UTD Analysis of a Shaped Subreflector in a Dual Offset-Reflector Antenna System

Kyutae Lim, Hwang Ryu, Sangseol Lee, and Jaehoon Choi

***Abstract*— The geometrical theory of diffraction (GTD) is known as an efficient high-frequency method for the analysis of electrically large objects such as a reflector antenna. However, it is difficult to obtain geometrical parameters in order to apply GTD to an arbitrary-shaped reflector, especially a subreflector. In this paper, the geometrical parameters of an arbitrary shaped subreflector for the uniform theory of diffraction (UTD) analysis are derived based on differential geometry. The radiation patterns of various subreflector types, including hyperboloidal and a shaped subreflector, are evaluated by UTD. The computed result for the hyperboloidal reflector agrees well with that obtained by uniform asymptotic theory (UAT).**

***Index Terms*—Geometrical theory of diffraction, reflector antennas.**

I. Introduction

In analyzing a dual offset-reflector antenna, the accurate calculation of a subreflector pattern is essential since it strongly affects the far-field pattern of the antenna system. The geometrical theory of diffraction (GTD) has many advantages in analyzing a subreflector over the well-known physical optics (PO) approach [1]. GTD not only gives more accurate results over a wide angle, but also requires less computation time than PO. On the other hand, there is difficulty in finding geometrical parameters, including the second-order derivatives on the reflector surface.

Keller's original GTD has the serious problem of producing inaccurate results at the shadow boundaries [2]. To overcome this difficulty, two uniform versions of GTD, the uniform theory of diffraction (UTD) [3], [4] and the uniform asymptotic theory (UAT) [5], [6], have been developed. UAT has been developed based on the Ansatz of Lewis *et al.* [7]. In UTD, Keller's diffraction coefficients have been modified by using the Pauli–Clemmow's method of steepest descent [8], [9].

The main difficulty that lies in the GTD analysis of an arbitrary shaped subreflector is the evaluation of geometrical parameters based on differential geometry. Lee *et al.* [10] presented the UAT solution for an arbitrary subreflector. Despite the wide usage of UTD, the UTD solution for an arbitrary subreflector has not yet been formulated.

Manuscript received August 23, 1995; revised August 12, 1997.

K. Lim is with the Digital Communication Laboratory, Samsung Advanced Institute of Technology, Suwon 440-600, Korea.

H. Ryu is with the Division of Computer Information and Electronics Engineering, Paichai University, Taejon 302-735, Korea.

S. Lee and J. Choi are with the Department of Radio-Science and Engineering, Hanyang University, Seoul 133-791, Korea.

Publisher Item Identifier S 0018-926X(98)03367-5.

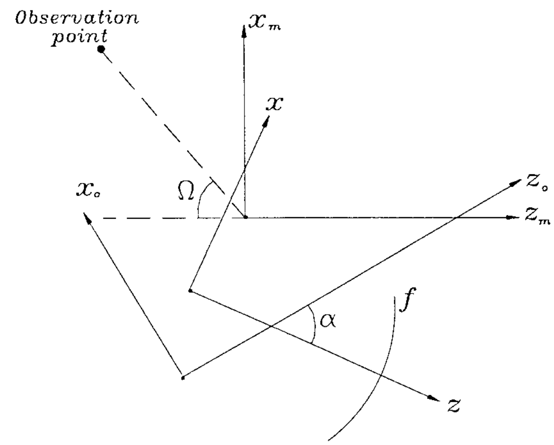

Fig. 1. The relationship among three coordinate systems for analyzing an arbitrary subreflector.

In this paper, the geometrical parameters of an arbitrary-shaped subreflector for UTD analysis are derieved using differential geometry. Then, the UTD scattered field patterns of subreflectors are obtained using these parameters. We assume that the reflector surface can be represented by a general coordinate system in order to retain generality. To obtain the GO field, we use the formulation in [10]. To show the validity of our solution, the scattered field pattern of a hyperboloidal reflector is compared with that of UAT. The field patterns of a Gregorian-type-shaped subreflector are also presented.

II. Geometrical Parameters

A. Geometry of the Reflector

To analyze a subreflector, we introduce three coordinate systems: (x_0, y_0, z_0), (x, y, z), and (x_m, y_m, z_m). The relation between three coordinates are depicted in Fig. 1. To make the problem more general, we assume that the subreflector surface is represented by an arbitrary coordinate system (x_0, y_0, z_0). The coordinate (x, y, z), which is used to define the edge of a subreflector, is defined such that the z axis of this coordinate passes through the center of the subreflector and the feed of the antenna is located at the origin of the coordinate system. The coordinate (x_0, y_0, z_0) is tilted by α to (x, y, z). The coordinate (x_m, y_m, z_m) is the coordinate for a main reflector and the observation points are defined by this coordinate system.

0018–926X/98$10.00 © 1998 IEEE

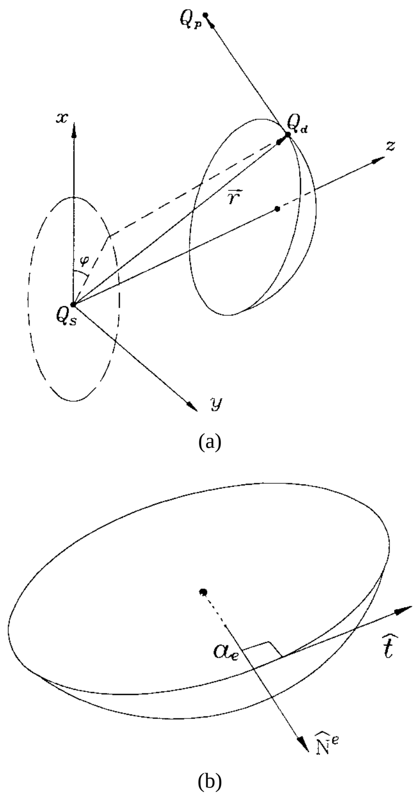

Fig. 2. The geometry of a subreflector. (a) Parametric expression of the edge. (b) Normal and tangential unit vectors on the edge and the radius of curvature of the edge.

The reflector surface is defined in the coordinates (x_0, y_0, z_0) as

$$z_0 = f(x_0, y_0). \tag{1}$$

Outward surface unit normal vector $\hat{N}^0$ is given in (x, y, z) coordinates by

$$\hat{N}^0 = N_1^0 \hat{x} + N_2^0 \hat{y} + N_3^0 \hat{z} \tag{2}$$

where

$$N_1^0 = \frac{f_{x_0} \cos\alpha + \sin\alpha}{\sqrt{f_{x_0}^2 + f_{y_0}^2 + 1}}, \quad N_2^0 = \frac{f_{y_0}}{\sqrt{f_{x_0}^2 + f_{y_0}^2 + 1}}$$
$$N_3^0 = \frac{f_{z_0} \sin\alpha - \cos\alpha}{\sqrt{f_{x_0}^2 + f_{y_0}^2 + 1}}$$

and $f_x = \partial f / \partial x$.

B. Differential Geometry of the Edge

To represent the closed contour of the edge illustrated in Fig. 2(a) using the parametric form, we define an edge in the (x, y, z) coordinate system as follows:

$$\vec{r} = g_1(\phi)\hat{x} + g_2(\phi)\hat{y} + g_3(\phi)\hat{z} \tag{3}$$

where $(g_1(\phi)), g_2(\phi), g_3(\phi))$ is the position on the edge for a given value of parameter ϕ and can be obtained by adopting the same procedure in [10].

The diffraction, source and observation points in (x, y, z) coordinates are given as

$$\text{diffraction point } Q_d;\ (x_d, y_d, z_d) = (g_1(\phi), g_2(\phi), g_3(\phi))$$

$$\text{source point } Q_s;\ (x_s, y_s, z_s) = (0, 0, 0)$$

$$\text{observation point } Q_p;\ (x_p, y_p, z_p).$$

The edge parameters are shown in Fig. 2(b) and can be determined from [11]. The unit tangential vector at the edge is

$$\hat{t} = \frac{\vec{r}'}{|\vec{r}'|} = t_1\hat{x} + t_2\hat{y} + t_3\hat{z} \tag{4}$$

where

$$t_i = \frac{g_i'}{\sqrt{g_1'^2 + g_2'^2 + g_3'^2}}, \qquad \text{for } i = 1, 2, 3$$

and the prime($'$) represents the derivative with respect to ϕ.

The unit normal vector and radius of curvature on the edge are given by

$$\widehat{N^e} = -\frac{\hat{t}'}{|t'|} = N_a^e\hat{x} + N_2^e\hat{y} + N_3^e\hat{z} \tag{5}$$

$$a_e = \frac{|t|}{|\hat{t}'|} = \frac{g_1'^2 + g_2'^2 + g_3'^3}{\sqrt{A_1^2 + A_2^2 + A_3^2}} \tag{6}$$

where

$$N_i^e = -\frac{A_i}{\sqrt{A_1^2 + A_2^2 + A_3^2}}, \qquad \text{for } i = 1, 2, 3$$

$$A_i = g_i'' - \frac{g_1' g_1'' + g_2' g_2'' + g_3' g_3''}{\sqrt{t_1^2 + t_2^2 + t_3^2}} g_i'.$$

The vector components of the edge-fixed coordinate system for the geometry under consideration are summarized in Table I. Note that the unit vectors $(\hat{s}^{i,d}, \hat{\phi}^{i,d}, \hat{\beta}^{i,d})$ correspond to the unit vectors $(\hat{s}', \hat{\phi}', \hat{\beta}')$ and $(\hat{s}, \hat{\phi}, \hat{\beta})$ in [3], respectively.

C. Other Geometrical Parameters

The angle between the incident ray and the edge is defined by

$$\beta_0^i = \cos^{-1}[\hat{s}^i \cdot \hat{t}] = \cos^{-1}(t_1 s_1^i + t_2 s_2^i + t_3 s_3^i). \tag{7}$$

By Keller's law of diffraction, the angle between the diffracted ray and the edge is the same as β_0^i.

The vector tangential to the surface and normal to the edge is given by

$$\hat{t}^0 = \hat{N}^0 \times \hat{t} = t_1^0\hat{x} + t_2^0\hat{y} + t_3^0\hat{z} \tag{8}$$

where

$$t_1^0 = N_2^0 t_1 - N_3^0 t_2, \quad t_2^0 = N_3^0 t_1 - N_1^0 t_3$$
$$t_3^0 = N_1^0 t_2 - N_2^0 t_1.$$

TABLE I
THE COMPONENTS OF THE EDGE-FIXED COORDINATE SYSTEMS. (a) THE INCIDENT RAY. (b) THE DIFFRACTED RAY

$\hat{s}^i =$	s_1^i	s_2^i	s_3^i	s^i
$s_1^i\hat{x} + s_2^i\hat{y} + s_3^i\hat{z}$	$\dfrac{x_d - x_s}{s^i}$	$\dfrac{y_d - y_s}{s^i}$	$\dfrac{z_d - z_s}{s^i}$	$\{(x_d - x_s)^2 + (y_d - y_s)^2 + (z_d - z_s)^2\}^{1/2}$
$\hat{\phi}^i =$	ϕ_1^i	ϕ_2^i	ϕ_3^i	ϕ^i
$\phi_1^i\hat{x} + \phi_2^i\hat{y} + \phi_3^i\hat{z}$	$\dfrac{s_2^i t_3 - s_3^i t_2}{\phi^i}$	$\dfrac{s_3^i t_1 - s_1^i t_3}{\phi^i}$	$\dfrac{s_1^i t_2 - s_2^i t_1}{\phi^i}$	$\{(s_2^i t_3 - s_3^i t_2)^2 + (s_3^i t_1 - s_1^i t_3)^2 + (s_1^i t_2 - s_2^i t_1)^2\}^{1/2}$
$\hat{\beta}^i =$	β_1^i	β_2^i	β_3^i	β^i
$\beta_1^i\hat{x} + \beta_2^i\hat{y} + \beta_3^i\hat{z}$	$\phi_2^i s_3^i - \phi_3^i s_2^i$	$\phi_3^i s_1^i - \phi_1^i s_3^i$	$\phi_1^i s_2^i - \phi_2^i s_1^i$	1

(a)

$\hat{s}^d =$	s_1^d	s_2^d	s_3^d	s^d
$s_1^d\hat{x} + s_2^d\hat{y} + s_3^d\hat{z}$	$\dfrac{x_p - x_d}{s^d}$	$\dfrac{y_p - y_d}{s^d}$	$\dfrac{z_p - z_d}{s^d}$	$\{(x_p - x_d)^2 + (y_p - y_d)^2 + (z_p - z_d)^2\}^{1/2}$
$\hat{\phi}^d =$	ϕ_1^d	ϕ_2^d	ϕ_3^d	ϕ^d
$\phi_1^d\hat{x} + \phi_2^d\hat{y} + \phi_3^d\hat{z}$	$\dfrac{s_2^d t_3 - s_3^d t_2}{\phi^d}$	$\dfrac{s_3^d t_1 - s_1^d t_3}{\phi^d}$	$\dfrac{s_1^d t_2 - s_2^d t_1}{\phi^d}$	$\{(s_2^d t_3 - s_3^d t_2)^2 + (s_3^d t_1 - s_1^d t_3)^2 + (s_1^d t_2 - s_2^d t_1)^2\}^{1/2}$
$\hat{\beta}^d =$	β_1^d	β_2^d	β_3^d	β^d
$\beta_1^d\hat{x} + \beta_2^d\hat{y} + \beta_3^d\hat{z}$	$\phi_2^d s_3^d - \phi_3^d s_2^d$	$\phi_3^d s_1^d - \phi_1^d s_3^d$	$\phi_1^d s_2^d - \phi_2^d s_1^d$	1

(b)

The unit vector $\hat{s}_i^i$, which lies in the incident plane and perpendicular to $\hat{t}$, is obtained as

$$\hat{s}_t^i = \hat{s}_1^{it}\hat{x} + \hat{s}_2^{it}\hat{y} + \hat{s}_3^{it}\hat{z} \tag{9}$$

where

$$s_j^{it} = \frac{\cos\beta_0 t_j - s_j^i}{\sin\beta_0}, \qquad \text{for } j = 1, 2, 3.$$

Simiarly, $\hat{s}_t^d$, which lies in the diffraction plane and is perpendicular to t', is given by

$$\hat{s}_t^d = \hat{s}_1^{dt}\hat{x} + \hat{s}_2^{dt}\hat{y} + \hat{s}_3^{dt}\hat{z} \tag{10}$$

where

$$s_j^{dt} = \frac{s_j^d - \cos\beta_0}{\sin\beta_0}, \qquad \text{for } j = 1, 2, 3.$$

The angle ϕ_0^i, the angle between $-\hat{s}_t^i$ and $\hat{t}_0$, is given by

$$\phi_0^i = \pi - [\pi - \cos^{-1}(-\hat{s}_t^i \cdot \hat{t}_0)]\text{sgn}(-\hat{s}_t^i \cdot \hat{N}^0). \tag{11}$$

Also, ϕ_0^d, the angle between $-s_0^d$ and $\hat{t}_0$, is expressed as

$$\phi_0^d = \pi - [\pi - \cos^{-1}(-\hat{s}_t^d \cdot \hat{t}_0)]\text{sgn}(\hat{s}_t^d \cdot \hat{N}^0). \tag{12}$$

The radii of curvature a_1 (tangential to the incident plane) and a_2 (perpendicular to the incident plane) are obtained as

$$a_{1,2} = \frac{EB_1^2 \pm 2FB_1B_2 + GB_2^2}{eB_1^2 \pm 2fB_1B_2 + gB_1^2}, \quad (+\text{for } a_1 \text{ and } -\text{for } a_2) \tag{13}$$

where

$$B_1 = s_1^i \cos\alpha + s_1^i \sin\alpha + (-s_1^i \sin\alpha + s_2^i \cos\alpha)f_{x_0}$$

$$B_2 = s_2^i + (-s_1^i \sin\alpha + s_3^i \cos\alpha)f_{y_0}$$

$$E = 1 + f_{x_0}^2, \quad F = f_{x_0}f_{y_0}, \qquad G = 1 + f_{y_0}^2$$

$$e = \frac{-f_{x_0x_0}}{\Delta}, \quad f = \frac{-f_{x_0y_0}}{\Delta}, \qquad g = \frac{-f_{y_0y_0}}{\Delta}$$

$$\Delta = \sqrt{f_{x_0}^2 + f_{y_0}^2 + 1}.$$

III. SCATTERED FIELD FORMULATION

Most of the reflector antennas (except for multifocal antennas) have single-reflection points and multiple-diffraction points. The total scattered field at the obserbation point Q_p is the simple vector addition of individual field components. Therefore, the scattered field $\vec{E}^{\text{scat}}$ can be expressed as

$$\vec{E}^{\text{scat}}(Q_p) = \vec{E}^r(Q_p) + \sum_{n=1}^{N_d} \vec{E}_n^d(Q_p) \tag{15}$$

where $\vec{E}^r$ is the reflected field obtained by GO and $\vec{E}_n^d$ is the nth diffracted field in the UTD expression. N_a is number of the diffraction points.

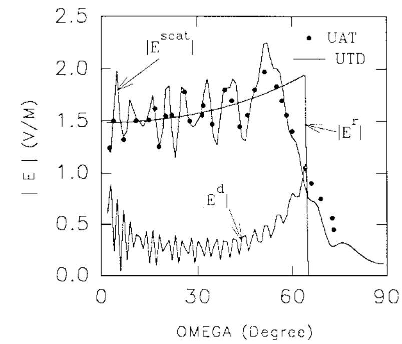

Fig. 3. Comparison of radiation patterns of the symmeric hyperboloidal reflector obtained by UAT and UTD.

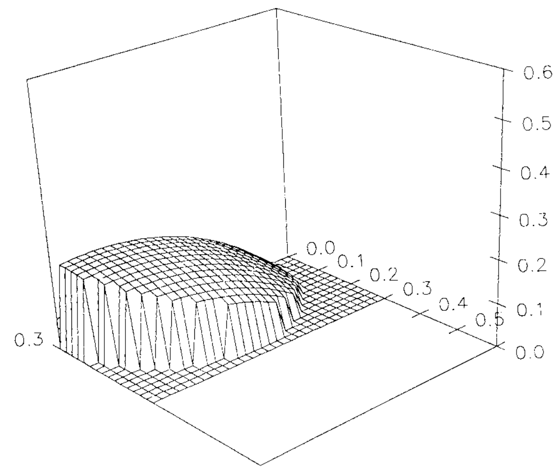

Fig. 4. Profile of the shaped subreflector represented by the global interpolation.

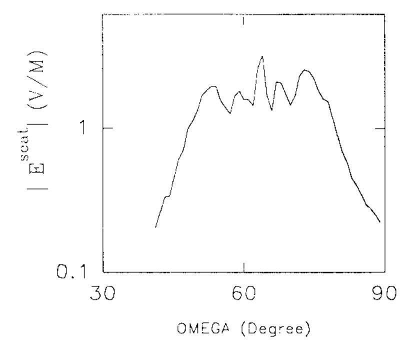

Fig. 5. Radiation pattern of the shaped subreflector obtained by UTD.

In order to obtain the GO field, it is necessary to determine the reflection point for a given observation point. For classical dual reflector antennas, the reflection point can be found easily from the fact that every reflected ray must pass through one focal point. However, for shaped dual reflector antennas, the subreflector does not have a focal point. Therefore, the reflection point on the subreflector of these antennas should be found by utilizing the stationary property of the path length at the reflection point. The GO field can be determined by the GO expressions given in [10].

To obtain the UTD diffracted fields, we should define the edge profile (g_1, g_2, g_3) numerically. The diffraction points can be found by applying Keller's law of diffraction to the edge. For a given diffraction point, the UTD parameters (for example, distance parameter, caustic distance, etc.) can be determined by the geometrical parameters obtained in Section II; then we can evaluate the diffracted field using the UTD parameters. Since the UTD formulations are presented in [12], we do not repeat them here.

IV. Numerical Analysis

A. Symmetric Hyperboloidal Subreflector

A hyperboloidal reflector is widely used as a subreflector for a Cassegrain antenna. To show the validity of our analysis, we compare the scattered field pattern of the symmetric hyperboloidal reflector is given by [10, Eq. 5.2].

We assume that the field incident upon the surface of a subreflector is given by

$$\vec{E}^i(r, \theta, \phi) = \frac{120\pi}{(r/\lambda)} e^{-jkr}[\sin \phi \hat{\theta} + \cos \phi \hat{\phi}]. \tag{16}$$

The observation points are far away from the center of the coordinate (x_m, y_m, z_m) system at a distance of 100 λ.

The scattered field patterns of the subreflector obtained by UTD and by UAT are compared in Fig. 3. There is no significant difference between two results. Also, we can observe that UTD diffracted fields eliminate the discontinuity of the GO field.

B. Offset-Shaped Subreflector

The surface profile of a shaped dual offset-reflector antenna is defined numerically and the sampling points are nonuniformly distributed. Conventionally, a surface is represented in closed form (quadratic formulation, for example) with a perturbation function [13]. Recently, the global interpolation method has been developed [14]. In this method, the analytic surface function can be obtained by expanding the surface in terms of the orthogonal functions. The surface characteristic is determined from the set of coefficients of the series.

The subreflector considered here is that of the shaped offset Gregorian-type antenna system, which has a circular aperture, the left-right symmetry, and no tilted structure [15], [16]. The design data of the reflector is presented in [16] and the reflector profile is depicted in Fig. 4. Since the system has left-right symmetry, only half of the reflector is presented. In this case, the surface defined coordinate (x_0, y_0, z_0) system is coincident with the coordinate (x_m, y_m, z_m) system. We transformed the discrete reflector profiles into the analytic function by expanding in terms of the Jaccobi polynomial sinusoidal functions [14].

It is difficult to determine the first and the second derivatives on the shaped subreflector accurately and smoothly. We overcome these difficulties by applying the local interpolation technique [14]. Furthermore, the modified Powell's method is utilized in finding the reflection point on the subreflector and the cost function used in this algorithm is defined by the reciprocal of path length [17]. The radiation field pattern of this reflector is shown in Fig. 5.

V. Conclusion

The subreflector of a dual offset-reflector antenna system has been analyzed by UTD. Geometrical parameters of an arbitrary shaped subreflector were derived by using differential geometry. By applying these parameters to the UTD field formulation, the diffracted field from the subreflector was evaluated. The GO fields were obtained by using the same formulas as the UAT. In the numerical computation, two types of subreflectors have been considered. The scattered field pattern of the symmetric hyperboloidal reflector shows a good agreement with UAT result. The field pattern of the shaped subreflector represented by global interpolation was presented. In the above two cases, one can observe that the UTD diffracted fields eliminate the discontinuities of GO fields at the shadow boundaries.

References

[1] Y. T. Lo and S. W. Lee, *Antenna Handbook.* New York: Van Nostrand Reinhold, 1988.
[2] J. B. Keller, "Geometrical theory of diffraction," *J. Opt. Soc. Amer.*, vol. 52, no. 2, pp. 116–130, Feb. 1962.
[3] R. G. Kouyoumjian and P. H. Pathak, "A uniform geometrical theory of diffraction for an edge in a perfectly conducting surface," *Proc. IEEE*, vol. 62, pp. 1448–1461, Nov. 1974.
[4] R. G. Kouyoumjian, "The geometrical theory of diffraction and its applications," in *Numerical and Asymptotic Techniques in Electromagnetics*, R. Mittra, Ed. New York: Springer-Verlag, 1975.
[5] S. W. Lee and G. A. Deschamps, "A uniform asymptotic theory of electromagnetic diffraction by a curved wedge," *IEEE Trans. Antennas Propagat.*, vol. AP-24, pp. 25–34, Jan. 1976.
[6] S. W. Lee, "Uniform asymptotic theory on electromagnetic edge diffraction: A review," in *Electromagnetic Scattering*, P. L. Uslenghi, Ed. New York: Academic, 1978.
[7] D. S. Ahluwalia, R. M. Lewis, and J. Boersma, "Uniform asymptotic theory of diffraction by a plane screen," *SIAM J. Appl. Math.*, vol. 16, pp. 783–807, 1968.
[8] W. Pauli, "On asymptotic series for functions in the theory of diffraction of light," *Phys. Rev.*, vol. 54, pp. 924–931, 1938.
[9] P. C. Clemmow, "Some extensions to the method of integration by steepest descents," *Quart. J. Mech. Appl. Math.*, vol. 3, pp. 241–256, 1950.
[10] S. W. Lee, P. Cramer, Jr., K. Woo, and Y. Rahmat-Samii, "Diffraction by an arbitrary sub-reflector: GTD solution," *IEEE Trans. Antennas Propagat.*, vol. AP-27, pp. 305–316, May 1979.
[11] S. W. Lee, "Differential Geometry for GTD Applications," Univ. Illinois, Urbana-Champaign, EM Lab Rep., Oct. 1977.
[12] D. A. McNamara, C. W. I. Pistorius, and J. A. G. Malherbe, *Introduction to the Uniform Geometrical Theory of Diffraction.* Boston, MA: Artech House, 1990.
[13] Y. Rahmat-Samii and V. Galindo-Israel, "Shaped reflector antenna analysis using the Jacobi–Bessel series," *IEEE Trans. Antennas Propagat.*, vol. AP-28, pp. 425–435, July 1980.
[14] V. Galind-Israel, W. A. Imbriale and Y. Rahmat-Samii, "Interpolation methods for shaped reflector analysis," *IEEE Trans. Antennas Propagat.*, vol. 36, pp. 441–444, Mar. 1988.
[15] K. Lim, D. Yun, J. Choi, and S. Lee, "Design of the shaped dual offset reflector antenna for FSS," in *APMC*, KAIST, Taejeon, Korea, Oct. 1995, pp. 10–13.
[16] K. Lim, "Design and analysis of the shaped dual offset reflector onboard satellite antenna," Ph.D. dissertion, Dept. Electron. Commun. Eng., Hanyang Univ., Seoul, Korea, 1996.
[17] W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling, *Numerical Recipes*. Cambridge, U.K.: Cambridge Univ. Press, 1986.

Kyutae Lim was born in Seoul, Korea, in 1968. He received the B.S., M.S., and Ph.D. degrees, all in electronic-communication engineering, from Hanyang University, Seoul, Korea, in 1991, 1993, and 1996, respectively.

In 1996, he joined the Digital Communication Laboratory, Samsung Advanced Institute of Technology, Kiheung, Korea, where he has been working on the development of millimeter-wave communication system. His research interests include design of antennas, including reflector and planar antenna, and numerical analysis of electromagnetic field by the UTD and the finite difference time domain (FDTD).

Hwang Ryu was born in Moonkyung, Korea, in 1965. He received the B.S. degree in 1987, the M.S. degree in 1990, and the Ph.D. degree in 1993, all in electronic communication engineering, from Hanyang University, Seoul, Korea.

From 1993 to 1994, he was a full-time Instructor at the Department of Electronic Engineering, Hanseo University, Seosan, Korea. In spring 1994, he joined the faculty of Paichai University, Taejeon, Korea, where he currently is an Assistant Professor in the Department of Computer, Information and Communication, and Electronics Engineering. His current research interests include analysis of scattering, antenna analysis, and design by using analytical and numerical technique, and adaptive antennas for mobile communications.

Sangseol Lee was born in Korea in 1937. He received the B.S. and M.S. degrees in electrical engineering, both from the Hanyang University, Seoul, Korea, in 1961 and 1966, respectively, and the Ph.D. degree from the Instut Nationale Polytechnique de Grenoble, France, in 1976.

From 1973 to 1975 he was an Associate Professor, the Kwangwoon University, Seoul, Korea. Since March 1975, he has been with the Department of Electronic Communication Engineering, Hanyang University, where he is currently a Professor. His interests include computational electromagnetics, scattering, and antenna analysis.

Dr. Lee was the President of the Korea Institute of Telematics and Electronics in 1996.

Jaehoon Choi was born in Seoul, Korea, in 1957. He received the B.S. degree in electronics engineering from the Hanyang University, Seoul, Korea, in 1980, and the M.Sc. and Ph.D. degrees, both in electrical engineering, from the Ohio State University, Columbus, in 1986 and 1989, respectively.

From 1988 to 1991, he was an Assistant Research Analyst at the Telecommunications Research Center, Arizona State University, Tempe. From 1991 to 1995 he was a Director of the Satellite Payload Research Division of Korea Telecom. He is now an Assistant Professor at the Department of Radio Science and Engineering, Hanyang University. His research interests include computational electromagnetics, microwave and millimeter-wave passive devices, and antenna and radio-wave propagation modeling.