Direct PO Optimized Dual-Offset Reflector Antennas for Small Earth Stations and for Millimeter Wave Atmospheric Sensors

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Abstract—**An efficient direct numerical synthesis method for dual offset reflector antennas is described which is directly based on the physical optics procedure for both reflectors (PO-PO-method) and where the reflector surfaces are advantageously characterized in the spatial domain by a two-dimensional Fourier-transformation. The method involves an evolution strategy optimization algorithm in order to shape immediately both reflectors, so as to generate the desired far field with prescribed criteria. The efficiency of the design method is demonstrated for two computer-optimized dual offset antenna design examples for space applications. The first example, a very compact optimum shaped Gregorian dual offset earth station antenna with high offset angle (70°) and small subreflector size (13 λ) achieves a very low sidelobe attenuation level within the envelope of only 23–25 log θ dBi, and low cross-polarization attenuation (38 dB). The second example, a shaped dual offset Cassegrain atmospheric sensor antenna for 200 GHz, demonstrates that beam scanning by more than 10 half-power beamwidths is possible with nearly constant half-power beamwidth by simply displacing linearly the subreflector. The consequent advantage is the very low mass to be moved. The theory is verified by available measured results.**

I. Introduction

USUAL numerical synthesis methods for shaped reflector designs are based on the established geometrical optics (GO) theory [1]–[3], [29]. However, in order to ensure good practical performance and agreement with measurements, a post design analysis procedure by the more accurate physical optics (PO) method [4]–[7], [14], [30], [31] is often applied [8], [29] since the GO technique neglects important design criteria, such as cross-polarization effects and the frequency dependency of the parameters. It is highly desirable to develop a numerical synthesis method which is directly based on the PO formulation and which includes immediately all important design goals, such as low sidelobes, low cross-polarization, small half-power beamwidth and high antenna efficiency.

More stringent requirements on sidelobe envelopes for earth-station antennas, such as the recent FCC recommendation of 29 − 25 log θ dBi gain near boresight, [5], [9], have stimulated increasing interest in suitably shaped dual offset reflector antennas [1]–[18]. Owing to the advantage of the offset geometry, these antennas are ideally suited for small earth-stations especially with main reflector diameters well below 100λ, where effects due to blockage and struts are significant to the sidelobe performance.

Moreover, for many applications, e.g., for space borne atmospheric sensor antennas [19]–[21], it is advantageous to steer the beam without moving the main reflector, especially for a high-gain reflector antenna where the main reflector is relatively large and heavy. Although it is possible to use a feed array [6] or to move the feed assembly [21], it is often desirable to develop simpler solutions.

The purpose of this paper is to apply the PO technique [4], [7], [14], [24], [25], [30], [31] directly for an efficient design of dual-offset reflector antennas of improved performance. The two main problems for a direct PO optimization of shaped dual reflector antennas are: 1) an adequate modeling of the surfaces so that the number of optimization parameters is low enough with respect to the available cpu time and computer memory; 2) a suitable formulation of the subreflector nearfield which should yield a good compromise between accuracy and required cpu time.

In order to reduce the number of the optimization parameters significantly, in this paper the subreflector and main reflector surfaces are characterized in the spatial domain by a two-dimensional discrete Fourier transformation. The subreflector nearfield is adequately modeled by the PO method instead of the GO technique often used [30], [31], and by utilizing additionally the Fresnel-formulation in the phase term in place of the usual Fraunhofer-formulation. The evolution strategy method, i.e., a suitably modified direct search procedure with a statistical variation of the parameters [28], is applied where no differentiation step is necessary, and, hence, the problem of local minima may be circumvented. The far field may be generated directly with respect to the desired design criteria, such as low sidelobes in specific planes, or nearly constant characteristic versus scan angle.

The efficiency of the design method is demonstrated in Fig. 1 for two computer-optimized dual offset antenna design examples for space applications: a very compact shaped

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Gregorian dual offset earth station antenna with high offset angle and small subreflector size, and a shaped dual offset Cassegrain atmospheric sensor antenna for 200 GHz, where the beam may be scanned by simply displacing the subreflector. The theory is verified by available measured results.

II. THEORY AND DESIGN

The scattered field $\vec{E}_S(\vec{r})$ of the reflector may be written in terms of the surface current density $\vec{J}_F$ induced on the reflector surface. The field in the Fraunhofer region radiated by a known surface current distribution flowing on a perfectly conducting surface is given by [4], [10]

$$\vec{E}_S(\vec{r}) = \frac{j\omega\mu}{4\pi} \cdot \frac{e^{-jkr}}{r} \int_{S'} (\vec{e}_r \times (\vec{e}_r \times \vec{J}_F))\, e^{jk\vec{e}_r \cdot \vec{r}\,'}\, dS', \tag{1}$$

where r is the distance from the source point on the reflector to the observation point in the far field, $\vec{e}_r$ is the unit vector along r, $\vec{r}\,'$ is the distance vector directed from the feed location to the reflector source point, k is the propagation constant $2\pi/\lambda$, and S' denotes the reflector surface.

The induced surface current density due to the source field is derived using the physical optics (PO) representation [4], [6], [7], [14]:

$$\vec{J}_F = \begin{cases} 2\vec{n}(\vec{r}\,') \times \vec{H}_i(\vec{r}\,'), & \text{on the illuminated side} \\ 0, & \text{on the shadowed side} \end{cases} \tag{2}$$

where $\vec{H}_i$ is the incident magnetic field. The PO integral provides an accurate solution for predicting the far field in the main beam region and out to several sidelobes [4], [14].

With (1) and (2), the radiated electric farfield described by the spherical coordinates r, θ, ϕ of the observation point may be expressed by [4], [6], [7], [14], [22]

$$\vec{E}_S(r, \theta, \phi) = \frac{j\omega\mu}{2\pi} \cdot \frac{e^{-jkr}}{r} \int_{S'} \vec{F}(r'(\theta', \phi'), \theta', \phi') \cdot e^{jk(\vec{e}_r \cdot \vec{r}\,' - r')}\, d\theta'\, d\phi', \tag{3}$$

where the reflector surface S' is described by the spherical coordinate system r', θ', ϕ'; $\vec{F}$ is a complex vector depending on the surface geometry and the incident field $\vec{H}_i$ [22], [23]

$$\vec{F} = 2r'e^{jkr'} \left[\left(\sin\theta' \frac{\partial r'}{\partial \theta'} H_{i\phi'} - \frac{\partial r'}{\partial \phi'} H_{i\theta'} \right) \vec{e}_{r'} + \left(\frac{\partial r'}{\partial \phi'} H_{ir'} + r' \sin\theta' H_{i\phi'} \right) \vec{e}_{\theta'} - \left(r' \sin\theta' H_{i\theta'} + \sin\theta' \frac{\partial r'}{\partial \theta'} H_{ir'} \right) \vec{e}_{\phi'} \right]. \tag{4}$$

The integral (3) is evaluated numerically by a subdivision of the reflector surface into a number of small patches [6], [7], [30], [31]. Integration of (3) is performed by using a method described by Ludwig [22] which has the advantage of high accuracy, computer speed and ease of utilization [26]. Within each patch region, the functions $\vec{F}$ and $(\vec{e}_r \cdot \vec{r}\,' - r)$ are approximated by a linear Taylor series in θ', ϕ', and the coefficients are determined by a best fit criterion to the values at the boundaries of the patch. The grid of the total reflector surface contains patches which are rectangular in θ' and ϕ'; along the edge, triangular patches are introduced. With these assumptions the contribution of each patch may be determined analytically [7]. The summation of the contributions of each patch element yields the electric far field for the given direction in θ, ϕ. The copolar components E_{CP} and the crosspolar components E_{XP} of the far field are given by (3) using "Ludwig's third definition."

As the coordinates of the feed and of the reflector field patterns do not in general coincide, the useful coordinate transformations given in [23] are applied. The feed is assumed to be a corrugated horn approximated by a point source with an angle dependent radiation pattern which is expressed in the feed coordinate system r_f, θ_f, ϕ_f by

$$\vec{E}_f(r_f, \theta_f, \phi_f) = U_0 \cdot 10^{[a/20(\theta_f/\theta_{f0})^2]} \cdot (\cos\phi_f\, \vec{e}_{\theta_f} - \sin\phi_f\, \vec{e}_{\phi_f}) \frac{e^{-jkr_f}}{r_f}, \tag{5}$$

where a (in decibels) is the relative amplitude level at the given angle θ_{f0}, and U_0 is a normalization constant (in volts) which is chosen so that the total emitted power of the feed is $P_f = 4\pi\text{W}$.

The synthesis method described in this paper involves an optimization procedure to shape the two reflectors by the immediate PO formulation, so as to generate the desired far field (Fig. 2) directly with all desired design criteria: sidelobe level below a specified envelope, maximum cross-polarization below a prescribed amount, and optimum antenna gain.

The subreflector and main reflector surfaces are characterized in the spatial domain by a two-dimensional discrete Fourier transformation. This reduces the number of the optimization parameters significantly. For the subreflector, $N_x^S \times N_y^S$ expansion points are chosen:

$$W_{rs}^S = \frac{1}{N_x^S N_y^S} \sum_{K=0}^{N_x^S-1} \sum_{L=0}^{N_y^S-1} Z_{KL}^S \cdot \exp\left(j2\pi [r^S K/N_x^S + s^S L/N_y^S]\right), \tag{6a}$$

the main reflector is described by $N_x^M \times N_y^M$ points:

$$W_{rs}^M = \frac{1}{N_x^M N_y^M} \sum_{K=0}^{N_x^M-1} \sum_{L=0}^{N_y^M-1} Z_{KL}^M \cdot \exp\left(j2\pi [r^M K/N_x^M + s^M L/N_y^M]\right). \tag{6b}$$

The reflector surface shapes may be varied by modifying the magnitude $|W_{rs}|$ of some significant complex coef-

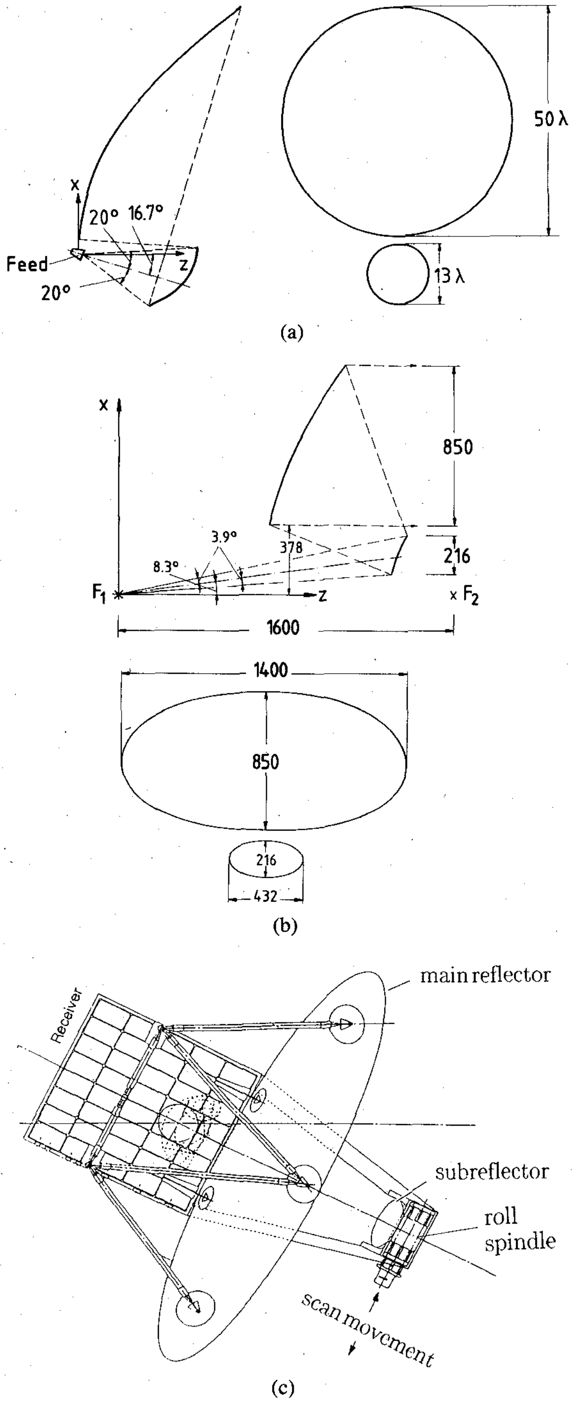


Fig. 1. Basic geometries of the shaped antennas (all dimensions in mm). (a) Very compact small-earth-station Gregorian dual offset antenna with high offset angle (about 70°). (b) Cassegrain dual offset atmospheric sensor (AMAS) antenna for 200 GHz with subreflector scan. (c) Principle of the scan mechanism.

ficients W_{rs} which have to satisfy the condition [27]:

$$W_{r+(N_x/2)s\pm(N_y/2)} = W^*_{(N_x/2)-r(N_y/2)\mp s}. \tag{7}$$

As is demonstrated in Fig. 3, only ten different coefficients $|W_{rs}|$ are sufficient to characterize the whole paraboloidal surface which is described by 400 sample points. The same is true for a shaped surface: the number of significant coefficients is about 20. The reflector shapes are controlled, therefore, in the optimization process by two coefficient vectors of significant coefficients $|W_{rs}^S|$ and $|W_{rs}^M|$, respectively; they can be varied so that the characteristic of the antenna conforms to that specified in the chosen error function sample points (Fig. 2).

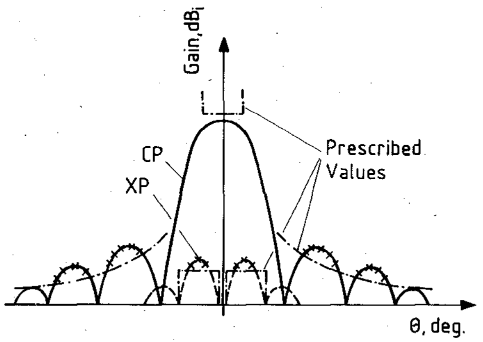


Fig. 2. Tolerance scheme for the optimization process (x denotes the chosen error function sample points).

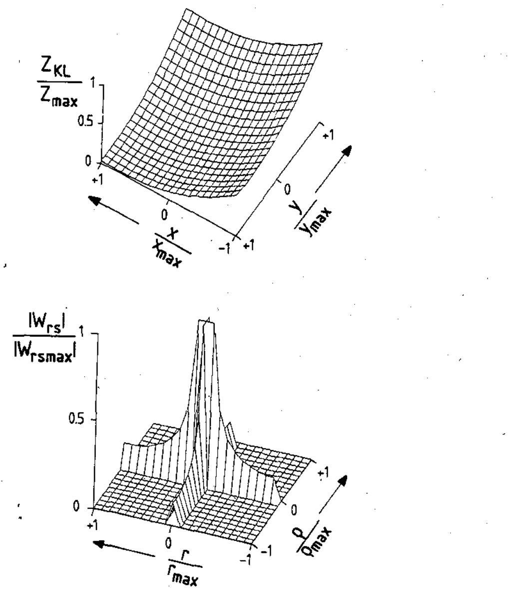


Fig. 3. Illustration of the modeling of the surfaces (at the example of a paraboloidal surface) by the Fourier transformation (6)) in the space domain with only ten different coefficients $|W_{rs}|$. Number of sample points: 400.

An adequate modeling of the subreflector nearfield is given by the PO method and additionally by a Fresnel-formulation of the phase term in (3) instead of the Fraunhofer-approximation:

$$\vec{E}_S^{\text{sub}} = \frac{j\omega\mu}{2\pi}\cdot\frac{e^{-jkr}}{r}\int_{S^{\text{sub}}}\vec{F} \cdot \exp\left[jk\left(\vec{e}_r\cdot\vec{r}\,' - r' + \frac{(\vec{e}_r\cdot\vec{r}\,')}{2r} - \frac{r'}{2r}\right)\right] \cdot d\theta'\, d\phi'. \tag{8}$$

By utilizing the preceding formulations, the direct PO optimization of shaped dual reflector antennas may be realized by an adequate optimization routine (Fig. 4). In our paper, the evolution strategy method [28] is applied where

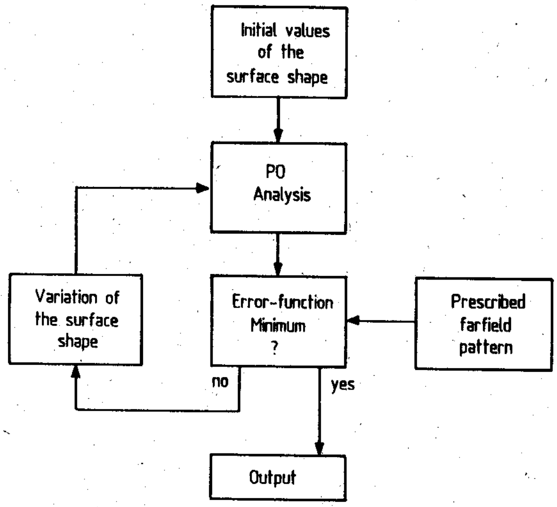


Fig. 4. Block scheme of the direct PO synthesis.

the parameters are varied statistically and the problem of local minima may be circumvented. An error function to be minimized

$$EF(W_{rs}) = \sum_{n=1}^{6} \left[\sum_{SPn}^{N_{SPn}} f_n(W_{rs}^S, W_{rs}^M, \theta_{SPn}) \cdot G_n \right]^2 \quad (9)$$

is defined, where the parameters to be optimized are the reflector shape functions W_{rs}^S, and W_{rs}^M, respectively, formulated by the two-dimensional Fourier Transform (6). The functions f and G in (9) are (cf. Fig. 2):

f_1 = (prescribed gain) − gain (θ_{SPn}),
f_2 = (CP power (θ_{SPn}))
− (prescribed CP envelope (θ_{SPn})); for $\phi = 90°$
f_3 = (XP power (θ_{SPn}))
− (prescribed XP envelope (θ_{SPn})); for $\phi = 90°$
$f_4 \equiv f_2$; but for $\phi = 45°$
$f_5 \equiv f_3$; but for $\phi = 45°$
$f_6 \equiv f_2$; but for $\phi = 0°$.

G_n are weighting functions, and N_{SPn} is the number of error sample points at θ_{SPn} for each function f_n.

About 20 to 40 error sample points have turned out to be sufficient for characterizing the prescribed antenna pattern for the small earth station antenna examples. For the scanned millimeter wave antenna, 200 error sample points and additionally three sample steps are used at different scan angles; 0°, and about five, and ten half-power-beamwidths. To maintain physically realistic parameters, each coefficient W_{rs} is limited by a suitably chosen upper and lower boundary, respectively. The basic geometry of the antenna has been calculated by using the relations given in [17]; this geometry was not changed during the optimization process.

Although it is possible to start the optimization with conical section shapes, in order to reduce the computing time, for the design of the compact earth station antennas we used the known geometrical optics (GO) procedure as described by Westcott [1], [13] for the initial values of the reflectors in our optimization process. Furthermore, an FFT algorithm (Cooley/Tuckey) is utilized for the transformations. Due to the complexity of the program, as well as concerning the cpu time necessary for an appropriate optimization procedure, the described program requires relatively long cpu running times. For the designed compact Gregorian type earth station antennas, a SIEMENS 7.881 scalar computer (3 Mflops, 7 Mbyte RAM) was used which corresponds approximately to a standard workstation. The total computing time for the optimization process of one set of reflector surfaces was about 15–20 hours. However, for the large scanned millimeter wave reflector antenna investigated in this paper, a SIEMENS VP200-EX vector computer (856 Mflops, 250 Mbyte RAM) was used for the computations. Nevertheless, 100 iterations steps of shaping this antenna required about 200 cpu hours.

III. RESULTS

For a verification of the theory, measured results reported in [16] of a conical section Gregorian antenna are chosen (Fig. 5(a)). One analysis step in the PO design is then used to calculate the antenna characteristic. Good agreement may be stated (Fig. 5(b)) between theory and measurements as is demonstrated by the characteristic in the asymmetry plane. The slight deviations concerning the crosspolarization are due to the relatively high feed horn crosspolarization of this example which was about −42 dB [16].

A small-earth-station dual offset Gregorian reflector antenna (Fig. 1(a)) with high offset angle (about 70°) is chosen for the first design example. About 1200 integration patches for the subreflector, and 2400 patches for the main reflector, respectively, have turned out to be necessary for calculating accurate results. For low far-out sidelobes, the subreflector edge taper is chosen to be −25 dB. In a first step, the antenna is synthesized by the well-known GO procedure [1], [13]. The result is shown in Fig. 6 (solid curves), for the two planes $\phi = 90°$ (symmetry plane), and 0° (asymmetry plane). It can be stated that the given specifications ($23 - 25 \log \theta$) are not met, and the cross polarization level is relatively high. The direct PO synthesis, however, using 900 iteration steps, achieves an antenna characteristic (Fig. 6, dashed curves) which meets the prescribed behavior. The significant reduction of the sidelobes obtained in all planes is demonstrated by the three-dimensional plots shown in Fig. 6(c); the dynamic range is chosen to be 35 dB.

Fig. 7 illustrates the difference in the z-dimension of the subreflector and main reflector obtained by the shaping procedure. Fig. 7(a) shows the shaped surfaces relative to the shape of the conical surfaces. Fig. 7(b) illustrates the difference in the subreflector shape obtained by the direct PO method after 900 iterations relative to the corresponding initial GO design; the peak to peak variation is about 0.1 λ. The PO design achieves an antenna efficiency of 75% including spillover, phase error and diffraction loss.

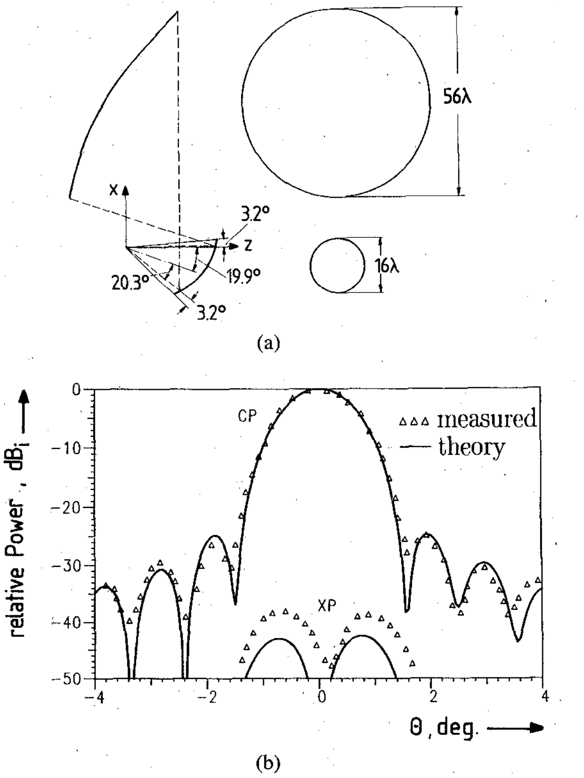


Fig. 5. Verification of the theory by a conical section Gregorian dual offset antenna [16]. (a) Basic geometry. (b) This theory (———) and measurements [16].

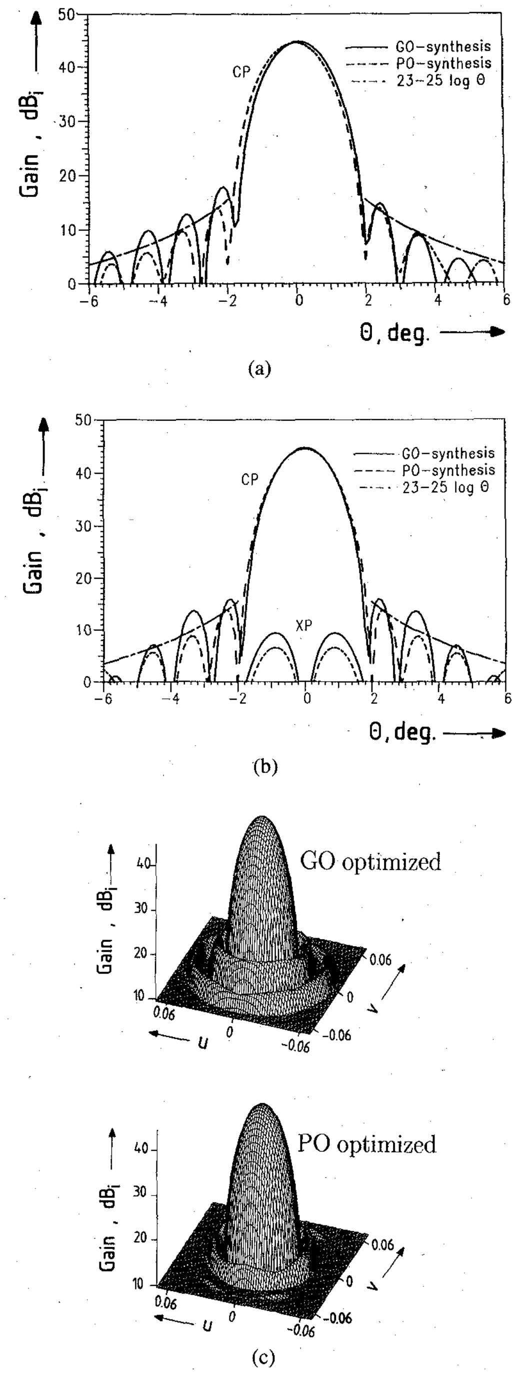


Fig. 6. Shaped small-earth station antenna of Fig. 1(a). Result of the conventional GO synthesis analyzed with 1 step in our PO optimization program, compared with the introduced direct PO optimization method after 900 iterations. (a) Characteristic in the symmetry plane ($\phi = 90°$); GO synthesis (solid curves), PO optimization method after 900 iterations (dashed curves). (b) Characteristic in the asymmetry plane. (c) Three-dimensional contour plots (plotted dynamic range: 35 dB); the abbreviations designate: $u = \sin\theta\cos\phi$, $v = \sin\theta\sin\phi$.

At the example of an optimum shaped Cassegrain dual offset millimeter-wave atmospheric sensor antenna for 200 GHz it is shown that beam steering may be achieved by simply displacing the subreflector (Fig. 1(c)). The basic geometry of the antenna is given in Fig. 1(b). The Cassegrain type offers the advantage of performing a high ratio $F/D = 1.0$ which provides a high beam deviation factor [32] in spite of a relatively compact configuration. Although a spherical reflector might have been also attractive from the viewpoint of low aberration versus scanning angle [32], the Cassegrain type has been preferred since it achieves a lower half-power beamwidth for a prescribed antenna size. Due to the high resolution in vertical direction [19], [20] and to the given geometrical limitations an antenna with elliptical reflectors is chosen; the subreflector edge taper is fixed upon -15 dB. About 8000 integration patches for the subreflector have turned out to be necessary for calculating accurate results. Note that the antenna is mounted at the satellite so that the main axis corresponds to the vertical direction (Fig. 1(c)).

Due to the required high vertical resolution of the sensor antenna of less than 6 km in a distance of 3000 km [20], a low half-power beamwidth (HPBW) was the most critical parameter of the antenna: it should be less than HPBW = 0.11° for a scan range of about seven half-power beamwidths. Without shaping, i.e. with the initial conical section surfaces, the HPBW is significantly increased as is shown by the vertical relative power characteristics at three different scan angles (0°, 0.46°, 0.92°), cf. Fig. 8(a). In a first step, only the subreflector was shaped. The characteristic obtained after 400 iteration runs for shaping the subreflector demonstrates that the HPBW is reduced significantly (Fig. 8(b)). This behavior was still improved by shaping additionally the main reflector as is demonstrated in Fig. 8(c), where further 150 iterations have been used.

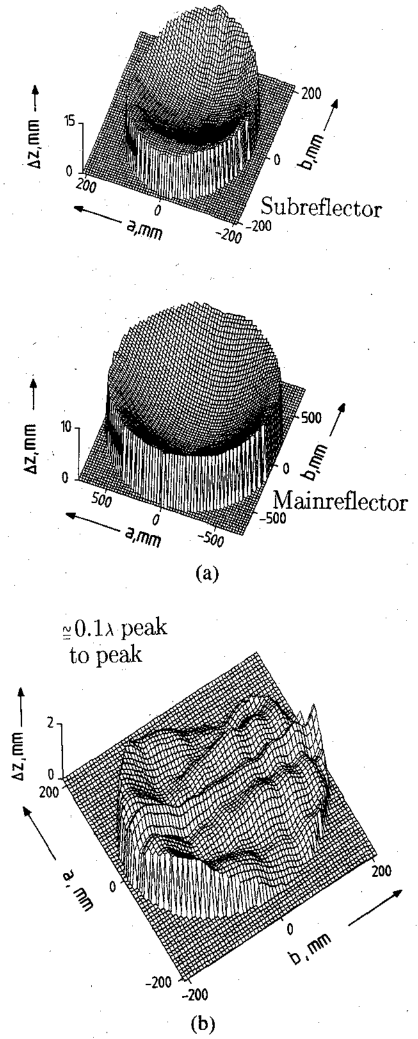
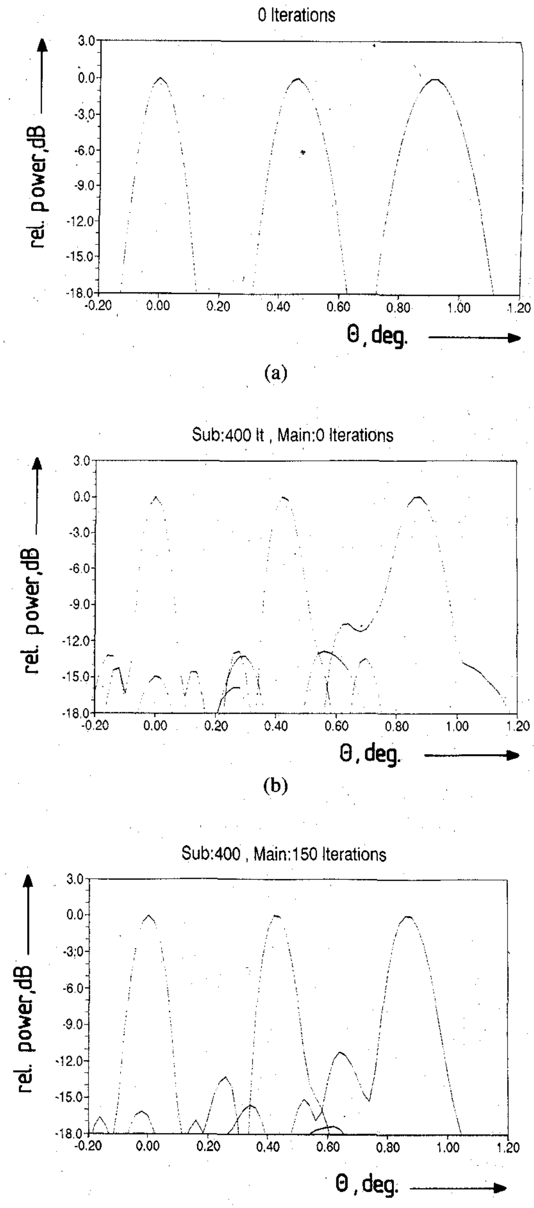


Fig. 7. Illustration of the difference in the z-dimension of the shaped surfaces. (a) PO shaped subreflector and main reflector relative to the corresponding paraboloid or ellipsoid, respectively. (b) PO shaped subreflector relative to the corresponding GO shaped subreflector.



(a)

(b)

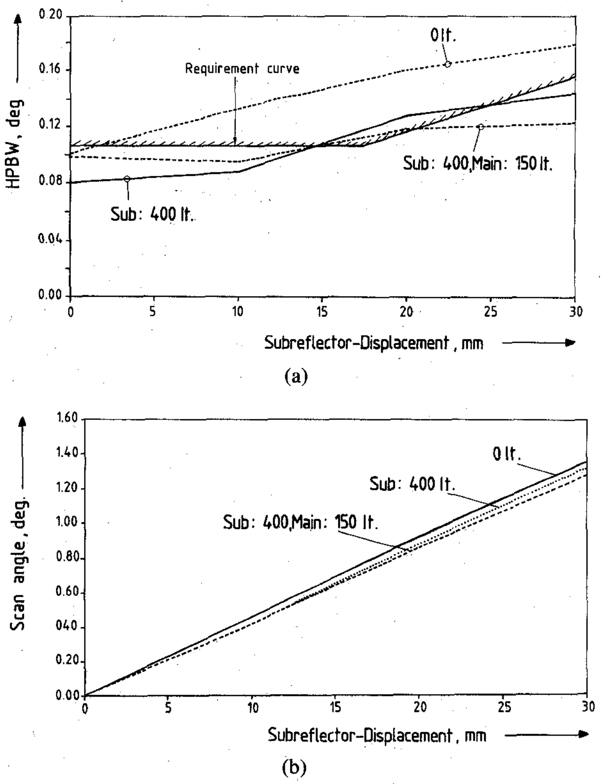
(c)

Fig. 8. Characteristics of the Cassegrain dual offset atmospheric sensor antenna of Fig. 1(b) in the main axis for three different scan angles (θ = 0°, 0.46°, 0.92°). (a) Conical sections for both reflectors (not shaped). (b) Conical section main reflector, shaped subreflector after 400 iterations. (c) Shaped main reflector with 150 iterations, shaped subreflector after 400 iterations.

The improvement of the interesting half-power beamwidth HPBW is illustrated in Fig. 9(a), where the HPBW is plotted as a function of the displacement of the subreflector in the lateral direction. Fig. 9(a) shows also the required HBPW limit which should be maintained for the desired vertical resolution of the sensor antenna. The HPBW curve for the shaped antenna in Fig. 8(c) meets the given requirements for the desired scan range relatively good. The subreflector is moved in lateral direction concerning its main axis (cf. Fig. 1(b)). The scan angle as a function of the displacement is plotted in Fig. 9(b). Since the higher resolution for the space borne sensor antenna is required in vertical direction, the complete antenna system is oriented so that the main axis of the main reflector is pointed to earth.

CONCLUSION

An efficient direct numerical synthesis method has been applied for shaped dual offset reflector antennas for space applications. Its efficiency is demonstrated for two computer-optimized design examples: A very compact Gregorian dual offset earth station antenna with very low sidelobe attenuation level, and a Cassegrain dual offset atmospheric sensor antenna which shows that beam scanning by more than 10 half-power beamwidths is possible with nearly constant half-power beamwidth by simply displacing the subreflector. Improved antenna characteristics are provided by applying an evolution strategy optimization algorithm which circumvents the problem of local minima. The number of the optimization parameters is significantly reduced by characterization of the subreflector and the main reflector surfaces in the spatial domain by a two-dimensional transform. As the theory in-



(a)

(b)

Fig. 9. Cassegrain dual offset atmospheric sensor antenna of Fig. 1(b). (a) Half-power beamwidths HPBW as a function of the subreflector displacement for the characteristics of Fig. 8; required HBW due to the desired vertical resolution of the atmospheric sensor antenna. (b) Scan angle as a function of the linear subreflector displacement.

cludes all relevant parameters, excellent agreement with available measured data of a Gregorian small earth station antenna demonstrates the validity of the approach.

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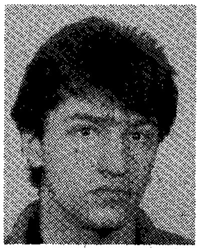

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