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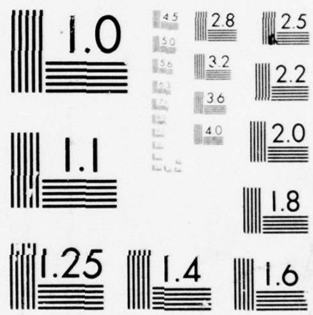


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RADC-TR-77-361
IN-HOUSE REPORT
OCTOBER 1977

# Effect of Fresnel Zone Blockage on Very Low Sidelobe Antennas

RONALD L. FANTE



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ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

Title of Report: Effect of Fresnel Zone Blockage on Very Low Sidelobe Antennas

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## REPORT DOCUMENTATION PAGE

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| | |
|---|---|
| 1. REPORT NUMBER: (14) RADC-TR-77-361 | 2. GOVT ACCESSION NO. |
| | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle): (6) EFFECT OF FRESNEL ZONE BLOCKAGE ON VERY LOW SIDELOBE ANTENNAS | 5. TYPE OF REPORT & PERIOD COVERED: In house |
| | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s): (10) Ronald L./Fante | 8. CONTRACT OR GRANT NUMBER(s) |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS: Deputy for Electronic Technology (RADC/EEA) Hanscom AFB Massachusetts 01731 | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61102F (16) 2305J401 (17) J4 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS: Deputy for Electronic Technology (RADC/EEA) Hanscom AFB Massachusetts 01731 | 12. REPORT DATE: (11) Oct[redacted]77 |
| | 13. NUMBER OF PAGES: 17 |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) | 15. SECURITY CLASS. (of this report): Unclassified (12) 18p. |
| | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Antennas
Sidelobes
Blockage
Radar

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Silver's method for estimating antenna sidelobes owing to blockage is accurate only for obstacles in the near field; it is unduly pessimistic for obstacles elsewhere in the Fresnel zone. A method for calculating the side-lobe level in the latter case is presented and applied to some problems that are typical as well as practical.

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## 1. INTRODUCTION

At present the United States Air Force is interested in the development of radars with -50 dB azimuthal sidelobes. In order to maintain such low sidelobes, unfortunately, it is necessary to find a radar site which is free from all main-beam blockage within quite a distance from the radar. In this paper, we will present an approximate method for estimating the effect of partial-beam blockage by an obstacle (such as a tree) located in the Fresnel zone of the antenna.

## 2. FORMAL THEORY

### 2.1 Field Scattered by the Obstacle

Consider an obstacle in the Fresnel zone of a radiating antenna, as shown in Figure 1. The far-electric field scattered by this obstacle can be written as[1]

(Received for publication 26 October 1977)

1. Morse, P., and Fishback, H. (1953) Methods of Theoretical Physics, vol. 2, McGraw-Hill, New York.

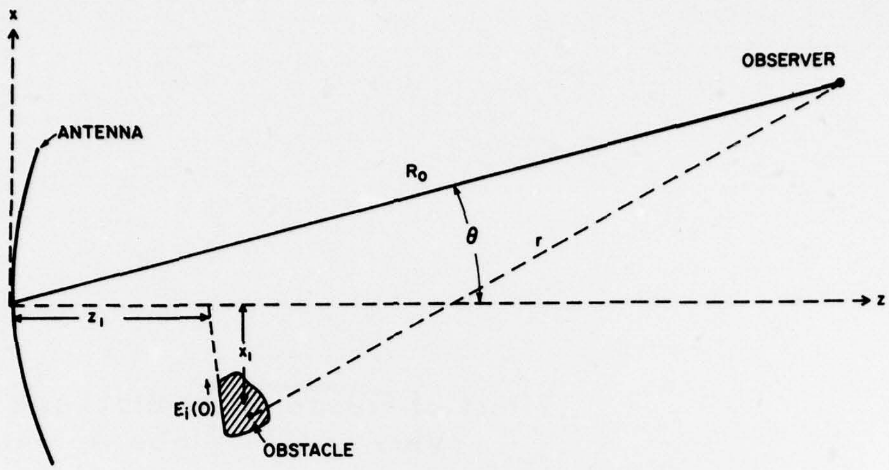


Figure 1. Obstacle in the Fresnel Zone of an Antenna

$$\underline{E}_s(\underline{x}) = \frac{k^2}{4\pi} \iiint_V (\epsilon - 1)\, \underset{\sim}{G}_o \cdot \underline{E}\, \frac{e^{-ikr}}{r} d^3 x'$$

$$= \frac{k^2 e^{-i\psi_o}}{4\pi R_o} \iiint_V (\epsilon - 1)\, \underset{\sim}{G}_o \cdot \underline{E}\, e^{ik(x' \sin\theta \cos\phi + y' \sin\theta \sin\phi + z' \cos\theta)}$$

$$dx'\, dy'\, dz' \quad , \qquad (1)$$

where

$k$ = the signal wave number,
$\epsilon$ = the relative (complex) permittivity of the obstacle,
$V$ = the volume of the obstacle,
$\underline{E}$ = the electric field inside the obstacle,
$\underset{\sim}{G}_o = \underset{\sim}{I} - \hat{v}\hat{v}$,
$\underset{\sim}{I}$ = the unit dyad,
$\hat{v} = \hat{x} \sin\theta \cos\phi + \hat{y} \sin\theta \sin\phi + \hat{z} \cos\theta$,
$\theta$ = the polar angle,
$\phi$ = the azimuthal angle,
$\hat{x}, \hat{y}, \hat{z}$ are unit vectors, and
$\psi_o = k(R_o - x_1 \sin\theta \cos\phi - y_1 \sin\theta \sin\phi - z_1 \cos\theta)$.

Let us now assume that the antenna is a planar, rectangular aperture lying in the $z = o$ plane. We further assume that the antenna is linearly polarized, and excited with an electric field distribution $\hat{x}\, e_o(x, y)$. Then the Fresnel-zone field, near the z-axis, in the plane $z = z_1$ can be approximated as

$$E_i(z_1) = \hat{x}\, \alpha(x, y)\, e^{-ikz_1} \quad , \tag{2}$$

where $\alpha(x, y)$ is plotted[2] for various aperture-field distributions. For the case of a square aperture with a cosine distribution in the x-direction and a cosine squared taper in the y-direction, the values of the relative axial field $\alpha_o \equiv \alpha(0, 0)/e_o(0, 0)$ are given in Figure 2, assuming the linear aperture dimension is 15 ft and the signal frequency 3.35 GHz. We observe that there is no significant dropoff in the field strength until $z_1$ is approximately 200 ft; consequently, for $z_1 \lesssim 200$ ft we can use the approximation

$$\alpha(x, y) \simeq e_o(x, y) \quad . \tag{3}$$

Next we need to calculate the field inside the obstacle. For mathematical simplicity, we shall assume that the obstacle is a homogeneous rectangular structure oriented as shown in Figure 3. We also assume that the transverse dimensions of the obstacle (that is, its x and y dimensions) are considerably larger than the signal wavelength. In this case, we may approximate the field transmitted into the obstacle by that which would be transmitted into a planar slab, of infinite extent in the x-y directions. Upon using the aforementioned assumptions, along with Eq. (2), and ignoring the effect of the obstacle on the aperture distribution, we find it straightforward to show that the electric field inside the obstacle is given by

$$\underline{E} \simeq \hat{x}\, \alpha(x, y) \left[ A\, e^{-ik_2 z'} + B\, e^{ik_2 z'} \right] e^{-ikz_1} \quad , \tag{4}$$

where

$$z = z_1 + z' \quad , \quad k_2 = k\, \epsilon^{1/2}$$

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2. Air Force Handbook, Electromagnetic Radiation Hazards, Air Force Communications Service (E-1 Standard) TO 31Z-10-4, 1 Aug. 1966.

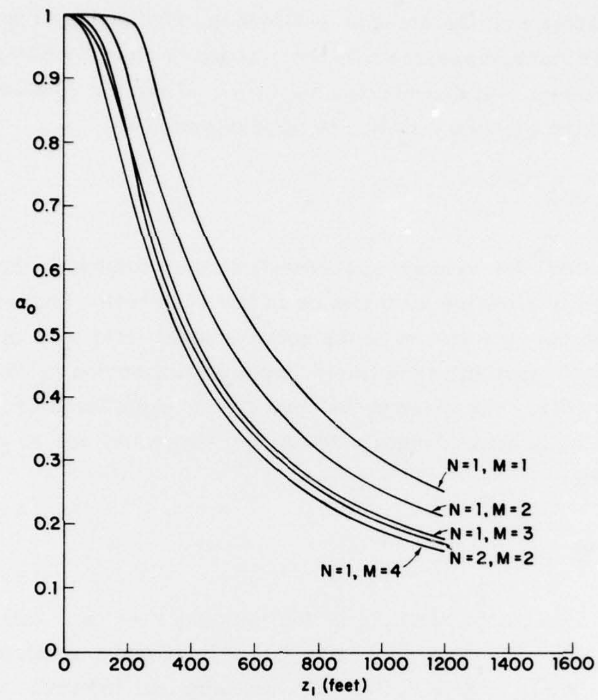


Figure 2. Values of $\alpha_0$ for a Square Aperture With $2L_1 = 2L_2 = 15$ ft and a taper $\cos^N(\pi x/2L_1)$ $\cos^M(\pi y/2L_1)$. The frequency is 3.35 GHz

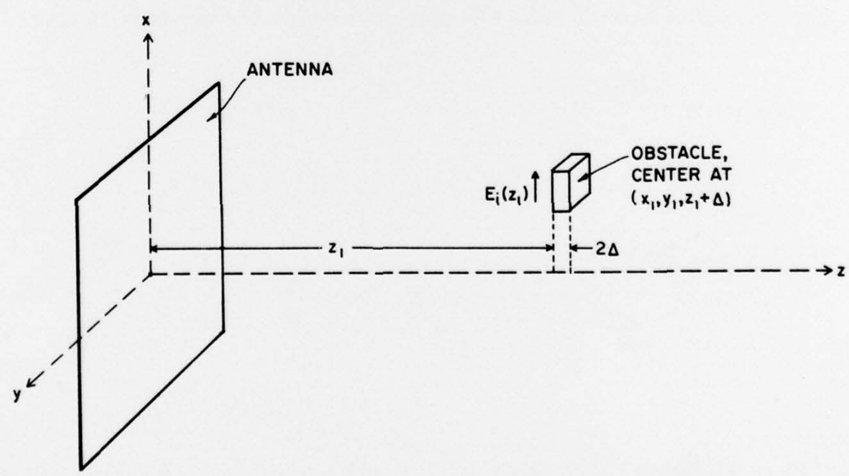


Figure 3. Rectangular Obstacle in the Fresnel Zone of a Planar Aperture

and

$$A = \frac{2(\epsilon^{1/2} + 1) \exp(i\,4\,k_2\,\Delta)}{(\epsilon^{1/2} + 1)^2 \exp(i\,4\,k_2\,\Delta) - (\epsilon^{1/2} - 1)^2} \quad , \tag{5}$$

$$B = \frac{2(\epsilon^{1/2} - 1)}{(\epsilon^{1/2} + 1)^2 \exp(i\,4\,k_2\,\Delta) - (\epsilon^{1/2} - 1)^2} \quad . \tag{6}$$

If we recall that $x = x_1 + x'$ and $y = y_1 + y'$ and then substitute Eq. (4) into Eq. (1), we obtain

$$\underline{E}_s = \frac{k^2\,F\,e^{-i\psi_1}}{4\pi R_o} \,(\underset{\sim}{G}_o \cdot \hat{x}) \iint_{S_o} dx'\,dy'\,\alpha(x_1 + x',\, y_1 + y')$$

$$e^{i\,k \sin\theta (x' \cos\phi + y' \sin\phi)} \quad , \tag{7}$$

where $S_o$ = transverse surface area of obstacle,

$$\psi_1 = k(R_o - x_1 \sin\theta \cos\phi - y_1 \sin\theta \sin\phi + 2z_1 \sin^2 \frac{\theta}{2}) \quad ,$$

$$F \equiv (\epsilon - 1) \int_0^{2\Delta} dz'\, e^{i\,k\,z' \cos\theta} \left[A\,e^{-i\,k_2\,z'} + B\,e^{i\,k_2\,z'}\right] \tag{8a}$$

$$\simeq \frac{-2\,e^{i\gamma}}{i\,k} \left[2\,i \sin\gamma - \frac{b(1 - e^{i\beta})}{a - b\,e^{i\beta}}\, e^{i\gamma}\right] \quad , \tag{8b}$$

and

$$\gamma = k\,\Delta(\epsilon^{1/2} + 1) \quad ,$$

$$\beta = 4\,k\,\Delta\epsilon^{1/2} \quad ,$$

$$a = (\epsilon^{1/2} - 1)^2 \quad ,$$

$$b = (\epsilon^{1/2} + 1)^2 \quad .$$

Note that Eq. (8a) is valid for all values of $\theta$, but Eq. (8b) is specialized to the case when $\theta$ is small, so that $\cos\theta \simeq 1$.

It is interesting to observe from Eq. (8) that when $|\epsilon| \to \infty$, $F \to (2i/k)$. Consequently, when $|\epsilon| = |\epsilon_r - i\sigma/\omega\epsilon_o|$ is very large, Eq. (7) reduces to

$$\underline{E}_s \to \frac{i\,k\,e^{-i\psi_1}}{2\pi R_o} (\underset{\sim}{G}_o \cdot \hat{x}) \iint_{S_o} dx'\, dy'\, \alpha(x_1 + x', y_1 + y')$$

$$e^{i\,k\sin\theta(x'\cos\phi + y'\sin\phi)} \quad . \tag{9}$$

Finally, if the obstacle is within 200 ft of the antenna, we may use the approximation in Eq. (3) to get

$$E_s \to \frac{i\,k\,e^{-i\psi_1}}{2\pi R_o} (\underset{\sim}{G}_o \cdot \hat{x}) \iint_{S_o} dx'\, dy'\, e_o(x_1 + x', y_1 + y')$$

$$e^{i\,k\sin\theta(x'\cos\phi + y'\sin\phi)} \quad . \tag{10}$$

Equation (10) is the standard result for the effect of near-field blockage by a perfectly conducting obstacle. In the opposite limit when $\epsilon$ is near unity, we find $F \simeq 2\Delta(\epsilon - 1)$, provided $k\Delta|\epsilon - 1| \ll 1$.

### 2.2 Direct Field of the Antenna

The far field of the antenna in the absence of any blockage can also be written in the same form as Eq. (7). From Silver[3] we have

$$\underline{E}_D = \frac{i\,k\,e^{-ikR_o} (\underset{\sim}{G}_1 \cdot \hat{x})}{4\pi R_o} \iint_{S_A} dx'\, dy'\, e_o(x', y')\, e^{i\,k\sin\theta(x'\cos\phi + y'\sin\phi)} \quad , \tag{11}$$

where $\underset{\sim}{G}_1 = (1 + \hat{z} \cdot \hat{v})\,\underset{\sim}{I} - \hat{v}\hat{v} - \hat{z}\hat{v}$, and $S_A$ is the area of the antenna aperture. For values of $\theta < 15^o$, we can approximate $\underset{\sim}{G}_1 \cdot \hat{x}$ by $2\hat{x} - 2\hat{z}\sin\theta\cos\phi$.

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3. Silver, S. (1965) Microwave Antenna Theory and Design, Dover, New York, p. 162.

## 2.3 Total Radiated Field

The total field radiated when an obstacle is located in the Fresnel zone of an antenna is obtained by combining Eqs. (7) and (11), provided it is acceptable to assume that the presence of the obstacle does not alter the aperture field distribution. Let us, therefore, combine Eqs. (7) and (11) and assume that $\theta < 15^{o}$, so that $\underset{\sim}{G}_1 \cdot \hat{x} \simeq 2\hat{x} - 2\hat{z} \sin\theta \cos\phi$ and $\underset{\sim}{G}_{o} \cdot \hat{x} \simeq \hat{x} - \hat{z} \sin\theta\cos\phi$. We obtain

$$\underline{E}_T = \frac{ik\,e^{-ikR_o}}{2\pi R_o}\,\hat{s}\left[\int_{-L_1}^{L_1} dx' \int_{-L_2}^{L_2} dy'\, e_o(x',y')\, e^{ik\sin\theta(x'\cos\phi + y'\sin\phi)}\right.$$

$$-\frac{ikF}{2}\, e^{i\psi_2}\int_{-X_o}^{X_o} dx' \int_{-Y_o}^{Y_o} dy'\, \alpha(x_1 + x', y_1 + y')$$

$$\left. e^{ik\sin\theta(x'\cos\phi + y'\sin\phi)}\right] , \qquad (12)$$

where $\hat{s} = \hat{x} - \hat{z}\sin\theta\cos\phi$, $\psi_2 = k(x_1 \sin\theta\cos\phi + y_1 \sin\theta\sin\phi - 2z_1 \sin^2\frac{\theta}{2})$, the aperture antenna has dimensions $2\,L_1$ and $2\,L_2$ in the x and y directions, respectively, and the obstacle has transverse dimensions $2X_o$ and $2Y_o$. Note that when $z_1 \lesssim 200$ ft, we can replace $\alpha(x_1 + x', y_1 + y')$ by $e_o(x_1 + x', y_1 + y')$.

In studying Eq. (12) further, we will assume that $z_1 > 200$ ft, because it is unlikely that a radar would be placed in a site with obstacles closer than that distance. We shall also assume that the obstacle is the principal source of the sidelobes. When we make this latter assumption, it is easy to see from Eq. (12) that the relative (that is, relative to the axial power density) sidelobe power density S is as follows:

$$S = \frac{\dfrac{k^2|F|^2}{4}\left|\displaystyle\int_{-X_o}^{X_o} dx' \int_{-Y_o}^{Y_o} dy'\, \alpha(x_1 + x', y_1 + y')\, e^{ik\sin\theta(x'\cos\phi + y'\sin\phi)}\right|^2}{\left|\displaystyle\int_{-L_1}^{L_1} dx' \int_{-L_2}^{L_2} dy'\, e_o(x',y')\right|^2} \qquad (13)$$

For the case of a square aperture with $e_o = \cos(\pi x/2L_1)\cos^2(\pi y/2L_1)$, we can rewrite Eq. (13) as

$$S = \left(\frac{\pi k}{8L_1^2}\right)^2 |F|^2 \left| \int_{-X_o}^{X_o} dx' \int_{-Y_o}^{Y_o} dy' \, \alpha(x_1 + x', y_1 + y') \right.$$

$$\left. e^{i k \sin\theta (x' \cos\phi + y' \sin\phi)} \right|^2 \tag{14}$$

In much of the Fresnel zone ($0.3 \lesssim p \leq 2$, where $p \equiv \lambda z_1/4L_1^2$) we have found that $\alpha(x, y)$ can be approximated by the analytic form

$$\alpha(x, y) = \alpha_o \exp\left\{- m_1 \left(\frac{x}{L_1}\right)^2 - m_2 \left(\frac{y}{L_1}\right)^2\right\} , \tag{15}$$

where the values of $m_1$ and $m_2$ depend on the aperture taper and p. Values of m for different aperture field tapers are presented in Table 1. Values of $\alpha_o$ are presented in Figure 2.

Table 1. Values of m for Different Aperture Field Tapers (Values of m versus $p = \lambda z_1/rL_1^2$, where $2L_1$ = aperture dimension and $\lambda$ = wavelength

| Cosine Taper | | Cosine-squared Taper | | Cosine-cubed Taper | | Cosine-fourth Taper | |
|---|---|---|---|---|---|---|---|
| p | m | p | m | p | m | p | m |
| 0.5 | 0.9 | 0.3 | 1.43 | 0.3 | 1.15 | 0.3 | 0.975 |
| 1.0 | 0.25 | 0.5 | 0.605 | 0.5 | 0.45 | 0.5 | 0.38 |
| 2.0 | 0.059 | 1.0 | 0.155 | 1.0 | 0.125 | 1.0 | 0.1 |
| | | 2.0 | 0.040 | 2.0 | 0.035 | 2.0 | 0.025 |

When the obstacle area is considerably smaller that the aperture area, it is possible to simplify Eq. (14) by realizing that $\alpha$ varies rather slowly over the extent of the obstacle. Consequently, we can approximate $\alpha(x_1 + x', y_1 + y')$ by $\alpha(x_1, y_1)$. If this is done and the integrals in Eq. (14) are then evaluated we find, after using Eq. (15), that

$$S(\theta, \phi) = \left(\frac{\pi k \alpha_o}{2}\right)^2 |F|^2 \left(\frac{X_o Y_o}{L_1^2}\right)^2 \exp\left\{-2m_1 \left(\frac{X_1}{L_1}\right)^2 - 2m_2 \left(\frac{y_1}{L_1}\right)^2\right.$$

$$\cdot \operatorname{sinc}^2 (kX_o \sin\theta \cos\phi) \operatorname{sinc}^2 (kY_o \sin\theta \sin\phi) \quad , \qquad (16)$$

where $x_1$ and $y_1$ are the coordinates of the center of the obstacle, we shall be primarily concerned with the azimuthal sidelobes. Consequently, we can set $\phi = \pi/2$ in Eq. (16). Also, for $\theta$ well outside of the main beam, the envelope of the function $\operatorname{sinc}^2 (kY_o \sin\theta)$ is $(kY_o \sin\theta)^{-2}$. Therefore, the magnitude of the azimuthal sidelobe at $\theta$ is

$$|S(\phi) = \pi/2| = \frac{\left(\frac{\pi k \alpha_o X_o}{2L_1}\right)^2 |F|^2 \exp\left[-2m_1 \left(\frac{X_1}{L_1}\right)^2 - 2m_2 \left(\frac{y_1}{L_1}\right)^2\right]}{(kL_1 \sin\theta)^2} . \qquad (17)$$

## 3. NUMERICAL EXAMPLES

### 3.1 Fence-like Obstacle

As a first example, let us consider the situation in Figure 4. The obstacle is assumed to be a metal fence or a very dense forest at a distance $z_1$ of 800 ft from the antenna. For this case $|F|^2 \simeq 4/k^2$, $\alpha_o \simeq 0.31$ and $p \simeq 1$. Because we are unable to perform the x- integration in Eq. (14), we will approximate $\alpha(x_1 + x')$ by $\alpha(x_1)$, where $x_1 = -2L_1$, (see Figure 4). If we assume the obstacle is infinitely long in the y - direction, we obtain from Eq. (14)

$$S\left(\phi = \frac{\pi}{2}\right) = \frac{0.094}{m_2} \exp\left[\frac{-(kL_1 \sin\theta)^2}{2m_2}\right] . \qquad (18)$$

From Table 1, we find $m_2 = 0.155$, so that for $\theta$ outside the main beam, the side-lobe level is smaller than -400 dB, which is clearly no problem.

### 3.2 Finite Obstacle

We now consider the same geometry as in Figure 4, except with the obstacle width, $2Y_o$, smaller than the aperture width. A pictoral illustration of the projection

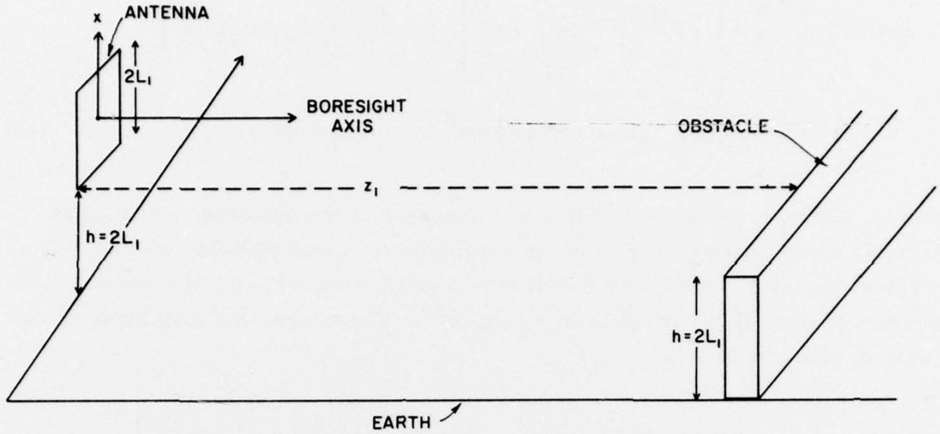


Figure 4. Fence-like Obstacle in the Fresnel Zone of an Antenna

of the obstacle onto the aperture is shown in Figure 5. In this case, we may use the approximate formula in Eq. (17) to obtain

$$\left|S\left(\phi = \frac{\pi}{2}\right)\right| = \frac{4.7 \times 10^{-6} \left(\frac{k|F|}{2}\right)^2}{\sin^2 \theta} \quad . \tag{19}$$

If the obstacle is metal or dense wood, such as a tree trunk

$$|F|^2 \simeq 4/k^2 \quad .$$

However, if the obstacle is the branches and leaves of a tree, it is difficult to specify $|F|$, although it is expected that $|F|^2 < 4/k^2$. In order to be pessimistic,* we can assume

$$|F|^2 \simeq 4/k^2 \quad ,$$

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*Note that for appropriate combinations of $\epsilon$ and $\Delta$ we find that $|F|^2 > 4/k^2$, but generally $|F|^2 \leq 4/k^2$ otherwise.

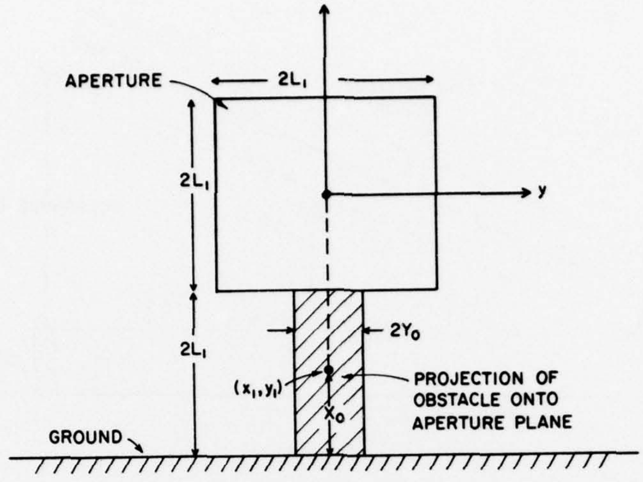


Figure 5. Projection of the Obstacle onto the Aperture Plane

so that

$$|S(\phi = \pi/2)| \simeq 4.7 \times 10^{-6}/\sin^2 \theta \quad .$$

Consequently, for $\theta = 10^{\circ}$ the sidelobe level produced by the obstacle will be -38.1 dB. This is unacceptable, because we require -50 dB sidelobes. However, when the main beam is elevated, we expect that the azimuthal sidelobe level will decrease. In order to study the effect of beam elevation, we realize that for a given beam elevation the value, $x_1$, of the location of the obstacle center is

$$x_1 = -2L_1 - 800 \tan \beta_o \text{ ft} \quad , \tag{20}$$

as is clear from Figure 6. For this case we get, in place of Eq. (19), the result

$$\left|S\left(\phi = \frac{\pi}{2}\right)\right| \simeq \frac{3.5 \times 10^{-5} \left(\frac{k|F|}{2}\right)^2}{\sin^2 \theta} \exp\left[-2(1 + 53.3 \tan \beta_o)^2\right] \tag{21}$$

If we again assume that $|F|^2 \simeq 4/k^2$, we obtain the results in Table 2.

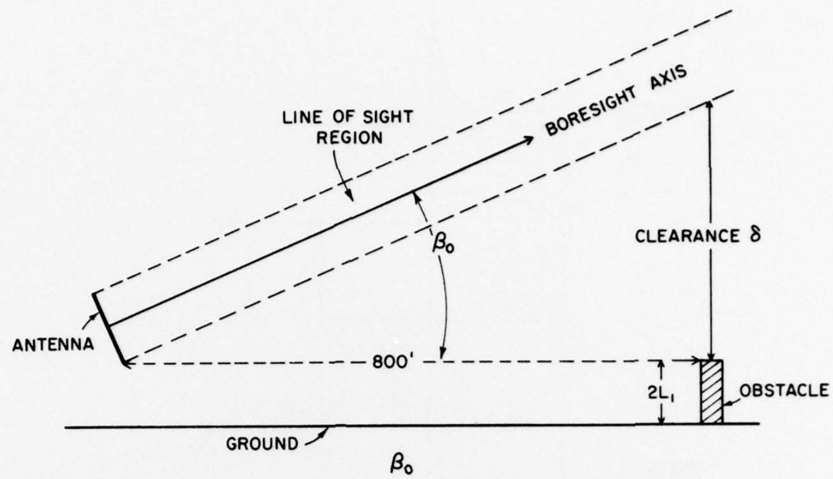


Figure 6. Effect of a Beam Elevation

Table 2. Azimuthal Sidelobe Levels for the Obstacle in Figure 5

| $\beta_o$ (degrees) | Clearance $\delta$ (ft) | $\lvert S(\theta = 6^o)\rvert_{dB}$ | $\lvert S(\theta = 10^o)\rvert_{dB}$ |
|---|---|---|---|
| 0 | 0 | -33.7 | -38.1 |
| 0.5 | 7 | -43.6 | -48.0 |
| 1 | 14 | -57.3 | -61.7 |
| 1.5 | 21 | -74.8 | -79.2 |

## 4. CONCLUSIONS

We have found that for high (complex) permittivity obstacles of transverse dimensions $2X_o$ and $2Y_o$ centered at $(x_1, y_1)$ relative to the aperture center, the relative azimuthal sidelobe level is

$$\left|S\left(\phi = \frac{\pi}{2}\right)\right| \simeq \frac{\left(\frac{\alpha_o X_o}{L_1}\right)^2 \exp\left[-2m_1\left(\frac{x_1}{L_1}\right)^2 - 2m_2\left(\frac{y_1}{L_1}\right)^2\right]}{(2L_1 \sin\theta/\lambda)^2} ,$$

where $2L_1$ is the linear aperture dimension, $\lambda$ is the wavelength, and $\alpha_o$ and m are given in Figure 2 and Table 1. By using the above result, we have shown that even when there is not actual aperture blockage, the effect of obstacles could lead to sidelobe levels greater than -50 dB. In general, it is not always sufficient that the entire aperture have a clear line of sight; this conclusion is illustrated pictorially in Figure 7.

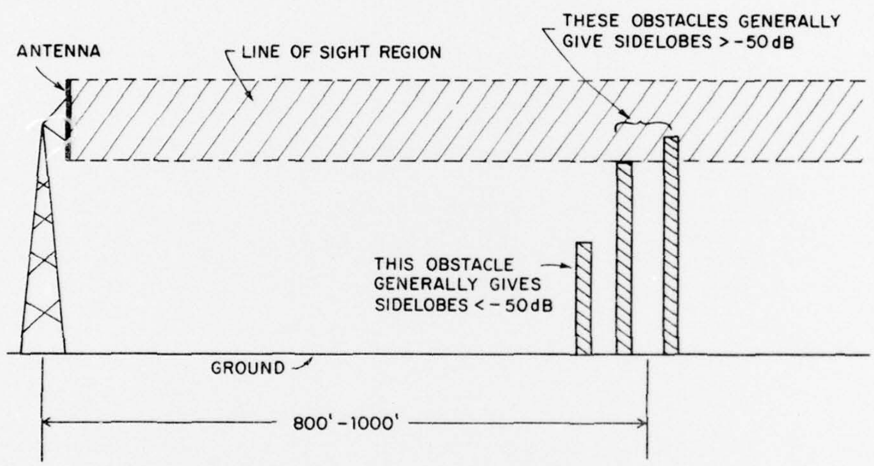


Figure 7. Pictorial Representation of the Results

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