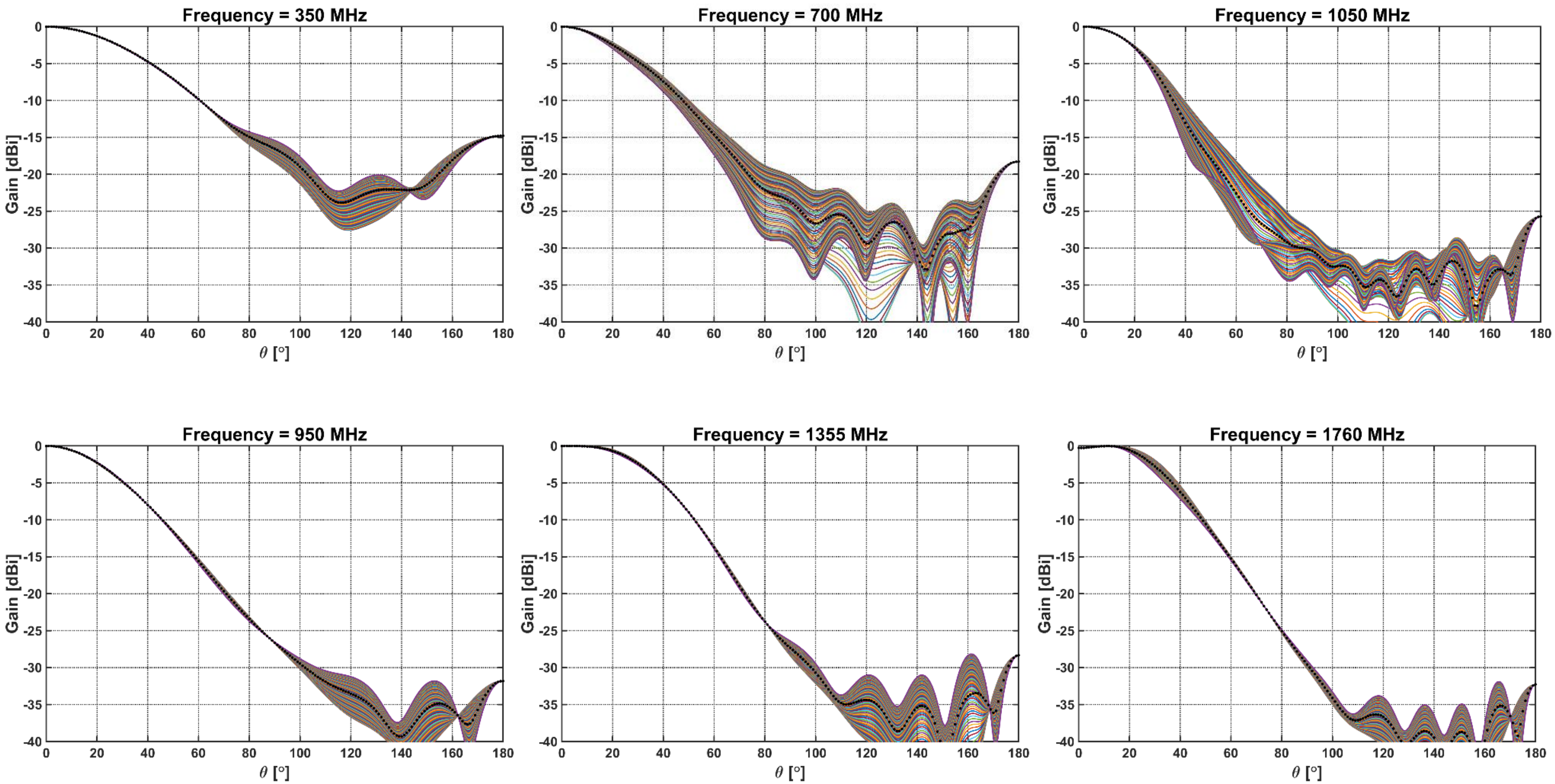
R. Lehmensiek, "A design methodology of the wideband orthogonal mode transducer for the SKA band 2 feed," in *Proc. 10th Eur. Conf. Antennas and Propag. (EuCAP)*, Davos, Switzerland, Apr. 2016, pp. 1-4.

R. Lehmensiek and I. P. Theron, "The design of the MeerKAT L-band feed," in *Proc. Int. Conf. Electromagn. Adv. Appl. (ICEAA)*, Cape Town, South Africa, Sep. 2012, pp. 321-324.

Feeds

Band 1

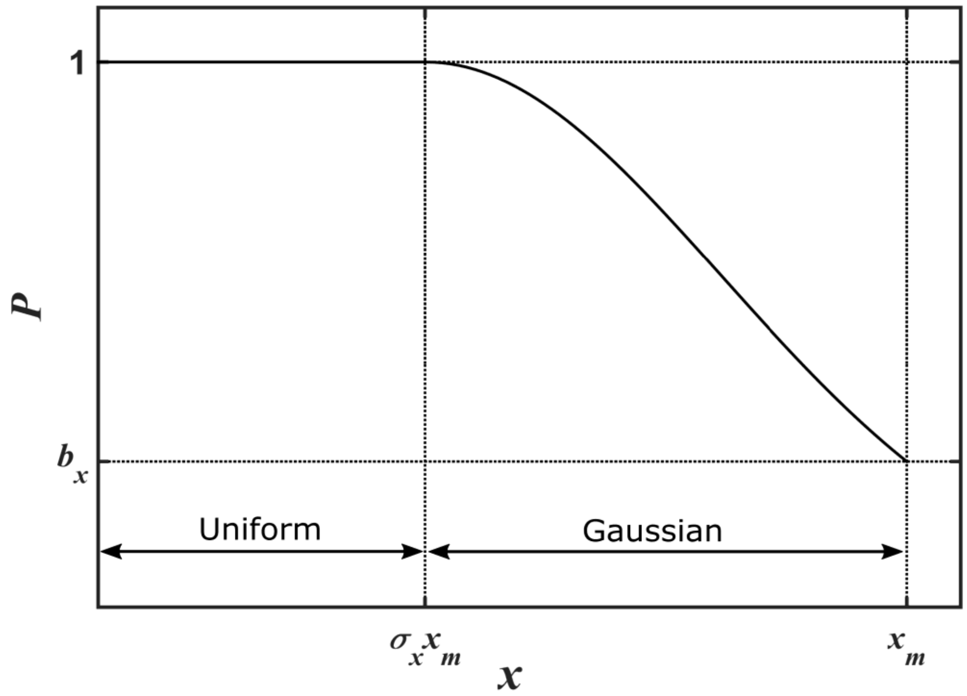
Band 2



Feeds

- **hybrid uniform/Gaussian function:**

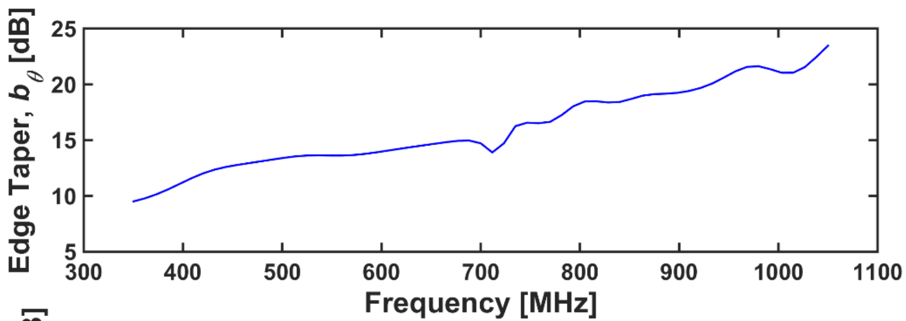
$$P = \begin{cases} 1, & 0 \le x \le \sigma_x x_m \\ \exp\left[-b_x\left(\dfrac{x-\sigma_x x_m}{x_m(1-\sigma_x)}\right)^2\right], & \sigma_x x_m \le x \le x_m \end{cases}$$

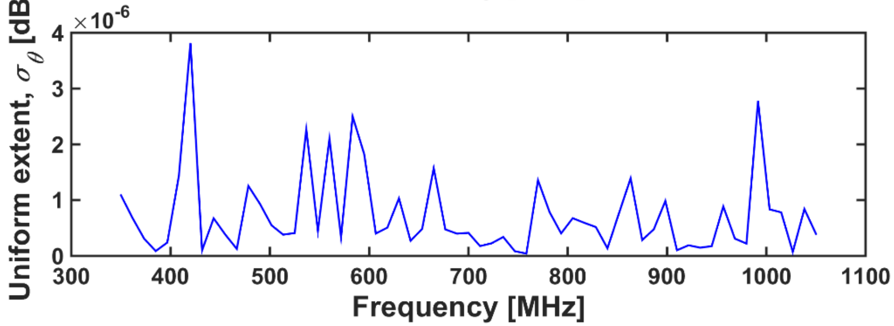


Feeds

Band 1

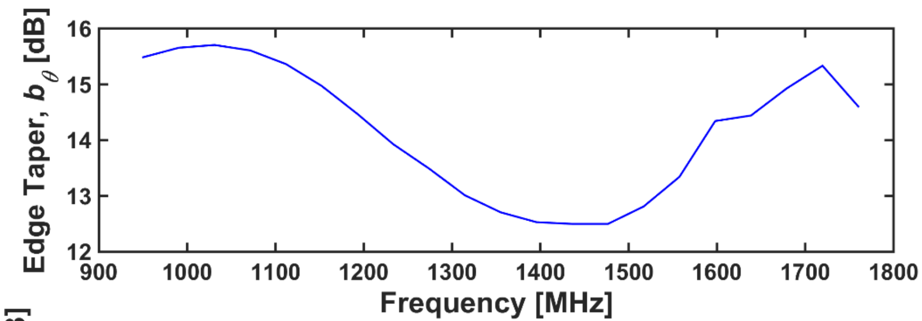
Quad-ridge flared horn

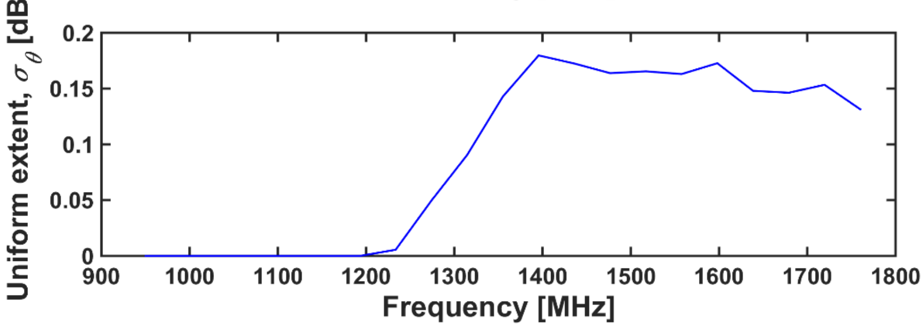




Band 2

Corrugated conical horn



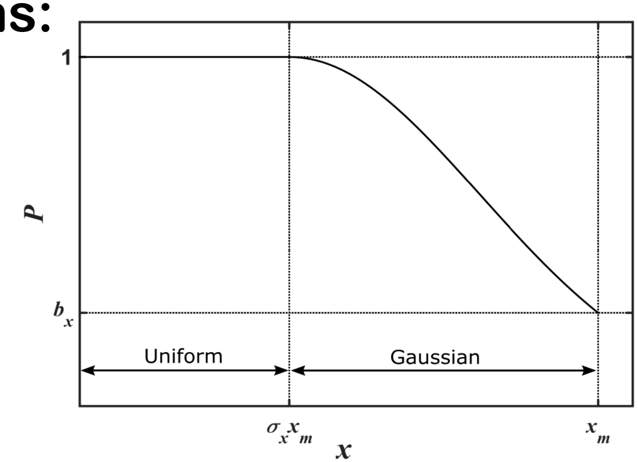


Mapping function

- Variety of feeds with pattern variation (phi, frequency, band)
- Analyses on dish leads to significant variation in performance parameters (diffraction)
- Choosing a mean feed pattern and shaping for a desired aperture distribution will not necessarily lead to an optimal mapping function

- Determine mapping function by optimisation
- Parameterized mapping function
- Use a parameterized feed pattern and aperture field distribution
- Model by hybrid uniform/Gaussian functions:

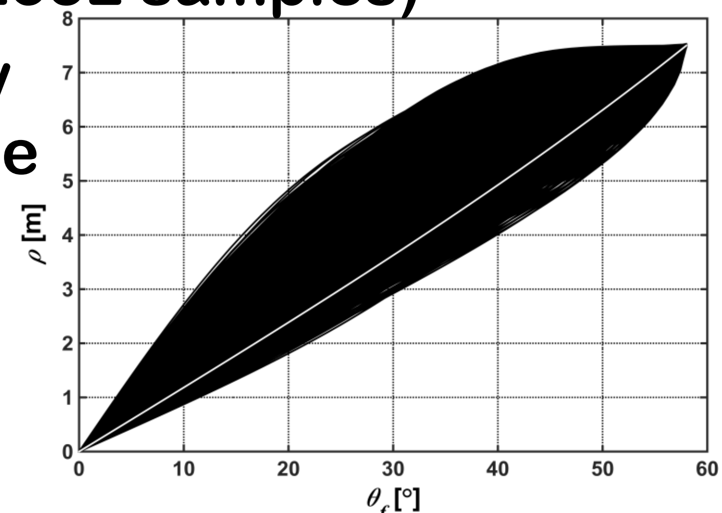
$$P = \begin{cases} 1, & 0 \le x \le \sigma_x x_m \\ \exp\left[-b_x\left(\dfrac{x-\sigma_x x_m}{x_m(1-\sigma_x)}\right)^2\right], & \sigma_x x_m \le x \le x_m \end{cases}$$



- $x \rightarrow \theta_f \; or \; \rho$
- $P \rightarrow \left|G(\theta_f)\right|^2 \; or \left|E(\rho)\right|^2$

Optimization methodology

- **Optimization parameter space:**
  - **Feed:** $\sigma_\theta = [0,\ 0.5]$, $b_\theta = [-17,\ -5]\text{dB}$
  - **Aperture:** $\sigma_\rho = [0,\ 0.7]$, $b_\rho = [-17,\ -5]\text{dB}$
- **Grid search optimization**
  - Not computationally effective (2352 samples)
  - Together with interpolation fully determines the parameter space
  - Exhaustive set of mapping functions



R. Lehmensiek, I. P. Theron and D. I. L. de Villiers, "Deriving an optimum mapping function for the SKA shaped offset Gregorian reflectors," *IEEE Trans. Antennas Propag.*, vol. 63, no. 11, pp. 4658-4666, Nov. 2015.

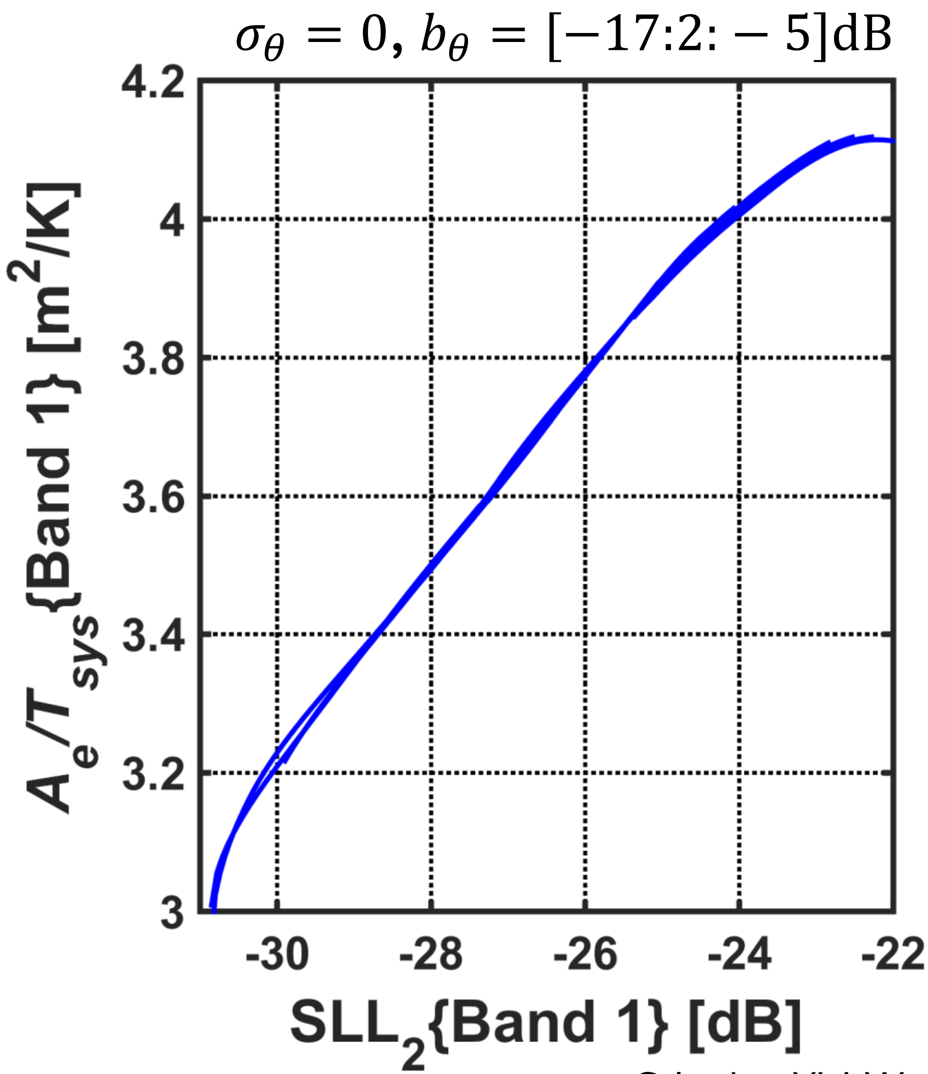
Computations

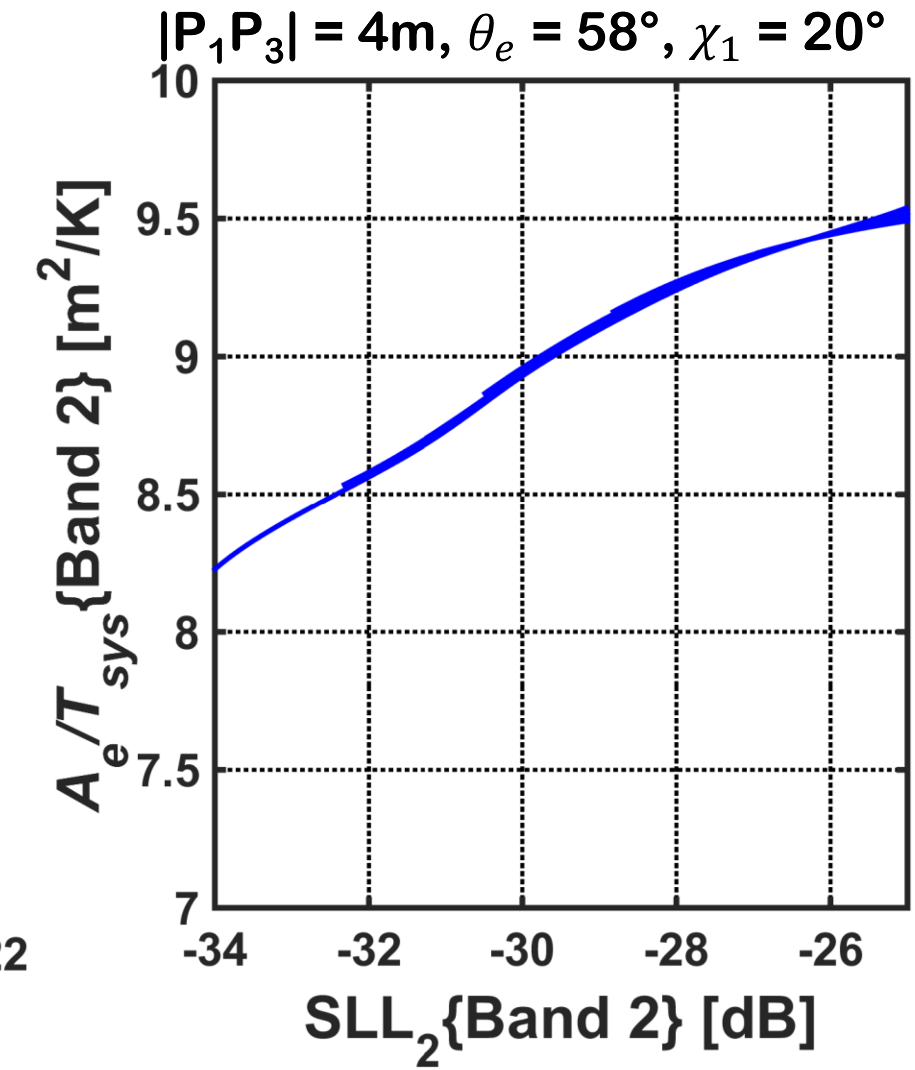
- Feed pattern —› dish —› secondary pattern —› performance parameters
- How to make the computations tractable?
- Approximations:
  - Simplistic dish model, no support structures, deformations, blockage
  - GRASP: PO/PTD, with spherical mode source
  - Linear vertical polarization
  - Number of frequency points: 61 (Band 1), 21 (Band 2)
  - Antenna noise temperature, diffraction compensated main reflector masking technique, $\theta_p = [0°: 10°: 70°]$

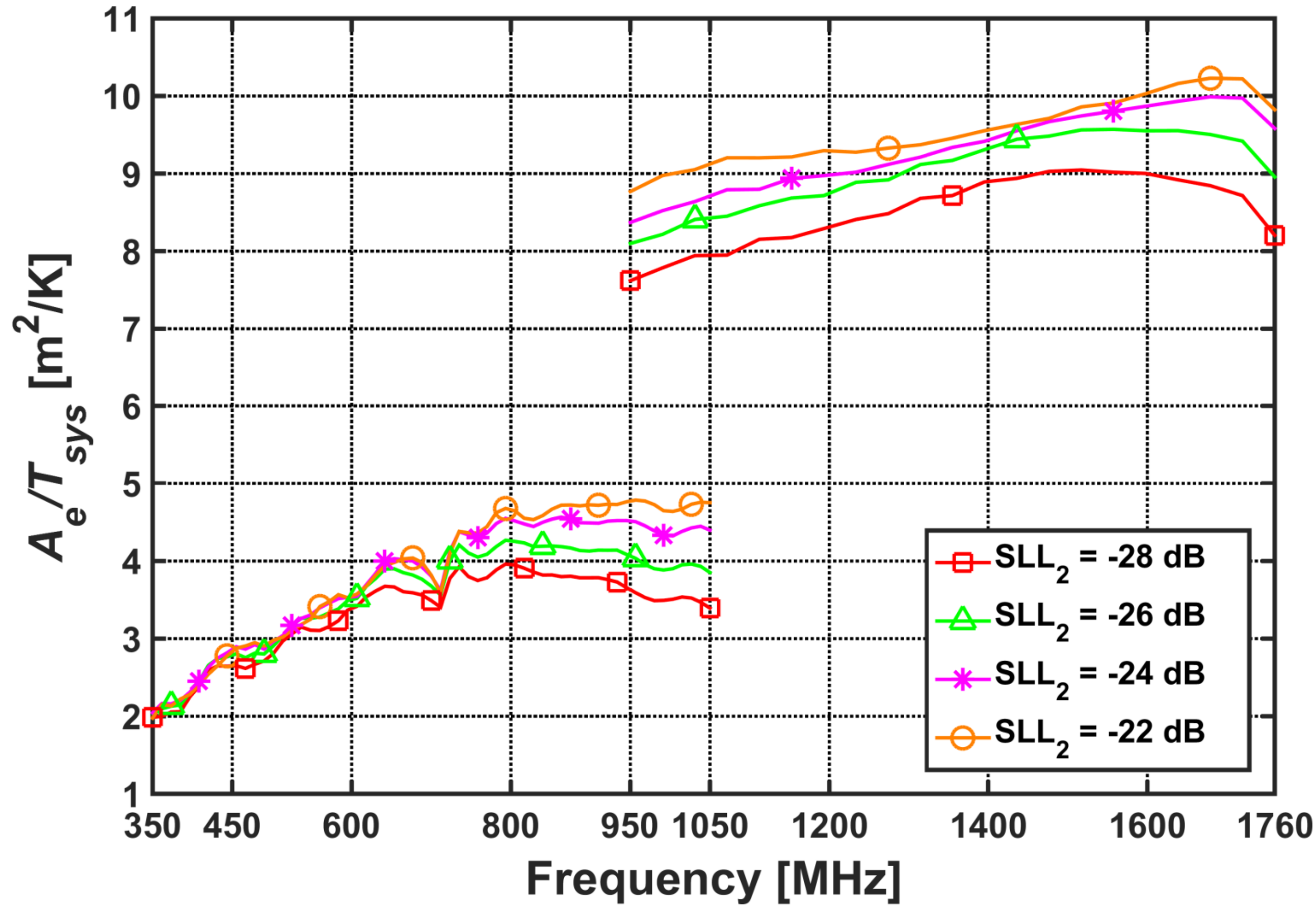
D. I. L. de Villiers and R. Lehmensiek, "Rapid calculation of antenna noise temperature in offset Gregorian reflector systems," *IEEE Trans. Antennas Propag.*, vol. 63, no. 4, pp. 1564-1571, Apr. 2015.

R. Lehmensiek and D. I. L. de Villiers, "Noise temperature approximations for offset Gregorian reflector systems," *IEICE Trans. Commun.*, vol. E101-B, no. 2, pp. 332-339, Feb. 2018.

Sensitivity versus SLL_2



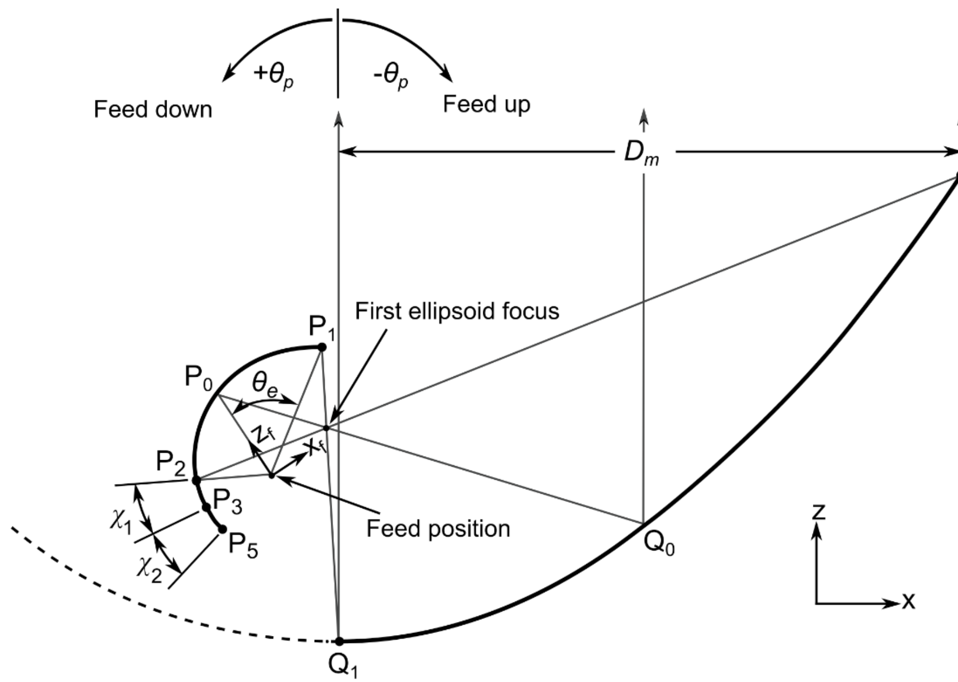




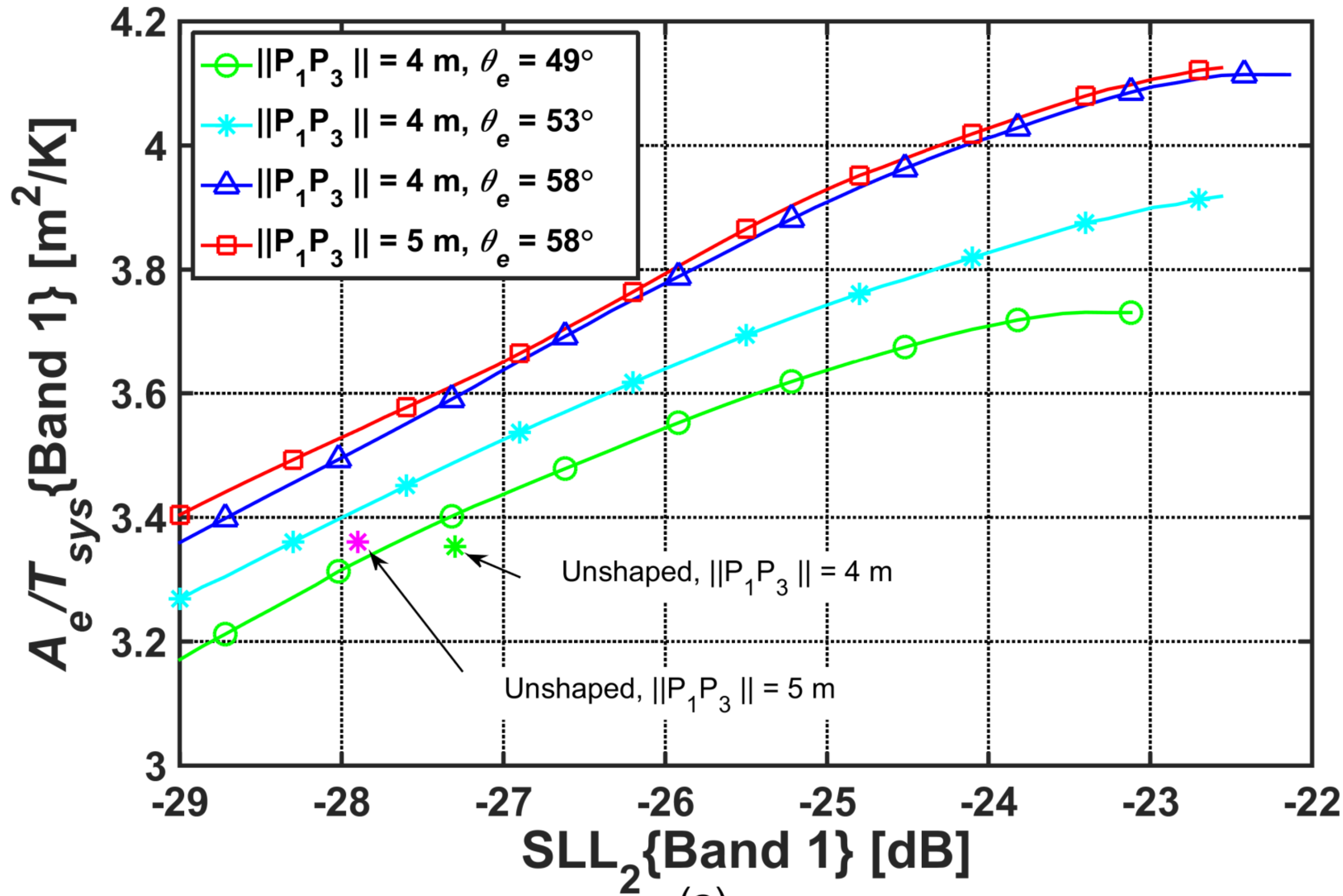
11
10
9
8
7
6
5
4
3
2
1
350
450
600
800
950
1050
1200
1400
1600
1760
Frequency [MHz]
A_e/T_{sys} [m^2/K]
SLL_2 = -28 dB
SLL_2 = -26 dB
SLL_2 = -24 dB
SLL_2 = -22 dB

Degrees of shaping

- **Results for: $|P_1P_3|$ = 4m, θ_e = 58°, χ_1 = 20°**
- **Effects of changing parameters**
  - $|P_1P_3|$ = 4m and 5m
  - θ_e = 49°, 53° and 58°
  - χ_2 = 0°, 10°, 20°, 30°

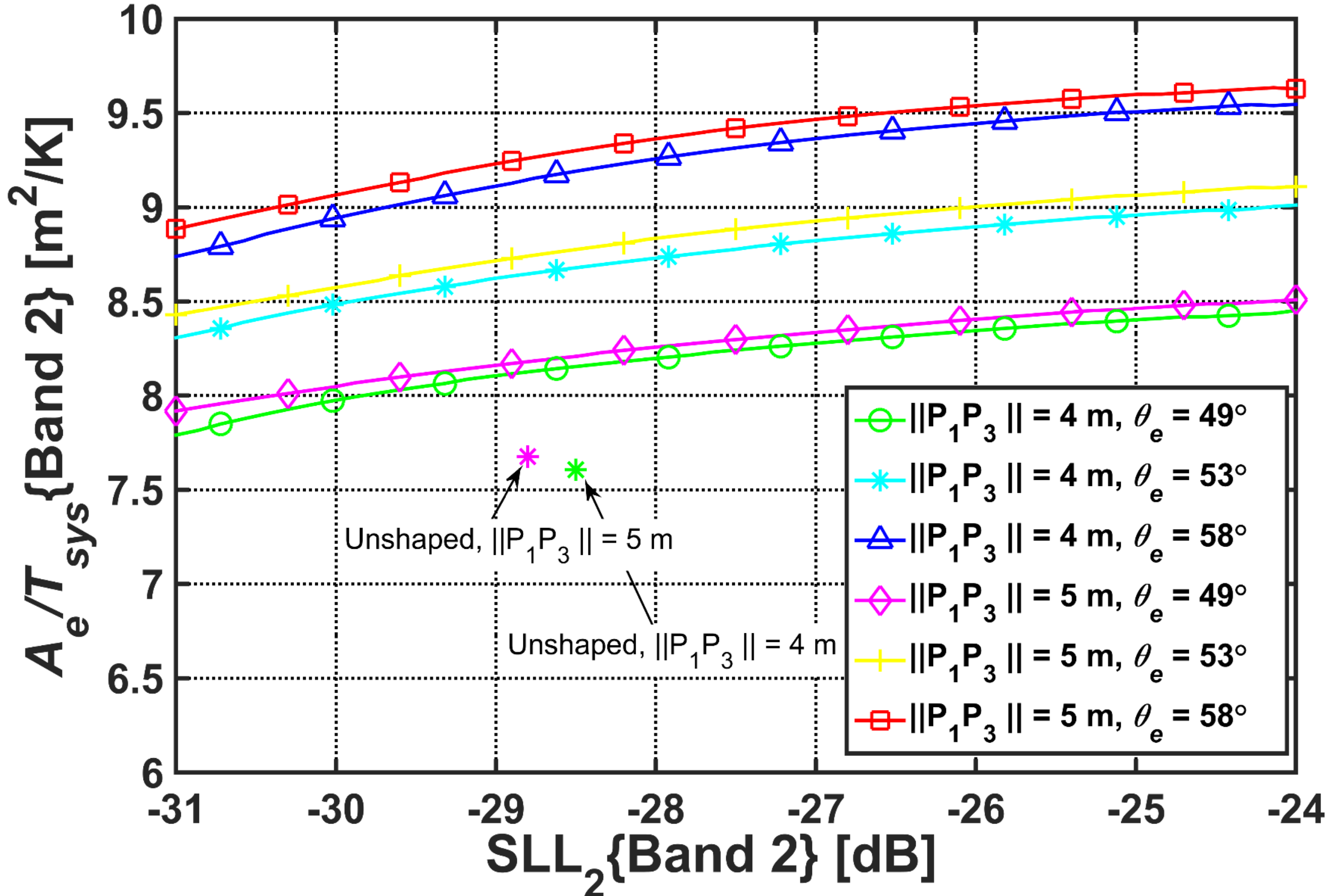


Degrees of shaping



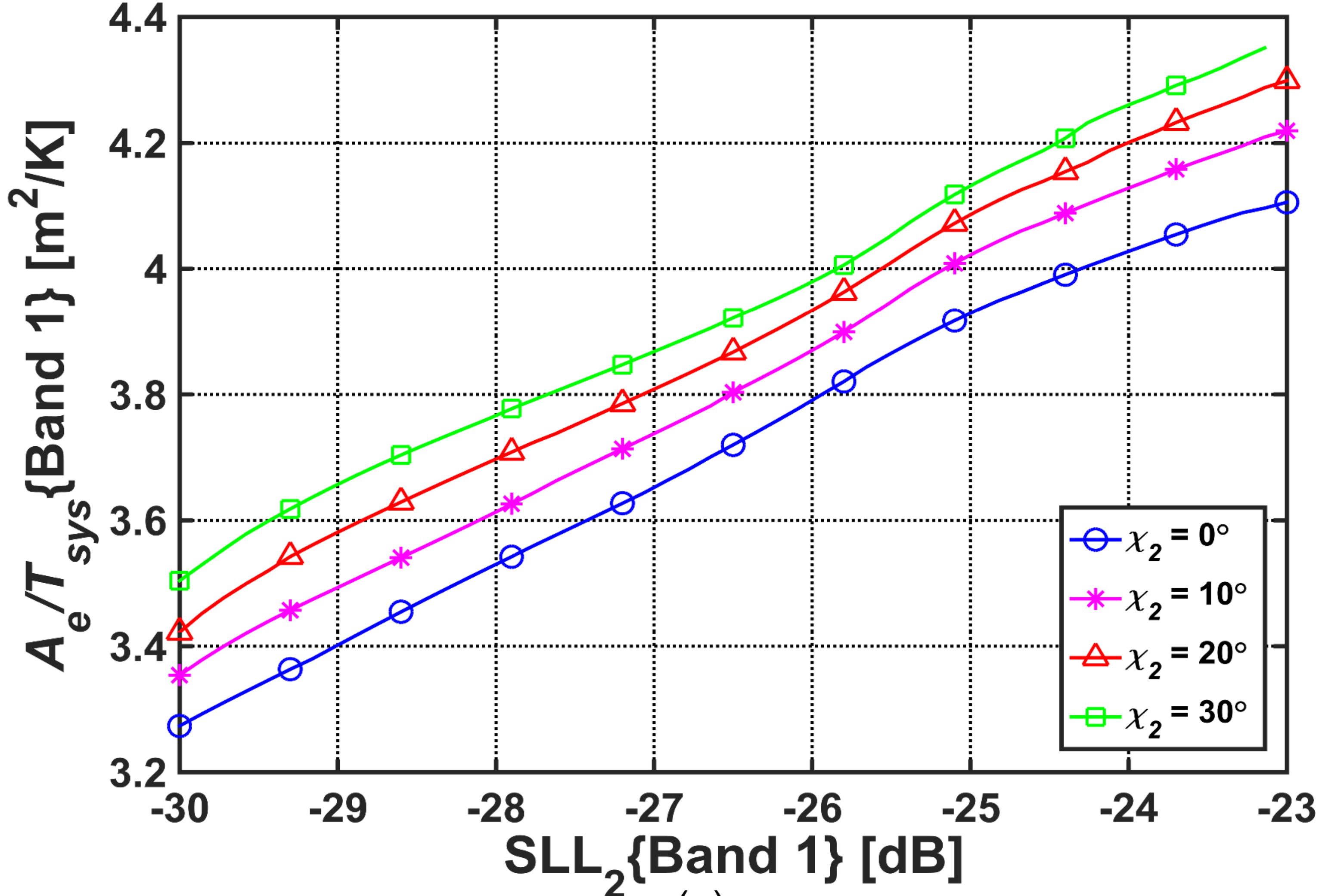
(a)

Degrees of shaping



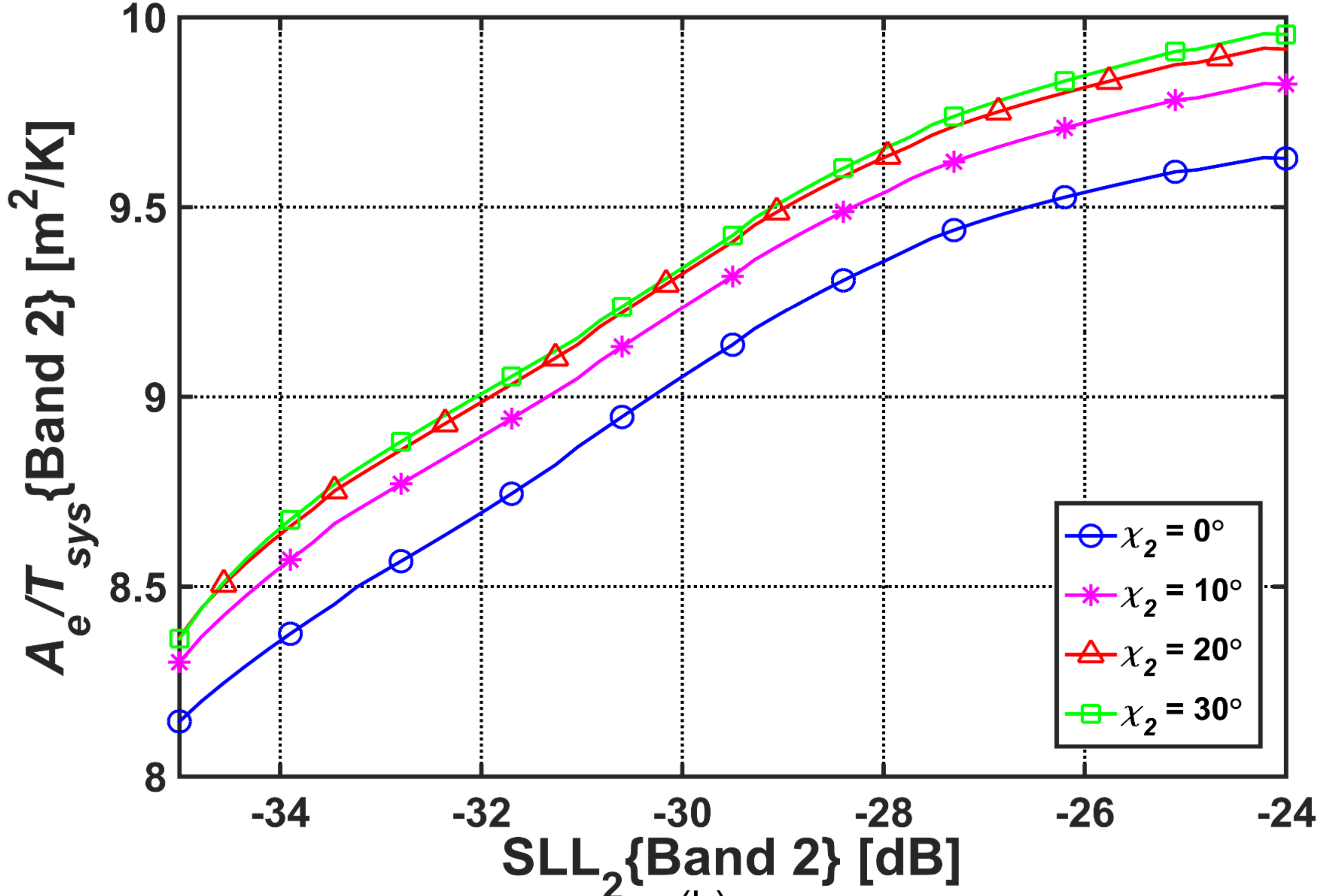
(b)

Sub-reflector extensions



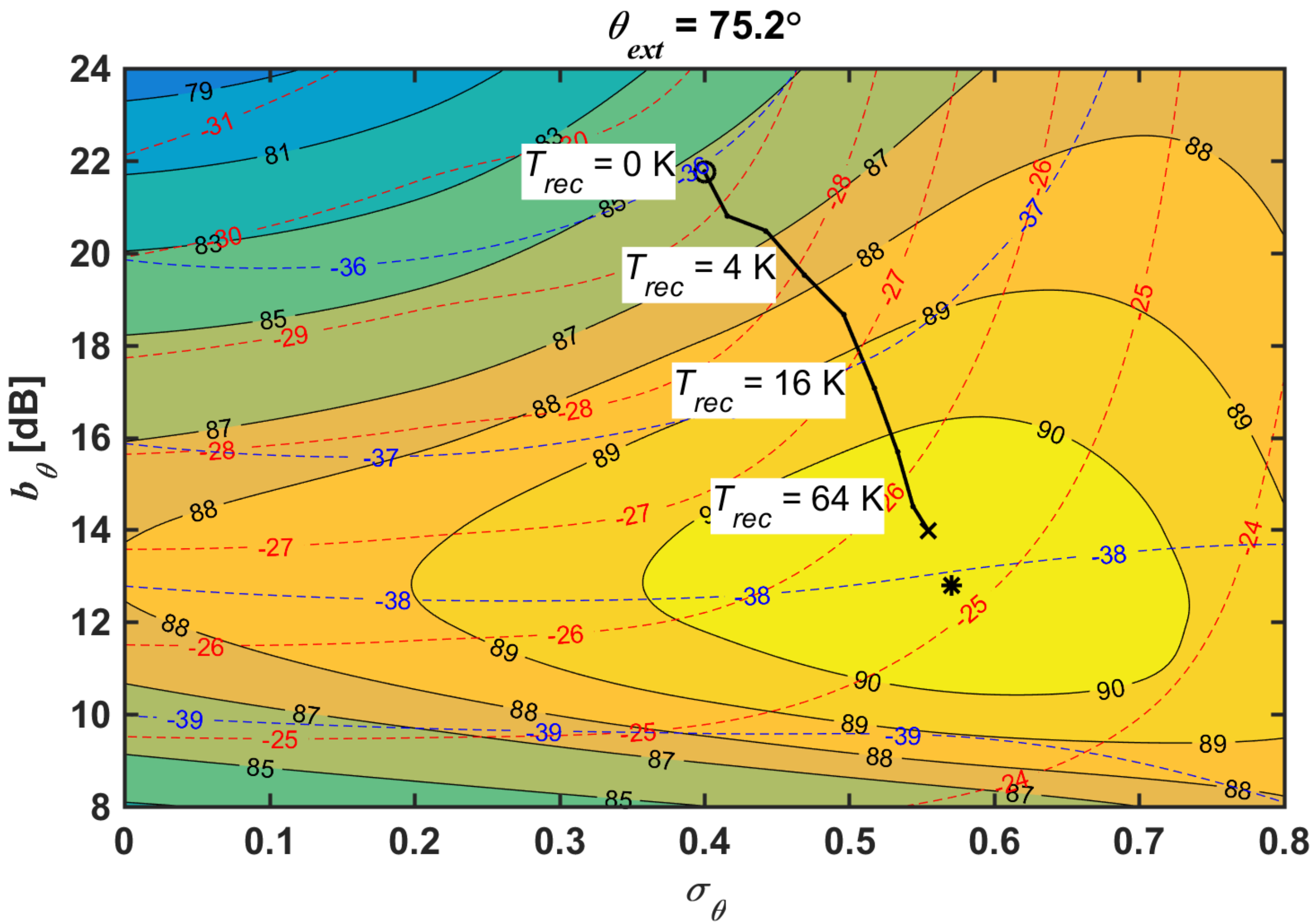
(a)

Sub-reflector extensions



(b)

Ideal feed performance limits

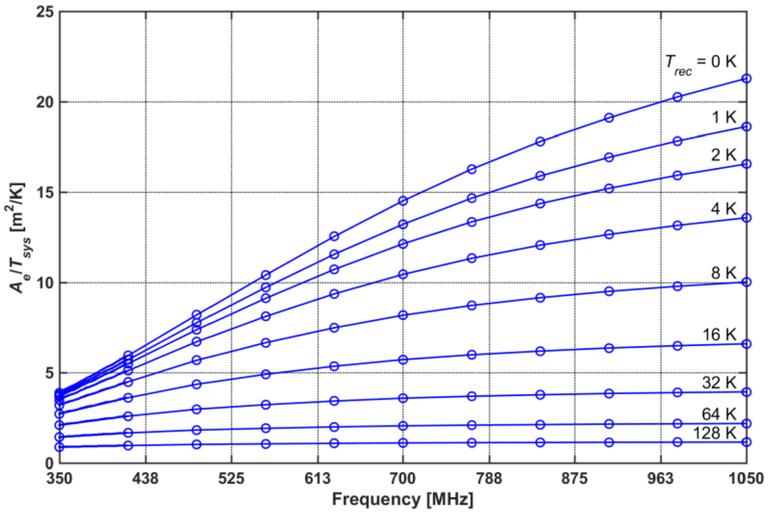


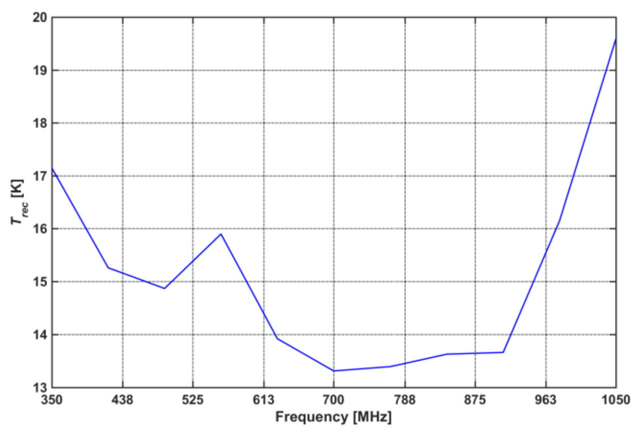
R. Lehmensiek and D. I. L. de Villiers, "Aperture efficiency performance limits of the SKA reflector system," in *Proc. IEEE Int. Symp. AP & USNC/URSI Nat. Radio Sci. Meet.*, San Diego, CA, Jul. 2017, pp. 989-990.

R. Lehmensiek and D. I. L. de Villiers, "On the performance limits of the SKA1-mid reflector system," in *32nd URSI General Assembly and Scientific Symposium (GASS)*, Montreal, QC, Canada, Aug. 2017.

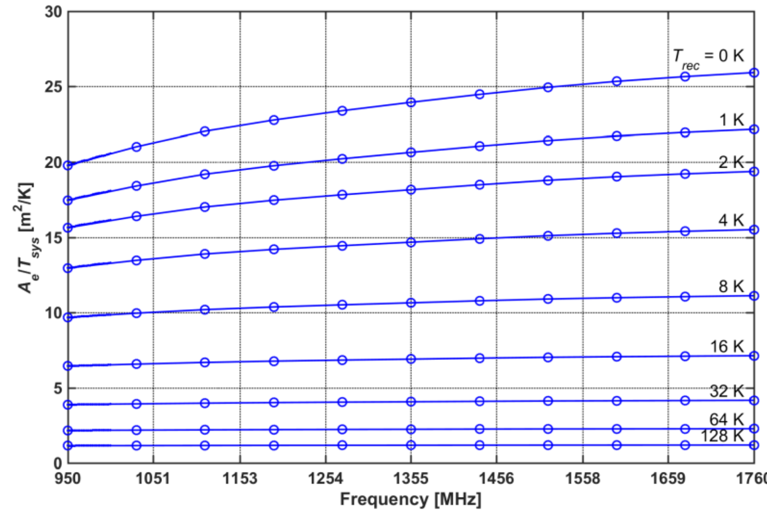
Performance limits

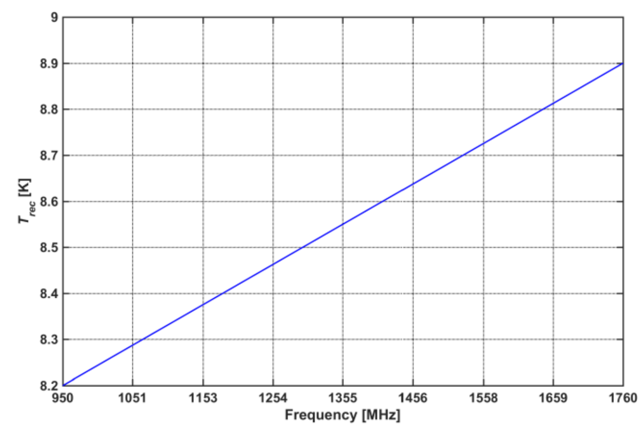
Band 1



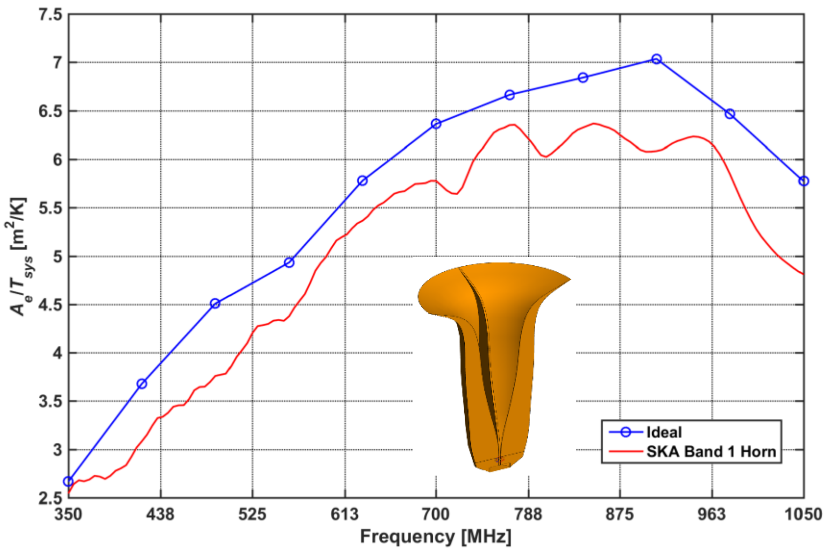


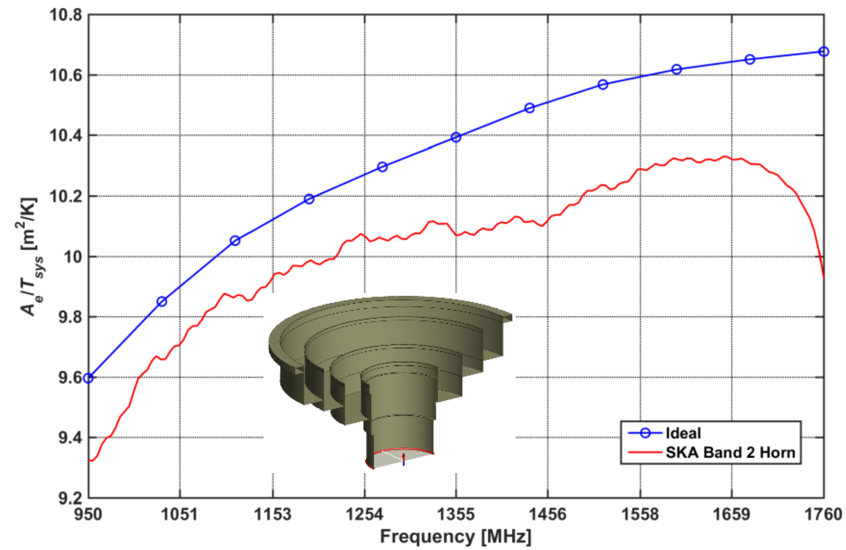
Band 2

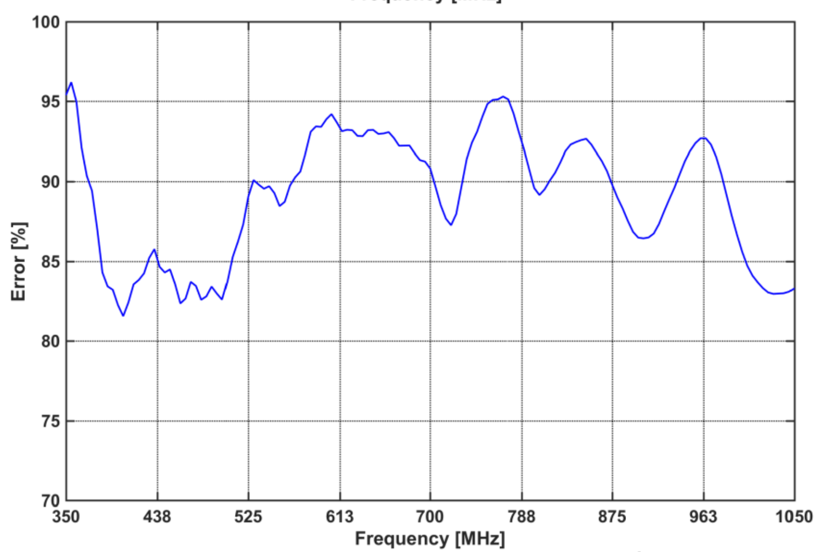


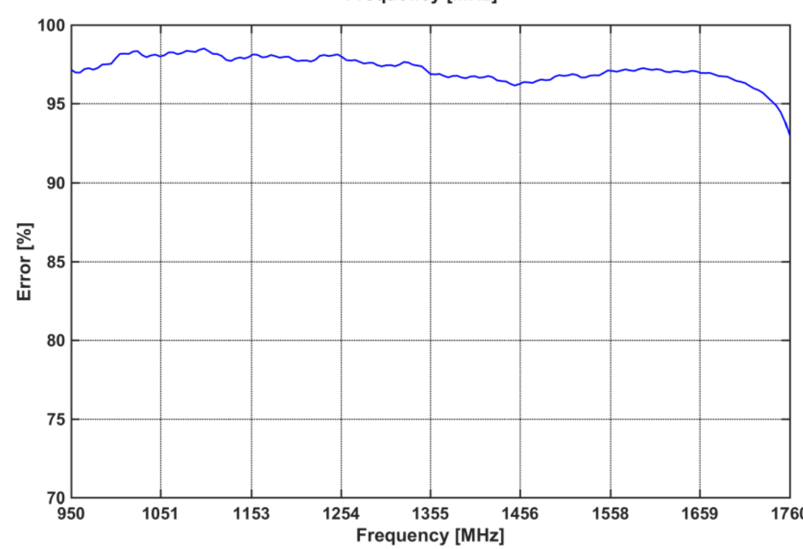


Performance limits







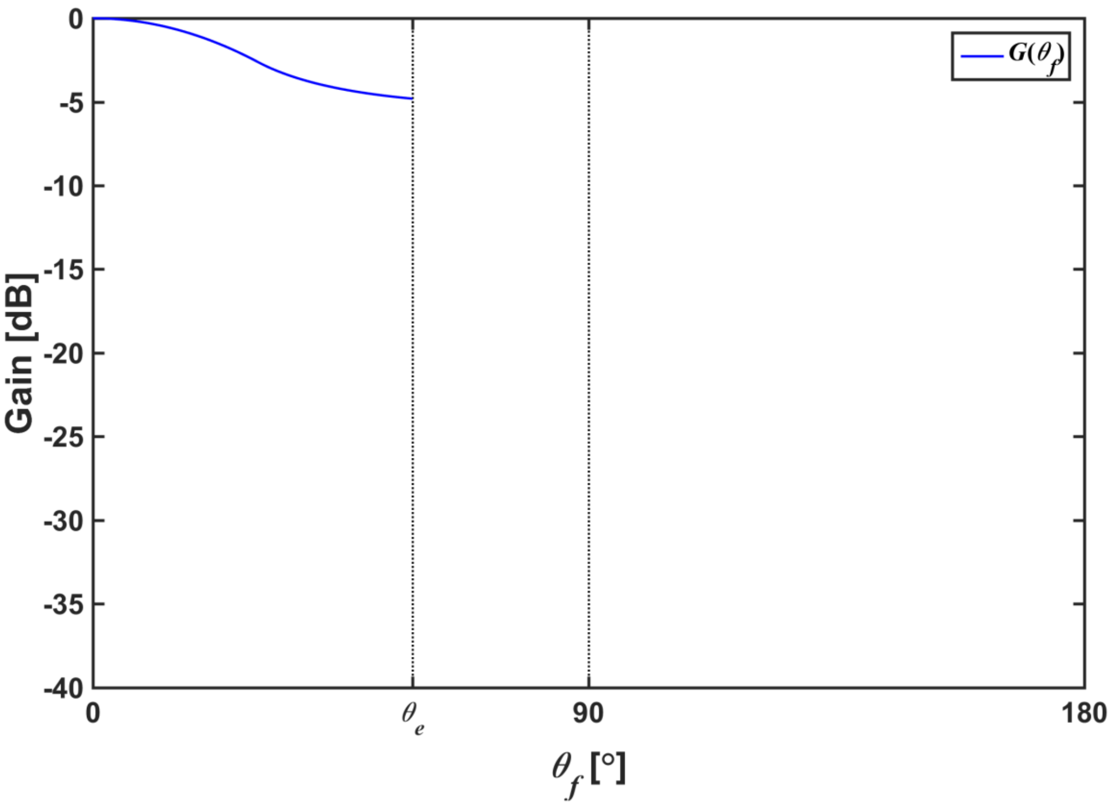


Conclusion

- Realistic frequency-dependent feed patterns
- Realistic receiver temperatures
- Accurate numerical EM analyses
- Exhaustive mapping function space
- Performance parameters: A_e/T_{sys} versus SLL_2

- Sub-reflector size only marginally improves performance
- Minimized edge illumination has best performance
- Optimizing for Band 1 does not significantly compromise the performance of Band 2
- Choice for SKA:
  - -24dB SLL_2 in Band 1 (-26 dB in Band 2)
  - θ_e = 58°, $|P_1P_3|$ = 5 m (PAF driven)
  - χ_1 = 20°, χ_2 = 20°

The parameterised Feed



- **Determine parameterised feed model**
- $\rho(\theta_f)$ **from optics design**
- **Maximise** η_a, $|E(\rho)|^2 = 1$

$$|G(\theta_f)|^2 = \frac{V_c |E(\rho)|^2 \rho(\theta_f)\rho'(\theta_f)}{\sin\theta_f}$$

$$\theta_f \leq \theta_e$$

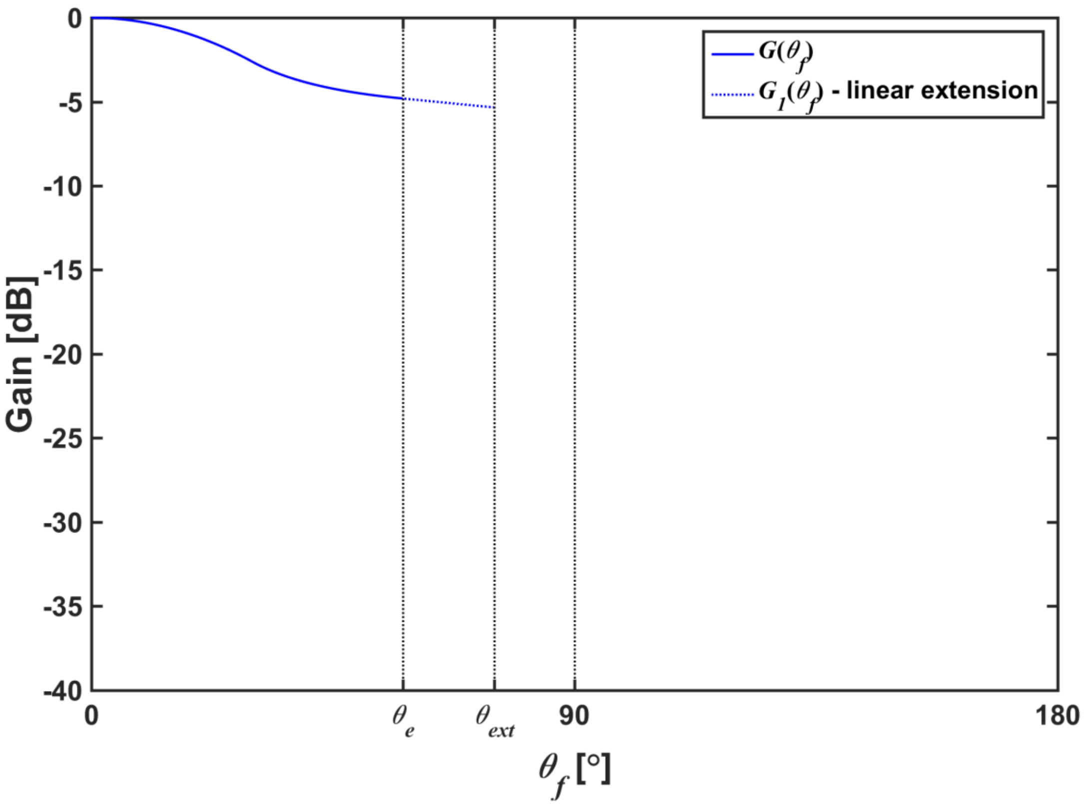
- **Maximise** η_{spill}
- **Minimise** T_{spill}

$$|G(\theta_f)|^2 = -100\,\mathrm{dB}$$

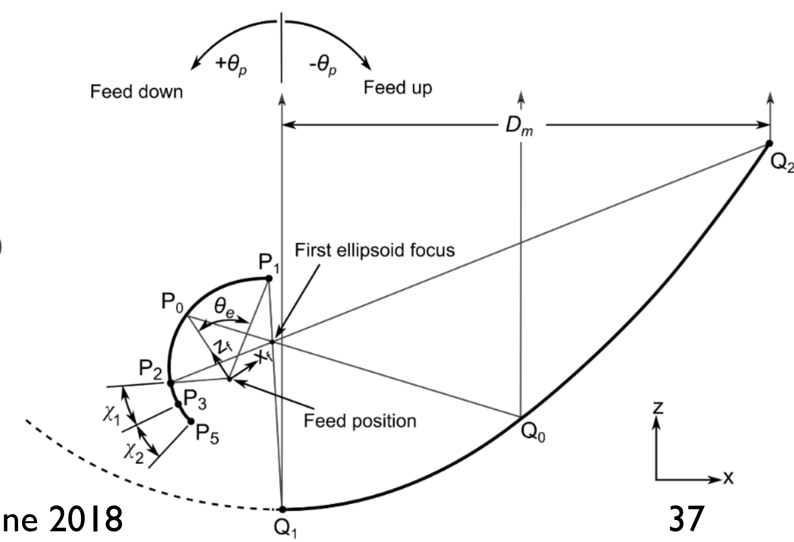
$$\theta_f > \theta_e$$

- **GO limit**
- **Ignores edge diffraction**

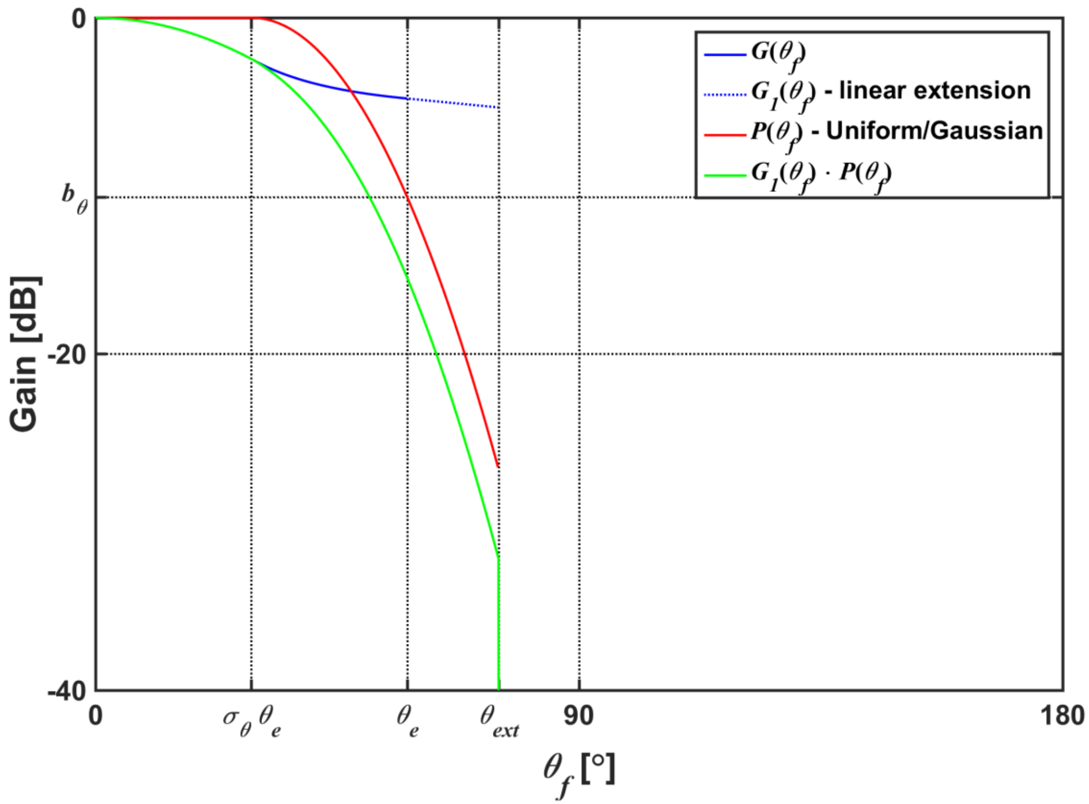
The Feed



- **SR extension - unsymmetric**
- **Trade-off between η_{ill} and η_{spill} (T_{spill})**
- **Slightly over illuminate the SR (extension)**
- **Linear interpolation**
  - **Parameter 1: θ_{ext}**

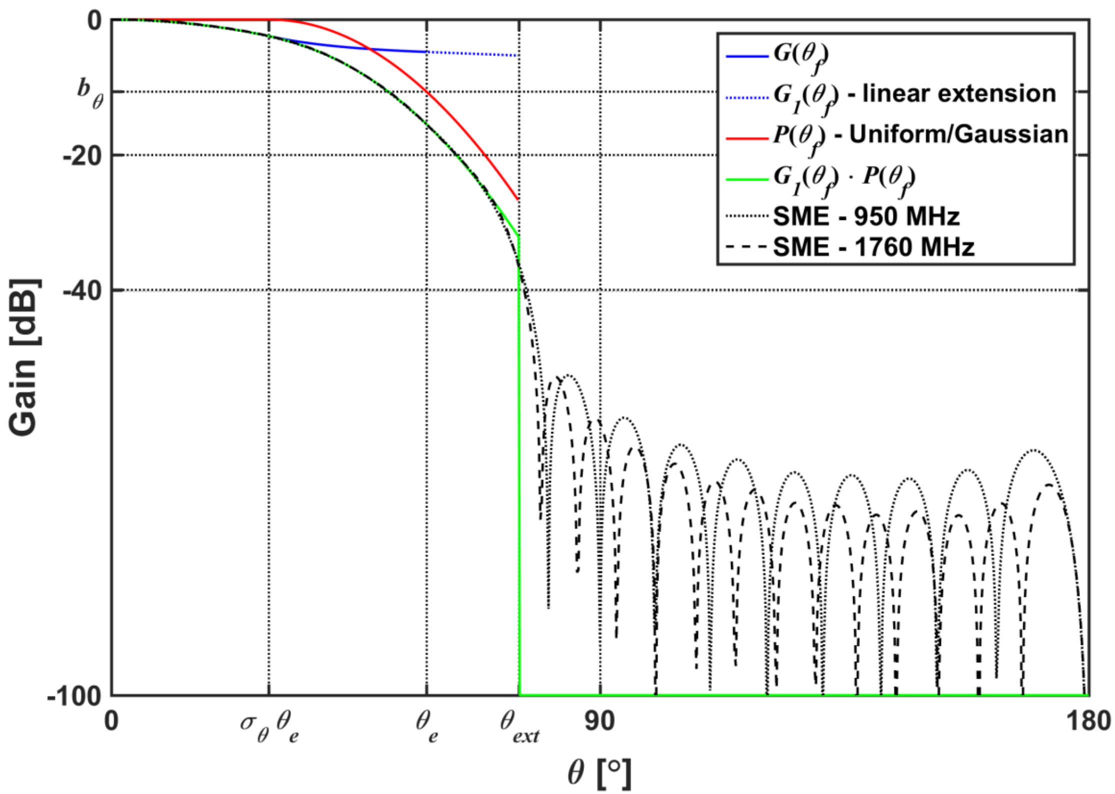


The Feed



- **Weighting function $P(\theta_f)$: Uniform/Gaussian**
  - **Parameter 2: b_θ**
  - **Parameter 3: σ_θ**
- **Parameterised Feed Pattern**
  - **Central part – identical to ideal case**
  - **Edge - stronger taper**
- **Discontinuous pattern**

The Feed



- **Limit feed size:**
  - **Band 1: 2r_0 = 1.3 m**
  - **Band 2: 2r_0 = 0.8 m**
- **Spatial filter**
- **Spherical Mode expansion**
- **Limit number of modes:**
- **In ϕ : BOR$_1$, $M = 1$**
- **In θ:**

$$N = kr_0 + \max(3.6\sqrt[3]{kr_0}, 10))$$

F. Jensen and A. Frandsen, "On the number of modes in spherical wave expansions," in *Proc. 26th Antenna Meas. Tech. Association (AMTA)*, Stone Mountain Park, GA, Oct. 2004, pp. 489-494.