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The Complete Electromagnetic Fields in the Focal Region of a Paraboloidal Reflector

**RONALD L. FANTE
RICHARD L. TAYLOR**

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

red:

J. Leon Poirier
J. LEON POIRIER

Acting Chief

Microwave Detection Techniques Br.
Electromagnetic Sciences Division

red:

Allan C. Schell
ALLAN C. SCHELL

Acting Chief

Electromagnetic Sciences Division

FOR THE COMMANDER:

John P. [unclear]

Final Office

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Contents

1. INTRODUCTION	5
2. THEORETICAL BACKGROUND	5
3. RESULTS	9
APPENDIX A	15

Illustrations

1. Reflector Geometry	6
2. Magnitude of the Fields Along the $y_0 = 0$ Axis for $z = 0.95F$	10
3. Phase of the Fields Along the $y_0 = 0$ Axis for $z_0 = 0.95F$	10
4. Magnitude of the Fields Along the $x_0 = 0$ Axis for $z_0 = 0.95F$	10
5. Phase of the Fields Along the $x_0 = 0$ Axis for $z_0 = 0.95F$	10
6. Magnitude of the Fields Along the $y_0 = 0$ Axis for $z_0 = 0.967F$	12
7. Phase of the Fields Along the $y_0 = 0$ Axis for $z_0 = 0.967F$	12
8. Magnitude of the Fields Along the $y_0 = 0$ Axis for $z_0 = 0.983F$	12
9. Phase of the Fields Along the $y_0 = 0$ Axis for $z_0 = 0.983F$	12
10. Magnitude of the Fields Along the $x_0 = 0$ Axis for $z_0 = F$ (focal plane)	13

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Illustrations

- | | | |
|-----|---|----|
| 11. | Phase of the Fields Along the $x_0 = 0$ Axis for $z_0 = F$ (focal plane) | 13 |
| 12. | Magnitude of the Fields Along an Axis Oriented at 45° with Respect to the x Axis, for $z_0 = 0.967F$ | 13 |
| 13. | Geometry for the Results in Figure 12 | 13 |

The Complete Electromagnetic Fields in the Focal Region of a Paraboloidal Reflector

1. INTRODUCTION

In designing optimum feed systems for Cassegrain reflector systems, it is highly desirable to have an accurate picture of the electromagnetic fields in the reflector focal region. In order to study these fields we have considered the case of a plane wave incident upon a large reflector, as shown in Figure 1, and have used the physical optics approximation to calculate the complete electromagnetic field distribution produced in the vicinity of the reflector focus.

2. THEORETICAL BACKGROUND

Let us consider a plane wave with electric and magnetic fields*

$$\underline{E}_i = E_0 \hat{y} \exp [i (\omega t + kz)] , \quad (1a)$$

$$\underline{H}_i = H_0 \hat{x} \exp [i (\omega t + kz)] , \quad (1b)$$

(Received for publication 29 September 1976)

*In Eq. (1) $\hat{x}$, $\hat{y}$, and $\hat{z}$ are unit vectors along x, y, and z. Also k is the wave-number = $2\pi/\lambda$, where λ is the signal wavelength.

incident from the right upon the reflector in Figure 1. If we assume that the reflector surface is described by the arbitrary function

$$z = f(x, y) \quad (2)$$

it can be shown¹ that the magnetic field scattered by the reflector is given, in the physical optics approximation, by

$$\underline{H}_S = -\frac{H_0}{2\pi} \iint_{S_0} dx dy \left\{ \left(\hat{z} - \frac{\partial f}{\partial x} \hat{x} - \frac{\partial f}{\partial y} \hat{y} \right) \times \hat{x} e^{ikz} \right\} \times \nabla \left(\frac{e^{-ikR}}{R} \right), \quad (3)$$

where R is the distance from a source point (x, y, z) on the reflector to the field point (x_0, y_0, z_0) , S_0 is the projection of the reflector surface onto the $x - y$ plane and $\hat{x}, \hat{y}$, and $\hat{z}$ are unit vectors.

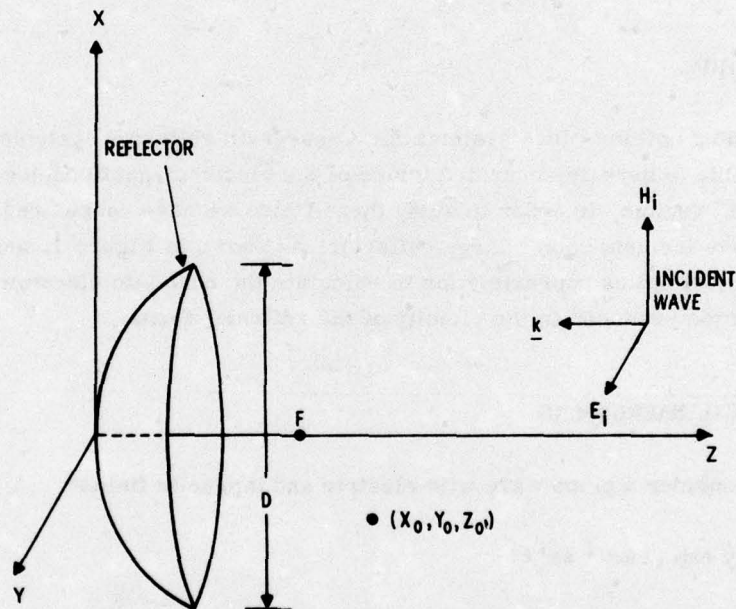


Figure 1. Reflector Geometry

1. Silver, S. (1965) Microwave Antenna Theory and Design, Dover (New York).

If we assume that the reflector surface is a parabola with a focus at $z = F$, then Eq. (2) becomes

$$z = \frac{1}{4F} (x^2 + y^2) , \quad (4)$$

and the projection of the reflector onto the x - y plane is a circle satisfying the equation

$$x^2 + y^2 = \left(\frac{D}{2}\right)^2 , \quad (5)$$

where D is the diameter of the reflector. If we now use Eqs. (4) and (5) in (3) we obtain, after some manipulation

$$\begin{aligned} \underline{H}_S(x_o, y_o, z_o) = & \frac{H_o}{2\pi} \int_{-D/2}^{D/2} dx \int_{-\gamma(x)}^{\gamma(x)} dy \phi(x, y) \\ & \times \left\{ \hat{x} \left[z_o - \frac{x^2}{4F} + \frac{y^2}{4F} - \frac{y_o y}{2F} \right] + \hat{y} \frac{(x_o - x)y}{2F} - \hat{z} (x_o - x) \right\} , \end{aligned} \quad (6)$$

where

$$\gamma(x) = \left[\left(\frac{D}{2}\right)^2 - x^2 \right]^{1/2} ,$$

$$\phi(x, y) = \left(\frac{ik}{R^2} + \frac{1}{R^3} \right) \exp \left[-ik \left\{ R - \frac{x^2}{4F} - \frac{y^2}{4F} \right\} \right] ,$$

$$R = \left[(x - x_o)^2 + (y - y_o)^2 + (z - z_o)^2 \right]^{1/2} .$$

The electric field distribution can be obtained by employing the Maxwell equation

$$\nabla \times \underline{H}_S = i\omega \epsilon_o \underline{E}_S . \quad (7)$$

The result for $\underline{E}_S$ is

$$\underline{E}_S(x_o, y_o, z_o) = \frac{H_o}{2\pi i\omega \epsilon_o} \int_{-D/2}^{D/2} dx \int_{-\gamma(x)}^{\gamma(x)} dy (x_o - x) \left[y_o - y + \frac{y}{2F} z_o - \frac{y}{2F} \left(\frac{x^2}{4F} + \frac{y^2}{4F} \right) \right] \theta(x, y) , \quad (8a)$$

$$E_y(x_o, y_o, z_o) = \frac{H_o}{\pi i \omega \epsilon_o} \int_{-D/2}^{D/2} dx \int_{-\gamma(x)}^{\gamma(x)} dy \phi(x, y) \quad (8b)$$

$$- \frac{H_o}{2\pi i \omega \epsilon_o} \int_{-D/2}^{D/2} dx \int_{-\gamma(x)}^{\gamma(x)} dy \theta(x, y) \left\{ \alpha(x, y) \left[z_o - \frac{x^2}{4F} - \frac{y^2}{4F} \right] + (x_o - x)^2 \right\},$$

$$E_z(x_o, y_o, z_o) = \frac{H_o}{i \omega \epsilon_o \pi} \int_{-D/2}^{D/2} dx \int_{-\gamma(x)}^{\gamma(x)} dy \frac{y}{2F} \phi(x, y)$$

$$- \frac{H_o}{2\pi i \omega \epsilon_o} \int_{-D/2}^{D/2} dx \int_{-\gamma(x)}^{\gamma(x)} dy \theta(x, y) \left\{ \frac{y}{2F} (x_o - x)^2 - (y_o - y) \alpha(x, y) \right\}, \quad (8c)$$

where

$$\alpha(x, y) = z_o - \frac{x^2}{4F} + \frac{y^2}{4F} - \frac{y_o y}{2F},$$

$$\theta(x, y) = \left\{ \frac{3}{R^5} + \frac{i3k}{R^4} - \frac{k^2}{R^3} \right\} \exp \left[-ik \left(R - \frac{x^2}{4F} - \frac{y^2}{4F} \right) \right].$$

Equations (6) and (8) are the formal expressions for the complete electromagnetic fields in the physical optics approximation. They represent a quite good approximation for the entire region $z > \frac{1}{4F}(x^2 + y^2)$, which is of interest to us. Of course, they are inaccurate for $z < 0$; over part of that region the geometrical theory of diffraction must be employed.

By observing Eqs. (6) and (8) it is clear that the scattered electric and magnetic fields possess certain symmetry properties. These are (for a fixed z_o)

$$H_x(x_o, -y_o) = H_x(x_o, y_o), \quad (9a)$$

$$H_x(-x_o, y_o) = H_x(x_o, y_o), \quad (9b)$$

$$H_y(x_o, -y_o) = -H_y(x_o, y_o), \quad (9c)$$

$$H_y(-x_o, y_o) = -H_y(x_o, y_o), \quad (9d)$$

$$H_z(x_0, -y_0) = H_z(x_0, y_0) \quad , \quad (9e)$$

$$H_z(-x_0, y_0) = -H_z(x_0, y_0) \quad . \quad (9f)$$

$$E_x(x_0, -y_0) = -E_x(x_0, y_0) \quad , \quad (10a)$$

$$E_x(-x_0, y_0) = -E_x(x_0, y_0) \quad , \quad (10b)$$

$$E_y(x_0, -y_0) = E_y(x_0, y_0) \quad , \quad (10c)$$

$$E_y(-x_0, y_0) = E_y(x_0, y_0) \quad , \quad (10d)$$

$$E_z(x_0, -y_0) = -E_z(x_0, y_0) \quad , \quad (10e)$$

$$E_z(-x_0, y_0) = E_z(x_0, y_0) \quad . \quad (10f)$$

Because of the aforementioned symmetry properties we have calculated $\underline{E}$ and $\underline{H}$ only for positive values of x_0 and y_0 ; the values for negative x_0, y_0 follow immediately from Eqs. (9) and (10).

3. RESULTS

We have developed a computer program to calculate the field components given by Eqs. (6) and (8). As an example of typical results of our program, we have studied a reflector such that

$$\frac{F}{D} = \frac{1}{3} \quad , \quad (11a)$$

$$\frac{D}{\lambda} = 60 \quad , \quad (11b)$$

where λ is the signal wavelength, and have calculated the field distribution in the planes $z_0 = 0.95F$, $0.967F$, $0.983F$, and $1.0F$. In Figures 2 and 3 we show* the amplitude and phase of the electric and magnetic fields in the plane $z_0 = 0.95F$. The fields shown are those along the line $y_0 = 0$, for differing values of x_0 . In Figures 4 and 5 we show the fields along the line $x_0 = 0$ for differing values of y_0 .

*In all the results of Figures 2 to 11 we have assumed $H_0 = 2\pi$.

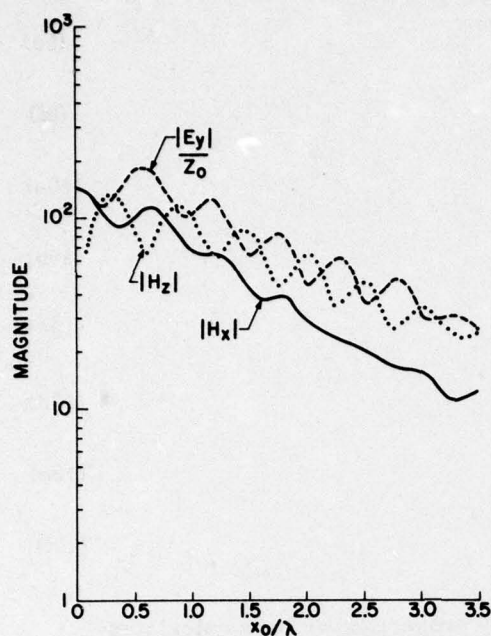


Figure 2. Magnitude of the Fields Along the $y_0 = 0$ Axis for $z = 0.95F$

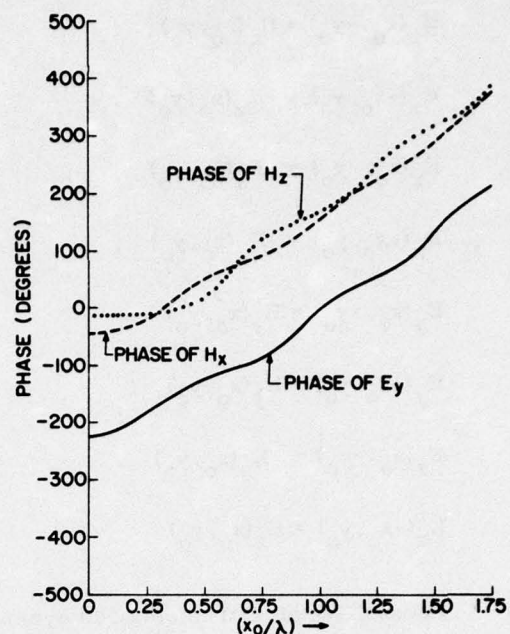


Figure 3. Phase of the Fields Along the $y_0 = 0$ Axis for $z = 0.95F$

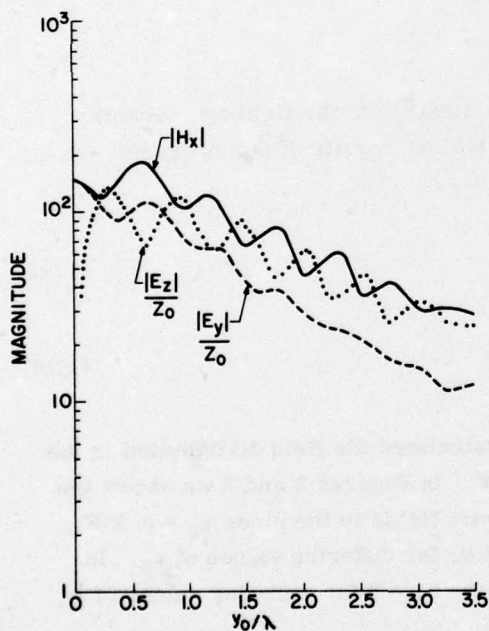


Figure 4. Magnitude of the Fields Along the $x_0 = 0$ Axis for $z_0 = 0.95F$

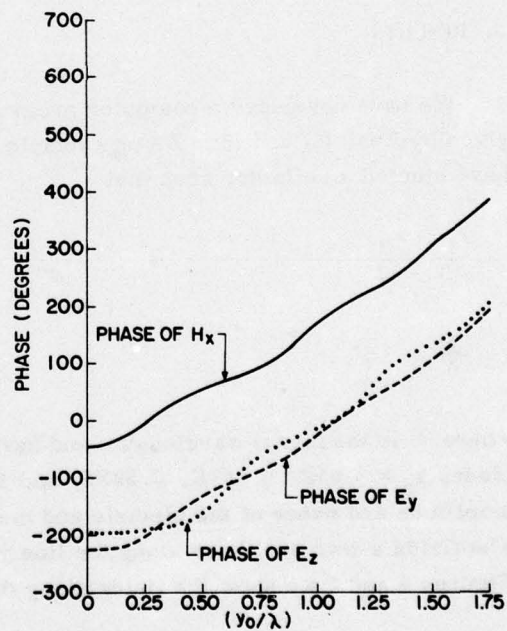


Figure 5. Phase of the Fields Along the $x_0 = 0$ Axis for $z_0 = 0.95F$

We note, upon comparing Figures 2 and 4, that if the results are known along the $y_0 = 0$ axis we can immediately obtain those along the axis $x_0 = 0$ by replacing $|H_x|$ by $|E_y|/Z_0$, $|H_z|$ by $|E_z|/Z_0$, and $|E_y|/Z_0$ by $|H_x|$, where Z_0 is the impedance of vacuum. Because of this duality, in the remaining figures we will only show results along either the $x_0 = 0$ or the $y_0 = 0$ axis. In Figures 6 and 7 we show the fields in the plane $z_0 = 0.967F$; in Figures 8 and 9 we show the results in the plane $z_0 = 0.983F$, and finally, in Figures 10 and 11 we show the results in the focal plane. The components E_x and H_y are now shown because they are both zero.

There are several observations which should be made regarding our results:

- (1) The results of Figure 10 for the transverse fields in the focal plane agree with those calculated earlier by Minnett et al.² (see Figure 11 of Minnett's paper, for our case $\theta_0 \sim 74^\circ$).
- (2) The cross-polarized fields $|E_z|/Z_0$ and $|H_z|$ are generally of the same order as $|H_x|$ and $|E_y|/Z_0$, except very near to the z_0 axis. This is true even in the focal plane, and even holds within the focal spot (that is, we call the transverse dimension of the first null in Figure 10 the focal spot size, and this is of order $\lambda F/D$) as can be seen from Figure 10, where $|E_z|/Z_0$ is small near the center of the focal spot (y_0 near zero) but is large near the outer edge ($y_0 \approx 0.5\lambda$).
- (3) In Figures 2 to 11 we have shown the fields on the x and y axes where $E_x = H_y = 0$. This should not imply that $E_x = H_y = 0$ off these axes. In Figure 12 we show the field distribution along an axis (see Figure 13) oriented 45° relative to the x axis in the plane z_0 . Note that both E_x and H_y are nonzero, although they are considerably smaller than the other field components.

2. Minnett, H. C. and Thomas, B. (1968) Fields in the image plane of symmetrical focusing reflectors. Proc. IEEE, 115:1419-1430.

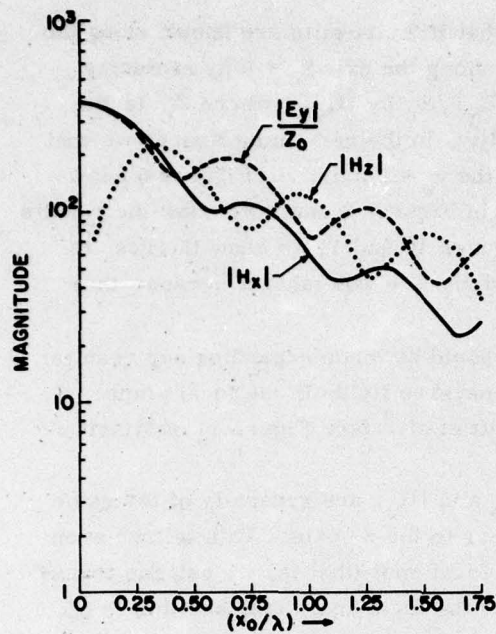


Figure 6. Magnitude of the Fields Along the $y_0 = 0$ Axis for $z_0 = 0.967F$

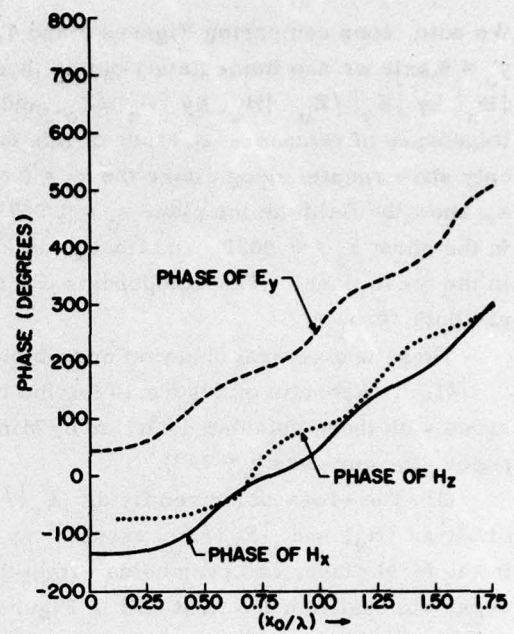


Figure 7. Phase of the Fields Along the $y_0 = 0$ Axis for $z_0 = 0.967F$

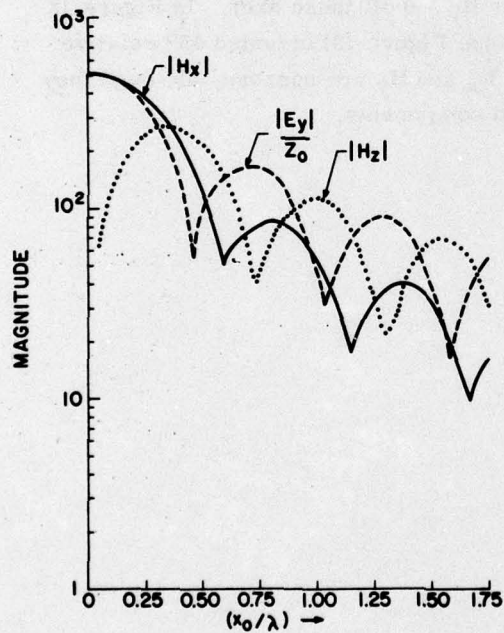


Figure 8. Magnitude of the Fields Along the $y_0 = 0$ Axis for $z_0 = 0.983F$

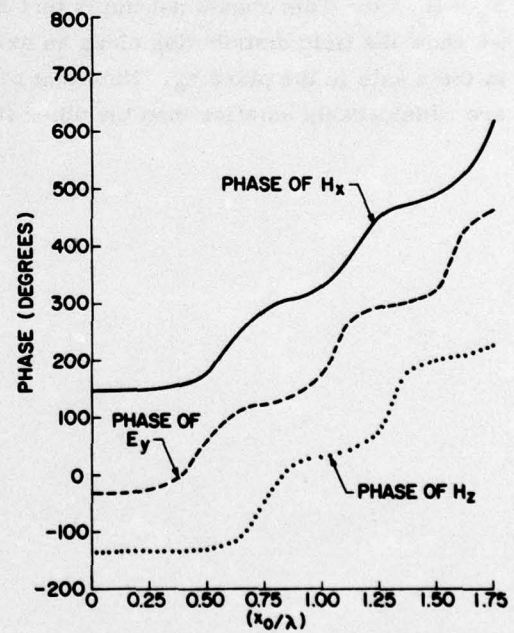


Figure 9. Phase of the Fields Along the $y_0 = 0$ Axis for $z_0 = 0.983F$

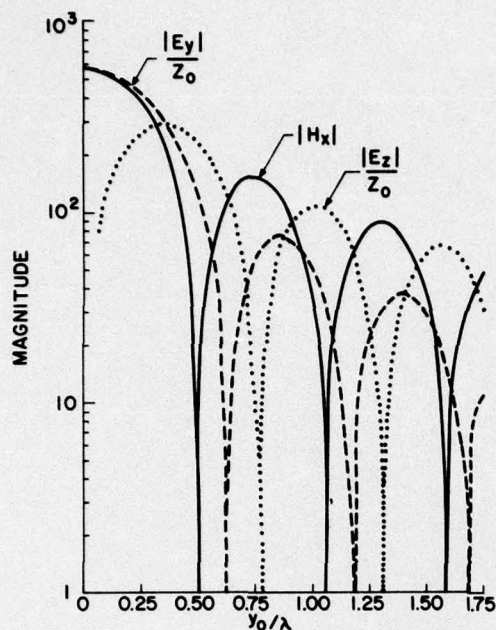


Figure 10. Magnitude of the Fields Along the $x_0 = 0$ Axis for $z_0 = F$ (focal plane)

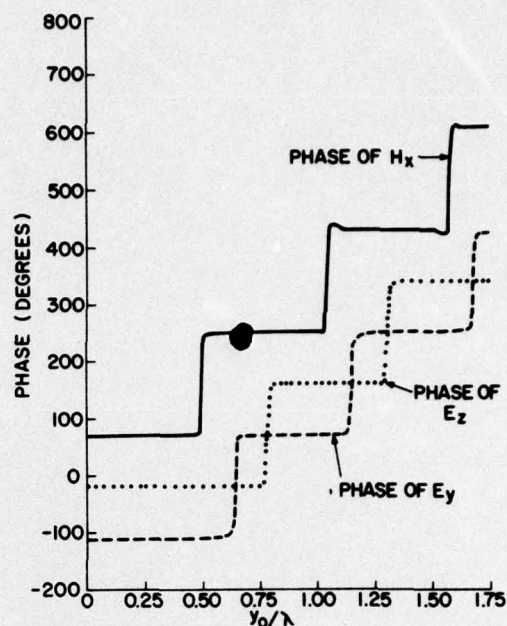


Figure 11. Phase of the Fields Along the $x_0 = 0$ Axis for $z_0 = F$ (focal plane)

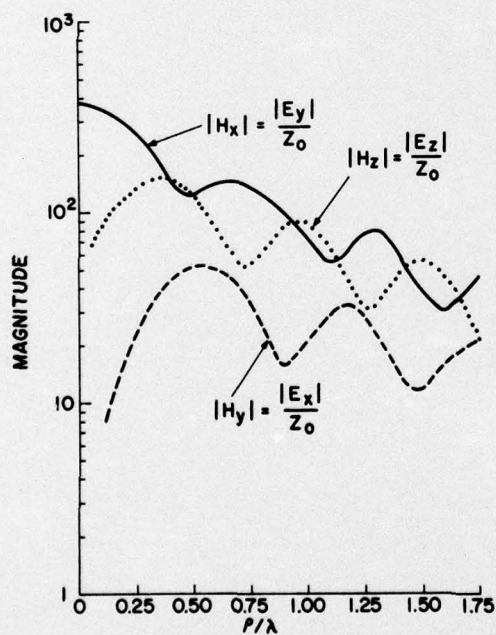


Figure 12. Magnitude of the Fields Along an Axis Oriented at 45° with Respect to the x Axis, for $z_0 = 0.967F$

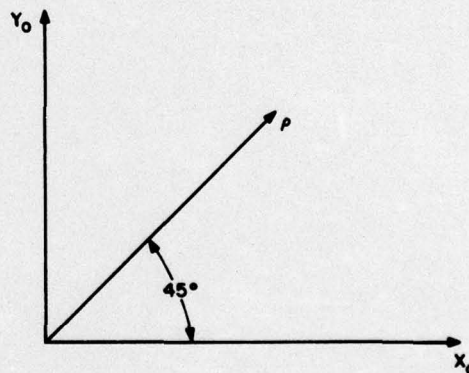


Figure 13. Geometry for the Results in Figure 12

Appendix A

In this appendix we present a Fortran listing of the computer program used to calculate $\underline{E}$ and $\underline{H}$. Note that the quantities printed out for $\underline{E}$ are actually the electric field normalized by Z_0 rather than $\underline{E}$. The inputs to the program are:

D = diameter of reflector,

F = focal length,

K = wavenumber = $2\pi/\lambda$,

X0, Y0, Z0 = coordinates of observation point,

XTOL = YTOL usually set to 10^{-3} .

```

PROGRAM MAIN(INPUT, OUTPUT)
IMPLICIT COMPLEX(Q)
COMMON/ONE/X0, ONE02F, ONE04F, Z0, K, Y0, DOV2SQ, QCONST
COMMON/QXI/QXINTEG(6)
COMMON/XTOL/XTOL
COMMON/YTOL/YTOL
REAL K
NAMELIST/XINPUT/ D, F, K, Z0, X0, Y0, XTOL, YTOL
READ XINPUT
QCONST = (1.0, 0.0) / CMPLX(0.0, K)
ONE02F = 0.5 / F
ONE04F = 0.25 / F
DOV2SQ = (D / 2.0)**2
XB = D / 2.0
XA = -XB
CALL XINTEG(XB, XA)
PRINT 600, QXINTEG
STOP
600 FORMAT(6H HX = ,1P2E12.5/6H HY = ,2E12.5/6H HZ = ,2E12.5/
1 6H EX = ,2E12.5/6H EY = ,2E12.5/6H EZ = ,2E12.5)
END

```

```

SUBROUTINE XINTEG(XB, XA)
IMPLICIT COMPLEX(Q)
COMMON/QXI/QXINTEG(6)
COMMON/QYI/QYINTEG(6)
COMMON/XTOL/TOL
DIMENSION QTWO(6), QFOUR(6), QENDS(6), QTOTAL(6)
H = (XB - XA) / 2.0
N = 1
CALL YINTEG(H+XA)
DO 10 J=1,6
  QTWO(J) = (0.0, 0.0)
10 QFOUR(J) = QYINTEG(J)
  CALL YINTEG(XA)
  DO 20 J=1,6
20 QENDS(J) = QYINTEG(J)
  CALL YINTEG(XB)
  DO 30 J=1,6
  QENDS(J) = QENDS(J) + QYINTEG(J)
30 QTCTAL(J) = (QENDS(J) + 4.0*QFOUR(J)) * H / 3.0
40 DO 50 J=1,6
50 QXINTEG(J) = QTCTAL(J)
  Y = H = H / 2.0
  N = 2 * N
  DO 60 J=1,6
  QTWO(J) = QTWO(J) + QFOUR(J)
60 QFOUR(J) = (0.0, 0.0)
  I = 0
70 I = I + 1
  CALL YINTEG(Y+XA)
  DO 80 J=1,6
80 QFOUR(J) = QFOUR(J) + QYINTEG(J)
  Y = Y + H + H
  IF(I .LT. N) GO TO 70
  IFLAG = 0
  PRINT *
  DO 90 J=1,6
  QTOTAL(J) = (QENDS(J) + 2.0*QTWO(J) + 4.0*QFOUR(J)) * H / 3.0
  QDENOM = QTOTAL(J)
  IF(CABS(QDENOM) .LT. TOL) QDENOM = CMPLX(TOL, 0.0)
  IF(CABS( (QXINTEG(J) - QTCTAL(J)) / QDENOM) .GT. TOL) IFLAG = 1
  PRINT *, CABS( QTOTAL(J) )
90 CONTINUE
  IF(IFLAG .EQ. 1) GO TO 40
  DO 100 J=1,6
100 QXINTEG(J) = QTOTAL(J)
  RETURN
END

```

```

SUBROUTINE YINTEG(X)
IMPLICIT COMPLEX(Q)
COMMON/ONE/X0, ONE02F, ONE04F, Z0, K, Y0, DOV2SQ, QCONST
COMMON/QQQ/QINT(6)
COMMON/QYI/QYINTEG(6)
COMMON/XXX/XDIFF, XDIFF2, XSQ, EX
COMMON/YTOL/TOL
REAL K
DIMENSION QTHO(6), QFOUR(6), QENDS(6), QTOTAL(6)
EX = X
XSQ = X**2
XDIFF = X0 - X
XDIFF2 = XDIFF**2
YB = GAMX = SQRT(DOV2SQ - XSQ)
YA = -GAMX
H = GAMX
N = 1
CALL FIELDS(H+YA)
DO 10 J=1,6
  QTHO(J) = (0.0, 0.0)
10 QFCUR(J) = QINT(J)
  CALL FIELDS(YA)
  DO 20 J=1,6
    QENDS(J) = QINT(J)
    CALL FIELDS(YB)
    DO 30 J=1,6
      QENDS(J) = QENDS(J) + QINT(J)
    30 QTOTAL(J) = (QENDS(J) + 4.0*QFCUR(J)) * H / 3.0
    DO 40 J=1,6
      QYINTEG(J) = QTOTAL(J)
      Y = H = H / 2.0
      N = 2 * N
      DO 60 J=1,6
        QTHO(J) = QTHO(J) + QFOUR(J)
      60 QFOUR(J) = (0.0, 0.0)
      I = 0
    70 I = I + 1
      CALL FIELDS(Y+YA)
      DO 80 J=1,6
        QFOUR(J) = QFOUR(J) + QINT(J)
      Y = Y + H + H
      IF(I .LT. N) GO TO 70
      IFLAG = 0
      DO 90 J=1,6
        QTOTAL(J) = (QENDS(J) + 2.0*QTHO(J) + 4.0*QFOUR(J)) * H / 3.0
        QDENOM = QTOTAL(J)
        IF(CABS(QDENOM) .LT. TOL) QDENOM = CMPLX(TOL, 0.0)
        IF(CABS((QYINTEG(J) - QTOTAL(J))/QDENOM) .GT. TOL) IFLAG = 1
    90 CONTINUE
      IF(IFLAG .EQ. 1) GO TO 40
      DO 100 J=1,6
        QYINTEG(J) = QTOTAL(J)
    100 QYINTEG(J) = QTOTAL(J)
      RETURN
      END

```

```

SUBROUTINE FIELDS(Y)
IMPLICIT COMPLEX(Q)
COMMON/ONE/X0, ONE02F, ONE04F, Z0, K, Y0, DOV2SQ, QCONST
COMMON/QQQ/QINT(6)
COMMON/XXX/XDIFF, XDIFF2, XSQ, X
REAL K
YSQ = Y**2
YDIFF = Y0 - Y
YDIFF2 = YDIFF**2
TERM1 = Z0 - ONE04F*(XSQ + YSQ)
RSQ = XDIFF2 + YDIFF2 + TERM1**2
R = SQRT(RSQ)
ONECR2 = 1.0 / RSQ
ONEOR = 1.0 / R
QCEXP = CEXP(CMPLX(0.0, -K*(R + TERM1 - Z0) ) )
QPHI = QCEXP * CMPLX(ONEOR, K) * ONEOR2
QTHETA = QCEXP * CMPLX(3.0*ONECR2-K**2, 3.0*K*ONEOR)*CNEOR2*ONEOR
TERM2 = Z0 - ONE04F * (XSQ - Y*(Y - 2.0*Y0) )
QINT(1) = QPHI * TERM2
QINT(3) = -QPHI * XDIFF
QINT(2) = -QINT(3) * Y * CNE02F
QINT(4) = XDIFF * (YDIFF + ONE02F*Y*TERM1) * QTHETA * QCONST
QINT(5) = (2.0*QPHI - QTHETA*(TERM2*TERM1 + XDIFF2) )*QCONST
QINT(6) = (2.0*QPHI*Y*CNE02F - QTHETA*(XDIFF2*Y*ONE02F - YDIFF*
1 TERM2) )*QCONST
RETURN
END

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