Design of Shaped-Beam Parabolic Reflector Antenna for Peninsular Malaysia Beam Coverage and its Overlapping Feed Issues

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Abstract **─** Design and performance of a shaped beam 12.2 GHz array-fed reflector antenna for broadcasting satellite is presented in this paper. Initial design, employing a cluster of feed horns illuminating a parabolic reflector is initially proposed for multi beam antenna (MBA) system to produce a contoured beam for Peninsular Malaysia. The precise feed positions are determined through a newly developed ray tracing program. Due to the small size of the coverage area, an issue with regards to physical constructability of the feed horns is raised. The MBA is modified by utilizing 18-element microstrip array as the feed, where each element positions are calculated by using the same caustic model. In this case, the preceding issue is solved, and high gain shaped beam coverage with uniform aperture is generated. This paper shows the results of the contoured beam antenna that have been achieved for beam scanned over a coverage size of approximately 0.9° long and 0.5° wide. Small variation of radiation level, which is less than 3dB within the edge of coverage (EOC), is also demonstrated in the performance analysis.

Index Terms **─** Antenna feeds, arrays, caustic model, ray tracing, reflector, satellite antenna.

I. INTRODUCTION

Reflector technologies have experienced many significant developments in the recent years. However, as satellite requirements become more stringent, the needs for shaped or contoured beam have rapidly increased. Contoured beam antennas have been used for various applications, such as high-speed internet access, broadcasting and military communication. In broadcasting satellite scenario, the needs for more compact and economical earth stations on user terminals have increased the power and bandwidth requirements of satellite [1]. Due to the demands for high quality of services, antennas with narrow beamwidth are requested. Narrow-beam antenna becomes desirable due to its ability to support high data rates while maintaining low satellite power. However, one spot beam can only support small coverage area on the earth [2]; thus, an approach to generate larger satellite footprint is requested. To guarantee constant high-gain signal availability to the coverage area, fine contoured beams shall be accurately designed.

Designing contoured beams involves reflector shaping and combination of multiple beams [3]. Reflector shaping technique can be performed by designing correct reflector curvature. Meanwhile, in the case of MBA, an array of feeds can be arranged to simultaneously generate multiple beams to form the desired contours. Through multi beams technique, higher gain and wider coverage are achieved at the same time. This MBA concept has been widely used by spacecraft manufacturers and researchers [3-9].

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Many studies have been conducted to determine the optimum feed positions of the reflector. One of them is through optimization of radiation pattern in physical optic (PO)-based tool [10]. However, in that case, the relation of feed locations and beam direction was not clarified. Some researchers have introduced the theoretical concept of caustics on parabolic surfaces. As a fundamental research, caustic surface equations at focal region for plane waves were derived in two planes [11]. In that literature, the equal-path-length model was demonstrated to express the rays. The focusing ability was defined based on the physical extent of the focal spots. The concept of determining focal surfaces based on caustic data has been employed in [12]. Here, an analytical program was developed to determine the best focal spot. In the program, all incoming rays to a reflector surface, scanned in elevation (EL) and azimuth (AZ) plane were observed. As a result, the best focal spots were shown in two-dimensional; however the important feed position data such as the caustic dependency on focal-length-to-diameter ratio (*F/D*) and the locus equation were not clarified.

Recently, a parametric study on obtaining the best focal point based on minimizing phase aberrations has been carried out [13]. For that particular study, a program is developed to analyze the phase errors when the beam is scanned to different target points. Comparisons with previous approaches have been made. However, the observations were for limited cases of *F/D*. Furthermore, similarly, the significant changes of caustic with respect to *F/D* were not explained by locus equations or curves. Optimum feed position is represented by maximum scan-gain contour in [14]. It was concluded that small *F/D* values tend to have a maximum scan-gain contour closer to Petzval surface. However, this study was performed for small *F/D* only, and not for *F/D*>1, which is more preferable for satellite MBA. In reflector antenna, the *F/D* is a crucial parameter [15]. Due to its importance, authors have developed a ray tracing program in MATLAB to calculate the optimum feed position of a parabolic for various *F/D* [16,17]. In the tool, a precise caustic model with an accurate caustic locus equation has been developed. The locus equation allows fast calculation of feed positioning, and is used to design a contoured beam for Peninsular Malaysia.

In this paper, two reflector feed designs are proposed. The initial design consists of a cluster of feed horns. However, due to some issues, an 18-element microstrip array is designed as a replacement. The design procedures are presented and discussed in detail in the next segment.

II. CONTOURED BEAM FOR PENINSULAR MALAYSIA COVERAGE

Figure 1 demonstrates the Malaysia region as viewed from satellite, which consists of two beams, B_1 and B_2 representing west and east part of the country respectively. In this paper, only the case of the west region, known as Peninsular Malaysia (B_1) is observed. To produce precise beam shape, B_1 shall consist of multiple smaller beams. In preliminary design, two spot beams denoted as B_{11} and B_{12} are used to construct B_1.

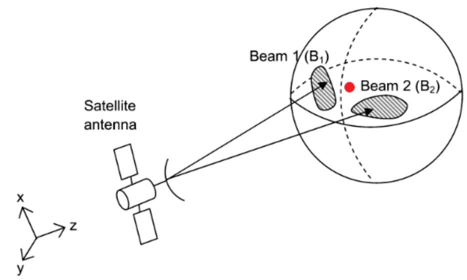

Fig. 1. Illustration of Malaysia beam from satellite point-of-view.

A. MBA concept

In designing the antenna system for B_1, several conditions are assumed. Figure 2 shows the application of multi beam technique to produce contoured beam for B_1, as viewed from 91.5°E orbital slot. The antenna field of view is centred at O. As Peninsular Malaysia is considered as geographically small, thus B_1 is designed to only comprise of two spot beams B_{11} and B_{12}, each having a narrow beamwidth, θ_{3dB}=0.5°.

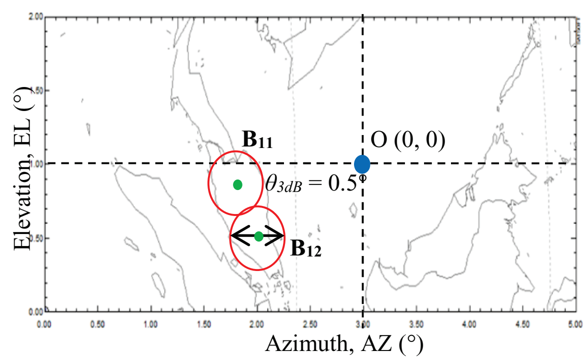

Fig. 2. Application of multi-beam technique for Peninsular Malaysia region by utilizing cluster feeds.

B. MBA design parameters

This section describes various parameters that influence the performance of the parabolic antenna.

Antenna diameter, *D*

D is chosen based on the θ_{3dB} and sidelobe level (SLL) requirements. In practice, trade-off between antenna directivity and θ_{3dB} to the SLL is a major consideration to antenna designers to yield high aperture efficiency [18]. Thus, characteristics of tapered distribution shall be taken into account. *D* is estimated as follows [19]:

$$D = (1.2 \pm 0.2 rads) \frac{\lambda}{\theta_{3dB}(rads)}. \quad (1)$$

The constant value reflects the aperture distribution, where 1 represents a uniform aperture with unity efficiency and high directivity. To reduce the SLL and by taking into account the trade-off, the value of 1.1 rads is chosen, and the D is calculated as 126λ or 3 m.

Focal-length-to-diameter ratio, *F/D*

F/D is a crucial parameter because it has strong effect on the achievable aperture and spillover efficiency. In designing satellite MBA, large *F/D* usually gives better scan performance [15]. For small F/D, especially in the case of *F/D*<0.5, the scan performance deteriorates and the caustic data used to determine feed position are less accurate. The behavior of caustic and its focusing ability for various *F/D* values have been studied in [17]. In this paper, the parameter *F/*D is set to 1.5 for better scanning performance, especially in the satellite application [8,10].

Design of radiating elements

Due to its good performance and simplicity, pyramidal horns are chosen as the feeds. Based on the single feed per beam concept, two feed horns of similar dimensions are employed to produce B_{11} and B_{12} simultaneously. The horn aperture size depends on the *F/D*. The data of how the increase of *F/D* relates to the raise in optimum horn dimension is shown in [15]. To estimate the horn size, the tilt angle between the horn to the reflector rim, θ_m is given as follows [18]:

$$\theta_m = 2\tan^{-1}\left(\frac{D}{4F}\right). \quad (2)$$

For *F/D* = 1.5, the θ_m is approximately 19°. The main concern in the horn design is to obtain radiation of at least -10 dB down at the reflector rim. This is to allow efficient illumination of reflector surface. After few adjustments and verifications using EM tool, the full dimensions of the feed horn, as illustrated in Fig. 3 is obtained as follows: *hh* = 54 mm, *hw* = 70 mm, *hl* = 63 mm, *wh* = 12 mm and *ww* = 37 mm.

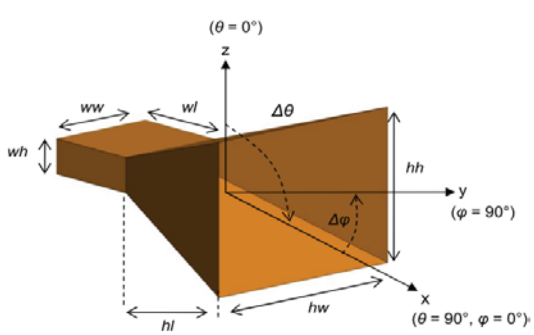

Fig. 3. Dimension of feed horn.

III. DETERMINATTION OF FEED POSITIONS

Beam deviation factor (BDF) concept has been widely used to demonstrate the dependency of feed position on *F/D* [20]. This model is very convenient to determine the optimum feed position based on the aperture-phase aberration for antennas with arbitral *F/D* value. However, there are some constraints. Due to the study model of deriving the expression, this method demonstrates the shifted beam θ_{B1} for one-dimensional lateral feed displacement F_1 only, as shown in Fig. 4. In designing MBA for B_1, the ray tracing program, together with a derived caustic locus is used.

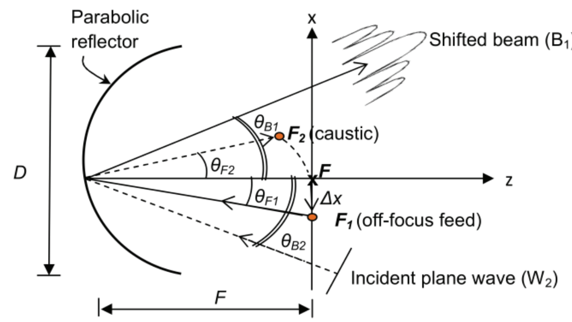

Fig. 4. Relationship of feed positions (F_1, F_2) and angles of radiated beams (θ_{B1}, θ_{B2}).

In the ray tracing model, the caustic point F_2 formed by the incoming wave from θ_{B2} is measured. The caustic movement in x and z component for various values of incident wave directions, $-\theta_{in}$ = 0° to 15° is demonstrated as shown in Fig. 5. Large θ_{in} are chosen at this stage to analyze the common behavior of the caustics and to observe the trajectory. D of 3 m is used and by considering the broadcasting satellite application, f = 12.2 GHz is selected. The results are compared to the approximate equation of caustic locus below, where $S(x, z)$ indicates the distance from the centre of reflector to the caustic point:

$$S(x,z) = F\cos\theta_{in}. \quad (3)$$

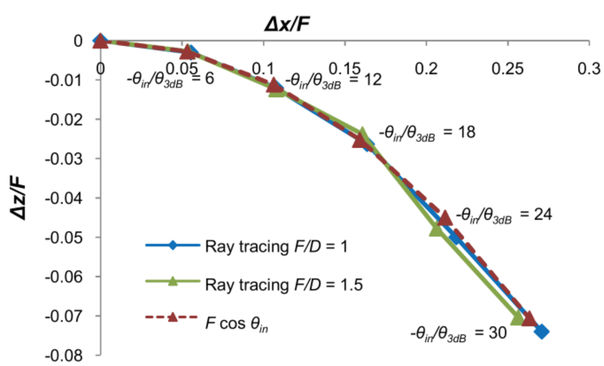

Fig. 5. Two-dimensional caustic positions.

From the good agreements of all curves, it is clarified that the optimum feed positions can be determined by equation (3). The feed positions of the MBA system can thus be calculated by using this method. It seems that higher accuracy is obtained at lower θ_{in}; thus, the application of ray tracing technique for designing contoured beam of Peninsular Malaysia is appropriate.

IV. EM COMPUTATIONS AND RADIATION CHARACTERISTICS OF MBA

The arrangement of the MBA in FEKO is shown in Fig. 6. The optimum positions for the feed horn of B_{11} and B_{12} are determined from equation (3). In the calculation, the incident beam directions θ_{in} are associated with the AZ (θ) and EL (φ) components. For B_{11} beam, the θ_{in} is (-1°, -0.6°), meanwhile for the B_{12} beam, the θ_{in} is (-1.16°, -0.17°). Both beams are very small in size; thus, the calculated caustics are very close to each other. This scenario has caused the horn apertures to be overlapped.

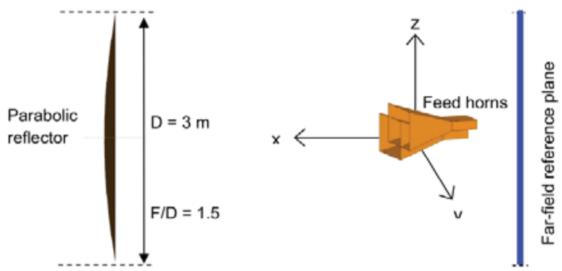

Fig. 6. A parabolic and two overlapped feed horns.

V. MICROSTRIP ARRAY FEED FOR CONTOURED BEAM OF PENINSULAR MALAYSIA

Due to the non-constructible structure, the overlapped feed horns shall be replaced with a physically realizable solution. One of the solutions is to use a microstrip array antenna. The first step is to compute the beam size of the whole B_1 region, denoted as θ_W and θ_L respectively in Fig. 7. Point 1 to 4 represents the min-max reference point.

Prior to designing the array feed, an on-focus square patch is first designed on a substrate having ε_r = 2.6, thickness h = 1.2 mm and tan δ = 0.0018. The single element size is 0.3λ in both sides. After a few adjustments, -11 dB return loss with almost 50 Ω impedance and a very good gain performance of 5.5 dBi is obtained at 12.2 GHz. The single patch element has wide beamwidth of θ_{3dB} = 100° for both E-plane and H-plane. In the case of array feed, the beamwidth of a single element patch does not play an important role, as the actual θ_{3dB} is determined through total number of elements on the array structure radiating on a single parabolic reflector. Thus, the single element design is then be duplicated to represent all four beam points on the required area. The positions of each feed elements are computed via ray tracing and translated into FEKO.

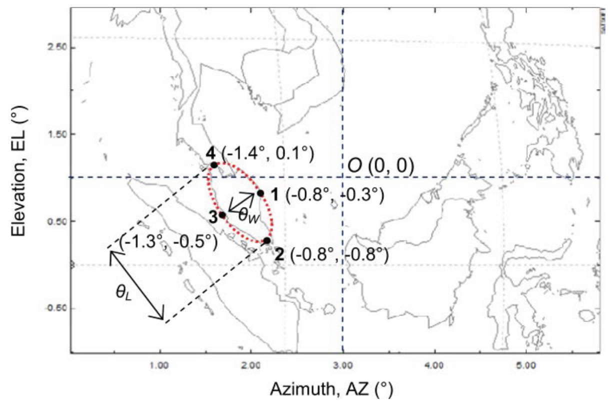

Fig. 7. Illustration showing the beam coverage for B_1 region with the -3 dB EOC points.

The calculated positions of all 4 beam points and the associated feeds, arranged together with 14 additional elements within the desired boundary are illustrated in Fig. 8. The figure also illustrates the overlapped horn areas that have been replaced by array elements. The randomly-distributed extra elements are added to ensure a good performance of the array system, particularly to achieve the desired beamwidth with uniform radiation gain (-3 dB) across the EOC.

All elements are assigned to various amplitude excitations A_i values from 0.3 to 1V to get uniform contour throughout EOC. Far-field simulation is performed based on the MoM-PO method, which is the integration of two techniques; method of moment (MoM) for microstrip array structure and physical optic (PO) for parabolic reflector. In this case, the dimension of the parabolic reflector is considered as electrically large, which is about 122λ; therefore, simulation of the parabolic reflector alone by using MoM involves a lot of memory usage and computation time. The simulation parameters are shown in Table 1.

Figure 9 shows the normalized contoured beam coverage for B_1, with four test points representing the maximum extent of the beam area, having -3 dB deviations from G_{max}. To ensure the correct beam size, the coordinates of all test points are compared with the actual peninsular beam. Table 2 presents the expected and the measured data taken at EOC. All measured EOC points match with the required test points, with the maximum deviation is around 0.05° only. Therefore, from these sets of results it can be concluded that a uniform contoured beam can be designed by the ray tracing method, regardless through the usage of horn arrays or multi-element microstrip as the feeds.

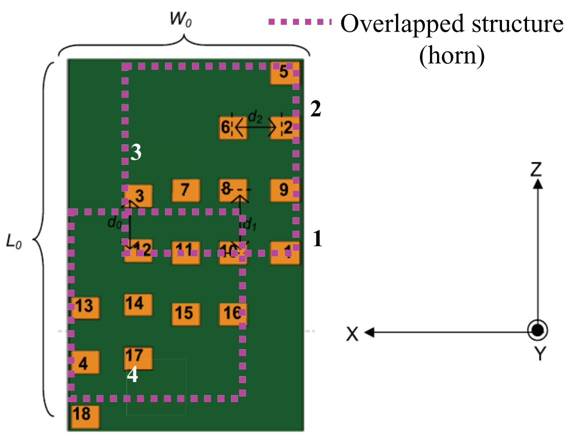

Fig. 8. Design concept of the microstrip array feed for Peninsular Malaysia and illustration of overlapped horn structure with the corresponding beam points.

Table 1: Simulation parameters

Items	Parameters	Details
Computer	Memory (RAM) Clock time	96 GB 1.8 GHz
Reflector	Mesh size	λ/2 (12.3 mm)
Array feed	Mesh size	λ/20 (1.23 mm)
Calculation process	Simulation memory Simulation time	59.43 GB 73.53 hours

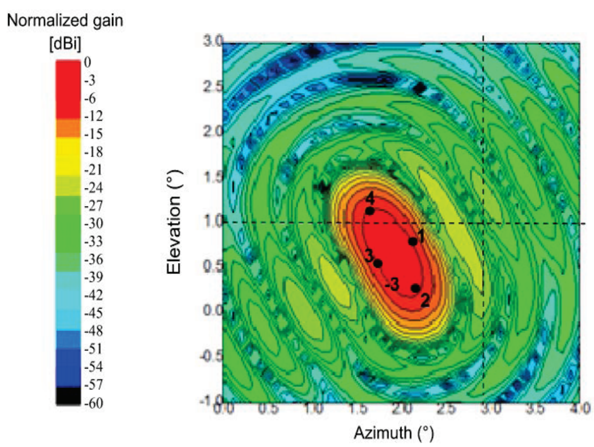

Fig. 9. Two-dimensional contoured beam for Peninsular Malaysia.

Table 2: Comparison of EOC data between calculated and obtained results

Beam Points	Required (°)	Obtained (°)
1	-0.80, -0.30	-0.81, -0.25
2	-0.80, -0.80	-0.81, -0.82
3	-1.3, -0.50	-1.3, -0.53
4	-1.4, 0.1	-1.4, 0.12

VI. EXCITATION COEFFICIENTS OF FEEDS

The displacement of feed from the focal plane introduces non-linear phase variation called phase error, which can cause gain loss, beamwidth changes and pattern distortion [15]. In designing contoured beam, the estimation of amplitude excitation A_i at the feeds is important in obtaining uniform amplitude distribution at the reflector beam. By controlling the A_i, the gain can be adjusted so that the associated power will be transmitted without any interruption. In the array feed for B_1, as shown in Fig. 10, all elements located at the edges of the structure are assigned at 1V. Meanwhile, to achieve broader beam and to reduce gain variation along EOC, the middle and adjacent elements are excited at 0.3V and 0.8V. This arrangement results in almost uniform amplitude distribution over the region.

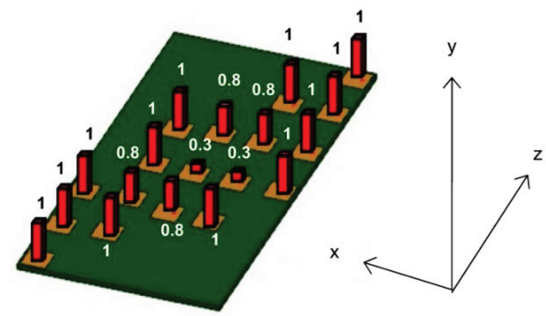

Fig. 10. Arrangement of radiating elements with the corresponding input A_i for B_1 beam.

Figure 11 demonstrates the distributions of magnetic field density for the antenna, which is useful to examine the behavior of induced currents at each element. Figure 12 shows the numerical data of the output H-field intensity. Theoretically, the induced current at each element is proportional to the input A_i. Based on the comparison between these two data, the correct relation is achieved.

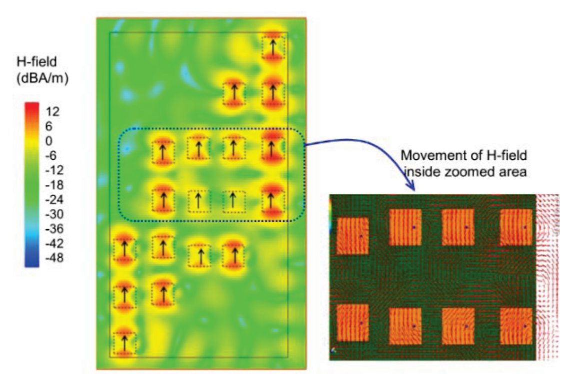

Fig. 11. Magnetic field distributions on the microstrip surface for B_1 beam.

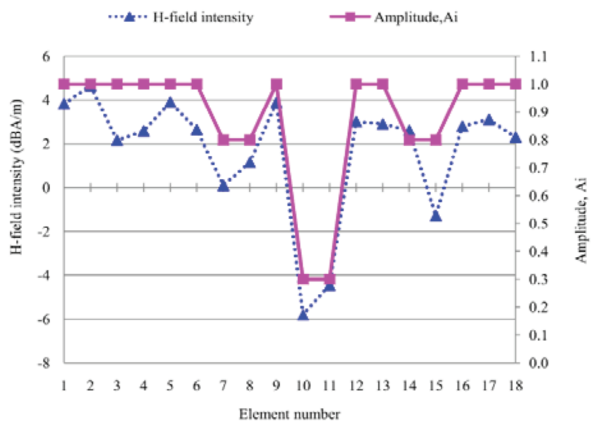

Fig. 12. Comparison between H-field intensity and input A_i for B_1 beam.

VII. CONCLUSION

A Ku-band satellite-mount antenna system to produce contoured beam coverage for Peninsular Malaysia is designed. Justifications and design equations of antenna parameters are shown. A design issue with regards to physical configuration of the initial feed horn design is discussed and an alternative solution is presented. Final antenna system, which consists of a single parabolic reflector, and a radiating feed that comprises of 18-element microstrip patch array are simulated and analyzed. The accuracy of the ray tracing method, developed to determine the precise positions of the feed elements are clarified in this paper through 3D EM solver. Uniform aperture distribution with less than -3 dB EOC gain variation and accurate beam shape with maximum angular deviation of 0.05° over the Peninsular Malaysia is obtained.

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