Proceedings of APCC2015 copyright © 2015 IEICE 14 SB 0087

Design and Analysis of a Satellite-mount Array-fed Parabolic Antenna by Electromagnetic Computations

N. H. Abd Rahman[1], M. T. Ali[1]
[1]Antenna Research Group, Microwave Technology Centre
Fac. of Electrical Engineering, Universiti Teknologi MARA
40450 Shah Alam, Selangor, Malaysia
nurulhuda0340@salam.uitm.edu.my

M. T. Islam[2]
Dep. of Electrical, Electronic & Systems Engineering
Faculty of Engineering & Built Environment, UKM
43600 UKM Bangi, Selangor, Malaysia
titareq@gmail.com

Y. Yamada[3]
[3]Malaysia Japan International Institute of Technology
Universiti Teknologi Malaysia Kuala Lumpur
54100 Kuala Lumpur, Malaysia
ndayamada@yahoo.co.jp

***Abstract*—Precise contoured beam is very important in designing antenna system for satellite broadcasting application. Through accurate contoured beam design, constant signal and optimum beam performance can be achieved throughout the region. For the case of Malaysia, two separate contoured beams for the peninsular and Borneo regions must be obtained. In this paper, a lightweight non-symmetrical array feed structure is designed to illuminate a single parabolic reflector. For this structure, calculation of the exact positions of radiating element on a widely distributed feed area is the most critical aspect in achieving an optimum contoured beam. Therefore, an accurate two-dimensional caustic locus graph is used to determine the position of the array elements on the radiating patch. Optimization of amplitude excitations of each element is performed to ensure less than -3dB variation along the edge of coverage (EOC). The performance of the multi-element asymmetrical patch feed integrated with parabolic reflector system are analyzed and verified through MOM-based FEKO solver.**

Keywords—Reflector antennas; satellite antennas; array feeds; ray tracing; geometrical optics

I. INTRODUCTION

Parabolic antennas are known for their high performance, ease of installation and simple structure. These antennas are widely used on satellites and ground stations that require high gain application. In broadcasting scenario, the needs for more compact and economical earth stations on user terminals have increased the performance requirements of satellite, especially in terms of the transmit power and data rates [1]. Therefore, antennas with narrow beamwidths are requested for their ability to support high data rates while maintaining low satellite power. However, in order to form a large satellite footprint that can cover the requested region, antenna system that can generate either multiple narrow beams or an optimized contoured beam shall be accurately designed [2, 3]. In the case of typical multi beam antenna (MBA) system, a large footprint can be simultaneously formed by employing multiple feed horns. Recently, due to the ease of fabrication, design flexibility and lightweight, microstrip array feeds are used to replace the feed horns. Through both techniques, higher gain and wider coverage are achieved at the same time [3-6]. However, among the main issues raised with regards to the microstrip design are the lower gain and the broader beamwidth characteristic as compared to the conventional horn structure, especially to produce non-symmetrical or contoured beam pattern.

Many studies have been performed to determine the optimum feed positions of the reflector [7-9] yet, in those studies; the relation of two-dimensional and precise feed locations to the incoming beam direction was not clarified. The substantial changes of caustics with respect to focal length to diameter ratio (*F/D)* were not clearly shown by any formulation or curves. Moreover, only limited cases of *F/D* were observed. Large *F/D* (more than 1) is more desirable in space application due to its high scanning ability and less aperture blockage. Therefore, the results presented in those works were inadequate to be used for designing contoured beam for Malaysia.

Authors have developed a ray tracing program in MATLAB to evaluate the optimum feed position of a parabolic reflector for various *F/D* [10]. In the tool, a precise caustic model with an accurate caustic locus equation and useful design charts have been developed for universal *F/D* values that can be used to design flexible non-symmetrical beam shape [11]. In this paper, microstrip array feed has been designed to illuminate a single reflector to produce beam shape of Malaysia region as shown in Figure 1. The positions of each feed element are determined accurately through the caustic modeling technique. The -3dB EOC gain along the contoured beam is obtained through optimization of excitation coefficients that is observed through magnetic field intensity of the radiating surfaces.

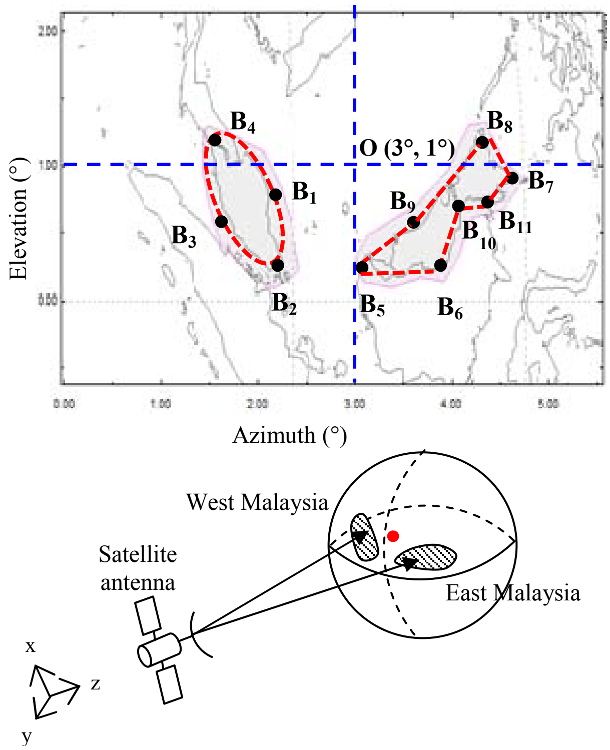

Figure 1. Application of multi-beam for Malaysia region with the -3dB EOC points

II. Relationship of Feed Points and Radiated Beams

Figure 2 shows the focal spot F_1 and F_2, the incident plane wave W_2 and the radiated beams. In the ray tracing program, for the incoming plane wave from θ_{B2} direction, all rays illuminating the parabolic reflector were taken into account. After the reflection, all rays concentrated in one point and a caustic was formed. The locus of caustics was expected to be on a curved line. In the radiation pattern calculation, shifted beam direction (B_1) is produced for the off-focus feed (F_1). From an expression of the antenna aperture phase change in feed displacement of dx, the equation of the beam deviation factor (BDF) was derived [12], as shown in (1).

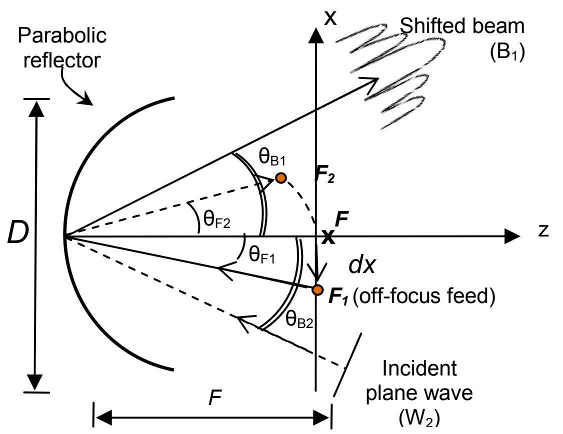

Figure 2. Feed positions and radiated beams

$$BDF = \frac{\sin\theta_B}{\tan\theta_F} = \frac{1+k(D/4F)^2}{1+(D/4F)^2} \quad (1)$$

This equation is very convenient for actual antennas having arbitral F/D value. However, the feed positions are limited to one-dimensional displacement. In this paper, the positions of feed elements are determined by using a universal design curve, known as locus of caustic. Thus, by using this technique, the application of (1) is improved due to the more accurate two-dimensional caustic locus.

III. Caustic Locus

Ray tracing method was performed in [11] for various configurations ($F/D \geq 1$) and incident angles based on the concept of geometrical optic (GO). From the behaviors of reflected rays in focal region, the two-dimensional off-axis displacements were obtained as shown in Figure 3. The variables were normalized against focal length F to demonstrate the universal change with respect to any incident direction θ_{in}. Based on the calculated results and analysis, caustics were approximated by a locus equation (2), where $S(x, z)$ represents the distance from the center of the reflector to the focal spot or caustic.

$$S(x,z) = F\cos\theta_{in} \quad (2)$$

From excellent agreements of all curves, it is recognized that the locus is determined by Equation (2). Thus, the method of determining the best feed positions is clarified. It is observed from Figure 3 that the relation is universal and valid for any antenna dimensions, thus to support the statement, the results obtained in the analysis are applied for the actual design of contoured beam for Malaysia shown in section IV.

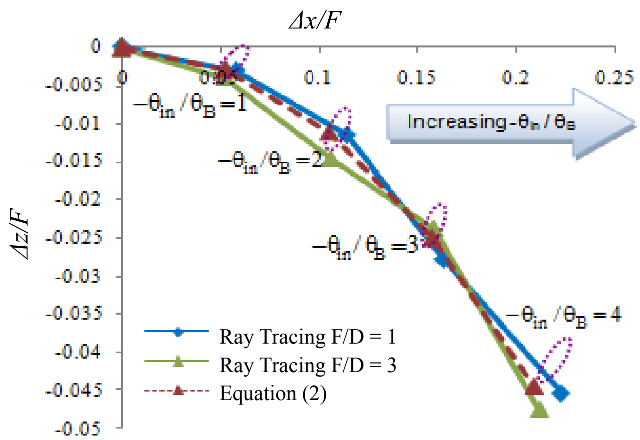

Figure 3. Universal two-dimensional caustic locus

IV. Antenna Design for Malaysia Contoured Beam

Figure 4 shows the relation between a feed position and its radiated beam, with the respective axis configurations as modeled in FEKO. To ensure efficient illumination, it is important to obtain the feed pattern of about 10 dB down in the direction of the rim for both sides of the reflector. Such configuration shall produce $2\theta_m$ beamwidth at -10 dB edge level. Based on the diagram, the reference points of the beam

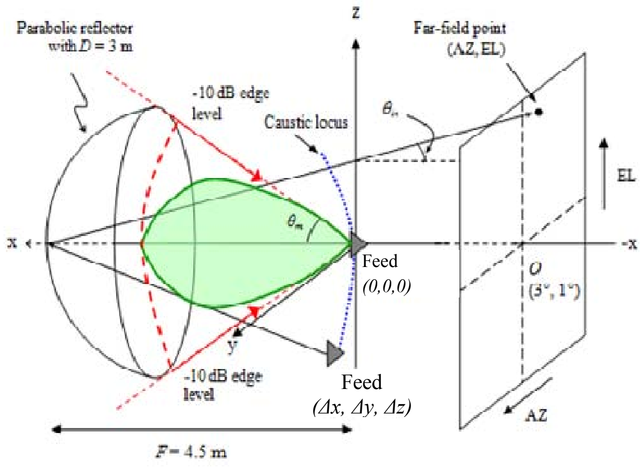

Figure 4. The relation between horn positions and radiated beams (represented by a point on far-field).

(B_1 to B_{11}) are represented by a specific point on far-field plane, denoted by azimuth and elevation coordinates (AZ, EL). In order to calculate the lateral feed displacement Δy and Δz, equation (1) is used for AZ and EL direction respectively, and to determine caustic movement in x-coordinate, equation (2) is used. Throughout the calculation, the incident beam angles θ_{in} for each far-field point are measured with respect to the x-axis. In this design, reflector diameter of 122λ is used and F/D of 1.5 is chosen based on the practicability and good scanning performance as compared to small F/D. The caustic behavior for this configuration is shown in Figure 5.

In designing microstrip array feed, caustic spots are computed based on the reference points shown in Figure 1. Each patch element, measured 0.33λ for both sides is designed on a polytetrafluoroethylene (PTFE) substrate having dielectric constant of $\varepsilon_r = 2.6$, thickness $h = 1.2$ mm and $\tan\delta = 0.0018$. Figure 6 and 7 show the corresponding feed elements, arranged together with additional elements within the respective boundary in FEKO. The randomly-distributed elements are added to the original configuration to ensure sufficient -3dB illumination across the EOC, low loss and high efficiency characteristics. The inter-element spacing, denoted as d_0, d_1 and d_2 are chosen in between the range of 0.5 λ to

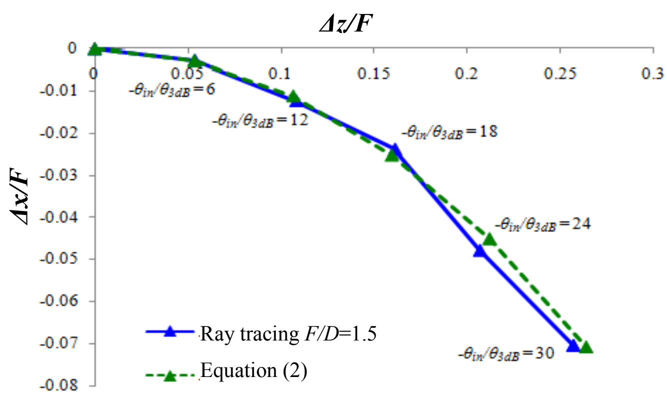

Figure 5. Two-dimensional caustic position for F/D =1.5

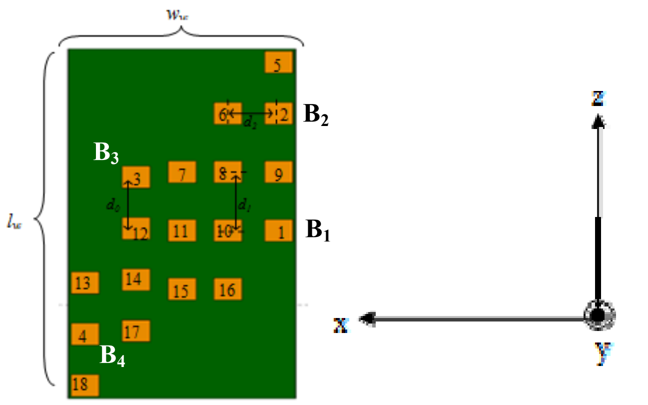

Figure 6. Arrangement of 18 radiating elements with the corresponding beam points for West Malaysia (w_w = 60 mm and l_w = 117.44 mm)

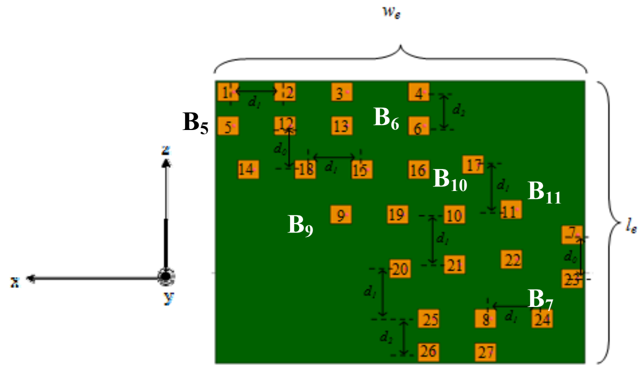

Figure 7. Arrangement of 27 radiating elements with the corresponding beam points for East Malaysia (w_e = 128 mm and l_e = 111 mm)

0.8 λ to reduce mutual coupling effects.

V. Optimization of Excitation Elements

Excitation coefficient of each element is optimized through amplitude adjustment to obtain uniform radiation throughout the coverage areas. Here, in-phase amplitude excitations, A_i are assigned from 0.3 to 1.3 V to obtain uniform contoured beam within less than 3dB gain variation with respect to G_{max} along EOC. The phase excitations are kept to default value 0°. Based on the A_i distribution, all elements located at the edge are assigned to maximum A_i value; meanwhile, to achieve broader -3dB beam width, the middle elements are assigned to minimum A_i value (0.3 V) and the adjacent elements are excited at ~0.8 V. This technique is performed to reduce gain variation between the far elements with the middle elements, which are expected to have the highest gain level. The final antenna design produced two contoured beams, as shown in Figure 8 and 9 respectively.

The microstrip element behaves as a perfect electric conductor at the surface; therefore, the E-field intensity is zero at the patch surface. Thus, in order to examine the behavior of induced currents at each element, the characteristics of H-field are observed. Figure 10 and 11 demonstrate the distributions of magnetic field (H-field) intensity for both feeds. Figure 12 and 13 show the numerical data of the output H-field intensity. Ideally, A_i and H-field intensity shall give similar pattern/ trajectory; however, this condition is impossible to be achieved in practical design due to other factors such as mutual coupling and grating lobes. Therefore, theoretically, the behaviors of the resultant magnetic currents are expected to be slightly different from the assigned input A_i.

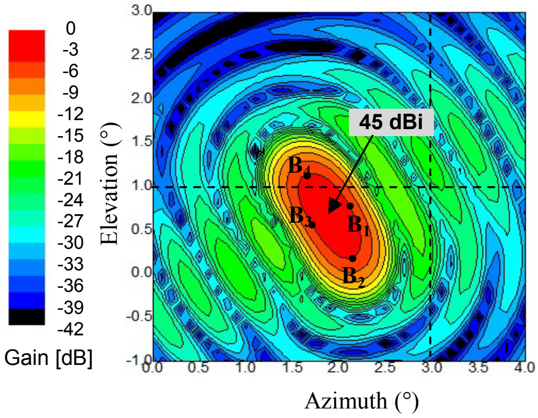

Figure 8. The contoured beam of West Malaysia

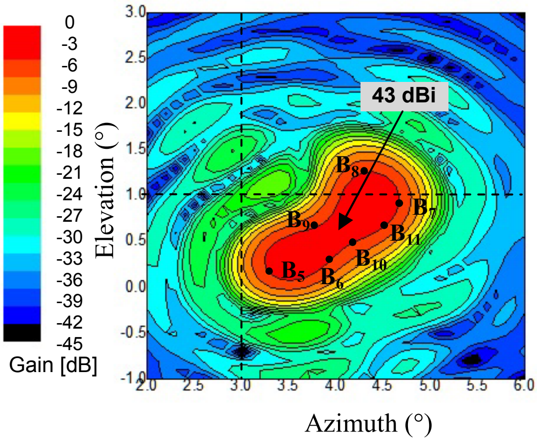

Figure 9. The contoured beam of East Malaysia

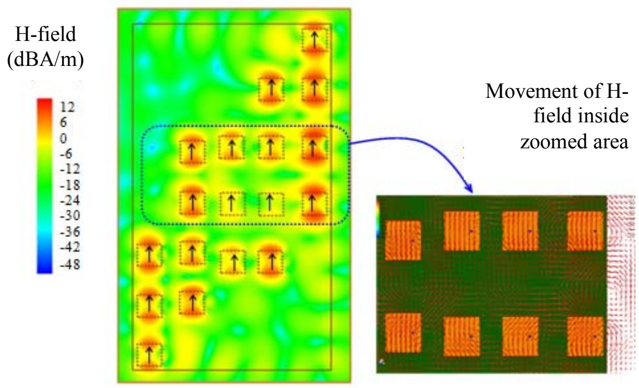

Figure 10. Magnetic field distributions on the microstrip surface for West Malaysia beam design

As observed from both figures, the induced current at each element is proportional to the input A_i. The H-field data behaves in similar manner as the A_i. There are only slight variations in the pattern, which are possibly caused by mutual coupling. Based on the comparison between these data, the correct relation is achieved. The optimization of contour through amplitude-only excitation seems successful in concentrating the energy towards the EOC. Table I shows the simulation parameters of the design, as simulated in FEKO. As shown in Table I, East and West beam are simulated separately to reduce the computation time and memory usage. However, if both were simulated simultaneously, the effects of mutual coupling between both beams are expected.

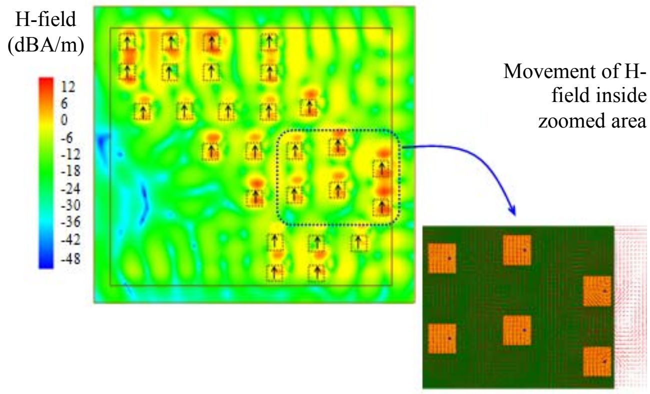

Figure 11. Magnetic field distributions on the microstrip surface for East Malaysia beam design

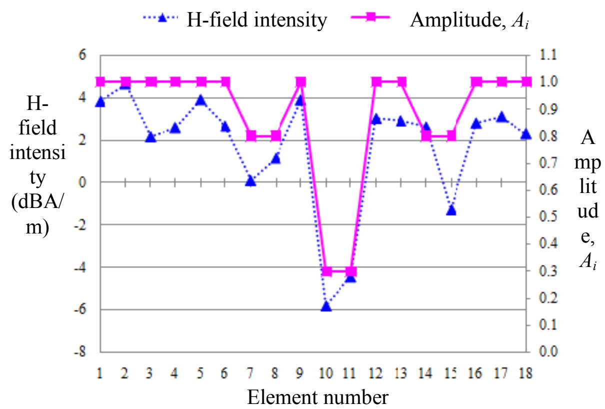

Figure 12. Comparison between magnetic field intensity and input amplitude excitation for West Malaysia beam design

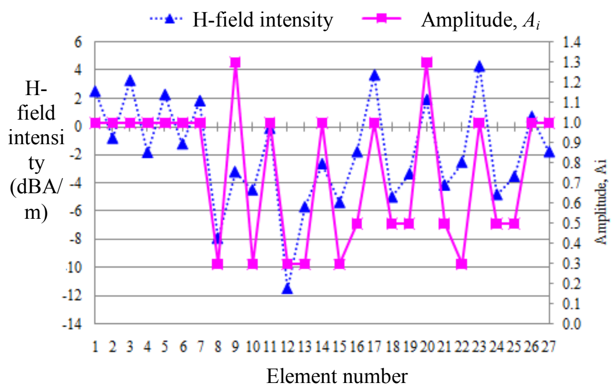

Figure 13. Comparison between magnetic field intensity and input amplitude excitation for East Malaysia beam design

TABLE I. SIMULATION PARAMETERS OF ARRAY-FED PARABOLIC DESIGN FOR MALAYSIA CONTOURED BEAM

Items	Parameters	Details
Parabolic reflector	Diameter, *D*	122λ
	Focal length, *F*	183λ
	Mesh size	λ/2
Microstrip array feed	Patch dimension	0.33 λ x 0.33λ (single)
	Mesh size	λ/20

VI. CONCLUSION

Two separate contoured beams were produced for Malaysia region by using parabolic reflector as the main antenna structure and microstrip array as the feeding elements. The locations of all feeds were accurately determined through caustic spot, calculated by using caustic locus derived in previous work. In the feed design, multi-element microstrip arrays were constructed on a PTFE substrate, and were arranged according to the desired beam areas on earth. The complexity of the design was due to the need to assign amplitude excitation coefficients in order to produce the desired -3 dB EOC results. After several series of amplitude optimization and simulations, contoured beams having sufficient beam width and gain for West and East Malaysia coverage was produced. Furthermore, based on the evaluation of magnetic field intensity, the optimization technique was accurate in producing the desired contours. Accuracy of caustic curve was also verified through 3D electromagnetic simulation in FEKO.

ACKNOWLEDGMENT

Authors would like to thank Universiti Teknologi MARA for continuous support towards this research project.

REFERENCES

[1] M. Nagasaka, S. Nakazawa and S. Tanaka, "A study on dual-polarization feed antenna for satellite broadcasting receiving reflector antenna," IEEE Antennas and Propagation Society International Symposium (APSURSI), pp. 1077-1078, 2014.

[2] G. Maral and M. Bousquet, Satellite Communications Systems: Systems, Techniques and Technology, Wiley, 2010.

[3] S. Rao, L. Shafai and S. K. Sharma, Handbook of Reflector Antennas and Feed Systems Volume 3: Applications of Reflectors, Artech House, Massachusetts, 2013.

[4] M. Schneider, C. Hartwanger and H. Wolf, "Antennas for multiple spot beam satellites," CEAS Space Journal, Vol. 2, No. 1-4, pp. 59-66, 2011.

[5] S. Huber, M. Younis, A. Patyuchenko, G. Krieger and A. Moreira, "Spaceborne Reflector SAR Systems with Digital Beamforming," IEEE Transactions on Aerospace and Electronic Systems, Vol. 48, No. 4, pp. 3473-3493, 2012.

[6] H. T. Chou, K. H. Bai, C. C. Sun, C. T. Yu and H. T. Hsu, "Design of multi-beam antenna array using tapered slot elements," URSI International Symposium on Electromagnetic Theory (EMTS), pp. 863-865, 2013.

[7] M. Mahajan, R. Jyoti, K. Sood and S. B. Sharma, "A method of generating simultaneous contoured and pencil beams from single shaped reflector antenna," IEEE Transactions on Antennas and Propagation, vol. 61, no. 10, pp. 5297-5301, 2013.

[8] A. Garcia-Pino, N. Llombart, B. Gonzalez-Valdes and O. Rubinos-Lopez, "A bifocal ellipsoidal Gregorian reflector system for THz imaging applications," IEEE Transactions on Antennas and Propagation, vol. 60, no. 9, pp. 4119-4129, 2012.

[9] S. Rao, "Advanced Antenna Technologies for Satellite Communications Payloads," IEEE Transactions on Antennas and Propagation, Vol. 63, No. 4, pp. 1205-1217, 2015.

[10] N. H. Abd Rahman, M. T. Islam, N. Misran, Y. Yamada and N. Michishita, "Design of a satellite antenna for Malaysia beams by ray tracing method," International Symposium on Antennas and Propagation, pp. 1385-1388, 2012.

[11] N. H. Abd Rahman, M. T. Islam, N. Misran, Y. Yamada and N. Michishita, "Generating Contoured Beams for Malaysia Region by Using Caustic Locus Graph," IEEE Antennas and Propagation Magazine, Vol. 56, No. 6, 328-336, 2014.

[12] C. A Balanis, Antenna Theory: Analysis and Design, New York: Wiley, 2005.