Educational Procedure for Designing and Teaching Reflector Antennas in Electrical Engineering Programs

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Abstract

This paper summarizes a simple procedure to design axisymmetric and offset single parabolic reflector antennas with circular apertures. The proposed procedure yields reasonably good results in practice and is specially suitable for introducing students to the geometry and basic electrical characteristics of reflector antennas. Computer simulations and measured data are also presented in support and validation of the analytical procedure. Together with the proposed procedure, the computer simulations and measurements were identified as the three major foundations necessary for properly teaching reflector antennas in Electrical Engineering programs.

Introduction

Reflector antennas can be considered as one of the most successful electrical devices of all time, in view of their importance in extensive and diverse modern engineering applications, ranging from communication systems and electronic warfare to radio astronomy and deep-space exploration[1]. Although there are several procedures available in the literature for designing reflector antennas, the few applicable to the offset geometry are not very practical and didactic[1]. In addition, an attempt is made to define and use design parameters within limits that are consistent with the current production of reflector antennas in the industry, in which the offset reflector represents more than 90% of the market[1].

The procedure herein introduced is derived from[1] and was developed with the sole intent of making the design of reflector antennas more accessible to undergraduate students. One of the main challenges of integrating design problems in the electrical engineering curriculum is to constrain an open-ended complex problem into a closed-form simple procedure valid within useful limits. Furthermore, in order for the students fully understand the electrical behavior of the device being designed, rather than just follow a step-by-step recipe, it is imperative to correlate performance results almost immediately after a given configuration is obtained. An attractive way to accomplish that is through computer simulations. Finally, real measured data is also needed to validate the whole process, while also providing the students with valuable manufacturing experience when possible.

Geometrical Parameters

The general geometry of the parabolic reflector antenna is shown in Fig. 1 and the parameters are defined in Table 1.

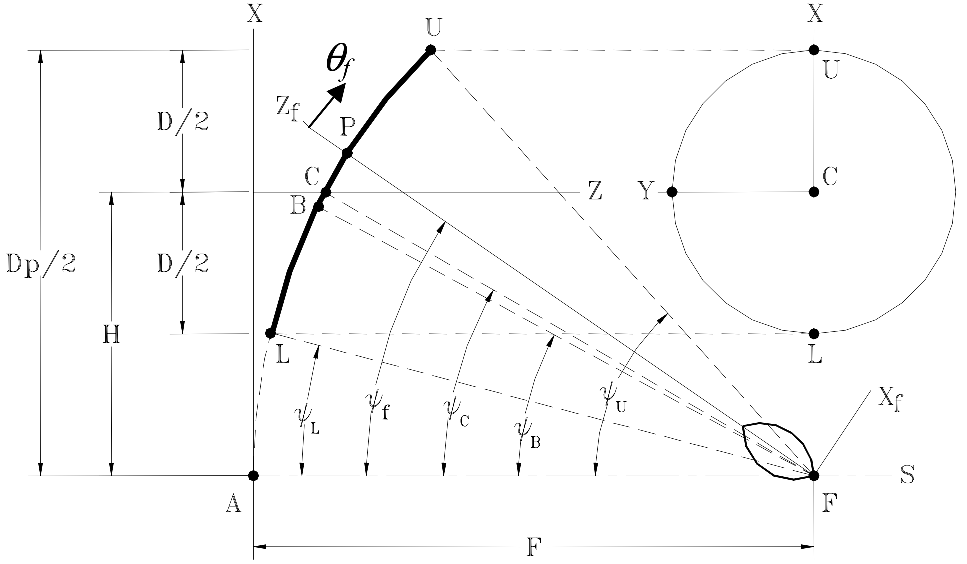

Figure 1. Geometry for the parabolic reflector antenna. See Table 1 for definition of symbols.

Table 1. Definitions of symbols for the parabolic reflector antenna of Fig. 1.

Symbols:	**Definitions:**
D	Diameter of the projected aperture of the parabolic main reflector ($D = D_{\mathrm{p}}$ for an axisymmetric paraboloid).
D_{p}	Diameter of the projected aperture of the parent paraboloid; $D_{\mathrm{p}} = D + 2H$.
H	Offset of reflector center ($H = 0$ for an axisymmetric paraboloid).
F	Paraboloid focal length.
Point F	Focal point.
Point A	Apex of the parent paraboloid.
Point B	Point on reflector which bisects subtended angle viewed from Point F.
Point C	Point on reflector which projects to the center of the projected aperture.
Point P	Point on reflector corresponding to the ray from the peak of feed pattern.
ψ_{f}	Angle of feed antenna pattern peak relative to reflector axis of symmetry (S); $\psi_{\mathrm{f}} = 0^0$ for an axisymmetric paraboloid.
ψ_{B}	Value of ψ_{f} which bisects the reflector subtended angle ($\psi_{\mathrm{U}} - \psi_{\mathrm{L}}$).
ψ_{C}	Value of ψ_{f} when the feed is aimed at the reflector point C.

Procedure for Designing Parabolic Reflector Antennas

The following steps summarize a simple procedure and corresponding rationale to design axisymmetric ($H = 0$) and offset reflector antennas.

A. Determination of Reflector Diameter:

The following equation is very useful to estimate a value of D to achieve a required gain[2] G

$$g_{[\text{Not in dB}]} = \varepsilon_{\text{ap}} \frac{4\pi A_{\text{p}}}{\lambda^2} = \varepsilon_{\text{ap}} \left(\frac{\pi D}{\lambda}\right)^2 \tag{1}$$

where A_{p} is the physical area of the antenna aperture and ε_{ap} is the *aperture efficiency*, typically 0.6 to 0.7 (60% to 70%) for many parabolic reflector systems used in practice. Note that $G = 10 \log g$ [dB].

B. Determination of Offset Distance:

The offset distance H controls the amount of blockage caused by the feed and supporting structure on the reflector projected aperture. Many reflectors nowadays are just fully offset paraboloids ($H = D/2$); i.e., the bottom of the reflector just touches its axis of symmetry. This configuration avoids the blockage from the feed supporting structure and waveguide, although part of the feed aperture is still directly in front of the reflector. Nevertheless, the total blockage area is still significantly smaller than the one presented by axisymmetric configurations ($H = 0$). Values of H larger than $D/2$ can overcome blockage but also increase the total volume occupied by the reflector, which in some cases is not recommended. In addition, the manufacturing process and associated adjustments become more difficult as H increases.

C. Selection of Reflector Curvature:

Values usually encountered in practice for the reflector curvature, F/D_{p}, are between 0.25 and 1.0, where $D_{\text{p}} = D + 2H$. Higher values ease the manufacturing process (i.e., the reflector is flatter), but require a narrower feed pattern to illuminate the reflector which results in larger feed antennas. A typical value nowadays is $(F/D_{\text{p}}) = 0.3$ which yields a compact design.

D. Determination of Feed Pattern:

An important parameter for determining the necessary feed pattern is the *reflector illumination* RI, which in dB is given by

$$\text{RI} = 20 \log\left[\cos^2\left(\frac{\theta_{\text{f}} + \psi_{\text{f}}}{2}\right)\right] + 20 \log\left(\cos^q \theta_{\text{f}}\right) \tag{2}$$

where the first term in the right side of (2) is normally referred to as *spherical spreading loss*, and accounts for the power spreading due to spherical propagation of the wave between the focal point and the parabolic reflector surface. The second term in the right side of (2) is the normalized feed pattern in dB of

$$C(\theta_{\mathrm{f}}) = \cos^{q} \theta_{\mathrm{f}} \qquad (3)$$

which is a pattern model widely used in practice. The main advantage of (3) is that the directivity of the feed, or its gain g_f if ohmic losses are not taken into account, can be found analytically in closed form with

$$g_{\mathrm{f\,[Not\ in\ dB]}} = 4q + 2 \qquad (4)$$

The parameter q can be obtained from (2) for a required reflector illumination RI in dB at a direction θ_{f} as

$$q = \frac{\frac{\mathrm{RI}}{20} - \log\left[\cos^{2}\left(\frac{\theta_{\mathrm{f}} + \psi_{\mathrm{f}}}{2}\right)\right]}{\log(\cos\theta_{\mathrm{f}})} \qquad (5)$$

An usual value for RI at the reflector edges, often referred to as *edge illumination* EI, is -11 dB and assures optimal gain performance for axisymmetric paraboloids[2] ($\psi_{\mathrm{f}} = 0^{\circ}$ and $\theta_{\mathrm{f}} = \psi_{\mathrm{L}} = \psi_{\mathrm{U}}$).

In offset reflectors, $\psi_{\mathrm{L}} \neq \psi_{\mathrm{U}}$ as shown in Fig. 1, but a specified value of EI at both edges can still be obtained, by solving for ψ_{f} the equation formed by imposing that $q(\theta_{\mathrm{f}} + \psi_{\mathrm{f}} = \psi_{\mathrm{L}}) = q(\theta_{\mathrm{f}} + \psi_{\mathrm{f}} = \psi_{\mathrm{U}})$, which yields $q(\theta_{\mathrm{f}} = \psi_{\mathrm{L}} - \psi_{\mathrm{f}}) = q(\theta_{\mathrm{f}} = \psi_{\mathrm{U}} - \psi_{\mathrm{f}})$. Once ψ_{f} is determined, the parameter q can be calculated directly from (5) for the specified value of RI (i.e., EI), at either $\theta_{\mathrm{f}} + \psi_{\mathrm{f}} = \psi_{\mathrm{L}}$ or $\theta_{\mathrm{f}} + \psi_{\mathrm{f}} = \psi_{\mathrm{U}}$, since they now should yield the same result. Under this condition, the edge illumination is called *balanced*, and yields near-minimum sidelobe levels over practical ranges of feed pointing, with only small penalties in gain and cross polarization[1]. A graphical technique to determine ψ_{f} for the same condition is particularly recommended when only measured feed patterns are available[1].

In practice, however, it is common to find offset systems employing $\psi_{\mathrm{f}} = \psi_{\mathrm{B}}$ or $\psi_{\mathrm{f}} = \psi_{\mathrm{C}}$; See Fig. 1. For either case the edge illumination EI is in general unbalanced. As a consequence, different values of q are obtained with (5), depending whether $\theta_{\mathrm{f}} + \psi_{\mathrm{f}} = \psi_{\mathrm{L}}$ or $\theta_{\mathrm{f}} + \psi_{\mathrm{f}} = \psi_{\mathrm{U}}$. A simple arithmetic mean can then be taken to specify the required feed pattern. Although approximate, this simple procedure yields reasonably good results in practice and is well suited for our purposes.

Once the parameter q is determined, (4) and (1) can be used to estimate the aperture diameter, or area, of the required feed antenna. A typical value of $\varepsilon_{\mathrm{ap}} = 0.55$ (55%) can be used for feed horns. A more exact approach is available when the feed antenna is an open-ended rectangular waveguide of wide and narrow dimensions a and b, or an open-ended circular waveguide of radius a. For those cases, the waveguide dimensions can be determined from (4) respectively with $g_{\mathrm{f}} = 32ab/\pi\lambda^{2}$ ($\varepsilon_{\mathrm{ap}} \approx 0.81$) or $g_{\mathrm{f}} = 10.5\pi a^{2}/\lambda^{2}$ ($\varepsilon_{\mathrm{ap}} \approx 0.84$). If the result indicates a feed antenna with an aperture considered too large, a higher value of RI (i.e., EI at the reflector edges) should be employed to avoid unnecessary blockage. For an offset reflector, a larger value of H can also be tried and the whole procedure needs to be repeated.

Design Results and Computer Simulations

The design procedure described in the previous section was successfully employed to design a 1.6-m just fully offset paraboloid, built and tested for satellite TV reception at the University of Brasilia – Brazil, where the author was previously teaching; See Fig. 2. The geometrical parameters are listed in Table 2 in conjunction with the simulation results obtained at 3.95 GHz with the computer code PRAC (Parabolic Reflector Analysis Code), developed by the author[1]. PRAC is a user-friendly code developed to analyze axisymmetric and offset parabolic reflector antennas, evaluating the radiation integral (physical optics surface current integration) with the Jacobi-Bessel method[1]. PRAC is currently being distributed with a textbook[2] and used by many universities and antenna manufacturers worldwide. Note from Table 2 that the computed aperture efficiency is higher than the values usually encountered in practice (overestimation of about 10% to 15% is typical), due mostly to losses and system imbalances not modeled by the computer simulations.

Figure 2. Offset parabolic reflector built and tested for satellite TV reception at C-band.

Conclusions

A simple educational procedure to design reflector antennas was described in detail. The procedure was specially developed to introduce the designing of reflector antennas to undergraduate students. The procedure yields results that present good correlation to computer and measured data, and was employed to design and manufacture a 1.6-m offset reflector antenna for satellite TV reception at the C-band. Three major blocks were found essential for the effective teaching of reflector antennas in Electrical Engineering: 1) Closed-form, step-by-step analytical design procedures, 2) Analysis software, and 3) Manufacturing of prototypes and measurements. Finally, it is worth mentioning that the computer programming of the design procedure itself must be avoided initially, as the use of simple analytical expressions aid the students to comprehend the basic geometry and electrical characteristics of the device being designed. Although the main conclusions herein addressed appear to be extendable to other engineering areas and devices, more evidence is currently needed to provide a more generic assessment of adroit design methodologies and their impact in engineering education.

Table 2. Geometrical parameters and performance values computed with the code PRAC at 3.95 GHz for the offset parabolic reflector of Fig. 2.

Parameters:	**Values and relation to design procedure:**
D	160 cm; design goal of at least 34.5 dBi in gain with $\varepsilon_{ap} = 0.65$ or 65% (see **step A** for further details). A gain of at least 34.5 dBi is recommended for satisfactory reception of satellite TV signals, as determined by a simple downlink analysis performed on-site.
H	80 cm; $H = D/2$ for a just fully offset paraboloid (see **step B**).
D_p	320 cm; $D_p = D + 2H$.
(F/D_p)	0.3 (see **step C**).
F	96 cm
Angles ψ_L & ψ_U	$\psi_L = 0^0$ and $\psi_U = 79.61^0$
ψ_f	42.91^0, yielding a *balanced* illumination with RI = EI = -15.77 dB at both reflector edges for a feed with $q = 5.83$ (see **step D** for further details). Note that $q = 5.83$ (measured feed taper of –13.5 dB at 40^0) represents a feed gain of about 14 dBi with an aperture diameter of 16.4 cm and $\varepsilon_{ap} = 55\%$ at 3.95 GHz.
	Performance values computed with PRAC at 3.95 GHz:
Gain	35.31 dBi
Crosspolar level	-21.72 dB
ε_{ap}	77.54 %

References

1. Marco A.B. Terada, "Reflector Antennas", *Encyclopedia of Electrical and Electronics Engineering* (invited), edited by John Webster, Vol. 18, pp. 360-379, John Wiley & Sons, 1999.

2. Warren L. Stutzman and Gary A. Thiele, *Antenna Theory and Design*, 2nd edition, John Wiley & Sons, 1998.

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Dr. Terada currently serves as an Assistant Professor of Electrical Engineering at New Mexico State University. His interests in research and development include applied electromagnetics and numerical methods, with emphasis on the design, manufacturing and testing of antennas and microwave devices applied to wireless networks (satellites, cellular, WLANs, etc.). Previous funded research included the application of neural networks, fuzzy logic and genetic algorithms to the synthesis of antennas and to the reduction of interferences in digital satellite communication systems. In addition, Dr. Terada has also interest in the development and implementation of technologies applied to distance learning, such as VSAT and wireless networks, cable, video, Internet and CDs. Dr. Terada has extensive academic, industrial and consulting experiences, having published several journal articles and symposium papers, including an invited chapter on reflector antennas for the *Wiley Encyclopedia of Electrical and Electronics Engineering* (John Wiley and Sons, 1999). Dr. Terada was a co-founder and has served as Editor-in-Chief of the *Journal of Microwaves and Optoelectronics* (ISSN 1516-7399), and has been recently involved with the design, manufacturing and testing of the *INTELSAT IX* satellite fleet (seven spacecraft operating in C and Ku bands).