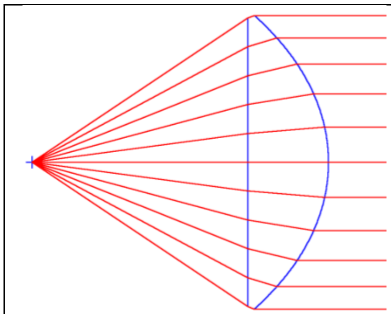
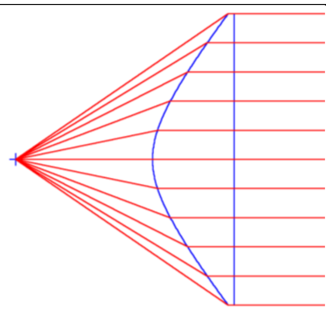
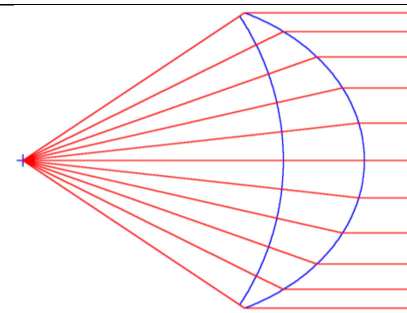
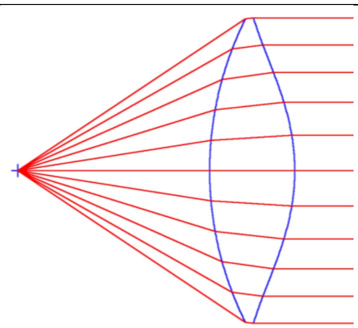
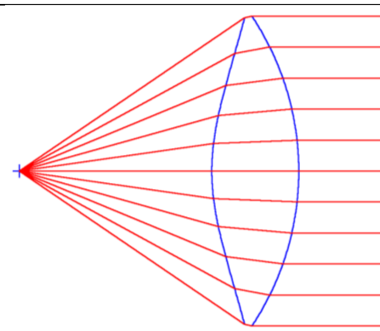
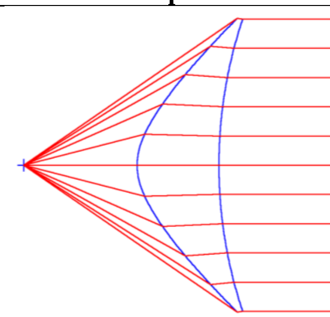
GRASP BOR-MoM Analyses of Dielectric Lenses

A dielectric lens can be added to a GRASP analysis (TICRA) by using the same BOR Mesh files used in CHAMP. The BOR Mesh file in GRASP has the option of including a coordinate system which can shift its position or its angular orientation. While CHAMP always locates the feed antenna on the axis, any GRASP feed model can be used and placed in any position. Being able to located the feed off-axis is a great advantage with the BOR-MoM analysis of GRASP because it can analyze the general case. Either the general MOM analysis or the BOR-MOM can be used with the lens and feed combination. The BOR-MOM analysis runs much quicker than the general MOM analysis and should be used. The GRASP BOR-MOM analysis runtime increases when the feed is increasing located off-axis and the BOR symmetry of the general problem is reduced. However, it only means that more modes must be included which increases runtime only linearly and the general rapid BOR analysis remains vastly improved from the 3d general analysis.

The various general two-surface lenses have been considered.

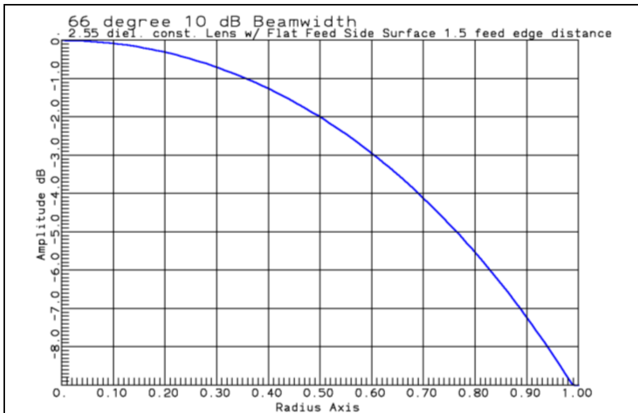
		
Flat Feed Side Surface	**Flat Radiation Side Surface**	**Concave Sphere Feed Side**
		
Convex Sphere Feed Side	**Convex Sphere Radiation Side**	**Concave Sphere Radiation Side**

General Two-Surface Lenses

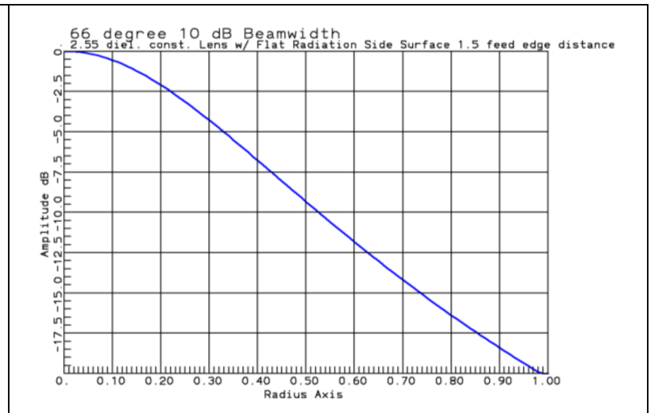
The "Flat Radiation Side" and "Concave Sphere Feed Side" lenses are the single refracting surface lens where the rays pass through one surface without refracting and all refraction takes place on the other surface. The other four lenses refract the rays at both surfaces. The lenses above use either flat or spherical surfaces on one surface and in general we could specify other types of surfaces and solve for the second surface through ray tracing. Notice that these lenses do not have spherical surfaces (including the flat surface as a sphere of infinite radius) on both sides as used in the lens maker's equation. This approach to lenses is normally discussed in college physics but it is a paraxial ray approximation that produces spherical aberration in the focus for these wide angle lenses.

The CHAMP analysis of lenses section fed the lenses with a 14.5 dB gain Pickett-Potter horn and included the interaction between the feed and lens. This 14.5 dB gain horn has a 10-dB beamwidth of about 66°, which we will replace with a Gaussian beam feed for direct comparison. Of course, in GRASP the feed and lens interaction cannot be included. Combinations of taper due to the ray trace through the lens and the feed taper are plotted below over a normalized lens radius using ray tracing analysis.

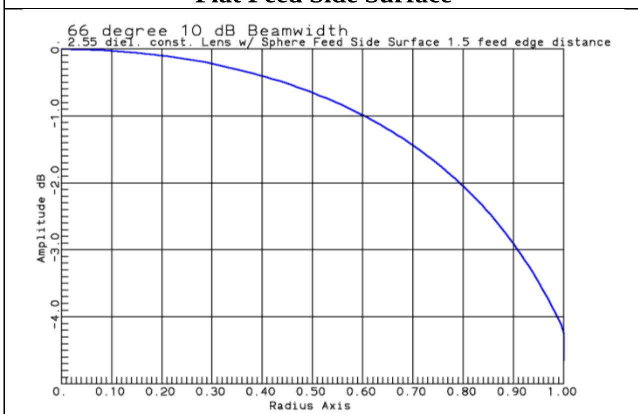
Ray tracing through the lenses produces the amplitude distribution using Eq. (9-11) by using a cubic spline between the aperture radius and the feed angle to compute the derivative in the equation. This operation produced the series of amplitude taper plots given below for the six lenses above.



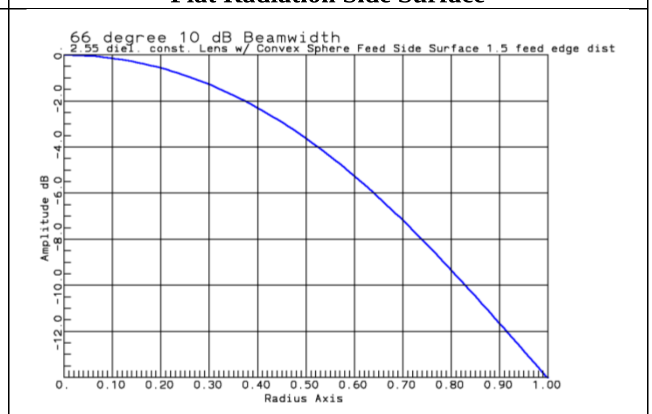
Flat Feed Side Surface



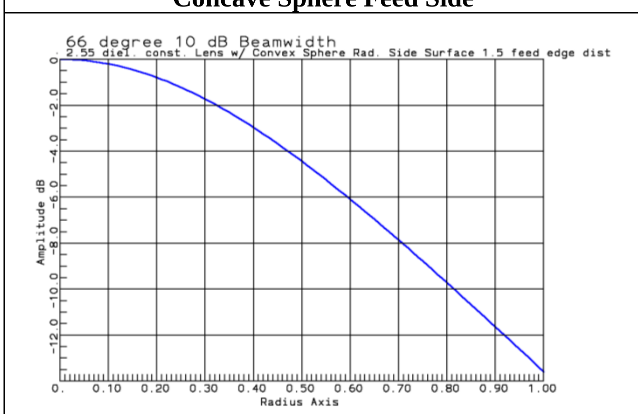
Flat Radiation Side Surface



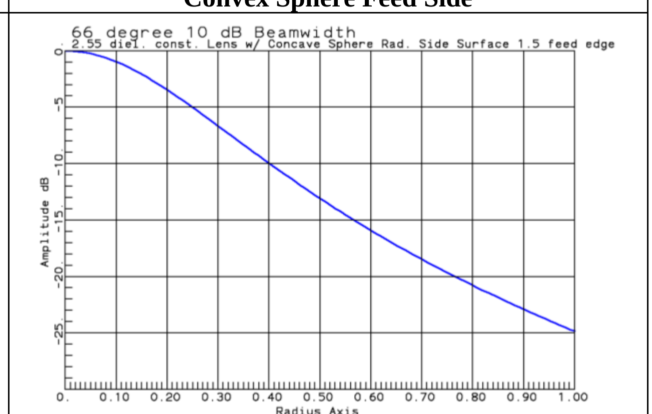
Concave Sphere Feed Side



Convex Sphere Feed Side



Convex Sphere Radiation Side



Concave Sphere Radiation Side

Aperture distribution of Lenses fed by 14.5 dB Gain Pickett-Potter Horn

Table 1 Amplitude Taper Loss using 66° 10-dB Beamwidth Feed using Ray Tracing Analysis

Flat Feed Side Surface	-0.43 dB
Flat Radiation Side Surface	-1.89
Concave Sphere Feed Side	-0.10
Convex Sphere Feed Side	-0.90
Convex Sphere Radiation Side	-0.84
Concave Sphere Radiation Side	-2.78

The program SPSLENS was written to compute the two lens surfaces with one specified as either a flat or sphere and generate TOR file additions to GRASP (or CHAMP) of the BOR Mesh file of the lens. The output file includes the TOR real variable ZLOFF to allow an arbitrary z-axis positioning of the lens. Cases below have the lens focus moved inside a horn aperture to its phase center. We handle the phase shift of ZLOFF in GRASP by either editing the variable to zero or moving the feed coordinate system of Gaussian beam to match. We either start GRASP as a blank project in which the feed and base coordinate systems are created or apply "save as" to a former project. Spherical cut object of the pattern and the frequency objects are created in the blank project. We store the GRASP project and edit its TOR file to add the BOR Mesh of the lens. The additions to the TOR file are printed in blue with some of the repetitive lines removed. The BOR_MoM analysis object is added, showed in red below which in this case was added using the GRASP GUI. This lens was grooved to reduce surface reflections with the grooves cut into material added to the lens surfaces to form a with a "coating". If we use the Lichtenecker logarithmic dielectric mixing equation for the coating to produce a layer with the square root of the lens material, the width of the gaps should equal the groove width. The groove depth should be $\lambda/4$ computed in the coating dielectric constant. The coating alters the effective focal length of the lens so SPSLENS allows adjustments to allow the groove to penetrate the design surfaces for hand optimization of groove layers. We store the TOR file edit and when we re-start the GRASP project and the lens is included.

Table 2 Gain of 10λ diameter Lens with 14.5 dB Gain Potter Horn Feed using CHAMP

Lens	Grooved Surface Lens	Smooth Surface Lens
Flat Feed Side Surface	29.58 input 5	29.19 input 6
Flat Radiation Side Surface	27.82 input 7	27.68 input 8
Concave Sphere Feed Side	29.78 input 9	29.64 input 10
Convex Sphere Feed Side	29.02 input 11	28.61 input 12
Convex Sphere Radiation Side	29.03 input 13	28.69 input 14
Concave Sphere Radiation Side	26.74 input 15	26.48 input 16

Table 3 Gain of 10λ diameter Lens with on-axis 66° 10 dB Gaussian Beam Feed using GRASP

Lens	Grooved Surface Lens	Smooth Surface Lens
Flat Feed Side Surface	29.58 input 5	29.19 input 6
Flat Radiation Side Surface	27.80 input 7	27.45 input 8
Concave Sphere Feed Side	29.77 input 9	29.54 input 10
Convex Sphere Feed Side	29.03 input 11	28.60 input 12
Convex Sphere Radiation Side	29.06 input 13	28.67 input 14
Concave Sphere Radiation Side	26.73 input 15	26.42 input 16

Edited TOR file

```
base_coor_sys  coor_sys
(
)

feed_coor_sys  coor_sys
(
  origin          : struct(x: -44.42 mm, y: 0.0 m, z: -3.2 mm),
  base            : ref(base_coor_sys)
)

frequency_range_1  frequency_range
(
  frequency_range  : struct(start_frequency: 10.0 GHz, end_frequency: 10.0 GHz,
number_of_frequencies: 1)
)

gaussian_beam_pattern  gaussian_beam_pattern
(
  frequency       : ref(frequency_range_1),
  coor_sys        : ref(feed_coor_sys),
  taper_angle     : 33.0,
  taper           : -10.0
)

spherical_cut  spherical_cut
(
  coor_sys        : ref(base_coor_sys),
  theta_range     : struct(start: -90.0, end: 90.0, np: 361),
  phi_range       : struct(start: 0.0, end: 90.0, np: 3),
  file_name       : lens_5.cut,
  comment         : "Field data in cuts",
  frequency       : ref(frequency_range_1)
)

ZLOFF  real_variable
(
  value           : -3.2
)

horn_bor_mesh_lens  bor_mesh
(
```

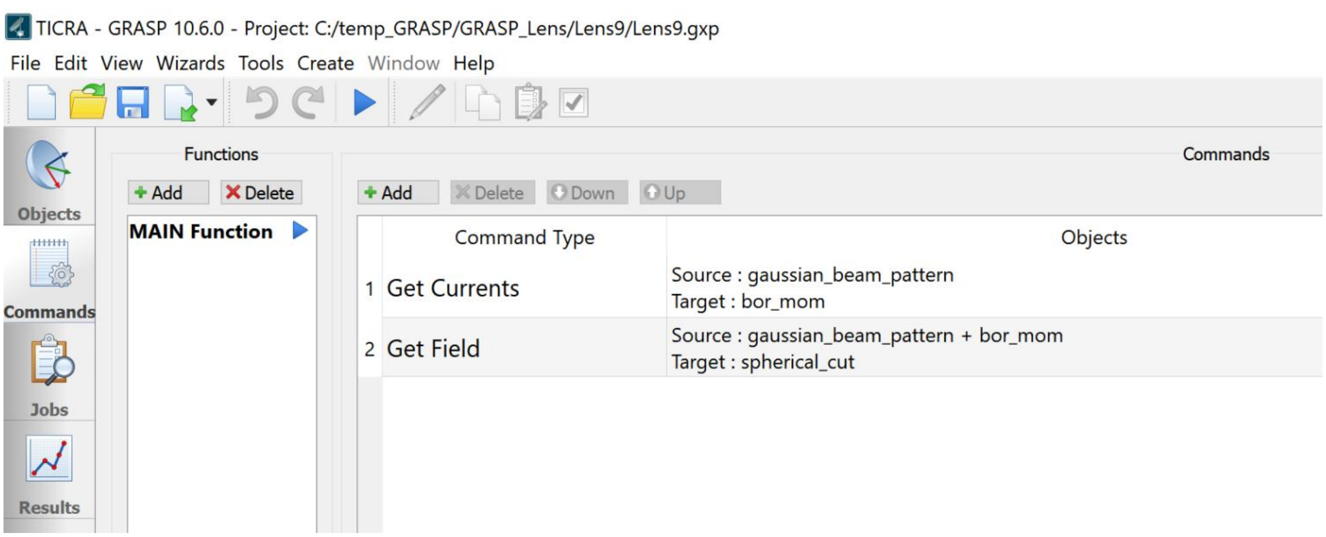
```
 regions        : table
  (
    1   2.55000E+00   1.00000E+00   0.00000E+00
  ),
 nodes          : table
  (
    1  "ref(ZLOFF)+2.6469e+02"   0.00000E+00
    2  "ref(ZLOFF)+2.6468e+02"   1.56250E+00
.
.
.
   256  "ref(ZLOFF)+2.3023e+02"   1.53480E+02
  ),
 linear_segments  : table
  (
    1    4    5    0    1  -1.00000E+00   0.00000E+00
    2    8    9    0    1  -1.00000E+00   0.00000E+00
.
.
.
    63   128   256    0    1  -1.00000E+00   0.00000E+00
  ),
 cubic_segments   : table
  (
    1    1    2    3    4    0    1  -1.00000E+00   0.00000E+00
    2    5    6    7    8    0    1  -1.00000E+00   0.00000E+00
.
.
.
    63   249   250   251   252    0    1  -1.00000E+00   0.00000E+00
    64   253   254   255   256    0    1  -1.00000E+00   0.00000E+00
  ),
 length_unit      : mm
)

bor_mom  bor_mom
(
 frequency       : ref(frequency_range_1),
 scatterer       : ref(horn_bor_mesh_lens)
)
```

```
//DO NOT MODIFY OBJECTS BELOW THIS LINE.
//THESE OBJECTS ARE CREATED AND MANAGED BY THE
//GRAPHICAL USER INTERFACE AND SHOULD NOT BE
//MODIFIED MANUALLY!
view_1  view
(
  objects         :
sequence(ref(view_1_coor_sys_plot),ref(view_1_feed_plot),ref(view_1_output_points_plot),
ref(view_1_bor_plot),ref(view_1_mom_plot))
)
.
.
.
```

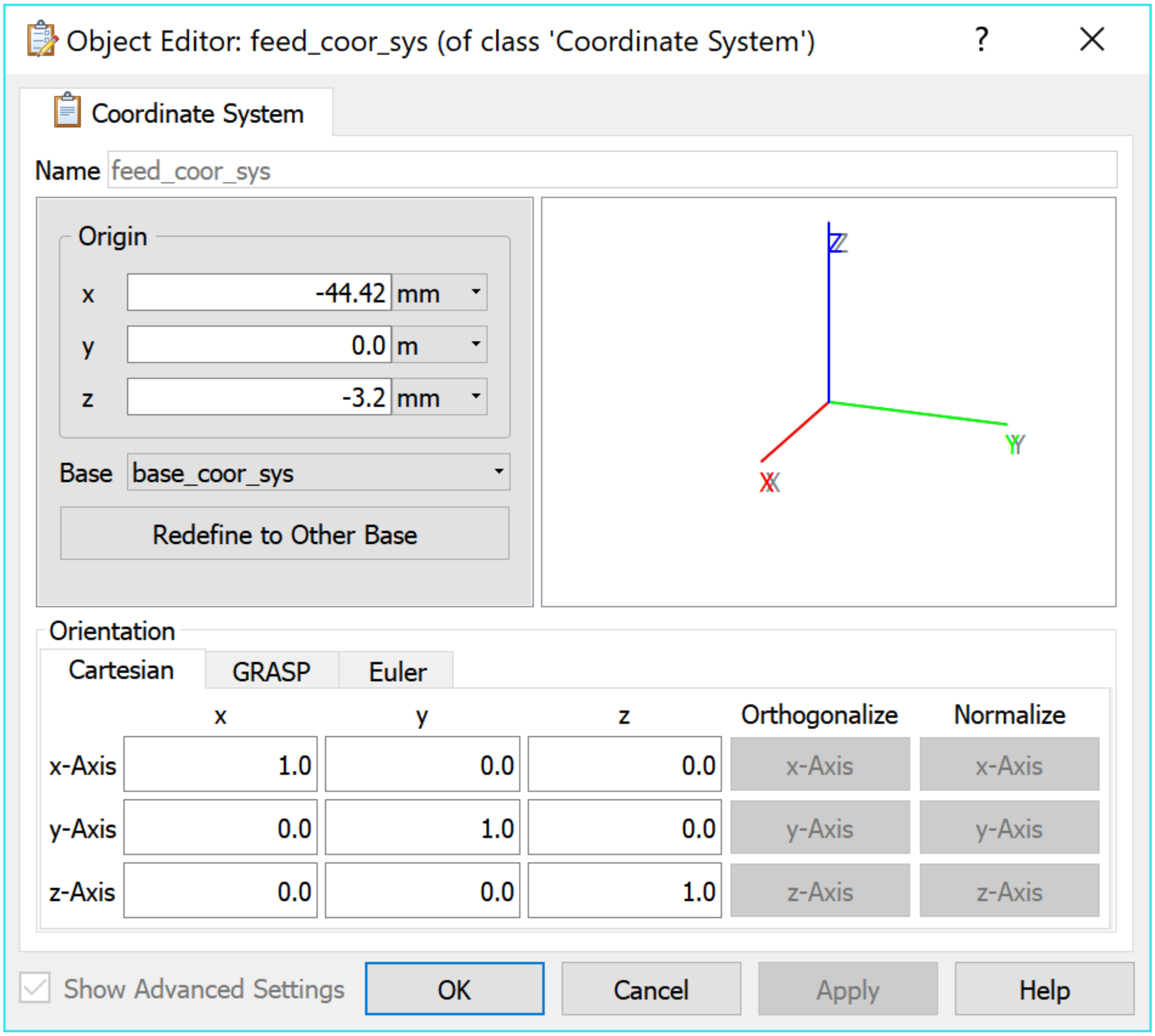
The following commands are used the analysis:

The first one is to feed the BOR-MoM analysis using the gaussian beam pattern. Increasing the asymmetry of the total problem by moving the feed or lens off-axis or by rotating the lens increases the runtime as more modes are included in the “Get Currents” operation.

The “Get Field” command includes the radiation from electric and magnetic surface currents of the lens and the direct radiation from the feed. This direct radiation adds the spillover pattern of the feed. The BOR-MoM computation of lens surface currents does not replace the radiation of the feed.

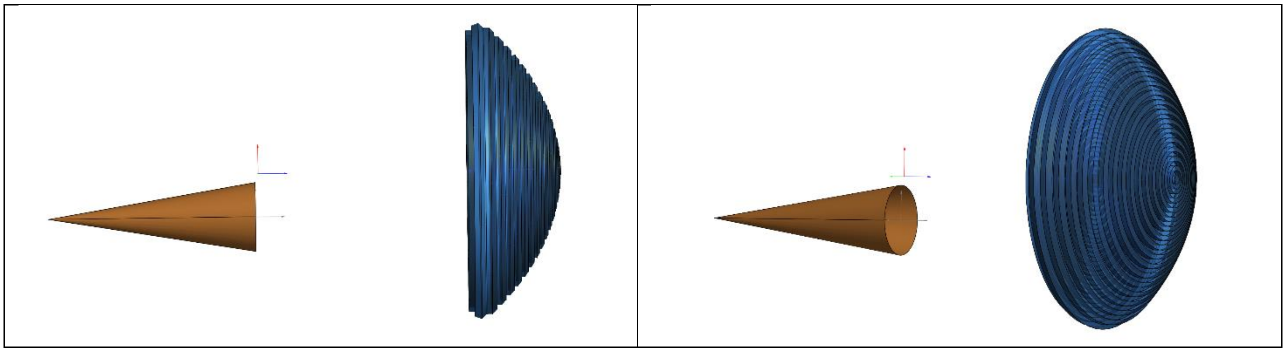


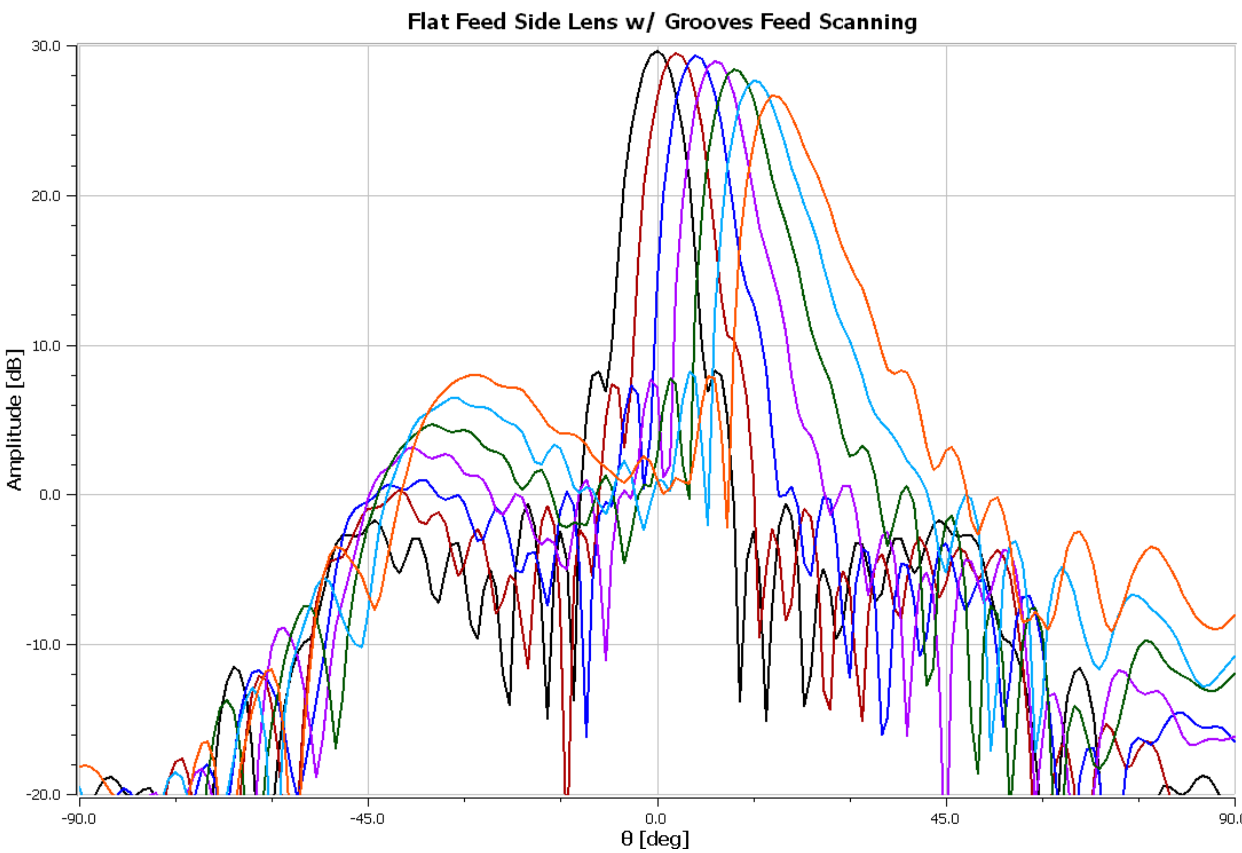
The following analyses illustrate the pattern effects of moving the feed laterally off-axis. The 14.5 dB Pickett-Porter horn has an aperture radius of 29.6 mm at 10 GHz. Six off-axis feed position of the equivalent Gaussian beam feed were selected at half aperture radial increments. To move the feed we edit the "feed_coor_sys" GRASP object between runs, as illustrated for 1.5 times the aperture radius:

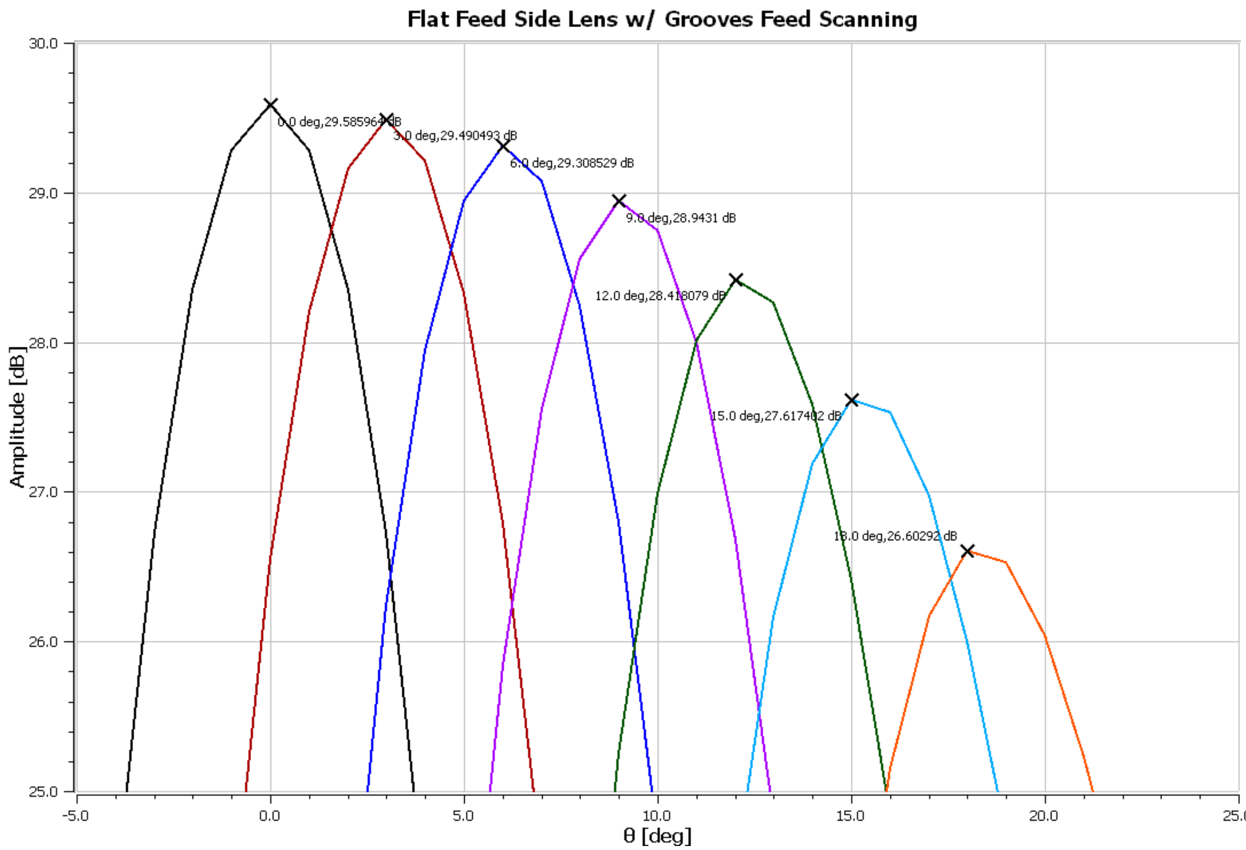


Note that the feed z-axis position of the Gaussian beam feed matches the phase center of the horn modeled in the CHAMP model which equals the ZLOFF GRASP variable.

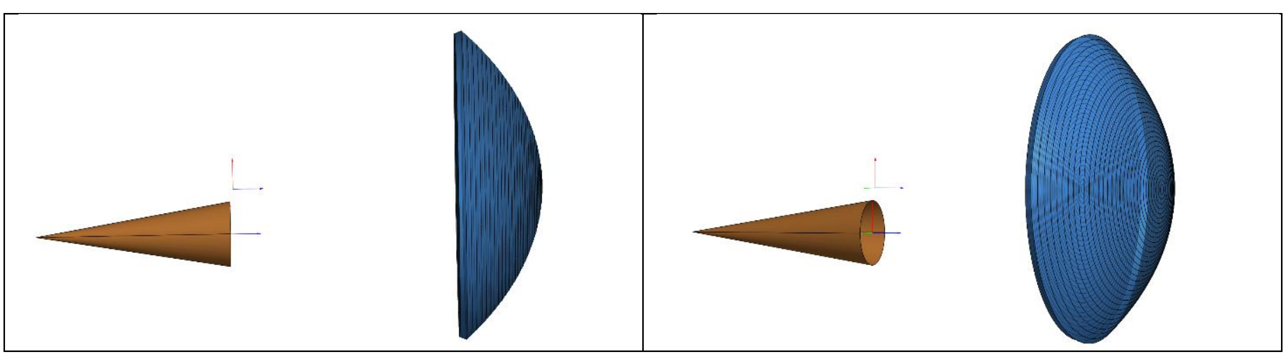
Flat Feed Side Lens with Grooved Surfaces #5

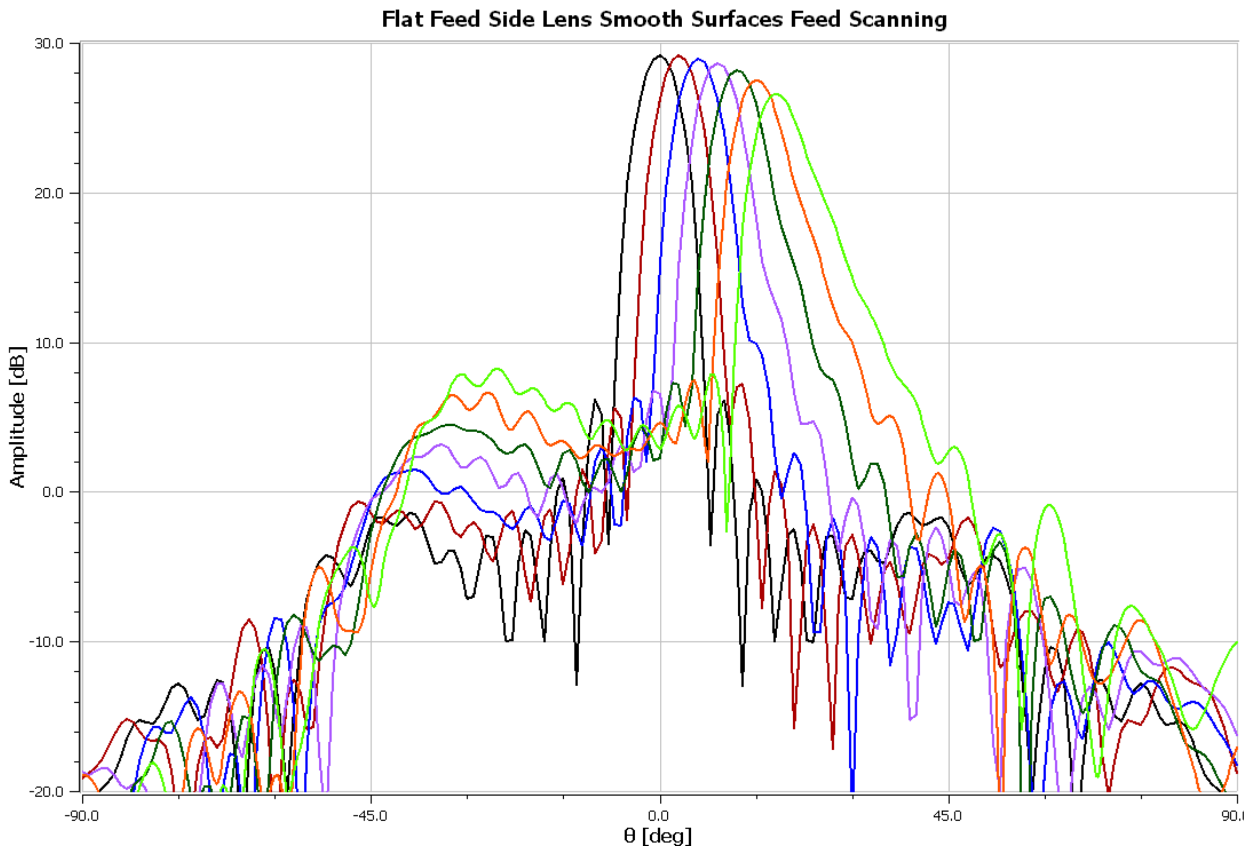


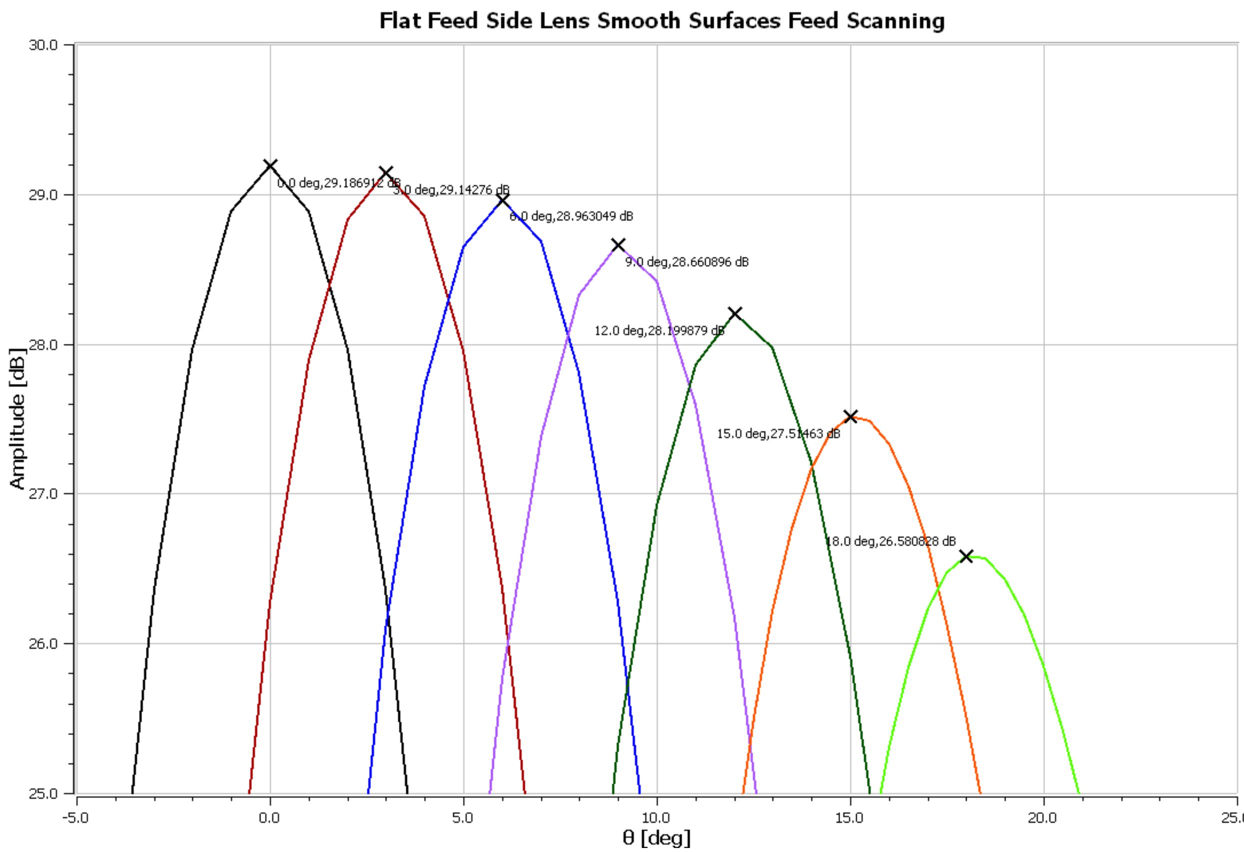




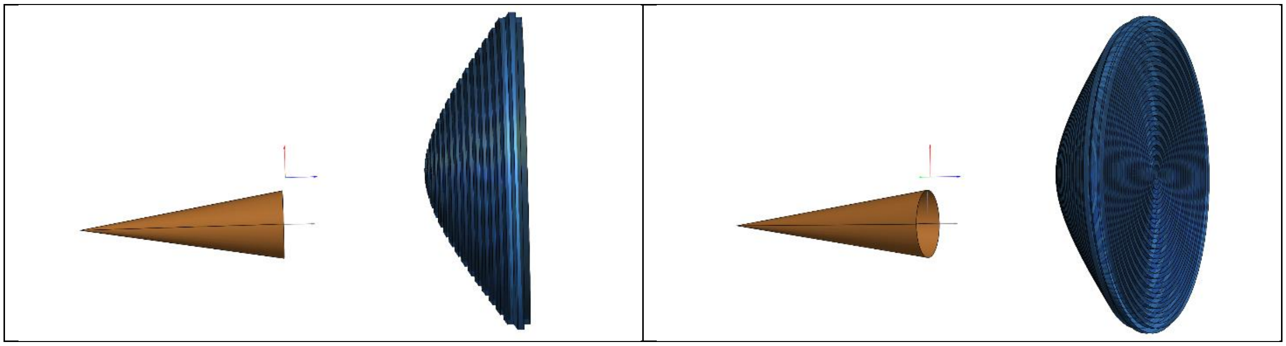
Flat Feed Side Lens with Smooth Surfaces #6

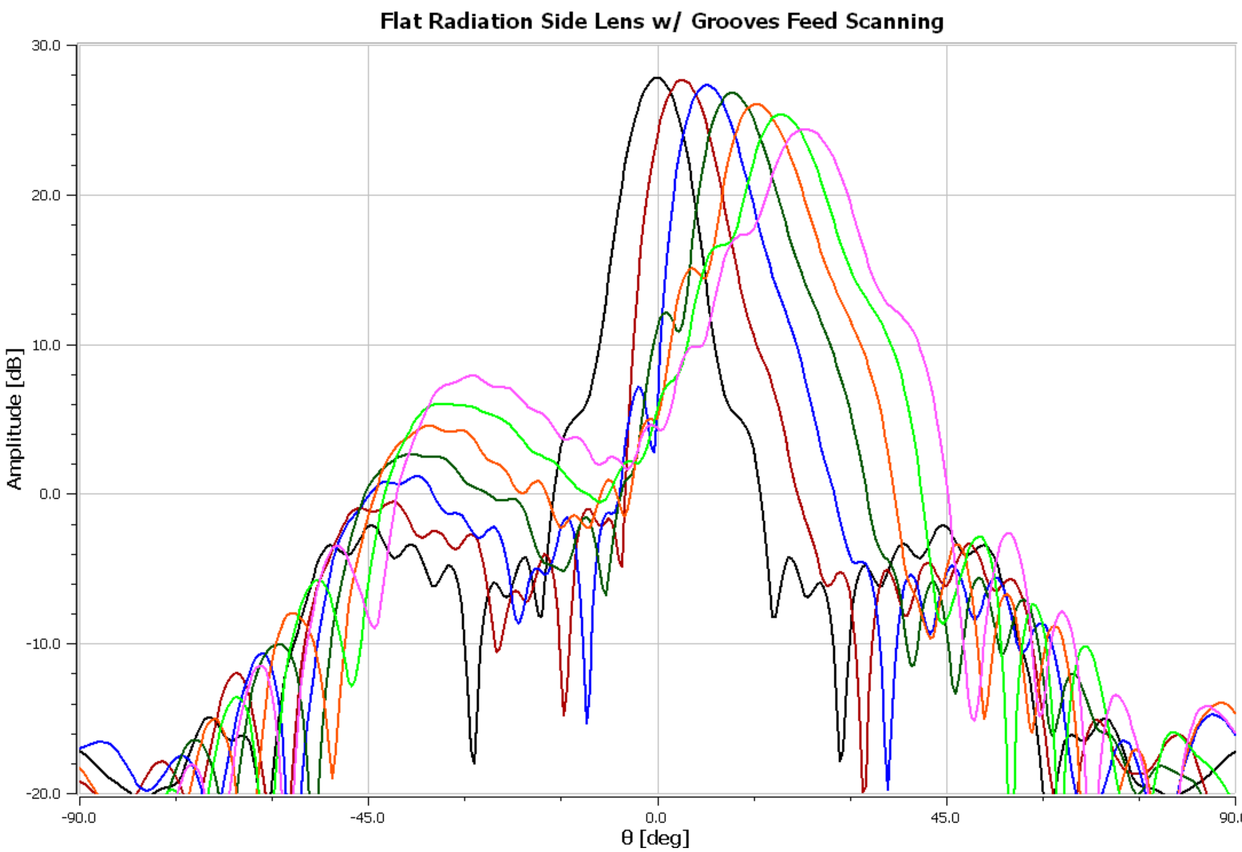


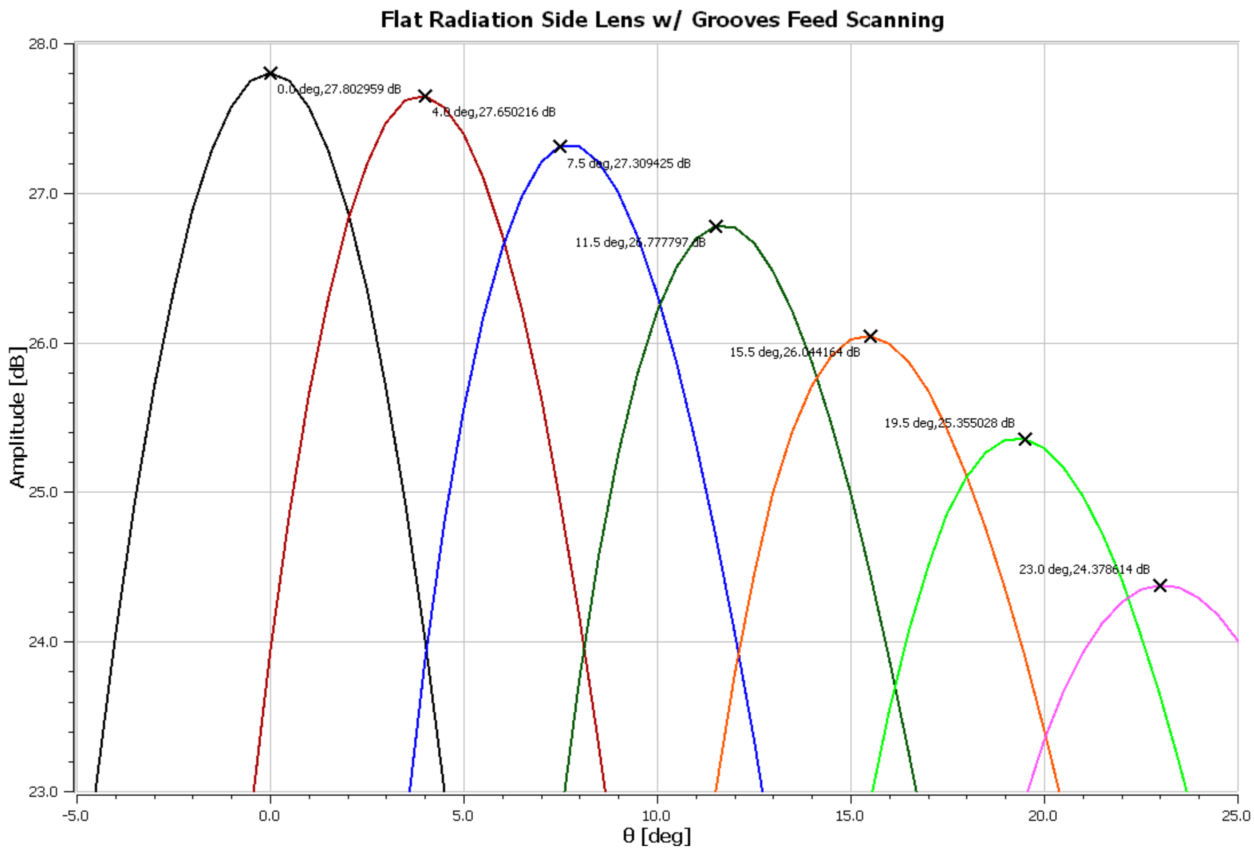

Flat Feed Side Lens Smooth Surfaces Feed Scanning
Amplitude [dB]
30.0
20.0
10.0
0.0
-10.0
-20.0
-90.0
-45.0
0.0
45.0
90.0
θ [deg]


Flat Feed Side Lens Smooth Surfaces Feed Scanning
Amplitude [dB]
30.0
29.0
28.0
27.0
26.0
25.0
-5.0
0.0
5.0
10.0
15.0
20.0
25.0
θ [deg]
0.0 deg,29.186912 dB
3.0 deg,29.14276 dB
6.0 deg,28.963049 dB
9.0 deg,28.660896 dB
12.0 deg,28.199879 dB
15.0 deg,27.51463 dB
18.0 deg,26.580828 dB

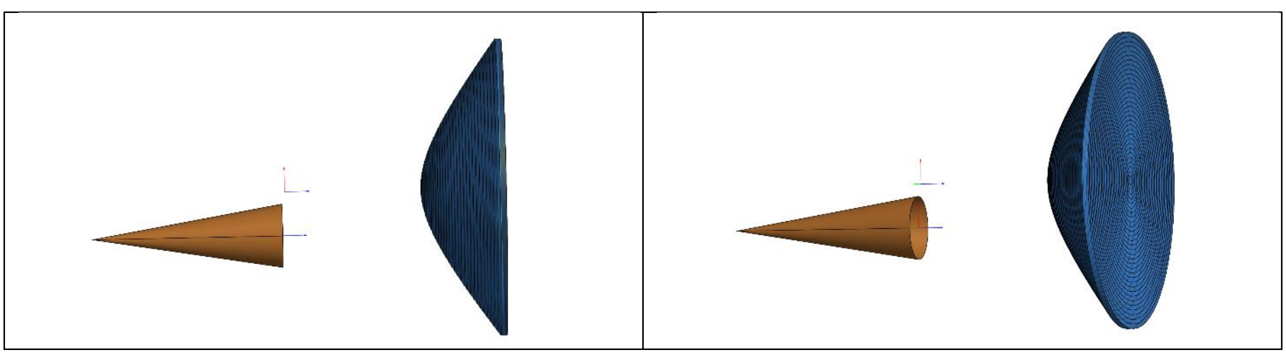
Flat Radiation Side Lens with Grooved Surfaces #7

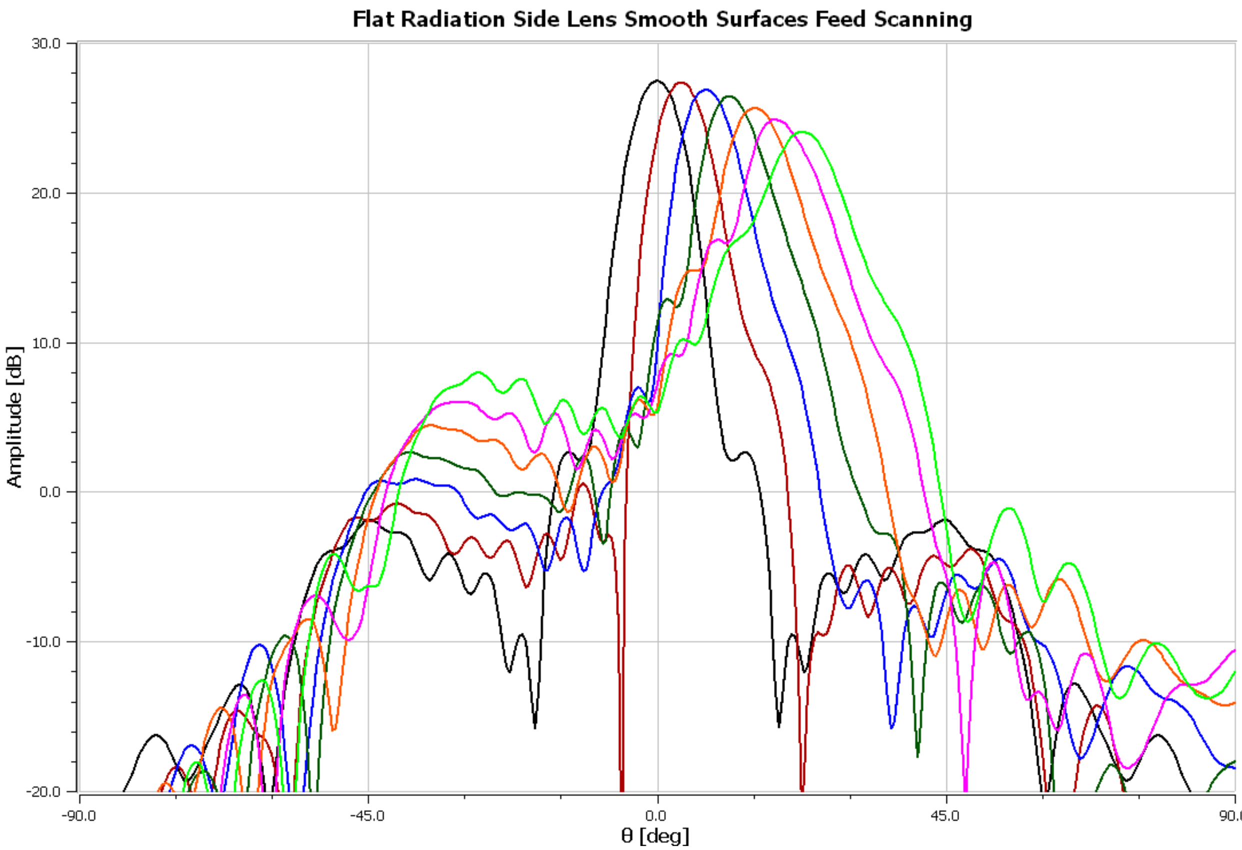


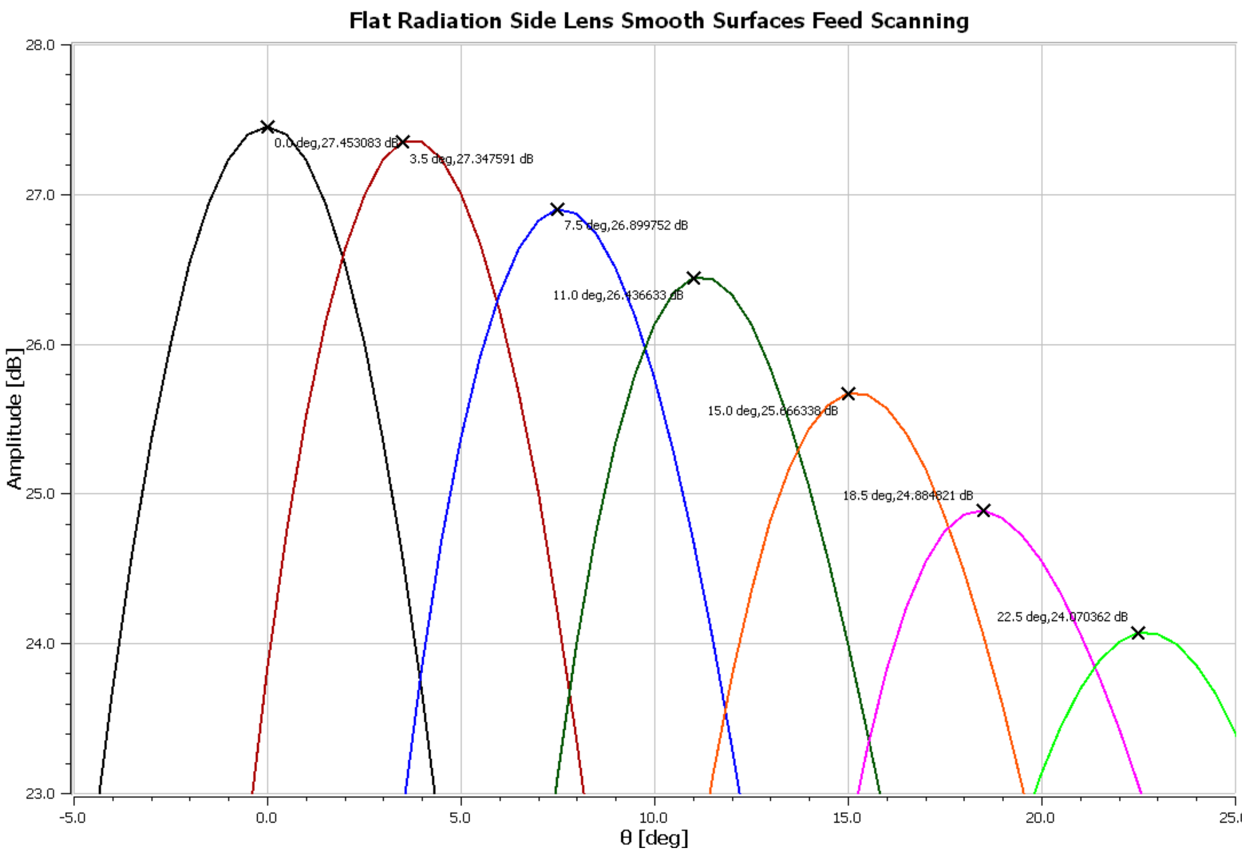




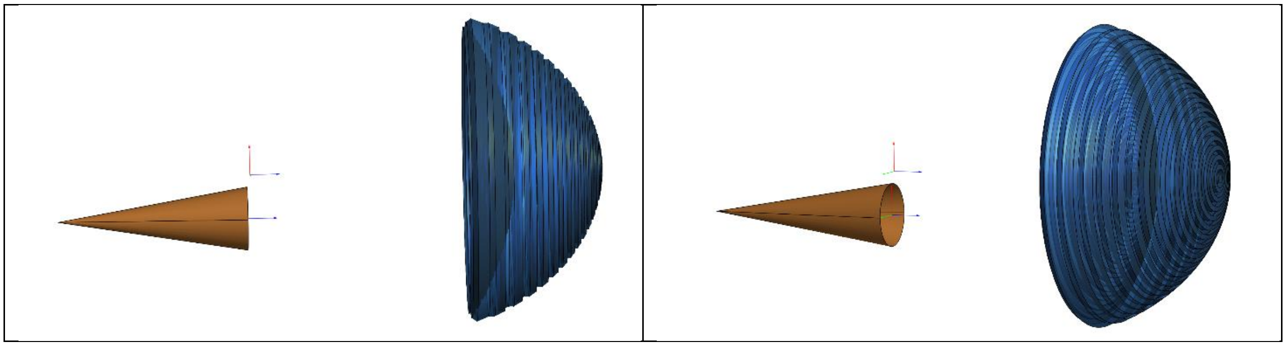
Flat Radiation Side Lens with Smooth Surfaces #8

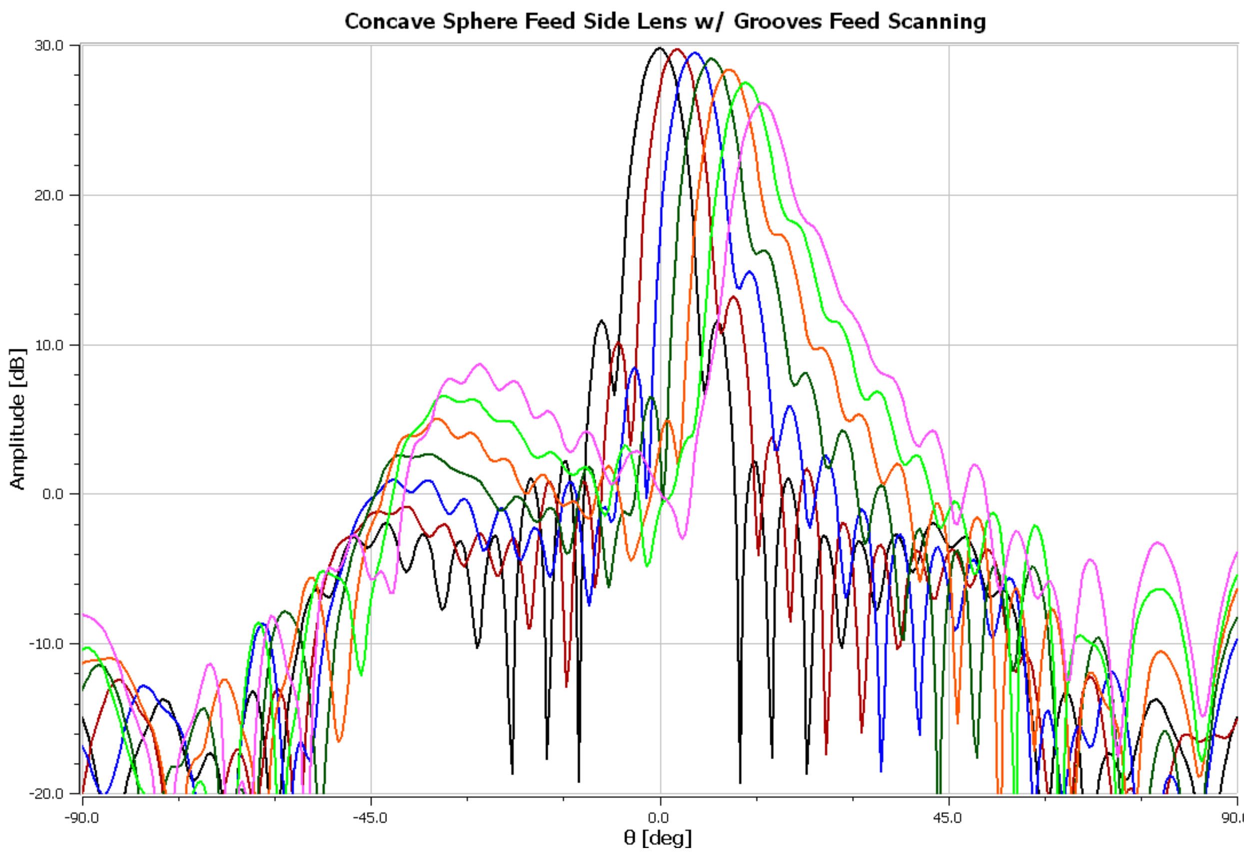


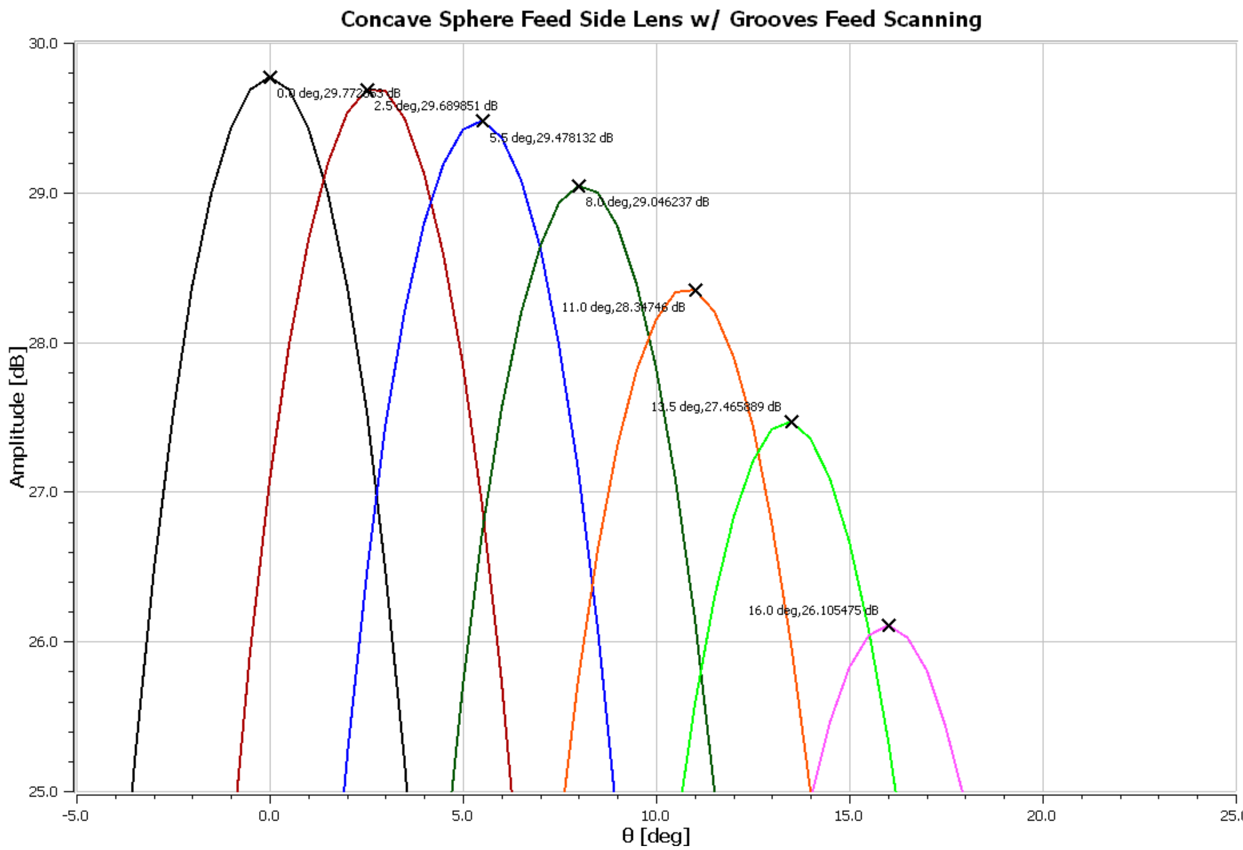

Flat Radiation Side Lens Smooth Surfaces Feed Scanning
Amplitude [dB]
θ [deg]


Flat Radiation Side Lens Smooth Surfaces Feed Scanning
0.0 deg,27.453083 dB
3.5 deg,27.347591 dB
7.5 deg,26.899752 dB
11.0 deg,26.436633 dB
15.0 deg,25.666338 dB
18.5 deg,24.884821 dB
22.5 deg,24.070362 dB
Amplitude [dB]
θ [deg]

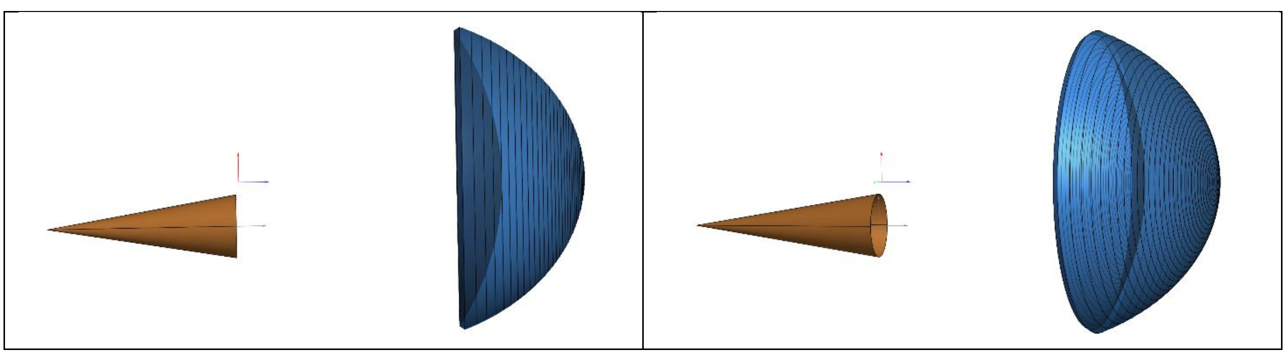
Concave Sphere Feed Side Lens with Grooved Surfaces #9

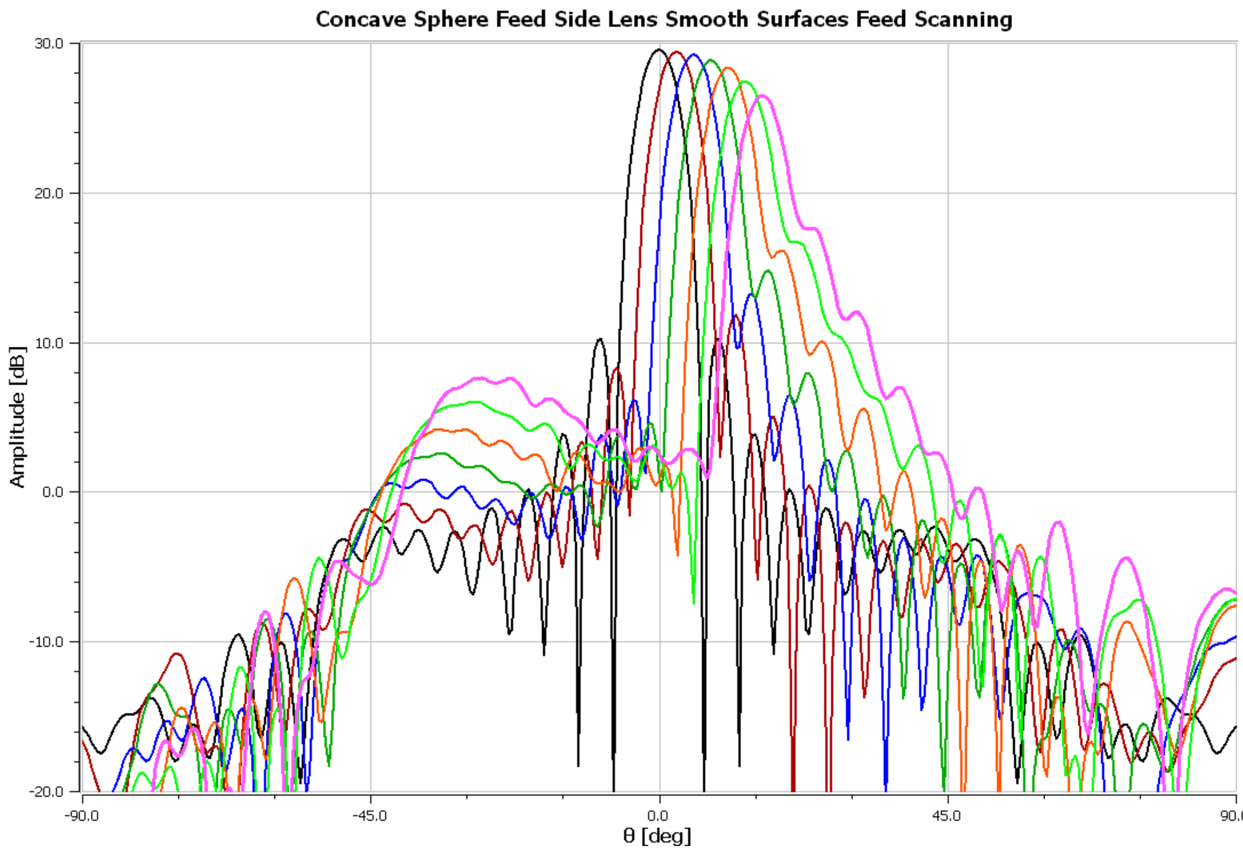


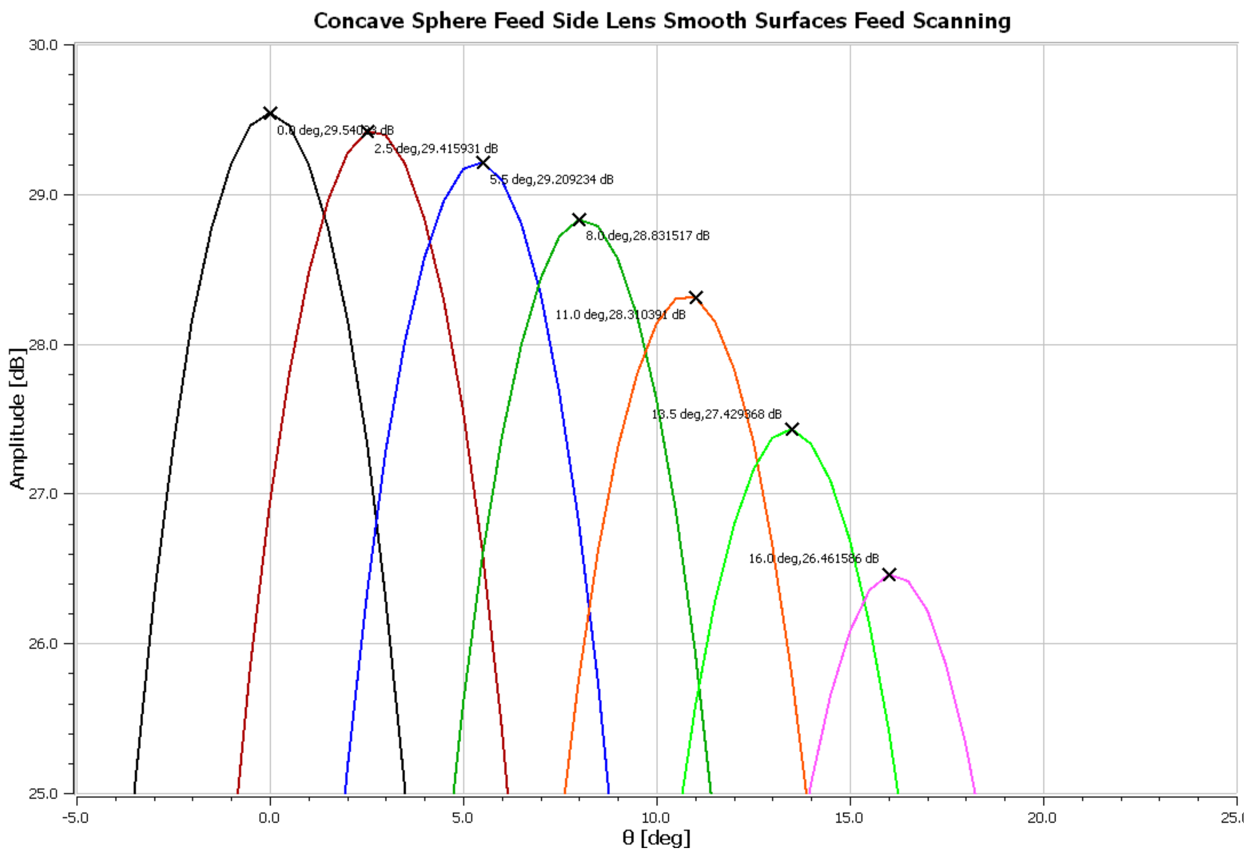




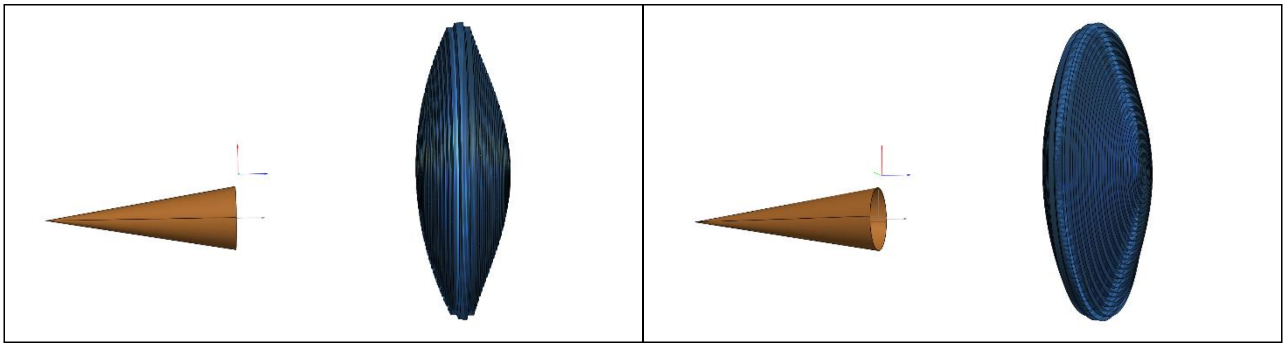
Concave Sphere Feed Side Lens with Smooth Surfaces #10

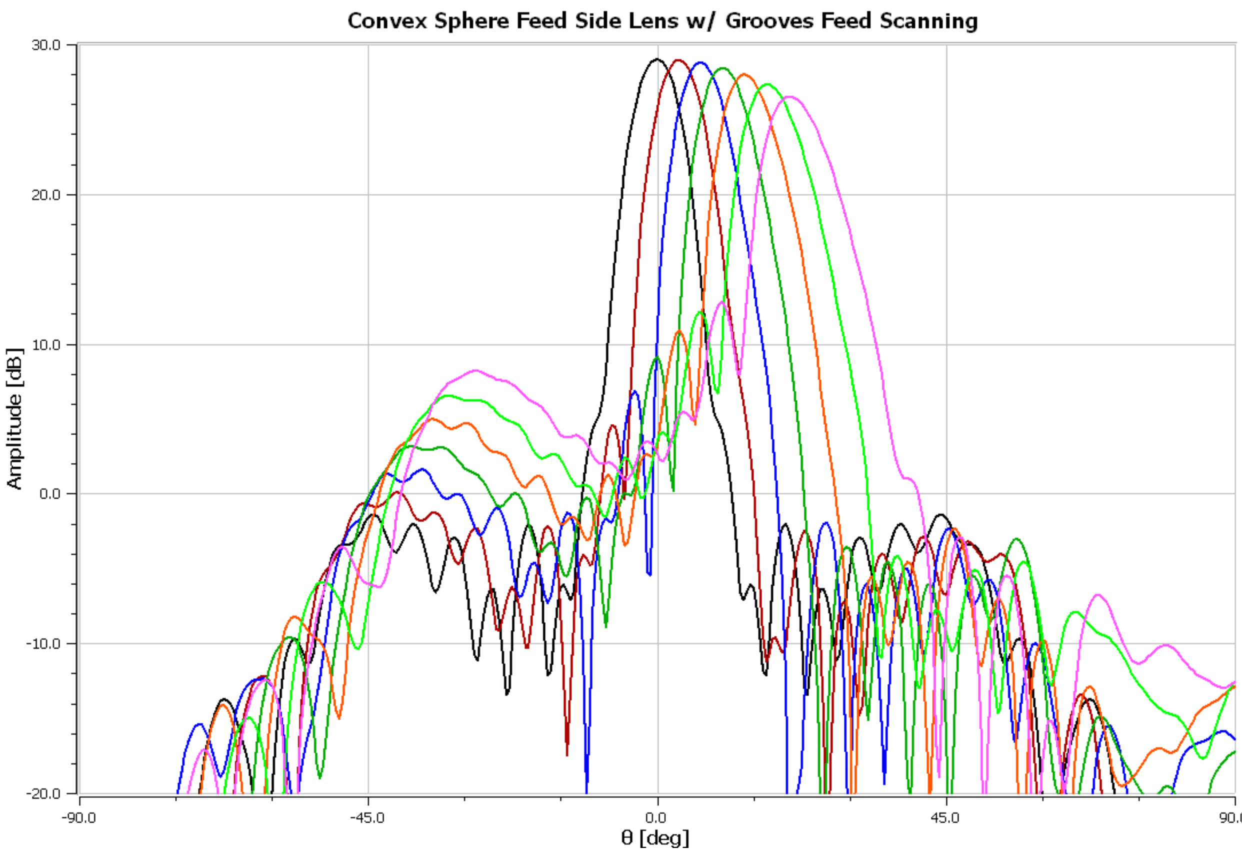


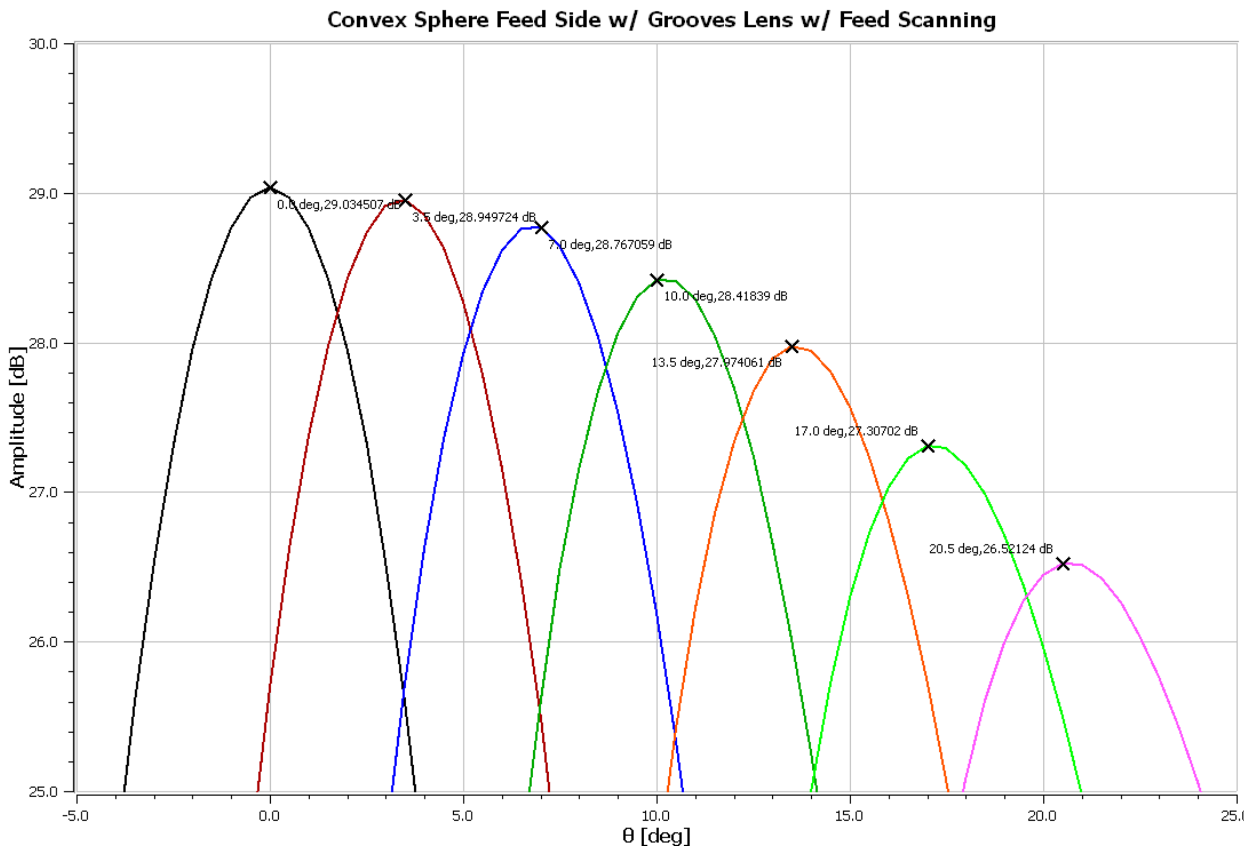

Concave Sphere Feed Side Lens Smooth Surfaces Feed Scanning
Amplitude [dB]
30.0
20.0
10.0
0.0
-10.0
-20.0
-90.0
-45.0
0.0
45.0
90.0
θ [deg]


Concave Sphere Feed Side Lens Smooth Surfaces Feed Scanning
Amplitude [dB]
30.0
29.0
28.0
27.0
26.0
25.0
-5.0
0.0
5.0
10.0
15.0
20.0
25.0
θ [deg]
2.5 deg,29.415931 dB
5.5 deg,29.209234 dB
8.0 deg,28.831517 dB
16.0 deg,26.461586 dB

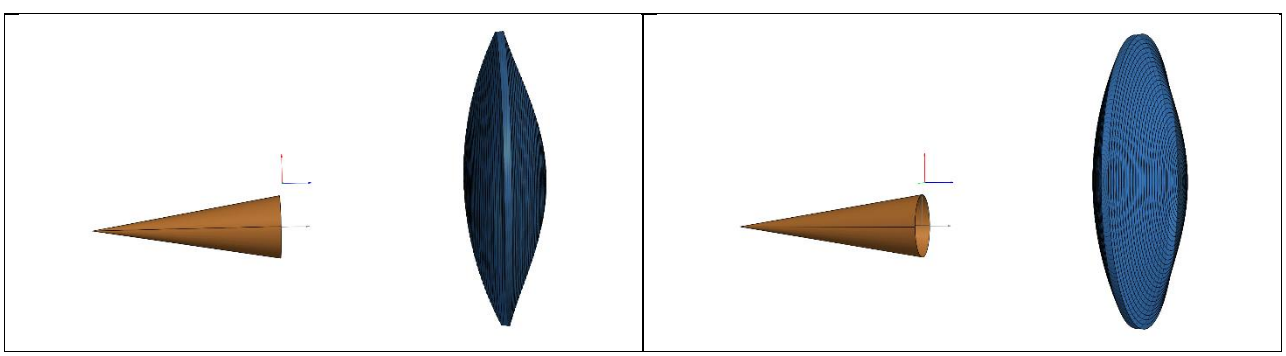
Convex Sphere Feed Side Lens with Grooved Surfaces #11

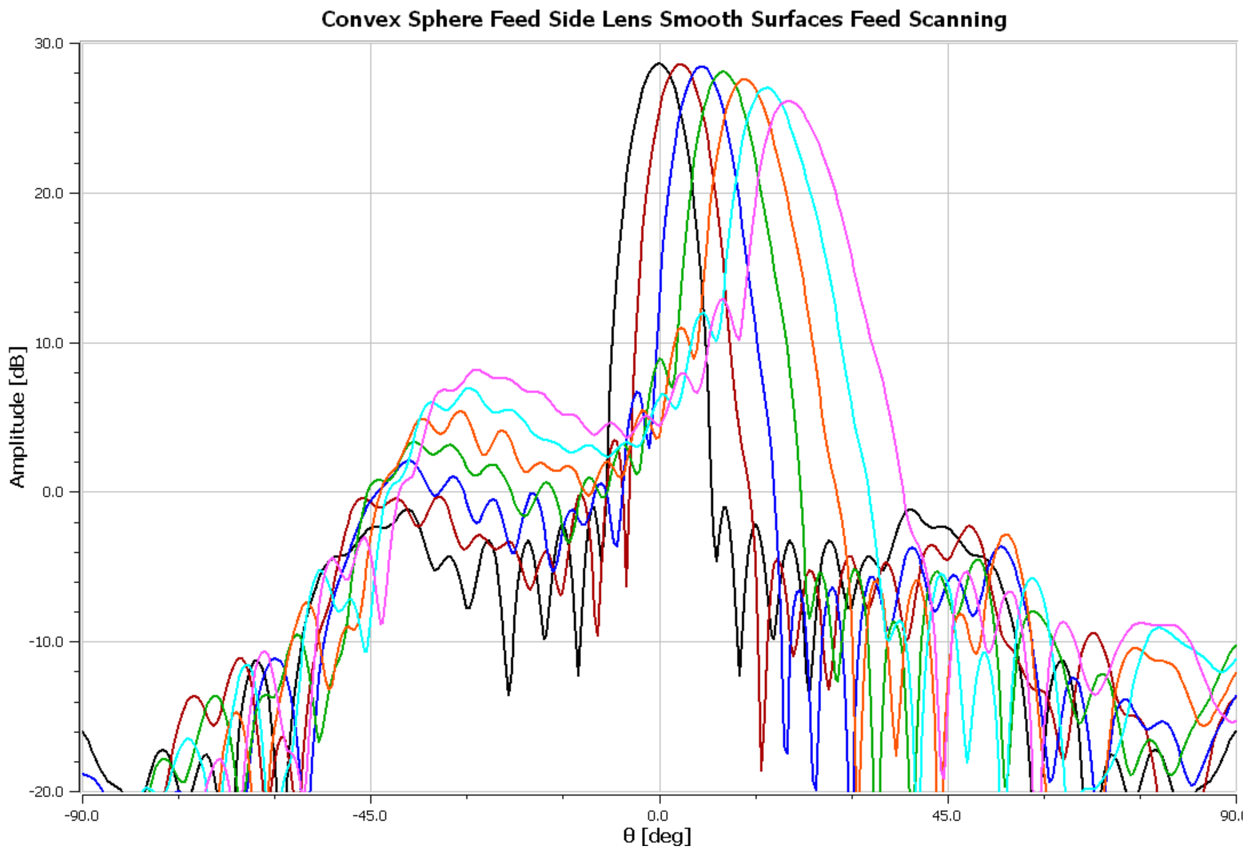


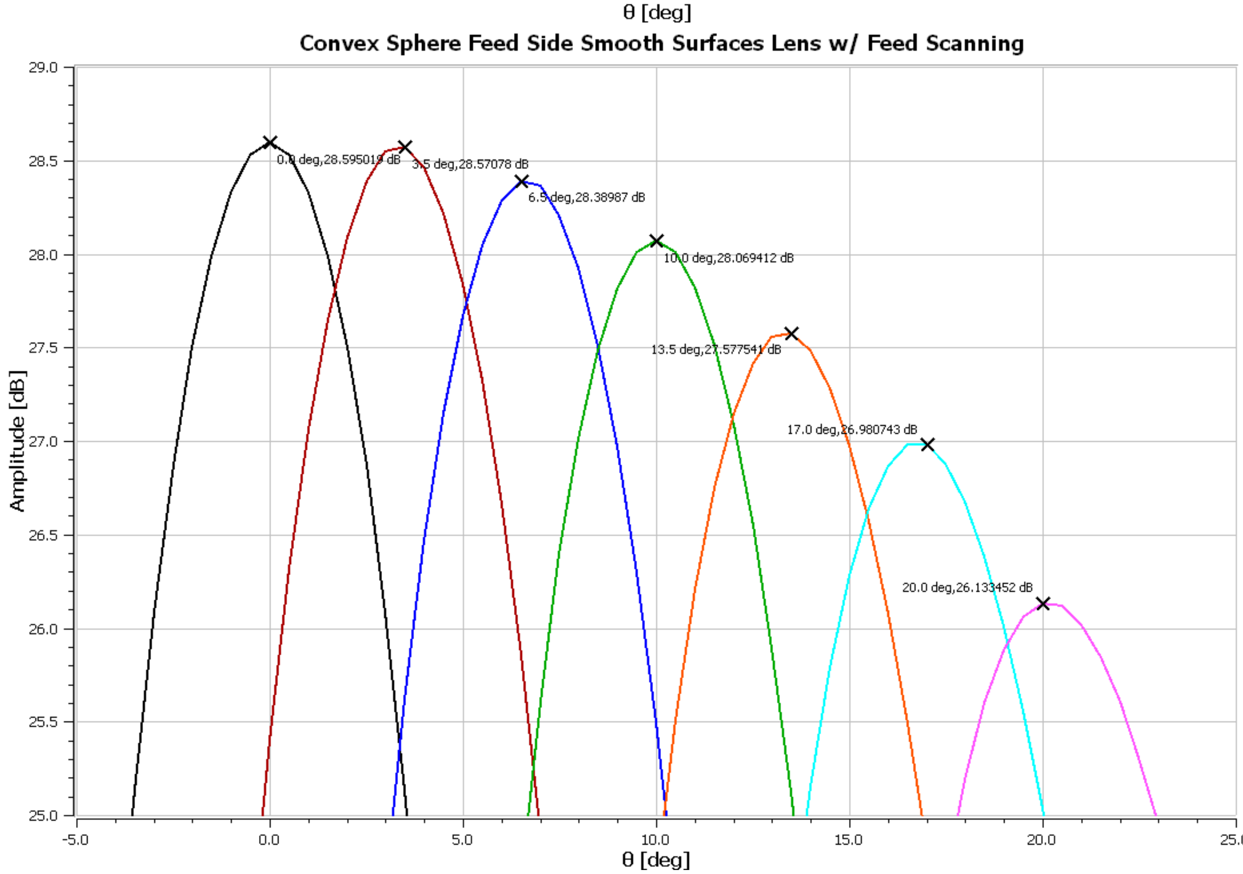




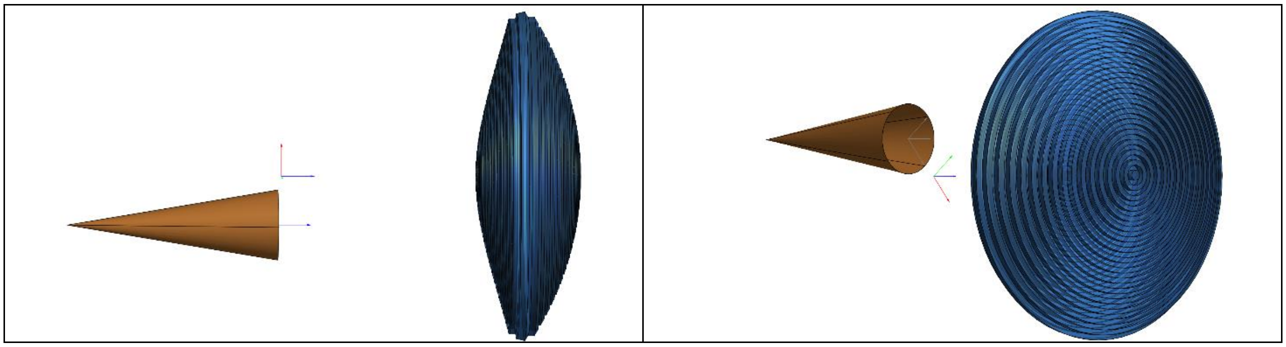
Convex Sphere Feed Side Lens with Smooth Surfaces #12

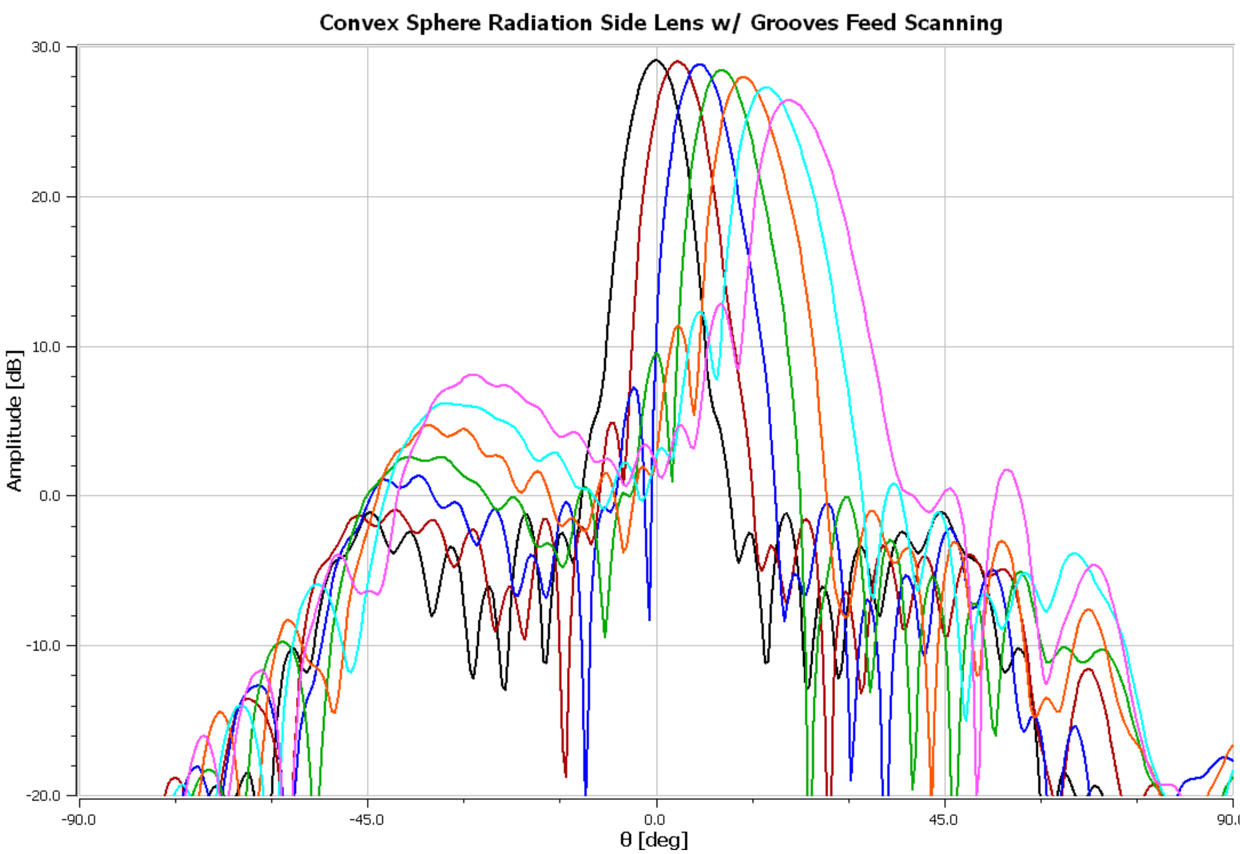


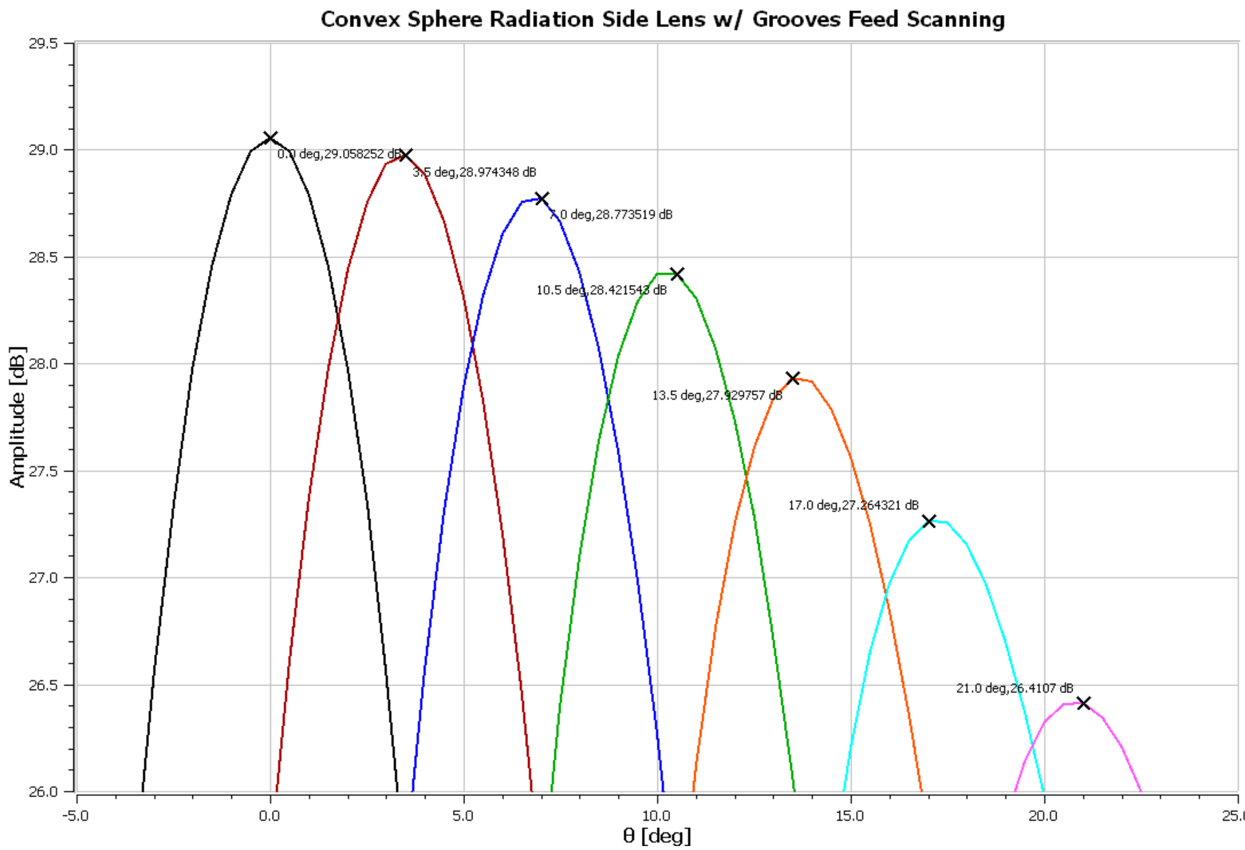

Convex Sphere Feed Side Lens Smooth Surfaces Feed Scanning
Amplitude [dB]
30.0
20.0
10.0
0.0
-10.0
-20.0
-90.0
-45.0
0.0
45.0
90.0
θ [deg]


Convex Sphere Feed Side Smooth Surfaces Lens w/ Feed Scanning
Amplitude [dB]
29.0
28.5
28.0
27.5
27.0
26.5
26.0
25.5
25.0
-5.0
0.0
5.0
10.0
15.0
20.0
25.0
θ [deg]
0.0 deg,28.595019 dB
3.5 deg,28.57078 dB
6.5 deg,28.38987 dB
10.0 deg,28.069412 dB
13.5 deg,27.577541 dB
17.0 deg,26.980743 dB
20.0 deg,26.133452 dB

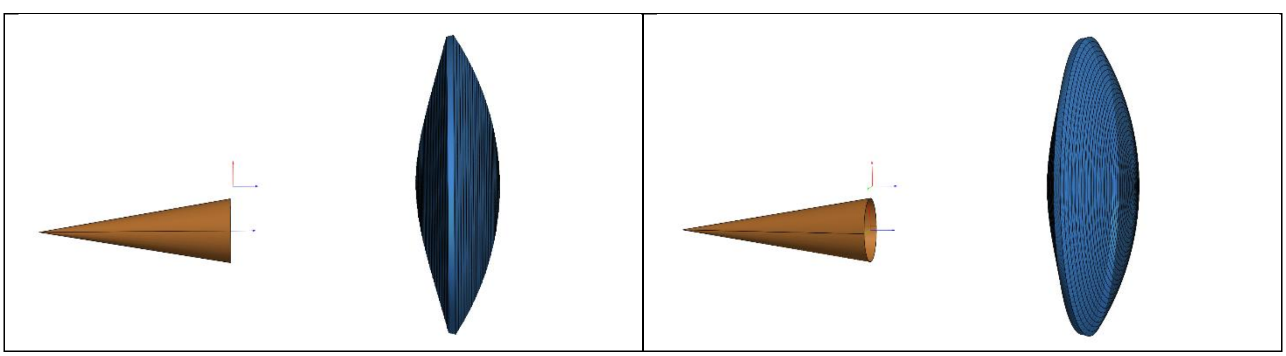
Convex Sphere Radiation Side Lens with Grooved Surfaces #13

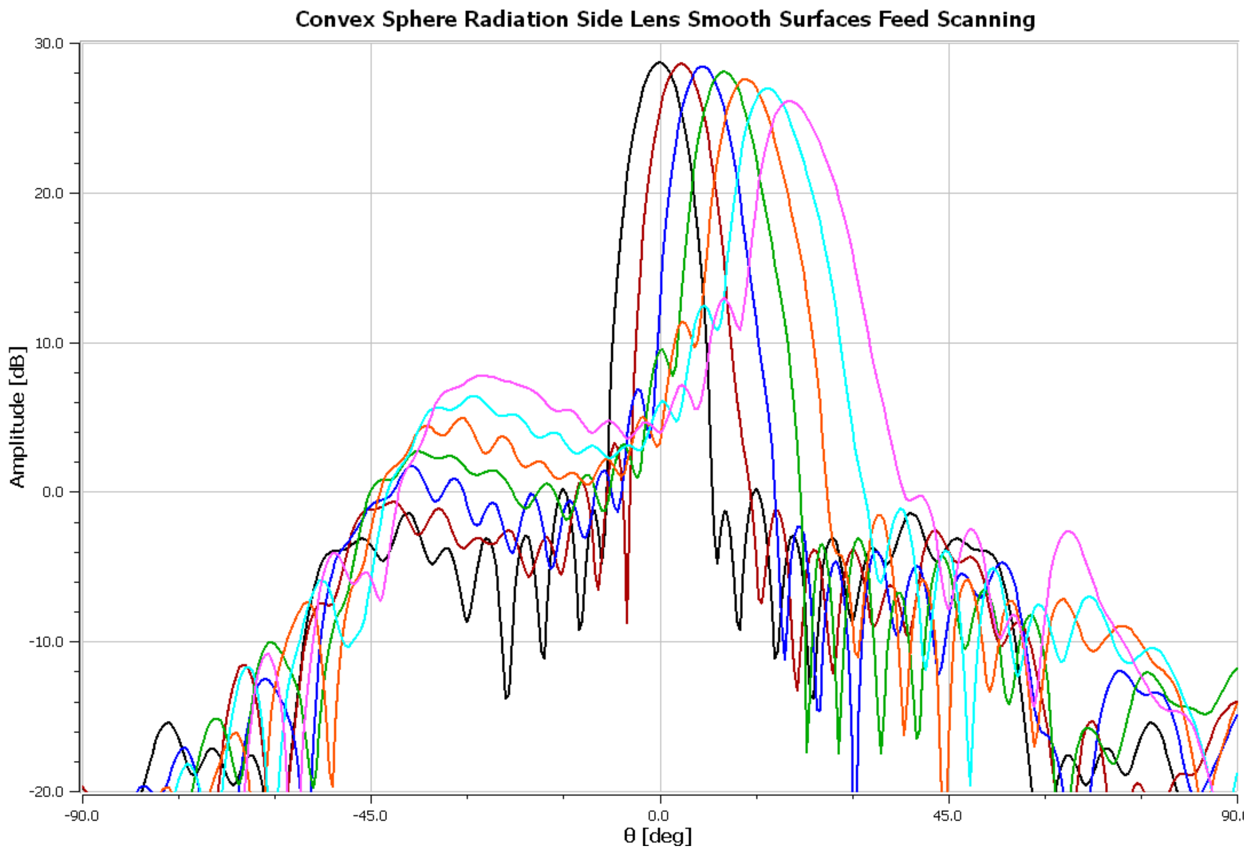


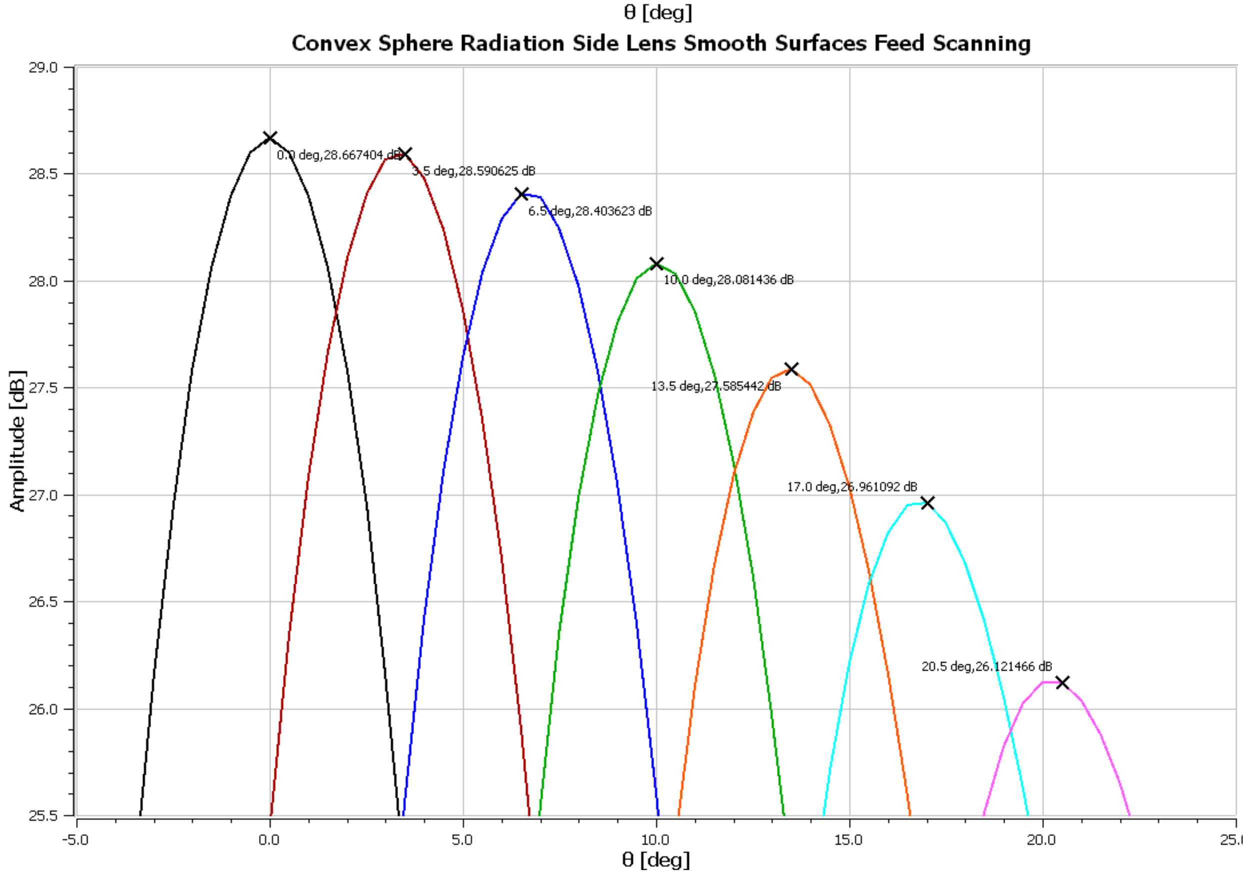




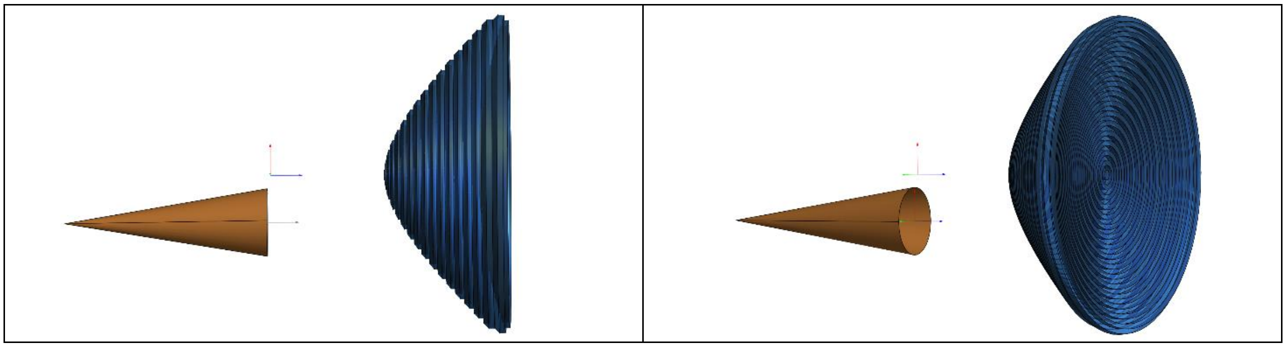
Convex Sphere Radiation Side Lens with Smooth Surfaces #14

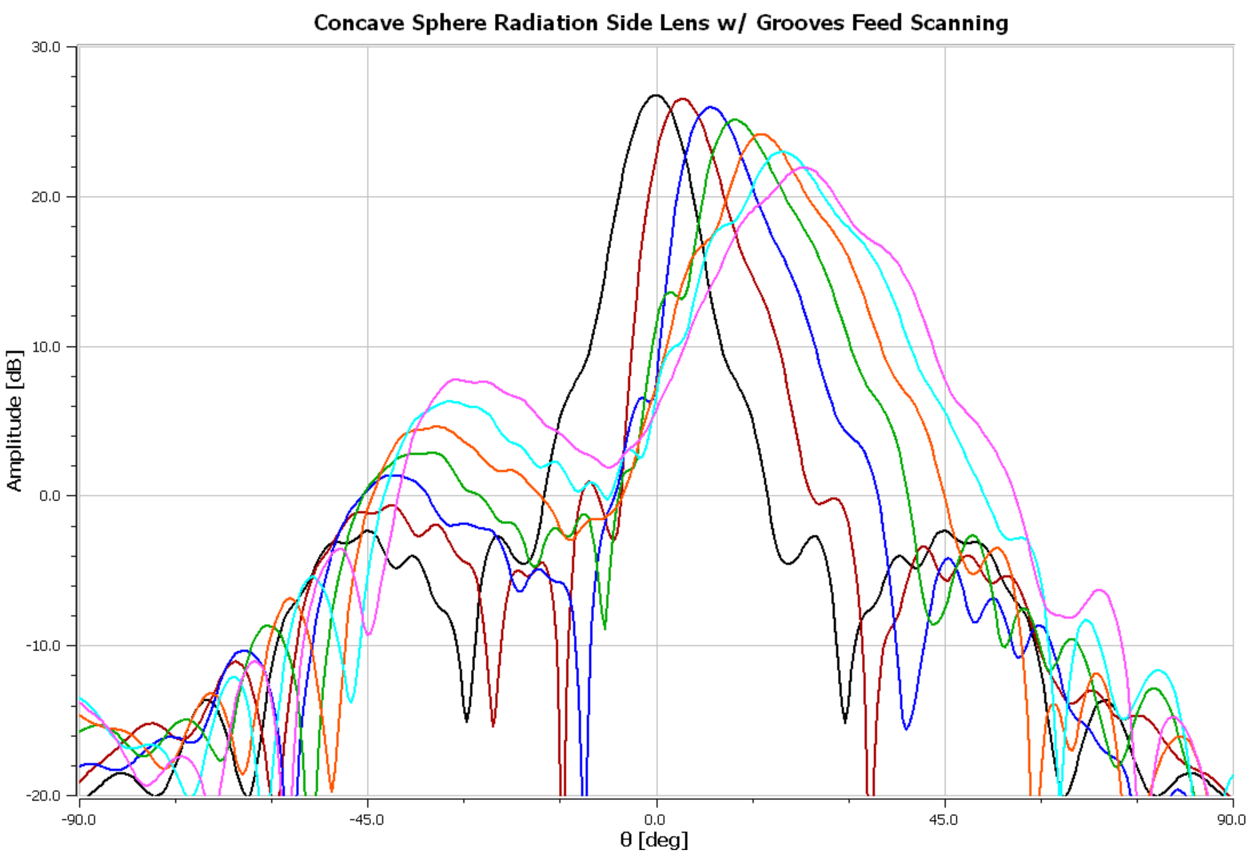


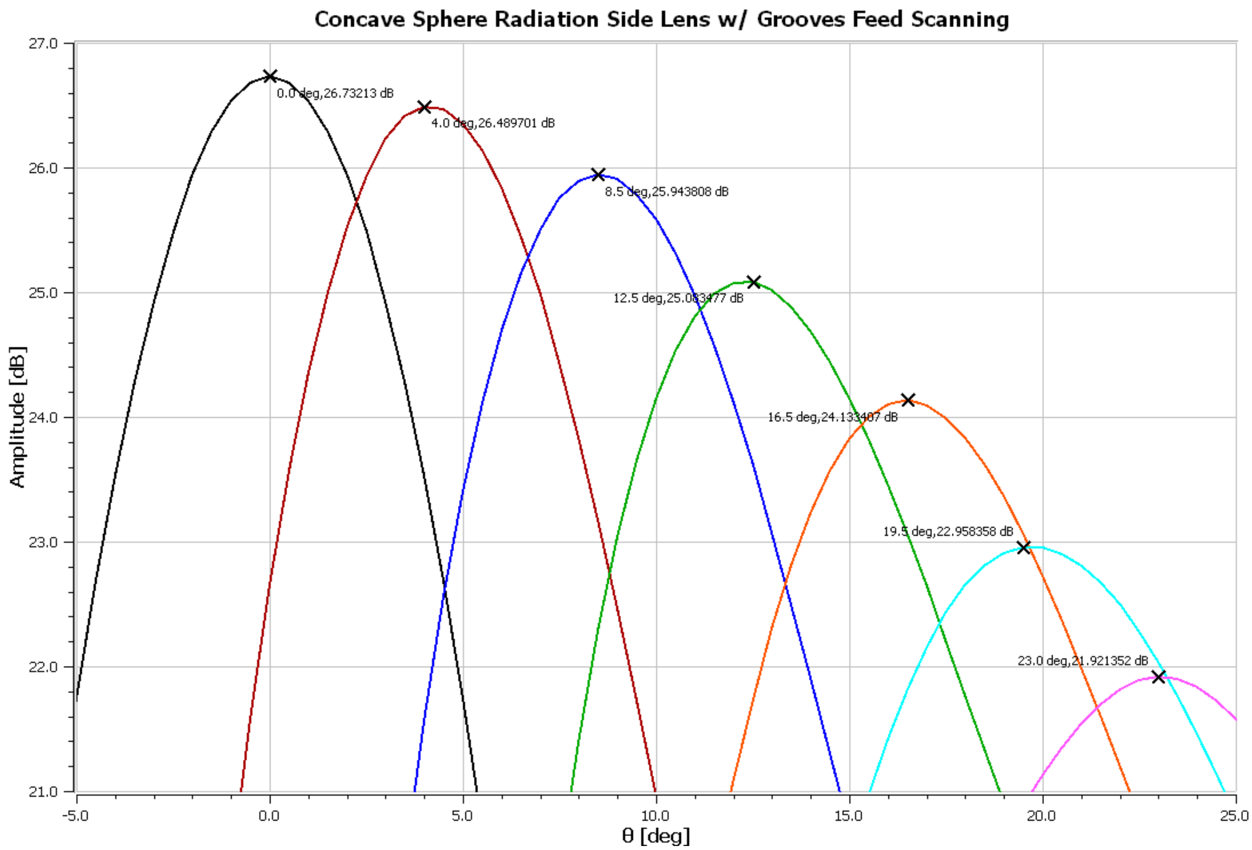

Convex Sphere Radiation Side Lens Smooth Surfaces Feed Scanning
Amplitude [dB]
θ [deg]


Convex Sphere Radiation Side Lens Smooth Surfaces Feed Scanning
Amplitude [dB]
θ [deg]
0.0 deg,28.667404 dB
3.5 deg,28.590625 dB
6.5 deg,28.403623 dB
10.0 deg,28.081436 dB
13.5 deg,27.585442 dB
17.0 deg,26.961092 dB
20.5 deg,26.121466 dB

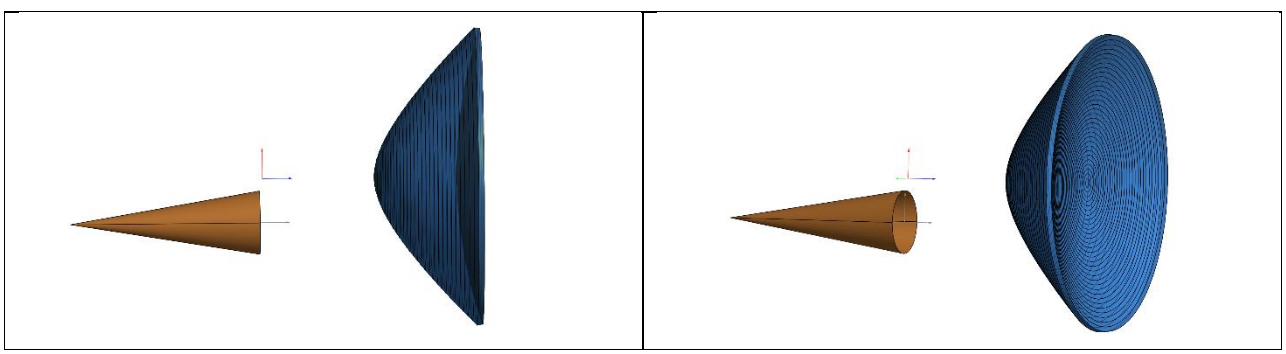
Concave Sphere Radiation Side Lens with Grooved Surfaces #15

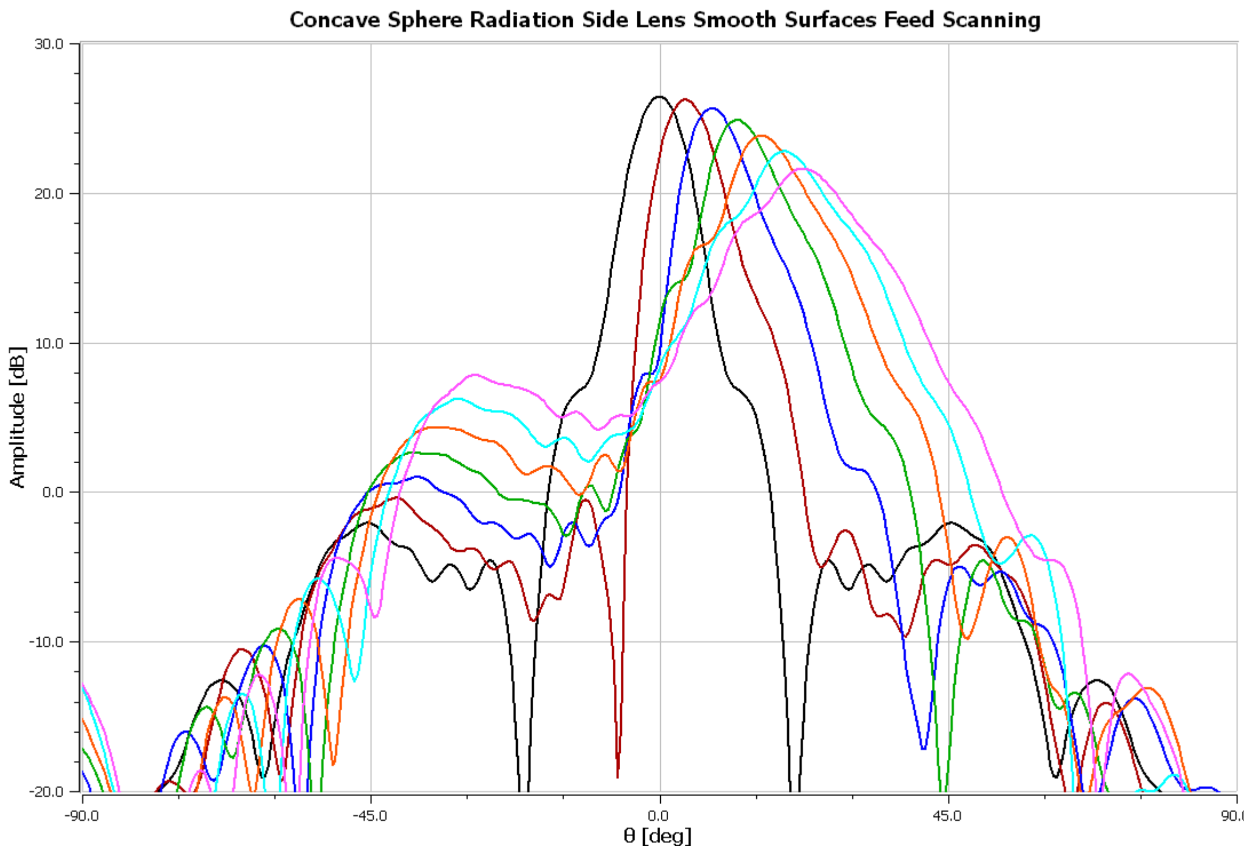


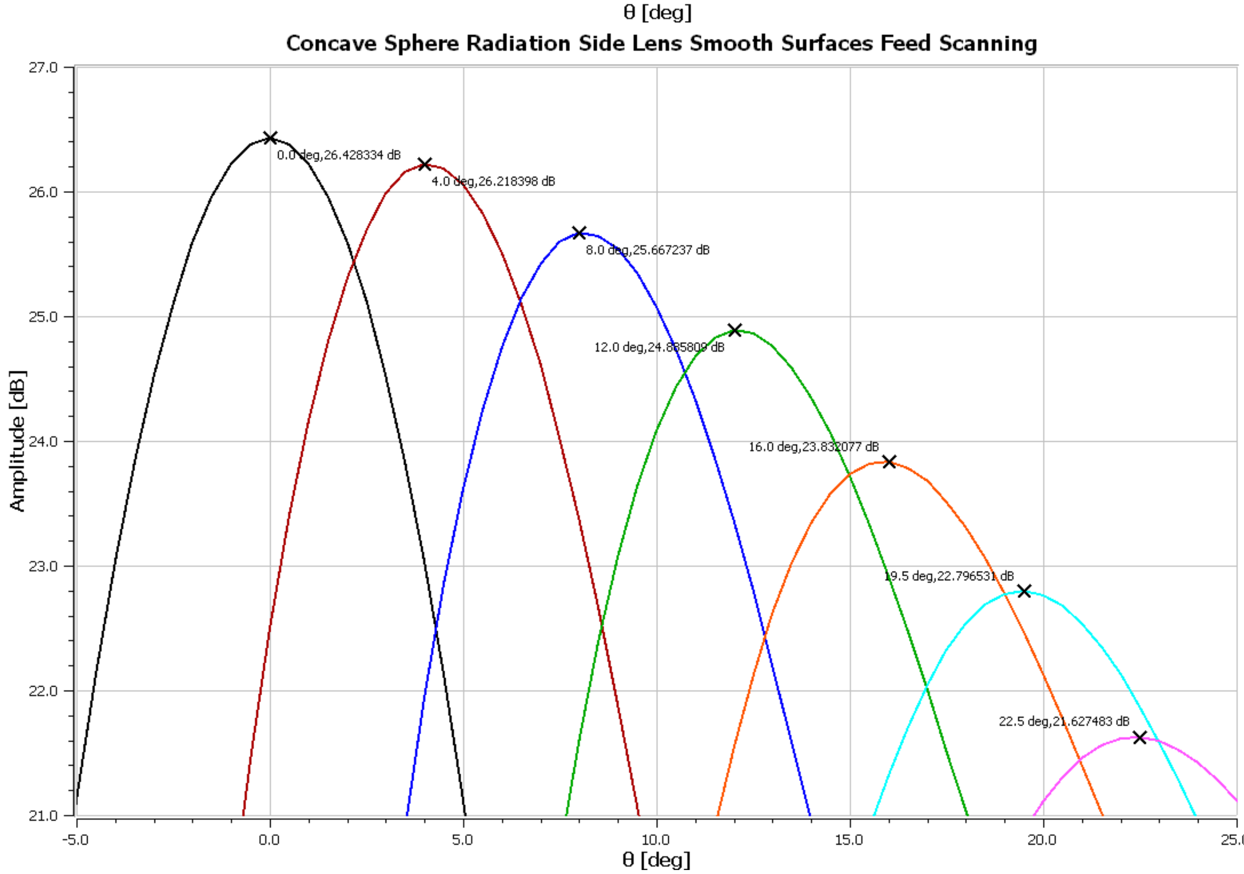




Concave Sphere Radiation Side Lens with Smooth Surfaces #16

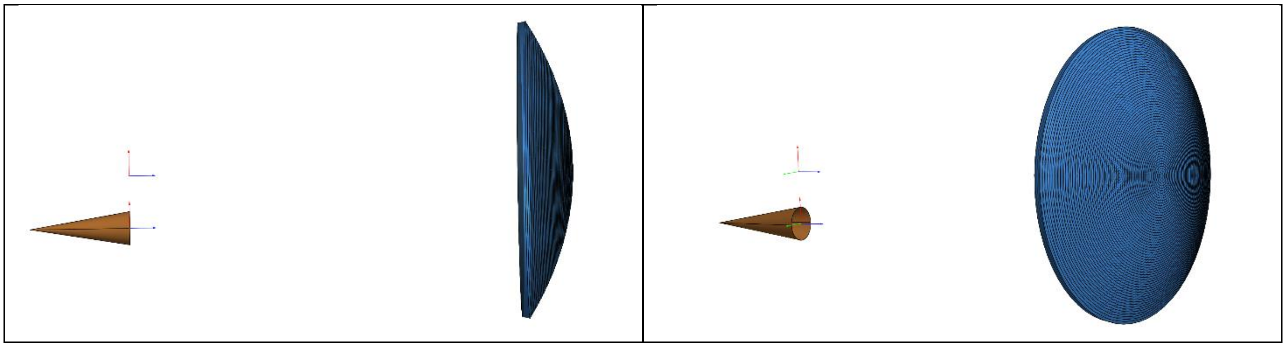



Concave Sphere Radiation Side Lens Smooth Surfaces Feed Scanning
Amplitude [dB]
θ [deg]

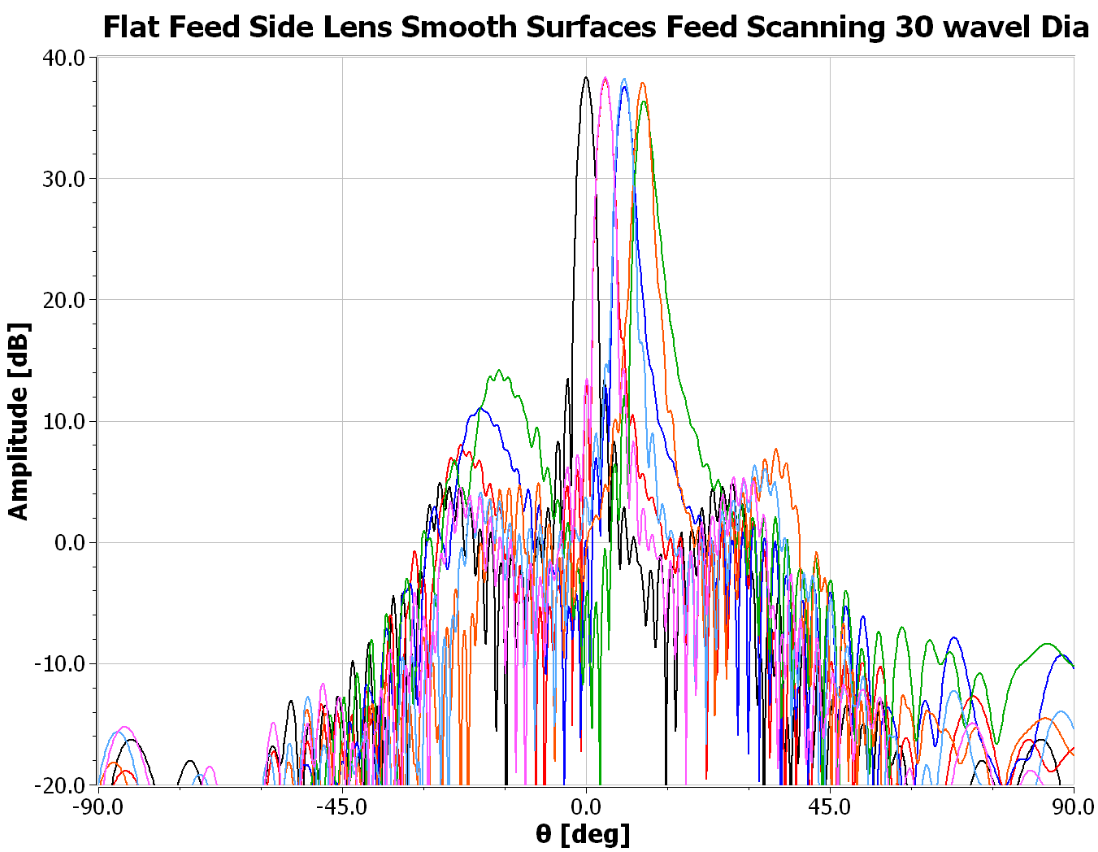

Concave Sphere Radiation Side Lens Smooth Surfaces Feed Scanning
Amplitude [dB]
θ [deg]
0.0 deg,26.428334 dB
4.0 deg,26.218398 dB
8.0 deg,25.667237 dB
12.0 deg,24.885809 dB
16.0 deg,23.832077 dB
19.5 deg,22.796531 dB
22.5 deg,21.627483 dB

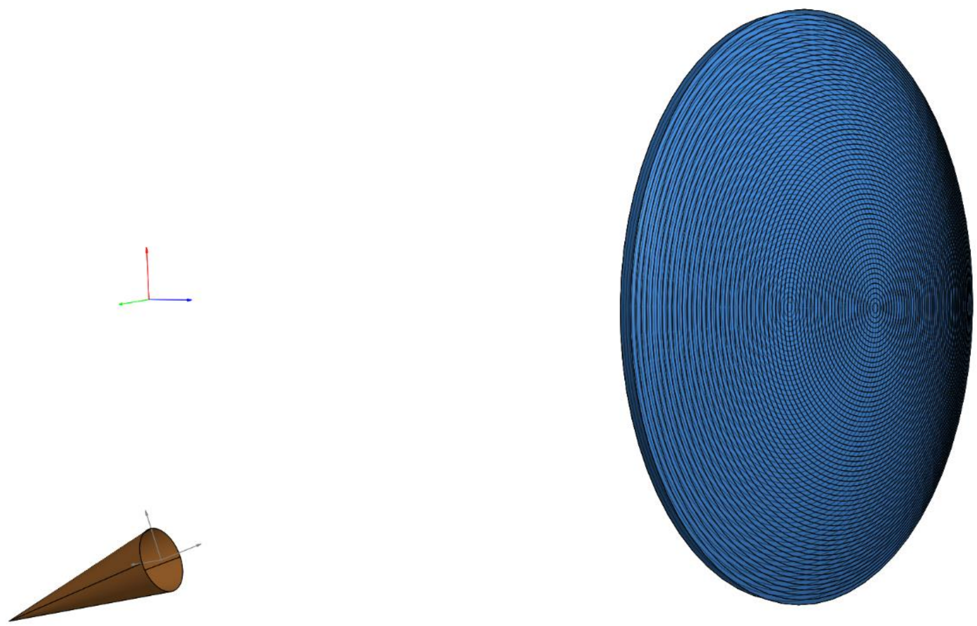
30 wavelength Diameter Lens Results

Ten wavelength diameter lens results fail to illustrate practical designs. The feed horn aperture is significant compared to the lens diameter. The flat feed side surface lens was selected because it approximately matches coma corrected lens geometry (Figure 9-10). This case uses a 900 mm diameter lens and a focal length (to flat surface) 1200 mm and operates at 10 GHz (~30λ).

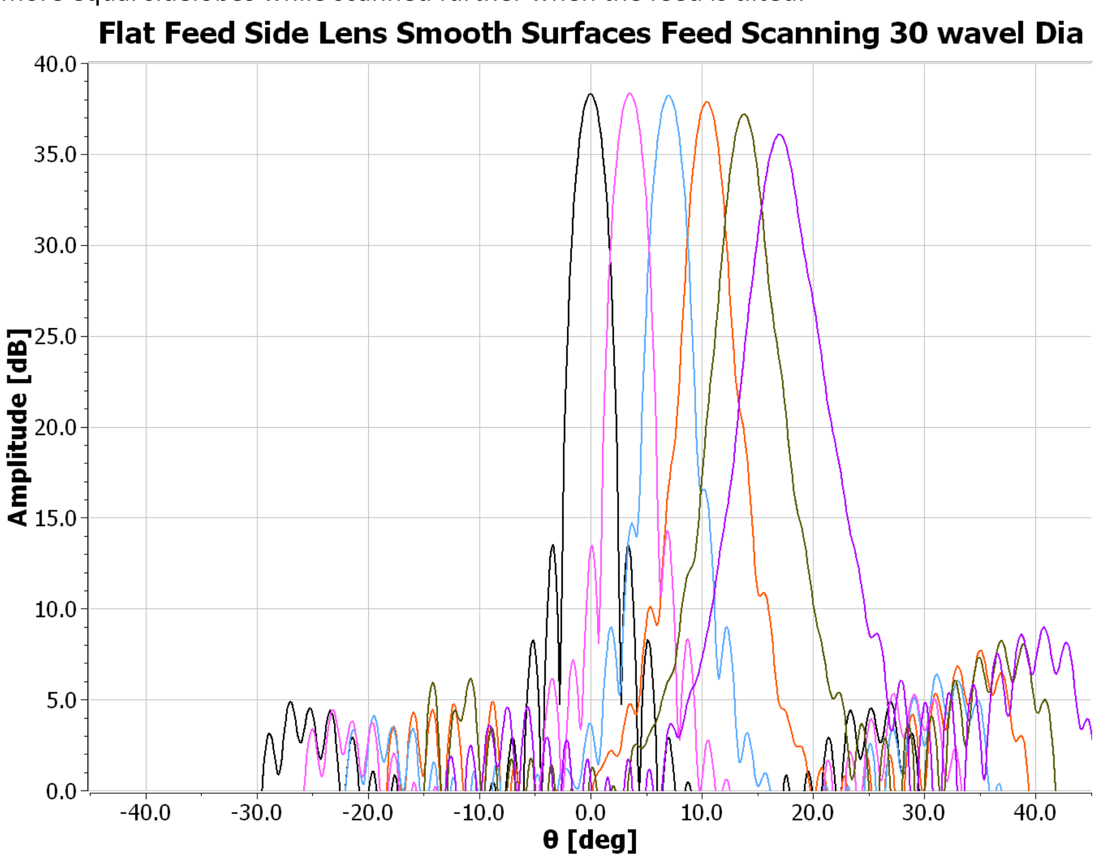


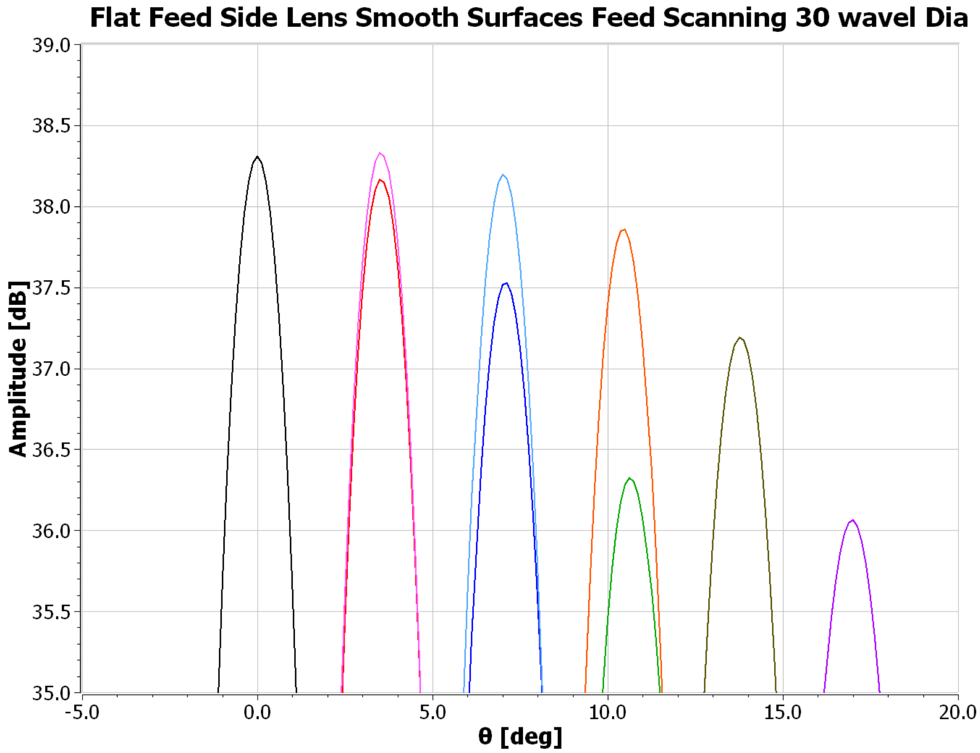
We offset the feed to scan the beam. The lens has good patterns when the feed is moved toward the rim of the lens, but it increasingly the feed pattern spills over the edge of the lens reducing gain and increases the spillover lobe. The pattern below shows the uneven sidelobes in the plane of scan. Included are patterns where the feed has been tilted to point to the center of the lens.



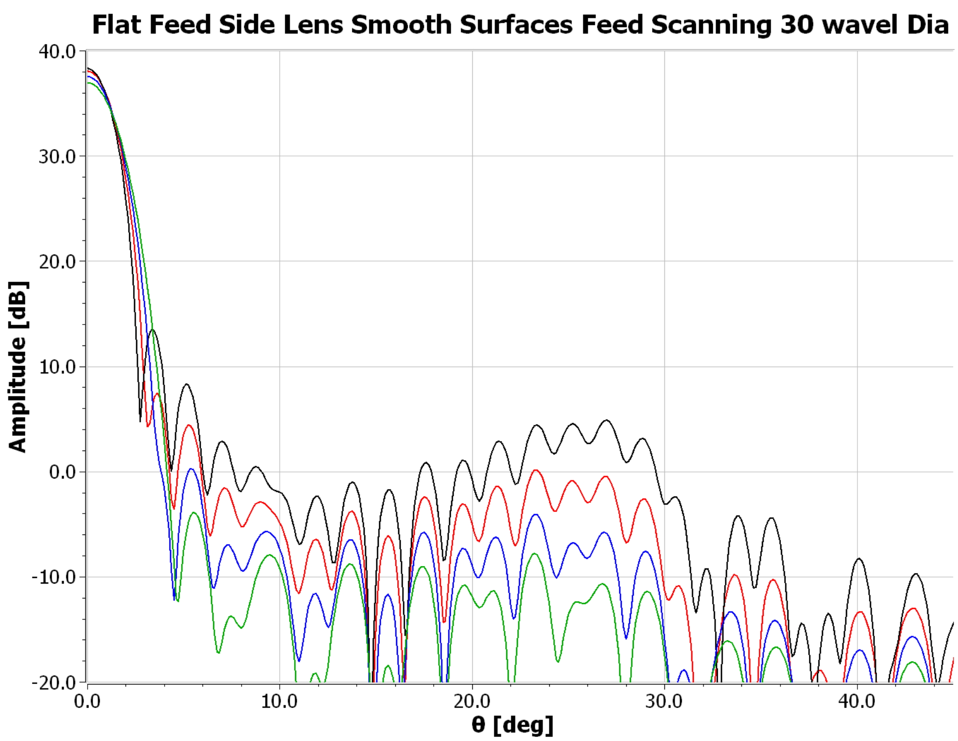


Feed has been tilted to point it to the lens center. If not tilted, significant power radiates beyond the rim. As the feed is moved further and further from the center axis, its tilt is increased. The patterns have more equal sidelobes while scanned further when the feed is tilted.



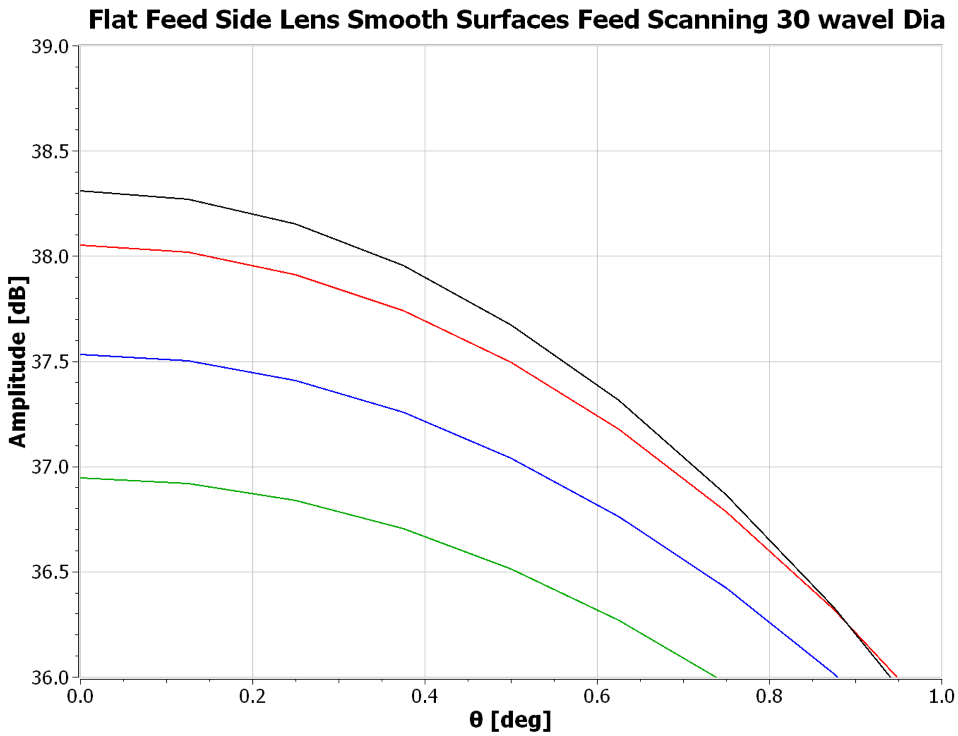


The upper peaks occur when the feed is tilted to the lens center. For 8.5 beamwidths of scan (400 mm feed offset on 450 mm radius) the gain drops about 2.2 dB and the previous plot shows little coma in the sidelobes. We can decrease the sidelobes by narrowing the feed beamwidth (increasing edge taper).



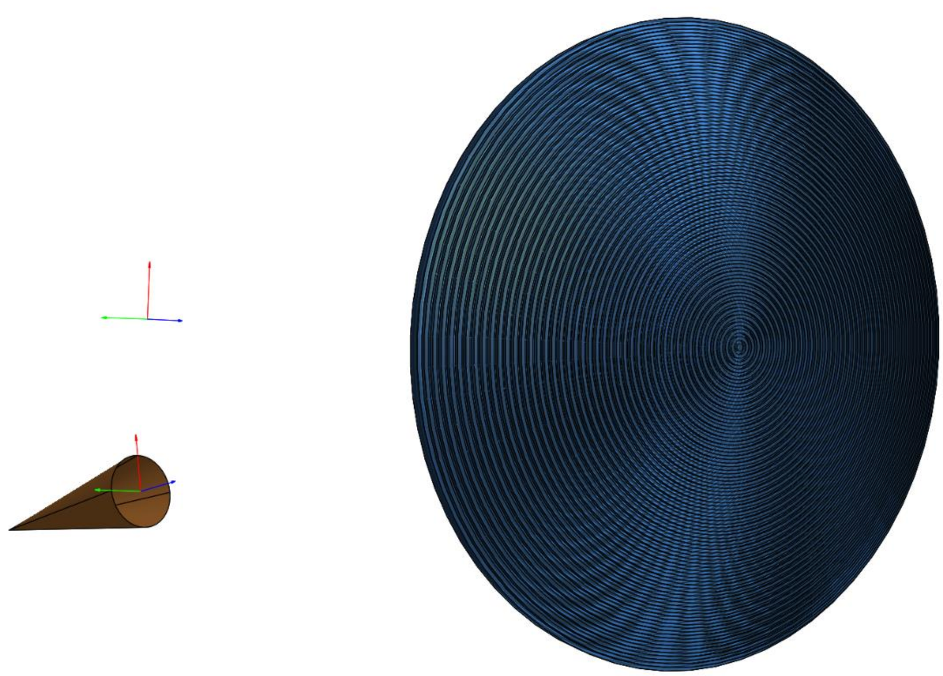
Feed beam edge tapers: 10- (black), 15-(red), 20-(blue), and 25-dB (green)

The gain drops a little at the feed antenna narrows its beam.



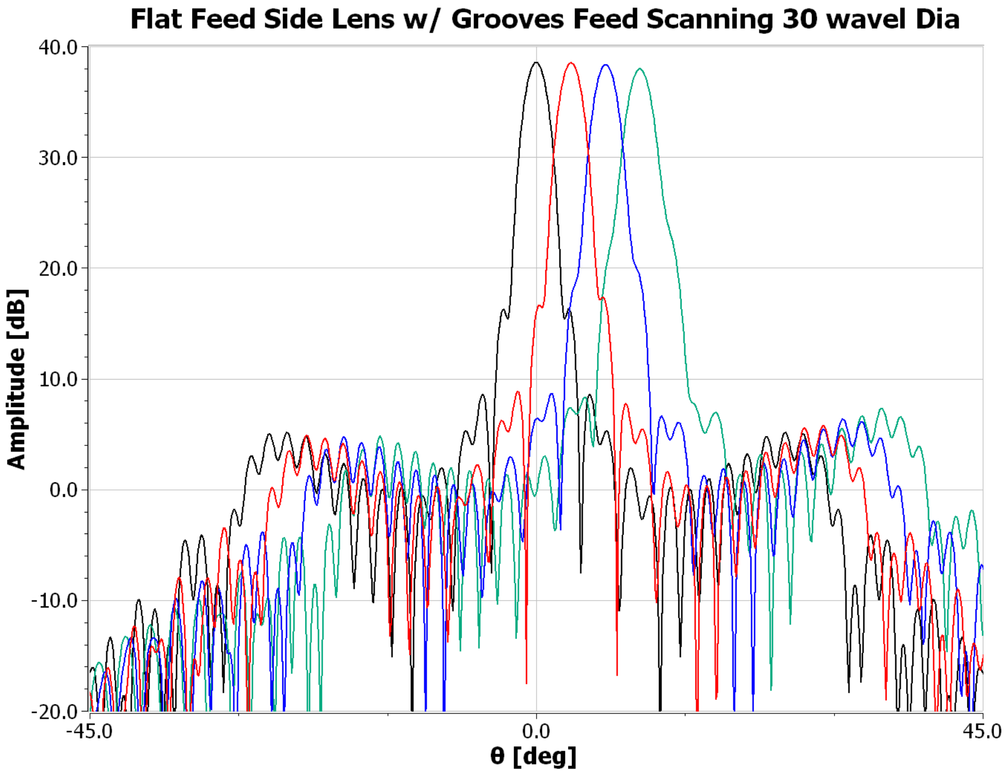
Feed beam edge tapers: 10- (black), 15-(red), 20-(blue), and 25-dB (green)

Adding surface matching ridges to the lens increases gain a little and shows similar results.

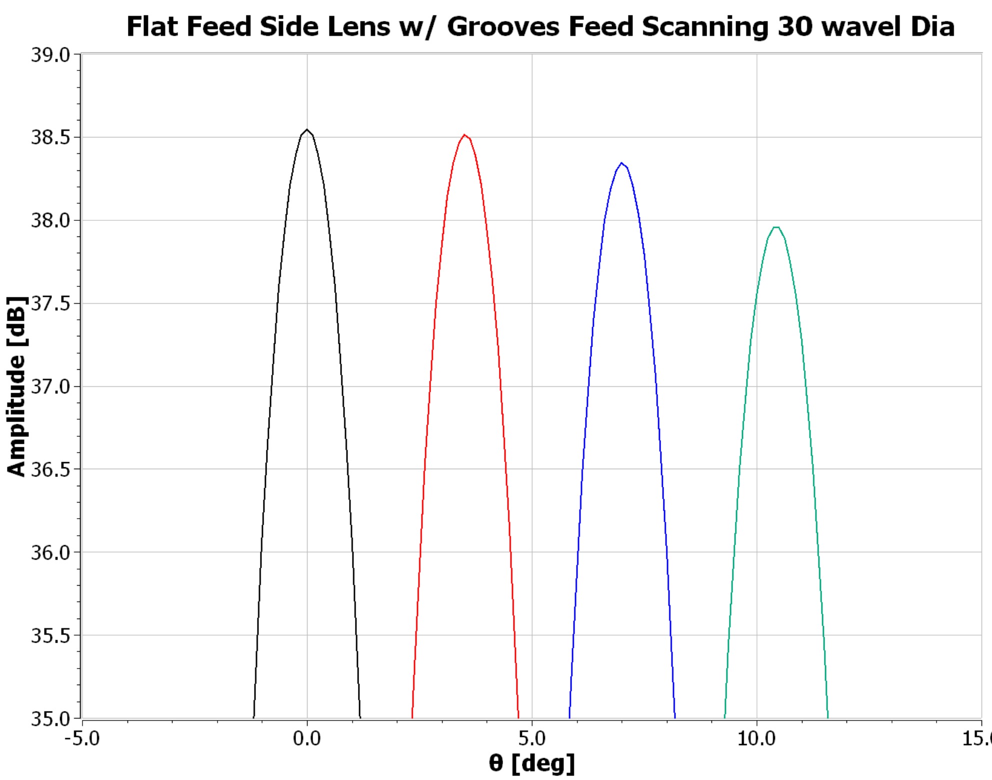


Ridged Flat Feed Side Lens with Tilted Offset Feed

Adding ridges increased GRASP runtimes, but the results are similar to the smooth surfaces lens.

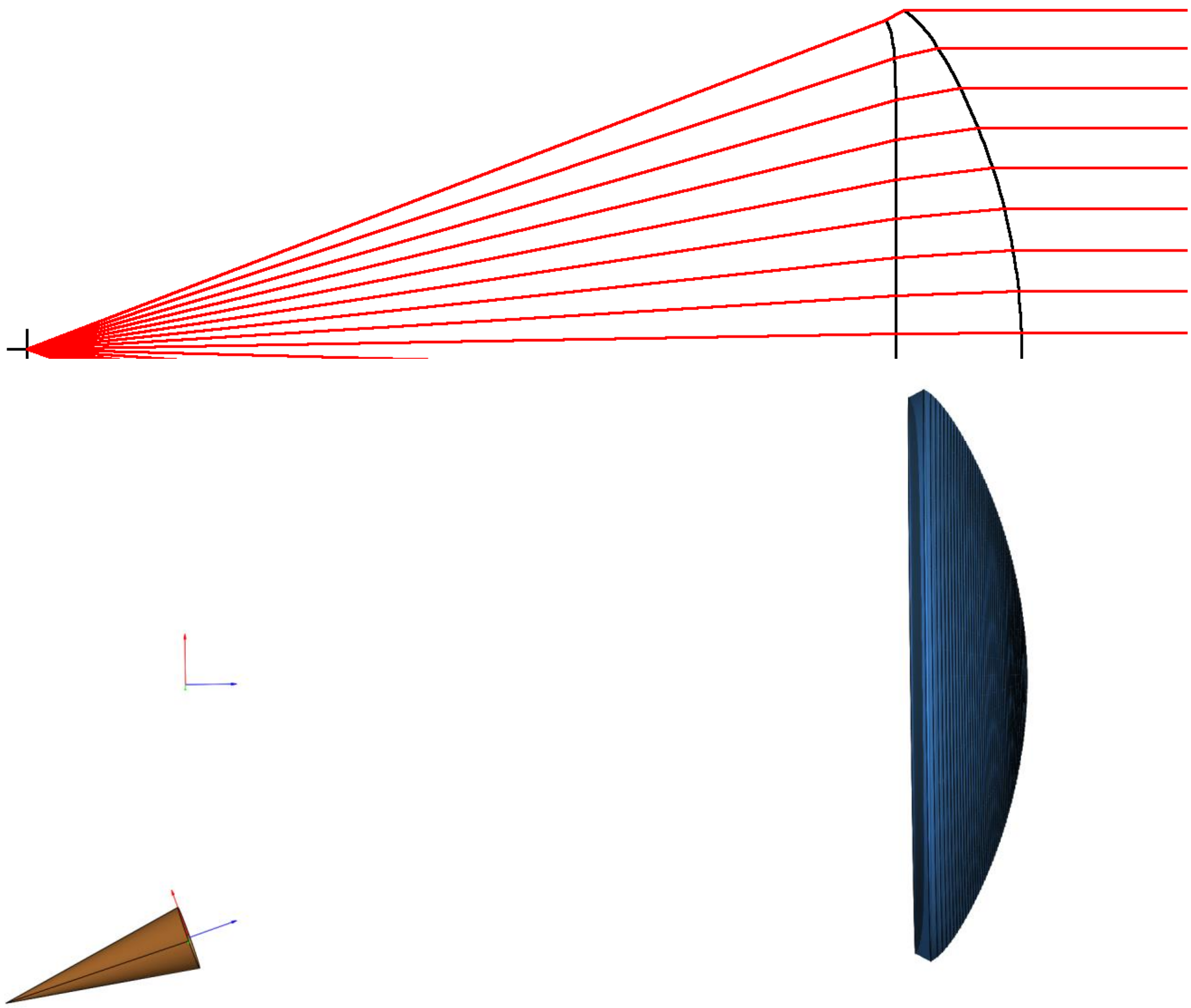


Feed Tilted to Point at Center of Lens



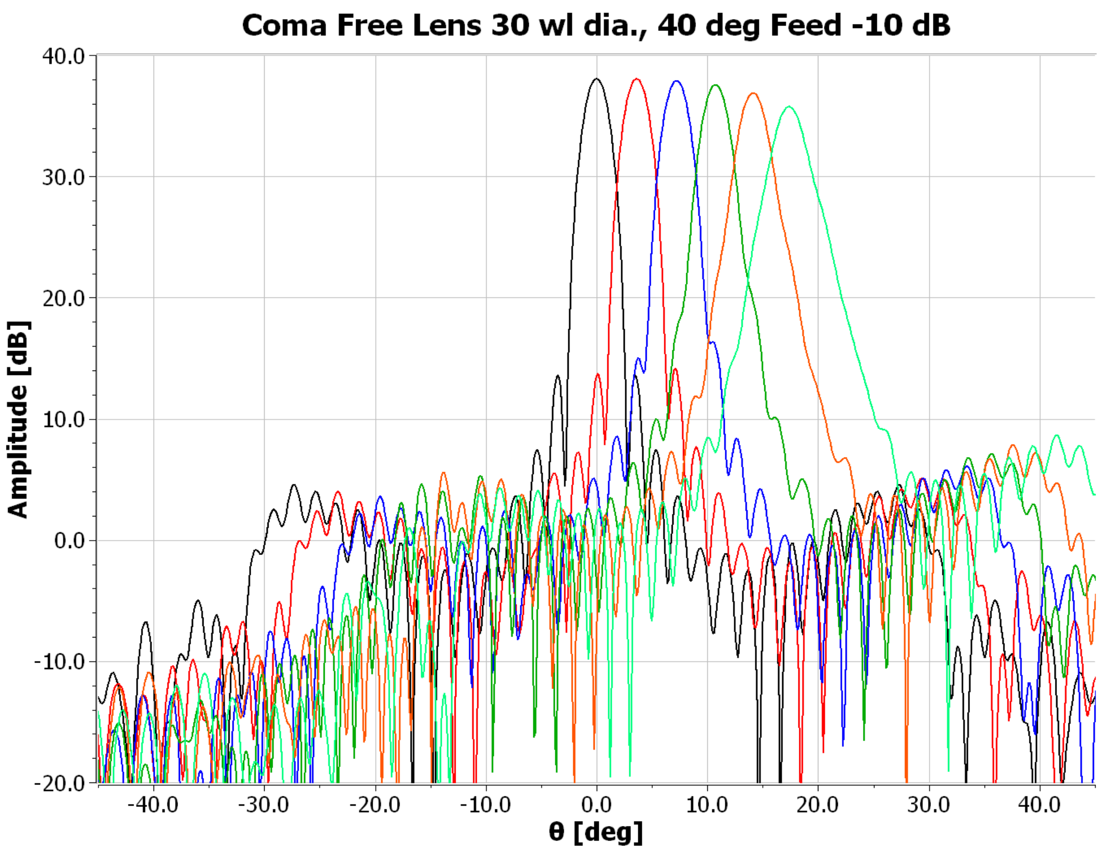
Coma Free 30λ Diameter Lens using Tilted Feed Scanning

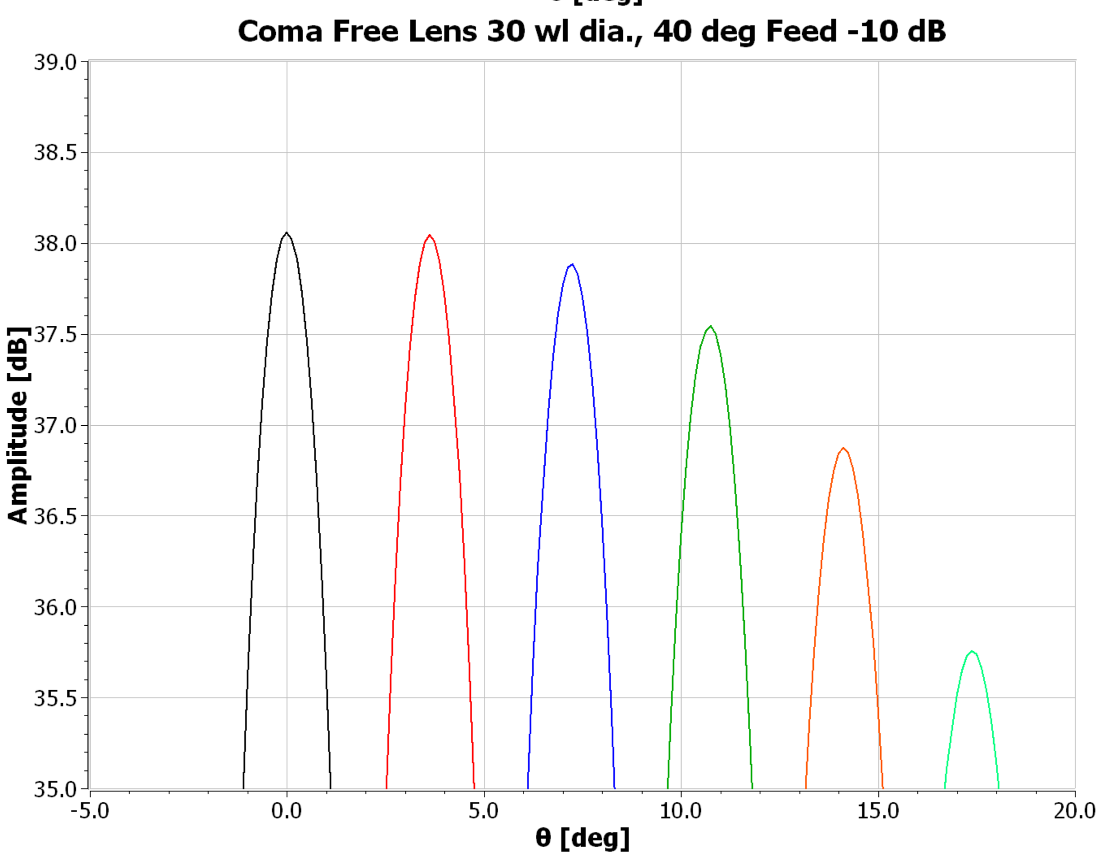
The coma free lens of Figure 9-10 was scaled to 900 mm diameter with 1157 mm focal length. The subtended angle at the feed is ~42°. A 40° 10-dB beamwidth feed is used to excite the lens. We tilt the feed when moved off-axis to point its beampeak at the center of the lens.



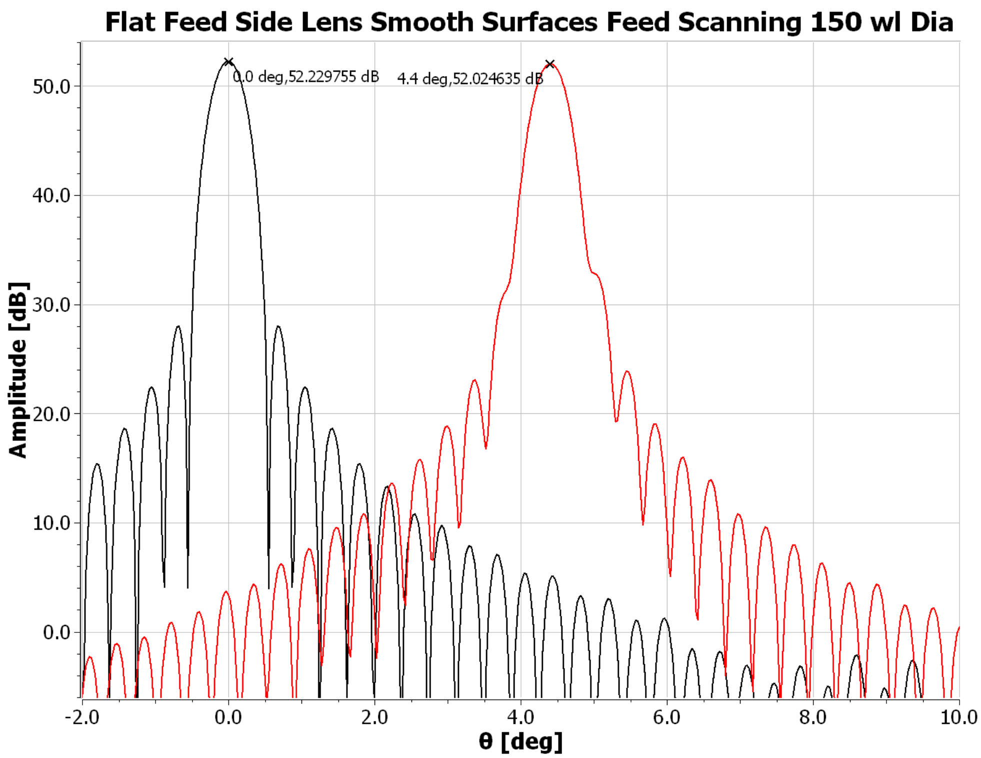
Offset Feed is rotated to point to center of lens

At 10 GHz the feed horn is approximately 80 mm. We move the feed off-axis in 80 mm steps: 80, 160, 240, 320, and 400 mm. Since the lens has a radius of 450 mm, we reach a limit at 400 mm. The pattern shows a little unbalance due to the closeness of the lower edge compared to the upper edge. However, the increased the angle to the lower edge relative to the feed center axis compared to the upper edge increases the upper spillover lobe compared to the lower angle lobe. Small adjustments of the pointing would equalize the lobes. The coma free lens design has about 0.2 dB less gain than one designed with a flat feed side. The rate of beam fall off with scan is approximately the same in both lens.

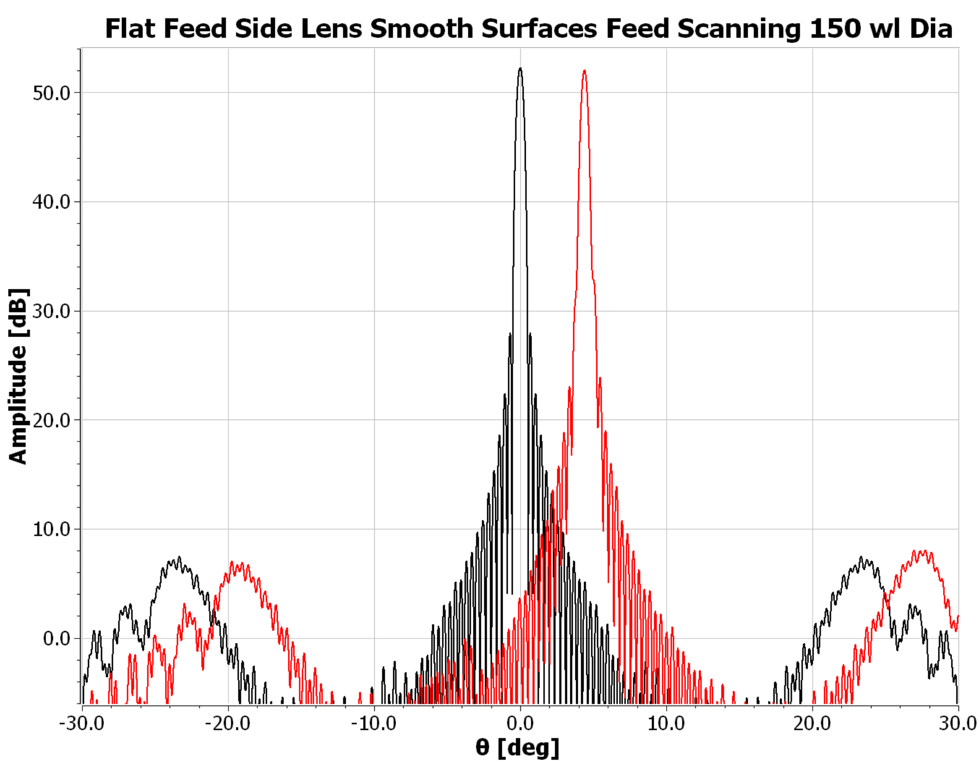

Coma Free Lens 30 wl dia., 40 deg Feed -10 dB
Amplitude [dB]
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-40.0
-30.0
-20.0
-10.0
0.0
10.0
20.0
30.0
40.0
θ [deg]


Coma Free Lens 30 wl dia., 40 deg Feed -10 dB
Amplitude [dB]
39.0
38.5
38.0
37.5
37.0
36.5
36.0
35.5
35.0
-5.0
0.0
5.0
10.0
15.0
20.0
θ [deg]

Feed Scanning of 150λ Diameter Flat Feed Side Lens



10 Beamwidths of Scan has improved coma compared to an equivalent reflector



Circular Taylor Distribution Lens, 40 dB n-bar = 8

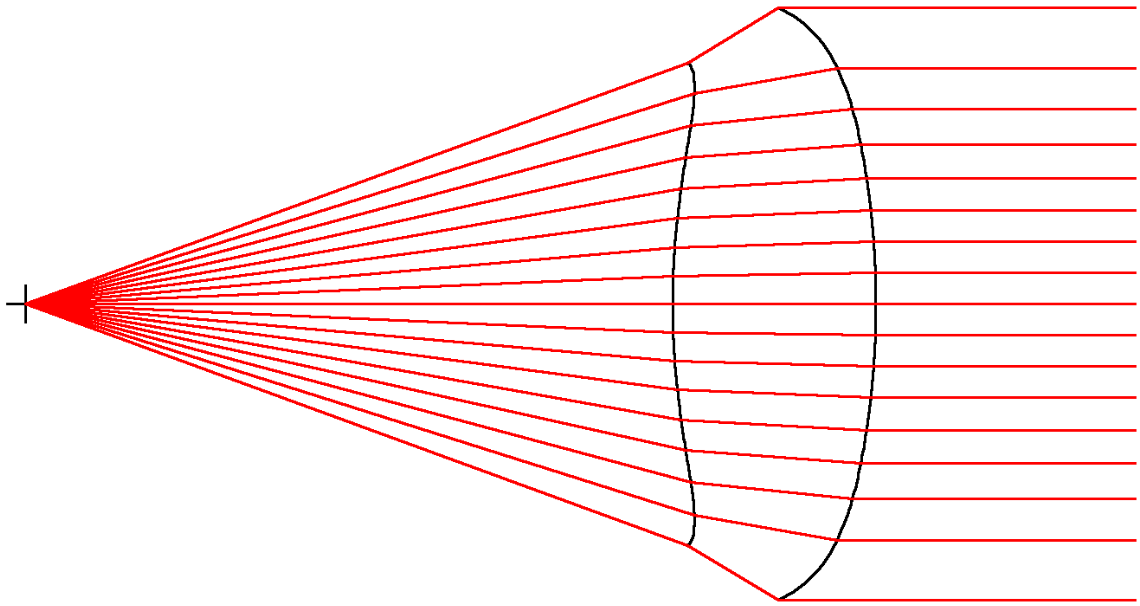
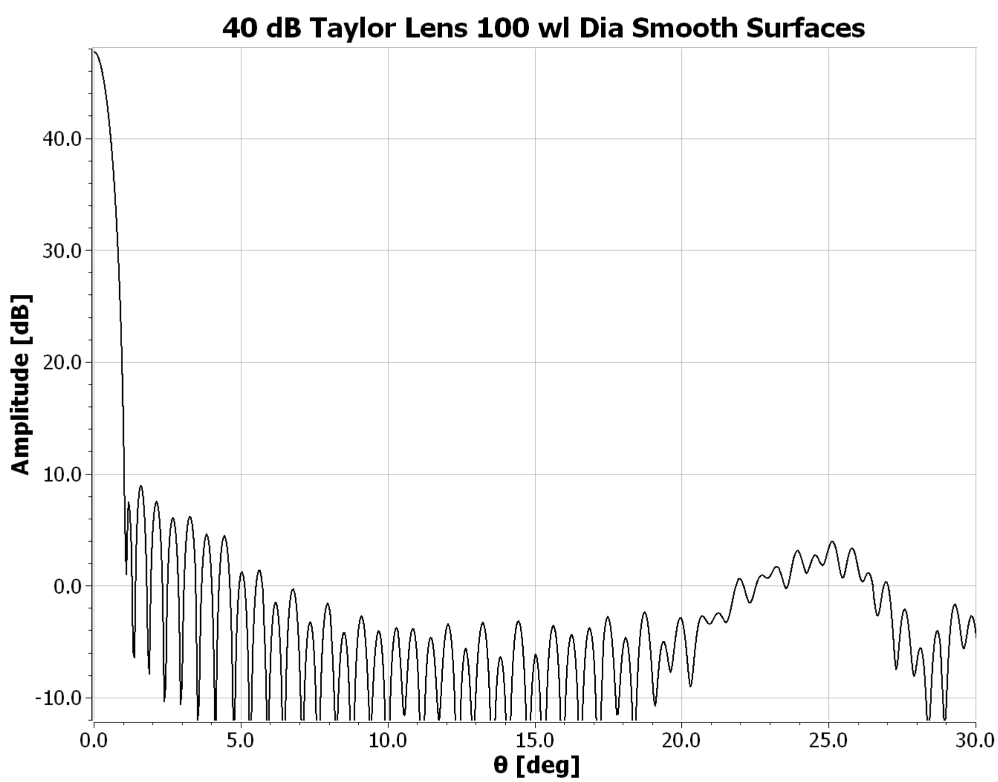
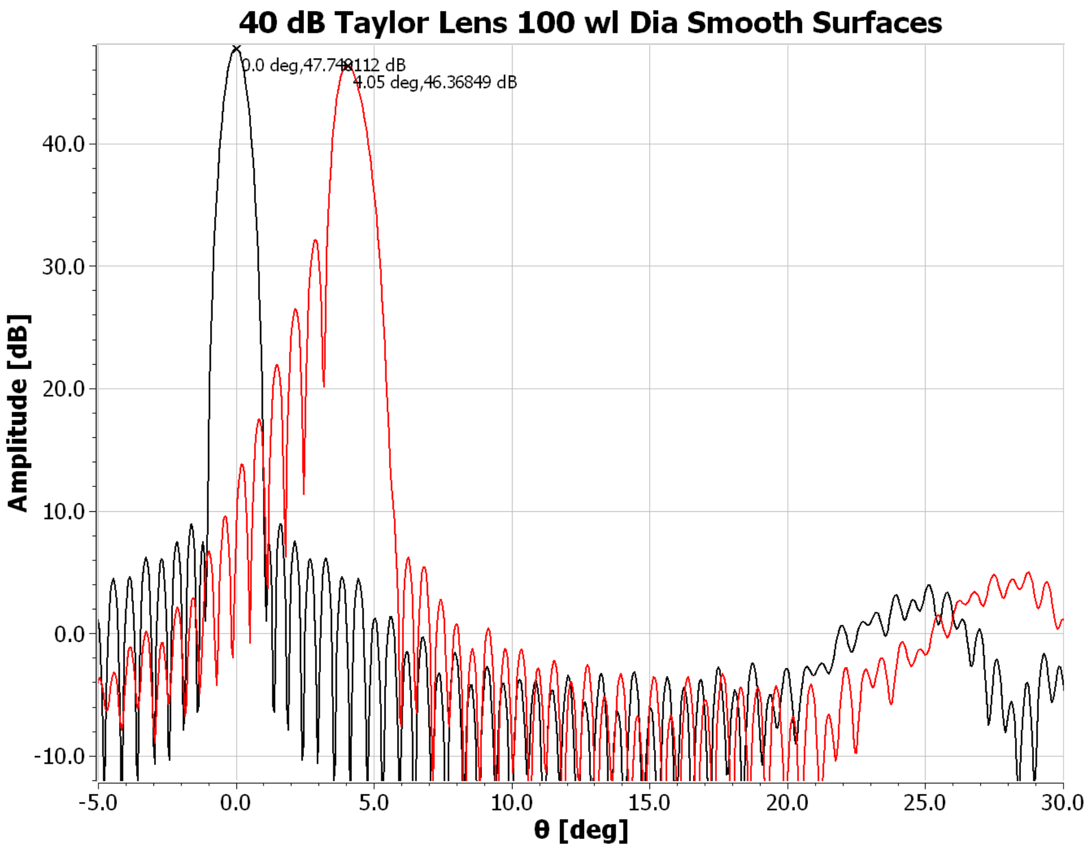


Figure 9-11 Circular Taylor Distribution 40-dB sidelobes ($\overline{n}$ = 8). The initial conditions were n = 1.6, diameter D = 32, focal distance f = 35, central thickness T = 10, and maximum feed angle ψ_m = 20º. Feed 36° 10-dB.



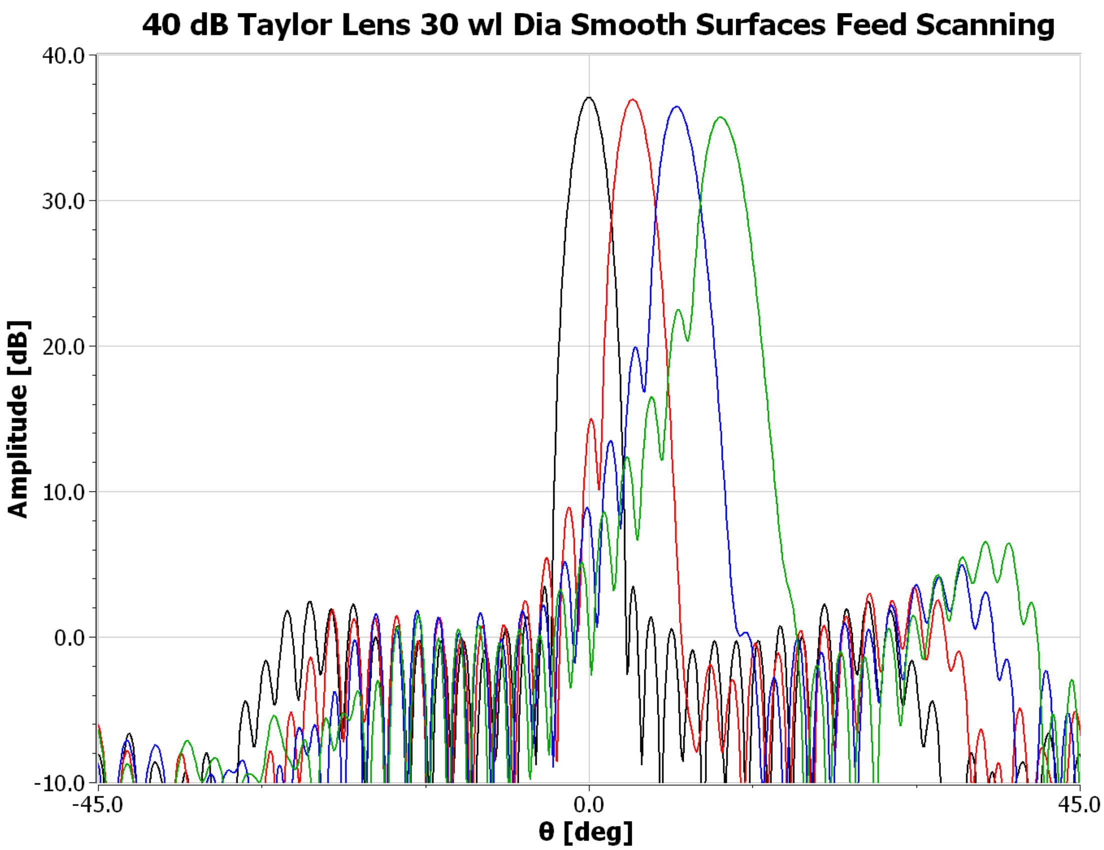
The plot above shows that the sidelobes are 40 dB down when the lens is 100λ in diameter using a Gaussian beam feed with 36° 10-dB beamwidth (the design value). The feed spillover lobe can be seen with its peak near 25° and is lower than 40 dB down because the lens has enough gain to overcome the direct spillovered pattern of the feed. The pattern above includes the efects of interactions between the two surfaces and reflection from the feed surface which produce small variations in the sidelobe peaks.



Feed Scanned Lens: 5.5 beamwidths

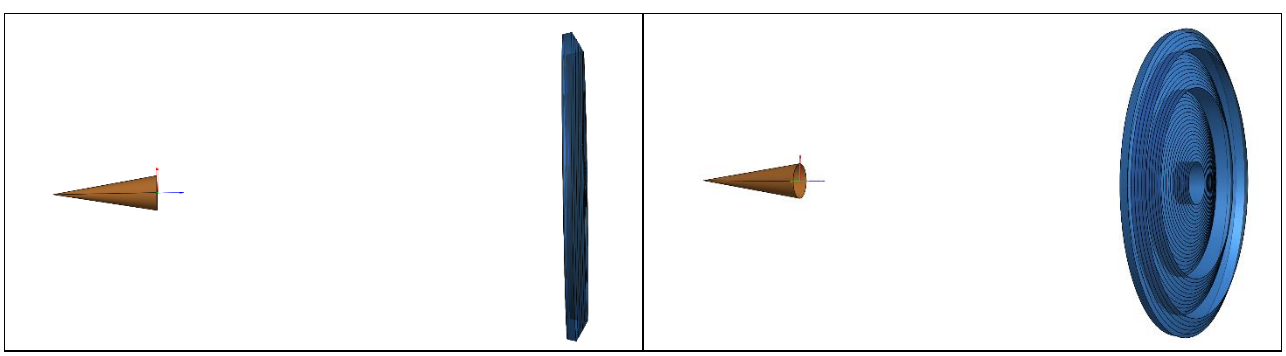
When we feed scan the dual shaped lens with a 40 dB circular Taylor Distribution (above), its pattern degrads rapidly with increasing scan and inner coma lobes form.

A smaller diameter lens, 30λ, fails to meet the design goal of 40 dB sidelobes because the feed spllover raises sidelobes. Like the case above significant coma lobes form and increase with increasing feed scan.

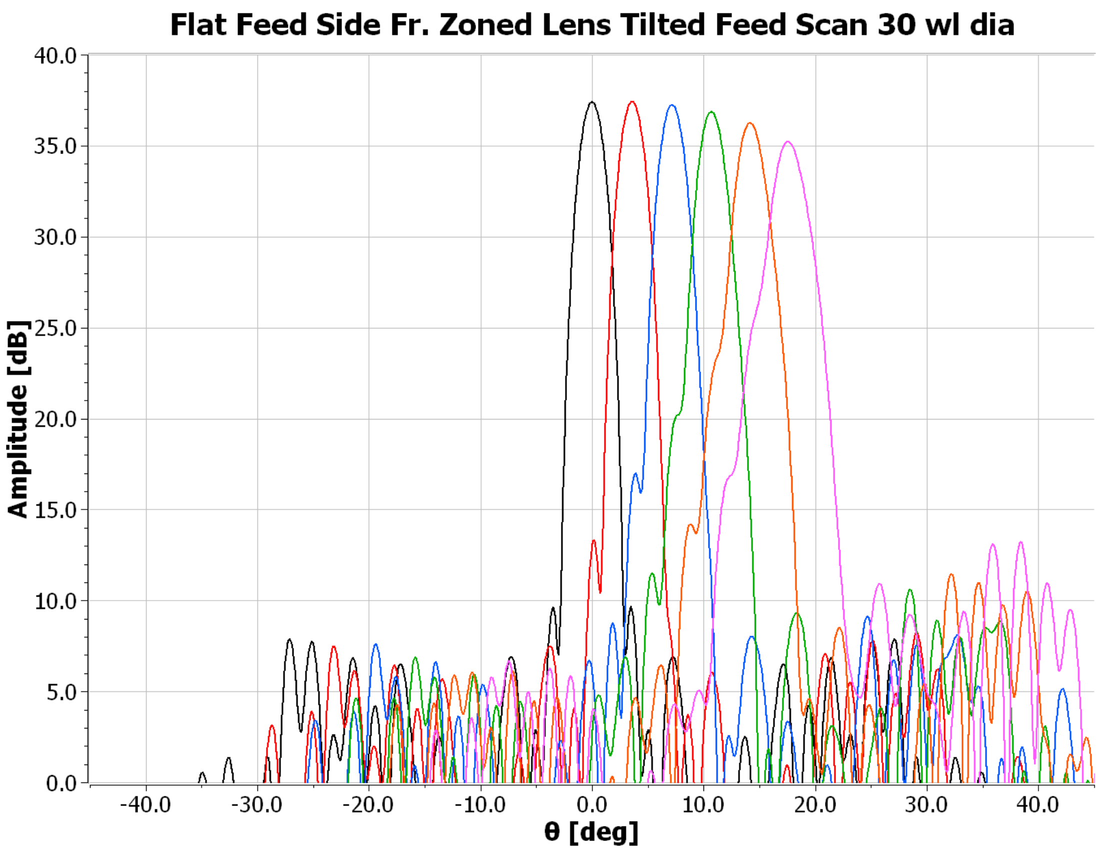


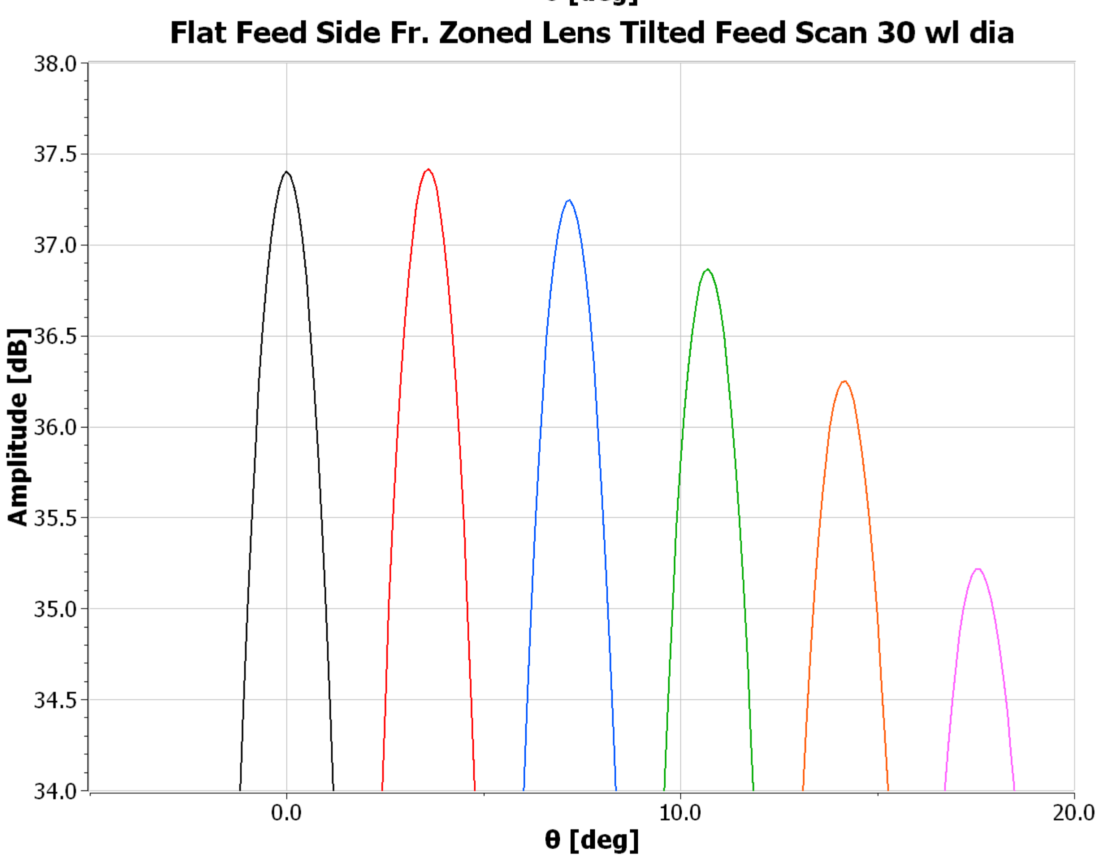
30 wavelength Diameter Zoned Lens using Flat Feed Side Design

The flat feed side lens has feed scan response as good as the coma free lens. By zoning the radiation side its thickness and weight can be greatly reduced. The 30λ diameter lens has 3 zones. The feed has been shifted axially and rotated to point the beam peak to the center of the lens.

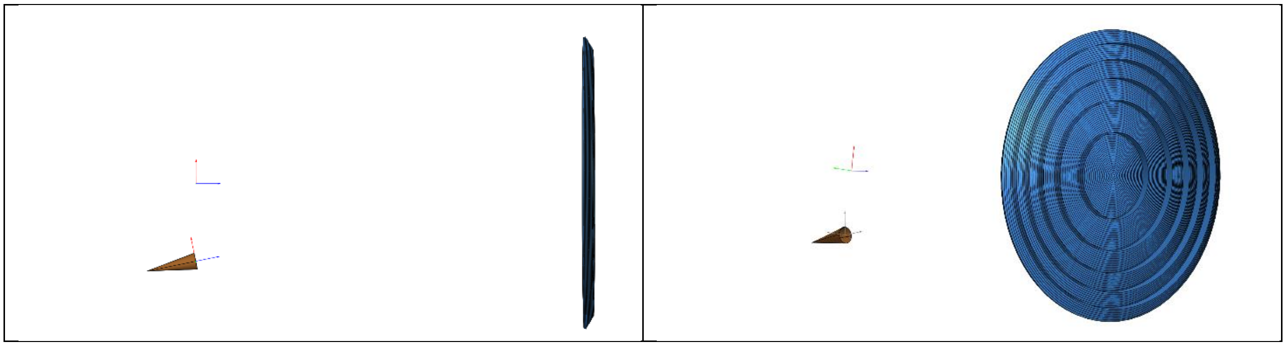


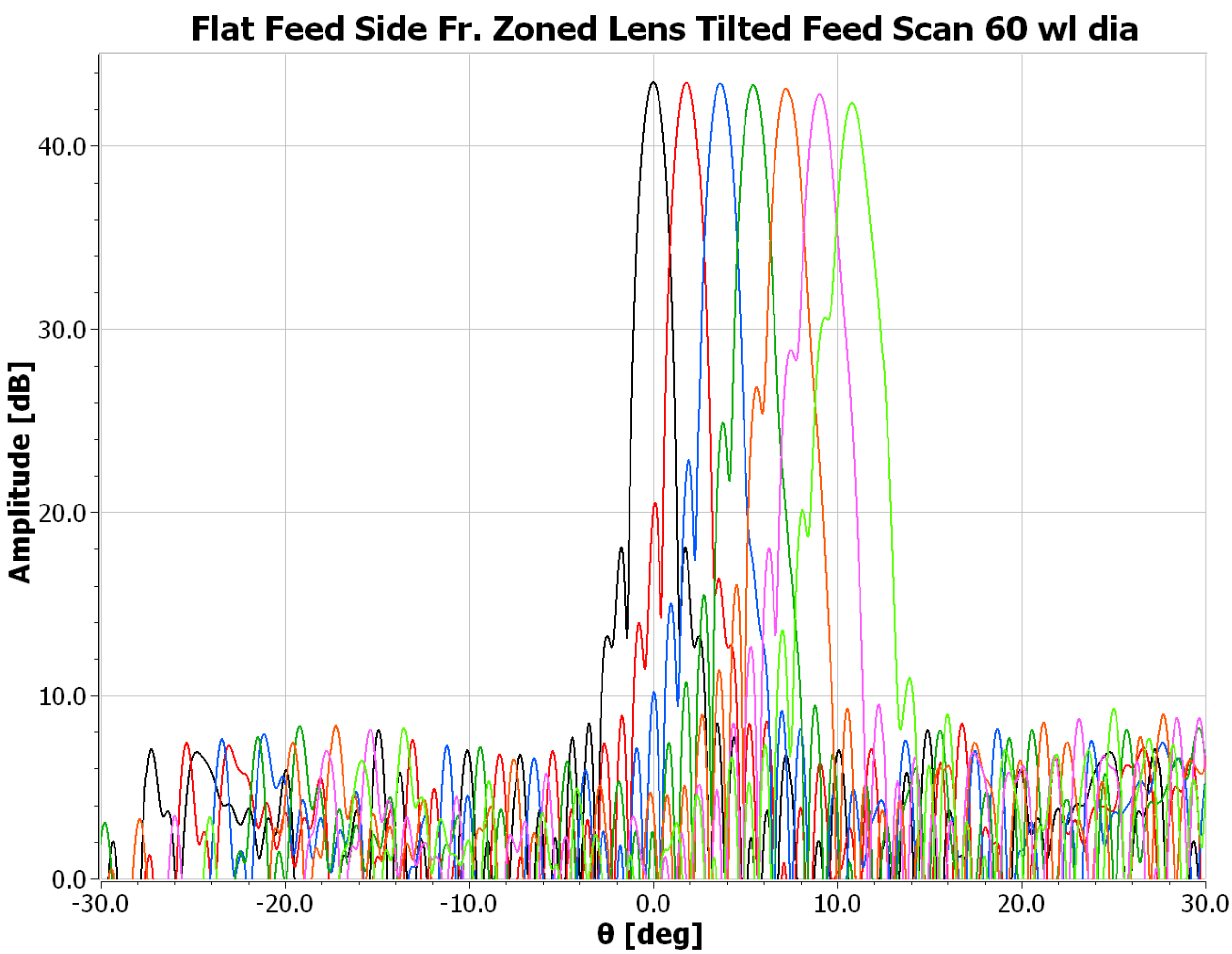
The analysis example has an operation frequency of 10 GHz with a diameter of 900 mm and a center focal distance of 1200 mm. A 40° 10-dB beamwidth gaussian beam feed is used to excite the lens. The feed is offset in 80 mm steps and rotated to reduce spillover. The pattern plots illustrate the excellent results of patterns with low coma for the scanned pattern.


Flat Feed Side Fr. Zoned Lens Tilted Feed Scan 30 wl dia
Amplitude [dB]
θ [deg]
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
-40.0
-30.0
-20.0
-10.0
0.0
10.0
20.0
30.0
40.0

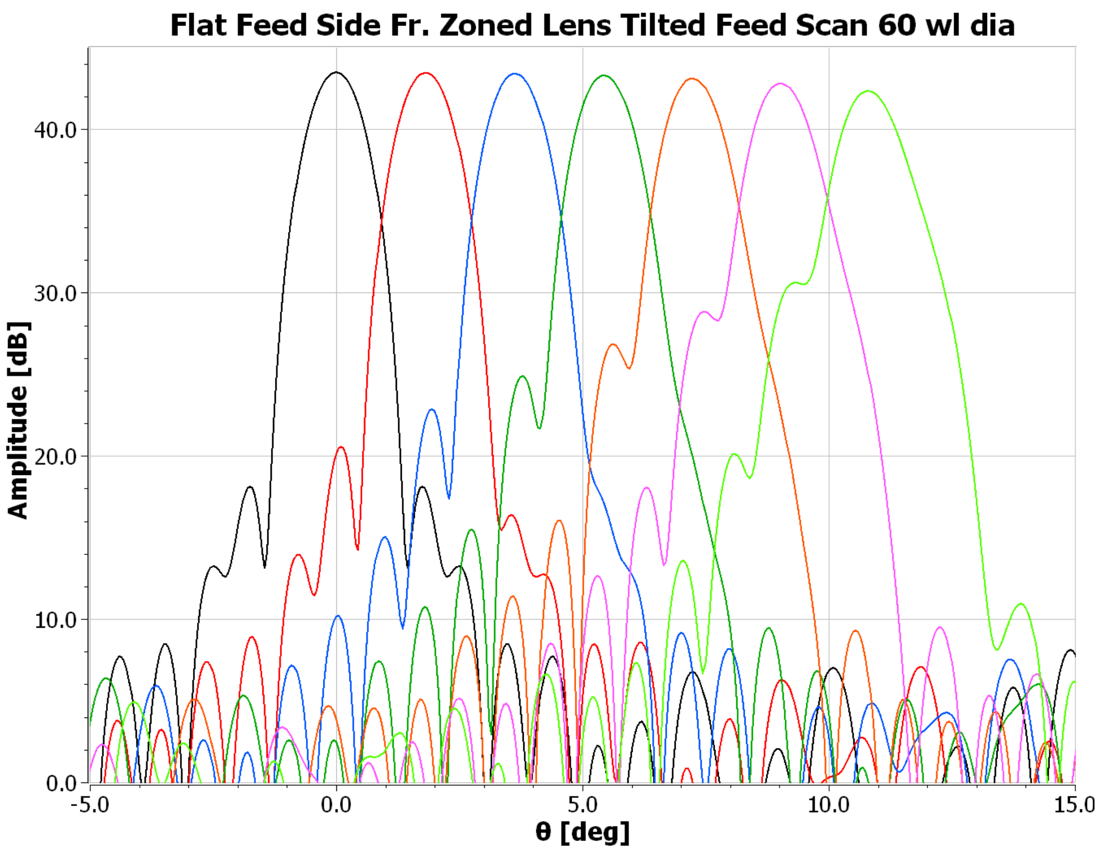

Flat Feed Side Fr. Zoned Lens Tilted Feed Scan 30 wl dia
Amplitude [dB]
θ [deg]
38.0
37.5
37.0
36.5
36.0
35.5
35.0
34.5
34.0
0.0
10.0
20.0

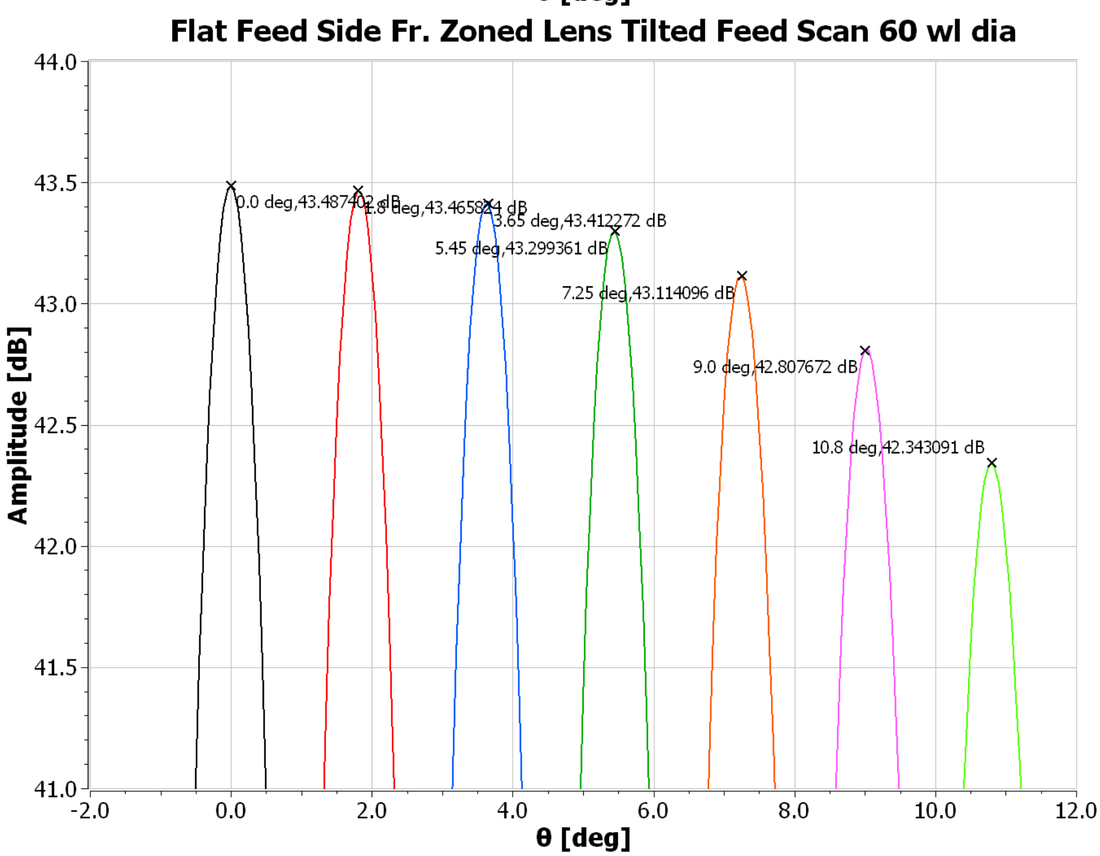
60 wavelength Diameter Zoned Lens using Flat Feed Side Design





This case is the same as the 30λ lens with dimensions doubled. The feed axial offset uses 80 mm steps and the same 40° 10-dB beamwidth feed. The radiation side of the lens has 5 zones.


Flat Feed Side Fr. Zoned Lens Tilted Feed Scan 60 wl dia
Amplitude [dB]
0.0
10.0
20.0
30.0
40.0
-5.0
0.0
5.0
10.0
15.0
θ [deg]


Flat Feed Side Fr. Zoned Lens Tilted Feed Scan 60 wl dia
Amplitude [dB]
41.0
41.5
42.0
42.5
43.0
43.5
44.0
0.0 deg,43.487402 dB
1.8 deg,43.465824 dB
3.65 deg,43.412272 dB
5.45 deg,43.299361 dB
7.25 deg,43.114096 dB
9.0 deg,42.807672 dB
10.8 deg,42.343091 dB
-2.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
θ [deg]