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**TDRS MA PHASED-ARRAY
ANTENNA SIMULATIONS**

**Ruben Caballero
Dr. Stephen Horan**

NMSU-ECE-95-013 May 1995

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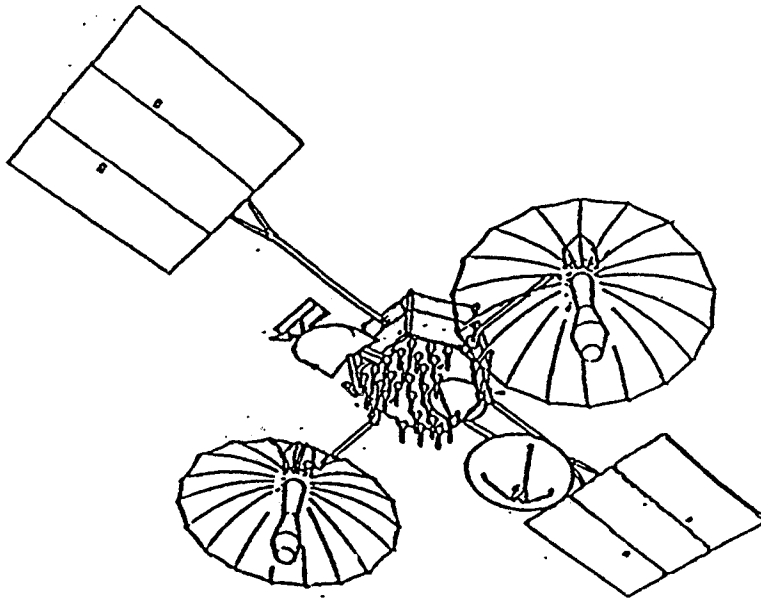
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TDRS
MA PHASED-ARRAY ANTENNA
SIMULATIONS
(part of the DAMA proposal)



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TABLE OF CONTENT

- Abbreviations.....	p. 3/22
- List of Figures.....	p. 4/22
- List of Tables.....	p. 5/22
- Background.....	p. 6/22
- Introduction.....	p. 7/22
- Theory.....	p. 8/22
- TDRS User Geometry.....	p. 8/22
- TDRS Array Antenna.....	p. 9/22
- Simulation of the MA Antenna.....	p.16/22
- Conclusion.....	p.21/22
- Recommendations.....	p.21/22
- References.....	p.22/22
- Appendix A - Program	p.A-1/5
- Appendix B - Matlab Pattern Simulations.....	p.B-1/24

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ABBREVIATIONS

DAMA	Demand Assignment Multiple Access
FOV	Field Of View
MA	Multiple-Access
NASA	National Aeronautics and Space Administration
NMSU	New Mexico State University
SMA	S-band Multiple Access
SN	Space Network
TDRS	Tracking and Data Relay Satellite
WSC	White Sands Complex
WSGT	White Sands Ground Terminal
WSMR	White Sands Missile Range

LIST OF FIGURES

- Figure 1 - Current and Proposed MA Coverage for DAMA Request
- Figure 2 - TDRS-User Range
- Figure 3 - ϕ and θ Angles Representation
- Figure 4 - TDRS with MA Antenna
- Figure 5 - Coordinate System of the MA Elements on the Antenna
- Figure 6 - Antenna Element Pattern
- Figure 7 - Helical Element Parameters

LIST OF TABLES

Table I. Coordinates of the MA Elements

Table II. Summary of the Simulations

BACKGROUND

Currently, the NASA's Space Network (SN) nominal user services are pre-scheduled to allocate service type and required equipment to a user of the network. The availability of a resource for a given user is then communicated back to the user prior to the requested service time. The current system does not easily allow a real time changes to add new users to the service schedule. Therefore a proposed Demand Assignment Multiple Access (DAMA) system for NASA's SN to improve the existing SN usage mode is underway at New Mexico State University (NMSU).

The goals of this project are to improve the current operational modes by

- (a) - reducing the support overhead required to maintain the overall scheduling requirements in this area;
- (b) - allowing for more users to access the system especially those who traditionally have not considered SN access available to them; and
- (c) - providing additional scheduling flexibility.

The document "Space Network Demand Assignment Techniques", prepared by Dr. Stephen Horan, Center for Space Telemetry and Telecommunications Systems at New Mexico State University, March 16 1995, presents a baseline concept for how this DAMA structure might be accomplished.

TDRS MA PHASED ARRAY ANTENNA SIMULATIONS

INTRODUCTION

One of the baseline concepts discussed in [1] is the S-band Multiple Access (SMA) capabilities of the SN. The current configuration for the return MA service is to use it in a spot beacon mode as shown in the left half of Figure 1 - Current and Proposed MA Coverage for DAMA Request. The user ephemeris is used to predict the position of the spot beacon and to track the movement of the user spacecraft.

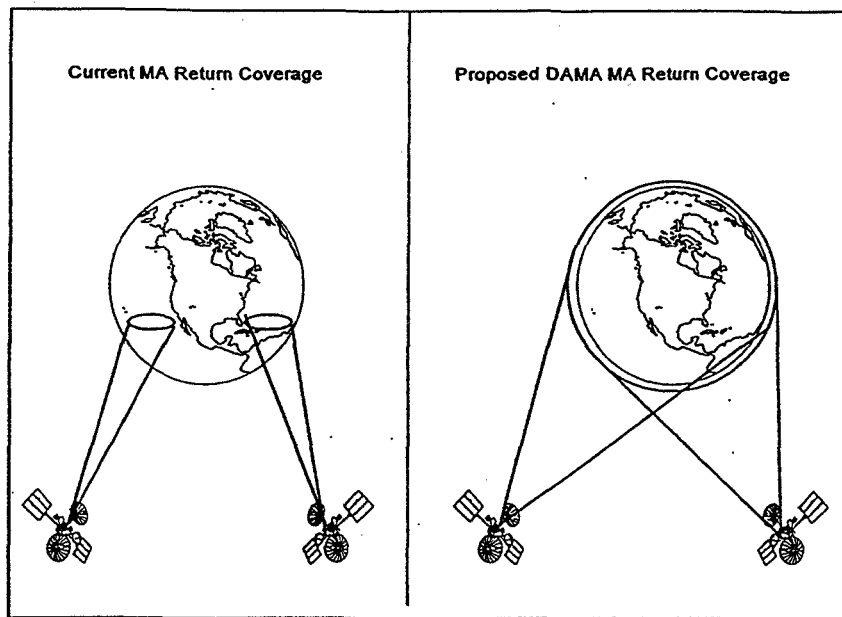


Figure 1 - Current and Proposed MA Coverage for DAMA Request

In the return service signal processing electronics at the White Sands Complex (WSC) ground station in New Mexico, weighting factors are added to the return signal from each SMA antenna element to provide the correct phase addition to form the spot beam. One set of weighting factors and associated signal processing equipment is required for each user being serviced by a Tracking and Data Relay Satellite (TDRS) within the SN. For the DAMA system, it is proposed to configure the SMA phased array to provide a global beacon from each TDRS in this SN as shown in the right half of Figure 1. This would require two sets of beam forming hardware at the WSC: one for each the east and west TDRS to provide a total of two global beacons with a zone of exclusion over the Indian Ocean as is found in the SA services. Two questions arise: Can the MA beam formers or antenna elements be configured to provide this global beam and if so, what are the performance characteristics of that beam? This report essentially answers these two questions by analysing and simulating the TDRS MA Antenna therefore producing different beam patterns by varying the effect of the elements on the

phased array antenna. It is to be kept in mind that more investigation has to be performed to finalise this work as stipulated in the recommendation section. Nonetheless, the basic idea is to come out with a beam pattern that has a minimum of loss in the Field Of View (FOV) of the TDRS.

First, some theory will be explained on the TDRS user geometry, the TDRS MA antenna and how the simulation program was written. Afterwards the results of the simulations of the MA antenna, conclusions and recommendations will be given.

THEORY

To be able to simulate the beam pattern of the TDRS Phased-Array Antenna, a program was written in Matlab Version 4.2b for Windows. Before showing the program and its results, some basic notions which were used to write this program must be understood.

TDRS User Geometry

Figure 2, shows the geometry or representative TDRS-User Ranges.

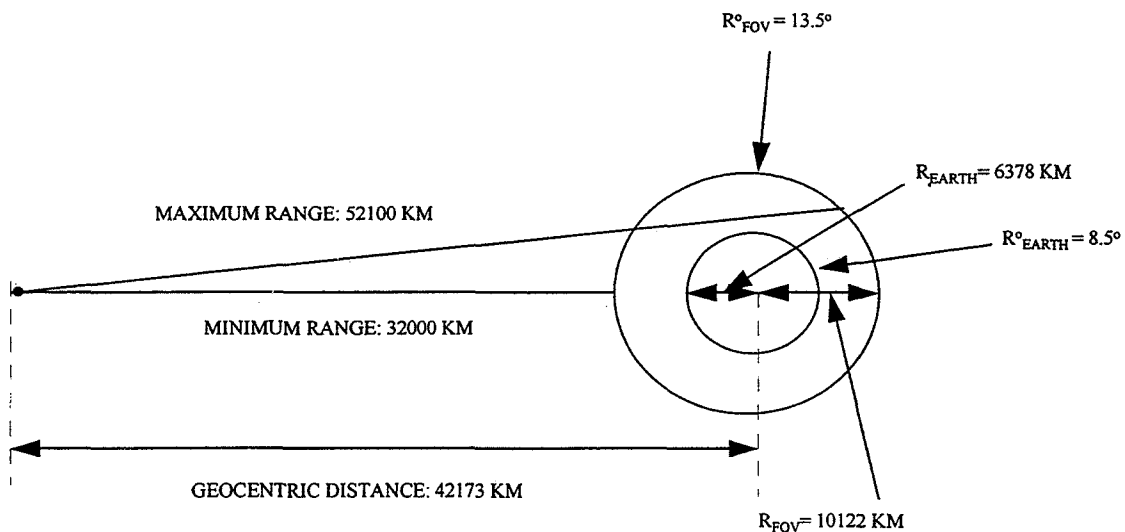


Figure 2. TDRS-User Ranges

where the earth radius (in degrees) seen by the spacecraft is calculated in the following manner:

$$R^{\circ}_{EARTH} = \sin^{-1}\left(\frac{6378 \text{ KM}}{42173 \text{ KM}}\right) = 8.7^{\circ} \approx 8.5^{\circ}$$

Also, the Filed Of View (FOV) of the spacecraft is given by

$$R_{FOV}^{\circ} = \sin^{-1}\left(\frac{10122\text{KM}}{42173\text{KM}}\right) = 13.9^{\circ} \approx 13.5^{\circ}$$

The approximation are made since the distances are not exact; these approximations are only for simulation purposes. Other variables or geometry that will be used for the simulation of this array antenna will be the angles: ϕ (phi) and θ (theta). These angles will be defined as:

- ϕ = the elevation angle from the Nadir (boresight); and
- θ = the clockwise rotation angle from + x (east).

Graphically these angles are represented and referenced as

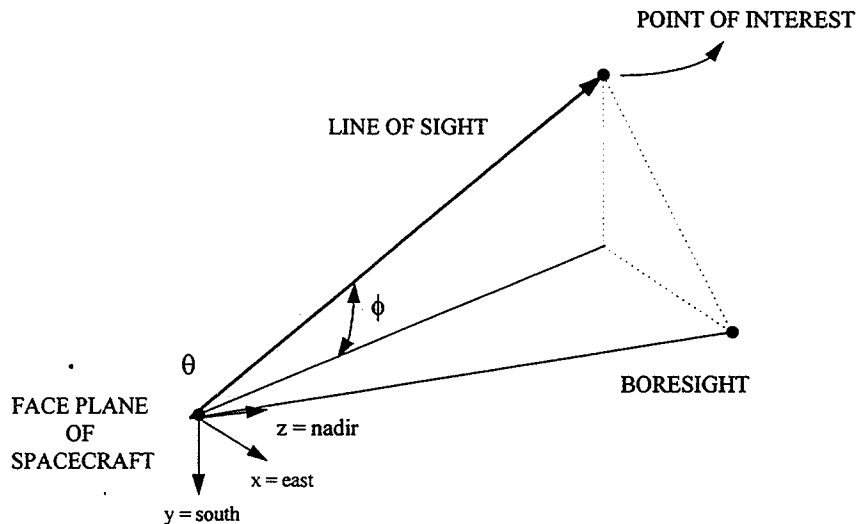


Figure 3 - ϕ and θ Angles Representation

As an example, White Sands Ground Terminal (WSGT) is at $\phi = 8.312^{\circ}$ and $\theta = 215.91^{\circ}$ (for the east TDRS). With these angles, it will then be possible to determine a direction cosine vector for each elements of the array antenna as it will be seen in the next section, the TDRS Array Antenna.

TDRS Array Antenna

A TDRS is able to support up to 20 separate return user services simultaneously through its multiple-access (MA) antenna. This antenna is a phased array of 30 helical antenna elements in fixed positions on the face of the antenna module on the TDRS as shown on the following figure (Figure 4- TDRS with MA Antenna).

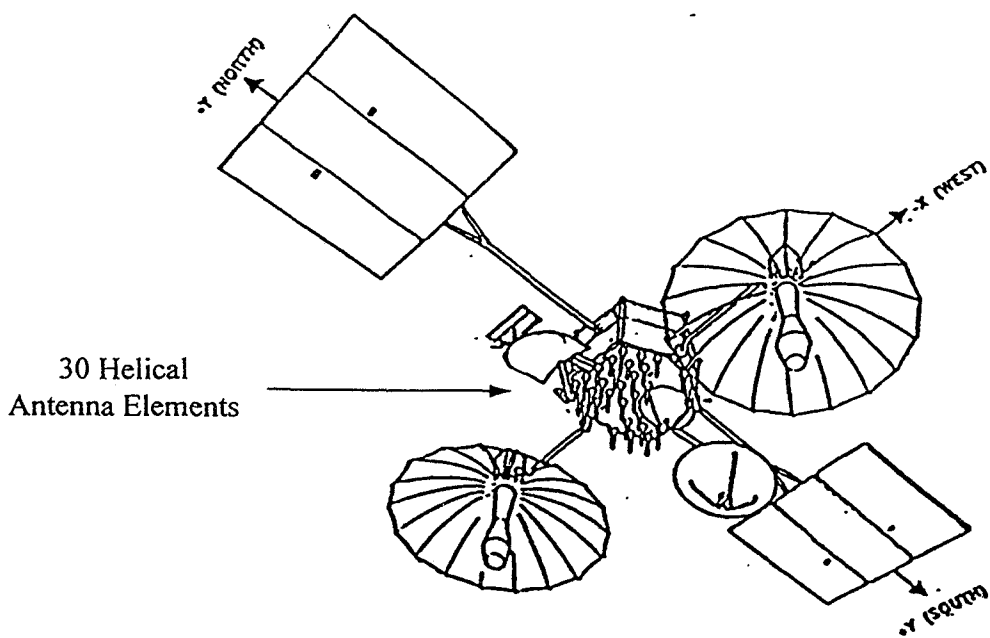


Figure 4. TDRS with MA Antenna

The signal which is received by each of the 30 elements is then transmitted to the ground segment via a separate frequency channel. Processing in the ground segment extracts the various user return signals by “forming a beam” utilizing the phase relationships resulting the 30-element geometry and the TDRS-to-user geometry (explained earlier). The beamforming is done entirely within the ground segment. The phase relationship between the 30 elements channel must be known accurately in order to calculate the phase shifts and form the receive beam.

The following figure shows the emplacement of the different elements on the MA antenna. As shown the coordinate system is right -handed with +x along the flight vector (east), +y pointed south, and +z pointed toward the Earth. Actually these coordinates correspond to the roll, pitch, and yaw axes respectively on the satellite.

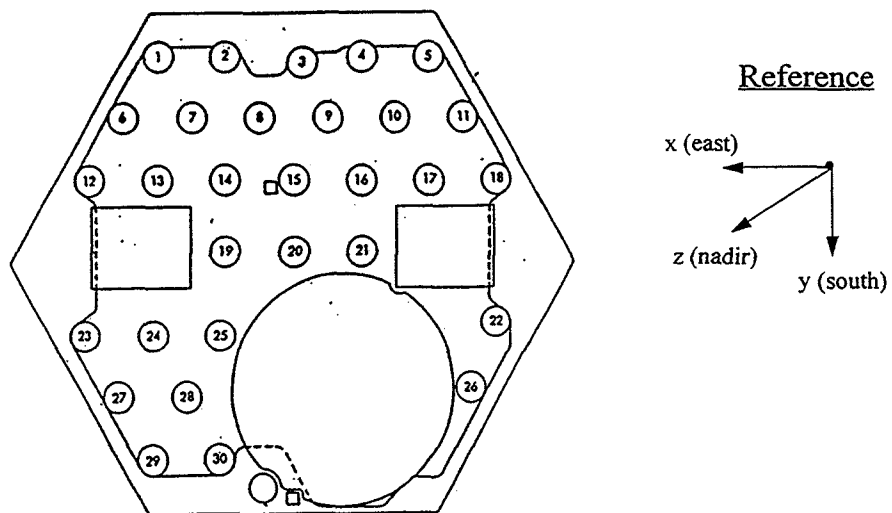


Figure 5 - Coordinate System of the MA Elements on the Antenna

The next table, Table I - Coordinates of the MA Elements, gives the nominal x,y,z positions of the receive elements on the TDRS (east) array antenna, with respect to the face plane of the spacecraft. All these values are in inches.

ANTENNA ELEMENTS	X COORDINATES	Y COORDINATES	Z COORDINATES
1	27.000	-38.966	0.000
2	13.500	-38.966	0.000
3	-1.500	-37.966	0.000
4	-13.500	-38.966	0.000
5	-27.000	-38.966	0.000
6	33.750	-27.275	0.000
7	20.250	-27.275	0.000
8	6.750	-27.275	0.000
9	-6.750	-27.275	0.000
10	-20.250	-27.275	0.000
11	-33.750	-27.275	0.000
12	40.500	-15.584	0.000
13	27.000	-15.584	0.000
14	13.500	-15.584	0.000
15	0.000	-15.584	0.000
16	-13.500	-15.584	0.000
17	-27.000	-15.584	0.000
18	-40.500	-15.584	0.000
19	13.500	-2.084	0.000
20	0.000	-2.084	0.000
21	-13.500	-2.804	0.000
22	-40.500	11.500	0.000
23	41.413	14.000	0.000
24	27.913	14.000	0.000
25	14.413	14.000	0.000
26	-35.500	24.000	0.000
27	34.663	25.691	0.000
28	21.163	25.691	0.000
29	27.913	37.382	0.000
30	14.413	37.382	0.000

Table I. Coordinates of the MA Elements

The file ELNOM.DAT in text format contains these values: see Appendix A p.A-5/5. These values will be used to determine the direction of the arriving plane wave to the antenna. In fact, using the angle defined in the previous section i.e. ϕ (phi) and θ (theta), Direction Cosine (DC) vectors can be defined. In vector analysis, a Direction Cosine is simply the magnitude of the component of the vector along one of the

coordinate axes divided by the absolute magnitude of the vector. The nominal DC were derived in [2].

The following DC for x,y and z are similar to those in [2] but the angles were defined differently:

$$\boxed{\begin{aligned} DC(x) &= \sin(\phi) \cos(\theta); \\ DC(y) &= \sin(\phi) \sin(\theta); \text{and} \\ DC(z) &= \cos(\phi). \end{aligned}} \quad (\text{equation 1})$$

Thus the direction or distances from the signal plane to the elements can be obtained by multiplying the position of the elements in respect to the spacecraft with the DC defined above:

$$\boxed{d = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots \\ x_{30} & y_{30} & z_{30} \end{bmatrix} \times \begin{bmatrix} DC(x) \\ DC(y) \\ DC(z) \end{bmatrix} = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots \\ x_{30} & y_{30} & z_{30} \end{bmatrix} \times \begin{bmatrix} \sin(\phi) \cos(\theta) \\ \sin(\phi) \sin(\theta) \\ \cos(\phi) \end{bmatrix}} \quad (\text{equation 2})$$

As an example: if the antenna is pointed toward Nadir then $\phi = 0^\circ$ and $\theta = 270^\circ$ then

$$\begin{aligned} DC(x) &= \sin(0^\circ) \cos(270^\circ) = 0; \\ DC(y) &= \sin(0^\circ) \sin(270^\circ) = 0; \text{and} \\ DC(z) &= \cos(0^\circ) = 1. \end{aligned}$$

Knowing the distance from the signal plane to the elements using the Direction Cosines, the relative time of flight can be calculated as:

$$\boxed{\tau = \frac{d}{c}} \quad (\text{equation 3})$$

where c is the speed of light i.e. 2.9986338×10^8 m/s. Since the distance (d) is in inches, the speed of light (c) will be converted to inches/nanosec given that 1 inch = 0.0254 m

$$\begin{aligned} \text{then } c &= 2.9986338 \times 10^8 \text{ m/s} \times (1 \text{ inch} / 0.0254 \text{ m}) \\ c &= 11.805644 \times 10^9 \text{ inch/sec} \end{aligned}$$

$$\text{or } c = 11.805644 \text{ inch/nanosec.}$$

Also the phase signal can be calculated using

$$\boxed{\Theta = 2\pi f_o \tau} \quad \text{rads} \quad (\text{equation 4})$$

where τ is the time of flight calculated earlier and f_0 is the operating frequency ($f_0 = 2.2875$ Ghz will be used as the downlink frequency).

The weights of each elements can then be calculated as (refer to [2]):

$$\boxed{\text{weights}(el) = \cos(\Theta) - j \sin(\Theta)} \quad (\text{equation 5})$$

where “el” stands for element. To simulate the patterns of these elements the Fourier Model and Geometric Model explained in detail in [2] will be used. As specified in these models, to generate the gain pattern of one element the “sinc” function will be utilized:

$$\boxed{G = (\text{sinc}(x))^2 = \left(\frac{\sin(x)}{x}\right)^2} \quad (\text{equation 6})$$

where for the helical elements on this antenna

$$\boxed{x = \frac{\phi}{32} \pi} \quad (\text{equation 7})$$

and ϕ is the elevation angle in degrees as defined earlier. Graphically we have:

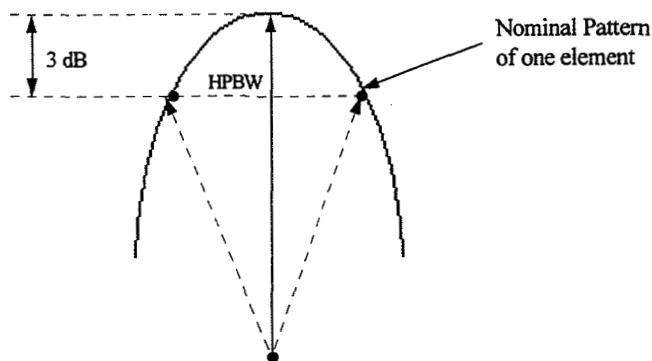


Figure 6 - Antenna Element Pattern

As an example, it is stipulated in [3] that the maximum gain of one element is 16 dB (boresight) and the nominal gain should be down to 13.3 dB at 13.5°.

Using equations 6 and 7 above:

for $\phi = 0$ (Boresight)

$$\text{then } x = \frac{0^\circ}{32} \pi = 0$$

$$G_o = (\sin c(0))^2 = \left(\frac{\sin(0)}{(0)} \right)^2 = 1 \quad (\text{using Hospital's Rule})$$

for $\phi = 13.5^\circ$

$$\text{then } x = \frac{13.5^\circ}{32} \pi = 1.3254$$

$$G_{13.5^\circ} = (\sin c(1.3254))^2 = \left(\frac{\sin(1.3254)}{(1.3254)} \right)^2 = 0.535678$$

Finally

$$\begin{aligned} [G_o] - [G_{13.5}] &= 10\log(1) - 10\log(0.535678) \\ &= 0 - (-2.71) \\ &= 2.71 \text{ dB} \end{aligned}$$

which meets the specification (given in [3]) of

$$16 \text{ dB} - 13.3 \text{ dB} = 2.7\text{dB}.$$

The 16 dB represents the maximum gain of the main lobe of one element and therefore 13.5° is approximately the Half Power Bandwidth (HPBW) since there is a loss of ≈ 3 dB.

Also these results were compared with theory using [4]. If

C = circumference of the helix;
S = spacing between turns = $C \tan(\alpha)$;
 α = pitch angle = $\tan^{-1}(S/C)$;
L = length of one turn = $\sqrt{C^2 + S^2}$;
N = number of turns;
A = axial length = $N \times S$; and
d = diameter of the helix conductor.

The following figure shows these different parameters.

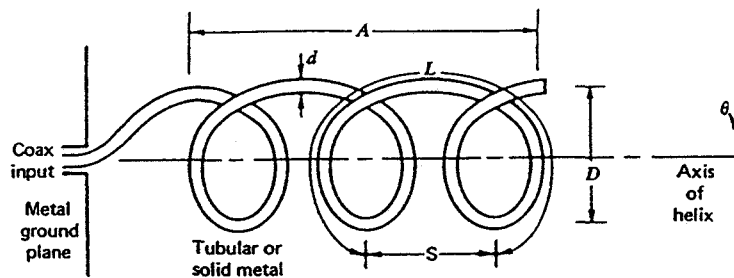


Figure 7. Helical Element Parameters (from reference [4])

If a frequency (downlink) of 2.2875 Ghz is used then

$$c = f \times \lambda = \text{speed of light}$$

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8 \text{ m/s}}{2.2875 \times 10^9 \text{ Hz}} = 0.131 \text{ m}$$

using some of the practical results from [4]: $C = 0.92\lambda$ and $\alpha = 13^\circ$

then $C = 0.92 \times 0.131 = 0.12 \text{ m}$

and

$$S = C \tan(\alpha) = 0.12 \times \tan(13^\circ) = 0.028 \text{ m}$$

Also since these elements have $N = 21$ turns and from [4], the Half Power Bandwidth (HPBW) is given by:

$$HPBW = \frac{52^\circ}{\left(\frac{C}{\lambda}\right) \times \sqrt{N \cdot \left(\frac{S}{\lambda}\right)}} \quad (\text{equation 8})$$

Then replacing the numerical values in this last expression:

$$HPBW = \frac{52^\circ}{\left(\frac{0.12}{0.131}\right) \times \sqrt{21 \cdot \left(\frac{0.028}{0.131}\right)}}$$

$$HPBW = 26.8^\circ$$

which corresponds approximately to the 13.5° (HPBW/2 = 13.4°) half power bandwidth calculated earlier. Also to calculate the gain, let's first find the directivity using the following formula from [4] again:

$$D = 15 \cdot \left(\frac{C}{\lambda} \right)^2 \cdot \frac{N \cdot S}{\lambda} \quad (\text{equation 9})$$

thus

$$D = 15 \cdot \left(\frac{0.12}{0.131} \right)^2 \cdot \frac{21 \cdot 0.028}{0.131}$$

$$D = 56.5$$

As stipulated in [4], “this directivity expression is a ratio (not decibel), and approximately equals the gain since the axial mode helix is nearly lossless”. Then

$$G = 10 \log(D) \quad (\text{equation 10})$$

$$G = 10 \log(56.5) = 17.52 \text{ dB}$$

which is similar to the specification gain that was mentioned earlier i.e. 16 dB. References [5] and [6] were also used for these calculations.

SIMULATION OF THE MA ANTENNA

Using all the theory mentioned in the previous sections and using part of reference [3] routines, a program was written in Matlab Version 4.2b for Windows to simulate the beam pattern of the MA antenna. This program was called PATTERN.M and the listing is in Appendix A page A-2/5 to A-5/5. The following parts of the program PATTERN.M must be noted. First this program needs the file ELNOM.DAT which contains the positions of the elements of the phased-array antenna with respect to the face plane of the spacecraft. Appendix A p.A-5/5 shows the content of this file which contains the same numbers presented in Table I in this report. Also the amplitude in dB given as the output in the simulations is in reference to the maximum gain of one element i.e. 16 dB as discussed earlier in the report. Thus if the maximum amplitude of a pattern is -1 dB, this means that it is 1 dB below the reference of 16 dB therefore the real gain is 15 dB. Table II- Summary of the Simulations (p.20/22) shows the values of HPBW and Gain for the different simulations. Finally to simulate for various angle of ϕ (phi) and θ (theta), these variables must be changed: see Change Variables Section in PATTERN.M.

A few simulation were performed and they will be briefly explained in the following paragraphs.

First Simulation: 30 Elements at Nadir ($\phi = 0^\circ$, $\theta = 270^\circ$)

The first simulation produced the beam pattern of the 30 elements combined together when the antenna is pointing at Nadir. To be able to simulate these elements some modifications had to be done in the program in Appendix A. First since the simulation was going to be performed at the Nadir, the “phi” and “theta” variables had to be given values of 0° and 270° respectively as shown in the Change Variables Section in PATTERN.M. Also the section EFFECT OF 30 ELEMENTS page A-4/5 was created and the variable “iel” in the for loop was identified as iel=1:30. It is to be noted that the other sections EFFECT OF ELEMENT # 20, EFFECT OF ELEMENTS # (14-15-16) and EFFECT OF ELEMENT # (19-20-21) were put in comments (“%” is the comment symbol in Matlab). Appendix B, p.B-2/24 to B-4/24 shows the results of the simulation of these elements (at Nadir). The first plot Appendix B p.B-2/22 shows that the gain varies significantly depending where we are situated in the FOV. This kind of pattern is not what is desired since the gain is not really constant over the FOV. The next plot (p.B-3/24) shows a transversal 2-D plot of this simulation to be able to observe the main lobe. The maximum gain of this main lobe is approximately 30 dB. The plot p.B-4/24 shows a contour plot of this simulation: top view.

Second Simulation: 30 Elements at WSGT ($\phi = 8.312^\circ$ and $\theta = 215.91^\circ$)

This second simulation gives similar results to the first one in respect to the fact that the gain is not constant. To be able to simulate these elements, some modifications were also done in the program. First, since the simulation was going to be performed at different angles than for Nadir, the “phi” and “theta” variables had to be given values of 8.312° and 215.91° respectively in the Change Variables Section in PATTERN.M. Also the section EFFECT OF 30 ELEMENTS page A-4/5 was kept identical as the last simulation. It is to be noted that the other sections EFFECT OF ELEMENTS were put in comments. Three plots are shown in page B-5/24 and p.B-7/24.

Third Simulation: Element #20 at Nadir ($\phi = 0^\circ$ and $\theta = 270^\circ$)

The third simulation was performed by using only one element and see its effect over the FOV. The element chosen was element number 20 (central element in the phased-array antenna). First, since the simulation was going to be performed at the Nadir, the “phi” and “theta” variables had to be given values of 0° and 270° respectively as shown in the Change Variables Section in PATTERN.M. Also the section EFFECT OF ELEMENT # 20 page A-4/5 was created and the variable “iel” in the for loop was identified as iel=20:20. It is to be noted that the other sections EFFECT OF ELEMENTS were put in comments (“%”). Appendix B, p.B-8/24 to B-11/24 show the results of the simulation of this element (at Nadir). The first plot shows a 3 Dimensional representation of the element over a range of -50° to 50° in the x and y axis. The main lobe has a gain of 0 dB relative to the reference of 16 dB as stipulated earlier. Also it was

mentioned earlier that the FOV of the TDRS is approximately 13.5° therefore a plot focusing only in that region is shown in the next page p.B-9/24. As seen the gain is almost flat in that range as desired. The next plot (p.B-10/24) shows a transversal (2-D) cut of this last plot : Gain in dB (z axis) and FOV in degrees (x axis). The loss at 13.5° is less than 3 dB (approximately 2.7 dB as calculated earlier in the report). These results are symmetric as shown in the next plot (p.B-11/24) where z axis is shown versus the y axis.

Fourth Simulation: Element #20 at WSGT ($\phi = 8.312^\circ$ and $\theta = 215.91^\circ$)

The fourth simulation was performed by using element number 20 again. This time the simulation was performed at $\phi = 8.312^\circ$ and $\theta = 215.91^\circ$ which is the emplacement of WSGT, therefore the “phi” and “theta” variables had to be given values of 8.312° and 215.91° respectively in the Change Variables Section in PATTERN.M. All the rest of the program was kept the same as the last simulation.

The first plot p.B-12/24 shows a 3 Dimensional representation of the element over a range of -50° to 50° in the x and y axis: as it can be seen this plot is very similar to the previous simulation at Nadir. The next plot shows a zoom in the -13.5° and 13.5° range (p.B-13/24). As seen the gain is almost flat in that range as desired (very similar to plot p.B-9/24). The next two plots show transversal (2-D) cuts of this last plot : Gain in dB(z axis) and FOV in degrees (x axis) and FOV in degrees (y axis). Again , these plots are very similar to the last simulation i.e. Element # 20 at Nadir

Fifth Simulation: Elements #19-20-21 at Nadir ($\phi = 0^\circ$ and $\theta = 270^\circ$)

The fifth simulation was performed by using the 3 central elements of the phased-array antenna and see the effect of combining the beam patterns over the FOV. The elements that were chosen are elements number 19, 20 and 21. First since the simulation was going to be performed at the Nadir, the “phi” and “theta” variables had to be given values of 0° and 270° respectively as shown in the Change Variables Section in PATTERN.M. Also, the section EFFECT OF ELEMENT #(19-20-21) page A-4/5 was created and the variable “iel” in the for loop was identified as iel=19:21. The other sections EFFECT OF ELEMENTS were put in comments (“%”). Appendix B, p.B-16/24 and B-17/24 show the results of the simulation of these elements combined together (at Nadir). The first plot shows a 3 dimensional (3-D) representation of the element over a range of -13.5° to 13.5° (desired FOV) in the x and y axis. The main lobe has a gain of approximately 9.5 dB relative to the reference of 16 dB as stipulated earlier. Thus the actual gain is approximately 25.5 dB (9.5 dB +16 dB). As seen the gain is not flat in that range (-13.5° to 13.5°) therefore the effect of adding other elements tends to produce sidelobes. The next plot shows a transversal (2-D) cut of this last plot : Gain in dB(z axis) and FOV in degrees (x axis).

Sixth Simulation: Elements #19-20-21 at WSGT ($\phi = 8.312^\circ$ and $\theta = 215.91^\circ$)

The sixth simulation also was performed using the 3 central elements of the phased-array antenna as the fifth simulation but this time the simulation was performed at WSGT. Since the simulation was going to be performed at the WSGT, the “phi” and “theta” variables had to be given values of 8.312° and 215.91° respectively in the Change Variables Section in PATTERN.M. Appendix B, p.B-18/24 and B-19/24 show the results of the simulation of these elements combined together (at WSGT). The first plot shows a 3 Dimensional representation of the element over a range of -13.5° to 13.5° (desired FOV) in the x and y axis. This plot is quite different from the last simulation at Nadir. It seems that the main lobe has been shifted. Again, the gain is not flat in that range which shows the effect of adding other elements tends to produce sidelobes. The next plot p.B-19/24 shows a transversal (2-D) cut of this last plot : Gain in dB(z axis) and FOV in degrees (x axis). The maximum gain of the main lobe is approximately 9.5 dB in reference to 16 dB again.

Seventh Simulation: Elements #(14-15-16) and (19-20-21) at Nadir ($\phi = 0^\circ$ and $\theta = 270^\circ$)

This simulation was performed by using the 6 central elements of the phased-array antenna and see the effect of combining the beam patterns over the FOV. The elements that were chosen are elements number 14, 15, 16, 19, 20 and 21. Again, since the simulation was going to be performed at the Nadir, the “phi” and “theta” variables had to be given values of 0° and 270° respectively as shown in the Change Variables Section in PATTERN.M. Also the sections EFFECT OF ELEMENT #(14-15-16) and EFFECT OF ELEMENT #(19-20-21) page A-4/5 were used and the variable “iel” in the for loop were identified as iel=14:16 and iel=19:21 respectively. The other sections EFFECT OF ELEMENTS were put in comments (“%”). Appendix B, p.B-20/24 and B-21/24 show the results of the simulation of these elements combined together (at Nadir). The first plot shows a 3 dimensional representation of the elements over a range of -13.5° to 13.5° (desired FOV) in the x and y axis. The main lobe has approximately a gain of 15.5 dB relative to the reference of 16 dB as stipulated earlier (total gain: approximately 31.5 dB). Again, as seen on the plot the gain is not flat in that range therefore the effect of adding other elements tends to produce sidelobes as dicussed earlier. But it is to be noted, that the symmetry is better than with 3 elements only. The next plot, p.B-21/24, shows a transversal (2-D) cut of this last plot : Gain in dB(z axis) and FOV in degrees (x axis).

Eight Simulation: Elements #(14-15-16) and (19-20-21) at WSGT ($\phi = 8.132^\circ$ and $\theta = 215.91^\circ$)

The last simulation also was performed by using the 6 central elements of the phased-array antenna as the seventh simulation but this time the simulation was performed at WSGT. Since the simulation was going to be performed at the WSGT, the “phi” and “theta” variables had to be given values of 8.312° and 215.91° respectively as

shown in the Change Variables Section in PATTERN.M. Appendix B, p.B-22/24 to B-24/24 show the results of the simulation of these elements combined together (at WSGT). The first plot shows a 3 Dimensional representation of the element over a range of -13.5° to 13.5° (desired FOV) in the x and y axis. This plot is quite different from the last simulation at Nadir. It seems that the main lobe has been shifted. Again, the gain is not flat in that range therefore the effect of adding other elements tends to produce sidelobes. The next two plots p.B-23/24 and B-24/24 show transversal (2-D) cuts of this last plot : Gain in dB(z axis) versus FOV in degrees (x axis) and FOV in degrees (y axis) respectively.

The following table, Table II. Summary of the Simulations, gives a comparison of the main lobes of the different simulation.

SIMULATION	RELATIVE MAXIMUM GAIN	MAIN LOBE		COMMENTS
		HPBW/2	GAIN at HPBW (≈ 3 dB less)	
FIRST SIMULATION (30 elements at Nadir) see p.B-2/24 to p.B-4/24	29.5 dB	$\approx 1^\circ$	26.5 dB	gain is not flat in the desired FOV i.e -13.5° to 13.5°
SECOND SIMULATION (30 elements at WSGT) see p.B-5/24 to p.B-7/24	29.5 dB	$\approx 1^\circ$	26.5 dB	gain is not flat in the desired FOV i.e -13.5° to 13.5°
THIRD SIMULATION (Element #20 at Nadir) see p.B-8/24 to p.B-11/24	0 dB	$\approx 13.5^\circ$	-2.7 dB	gain is flat in FOV but the relative max gain is lower
FOURTH SIMULATION (Element #20 at WSGT) see p.B-12/24 to p.B-15/24	≈ 1.5 dB	$\approx 13.5^\circ$	≈ -1.5 dB	gain is flat in FOV but the relative max gain is lower
FIFTH SIMULATION (Elements #19-20-21 at Nadir) see p.B-16/24 and p.B-17/24	9.5 dB	depends on what axis x axis : $\approx 1^\circ$ y axis : $\approx 13.5^\circ$	≈ 6.5 dB	gain not flat in the desired FOV
SIXTH SIMULATION (Elements #19-20-21 at WSGT) see p.B-18/24 and p.B-19/24	9.5 dB	depends on what axis x axis : $\approx 1^\circ$ y axis : $\approx 13.5^\circ$	≈ 6.5 dB	main lobe is shifted compared to the fifth simulation
SEVENTH SIMULATION (Elements #(14-15-16) & #(19-20-21) at Nadir) see p.B-20/24 and p.B-21/24	15.5 dB	$\approx 3.5^\circ$	12.5 dB	gain not flat in the desired FOV
EIGHTH SIMULATION (Elements #(14-15-16) & #(19-20-21) at WSGT) see p.B-22/24 to p.B-24/24	15.5 dB	$\approx 3.5^\circ$	12.5 dB	main lobe is shifted compared to the seventh simulation

Table II. Summary of the Simulations

Note: Table II is referenced to 16 dB (gain relative to a single element). Thus the true value of the gains in the table are found by adding 16 dB to any gain.

CONCLUSION

It seems that throughout all the simulations performed and shown in this report, the best result for a whole coverage over the FOV of the TDRS is obtained by using only one element (in this case element # 20 was simulated). Nonetheless, it is to be noted that the simulation of elements #(14-15-16) & (19-20-21) gave good results even if it does not cover the whole FOV. Certainly by performing simulations choosing different combinations of elements, results similar but not identical to what was found with one element would be acquired. The results will be similar and not identical since by adding more elements, sidelobes are created in the FOV as noted in the simulations.

RECOMMENDATION

- The TDRS MA Antenna should be looked into more closely to see if only one element has enough power to cover the whole FOV. A link budget should therefore be performed;
- More simulations should be done to be able to determine the best pattern covering the whole FOV with a minimum of attenuation; and
- Actual measurements with the antenna should be accomplished to compare the real measurements of gain and FOV to the simulations in this report.

REFERENCES

- [1] "Space Network Demand Assignment Techniques", by Dr. Stephen Horan, Center for Space Telemetry and Telecommunications Systems, New Mexico State University, March 16 1995.
- [2] "Practical Simulation of Radar Antennas and Radomes", Herbert L.Hirsch and Douglas C. Grove, Artech House, Inc. 1987.
- [3] "Supporting Engineering Analysis and Data for the multiple Access Beamforming equipment", prepared by Telephonics Corporation, Command Systems Division, Report: SDRL No. HE-08 November 23,1992.
- [4] "Antenna Theory and Design", by Warren L. Stutzman and Gary A. Thiele, John Wiley & Sons, 1981.
- [5] "Theory and Analysis of Phased Array Antennas", by Noach Amitay, Victor Galindo and Chen Pang Wu, Wiley-Interscience, a division of John Wiley & Sons, Inc., 1972.
- [6] "Practical Phased Array Antenna Systems", by Eli Brookner, Artech House Inc., 1991.

APPENDIX A

PROGRAM

- Listing of program PATTERN.M p.A-2/5
- Position of the MA elements on the TDRS antenna:
file ELNOM.DAT p.A-5/5

```

%*****
%*****
%***** PROGRAM      : pattern.m          *****
%***** SOFTWARE USED: Matlab Version 4.2b for Windows *****
%***** DATE         : 10 April 1995      *****
%***** DESCRIPTION  : This program will simulate the TDRS ****
%*****              : phased-array antenna elements          ****
%*****
%*****

```

```

clear;          % clearing all variables in the Matlab environment
load elnom.dat; % file containing the NOMinal ELEment positions ...
                % ...on the MA TDRS antenna

```

```

% CHANGE VARIABLES SECTION

```

```

phi= 0;        % elevation angle from Nadir
theta = 270;   % clockwise rotation angle from +x (east)

```

```

% INITIALIZE VARIABLES

```

```

ix = 1;        % index position of x,y and z for the antenna...
iy = 2;        % ... elements.
iz = 3;

```

```

phi_min = -13.5; % minimum value for the elevation angle phi
phi_max = 13.5;  % maximum value for the elevation angle phi
phi_inc = 0.5;   % increment for the angle phi
floor_gain = -30;
dataline = zeros(1,4096); % initialize the gain vector

```

```

% USE THE VALUES OF PHI AND THETA TO PRODUCE THE BEAM PATTERN

```

```

xsinc = phi/32; % equation 7 page 13/22 in report
gnom = 10 * log10((sinc(xsinc))^2); % equation 6 page 13/22 in report
rphi = pi*phi/180; % convert phi in degrees to radians
rtheta = pi*theta/180; % convert theta in degrees to radians
dc(ix) = cos(rtheta)*sin(rphi); % Direction Cosine equations...
dc(iy) = sin(rtheta)*sin(rphi); % ... see equation 1 page 12/22 ...
dc(iz) = cos(rphi); % ... in report

```

```

% CALCULATE THE WEIGHTS OF EACH ELEMENTS
% (based on the conjugate of the desired signal)

for iel = 1:30

    disnom = dc(ix)*elnom(iel,ix)+dc(iy)*elnom(iel,iy)+dc(iz)*elnom(iel,iz);
    timenom = disnom/11.805644;          % 11.805644 is speed of light in inches/nanosec
                                        % ... timenom is the relative time of flight...
                                        % ... to the element: see report page 12/22 ...
                                        % ... equation 3.
    phsnom = 2*pi*timenom*2.2875; % phsnom is the phase signal where 2.2875 GHz...
                                        % ... represents the downlink frequency: ...
                                        % ... see report page 12/22 equation 4.
    weights(iel)= cos(phsnom)- j*sin(phsnom); % weight of each element: equation 5 ...
                                                % ... report page 13/22.

end; %for iel

% CREATE THE BEAM PATTERN

column = 0;
for xaxis = phi_min:phi_inc:phi_max % x axis pattern

    column = column + 1;
    dataline = xaxis;
    line_inc = 0;
    yaxis = phi_min;

    while ((yaxis >= phi_min) & (yaxis <= phi_max)) % y axis pattern
        loop = 0;
        phi = sqrt(xaxis^2 + yaxis^2);

        while ((phi > phi_max) & (yaxis <= phi_max))
            line_inc = line_inc + 1;
            dataline(line_inc)= floor_gain;
            yaxis = yaxis + phi_inc;
            phi = sqrt(xaxis^2 + yaxis^2);
            loop = loop + 1; % we were in the loop
        end % while phi & yaxis

        if(phi == 0)
            theta = 0;
        else
            theta = atan2(yaxis,xaxis); % the result of atan2(y,x)...
                                        % ... is in the interval ...
                                        % ...[pi -pi].
        end %if phi=0

        xsinc = phi/32;
        rphi = pi*phi/180;
        dc(ix) = cos(theta)*sin(rphi); % calculate the DC for the ...
        dc(iy) = sin(theta)*sin(rphi); %... values of phi and theta...
        dc(iz) = cos(rphi); %... to plot the beam pattern.
        signom = 0;
    end
end

```

```

% EFFECT OF ELEMENT #20
% for iel = 20:20
% disnom = dc(ix)*elnom(iel,ix)+ dc(iy)*elnom(iel,iy)+ dc(iz)*elnom(iel,iz);
% timenom = disnom/11.805644;
% phsnom = 2*pi*timenom*2.2875;
% signom = signom + (cos(phsnom)+ j*sin(phsnom))* weights(iel);
% end; %for iel = 20

% EFFECT OF ELEMENTS # (14-15-16)
%for iel = 14:16
% disnom = dc(ix)*elnom(iel,ix)+dc(iy)*elnom(iel,iy)+dc(iz)*elnom(iel,iz);
% timenom = disnom/11.805644;
% phsnom = 2*pi*timenom*2.2875;
% signom = signom + (cos(phsnom)+ j*sin(phsnom))* weights(iel);
%end; %for iel 14 to 16

% EFFECT OF ELEMENTS # (19-20-21)
%for iel = 19:21
% disnom = dc(ix)*elnom(iel,ix)+dc(iy)*elnom(iel,iy)+dc(iz)*elnom(iel,iz);
% timenom = disnom/11.805644;
% phsnom = 2*pi*timenom*2.2875;
% signom = signom + (cos(phsnom)+ j*sin(phsnom))* weights(iel);
%end; %for iel 19 to 21

% EFFECT OF 30 ELEMENTS
for iel = 1:30
    disnom = dc(ix)*elnom(iel,ix)+dc(iy)*elnom(iel,iy)+dc(iz)*elnom(iel,iz);
    timenom = disnom/11.805644;
    phsnom = 2*pi*timenom*2.2875;
    signom = signom + (cos(phsnom)+ j*sin(phsnom))* weights(iel);
end; %for iel 1 to 30

num_el = 1;    % number of elements
gain = 10*log10(((abs(signom))*sinc(xsync))^2)/(num_el)^2)-gnom; % total gain

if (gain < floor_gain)
    gain = floor_gain;
end; %if gain

if loop == 0
    line_inc = line_inc + 1;
    dataline(line_inc) = gain;
    yaxis = yaxis + phi_inc;
end; %if loop = 0

end; %while yaxis

xx(1:(line_inc),column) = (ones(1,line_inc)*xaxis)';    % setting x axis values to plot
yy(1:(line_inc),column) = (phi_min:phi_inc:phi_max)'; % setting y axis values to plot
zz(1:(line_inc),column) = (dataline)';                % setting z axis values to plot

end; % for xaxis
mesh(xx,yy,zz); % plot the Beam Pattern in 3-D
% plot(elnom(:,1),elnom(:,2),'*'); % plot the MA Antenna Phased-Array Element Placement

```

FILE: ELNOM.DAT

% Description: This file contains the coordinates x,y,z of the MA elements on the TDRS Phased-Array Antenna with respect to the center of the spacecraft.

27.0000 -38.966 0
13.5000 -38.966 0
-1.500 -37.966 0
-13.500 -38.966 0
-27.000 -38.966 0
33.750 -27.275 0
20.250 -27.275 0
6.750 -27.275 0
-6.750 -27.275 0
-20.250 -27.275 0
-33.750 -27.275 0
40.500 -15.584 0
27.000 -15.584 0
13.500 -15.584 0
0.000 -15.584 0
-13.500 -15.584 0
-27.000 -15.584 0
-40.500 -15.584 0
13.500 -2.084 0
0.000 -2.084 0
-13.5000 -2.084 0
-40.500 11.500 0
41.413 14.000 0
27.913 14.000 0
14.413 14.000 0
-35.500 24.000 0
34.663 25.691 0
21.163 25.691 0
27.913 37.382 0
14.413 37.382 0

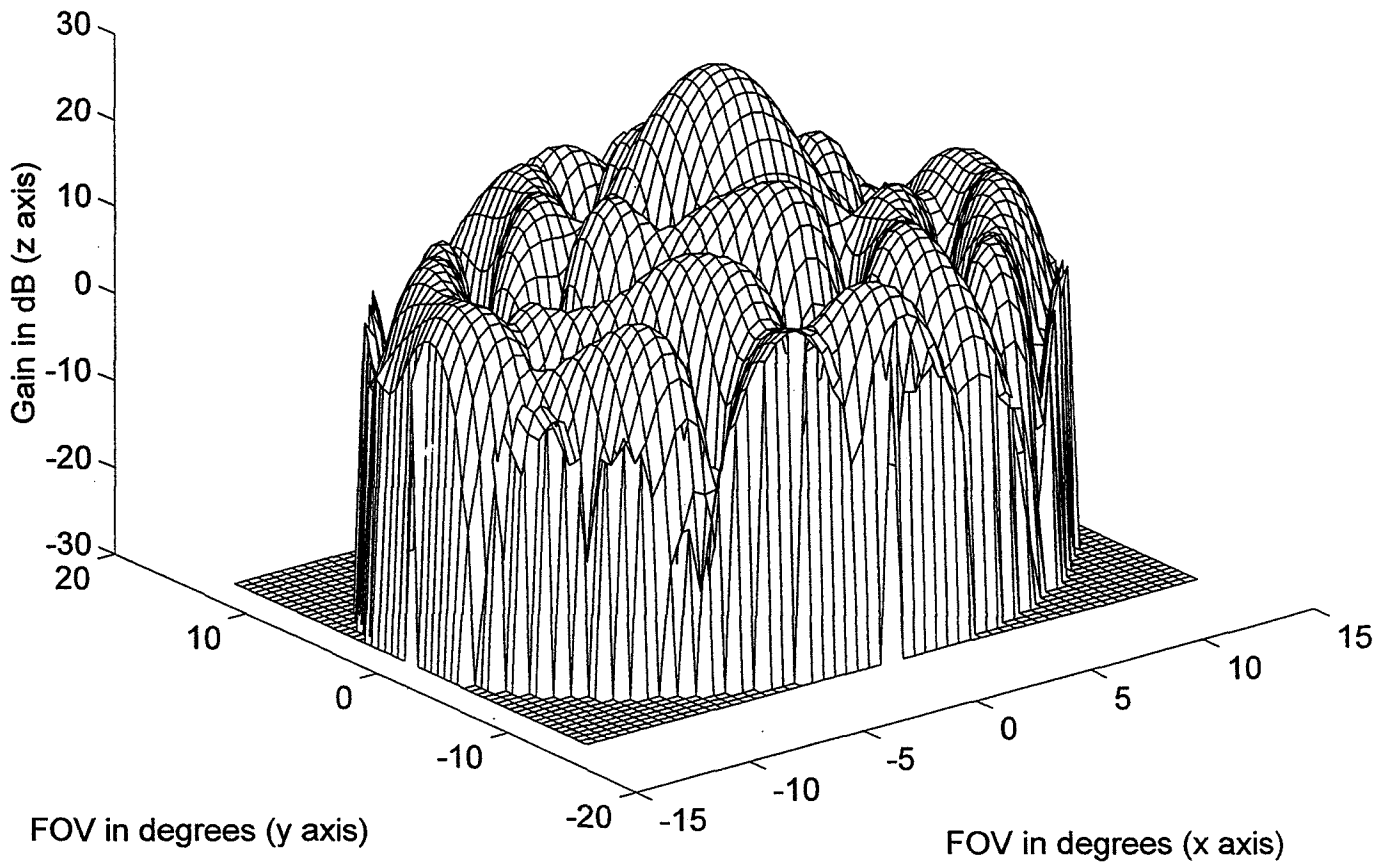
APPENDIX B

MATLAB BEAM PATTERN SIMULATIONS

- First Simulation:
30 Elements at Nadir ($\phi = 0^\circ$, $\theta = 270^\circ$)..... p.B-2/24
- Second Simulation:
30 Elements at WSGT ($\phi = 8.312^\circ$ and $\theta = 215.91^\circ$)..... p.B-5/24
- Third Simulation:
Element #20 at Nadir ($\phi = 0^\circ$ and $\theta = 270^\circ$)..... p.B-8/24
- Fourth Simulation:
Element #20 at WSGT ($\phi = 8.312^\circ$ and $\theta = 215.91^\circ$)..... p.B-12/24
- Fifth Simulation:
Elements #19-20-21 at Nadir ($\phi = 0^\circ$ and $\theta = 270^\circ$)..... p.B-16/24
- Sixth Simulation:
Elements #19-20-21 at WSGT ($\phi = 8.312^\circ$ and $\theta = 215.91^\circ$)..... p.B-18/24
- Seventh Simulation:
Elements #(14-15-16) and (19-20-21)
at Nadir ($\phi = 0^\circ$ and $\theta = 270^\circ$).....p.B-20/24
- Eight Simulation:
Elements #(14-15-16) and (19-20-21)
at WSGT ($\phi = 8.312^\circ$ and $\theta = 215.91^\circ$).....p.B-22/24

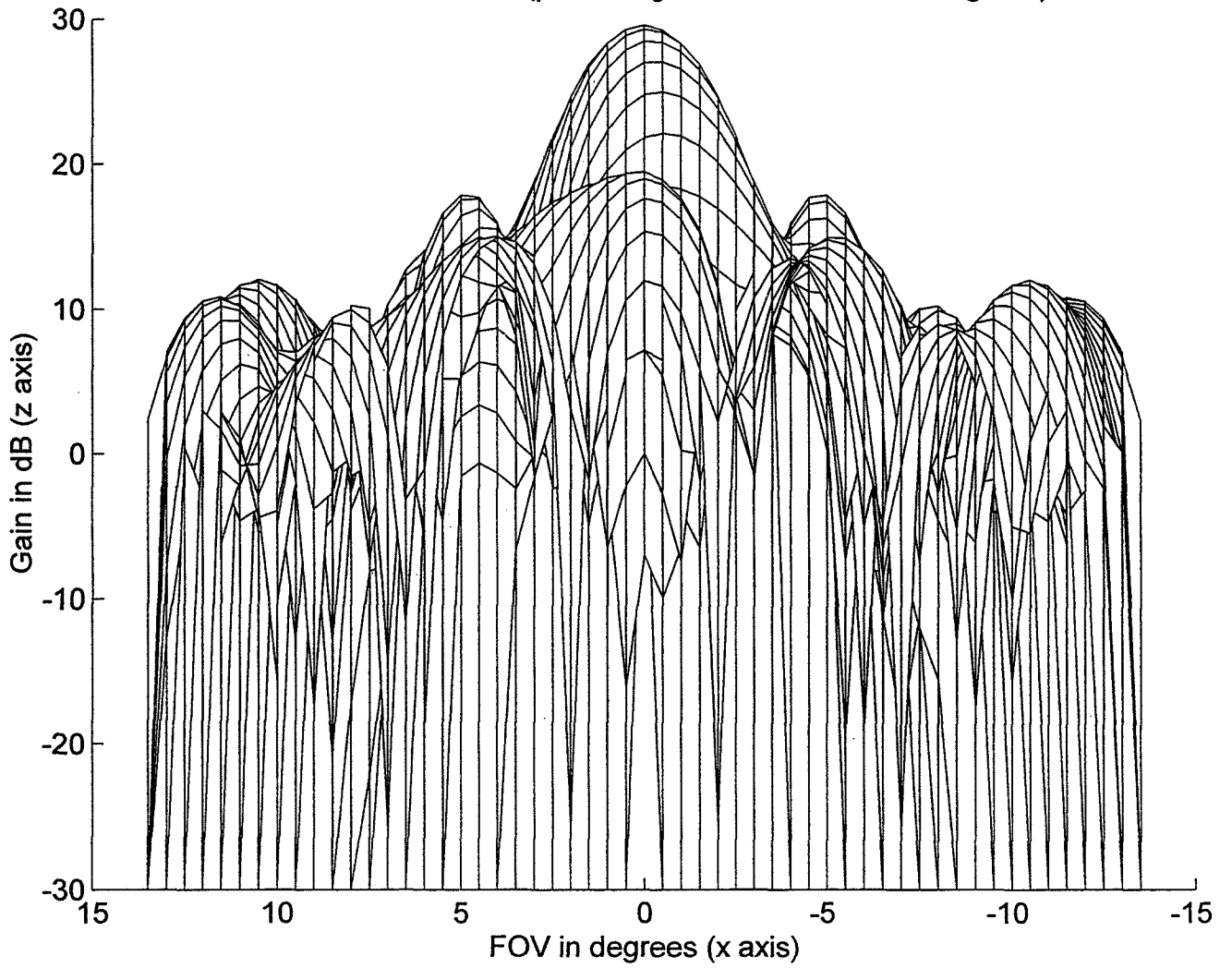
FIRST SIMULATION

30 Elements at Nadir ($\phi=0$ degrees and $\theta=270$ degrees)



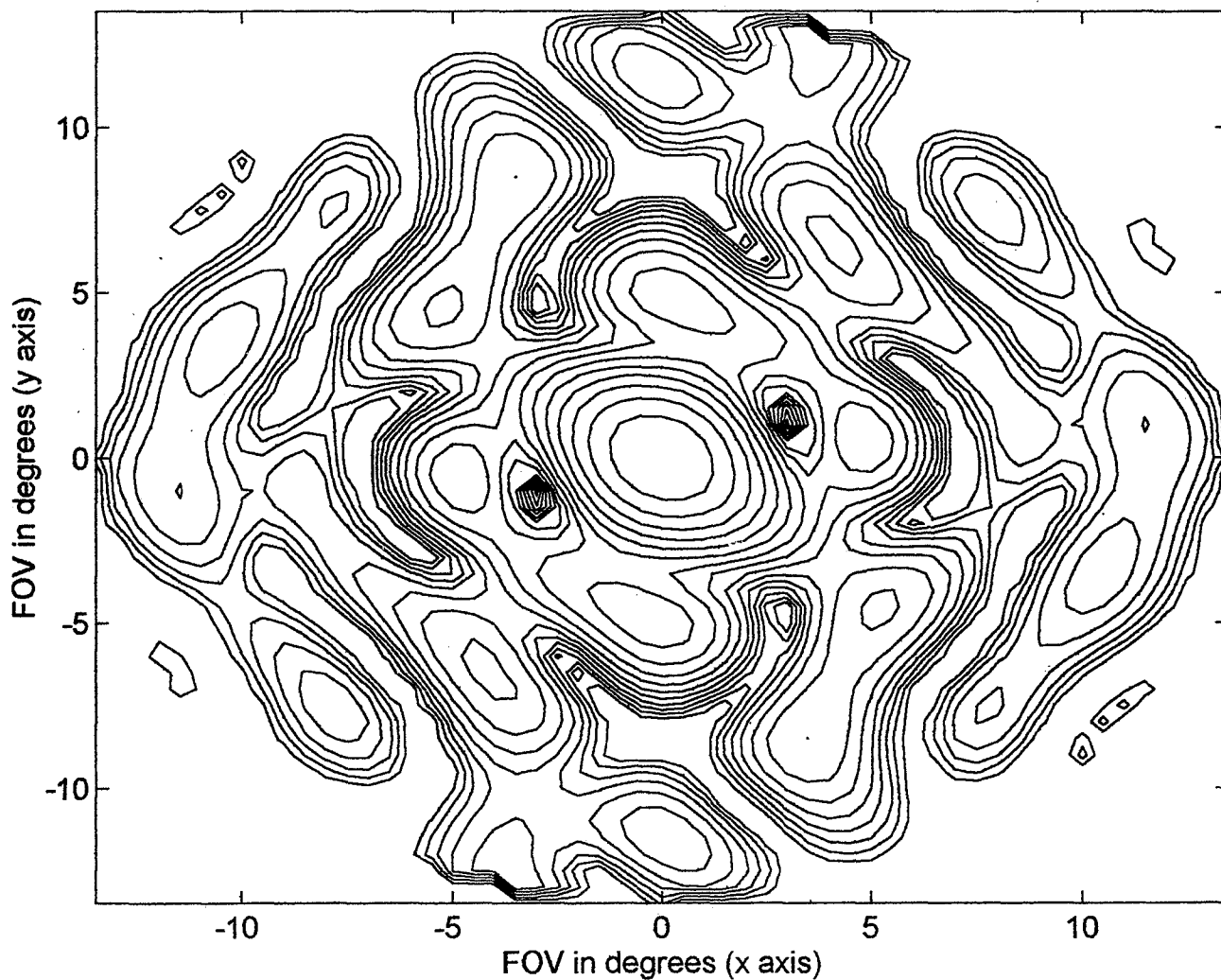
FIRST SIMULATION

30 Elements at Nadir ($\phi=0$ degrees and $\theta=270$ degrees)



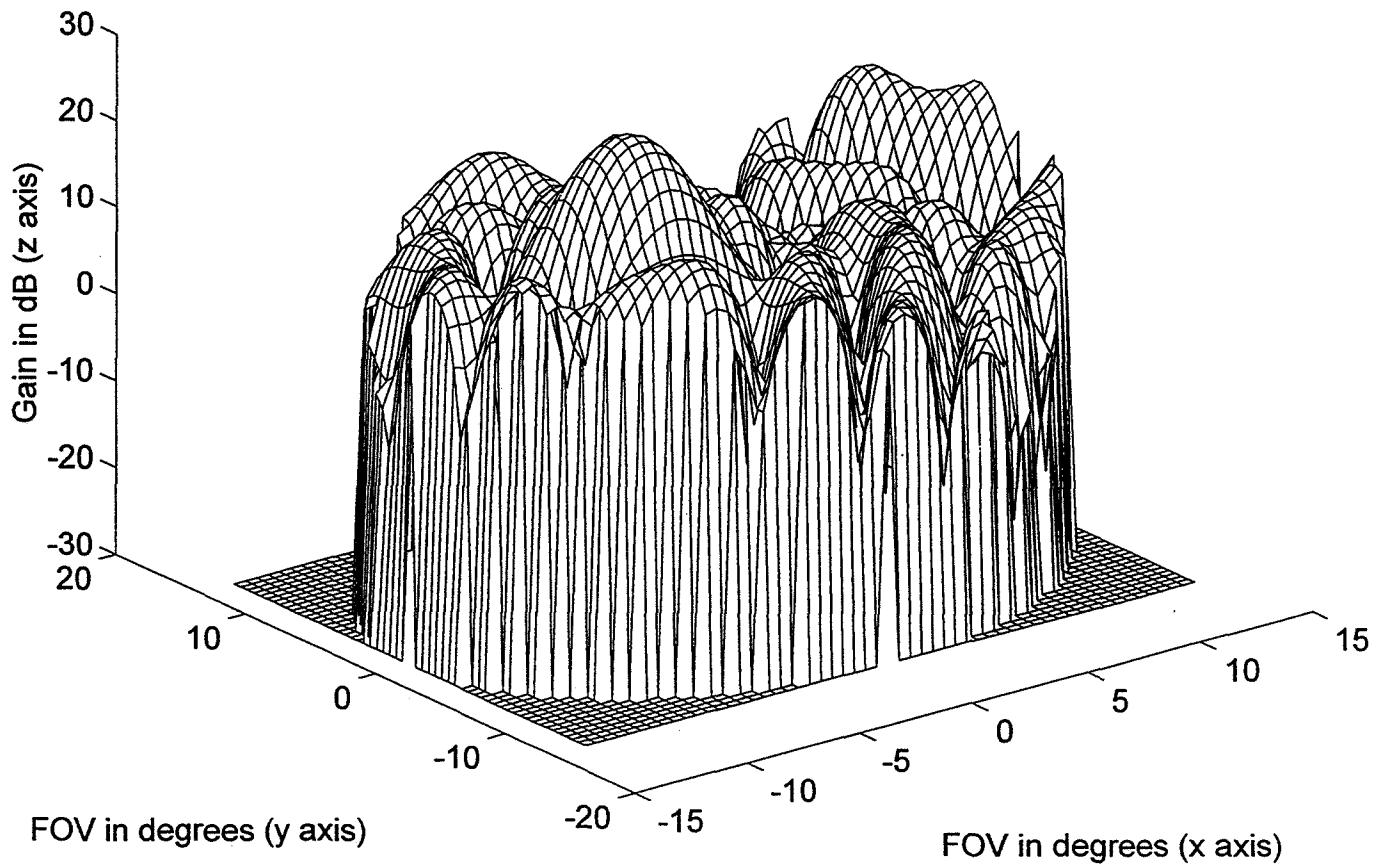
FIRST SIMULATION

CONTOUR: 30 Elements at Nadir (phi=0 degrees and theta=270 degrees)



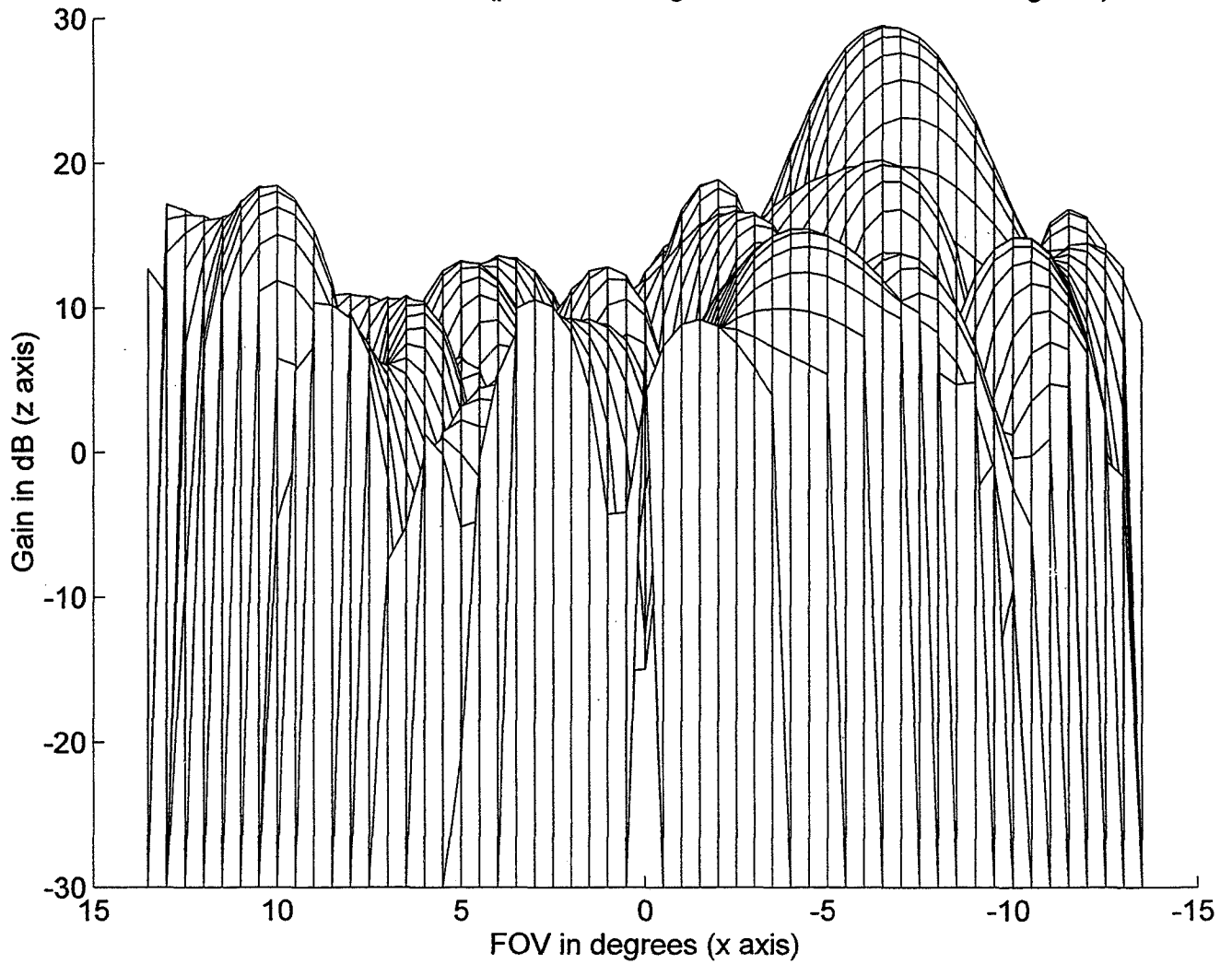
SECOND SIMULATION

30 Elements at WSGT ($\phi=8.312$ degrees and $\theta=215.91$ degrees)



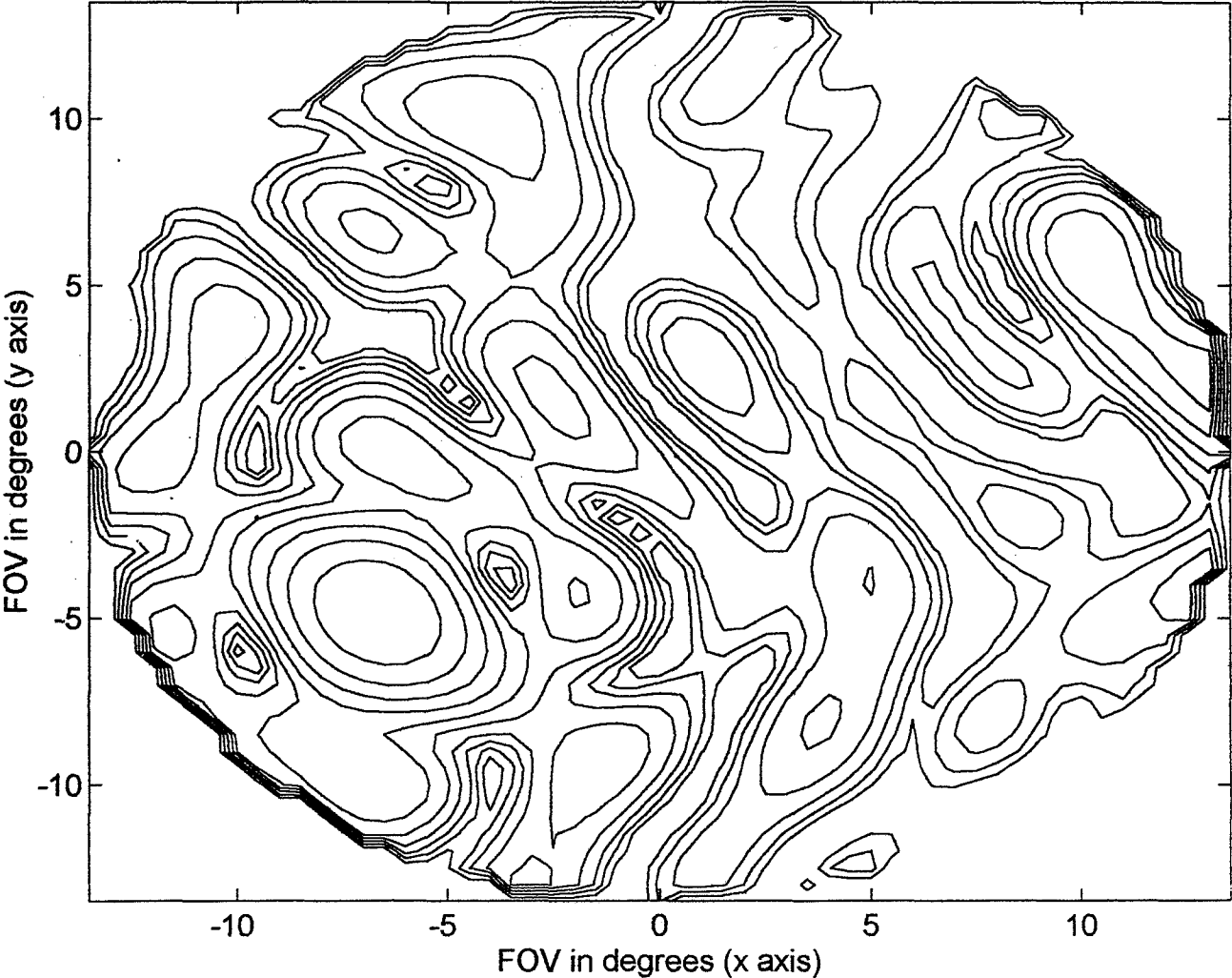
SECOND SIMULATION

30 Elements at WSGT ($\phi=8.312$ degrees and $\theta=215.91$ degrees)



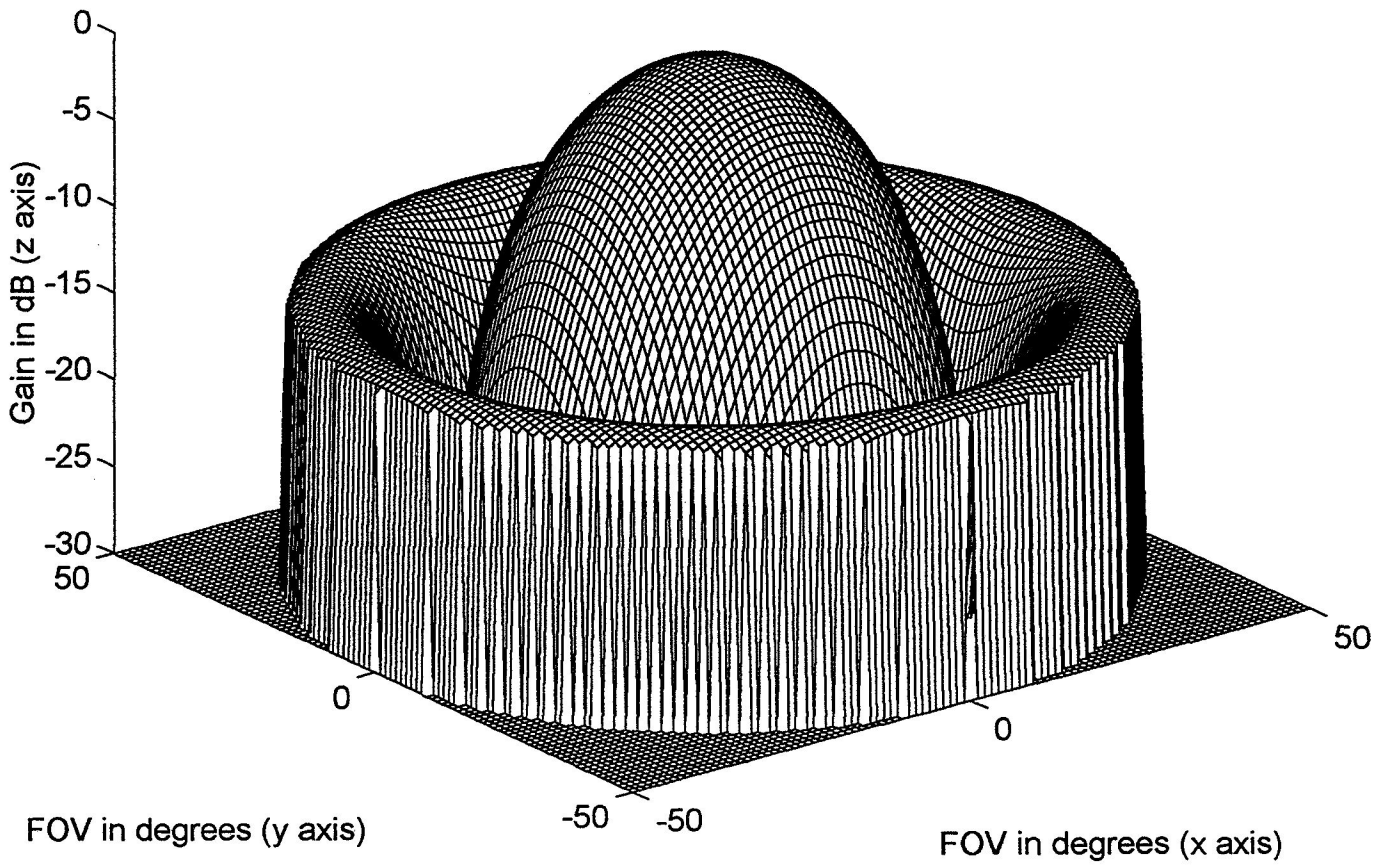
SECOND SIMULATION

CONTOUR: 30 Elements at WSMR ($\phi=8.312$ degrees and $\theta=215.91$ degrees)



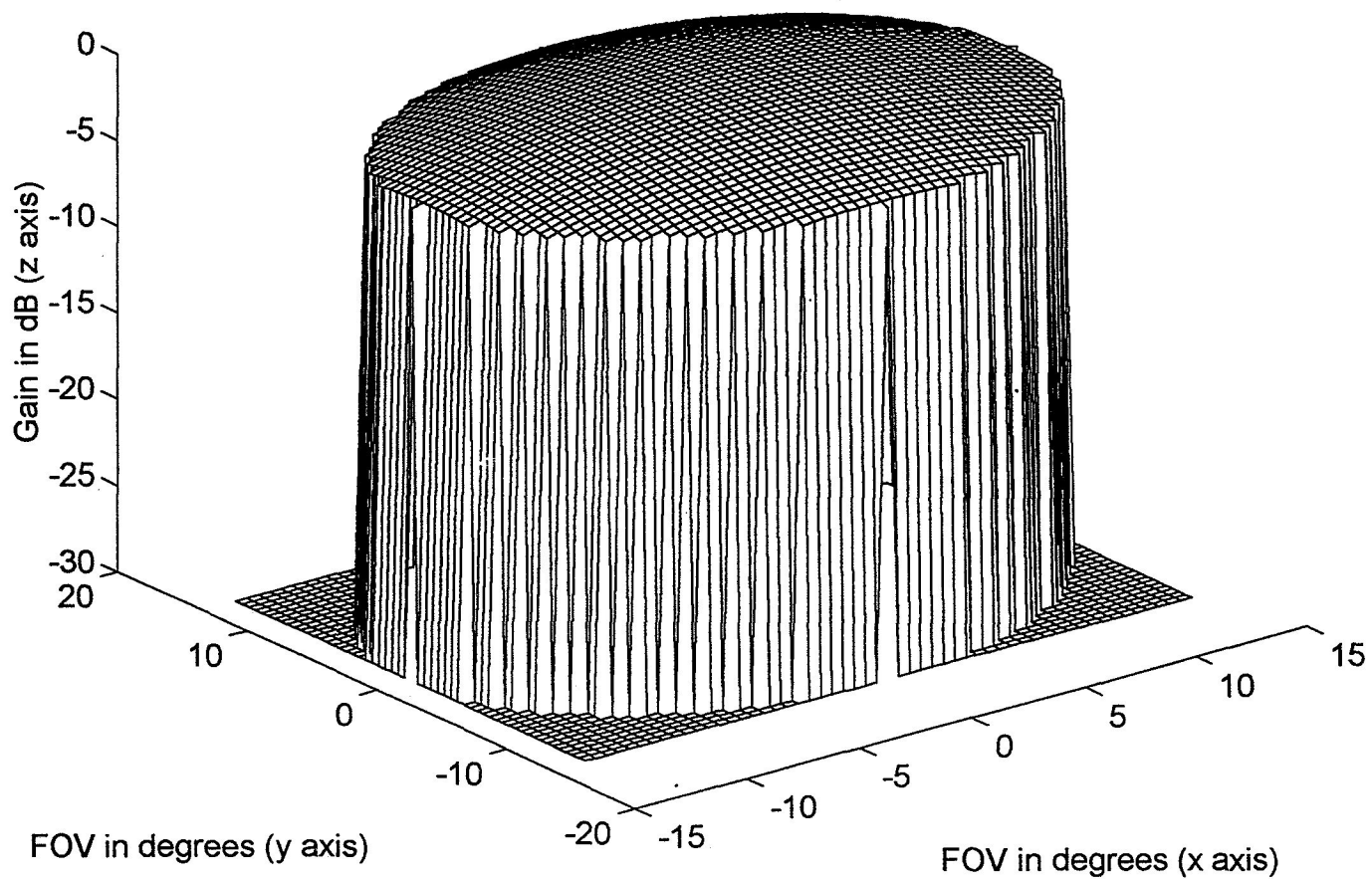
THIRD SIMULATION

Element #20 at Nadir ($\phi=0$ degrees and $\theta=270$ degrees)



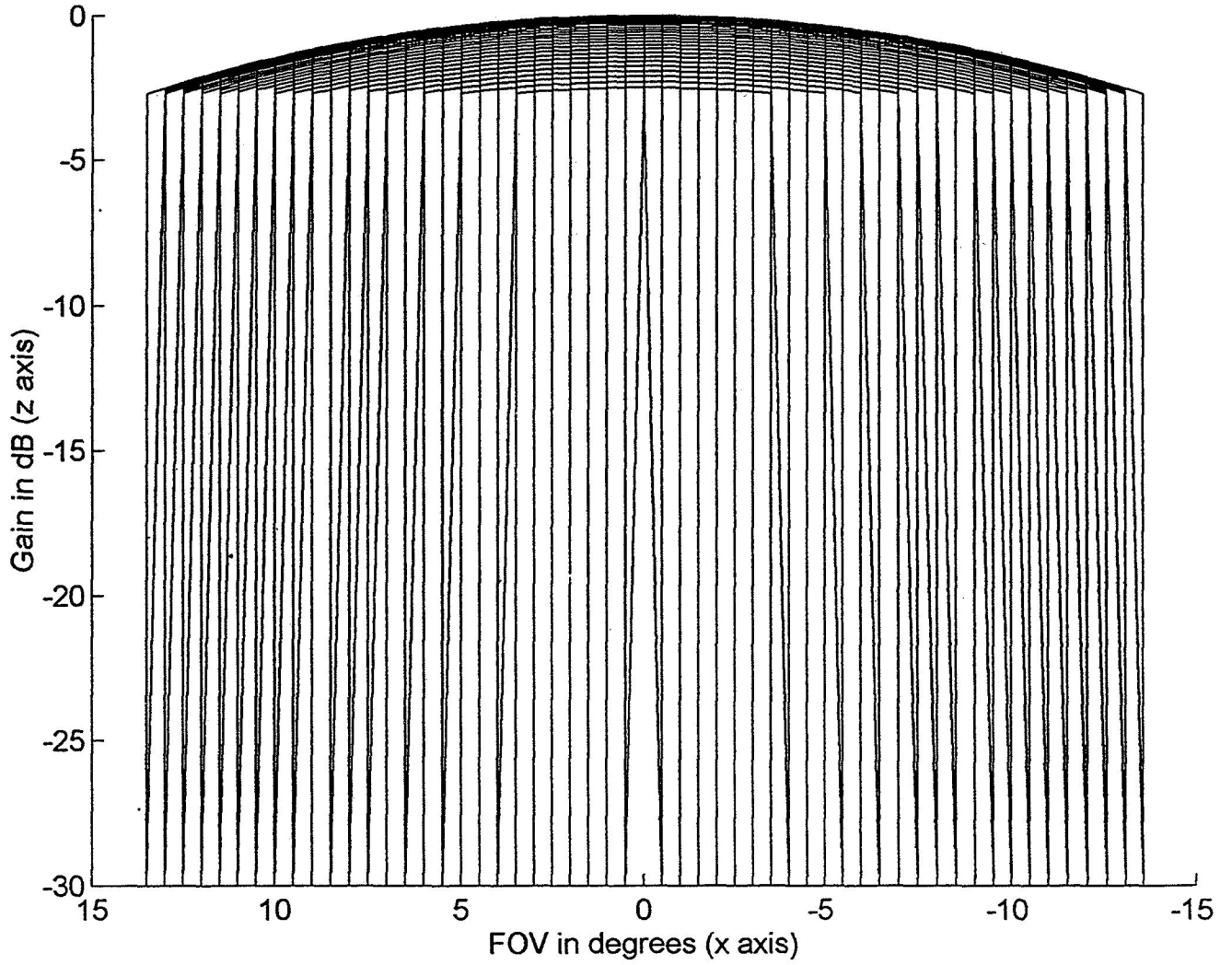
THIRD SIMULATION

Element #20 at Nadir ($\phi=0$ degrees and $\theta=270$ degrees)



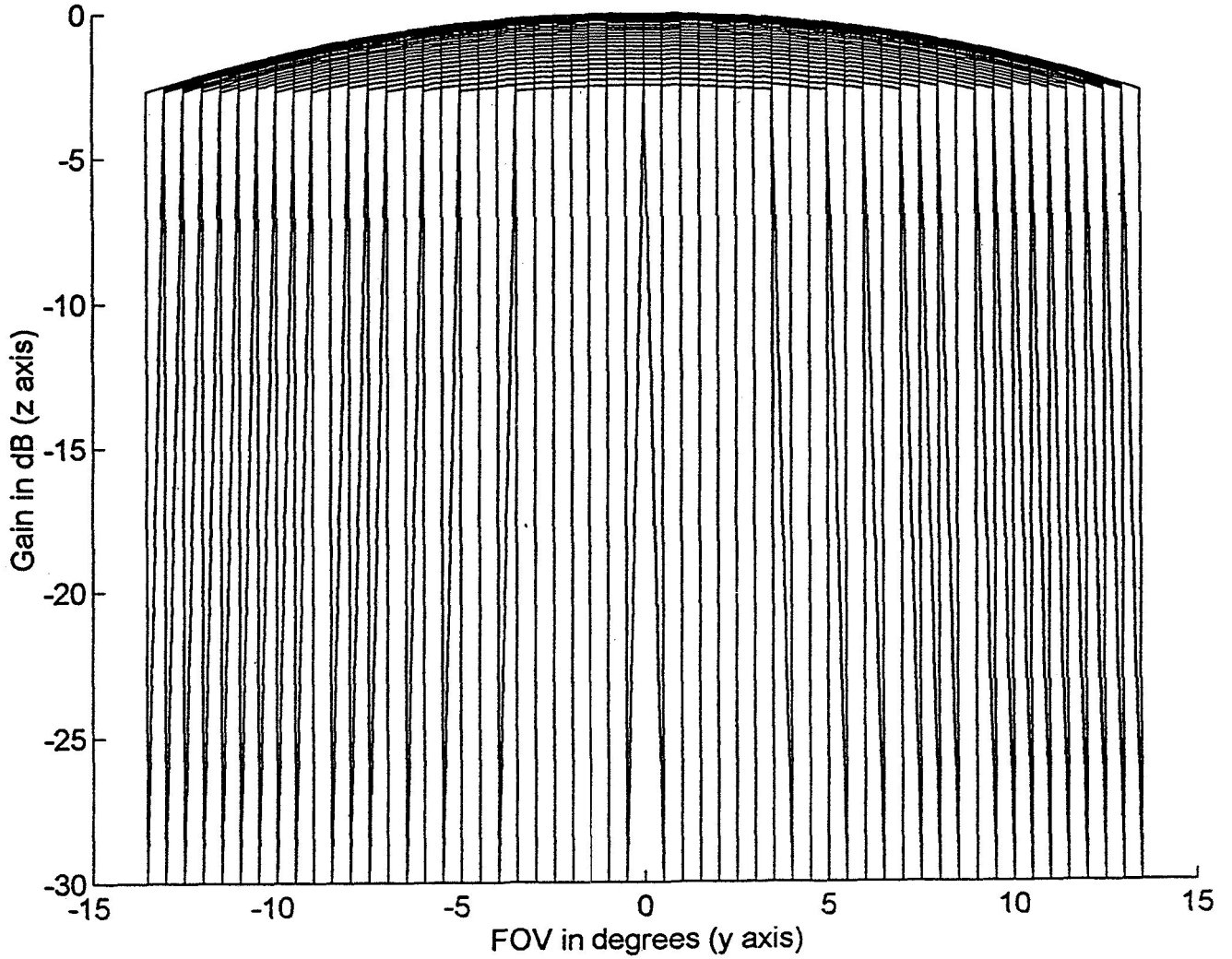
THIRD SIMULATION

Element #20 at Nadir (phi=0 degrees and theta=270 degrees)



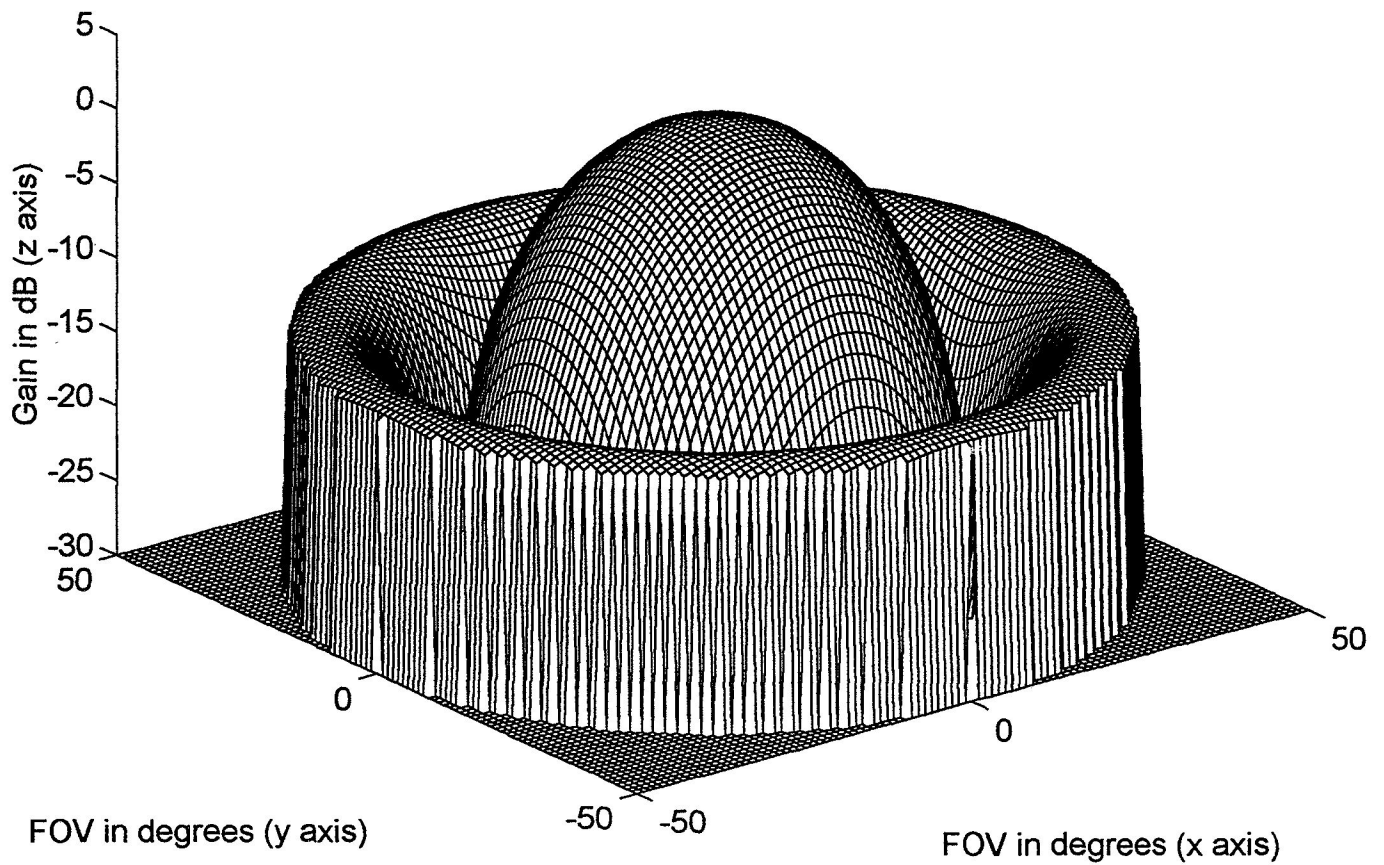
THIRD SIMULATION

Element #20 at Nadir ($\phi=0$ degrees and $\theta=270$ degrees)



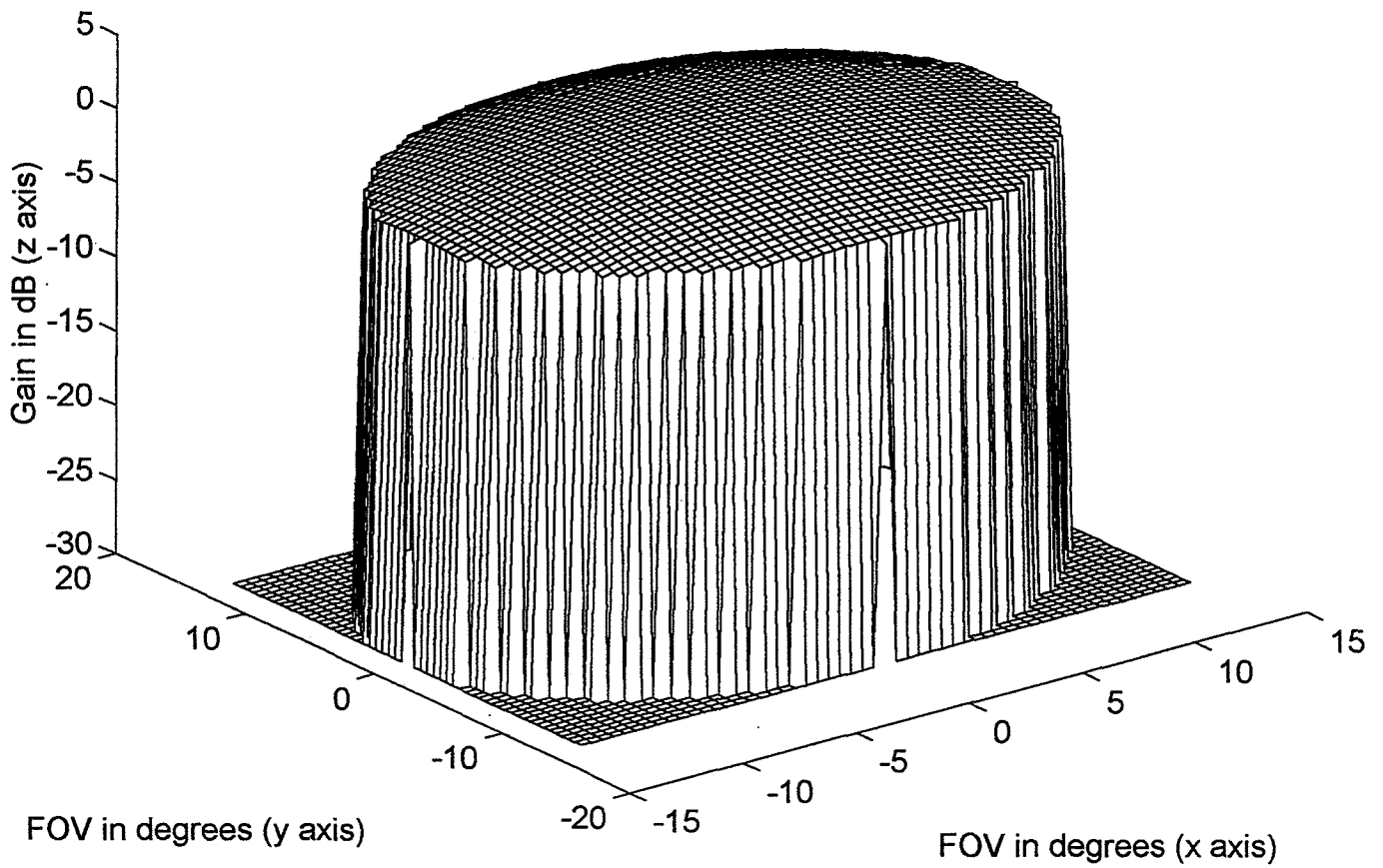
FOURTH SIMULATION

Element #20 at WSMR ($\phi=8.312$ degrees and $\theta=215.91$ degrees)



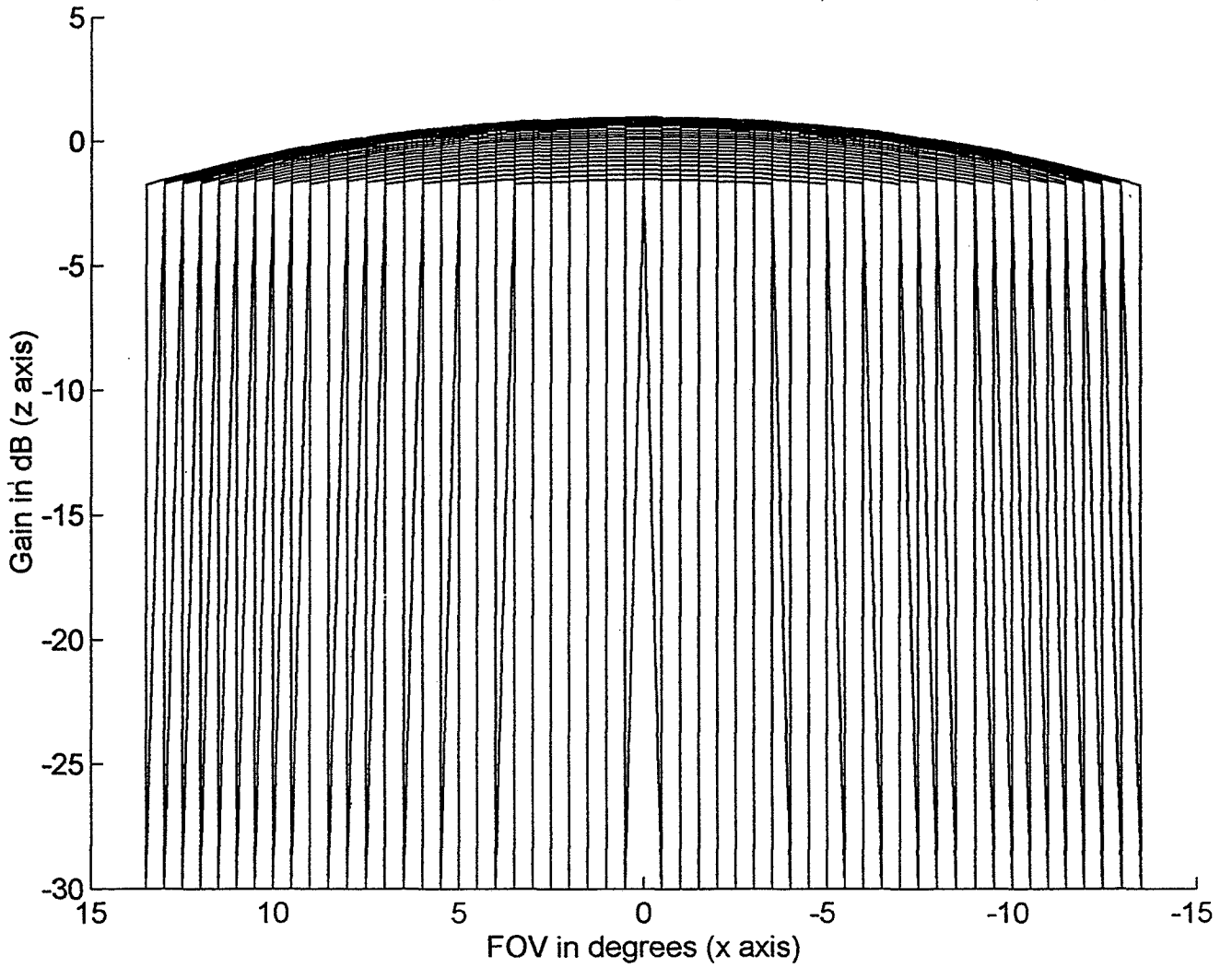
FOURTH SIMULATION

Element #20 at WSMR ($\phi=8.312$ degrees and $\theta=215.91$ degrees)



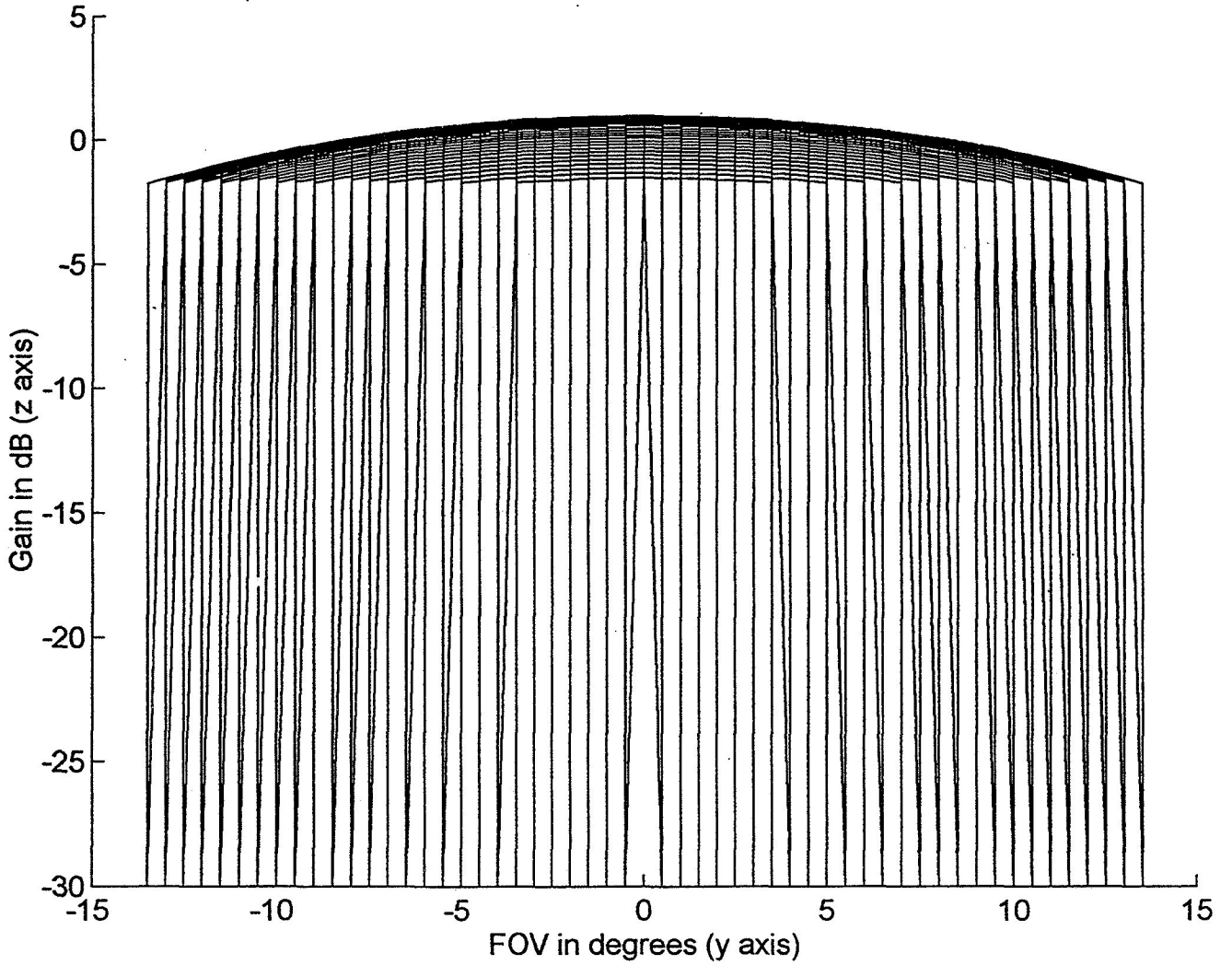
FOURTH SIMULATION

Element #20 at WSMR (phi=8.312 degrees and theta=215.91 degrees)



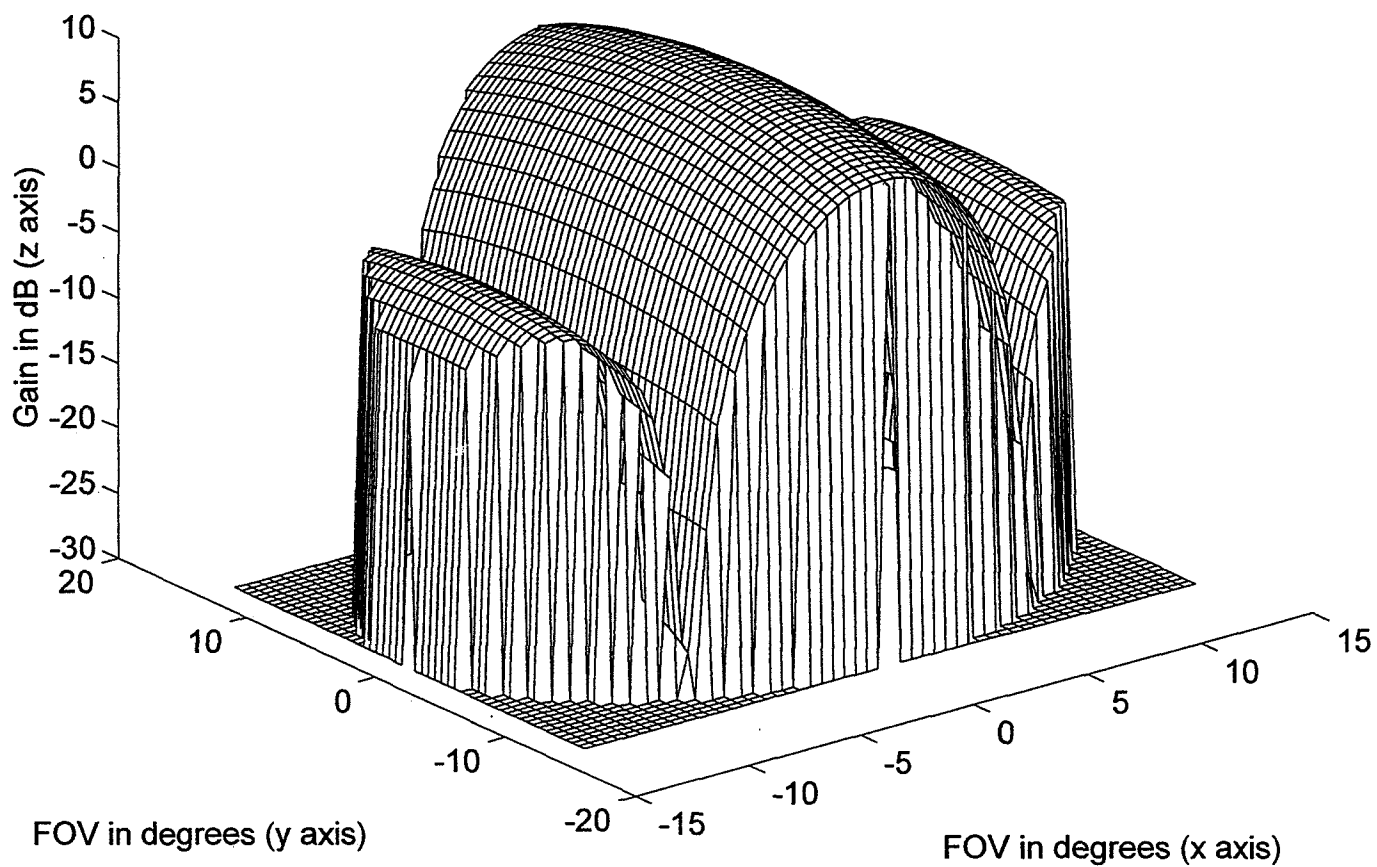
FOURTH SIMULATION

Element #20 at WSMR ($\phi=8.312$ degrees and $\theta=215.91$ degrees)



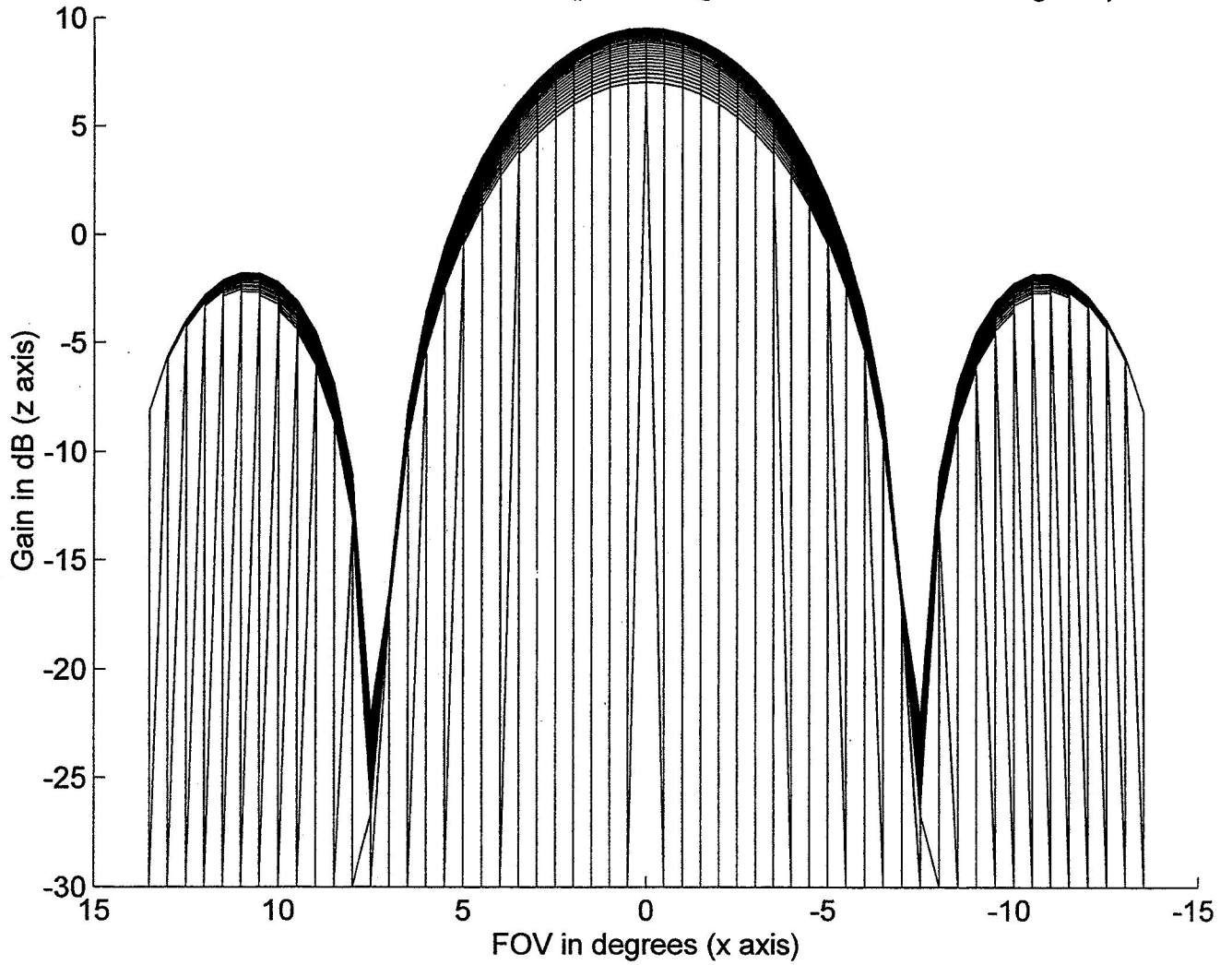
FIFTH SIMULATION

Elements #19-20-21 at Nadir ($\phi = 0$ degrees and $\theta = 270$ degrees)



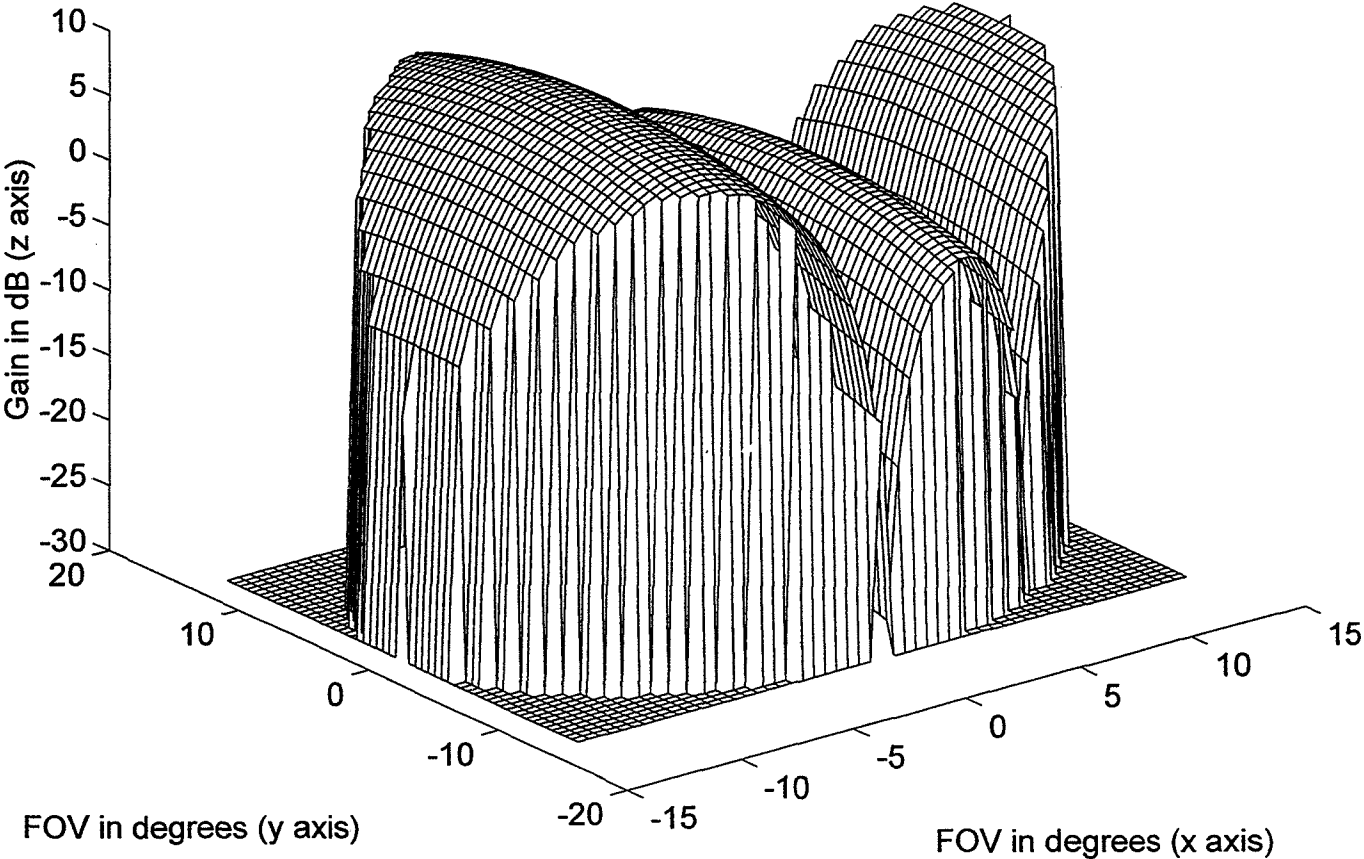
FIFTH SIMULATION

Elements #19-20-21 at Nadir ($\phi = 0$ degrees and $\theta = 270$ degrees)



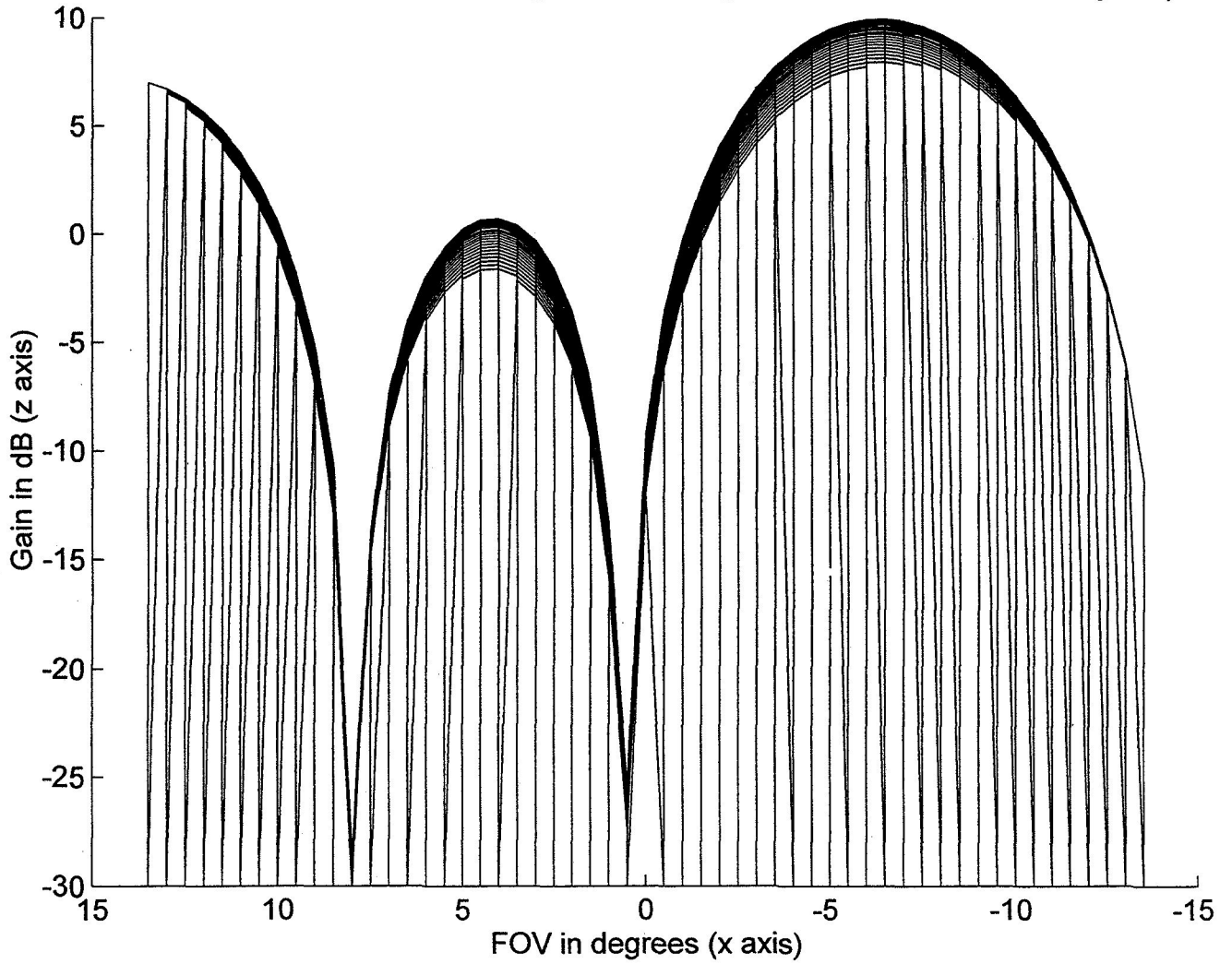
SIXTH SIMULATION

Elements #19-20-21 at WSGT ($\phi= 8.312$ degrees and $\theta = 215.91$ degrees)



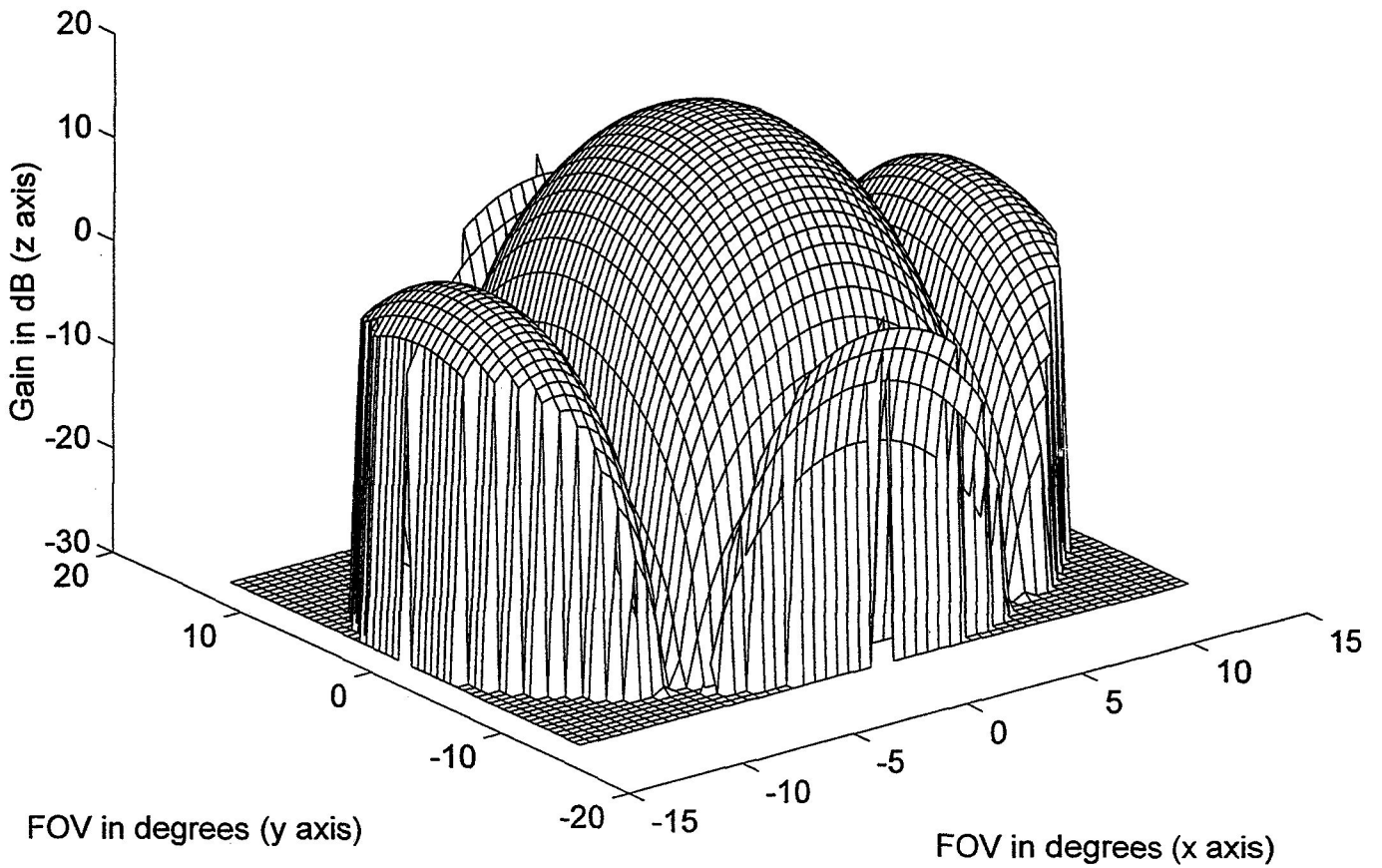
SIXTH SIMULATION

Elements #19-20-21 at WSGT ($\phi = 8.312$ degrees and $\theta = 215.91$ degrees)



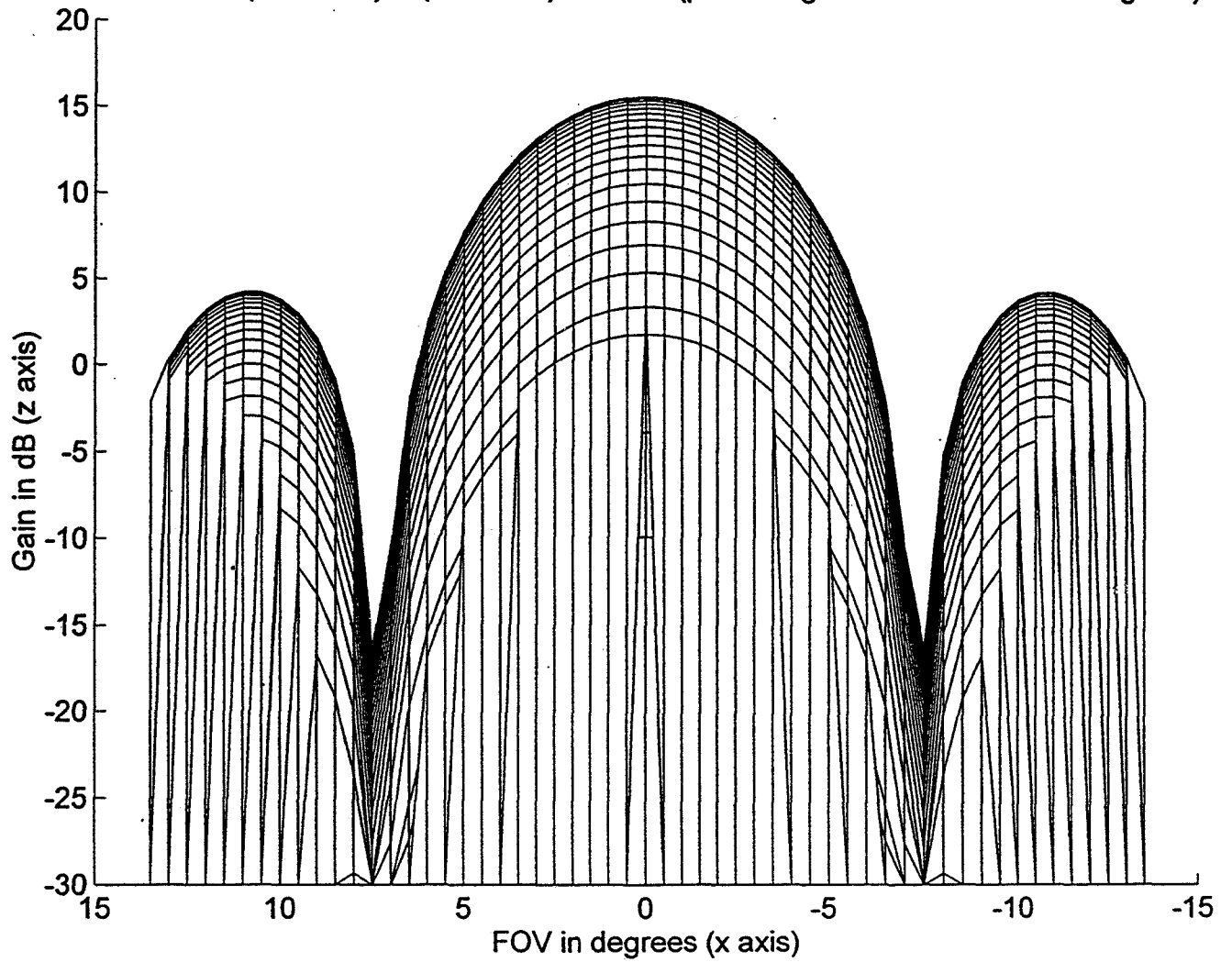
SEVENTH SIMULATION

Elements #(14-15-16) & (19-20-21) at Nadir ($\phi=0$ degrees and $\theta=270$ degrees)



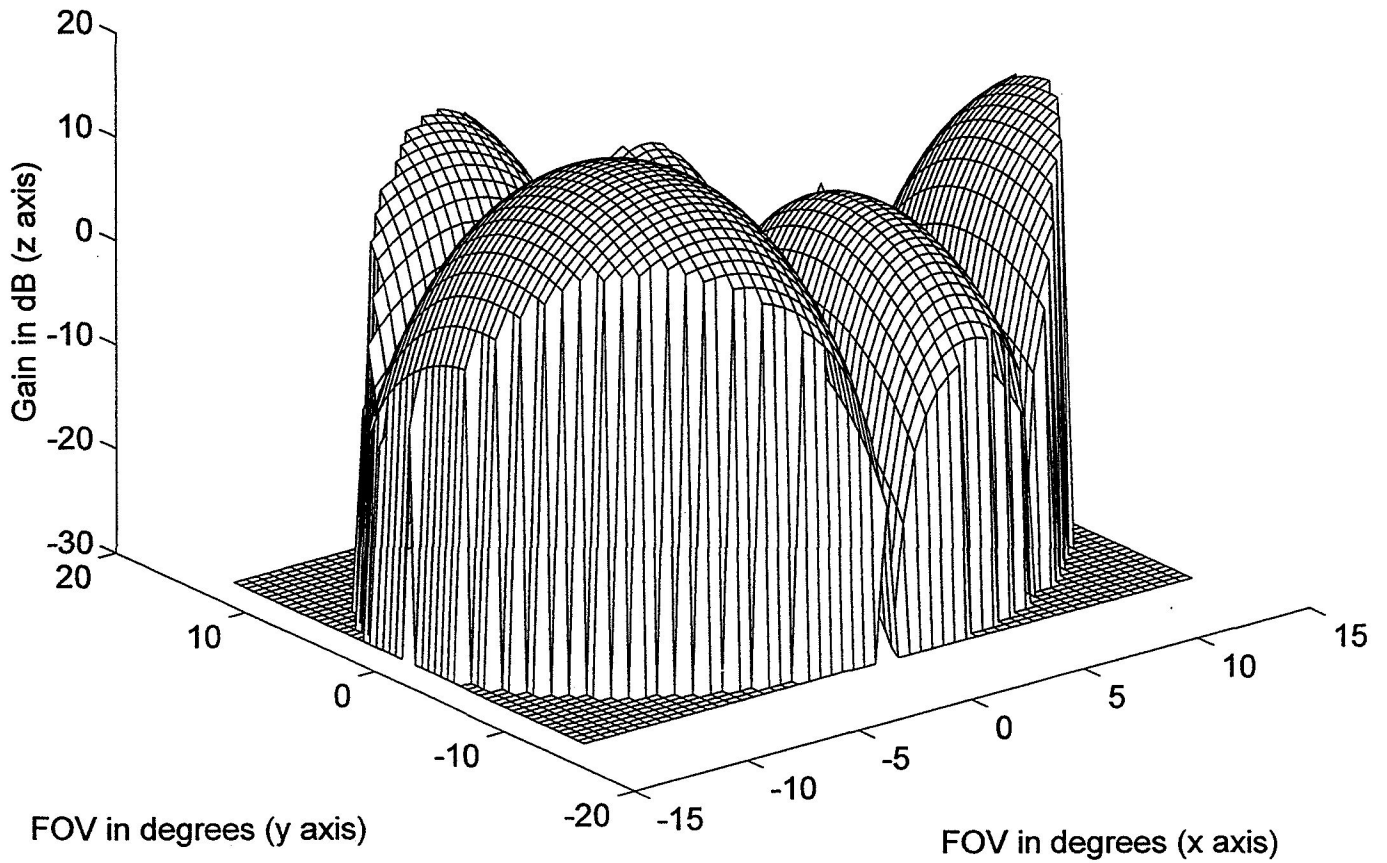
SEVENTH SIMULATION

Elements #(14-15-16) & (19-20-21) at Nadir ($\phi=0$ degrees and $\theta=270$ degrees)



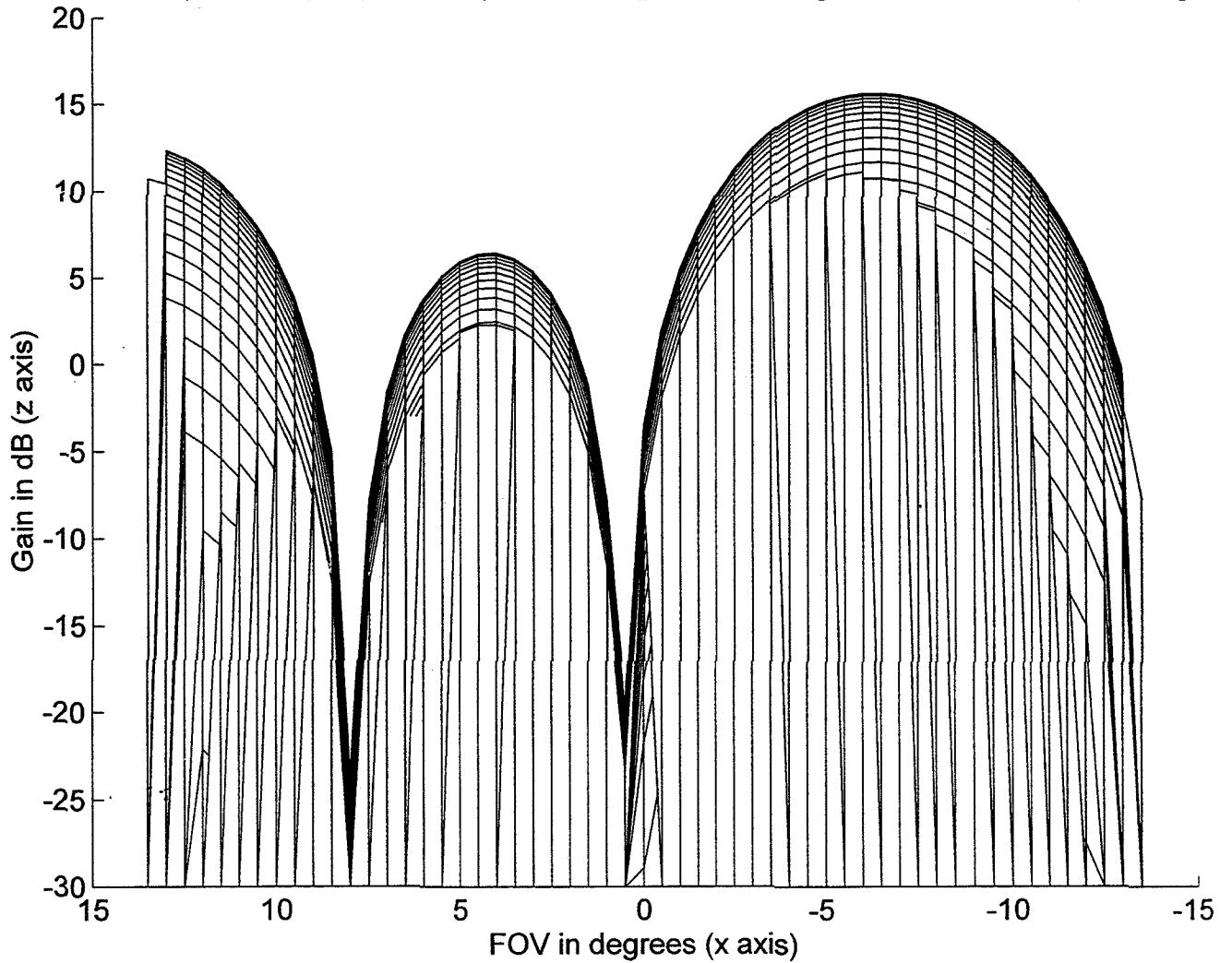
EIGHT SIMULATION

Elements #(14-15-16) & (19-20-21) at WSGT ($\phi=8.132$ degrees and $\theta=215.91$ degrees)



EIGHT SIMULATION

Elements #(14-15-16) & (19-20-21) at WSGT ($\phi=8.132$ degrees and $\theta=215.91$ degrees)



EIGHT SIMULATION

Elements #(14-15-16) & (19-20-21) at WSGT ($\phi=8.132$ degrees and $\theta=215.91$ degrees)

