Towards an Optics Design for the SKA

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SKA AFRICA
SQUARE KILOMETRE ARRAY

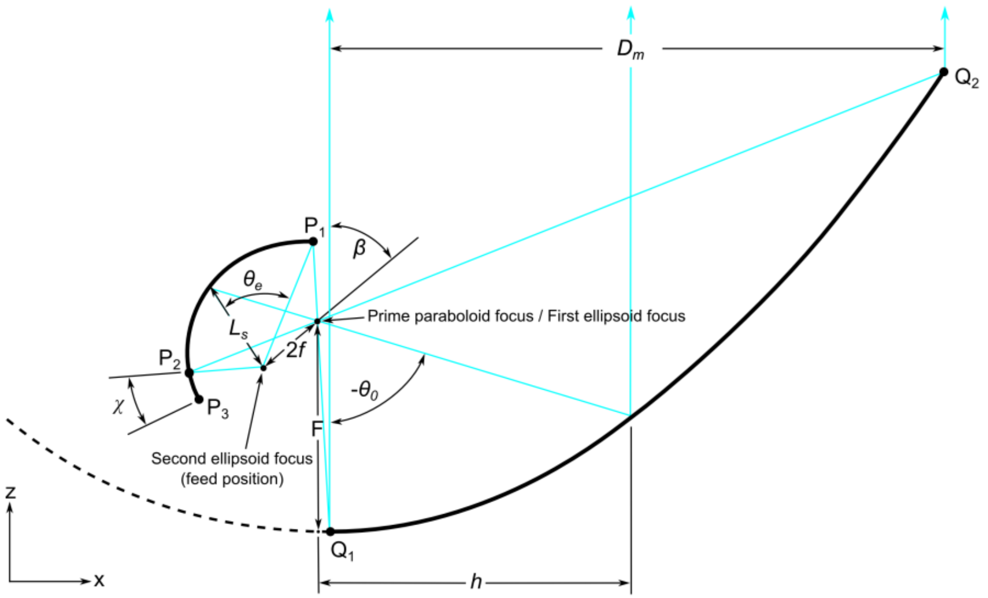
SKA SQUARE KILOMETRE ARRAY

EMSS ANTENNAS

Photo credit: Dr Nadeem Oozeer, SKA-SA.

Outline

- Introduction to SKA
- Optics requirements
- Optics design process and selection
- Example analysis
- Conclusion



Background

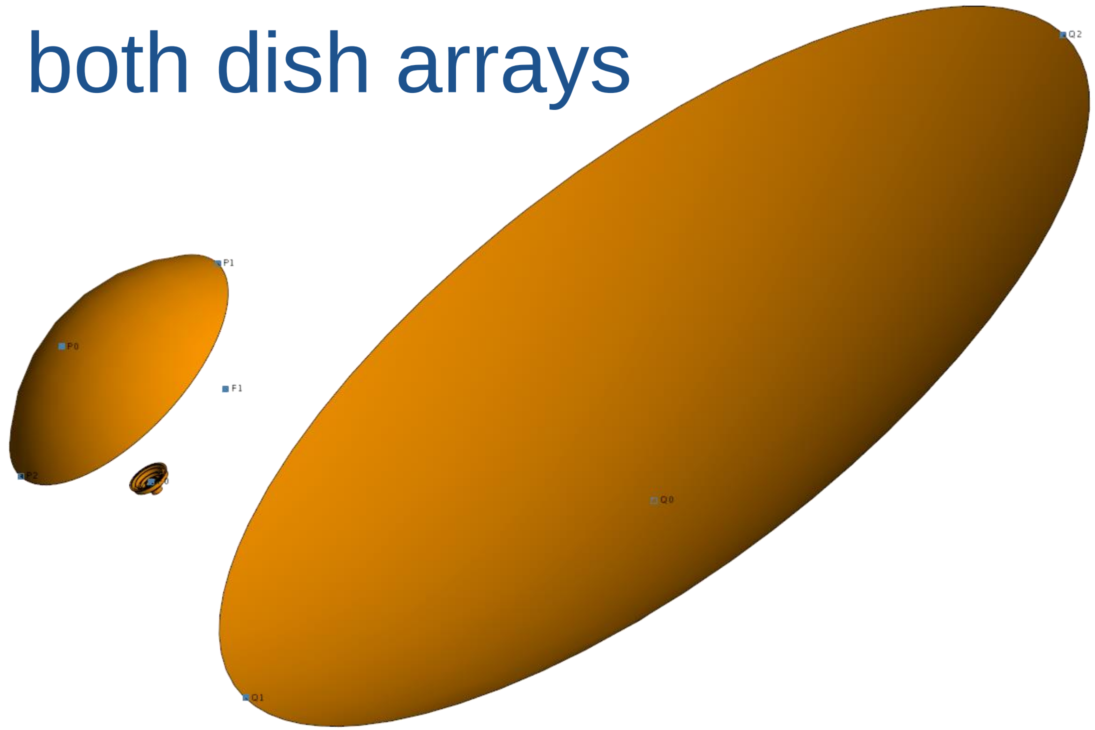
- SKA will be world's largest radio telescope
  - Interferometer with receiving aperture of 1 km^2
- Key science projects:
  - Probing the "dark ages" / Epoch of Reionization
    - Observing highly red shifted neutral hydrogen (21cm)
  - Strong field tests of gravity
    - Testing general relativity
    - High precision pulsar timing observations
  - Galaxy evolution, cosmology and dark energy
    - How do stars form?
    - Conducting both wide and deep surveys
  - Origin and evolution of cosmic magnetism
  - Search for exoplanets ("cradle of life")
    - Imaging nearby objects

Background

- SKA needs to be very general
  - Different requirements for the key science
  - “Exploration of the unknown”
    - Outstanding questions of SKA era currently unknown
- SKA baseline design (March 2013)
  - SKA1-mid (MeerKAT as precursor)
    - 64x13.5m MeerKAT & 190x15m SKA1 dishes
  - SKA1-survey (ASKAP as precursor)
    - 32x12m ASKAP & 60x15m SKA1 dishes
  - SKA1-low
    - ≈ 250 000 Log-P’s

Background: Dish Requirement

- SKA baseline prescribes:
  - Offset Gregorian dual reflector system
  - Aperture diameter, D_m, is 15 m
- Ideally same dish both dish arrays



Background: Frequency bands

- SKA1-mid: Five 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 5: 4.6 – 13.8 GHz (3:1)

- SKA1-survey: Three wide FoV feeds (PAFs):
  - Band 1: 350 – 900 MHz (2.57:1)
  - Band 2: 650 – 1670 MHz (2.57:1)
  - Band 3: 1.5 – 4 GHz (2.67:1)

- Future upgrades: wideband feeds (10:1)

Feeds

- Wide variety of feeds
  - Different ideal beam widths
- Some can be optimised for wider range of beam widths
- Conflicting requirements: e.g.
  - Pulsar research need maximum boresight gain with less regard to SLLs
  - Wide-field imaging requires stable beams with low SLLs rather than absolute sensitivity

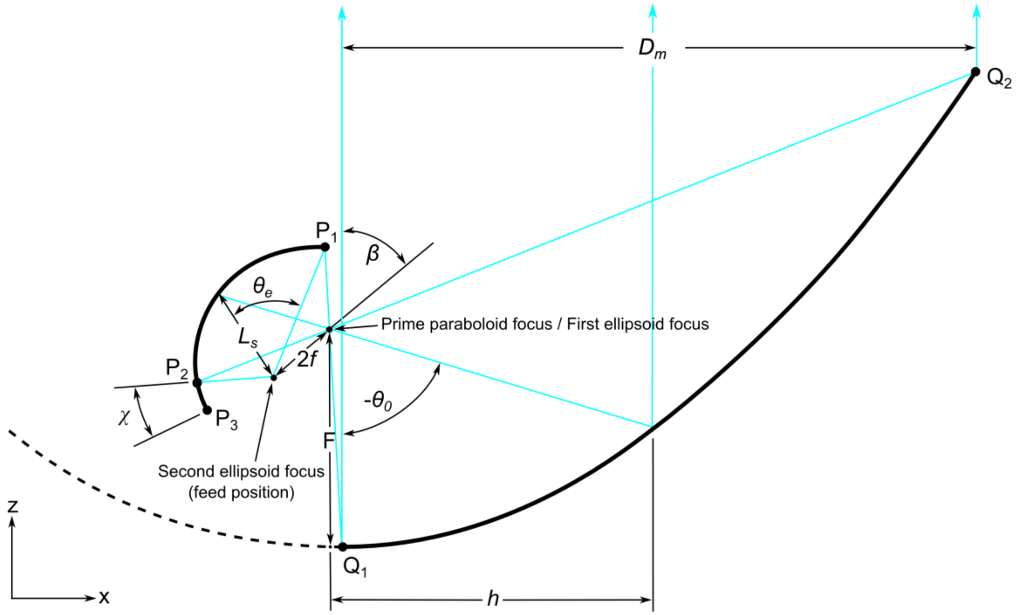
Optics Design

- How to design the optics “for everything”
  - Choose a number of possible dish designs
  - Optimise as many feeds as possible for each of these
- Determine performance criteria
  - Outside the scope of this presentation
- Do a trade-off study between
  - System’s possible EM performance
  - Mechanical complexity / cost

Dish Options

- Offset Gregorian Geometry
  - Defined by 6 parameters
- Mizugutch condition for optimal cross-pol
  - Reduce to 5 parameters
- Projected diameter is fixed
  - Left with 4 parameters
- Sets proposed by Christophe Granet

Dish Geometry



D_m	Main reflector diameter, projected in direction of main beam.
θ_0	Offset angle of the centre of the main reflector, linked to h.
L_s	Distance from the angular centre of the sub-reflector (relative to the feed point) to the secondary focus.
θ_e	Half the angular width of the sub-reflector as measured from the feed.
β	Angle between the optical axis and sub-reflector foci axis.

Dish Options

- D_m and θ_e prescribed
- Rest determined in terms of model size
  - Sub-reflector "size" $\|P_1P_2\|$
  - Main reflector "size" $\|Q_1Q_2\|$
  - Clearance $\|x_{P1}x_{P2}\|$
- Iterative determination
  - θ_0, β, L_s

Dish Options

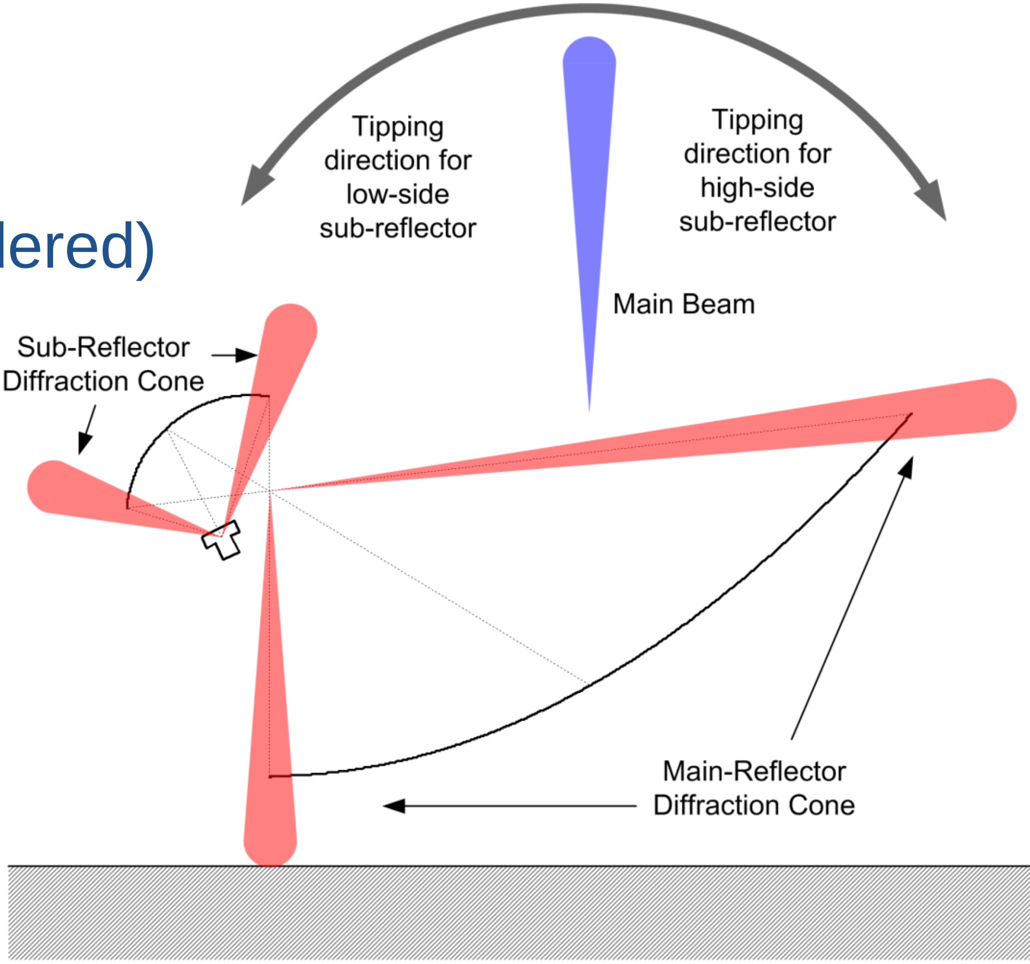
- Select the basic parameter sets
- Feed half angle
  - Main differentiator between feeds
  - Larger feed angles start to cause blockage
  - Little mechanical impact for a given main reflector
  - Wideband & PAFs favour larger θ_e
  - Octave band horn feeds favour smaller θ_e
  - θ_e = [58°, 53°, 49°], i.e. $F_e/d \approx$ [0.45, 0.5, 0.55]

Dish Options

- Sub-reflector size
  - Larger is better for EM performance at low frequency
  - Smaller is preferred from mechanical considerations
  - $\|P_1P_2\|$ = [4, 5, 6] m
- Main reflector size (depth)
  - Very little EM impact
  - Mechanical trade between reflector size and feed boom length
  - $\|Q_1Q_2\|$ = 18.2 m from existing mechanical trades
- Offset angle
  - Little influence on dish performance
  - Selected $\theta_0 = -69°$ to make $\|x_{P1}x_{P2}\| \approx 0.5$ m
  - Implies MR size is the same

Tipping

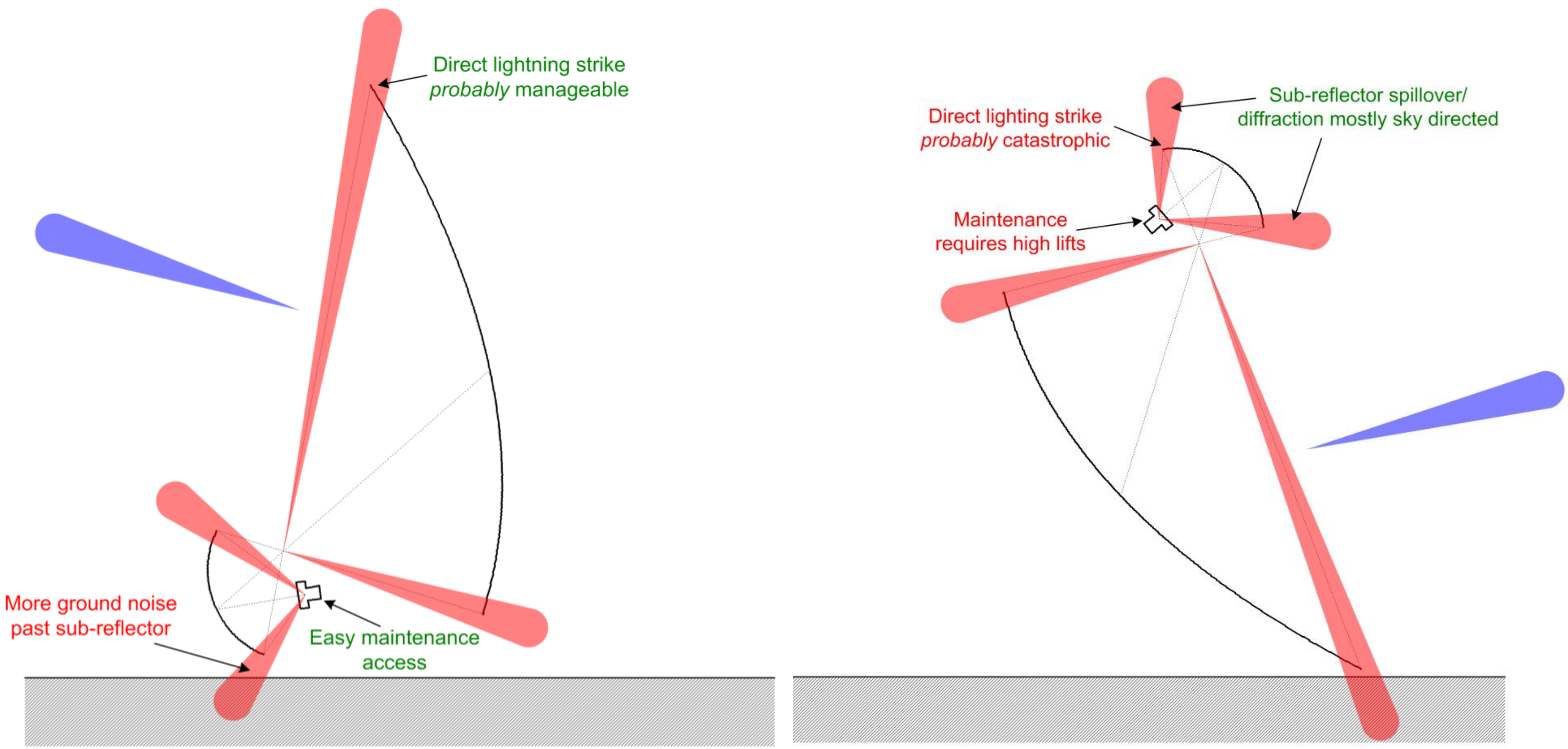
- Possibilities:
  - Feed up
  - Feed down
  - Cradle mount (not considered)



Tipping

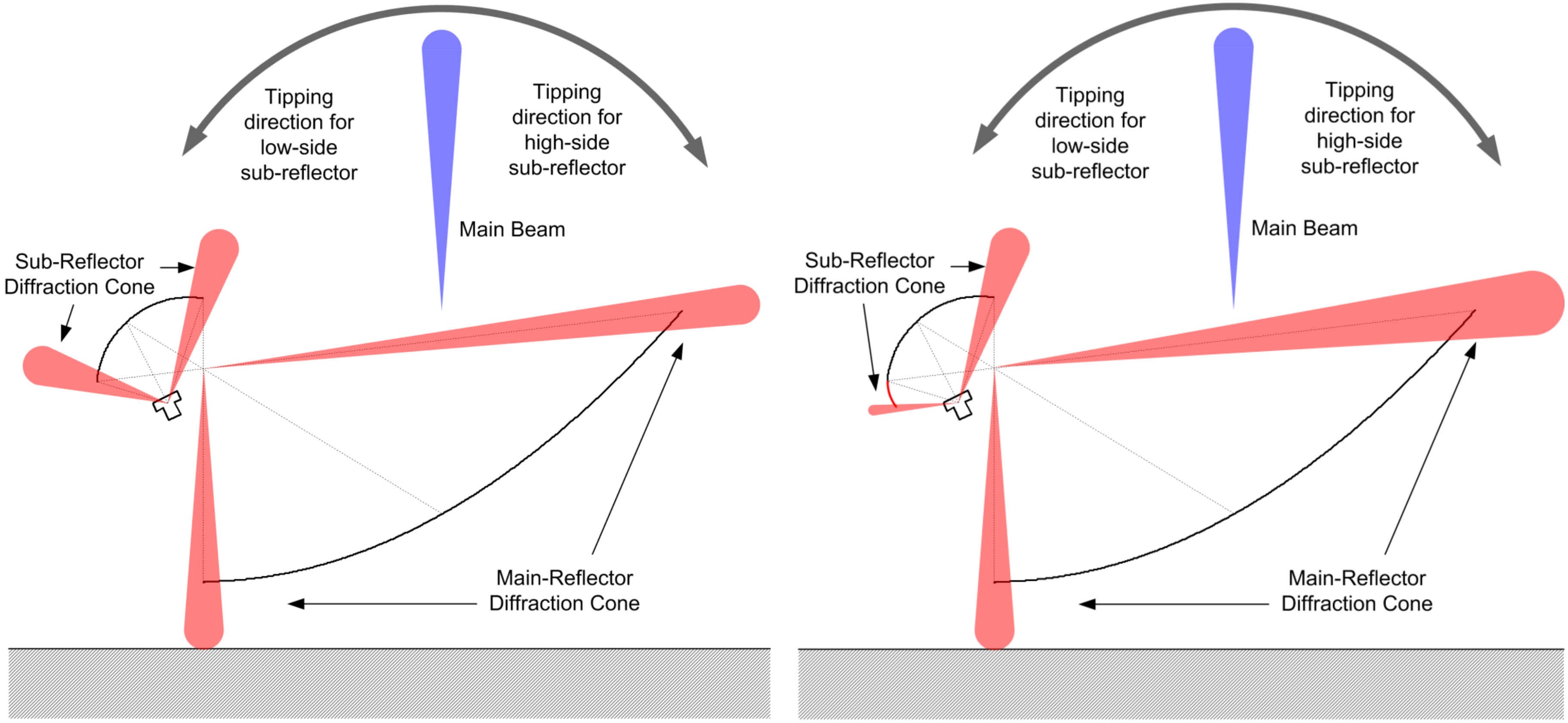
Feed down

Feed up



Shielding Spillover

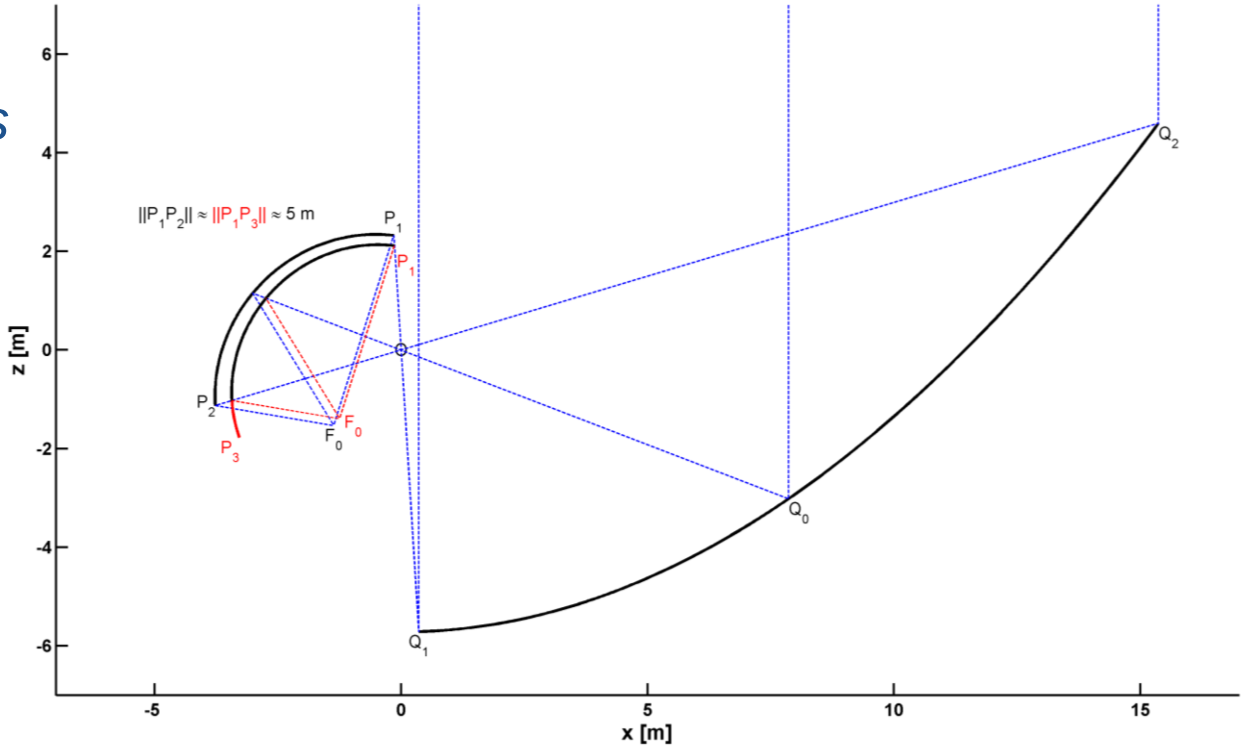
- Extend SR (or MR) to shield spillover
- Less expensive for feed-down (SR extended) tipping



SR Extension

- Extension only considered for feed down
- Extension angle, $\chi = 20°$; from MeerKAT design
- Changes L_s

SKA_U_TE3_SR2_MR1_EX0(1): D_m = 15 m, θ_0 = -69°, θ_e = 49° (F_{eq}/D = 0.54857), β = 41.7°, L_s = 3.148(2.866) m
Additional: F = 5.71871 m, h = 7.86072 m, 2f = 2.04977(1.86615) m, e = 0.321824



Dish Options

TABLE I. PARAMETERS FOR THE UNSHAPED DISH CANDIDATES FOR CASES WITHOUT ($\chi = 0°$) AND WITH ($\chi = 20°$) A SUB-REFLECTOR EXTENSION.

Approximate Requirements		**Primary Parameters**			
$\lVert Q_1Q_2 \rVert \approx 18.2$m, $\lVert x_{P_1} x_{Q_1} \rVert \approx 0.5$m		$D_m = 15$ m; $\theta_0 = -69°$			
$\approx F_e/D$	$\approx \lVert P_1P_2 \rVert$ (or $\lVert P_1P_3 \rVert$) [m]	θ_e [°]	β [°]	L_s [m] for $\chi = 0°$	L_s [m] for $\chi = 20°$
0.45	4	58	57.6	2.154	2.004
	5			2.694	2.506
	6			3.234	3.009
0.5	4	53	48.8	2.342	2.155
	5			2.929	2.695
	6			3.516	3.236
0.55	4	49	41.7	2.517	2.292
	5			3.148	2.866
	6			3.779	3.441

Shaping Dish

- Shaping allows control over the aperture distribution
- Can improve efficiency while controlling sidelobes
- Can also reduce far sidelobes
  - Use lower edge illumination
  - Act as an “extension”
- Need pattern
- Significantly increases the parameter space

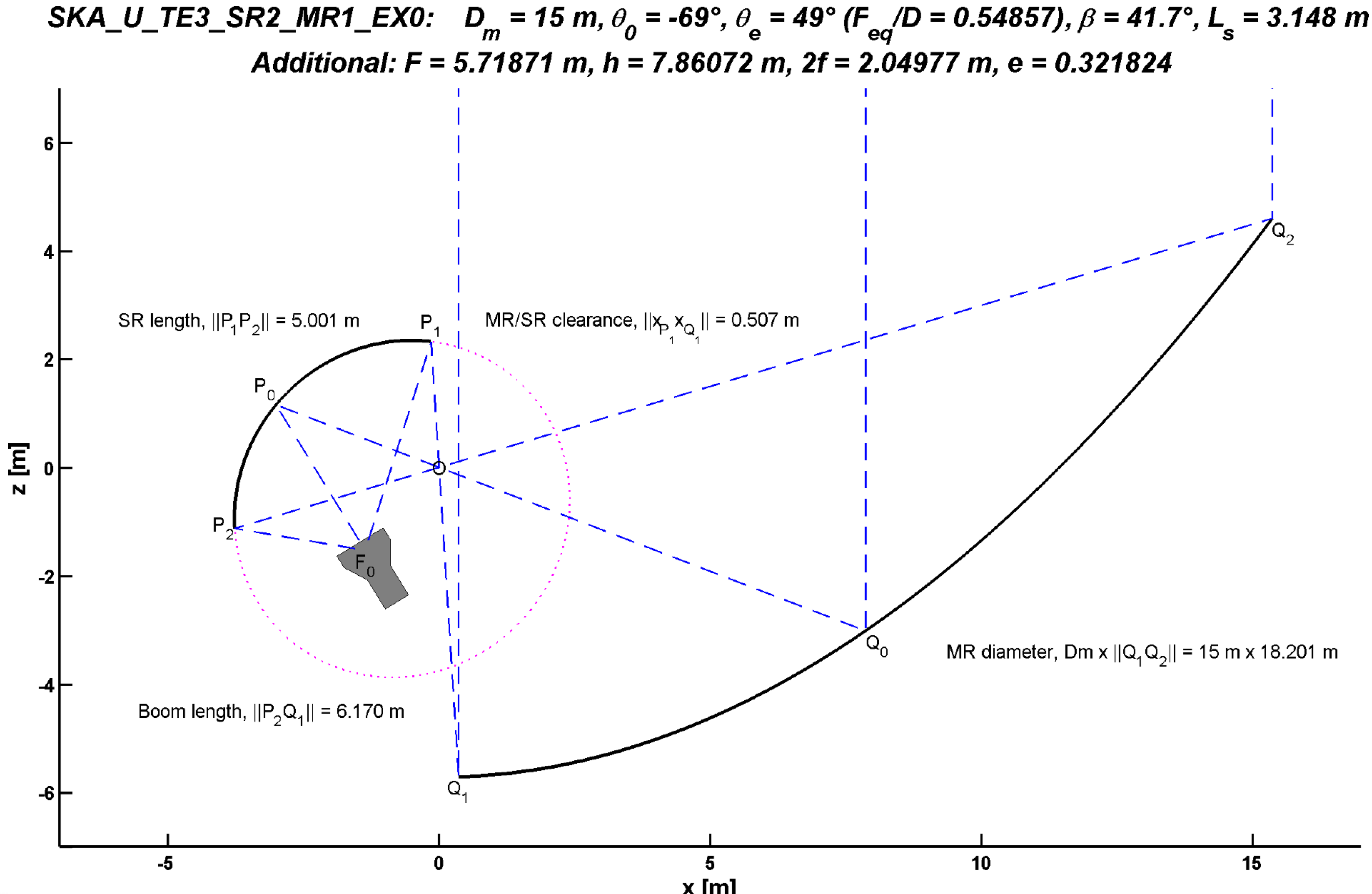
Design Process

- First, determine "best" unshaped dish
  - Comparison of different designs
    - EM performance of all feeds
    - Mechanical complexity / cost
  - Outcome: unshaped dish design and a set of feeds for this dish design
- Second, determine shaped dish
  - Determine EM performance improvement with a shaped dish using the optimised feeds
- Final selection

EM Analyses

- Illustrative example of EM analyses
- Band 2
- Dish:
  - D_m = 15 m, θ_0 = -69°, θ_e = 49°, β = 41.7°
  - without extension, L_s = 3.148 m
  - with extension, L_s = 2.866 m
- Feed: scaled MeerKAT horn

Example 1:

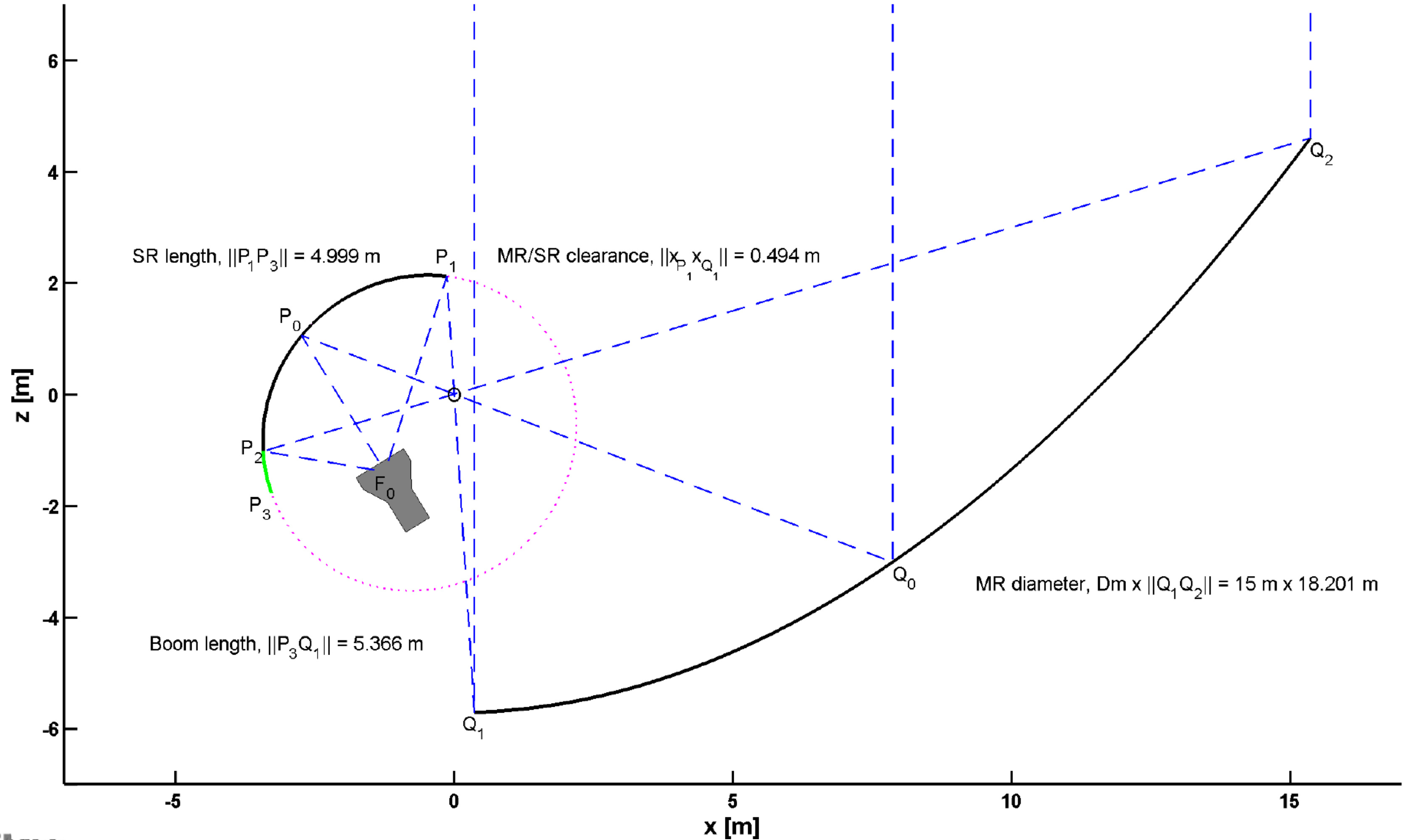


SKA_U_TE3_SR2_MR1_EX0: D_m = 15 m, θ_0 = -69°, θ_e = 49° (F_{eq}/D = 0.54857), β = 41.7°, L_s = 3.148 m
Additional: F = 5.71871 m, h = 7.86072 m, 2f = 2.04977 m, e = 0.321824
SR length, $||P_1P_2||$ = 5.001 m
MR/SR clearance, $||x_{P_1}x_{Q_1}||$ = 0.507 m
MR diameter, Dm x $||Q_1Q_2||$ = 15 m x 18.201 m
Boom length, $||P_2Q_1||$ = 6.170 m
P_0
P_1
P_2
F_0
Q_0
Q_1
Q_2
z [m]
x [m]
6
4
2
0
-2
-4
-6
-5
0
5
10
15

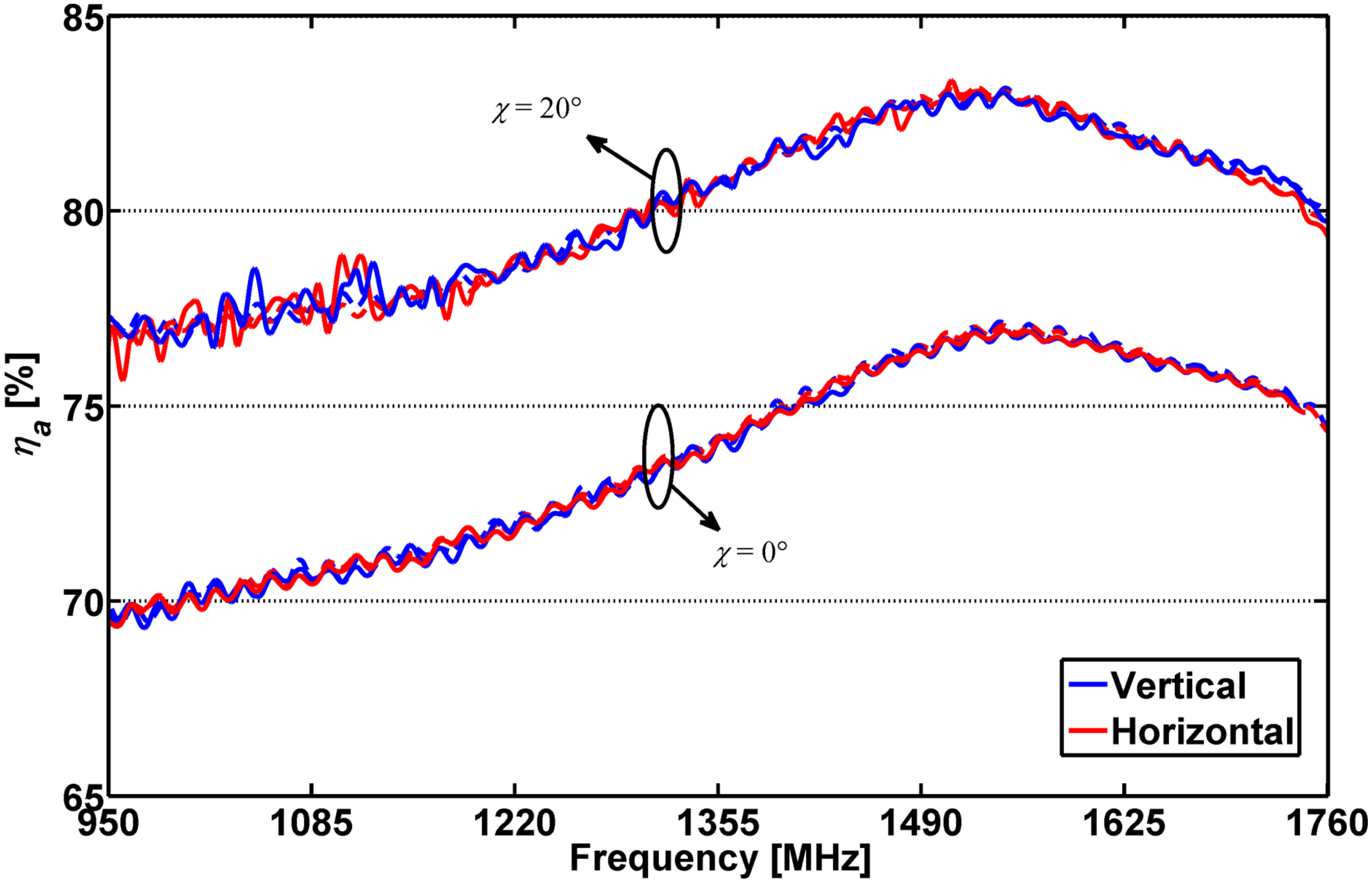
Example 2:

SKA_U_TE3_SR2_MR1_EX1: D_m = 15 m, θ_0 = -69°, θ_e = 49° (F_{eq}/D = 0.54857), β = 41.7°, L_s = 2.866 m

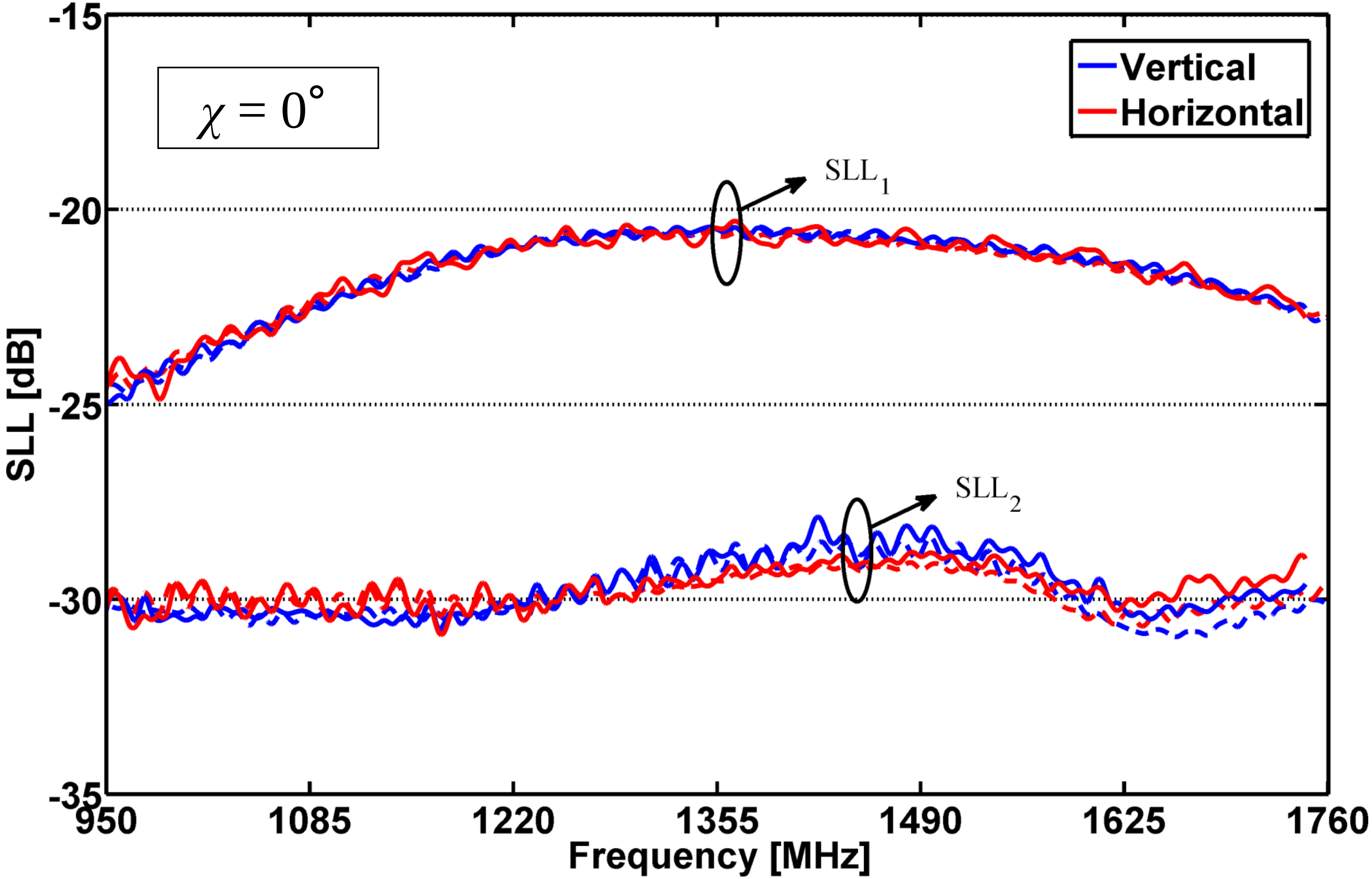
Additional: F = 5.71871 m, h = 7.86072 m, 2f = 1.86615 m, e = 0.321824



Aperture Efficiency



Maximum Sidelobes



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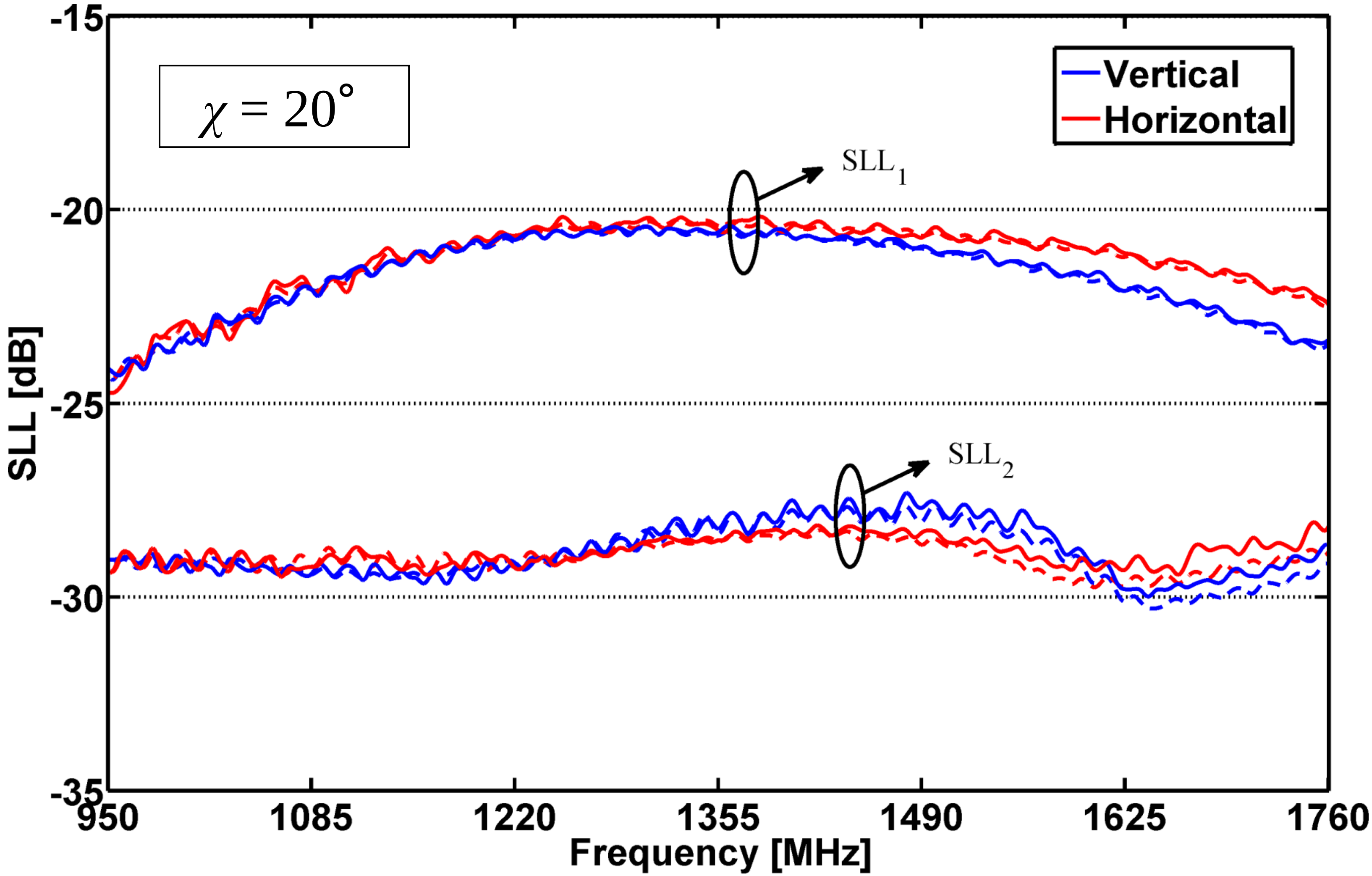
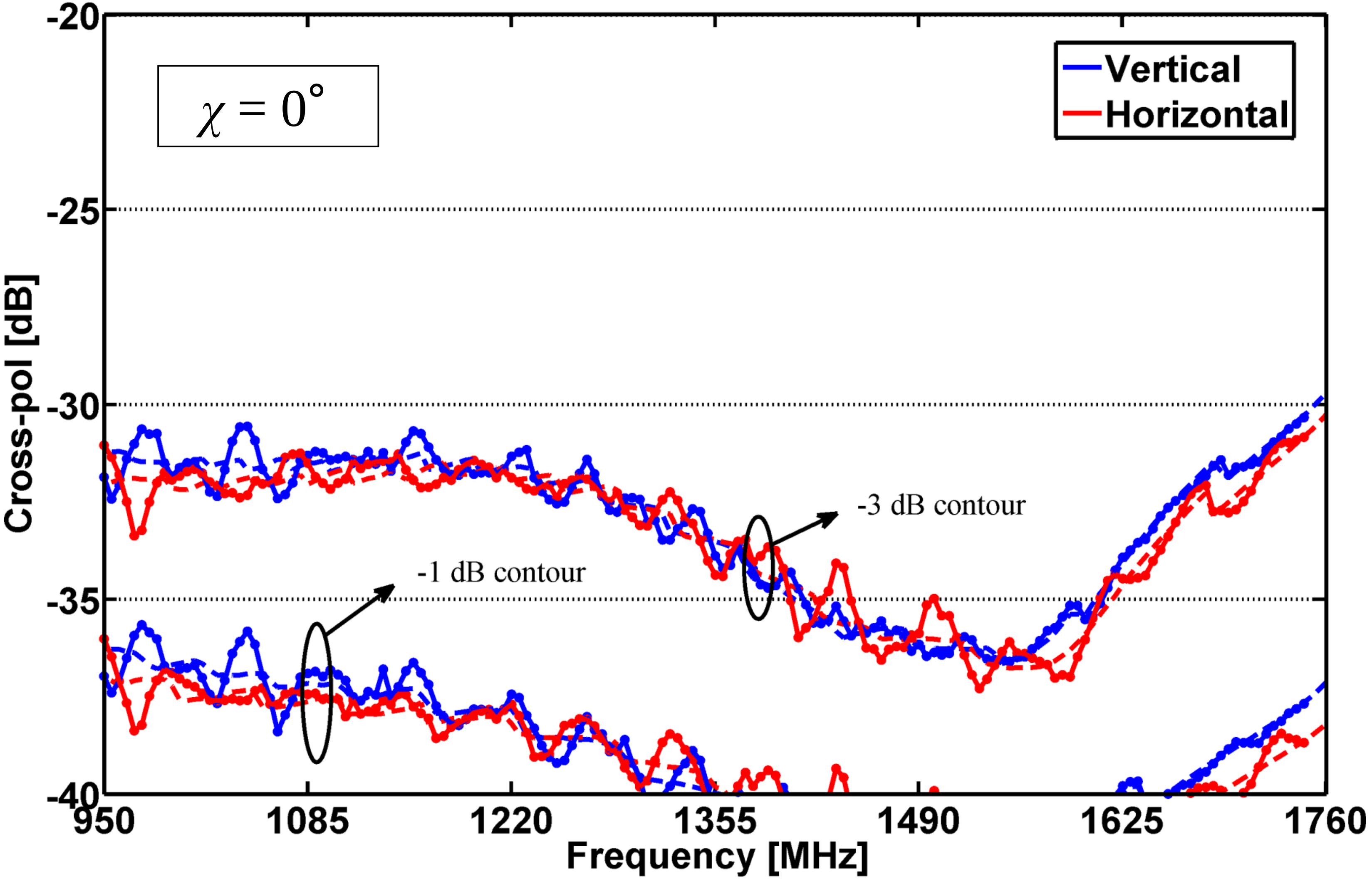
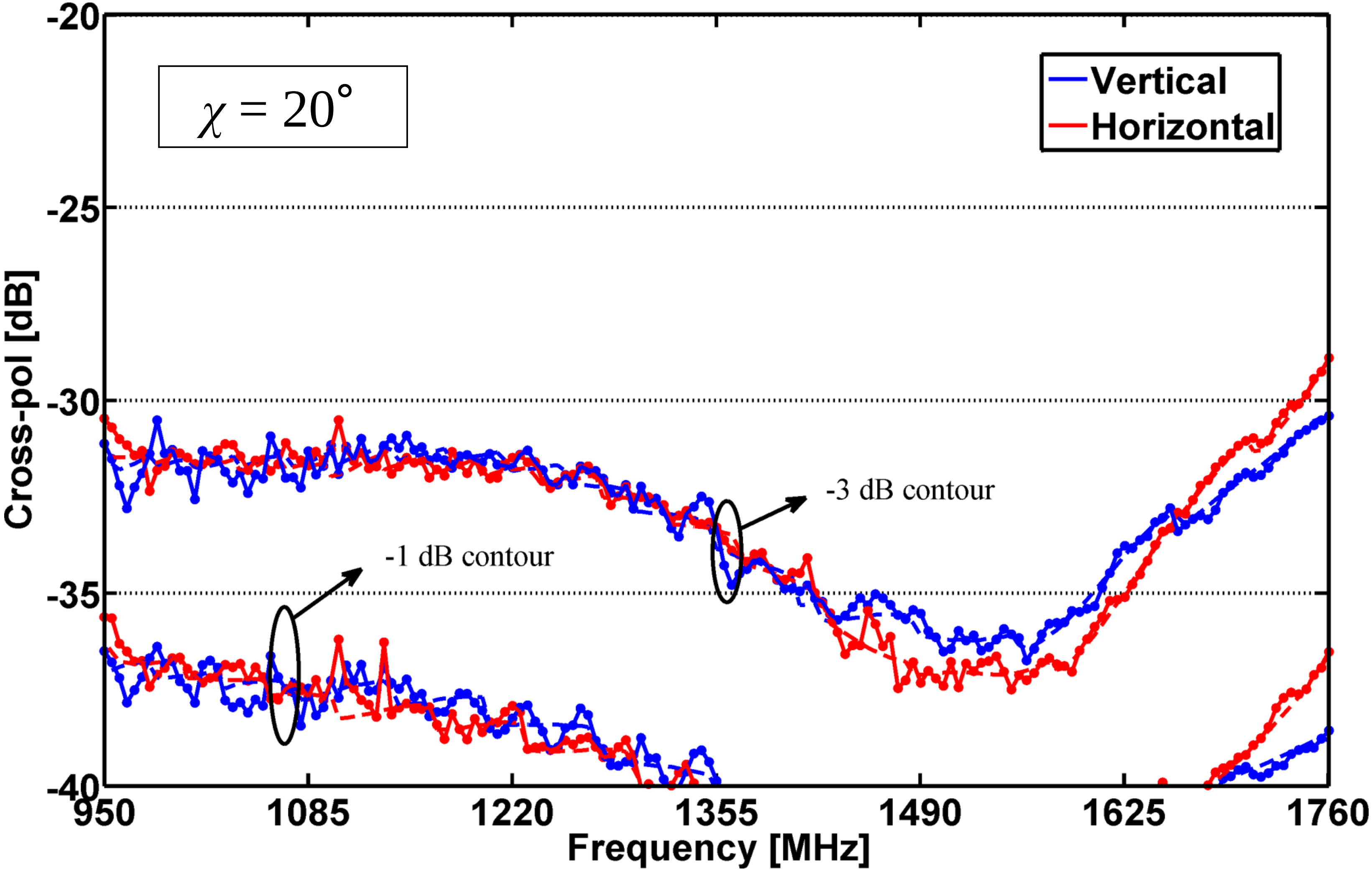


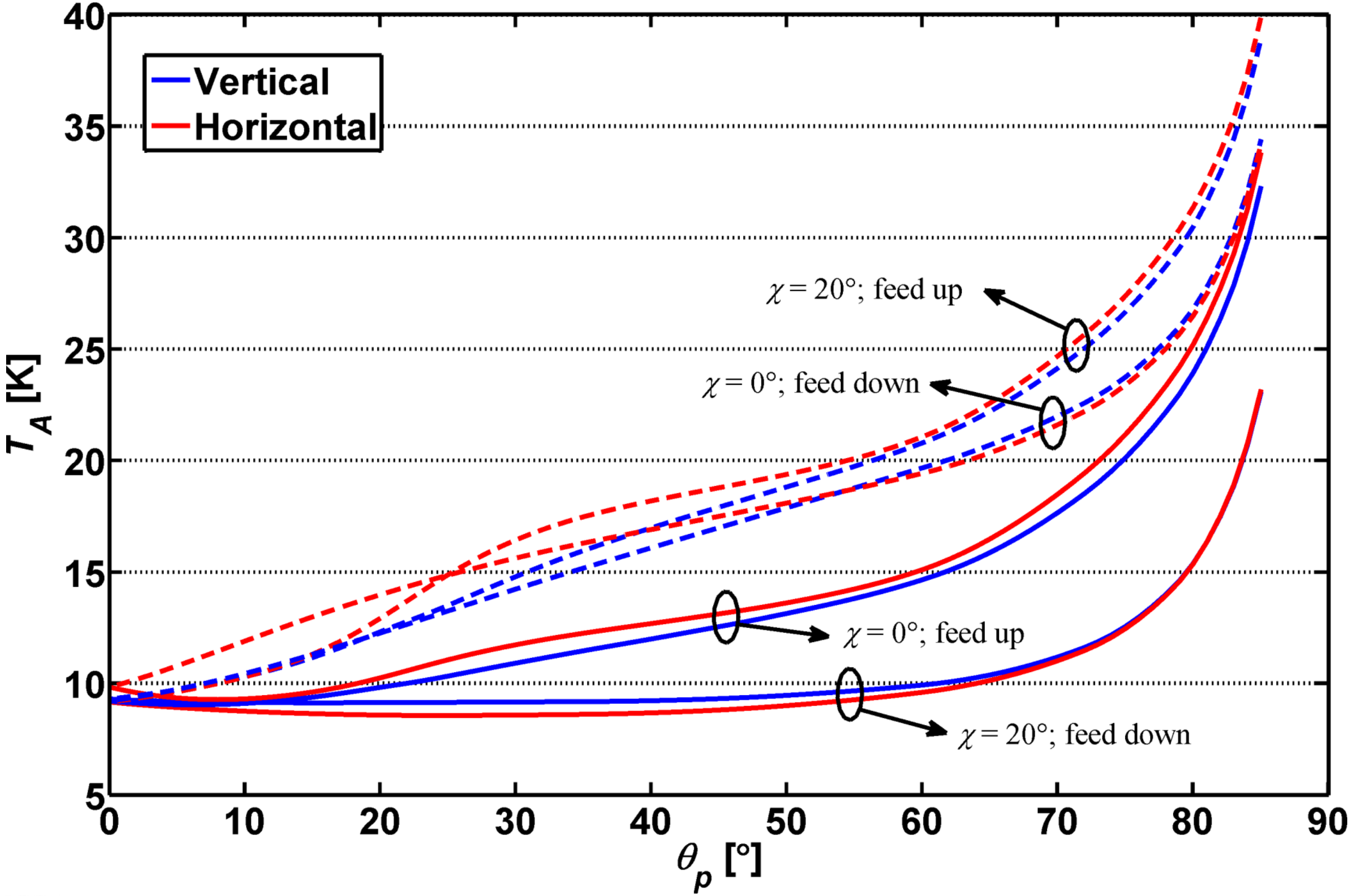
Maximum Cross-polarisation



Maximum Cross-polarisation



Tipping Curves



Conclusions

- Presented the process to derive the reflector geometry for SKA
- Currently starting

Artist's impression of
SKA dishes
(Credits: http://www.ska.ac.za)