Advancements in Achieving What is Asked of a Compact Range

David J. Wayne
John McKenna
Scott T. McBride
MI Technologies
Suwanee, Georgia, USA
dwayne@mitechnologies.com
smcbride@mitechnologies.com
jmckenna@mitechnologies.com

Abstract **- What is achievable in compact range performance is usually constrained by several factors. The desire for lower frequency performance must be weighed against the economics of reflector and chamber size. The desire for higher frequency performance puts demands on the reflector's surface accuracy. Consistency of performance across a waveguide band levies demands on compact range feeds.**

This paper addresses a recent compact range development by MI Technologies that achieves desired extended low frequency and millimeter wave performance (1 to 110GHz) while maintaining a cost effective reflector size and a small range footprint. The paper will explore the conventional rule-of-thumb relationships between feed, reflector, edge treatments and range geometries while contrasting them to the resultant design. The paper will highlight an impressive new family of compact range feeds and advancements in cost effectively achieving a superior reflector surface.

Keywords – Compact Range, Reflector, Feed, Edge treatment, Surface Accuracy

I. INTRODUCTION

This paper will explore design methodologies considered in a recent compact range development. It will define the requirements and constraints, discuss the ramifications to elements of the design, perform conventional design calculations that will show incompatibilities in staying within the constraints, and show how the incompatibilities were overcome.

II. REQUIREMENTS AND CONSTRAINTS

Every compact range development starts with the requirements and constraints. The pertinent parameters in this case study are as follows in Table 1;

TABLE 1 REQUIREMENTS AND CONSTRAINTS

Frequency 1 to 110 GHz
6'x6'x6' Quiet Zone
40'x 26'x 24' (LxWxH) interior chamber dimensions
Amplitude Taper ≤ 1 dB
Amplitude Ripple ≤ +/- 0.5 dB
Phase variation ≤ +/5 deg. for 1 to 18 GHz
Phase variation ≤ +/- 10 deg. 18 to 40 GHz
Phase variation ≤ +/- 20 deg. 40 to 110 GHz
Cross Polarization ≤ -30 dB

III. MAXIMUM AVAILABLE SPACE

Because of the constraint of the room size, the design starts with determining the maximum space available for the reflector. The next step will be to determine the combination of reflector body and edge treatment size within that space to deliver the desired performance. To determine the space available for the reflector a chamber layout analysis is performed. Appropriate absorber is selected and, allowing for an air gap of at least 2 wavelengths at the lowest desired frequency between the absorber and the reflector, and allowing height for the compact range feed positioner yields the allowable reflector dimensions to be 194 inches high and 222 inches wide as shown in Table 2. The combination of reflector body and edge treatment must fit within this space.

TABLE 2 AVAILABLE SPACE FOR REFLECTOR

Vertical Space		
Chamber Height		288
Floor Absorber Thickness	(inches)	-18
Floor absorber to Reflector allowing for feed positioner	(inches)	-34.4
Air Gap - Reflector to Ceiling Absorber	(inches)	-23.6
Ceiling Absorber Thickness	(inches)	-18
Available Vertical Space for Reflector	(inches)	194
Horizontal Space		
Chamber Width	(inches)	312
Side Wall Absorber Thickness (Total both sides)	(inches)	-36
Air Gap - Side Wall Absorber to Reflector (Total both sides)	(inches)	-54
Available Horizontal Space for Reflector	(inches)	222

IV. SELECTING THE REFLECTOR GEOMETRY

The desired lowest frequency, in conjunction with the amplitude ripple and phase variation requirements, will drive the size of the reflector. Conventional wisdom as reported in [1] suggests the body size of a reflector should be 25 to 30 wavelengths with edge treatments of at least 4 to 5 wavelengths. For 1 GHz (λ = 0.98'), this results in a reflector body approximately 25 to 30 ft. with serrations of 4 to 5 ft.

Since the width and height of the room is only 26' by 24'. This is a problem.

To stay within the constraints of the chamber size, the design strategy seeks a reflector size smaller than the conventional wisdom would suggest. The width and height of the room are the constraining factors. The length of the room is larger in comparison and should allow for some flexibility in selecting the focal length and placement of the quiet zone.

V. RELATIONSHIP BETWEEN REFLECTOR SIZE AND LOCATION OF THE QUIET ZONE

Another approach to estimating reflector body size and also locating the quiet zone is to use the Fresnel zone construction [2], i.e., body size should be large enough that every location of the perimeter in the rear of the quiet zone (Z) is illuminated by at least one Fresnel zone on the reflector body This implies a supplemental enlarging of the reflector body beyond the transverse area of the quiet zone in Figure 1.

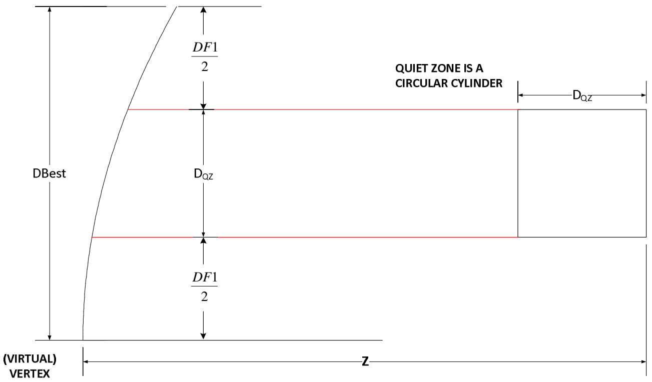

Figure 1 Elevation view

If $D_{F1} << 2z$ as is usual in compact range design, the diameter D_{F1} of the first Fresnel zone is, from [2]:

$$D_{F1} = 2\sqrt{z\lambda} \tag{1}$$

and the estimated reflector body diameter $D_{B_{est}}$ is

$$D_{B_{est}} = D_{F1} + D_{QZ}\ , \tag{2}$$

where D_{QZ} is the quiet-zone diameter.

For example, Figure 2 shows the results of equation (2) calculating the minimum estimated body size D_{Best} as a function of the placement of the rear of the quiet zone Z for the desired lowest operational frequency 1GHz and quiet zone diameter 6 feet.

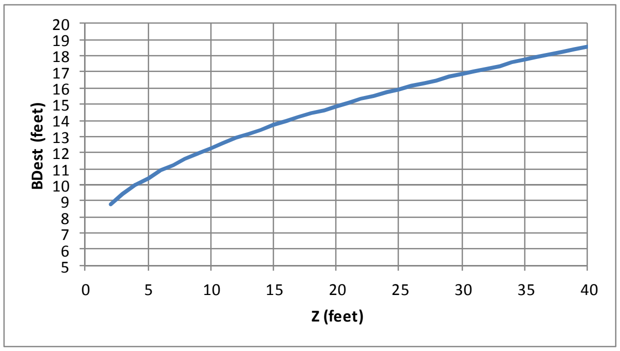

Figure 2 Estimated reflector body size for D_{QZ} = 6 ft @ 1 GHz

The important point in the relationship is that the further the quiet zone is located away from the reflector, the larger the reflector must be to satisfy the Fresnel zone criteria. Substituting the allowable space for the reflector (194' x 222") as D_{Best} into equation (2) or reading the results directly from Figure 2, shows the back of the quiet zone Z should be no more than 26.3 ft from the reflector.

Figure 3 is useful in visualizing what is happening with the Fresnel zone criteria. The reflector body can be thought of as a slit aperture through which an incident wavefront passes [3]. The observation point is the back corner of the quiet zone. The dark regions are regions of severe interference akin to being in the shadow of the aperture. The transition regions changes from dark to light. The light region is where the light passing thru the aperture is free of interference. It is desired to place the quiet zone in this region which we have noted from (2) or Figure 2 to be Z< 26.3 ft.

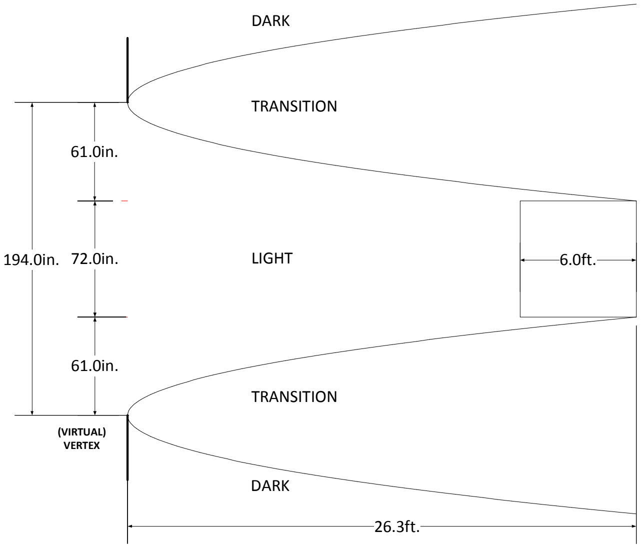

Figure 3 Fresnel zone - light, dark & transition regions

VI. OPERATING IN THE NEAR-FIELD REGION

Another methodology to placing the quiet zone is by analyzing the reflector as a radiating aperture. Reference [4] provides a good description of the theory of near field radiation and

Brumley [1] develops the thought into some useful simple equations. The collimating reflector produces a plane wave in the vicinity of the reflector surface. Compact ranges generally operate in this collimated near field region. As the wave propagates away from the reflector the beam begins to form, transitioning from the near-field region to a quasi far-field region to the far field. Brumley [1] presents the equation that can be used to determine the location of the various regions.

$$Z = ND^2/\text{wavelength} \qquad (3)$$

Where Z is the distance of the region from the vertex and D is the diameter of the aperture (reflector body). Note if N=2 this becomes the familiar equation for the beginning of the far field region.

The near field extends from the reflector surface to N= 0.15. The radiating near-field region extends from N=0.15 to N = 0.30. Beyond that is the quasi far-field region until the far field is achieved at N=2. Brumley's work [1] suggests the radiating near-field region can be successfully utilized under the right conditions. With this in mind, we use equation (3) to determine where the near-field region ends for a rectangular aperture, starting with an aperture (reflector body) that totally fills the available space and then reducing the body size as serration length is added up to 4 wavelengths.

For the vertical direction with no edge treatment Z = 40 ft
For the horizontal direction with no edge treatment Z = 52 ft

For the vertical direction with 4 λ edge treatment Z = 11 ft
For the horizontal direction with 4 λ edge treatment Z = 17 ft

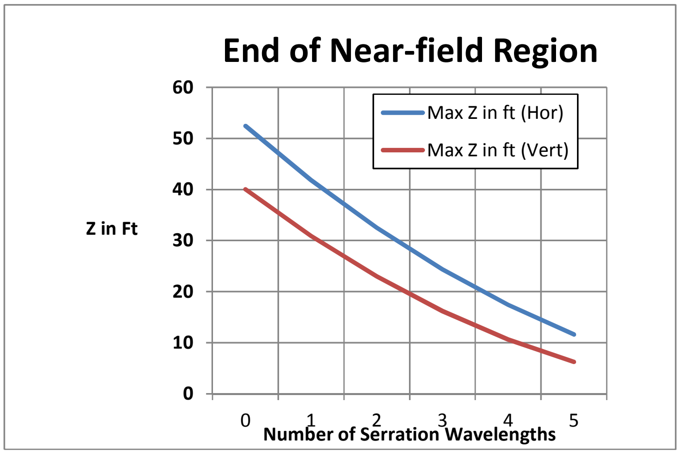

Figure 4 Near-field region for reduced body sizes as a function of edge treatment size for 1 GHz

Figure 4 shows the maximum distance where the quiet zone can be placed downrange of the reflector to maintain operation in the near-field region for different proportions of edge treatment to body size. At the same time, the quiet zone must not be too close to the feed in order to limit stray signal emitting back from the feed and to stay above all the reflector's local normal vectors. The final selected focal length may put the quiet zone into the quasi near-field region in which case the final selected combination of body and serration geometry must be made to work for this region.

VII. RELATIONSHIP BETWEEN FEED AND FOCAL LENGTH

In order to minimize the reflector size, the quiet zone should be as close to the reflector as possible. This places demands on the compact range feed to be broad beamed to cover the quiet zone. A broad beam allows a shorter focal length and thus a closer placement of the quiet zone. The selection of the compact range feed is very important. An appropriate compact range feed would have a radiation pattern such that its phase would be constant over the area of the quiet zone with less than 1 dB amplitude taper. There will be an additional small contribution (0.1 to 0.2 dB) to taper due to the free space loss of the transmitted signal from the feed to the reflector and the shape of the reflector. There is essentially no free space loss from the reflector surface to the quiet zone as a result of the collimated plane wave produced by the reflector's parabolic shape. To meet the 1 dB taper requirement and to account for space-loss induced taper we will design for a beamwidth of at least 0.8 dB at the boundaries of the quiet zone. Once the focal length is selected, the contribution of the space-loss induced taper can be calculated using the approximate equation offered by [5].

$$\text{Reflector induced taper} = 0.54*(D/FL)^2 \text{ dB} \qquad (4)$$

Offset compact range reflectors angle the feed to properly illuminate the reflector [6]. Therefore the angle of the feed with respect to the reflector enters in to the geometric relationship. A discussion of the relationship can be found in [5] & [6] to relate the feed angle and focal length to the beamwidth that illuminates the quiet zone. However the contribution of the feed angle is small. For our purposes we will use the simple geometric relationship shown in Figure 5 to derive an initial candidate beam width for the feed.

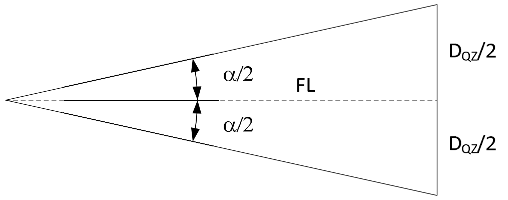

Figure 5 Geometry of focal length to quiet zone

We desire the 0.8 dB beamwidth (α) of the feed to illuminate the quiet zone. Using the simplified geometric relationship as shown in Figure 5 we can express the relationship between focal length, field beam width and quiet zone size to be:

$$FL = (D_{QZ}/2)/(\tan \alpha/2) \qquad (5)$$

The perfect compact range feed maintains a consistent broad beamwidth across its frequency band. It also has good cross-polarization characteristics and good E and H plane symmetry.

Achieving all three is not an easy task. Most available feeds on the market have either narrow beamwidth with good cross polarization or broad beamwidth at the expense of cross polarization. Also the beamwidth of most feeds decrease with increasing frequency. As the beamwidth narrows the amplitude taper performance suffers. Unfortunately most commercially available feeds that have sufficient good cross polarization only achieve about 16 degree beamwidth at 0.9 dB. From (5), this would necessitate a focal length of 21 ft and a placement of the back of the quiet zone out past 27 ft. Referring back to Figure 2 and looking at Z = 27 results again in conventional wisdom that says the size of the reflector wants to be larger than the available space.

With this in mind the family of MI-233 compact range feeds was selected. It has been developed specifically for use in compact ranges and has both a broad beam and the necessary cross polarization performance (-35dB). It achieves the desired characteristics impressively maintaining a consistant 1 dB beamwidth across the frequency band.

We desire the 0.8 dB beam width of the feed to illuminate the quiet zone. Using the simplified geometric relationship as shown in Figure 5 and the 0.8 dB beamwidth of the MI-233 feed, which is 28 degrees, we calculate that this selection of feed allows the focal length FL to be as close to the reflector as 12 ft.

$$FL = (D_{QZ}/2)/\text{Tan}\ (28/2) = 12\ \text{ft}. \qquad (6)$$

VIII. MECHANICAL INTERFERENCE CONSTRAINTS

The quiet zone must be placed far enough behind the feed positioner, which is at the focal point, to allow for proper operation of the positioner with its offset arm and to avoid back radiation of the feed into the quiet zone. To accomplish this, the back of the quiet zone is set to a position of

$$Z = FL + FeedClearance + QZ \qquad (7)$$

Where

- Z = distance from reflector to back of QZ
- FL= focal length
- Feed clearance = 5 ft
- QZ = quiet zone depth = 6 ft

For a 12 ft focal length this puts the QZ at Z = 17 to 23 ft. It is worth noting that this may encroach into the quasi near-field region as determined from Equation (3) and Figure 4 depending on the final selection of the size of the edge treatment.

Summarizing to this point, we find that conventional design rules lead us to a reflector design that is much larger than the room will allow. Our task remains to find a combination of edge treatment and body size that will fit into 194 inch Height and 222 inch width with approximately a 12 ft focal length, with the quiet zone placed as close as possible to or within the near-field region.

IX. DESIGNING THE EDGE TREATMENTS

Edge treatments are used to manage the diffraction that occurs at the otherwise abrupt boundary of the reflector body. Two main types are typically employed, either rolled edges or serrated edges. A discussion of the relative advantages of each has been a subject of much discussion over the years. The reader is referred to [7] for more information. Here we will select serrated edges.

One view of the edge treatment's purpose is that it should gracefully transition the reflected field from nearly uniform full strength directly in front of the body to zero strength just outside the edge-treatment envelope. With traditional metallic serrations, this field taper might be approximated by decreasing the percentage of reflecting serration area in a controlled manner over the edge-treatment region. In other words, there is essentially 100% metal where the serration meets the body, and essentially 0% metal over a rectangle at the serration tips. As a first-order approximation, we then ought to be able to control the field taper shape between those bounds through design of the serration shapes.

We know from microwave holography that if the field on one plane is known, the field that would be measured on another plane can be determined. A holographic model was therefore constructed to estimate the quiet-zone field from the estimated field directly in front of the reflector. This reflector field is estimated as unity within the serration outline and zero outside that boundary. The reflector field is first filtered to suppress any spectral components that would not propagate toward the quiet zone, and then holographically propagated to the quiet-zone plane. The standard metrics of amplitude and phase quiet-zone ripple can then be compared among candidate serration shapes, with the more promising shapes modeled with more rigorous tools such as Grasp[8].

The filtered reflector field can also provide some information about the effectiveness of the edge treatment. In Figure 6 we see that estimate of filtered field at 1.5 GHz for a standard MI-506C reflector. This filtered field is the approximated field immediately in front of the reflector, with spectral components removed that do not propagate toward the quiet zone. The MI-506C reflector is specified to operate down to 2 GHz. However, attempts to extend its low-frequency performance by lengthening serrations did not yield improvement proportional to serration length.

In Figure 6 we see that the absence of serrations in the corners leads to abrupt transitions from full to zero field strength in those corners. Abrupt transitions in the field that radiates back to the quiet zone (the filtered field) lead to ripple throughout the quiet zone, and are therefore to be avoided. Since these corner features were present regardless of the serration length, it seems likely that they were limiting the low end of the reflector's frequency range.

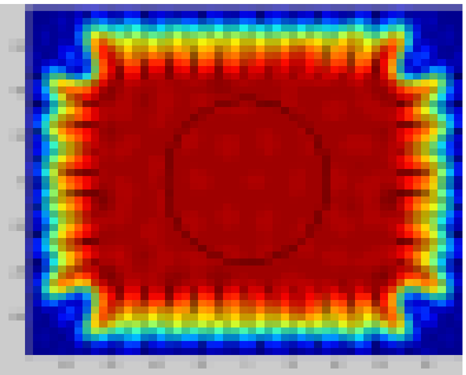

Figure 6 Filtered field showing discontinuity in corners for Standard MI-506C reflector

Figure 7 shows an alternative serration profile's filtered reflector field, this time at 1 GHz. The serration shapes have been redesigned here with the goal of producing a better taper of the filtered reflector field, which should result in a smoother quiet-zone field. Also included in the modification was a lengthening of the serrations by 50% to improve low-frequency performance. It was found that lengthening the serrations was more effective than increasing the body size. The resulting geometry shown in Figure 7 utilizes the full space available for the reflector.

Figure 7 comes close to the field-taper characteristics we are trying to achieve with the serrations. Though some ripple has been induced in front of the body, the taper in the entire serration region appears smooth and gradual. This serration profile was then modeled in Grasp [8], with good results down to 1 GHz. The serration profile was a key element of the final design achieving the desired low frequency performance.

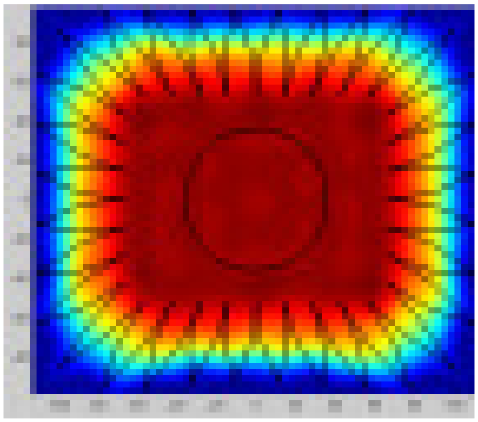

Figure 7 Filtered reflector field with uniform taper in serration region for modified MI-506C reflector

X. HIGH FREQUENCY PERFORMANCE AND SURFACE ACCURACY

The desired high frequency in conjunction with the amplitude ripple and phase variation requirement suggests the surface of the reflector must be extremely uniform only allowing very small deviations with respect to the desired paraboloidal shape. Joy & Wilson [9] offer 3 models for determining the expectant amplitude ripple due to surface deviations d as follows:

1) Model 1 Sinusoidal surface error, d is the peak of the sinusoidal surface deviation

$$Ripple(dB) = \pm 20 Log(1 - \frac{4\pi d}{\lambda}), \quad (8)$$

2) Model 2 Single Fresnel zone dimple, d is the peak of a simple dimple with diameter = 1 fresnel zone

$$Ripple(dB) = \pm 20 Log(1 - \frac{8d}{\lambda}) \quad (9)$$

3) Model 3 Random collection of bumps, d is an RMS value of surface deviation with diameters small with respect to a fresnel zone.

$$Ripple(dB) = \pm 20 Log(1 - \frac{2\pi d}{\lambda}) \quad (10)$$

Figure 8 plots calculated peak-to-peak amplitude ripple as a function of surface deviation d, according to the three equations and models. We see that Model 1 predicts the most severe response. Model 2 is more in line with our experiences at MI Technologies. Model 2 suggests that to achieve the 1dB amplitude ripple requirement requires a surface quality with deviations equal to or less than 0.0008 inches while Model 3 suggests the surface should have less than 0.001 RMS of deviation or less.

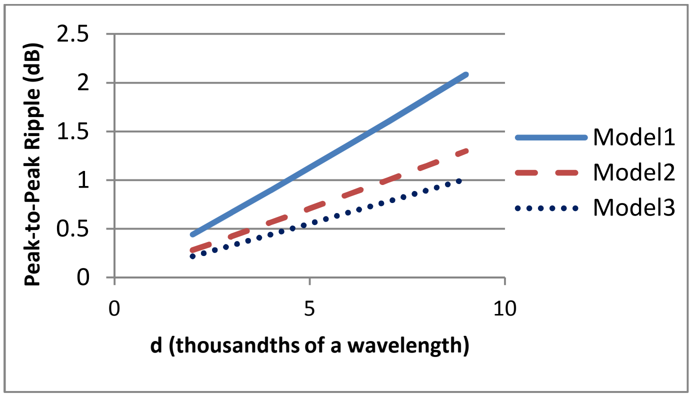

Figure 8 Models of surface accuracy

Figure 9 is a contour surface plot of a previously installed MI Technologies reflector with a 6 ft quiet zone. The measurements were made with a FARO® tracking laser. The plot shows the surface deviation as compared to the desired paraboloidal reflector body. It is representative of MI

Technologies' finishing process which is capable of achieving surface quality sufficient for W-Band operation. The example reflector achieved a deviation of 0.0006 inch RMS within the quiet zone and 0.0008 inch RMS across the whole reflector.

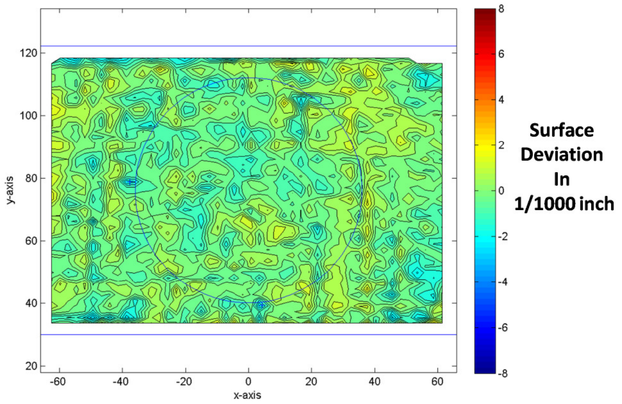

Figure 9 Reflector with W-Band surface quality

XI. FINALIZING THE DESIGN

Now that we have a candidate body size, edge treatment design, focal length and feed beamwidth, the next step is to model the system using GRASP [8]. The ratio of serration length-to-body size was iterated parametrically, within the constraints of the available space until suitable performance was achieved. Figure 10 shows the final geometry.

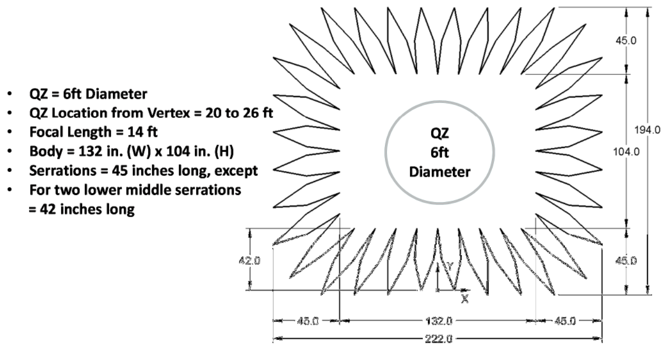

Figure 10 Final reflector design

Figure 11 shows the results of the GRASP [8] simulation. The data shows all the performance parameters form Table 1 meeting their requirements for amplitude taper and ripple, and phase variation at low frequency. The data included cuts through the quiet zone of various combinations of polarization, cut angle, position in the quiet zone and frequencies.

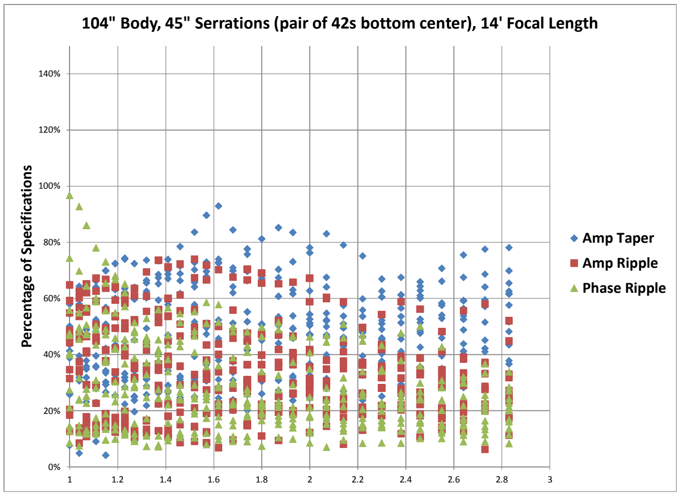

Figure 11 Predicted low-frequency results using GRASP

XII. CONCLUSION

A recent compact range development was discussed exploring selected design methodologies. The requirements and constraints of a compact range were given. The ramifications to elements of the design were discussed. Conventional design calculations were performed that showed incompatibilities in staying within the constraints. A design process was presented that resulted in overcoming the constraints and predicts achieving the desired performance.

REFERENCES

[1] S. Brumley, "Low frequency operation, design and limitations of the compact range reflector", AMTA proceedings pp 157-162, October 1994

[2] M. Born and E. Wolf, Priciples of Optics, 7th ed., Cambridge University Press, 2011, isbn-13 978-0-521-64222-4, p417.

[3] J. W. Goodman, "Introduction to Fourier optics" 3rd ed, Stanford University, Roberts & Co publishing , 2005, Chapter 4.2, pp 66-74

[4] R. Hansen, Microwave Scanning Antennas, Peninsula publishing, 1985

[5] M. Boumans "Influence of range geometry and feed characteristics on compact range system level performance", AMTA proceedings pp 221-226, Oct 2004

[6] Richard C. Johnson, "Some Design Parameters for Point-Source Compact Ranges" IEEE Trans. Antennas Propagat., vol AP-34, no. 6 June 1986

[7] T. H. Lee and W. D. Burnside, "Performance trade-off between serrated edge and blended rolled edge compact range reflectors" IEEE Trans. Antennas Propagat., vol 44, no. 1 January 1996

[8] Knud Pontoppidan editor "GRASP8 Technical Description", TICRA Engineering Consultants, Laederstraede 34 DK-1201 Copenhagen K Denmark

[9] E. B. Joy and R. E. Wilson, Spectral Evaluation of Reflector Surfaces Used for Compact Ranges", AMTA Proceedings pp 111-115, Sept. 1986