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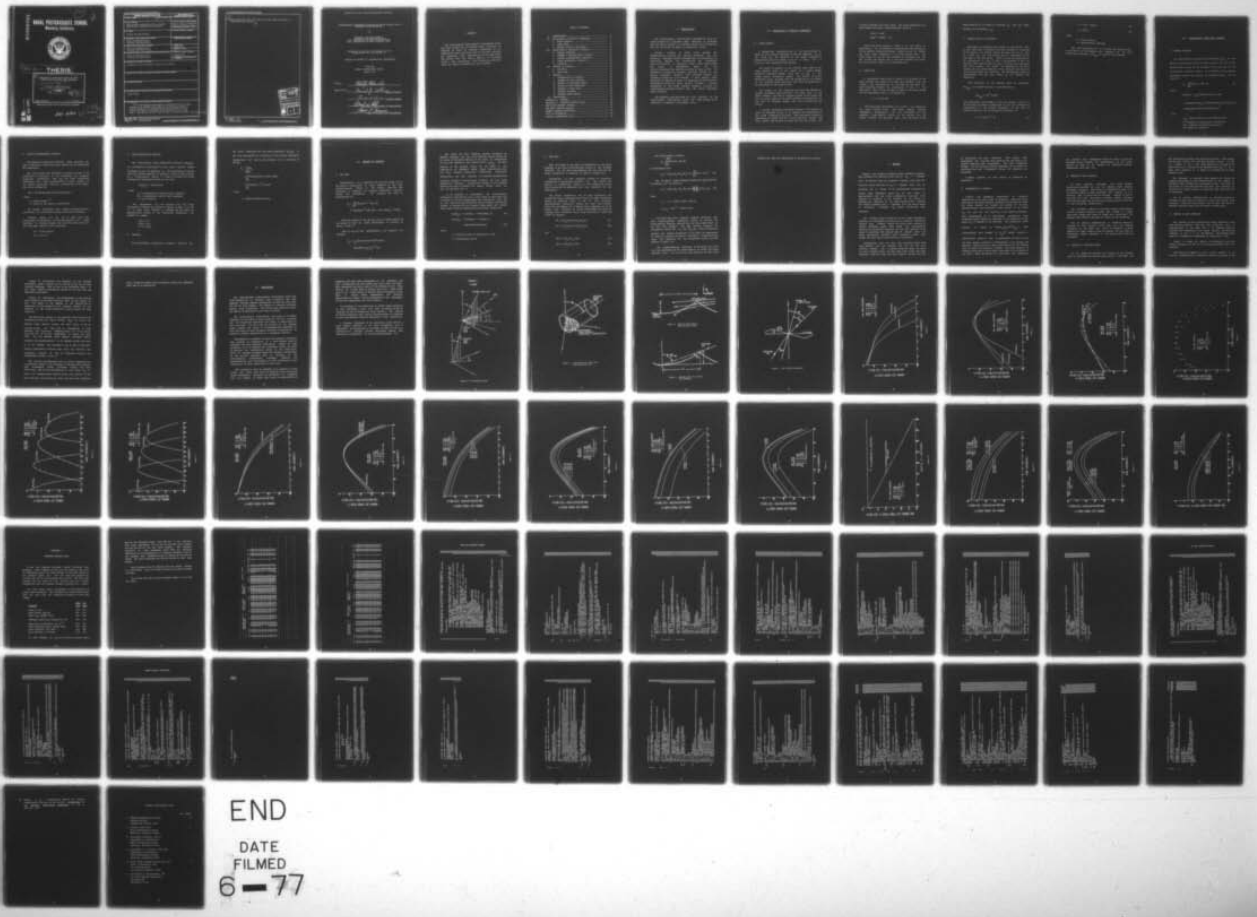

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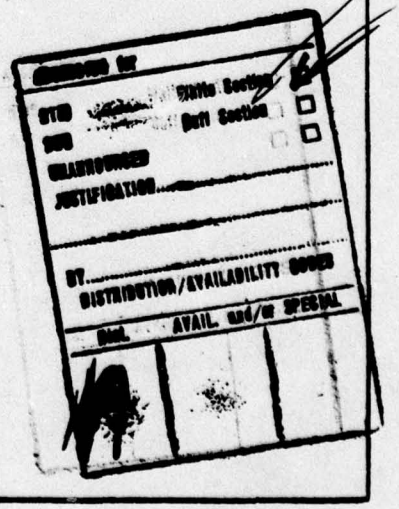

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POWER-DENSITY DISTRIBUTION BELOW THE OCEAN SURFACE DUE TO INCIDENT LASER RADIATION

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ABSTRACT

The time-averaged power-density distribution below the ocean surface due to incident laser radiation is examined by means of computer simulation of the geometrical optics involved with the air/sea interface and subsequent ocean penetration by the laser beam. The effects over the entire spectra of incidence angles, wind velocities, wind directions, beam spot sizes and depths of penetration are analyzed.

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I. INTRODUCTION

The time-averaged power-density distribution below the ocean surface due to incident laser radiation is examined over the entire spectra of incidence angles, wind velocities and wind directions by means of geometrical optics.

Current interest in using laser systems for communications through the air-sea interface and for detecting submerged objects necessitates the development of prediction methods for determining the subsurface power-distribution of radiation from a laser source above the ocean. A mathematical model for the optical-communications application done by Karp in Ref. 1 is developed in terms of a radiance function related to the mutual coherence function with accurate results for incidence angles out to 45 degrees. A more general model developed by Swennen in Refs. 2-4 examines the power-density distribution below the ocean surface through a rigorous assessment of the ocean surface geometry allowing for theoretically accurate results over the entire incidence angle spectrum.

The computer code developed for this analysis of the power-density distribution below the ocean surface is an expansion of Swennen's theory[Refs. 2-4].

II. DESCRIPTION OF PHYSICAL PARAMETERS

A. OCEAN SURFACE

A geometrical representation of the ocean surface in terms of local slopes developed by Cox and Munk[Ref. 5] is the basis for the analysis of the power probability distribution below the ocean, as it is in Refs. 2-4. A review of this representation follows.

The center of symmetry of the incident laser beam on the ocean surface facet is the center of a right- handed cartesian coordinate system, point "O" in Fig. 1. The z-axis points vertically upward. The y-axis is in the horizontal plane, colinear with the projection of the center of the incident laser beam onto that plane and pointing in the direction of the laser source.

The slopes of the ocean surface facet are defined by angular parameters Alpha and Beta. The angle Beta is the angle between the line of steepest ascent of the facet and the x-y plane; Alpha is the angle between the projection of the line of steepest ascent onto the x-y plane and the y-axis.

A second cartesian coordinate system at the surface is used, as explained in Ref. 2, to simplify the computation of the slope probability function. This coordinate system is designated by primes with the y'-axis pointing towards the wind source and rotated an angle Chi from the y-axis. The

z'-axis coincides with the z-axis. The slope parameters are also primed with their transformations given by:

$$Beta' = Beta$$

$$Alpha' = Alpha - Chi$$

Below the ocean surface a depth Z at the point of observation, O', is centered a translational transformation of the surface coordinate system. Angles Mu and Nu define the laser beam refracted to O' by any surface facet. The first angle, Mu, is the angle between the refracted ray and the z-axis; the second, Nu, is the angle between the y-axis and the vertical plane of the refracted ray.

B. LASER BEAM

A cylindrical laser beam of radius a is incident on the ocean surface wave facet at an angle Psi measured from the z-axis. The intersection of the beam and the facet is a flat elliptical surface as illustrated in Fig. 2. The semi-minor axis of the ellipse is equal to the beam radius and the semi-major axis, b, is defined by:

$$b = a * \sec Psi$$

The analytical development, as in Refs. 2-4, begins at the ocean surface facet. The laser source, aiming, atmospheric propagation, etc. are extraneous to this analysis. Power density values at the surface are not quoted because the analysis deals with the ratio of the

power density at the depth of interest, P_d, and the power density at the surface, P_{ds}.

C. MAXIMUM ANGLE OF INCIDENCE

The angle of incidence with respect to the z-axis, Psi, of the laser beam is analyzed from zero degrees to a maximum of 84 degrees. At greater angles the beam will not be able to strike all the wave facets within a wavelength of the wave due to the wave height. There is also the possibility, as illustrated in Fig. 3, that a ray incident at Psi > 84 degrees could pass through the wave, re-enter the atmosphere and then re-enter the ocean; or, depending on the local slopes, the ray could undergo a total internal reflection if the Critical Angle were exceeded. The mathematical model of Swennen[Refs. 2-4] and this thesis do not address this situation.

This limitation on the maximum angle of incidence, Psi_{max}, is derived from Fig. 4 and defined by:

$$Psi_{max} = \tan^{-1}(L/2H)$$

The significant wave height, H, and the average period, T, of the wave are given by equations (1) and (2) as defined by Pierson[Ref. 7]. The average wavelength of the wave is given by equation (3) as defined by Hill[Ref. 8].

$$H = 2.14\times10^{-2} * W^2 \qquad (1)$$

$$T = 0.81 * (2W/g) \quad (2)$$

$$L = gT^2/2 \quad (3)$$

where

W = wind velocity

g = gravitational constant

For wind velocities of 1 to 14 m/sec the maximum angle of incidence is 84.2 degrees (±0.4 degrees) for all wind velocities; therefore, Psi_{max} is limited to 84 degrees.

III. POWER-DENSITY PROABILITY INTEGRAL

A. GENERAL EQUATION

The power-density probability distribution (P_d) at the point of observation below the ocean surface (O') due to the entire beam is given by the integral of dP_d over all of the contributing surface facets. As a function of the angular parameters (Mu,Nu) the integral as defined in Refs. 2-4 is given by:

$$P_d = \iint_{\mu\,\nu} F(Mu,Nu)\ dMu\ dNu \qquad (4)$$

where

$$F(Mu,Nu) = P_{ds}*T*DTF*\cos(WI)*\sec(WR)$$

$$*[\cos(Mu)*\cos(Mu_0)+\sin(Mu)*\sin(Mu_0)*\cos|Nu-Nu_0|]$$

$$*P(Z'_x,Z'_y)*\tan(Beta)*\sec^2(Beta)*J^{-1}$$

and

P_{ds} = power density at the surface facet

T = Fresnel's transmittance coefficient

DTF = diffuse transmittance function

WI = angle of incidence

WR = angle of refraction

Mu_0 = first quadrant angle the refracted center ray of the beam makes with the positive z-axis

Nu_0 = positive angle the projection of the refracted center ray of the beam onto the xy-plane makes with the y-axis measured from the latter to the former

$P(Z'_x, Z'_y)$ = time-average slope distribution function

The development of equation (4) is described in great detail in Refs. 2-4 and will not be repeated here; however, for clarity the major components of equation (4) will be discussed.

B. FRESNEL'S TRANSMITTANCE FUNCTION

Fresnel's transmittance coefficient (T) is defined as the intensity ratio of the transmitted to the incident beam energy.

The ccllimated incident laser beam is composed of two polarization components, a transverse magnetic or parallel polarization ($T_{//}$) and a transverse electric or normal polarization ($T_{\perp}$). Resolving the refracted beam into its components ($T_{\perp}, T_{//}$) is a complex task due to rotation of the plane of incidence about all three coordinate axis over the range of integration. In order to deal with this complexity the beam is assumed to be rendered diffuse and unpolarized below the ocean surface due to scattering, propagation

direction variations and phase changes. This assumption allows for the averaging of $T_{\perp}$ and $T_{//}$ to obtain the value of T.

$$T = (T_{\perp} + T_{//})/2$$

The equations for $T_{\perp}$ and $T_{//}$ used by Swennen[Refs. 2-4] are:

$$T_{\perp} = [\sin(WI)*\sin(WR)/\sin(WI+WR)]^2 \quad (5)$$

$$T_{//} = [\sin(WI)*\sin(WR)/\sin(WI+WR)*\cos(WI-WR)]^2 \quad (6)$$

Equations (5) and (6) are in disagreement with those developed by Born[Ref. 9] and Fowles[Ref. 10], given by:

$$T_{\perp} = [2*\cos(WI)*\sin(WR)/\sin(WI+WR)]^2 \quad (7)$$

$$T_{//} = [\cos(WI)*\sin(WR)//\sin(WI+WR)*\cos(WI-WR)]^2 \quad (8)$$

Equations (5) and (6) will give erroneously high values for the Fresnel transmittance function, especially at higher angles of incidence. Because of this, equations (7) and (8) are used in this modeling.

The geometry of the ray refraction through the ocean surface is illustrated in Fig. 5.

C. DIFFUSE TRANSMITTANCE FUNCTION

The diffuse transmittance function (DTF) accounts for beam attenuation below the ocean surface due to scattering and absorbtion.

The six-constant DTF developed by Duntley in Ref. 11 is simplified to a function of two constants; the backward scattering coefficient (BS) and the total absorbtion coefficient (AC). This simplification is valid because of the random scattering particle orientation in the ocean. The DTF is defined by:

$$DTF = K/[(AC+BS)*\sinh(K*Z)+K*\cosh(K*Z)]$$

where

$$K = [AC*(AC+2BS)]^{1/2}$$

Z = depth of the point of observation

In current terminolgy this method of accounting for attenuation is a zero-angle forward scattering technique.

Typical values for BS and AC were used from measurements by Tyler[Ref. 12] and Duntley[Ref. 13]. These represent an average between cool and warm ocean waters in the blue-green spectrum (4800 angstrom).

$$BS = 0.065 \text{ percent}$$

$$AC = 0.044 \ m^{-1}$$

D. SLOPE PROBABILITY FUNCTION

The time-average slope probability function, $P(Z'_x, Z'_y)$, is a statistical distribution of the ocean surface slopes developed by Cox and Munk[Ref. 5]. The distribution derived from the surface geometry is Gaussian, which is then altered by a Gram-Charlier series in order to account for slope skewness and peakedness caused by the wind.

$$P(Z'_x, Z'_y) = f(Xi, Eta, W)$$

where

Xi = standardized crosswind slope component
Eta = standardized upwind slope component
W = wind velocity

The development and the equation for the slope probability function are covered in detail in Refs. 2,4, and 5. A clean ocean surface is assumed and the limits of applicability placed on the functional parameters are adhered to, namely:

$$|Xi| \leq 2.5$$
$$|Eta| \leq 2.5$$
$$W \leq 14 \text{ m/sec}$$

E. JACOBIAN

The power-density probability integral, equation (4),

was first developed over the slope components (Z'_x, Z'_y). It was then transformed to a function of the angular parameters (Alpha,Beta) and then by the Jacobian (J) to a function of (Mu,Nu).

$$P_d = \iint_{Z'_x Z'_y} dP_d$$

$$= \iint_{\alpha\beta} F(\text{Alpha},\text{Beta})\ d\text{Alpha}\ d\text{Beta}$$

$$= \iint_{\mu\nu} F(\text{Mu},\text{Nu})\ J^{-1}\ d\text{Mu}\ d\text{Nu}$$

where

$$J = \partial(\text{Mu},\text{Nu})/\partial(\text{Alpha},\text{Beta})$$

IV. METHODS OF SOLUTION

A. FAR ZONE

Swennen[Refs. 2-4] observed that when the depth (Z) of the point of observation is large compared to the beam cross-sectional radius at the surface (Z/a>100) the integrand of equation (4) remains essentially constant during the integration. The integral can then be approximated by:

$$P_d = \int_{\mu}\int_{\nu} F(Mu,Nu) * J^{-1}\, dMu\, dNu$$

$$\simeq F(Mu,Nu) * J^{-1}\, \Delta Mu\, \Delta Nu \; ; \text{ with } Mu=Mu_0 \;\&\; Nu=Nu_0$$

The area $\Delta Mu \Delta Nu$ in the (Mu,Nu) plane is approximated by an ellipse of area ΔA, whose development is covered in detail in Ref. 3.

This is the Far Zone approximation and equation (4) beccmes:

$$P_d = P_{ds} * T * \tan(Beta) * \sec^2 * \cos(WI)$$

$$* \sec(WR) * P(Z'_x, P'_y) * J^{-1} * \Delta A$$

The basic Far Zone computer program developed in FORTRAN language and run on the IBM 360 system solves for the ratio of the power density at the point of observation to the power density at the surface facet, P_d/P_{ds}. The main portion of the program allows for the entry of any combination of variables (wind, depth, beam radius, Psi, Chi, Nu_0, backward scattering coefficient, absorbtion coefficient), and also computes the diffuse transmittance function, Fresnsl's transmittance function and the slope probability function. Subroutines common to all variable entries are used to compute the angles (Alpha, Beta, WI, WR), the Jacobian and A.

It is possible to investigate the power-density probability distribution over a wide range of variables with a minimal of storage requirements and computation time due to the use of an IBM System/360 Source Library subroutine, NLNSYS, in solving for the coupled (Alpha,Beta) and (Mu,Nu) angle pairs from the simultaneous non-linear equations:

$$\cos(Mu_0) = [\cos(Psi) + K*\cos(Beta)]/n \quad (9)$$

$$\cot(Nu_0) = \cot(Alpha) - \sin(Psi)/K *\sin(Alpha)*\sin(Beta) \quad (10)$$

where

n = relative index of refraction (1.33)

K = K(Psi,Alpha,Beta,n)

B. NEAR ZONE

When the depth of the point of observation is not large compared to the beam cross-sectional radius at the surface ($Z/a<100$) the Far Zone approximation does not hold and the double integration of equation (4) must be carried out.

Swennen[Ref. 2] used Simpson's method of numerical integration to approximate equation (4). The method was subject to singularity points in the integration limits which increased the complexity and time required for the computation.

The double integration can be more accurately and relatively simply approximated by using the Gauss Quadrature system of solution, Refs. 14 and 15. The Two-Point Gauss-Legendre Quadrature method was used. This method, valid for polynomials up to degree three (equation (4) is of degree two), consists of first transforming the function $F(Mu,Nu)$ into a function $F(s,t)$ whose interval is $-1\leq s\leq 1$ and $-1\leq t\leq 1$ by letting:

$$Mu = [(Mu_u - Mu_l)*s + Mu_u + Mu_l]/2 \tag{11}$$

$$Nu = [(Nu_u - Nu_l)*t + Nu_u + Nu_l]/2 \tag{12}$$

and

$$dMu = [(Mu_u - Mu_l)/2]ds \tag{13}$$

$$dNu = [(Nu_u - Nu_l)/2]dt \tag{14}$$

The power-density integral

$$P_d = \int_{\mu_l}^{\mu_u}\int_{\nu_l}^{\nu_u} F(Mu,Nu)\, dMu\, dNu$$

is transformed into

$$P_d = [(Mu_u - Mu_l)(Nu_u - Nu_l)/4]^* \int_{-1}^{1}\int_{-1}^{1} F(s,t)\, ds\, dt \qquad (15)$$

The Two-Point Gauss-Legendre Quadrature approximation of equation (13) is given by:

$$P_d = [(Mu_u - Mu_l)(Nu_u - Nu_l)/4]^* \sum_{i=0}^{1}\sum_{j=0}^{1} W_i * F(s_i, t_j) \qquad (16)$$

where

$W_i = 1.0$ = Gauss weight factors

$s_i, t_j = \pm(3)^{-2}$ = Gauss roots

The basic Near Zone computer program developed uses this Gauss-Legendre Quadrature method in solving the power-density integral coupled with the same subroutines as the Far Zone program. The main program computes the integration limits (Mu_u, Mu_l) and (Nu_u, Nu_l) after determining whether the surface projection of the point of observation is inside or outside the beam's horizontal cross-sectional area. The equations for the integration limits are well defined in Refs. 2-4.

The transformations described by equations (11)-(15) are then performed and the power-density is solved for using equation (16). As in the Far Zone program, the Near Zone

program can take any combination of variables as entries.

V. RESULTS

Results for oblique incidence angles ($0 < Psi \leq 84$ degrees) were obtained for vertical plane cuts at $Nu_0 = 0$ degrees over the entire range of variables; however, valid data for vertical planar sections at $Nu_0 \neq 0$ degrees could not be obtained due to values of the standardized crosswind and upwind slope components being out of the range of applicability for the slope probability function. This problem is believed to be inherent in the method of mathematical analysis of the ocean surface used. Results for normal incidence (Psi = 0 degrees) over the entire range of variables, including Nu_0 planar variations, were obtained.

The validity check carried out on the slope probability function, as discussed in Section III.D, clearly identified invalid data. Another source of invalid data occurred at higher incidence angles (Psi) where the simultaneous solution of non-linear equations (9) and (10) resulted in an angle of incidence (WI) greater than 90 degrees while the slope probability function still indicated valid. This output was also easily identified and eliminated.

Computations with the Near Zone solution method used more computer time and storage than did the Far Zone solution method. For a computer solution using one value for each variable entry, the Near Zone used 36 per cent more computer time and 8 per cent more computer storage than did

an equivalent Far Zone solution. The higher time requirement for the Near Zone solution was due mainly to a greater compiling time requirement. The time difference between the two solution methods decreased as the number of variables that were incremented during one computer run increased.

A sample computer run with output is presented in Appendix B.

A. PRESENTATION OF RESULTS

Results are presented graphically to simplify comparisons of the wide range of variables. Vertical-planar sections of the power density probability distribution below the ocean surface cut through the center of the beam cross-section at the horizontal ocean surface at an angle Nu_0 are used for the majority of the results presented. This presentation is in rectangular coordinates with normalized power density in decibels on the ordinate and the angle Mu_0 in degrees on the abscissa. The normalized power density is equal to $10*\log_{10}[(P_d*Z^2)/P_{ds}]$. This normalization with respect to P_{ds}/Z^2 should produce a distribution function that is independent of depth in the Far Zone regime, according to Swennen[Ref. 2-4], because the multiple slopes seen in a beam cross-section at the surface tend to render the radiation diffuse. The power density of diffuse radiation at large depths decreases as the square of the depth. When the effects of scattering and absorption

are included this independence does not occur, as will be discussed later; however, the normalization of the power density is used in all regimes for continuity and for comparisons with Refs. 2-4.

B. EFFECTS OF WIND VELOCITY

As wind velocity increases, the power density distribution spreads out and the maximum power density decreases slightly. This effect is presented in Figs. 6-11 for various angles of beam incidence with respect to the vertical (Psi = 0,30,60 and 84 degrees). Figures 10 and 11 also show the close correlation between results obtained from the Near Zone and the Far Zone solution methods for Psi = 0 and 40 degrees, respectively.

The spreading effect on the power density distribution is due to larger refraction angles (WR) caused by higher wave facet slopes that occur at higher wind velocities. The maximum power density decrease is caused by the spreading.

For an optical communication or detection system an increase in wind velocity would mean that the maximum intensity of the beam that could be focused to a point beneath the ocean surface would be reduced, but the width of receivable signal radiation or the search width would be increased.

C. EFFECTS OF INCIDENCE ANGLE

As the angle of incidence with respect to the vertical (Psi) is increased the maximum power density decreases and

the distribution shifts away from the vertical. This effect can be seen in Figs. 6-11 and more clearly in Figs. 12 and 13. Figure 12 is a Far Zone solution at a depth of 50 meters for Psi = 0,30,60 and 84 degrees while Fig. 13 is a Near Zone solution at a depth of 10 meters for the same values of Psi.

The decrease in maximum power density is a result of greater reflectance at the surface facet as the angles of incidence (WI) increase with increases in Psi. The shift in the center of the distributions away from the vertical is caused by the higher angles of refraction (WR) that occur as WI increases.

For an optical communication or detection system an increase in Psi would be expected to lower the maximum beam intensity below the ocean surface and to shift the point of maximum intensity away from the point of water entry.

D. EFFECTS OF WIND DIRECTION

The effects of wind direction are small compared to the wind velocity effects. When the wind direction (Chi) is perpendicular to the beam (Chi = 90 degrees) there is slightly less spreading of the power density distribution compared to Chi = 0 or 180 degrees. The maximum power density is essentially unaffected by variations in Chi.

Figure 14 shows the effect of variations in Chi for normal incidence and Fig. 15 for oblique incidence (Psi = 40 degrees).

Wind direction appears to be of little concern to an optical communication or detection system as related to the

power density distribution below the ocean surface.

E. EFFECTS OF SPOT SIZE

Figures 16 and 17 show the effect of increasing the incident beam spot radius from 0.1 to 0.5 meters for Psi = 0 and 40 degrees, respectively. This is done with the assumption that the energy per unit area remains constant; therefore, the total energy must increase. The power density spreads out and increases in intensity uniformly over the distribution as the spot size is increased.

Since the equations used in this solution method deal with the ratio of P_d/P_{ds}, these results simply mean that more power in a larger beam will produce a more intense and more widely distributed pattern below the ocean surface.

F. EFFECTS OF DEPTH

The decrease of power density with increases in depth is illustrated in Figs. 18 and 19 for Psi equal to 0 and 40 degrees, respectively. The decrease is linear for the normalized power density as can be seen in Fig. 20.

Scattering and absorption cause this decrease in the power density. As the depth increases the diffuse transmittance function (DTF) rapidly becomes an inverse function of the sum of the hyperbolic sine of the depth and the hyperbolic cosine of the depth,

$$DTF = f[\,(\sinh Z + \cosh Z)^{-1}\,]$$

which means the DTF decreases rapidly with increases in depth and approaches zero in the limit. This agrees with the thecry cf Preisendorfer[Ref. 16].

Swennen's prediction of a constant normalized power density distribution in the Far Zone regime due to the diffusing effects of the ocean in Refs. 2-4 holds only when the effects of scattering and absorption are ignored. One computer run was made with the DTF set equal to one to illustrate this effect in Fig. 20.

Figures 21 and 22 illustrate the decrease in power density with depth, non-dimensionalized with respect to spot size, Z/a, again for Psi equal to 0 and 40 degrees, respectively.

An optical communication or detection system will be limited greatly by the power density decrease associated with depth.

G. MAXIMUM POWER DENSITY

The maximum obtainable power density available over the spectrum of incidence angles (Psi = 0 - 84 degrees) for a given set of conditions is presented in Figs. 23 and 24. The maximum power density obtainable does not occur for normal incidence, but for a small value of Psi, because of the fact that as the wind increases the most probable slope is not zero but a small angle. The maximum obtainable power density then drops continuously with increases in Psi after the peak that occurs around Psi = 10 - 15 degrees.

Figure 23 illustrates the decrease in the maximum obtainable power density for all values of Psi as the wind velocity increases. This is due to the spreading effect on the power density distribution caused by the wind that was described previously.

Figure 24 illustrates the independence of the maximum power density on the wind direction (Chi) for all values of Psi. Chi equal to 270 degrees is not plotted but is equivalent to the condition at 90 degrees because of the symmetry of the slope probability function about the wind direction.

The angle with respect to the vertical from the point of observation below the ocean surface (Mu_0) at which the maximum power density occurs for each value of Psi is plotted in Fig. 25. The plot is independent of wind velocity and direction. Examining Figs. 16 - 19 it can be seen that Fig. 25 is also independent of depth and spot size. Mu_0 for maximum power density increases nearly linearly from approximately 1 to 56 degrees as Psi goes from 0 to 84 degrees. The increase in Mu_0 is due to the power density distribution shifting away from the vertical for increasing valules of Psi as discussed earlier and illustrated in Figs. 12 and 13.

The obvious consideration with an optical communication or detection system is the decrease in maximum power density that accompanies higher incidence angles and wind velocities. The strong independence of the angle Mu_0 at which the maximum power density occurs with respect to the wind velocity, wind direction, depth and spot size indicates

that a satellite based laser navigation system for submarine usage may be a possibility.

VI. CONCLUSIONS

The time-averaged power-density distribution below the ocean surface due to incident laser radiation has been examined through computer simulations in both the Near Zone and the Far Zone regimes. The effects of altering incidence angles, wind velocities, wind directions, beam spot sizes and depths of penetration have been presented.

The power-density distribution was found to be highly dependent on the angle of beam incidence, the wind velocity and the attenuation associated with depth of penetration of the laser beam. The fact that the location of the maximum power density was found to be fundamentally dependent on only the angle of beam incidence indicates a possibility of direction finding capabilities by a submerged receiver.

Improvements in computer systems and analysis techniques have allowed an examination of a much broader range of variables than were possible heretofore. Angles of beam incidence up to 84 degrees were considered within the range of validity for restrictions placed on the simulation. Above 84 degrees incidence angle the possible interactions at the air/sea interface make an analysis of the power-density distribution extremely complex, and experimentation will be necessary to give indications of the feasibility of laser operations in this area.

This simulation could be extended to an analysis of much larger spot sizes that would be expected from a satellite based transmitter. Prettyman and Cermak[Ref. 17] suggested that the effects of larger spots could be approximated by

assuming each wave facet independent of its neighbors and then integrating over the larger spot area, since the small spot represents the outer limit of the effects of the ocean surface on a laser beam of greater spot size. There would have to be a large number of surface facets contained in the spot to insure facet independence and accurate approximations, hence a strong dependence on the wavelength of the wave associated with wind velocity.

An extension of the simulation to pulsed laser radiation is also warrented, since this mode of operation may be required for air-to-subsurface laser systems. The effects of pulsed radiation occur nearly instantaneously as compared to the time-averaged analysis performed in this simulation.

A further refinement of the simulation would involve a more complex modeling of the beam attenuation due to scattering and absorption in the ocean through the use of a diffusion or a multiple forward scattering method, both described by Bucher[Ref. 18] and Preisendorfer[Ref. 16].

APPENDIX A

FIGURES

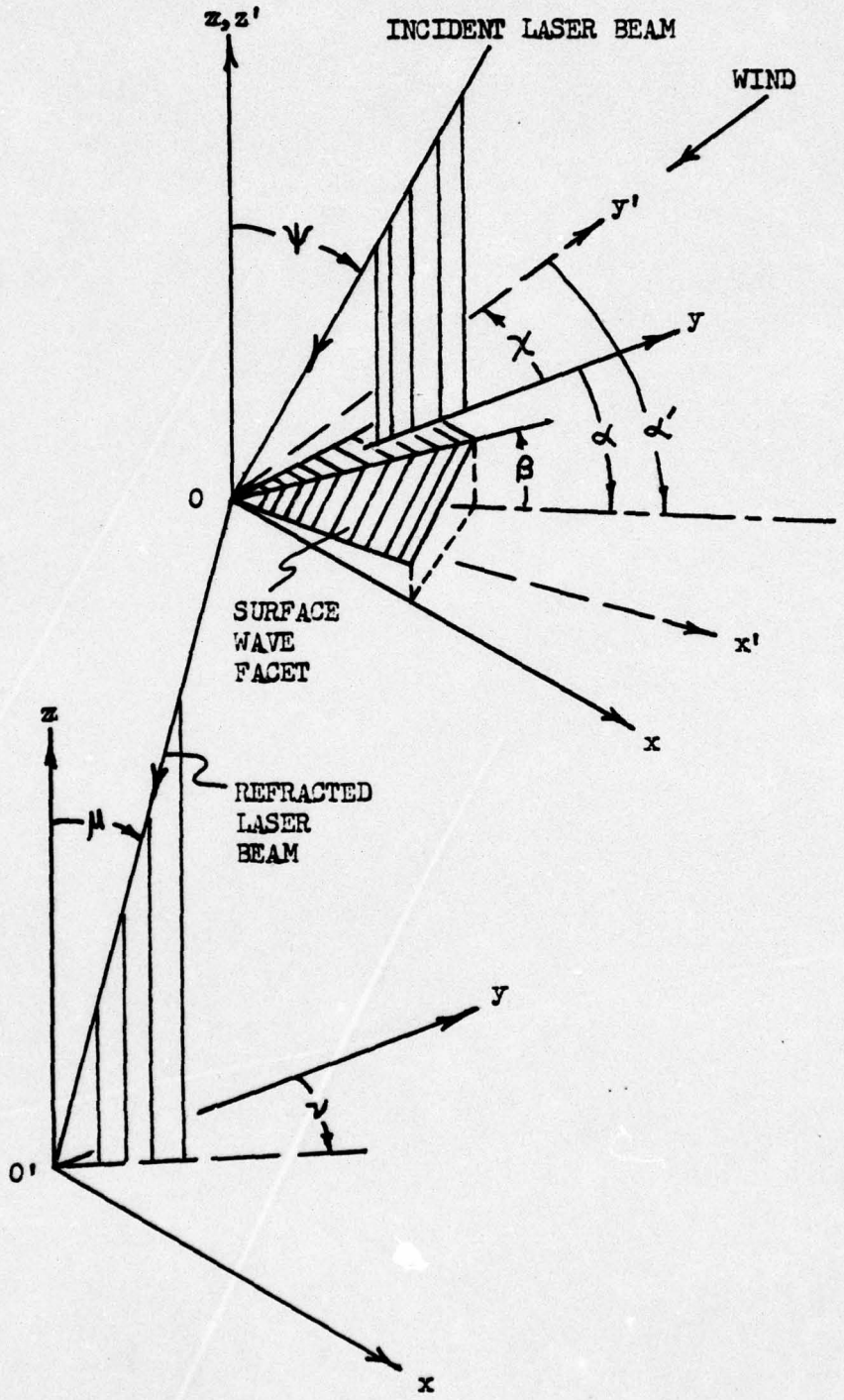

Figure 1: Coordinate systems

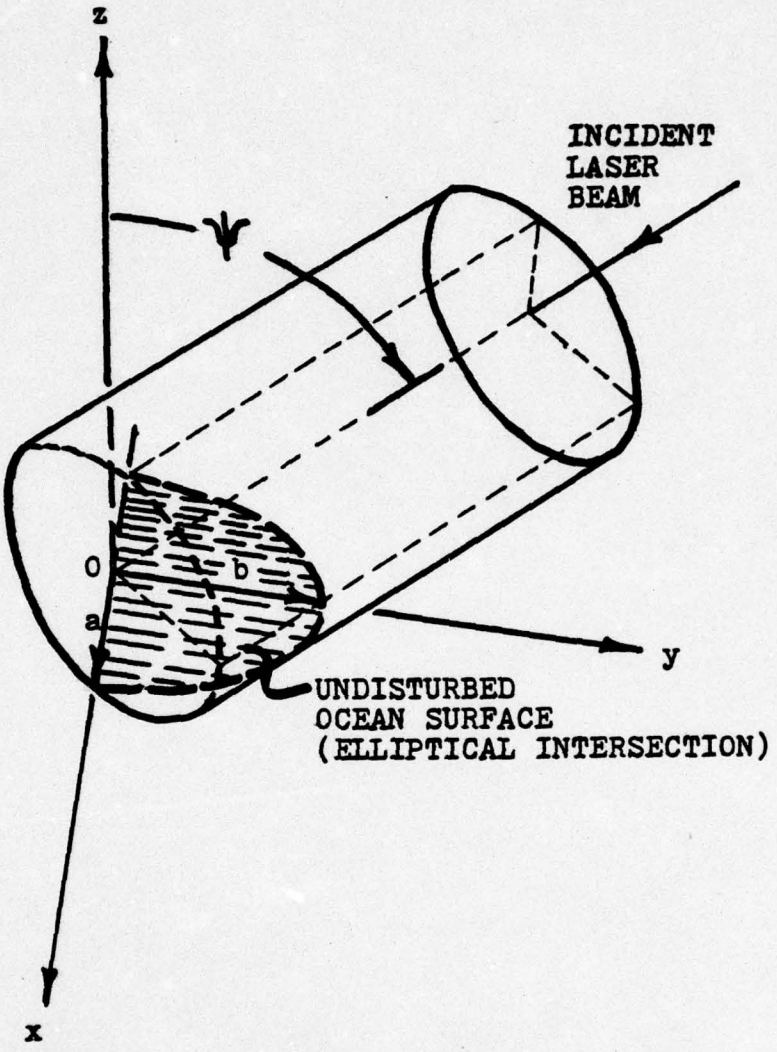

Figure 2: Intersection of laser beam with ocean wave facet

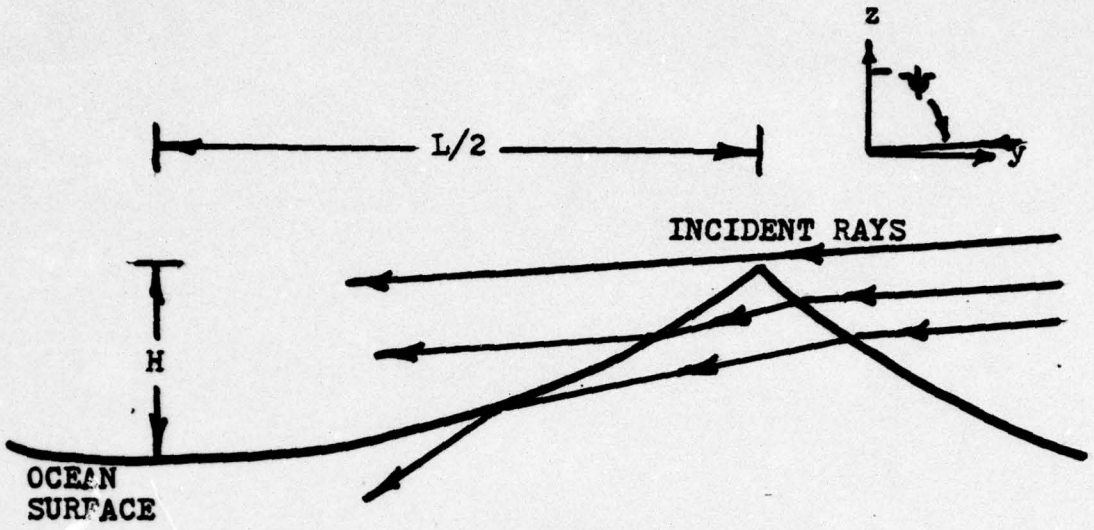

Figure 3: Possible beam paths at high incidence angles

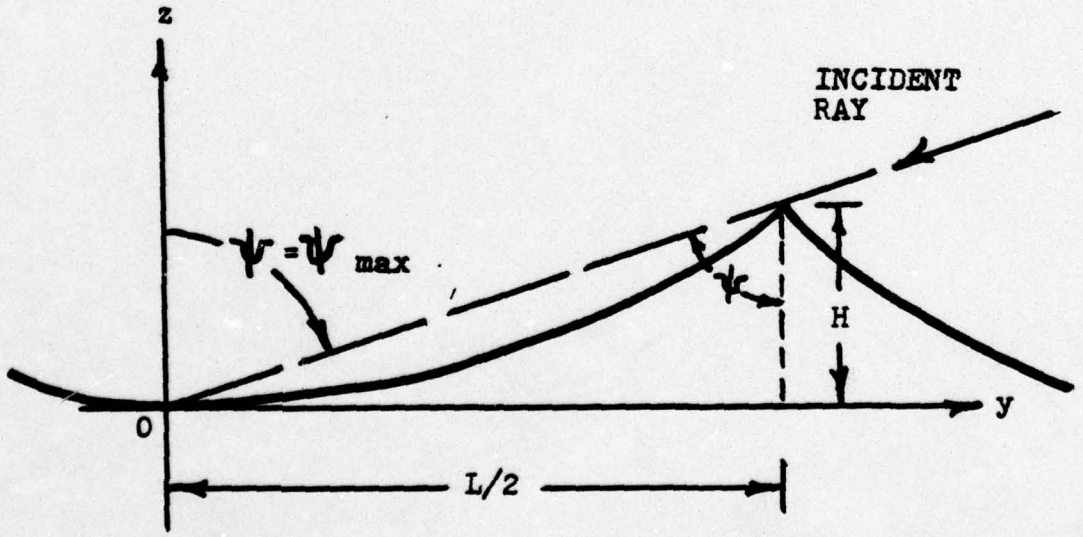

Figure 4: Maximum angle of incidence wave geometry

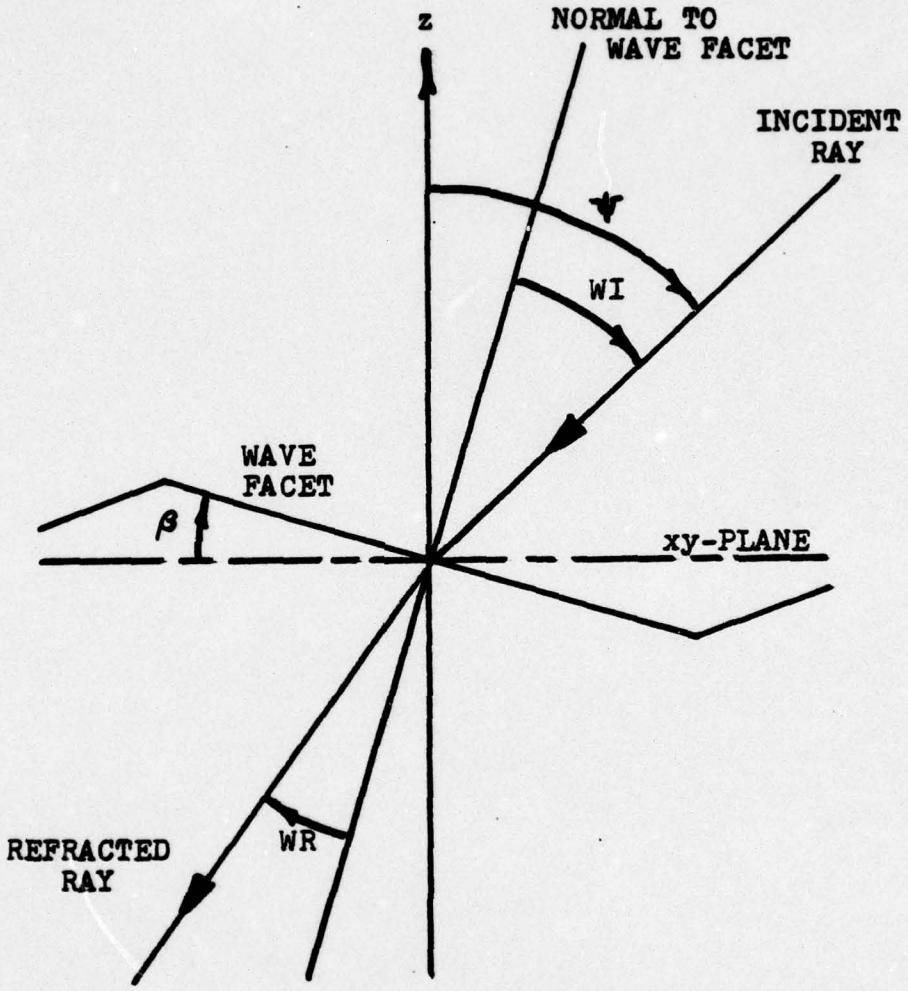

Figure 5: Ray refraction geometry

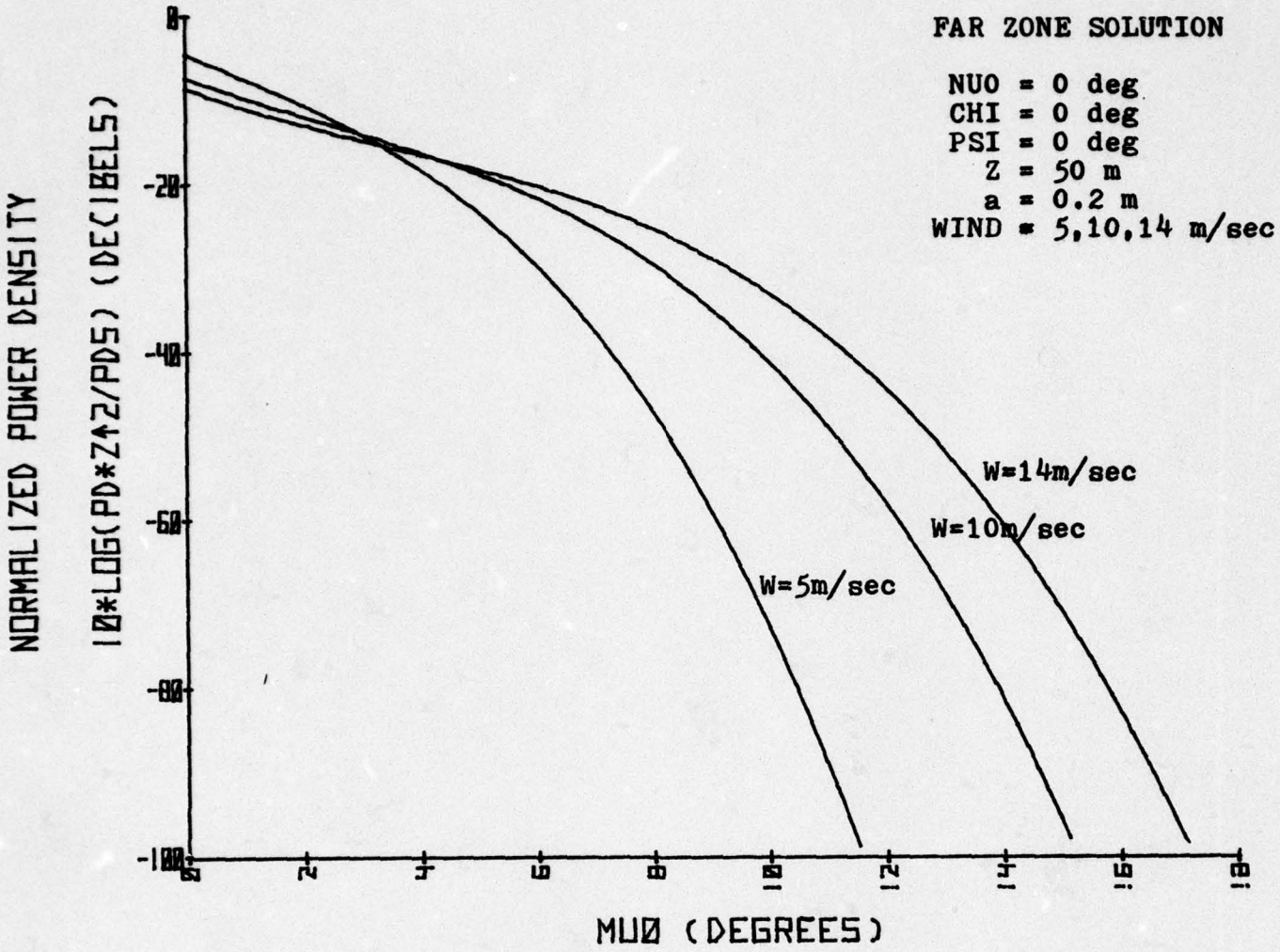
FAR ZONE SOLUTION
NUO = 0 deg
CHI = 0 deg
PSI = 0 deg
Z = 50 m
a = 0.2 m
WIND = 5,10,14 m/sec
W=14m/sec
W=10m/sec
W=5m/sec
NORMALIZED POWER DENSITY
10*LOG(PD*Z↑2/PDS) (DECIBELS)
MUØ (DEGREES)

Figure 6

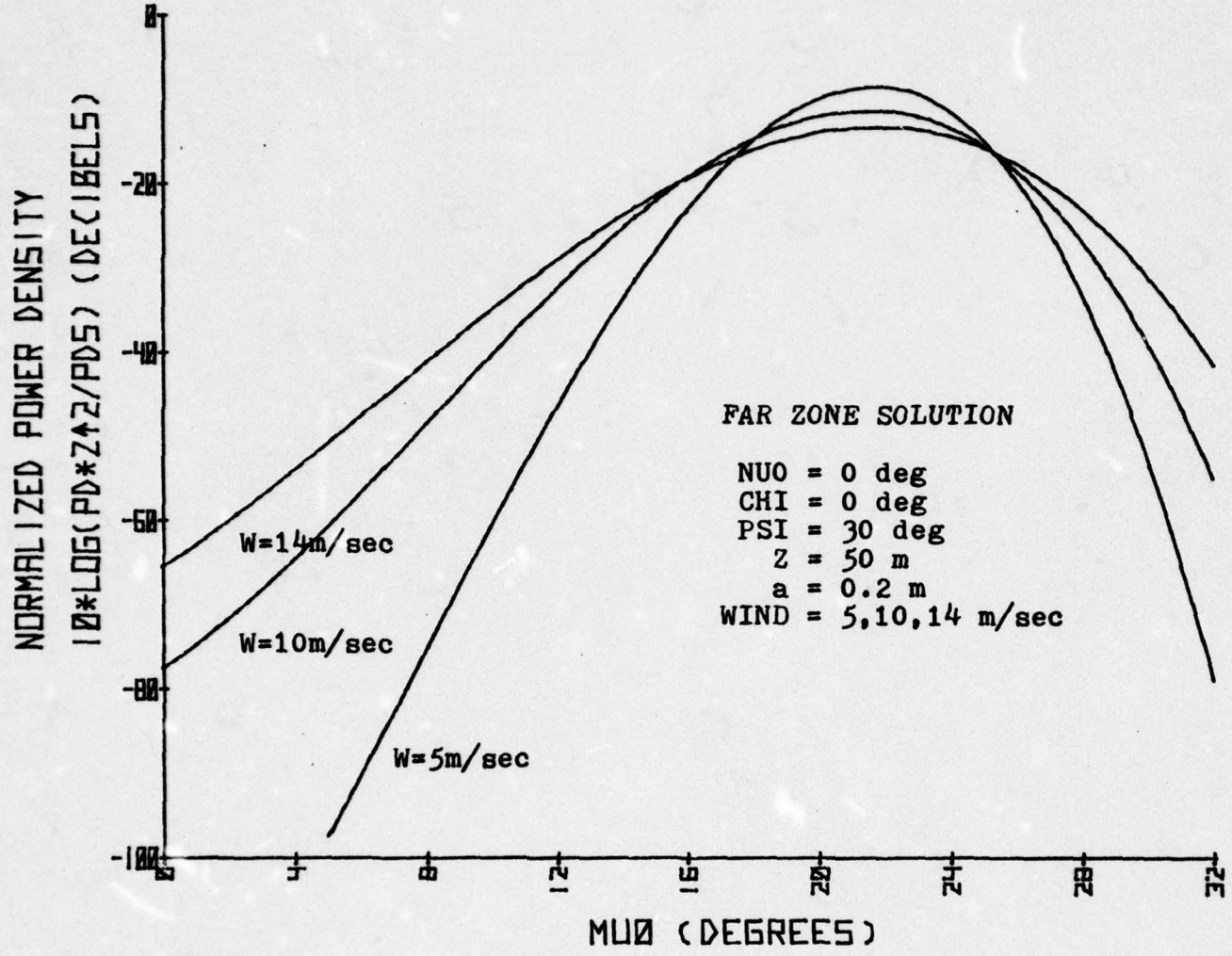
NORMALIZED POWER DENSITY
10*LOG(PD*Z↑2/PD5) (DECIBELS)
0
-20
-40
-60
-80
-100
0
4
8
12
16
20
24
28
32
MU0 (DEGREES)
W=14m/sec
W=10m/sec
W=5m/sec
FAR ZONE SOLUTION
NUO = 0 deg
CHI = 0 deg
PSI = 30 deg
Z = 50 m
a = 0.2 m
WIND = 5,10,14 m/sec

Figure 7

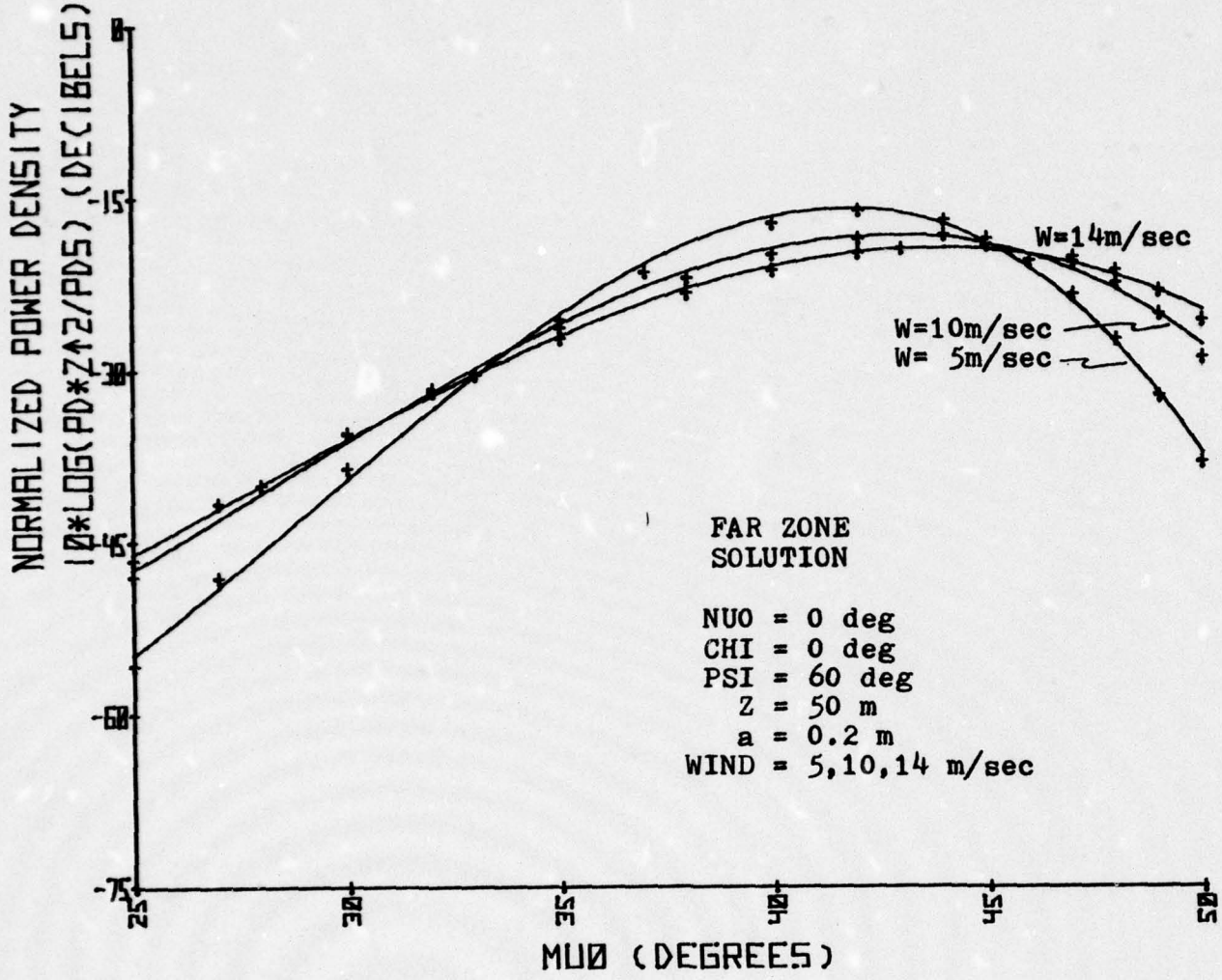
NORMALIZED POWER DENSITY
10*LOG(PD*Z↑2/PDS), (DECIBELS)
0
-15
-30
-45
-60
-75
25
30
35
40
45
50
MU0 (DEGREES)
W=14m/sec
W=10m/sec
W= 5m/sec
FAR ZONE
SOLUTION
NUO = 0 deg
CHI = 0 deg
PSI = 60 deg
Z = 50 m
a = 0.2 m
WIND = 5,10,14 m/sec

Figure 8

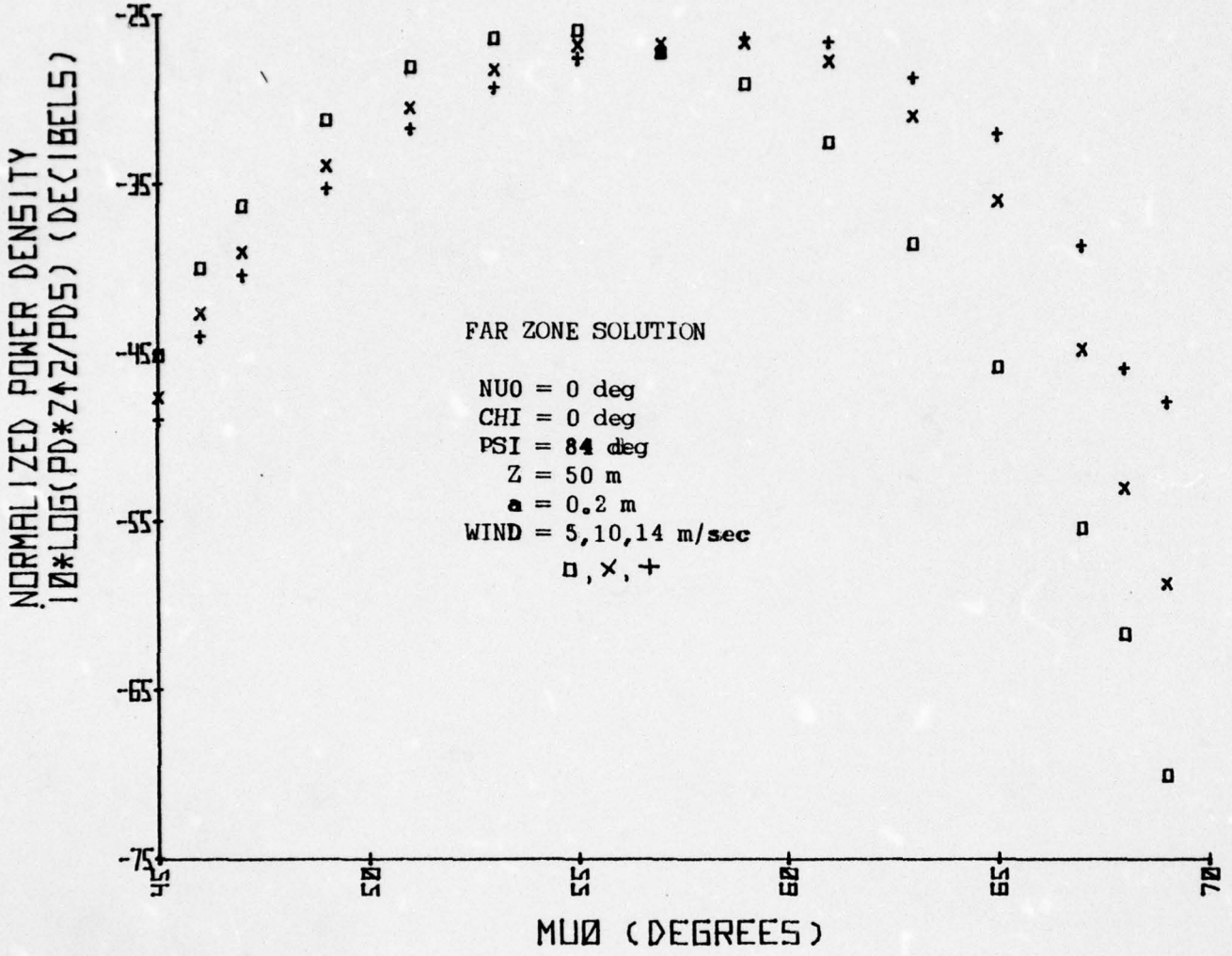
NORMALIZED POWER DENSITY
10*LOG(PD*Z↑2/PD5) (DECIBELS)
-25
-35
-45
-55
-65
-75
45
50
55
60
65
70
MU0 (DEGREES)
FAR ZONE SOLUTION
NU0 = 0 deg
CHI = 0 deg
PSI = 84 deg
Z = 50 m
a = 0.2 m
WIND = 5,10,14 m/sec
□, ×, +

Figure 9

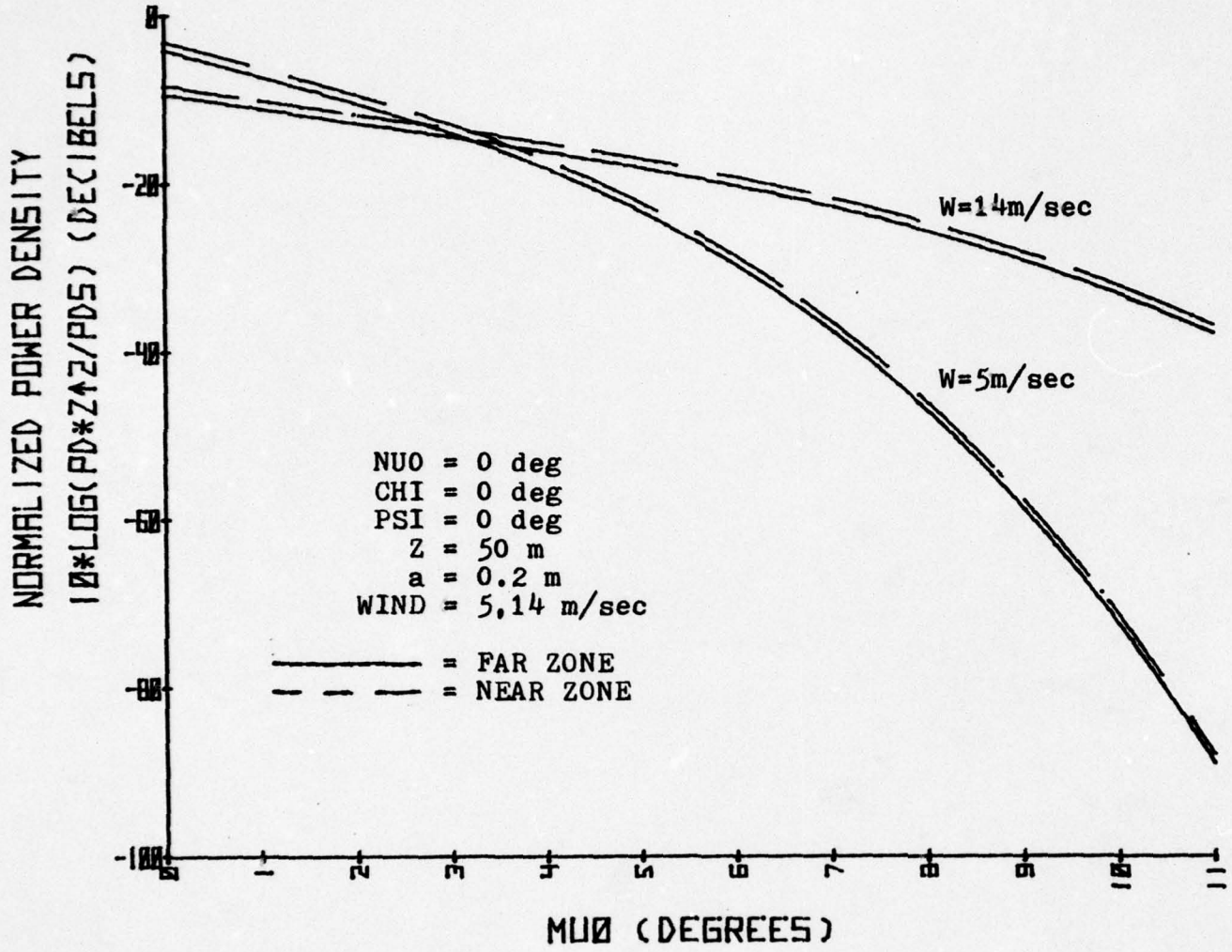
NORMALIZED POWER DENSITY
10*LOG(PD*Z↑2/PDS) (DECIBELS)
W=14m/sec
W=5m/sec
NUO = 0 deg
CHI = 0 deg
PSI = 0 deg
Z = 50 m
a = 0.2 m
WIND = 5,14 m/sec
= FAR ZONE
= NEAR ZONE
MUØ (DEGREES)

Figure 10

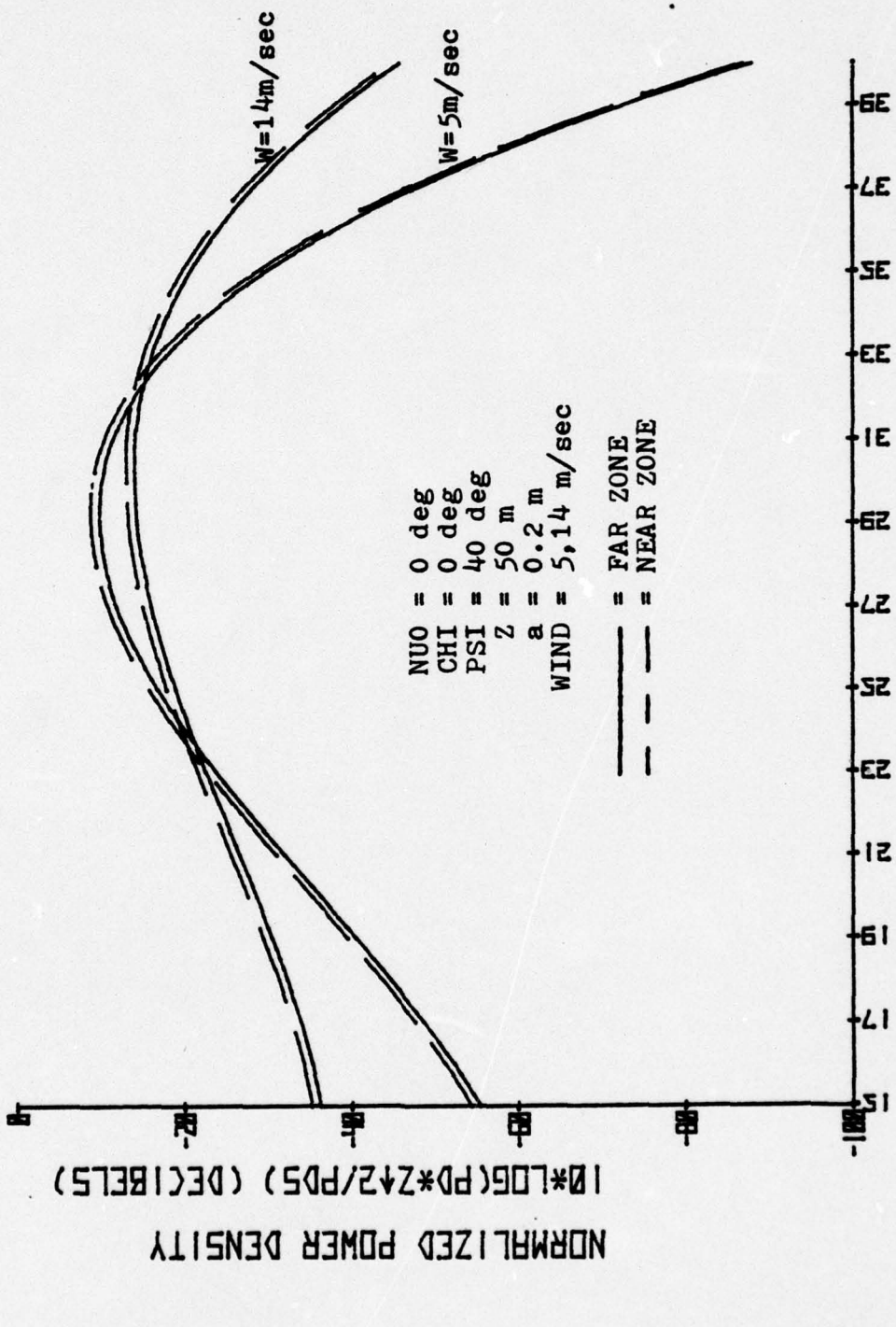
NORMALIZED POWER DENSITY
10*LOG(PD*Z^2/PD5) (DECIBELS)
MU0 (DEGREES)
W=14m/sec
W=5m/sec
NU0 = 0 deg
CHI = 0 deg
PSI = 40 deg
Z = 50 m
a = 0.2 m
WIND = 5,14 m/sec
= FAR ZONE
= NEAR ZONE

Figure 11

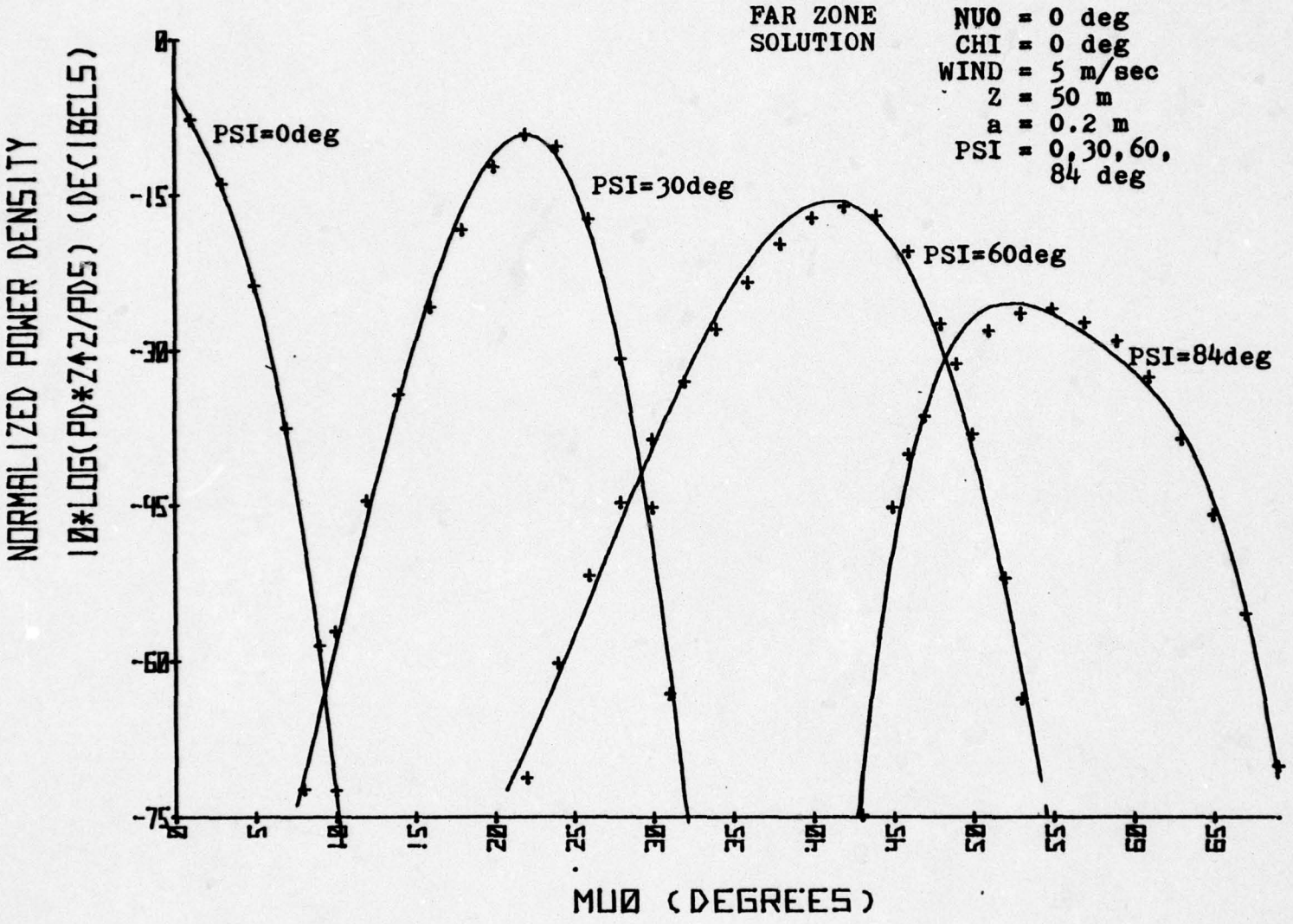
FAR ZONE
SOLUTION
NUO = 0 deg
CHI = 0 deg
WIND = 5 m/sec
Z = 50 m
a = 0.2 m
PSI = 0, 30, 60, 84 deg
PSI=0deg
PSI=30deg
PSI=60deg
PSI=84deg
NORMALIZED POWER DENSITY
10*LOG(PD*Z↑2/PDS) (DECIBELS)
MUØ (DEGREES)

Figure 12

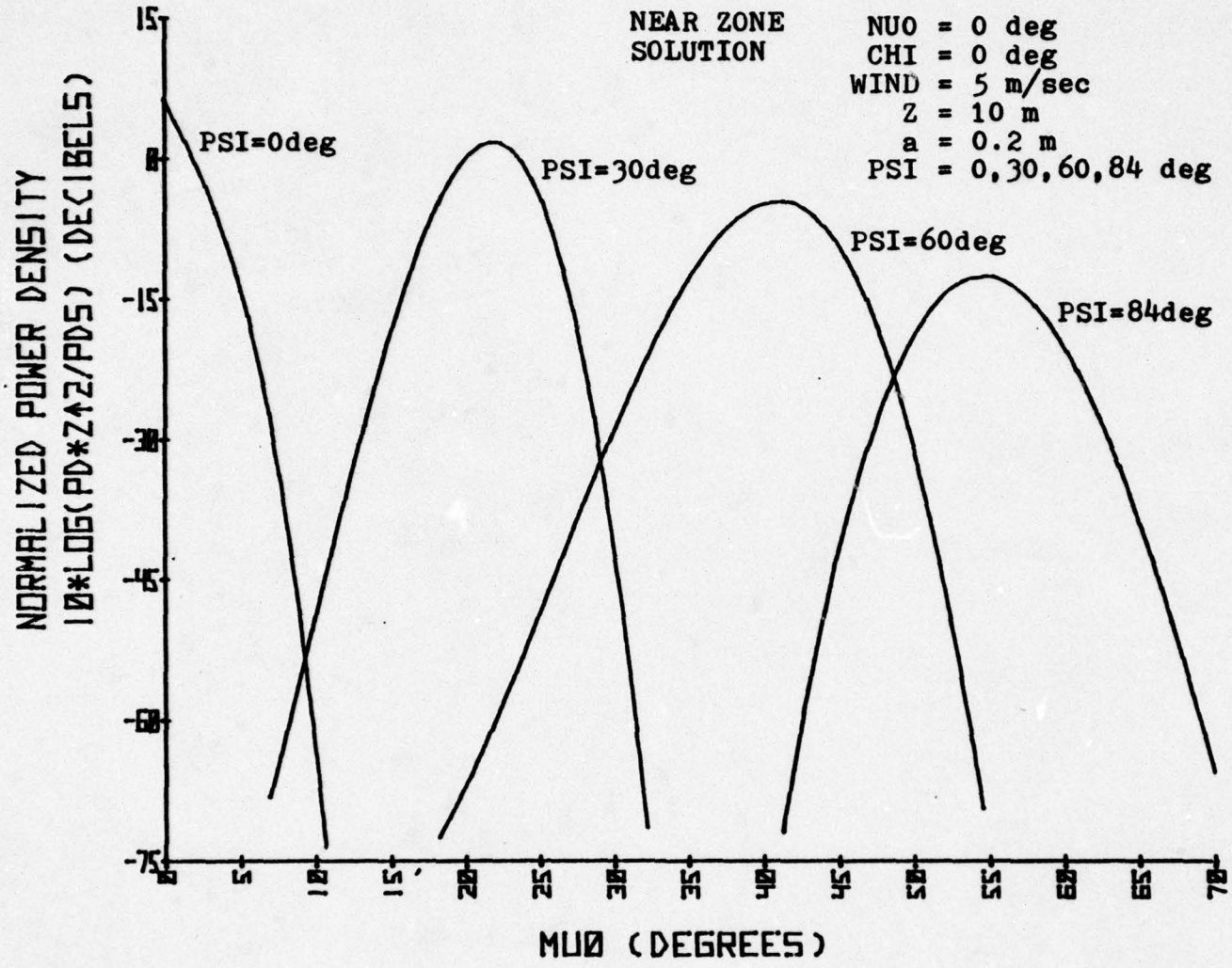
NEAR ZONE
SOLUTION
NUO = 0 deg
CHI = 0 deg
WIND = 5 m/sec
Z = 10 m
a = 0.2 m
PSI = 0,30,60,84 deg
PSI=0deg
PSI=30deg
PSI=60deg
PSI=84deg
NORMALIZED POWER DENSITY
10*LOG(PD*Z↑2/PDS) (DECIBELS)
MU0 (DEGREES)

Figure 13

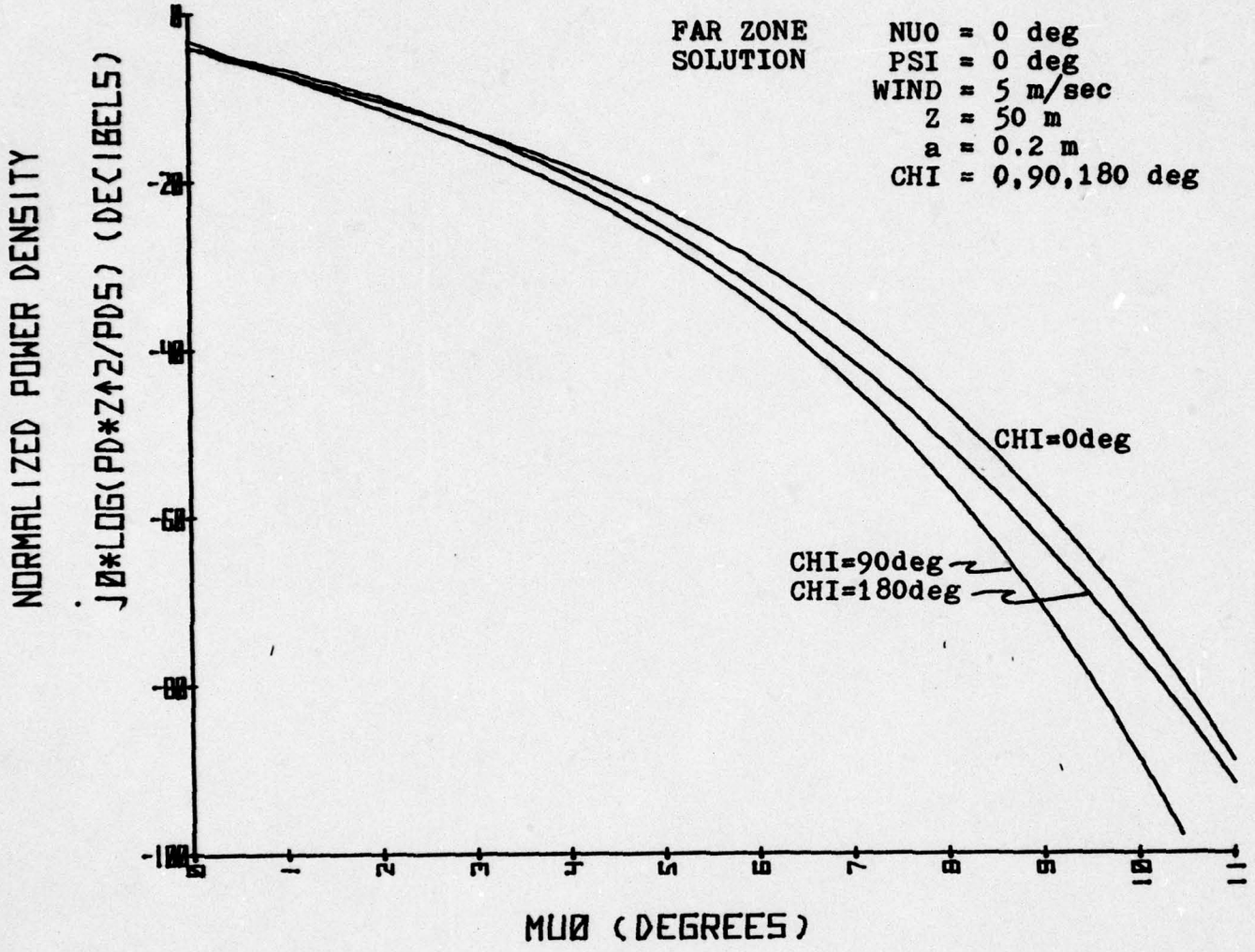
FAR ZONE
SOLUTION
NUO = 0 deg
PSI = 0 deg
WIND = 5 m/sec
Z = 50 m
a = 0.2 m
CHI = 0,90,180 deg
CHI=0deg
CHI=90deg
CHI=180deg
NORMALIZED POWER DENSITY
J0*LOG(PD*Z↑2/PD5) (DECIBELS)
MU0 (DEGREES)

Figure 14

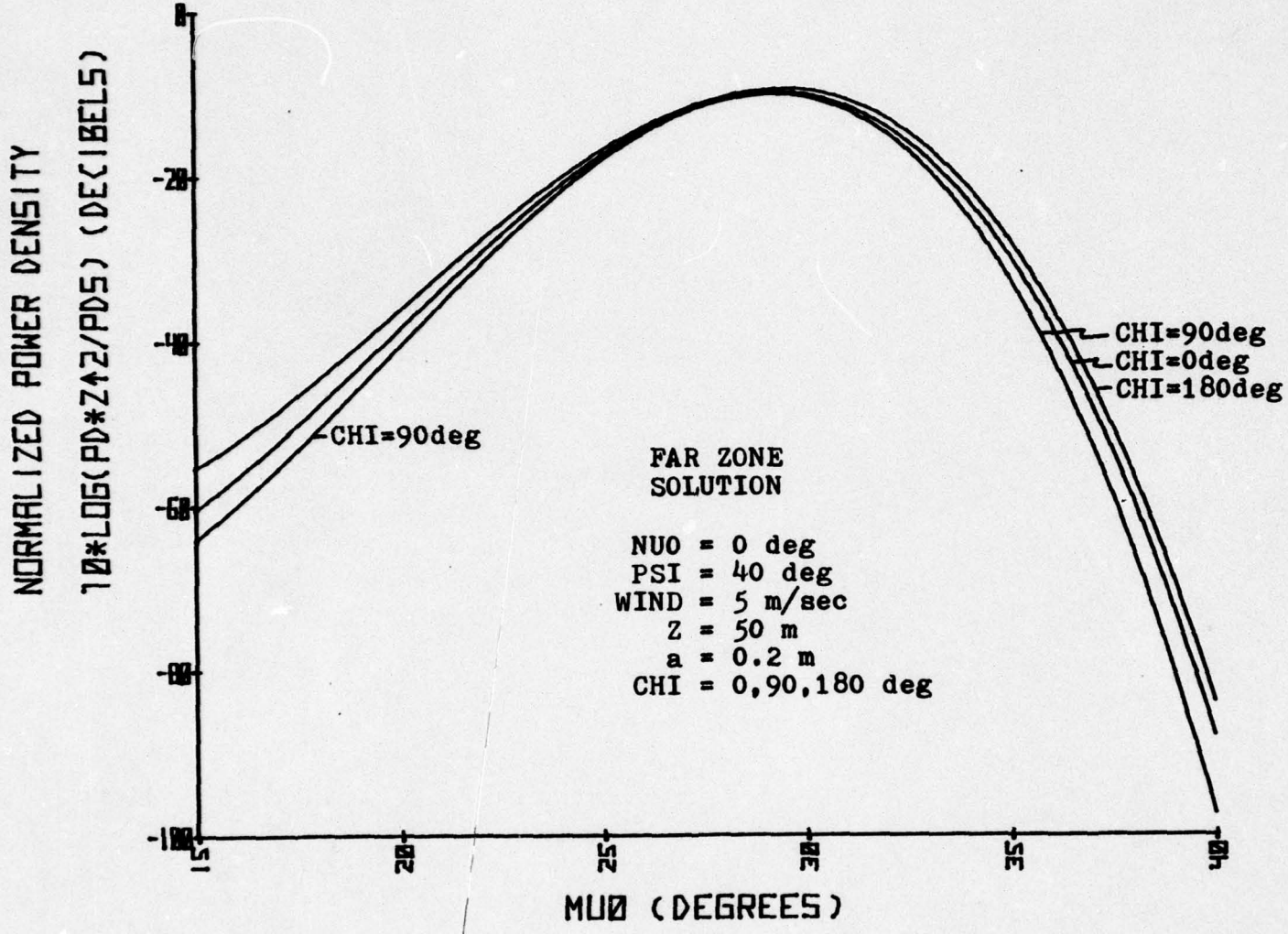
NORMALIZED POWER DENSITY
10*LOG(PD*Z↑2/PD5) (DECIBELS)
CHI=90deg
CHI=90deg
CHI=0deg
CHI=180deg
FAR ZONE
SOLUTION
NUO = 0 deg
PSI = 40 deg
WIND = 5 m/sec
Z = 50 m
a = 0.2 m
CHI = 0,90,180 deg
15
20
25
30
35
40
MU0 (DEGREES)

Figure 15

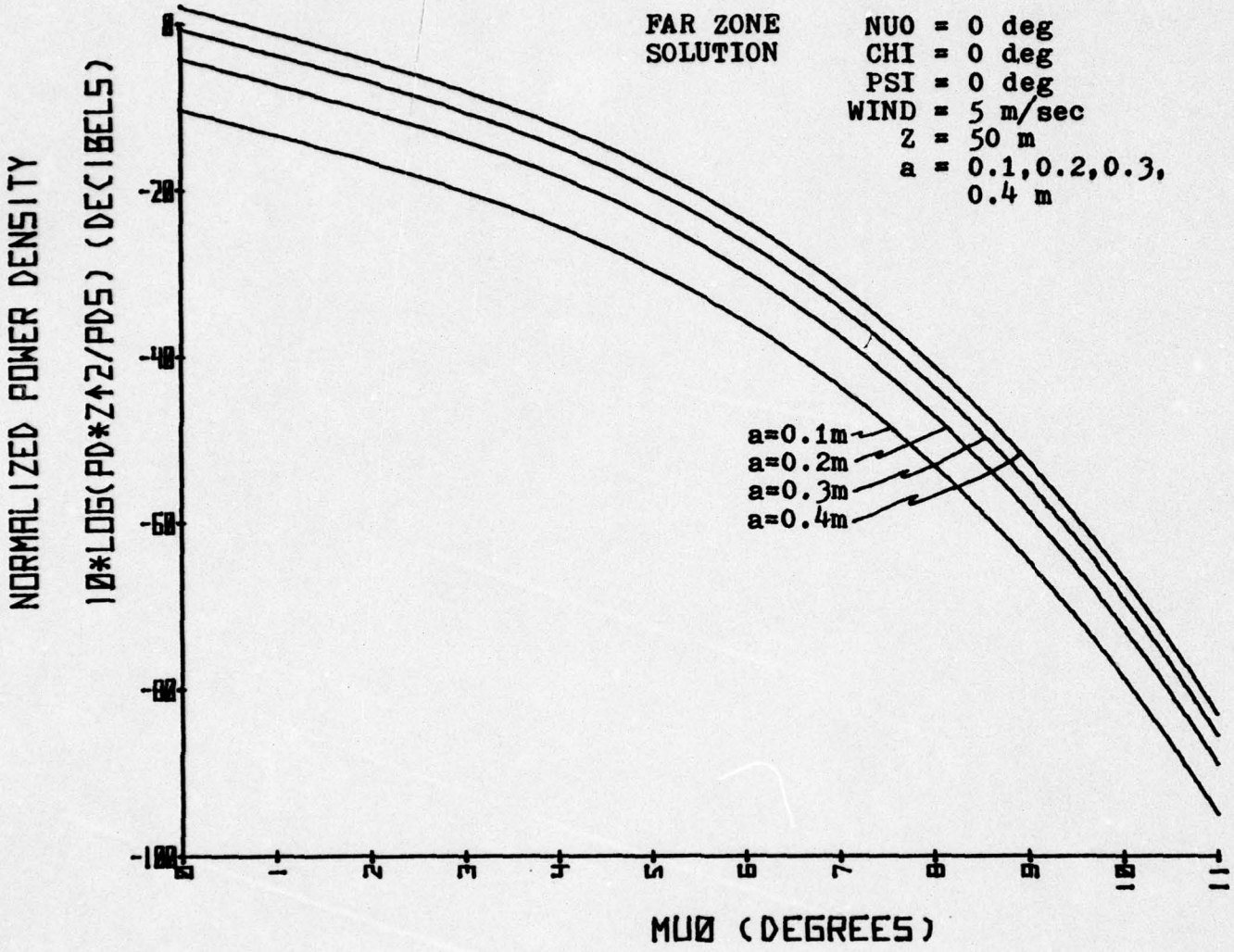
FAR ZONE
SOLUTION
NUO = 0 deg
CHI = 0 deg
PSI = 0 deg
WIND = 5 m/sec
Z = 50 m
a = 0.1,0.2,0.3,
0.4 m
a=0.1m
a=0.2m
a=0.3m
a=0.4m
NORMALIZED POWER DENSITY
10*LOG(PD*Z↑2/PD5) (DECIBELS)
-20
-40
-60
-80
-100
0
1
2
3
4
5
6
7
8
9
10
11
MU0 (DEGREES)

Figure 16

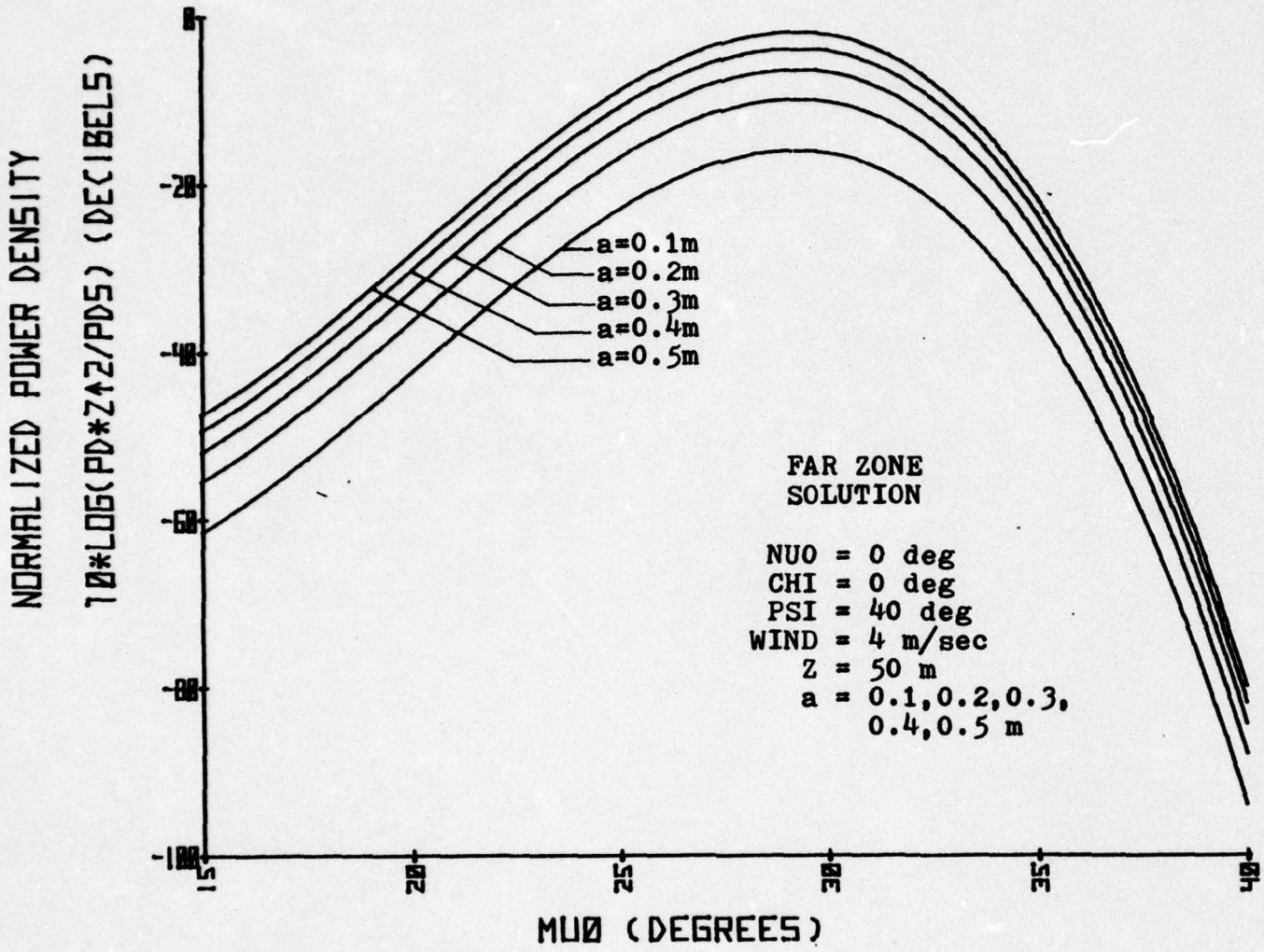
NORMALIZED POWER DENSITY
10*LOG(PD*Z↑2/PDS) (DECIBELS)
a=0.1m
a=0.2m
a=0.3m
a=0.4m
a=0.5m
FAR ZONE
SOLUTION
NUO = 0 deg
CHI = 0 deg
PSI = 40 deg
WIND = 4 m/sec
Z = 50 m
a = 0.1,0.2,0.3,
0.4,0.5 m
MU0 (DEGREES)

Figure 17

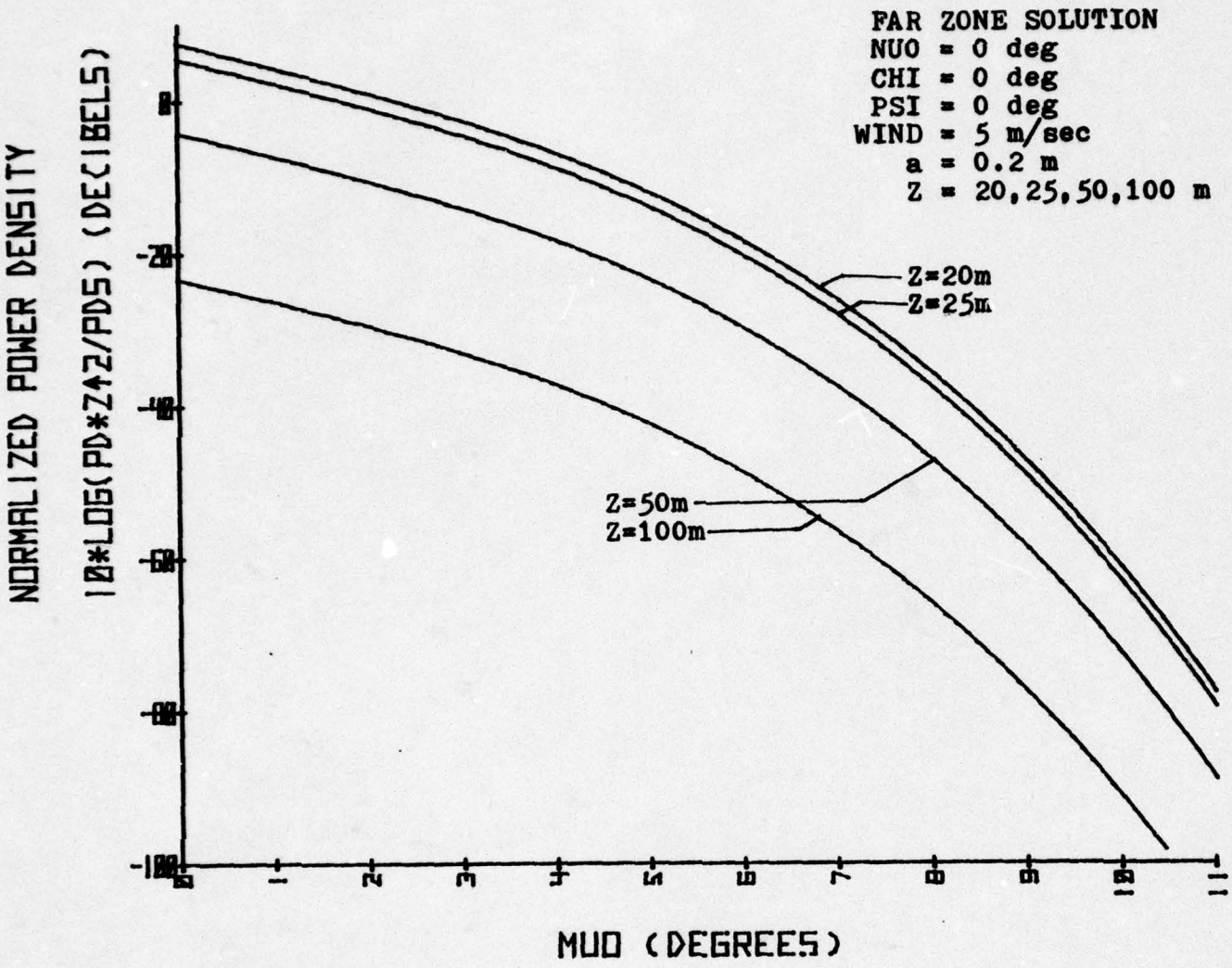
FAR ZONE SOLUTION
NUO = 0 deg
CHI = 0 deg
PSI = 0 deg
WIND = 5 m/sec
a = 0.2 m
Z = 20,25,50,100 m
Z=20m
Z=25m
Z=50m
Z=100m
NORMALIZED POWER DENSITY
10*LOG(PD*Z↑2/PDS) (DECIBELS)
MUO (DEGREES)

Figure 18

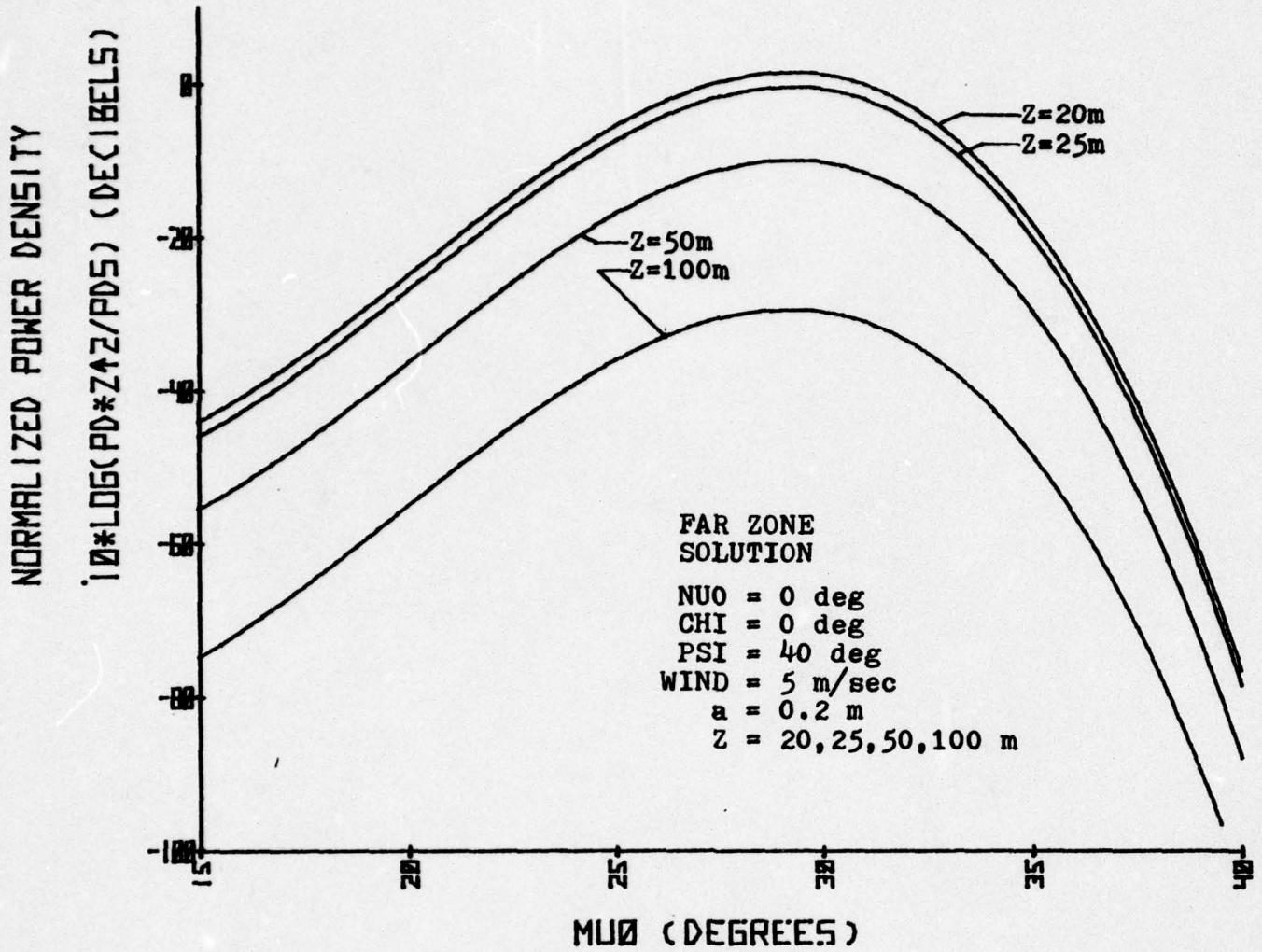
NORMALIZED POWER DENSITY
10*LOG(PD*Z^2/PD5) (DECIBELS)
Z=20m
Z=25m
Z=50m
Z=100m
FAR ZONE
SOLUTION
NUO = 0 deg
CHI = 0 deg
PSI = 40 deg
WIND = 5 m/sec
a = 0.2 m
Z = 20,25,50,100 m
15
20
25
30
35
40
MU0 (DEGREES)

Figure 19

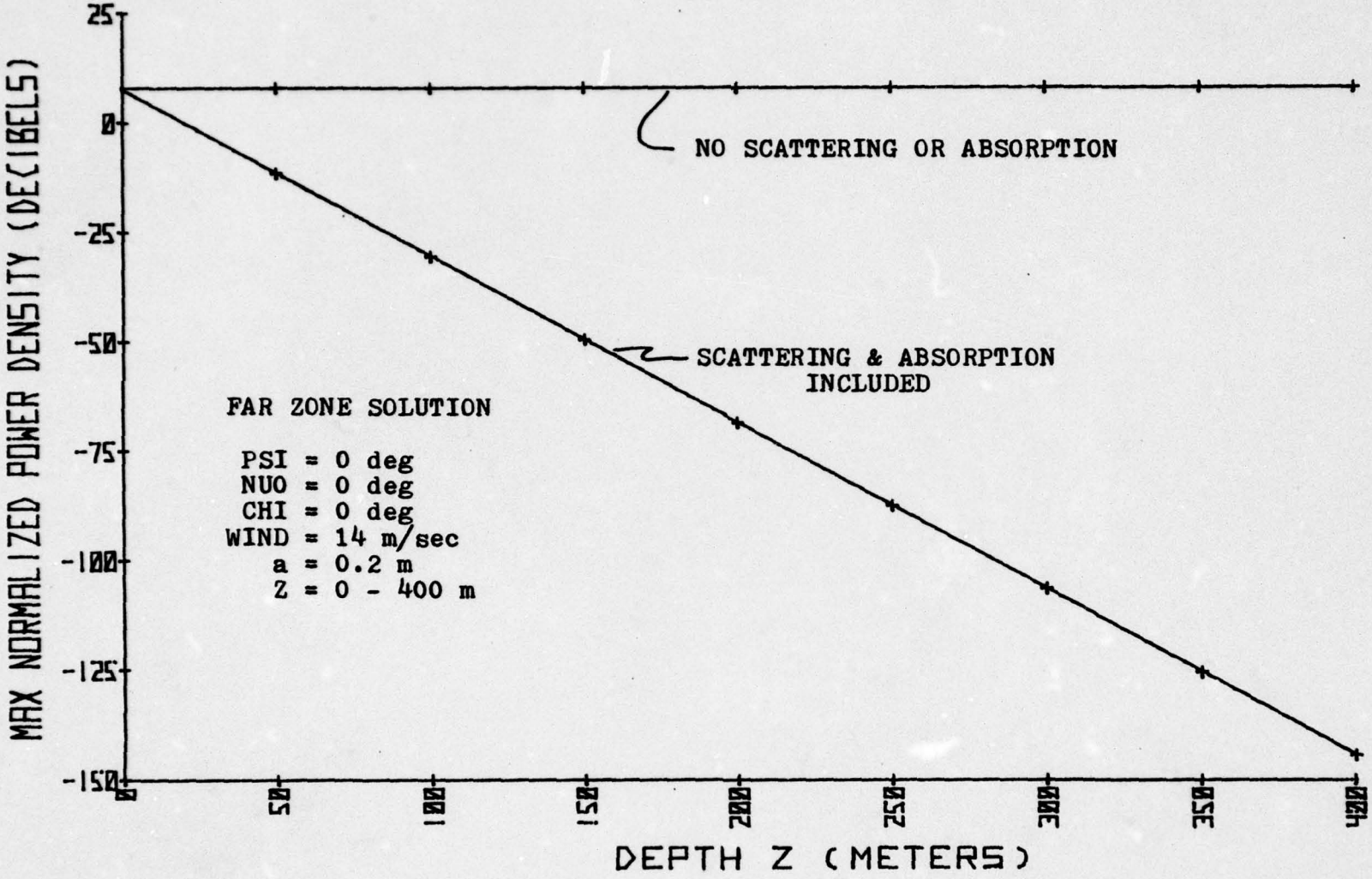
MAX NORMALIZED POWER DENSITY (DECIBELS)
25
0
-25
-50
-75
-100
-125
-150
0
50
100
150
200
250
300
350
400
DEPTH Z (METERS)
NO SCATTERING OR ABSORPTION
SCATTERING & ABSORPTION
INCLUDED
FAR ZONE SOLUTION
PSI = 0 deg
NUO = 0 deg
CHI = 0 deg
WIND = 14 m/sec
a = 0.2 m
Z = 0 - 400 m

Figure 20

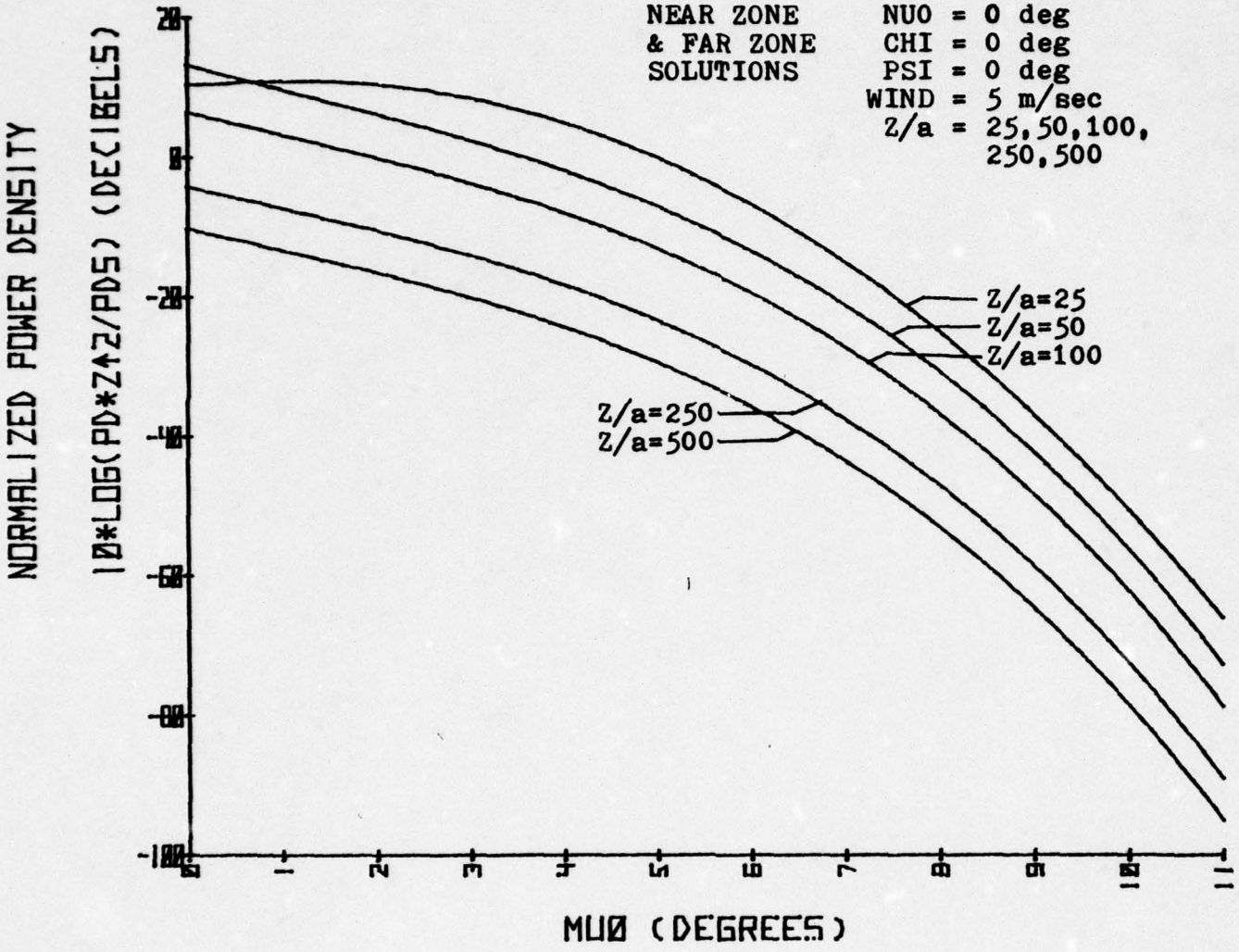
NEAR ZONE
& FAR ZONE
SOLUTIONS
NUO = 0 deg
CHI = 0 deg
PSI = 0 deg
WIND = 5 m/sec
Z/a = 25,50,100,
250,500
Z/a=25
Z/a=50
Z/a=100
Z/a=250
Z/a=500
NORMALIZED POWER DENSITY
10*LOG(PD*Z↑2/PDS) (DECIBELS)
MU0 (DEGREES)

Figure 21

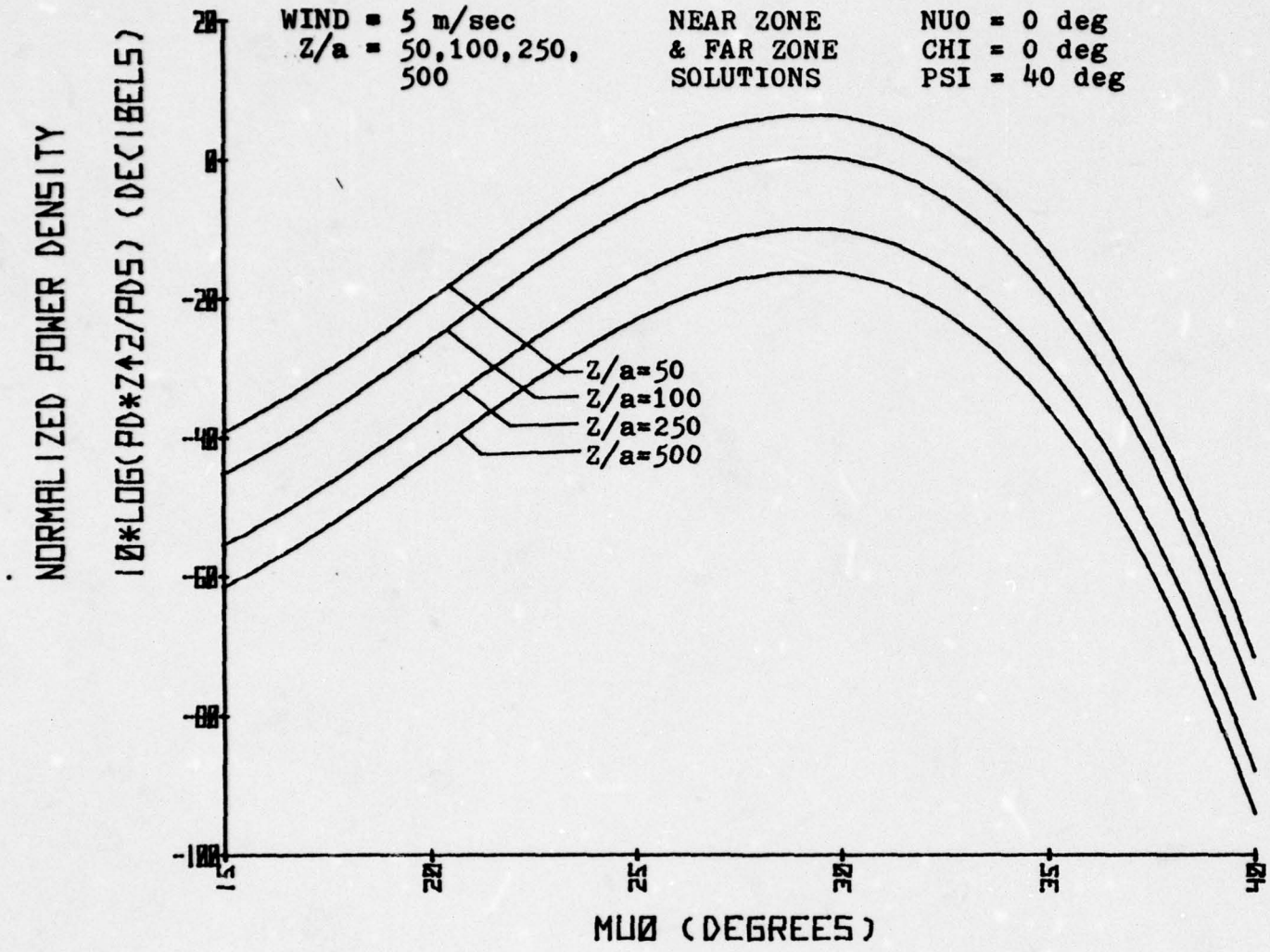
WIND = 5 m/sec
Z/a = 50,100,250,
500
NEAR ZONE
& FAR ZONE
SOLUTIONS
NUO = 0 deg
CHI = 0 deg
PSI = 40 deg
NORMALIZED POWER DENSITY
10*LOG(PD*Z↑2/PDS) (DECIBELS)
Z/a=50
Z/a=100
Z/a=250
Z/a=500
MU0 (DEGREES)

Figure 22

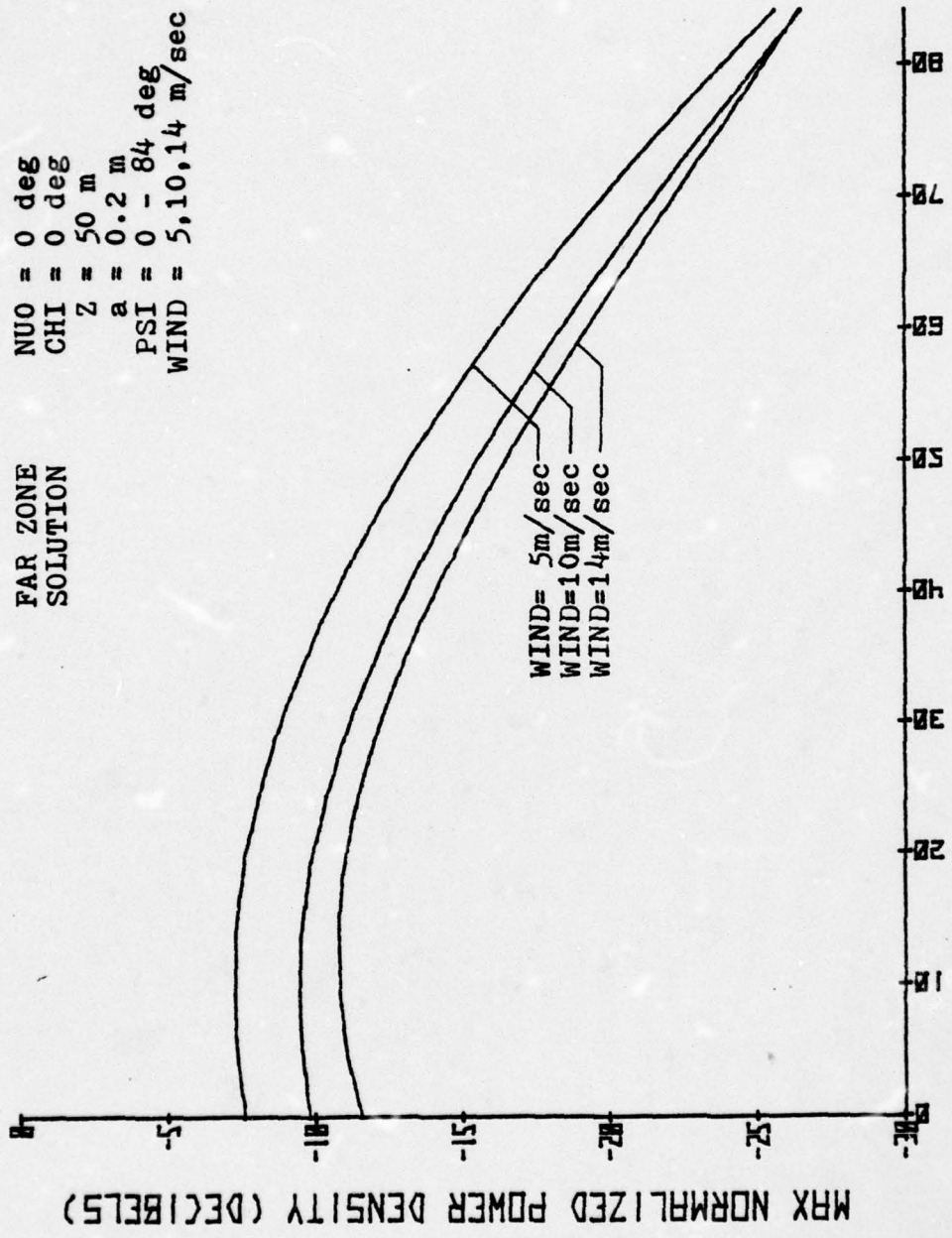
FAR ZONE
SOLUTION
NUO = 0 deg
CHI = 0 deg
Z = 50 m
a = 0.2 m
PSI = 0 - 84 deg
WIND = 5,10,14 m/sec
WIND= 5m/sec
WIND=10m/sec
WIND=14m/sec
MRX NORMALIZED POWER DENSITY (DECIBELS)
PSI (DEGREES)

Figure 23

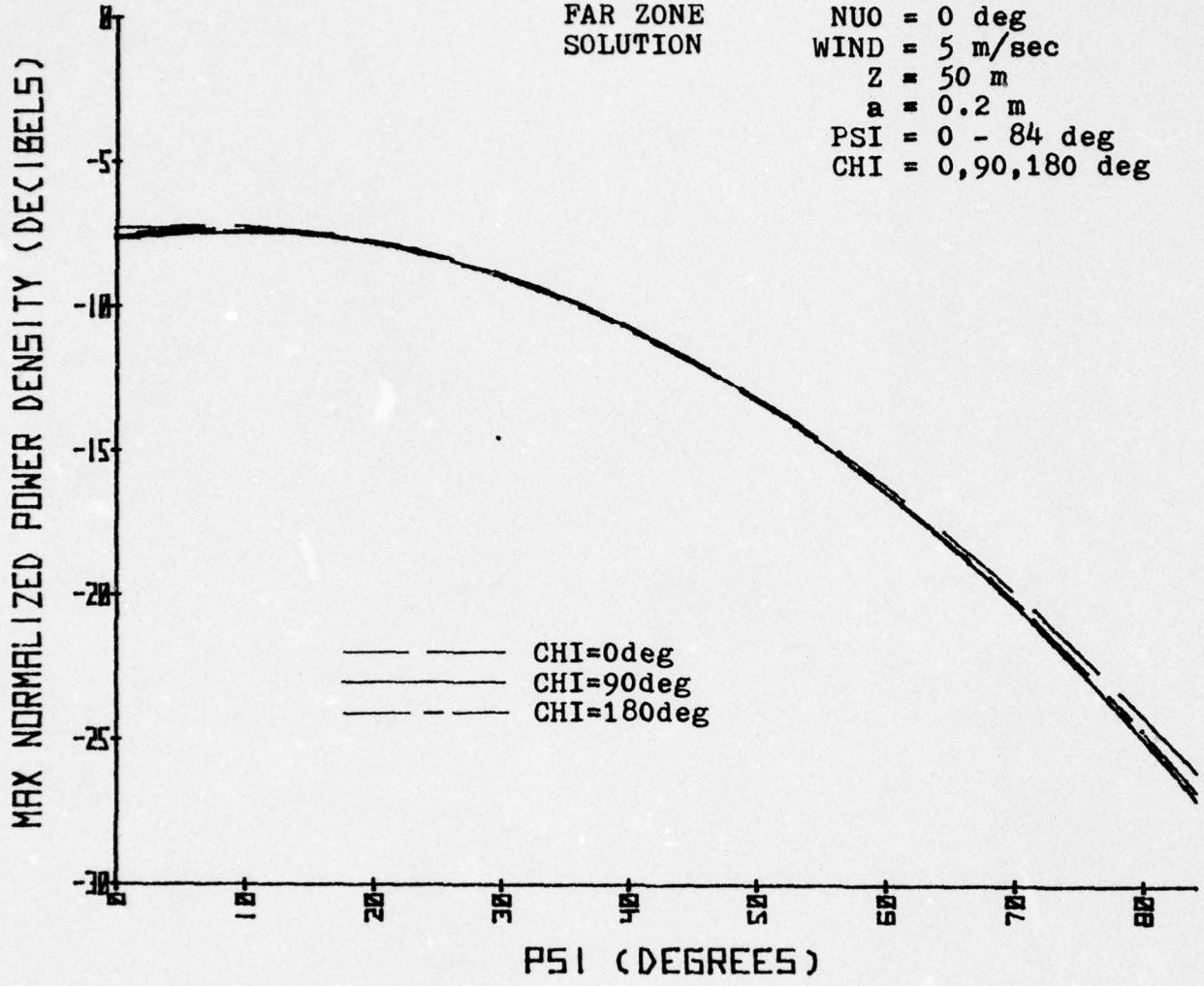
FAR ZONE
SOLUTION
NUO = 0 deg
WIND = 5 m/sec
Z = 50 m
a = 0.2 m
PSI = 0 - 84 deg
CHI = 0,90,180 deg
MAX NORMALIZED POWER DENSITY (DECIBELS)
-5
-10
-15
-20
-25
-30
0
10
20
30
40
50
60
70
80
PSI (DEGREES)
CHI=0deg
CHI=90deg
CHI=180deg

Figure 24

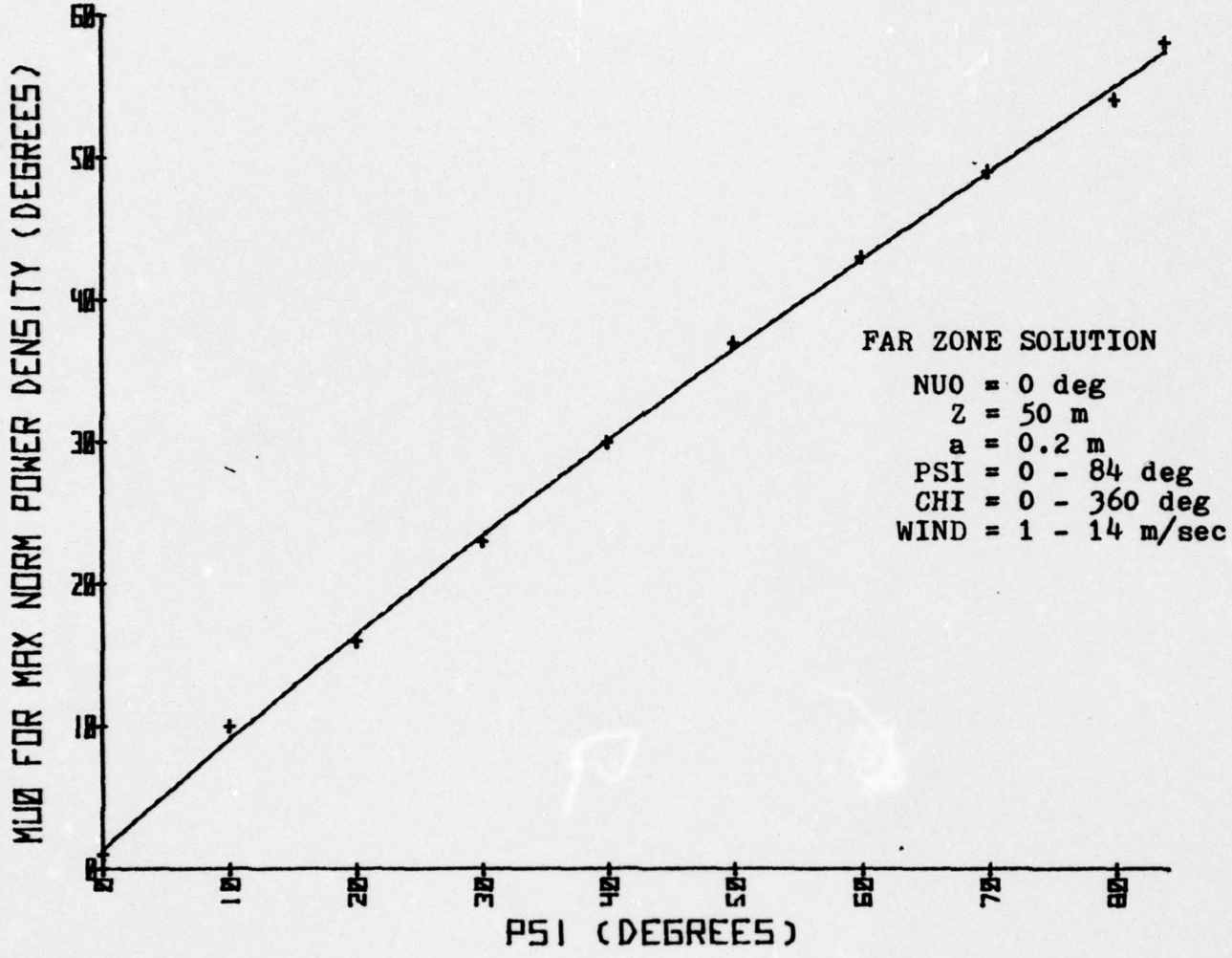
MU0 FOR MAX NORM POWER DENSITY (DEGREES)
PSI (DEGREES)
FAR ZONE SOLUTION
NUO = 0 deg
Z = 50 m
a = 0.2 m
PSI = 0 - 84 deg
CHI = 0 - 360 deg
WIND = 1 - 14 m/sec

Figure 25

APPENDIX B

COMPUTER PROGRAM USAGE

To use the computer programs listed following this Appendix, first compute the ratio of the depth of the point of observation below the ocean surface to the beam radius at the surface facet, Z/a. Use the Near Zone program for $Z/a \leq 100$ and the Far Zone program for $Z/a > 100$. The Near Zone program may be used for any value of Z/a, but a slight computation time and computer storage increase will result.

The only other basic requirement is the selection of eight input variables. The variables are listed below along with the line from the respective program in which they appear.

VARIABLE	NEAR ZONE	FAR ZONE
Depth, Z (m)	470	440
Beam radius, RAD (m)	480	450
Angle Nu_0, NUORUN (deg)	490	480
Backward scattering coefficient, BS	560	530
Absorption coefficient, AC (m^{-1})	570	540
Beam incidence angle, PSIRUN (deg)	630	590
Wind direction, CHI (rad)	680	640
Wind velocity, W (m/sec)	710	670

Z, RAD, NUORUN, BS and AC are direct program inputs

made on the indicated lines. PSI, CHI and W are selected from DATA statements 430 and 440 in the Near Zone program and 420 and 430 in the Far Zone program. The variable locations in DATA statements were used for multiple variations of the parameters in a slightly different form of the program than presented which is easily set up with DO LOOPS. The entry variables may also be varied in this same manner.

Both programs must be combined with the common package of subroutines that are listed following the basic program listings.

The cutput from both listed programs appear on the next two pages.

NEAR ZONE SOLUTION DEPTH= 10.00 M DTF= 0.37845 WIND=14.3 M/SEC
PSI=40.0 DEG RAD= 0.2 M VALID=1
NUO= 0.0 DEG CHI= 0.0 DEG INVALID=0

NUO	ALPHA	B	W1	W2	T	JACOB	PSLOPE	PRATIO	PWRDEN	MUO	VALIDITY	XI	ETA
15	0.0	29.93	69.93	44.93	0.2599	0.5512	1.7628E-01	8.5223E-05	-20.69	15	0	0.0	2.7
16	0.0	28.32	68.32	44.32	0.2869	0.4609	2.3785E-01	1.3573E-04	-18.67	16	0	0.0	2.6
17	0.0	26.66	66.66	43.66	0.3143	0.3841	3.1509E-01	2.1025E-04	-16.77	17	1	0.0	2.4
18	0.0	24.92	64.92	42.92	0.3420	0.3186	4.1207E-01	3.1886E-04	-14.96	18	1	0.0	2.2
19	0.0	23.11	63.11	42.11	0.3698	0.2624	5.3529E-01	4.7685E-04	-13.22	19	1	0.0	2.0
20	0.0	21.23	61.23	41.23	0.3975	0.2143	6.9461E-01	7.0772E-04	-11.50	20	1	0.0	1.8
21	0.0	19.26	59.26	40.26	0.4250	0.1730	9.0404E-01	1.0475E-03	-9.80	21	1	0.0	1.7
22	0.0	17.20	57.20	39.20	0.4521	0.1376	1.1812E 00	1.5486E-03	-8.10	22	1	0.0	1.5
23	0.0	15.04	55.04	38.04	0.4788	0.1073	1.5449E 00	2.2867E-03	-6.42	23	1	0.0	1.3
24	0.0	12.78	52.78	36.78	0.5048	0.0814	2.0097E 00	3.3303E-03	-4.78	24	1	0.0	1.1
25	0.0	10.41	50.41	35.41	0.5300	0.0592	2.5767E 00	4.7751E-03	-3.21	25	1	0.0	0.9
26	0.0	7.92	47.92	33.92	0.5542	0.0403	3.2231E 00	6.6605E-03	-1.76	26	1	0.0	0.7
27	0.0	5.32	45.32	32.32	0.5775	0.0242	3.8914E 00	8.9460E-03	-0.48	27	1	0.0	0.4
28	0.0	2.58	42.58	30.58	0.5995	0.0105	4.4854E 00	1.1450E-02	0.59	28	1	0.0	0.2
29	0.0	-0.28	39.72	28.71	0.6202	0.0010	4.8795E 00	1.3807E-02	1.40	29	1	0.0	0.0
30	0.0	-3.30	36.70	26.70	0.6395	0.0109	4.9488E 00	1.5517E-02	1.91	30	1	0.0	0.3
31	0.0	-6.44	33.56	24.56	0.6573	0.0192	4.6105E 00	1.6067E-02	2.04	31	1	0.0	0.5
32	0.0	-9.72	30.28	22.28	0.6735	0.0262	3.8757E 00	1.4895E-02	1.73	32	1	0.0	0.6
33	0.0	-13.14	26.86	19.86	0.6880	0.0323	2.8715E 00	1.2234E-02	0.88	33	1	0.0	1.1
34	0.0	-16.69	23.31	17.31	0.7008	0.0376	1.8156E 00	8.5815E-03	-0.66	34	1	0.0	1.4
35	0.0	-20.37	19.63	14.63	0.7117	0.0422	9.3345E-01	4.9045E-03	-3.09	35	1	0.0	1.8
36	0.0	-24.15	15.85	11.85	0.7206	0.0464	3.5898E-01	2.1022E-03	-6.77	36	1	0.0	2.1
37	0.0	-28.02	11.98	8.98	0.7277	0.0503	8.4646E-02	5.5445E-04	-12.56	37	0	0.0	2.5
38	0.0	-31.97	8.03	6.03	0.7328	0.0540	1.7671E-03	1.3010E-05	-28.86	38	0	0.0	3.0
39	0.0	-35.97	4.03	3.03	0.7359	0.0578	-6.2004E-03	5.1563E-05	-22.88	39	0	0.0	3.5

F&P ZONE SOLUTION DEPTH= 50.00 M DTF= 0.01121 WIND=14.0 M/SEC
PSI=40.0 DEG BSF= 0.2 M VALID=1
MUD= 0.0 DEG CH = 0.0 DEG INVALID=0

MUD	ALPHA	R	WI	WR	T	JACOB	DAREA	PSLOPE	PRATIO	PWRDEN	MUC	VALIDITY	XI	ETA
15	0.0	29.93	69.93	44.93	0.2599	0.5512	2.2846E-04	1.7628E-01	7.9106E-08	-37.04	15	0	0.0	2.7
16	0.0	28.32	68.32	44.32	0.2969	0.4609	2.1142E-04	2.3765E-01	1.2603E-07	-35.02	16	0	0.0	2.6
17	0.0	26.66	66.66	43.66	0.3143	0.3841	1.9628E-04	3.1509E-01	1.9531E-07	-33.11	17	1	0.0	2.4
18	0.0	24.92	64.92	42.92	0.3423	0.3186	1.8170E-04	4.1207E-01	2.9471E-07	-31.33	18	1	0.0	2.2
19	0.0	23.11	63.11	42.11	0.3698	0.2624	1.6946E-04	5.3529E-01	4.4079E-07	-29.58	19	1	0.0	2.0
20	0.0	21.23	61.23	41.23	0.3975	0.2143	1.5934E-04	6.9461E-01	6.5843E-07	-27.84	20	1	0.0	1.8
21	0.0	19.26	59.26	40.26	0.4250	0.1730	1.4818E-04	9.0404E-01	9.6350E-07	-26.16	21	1	0.0	1.7
22	0.0	17.20	57.20	39.20	0.4521	0.1376	1.3892E-04	1.1812E 00	1.4326E-06	-24.46	22	1	0.0	1.5
23	0.0	15.04	55.04	38.04	0.4788	0.1073	1.3108E-04	1.5449E 00	2.1231E-06	-22.75	23	1	0.0	1.3
24	0.0	12.78	52.78	36.78	0.5048	0.0814	1.2235E-04	2.0097E 00	3.0907E-06	-21.13	24	1	0.0	1.1
25	0.0	10.41	50.41	35.41	0.5300	0.0592	1.1500E-04	2.5767E 00	4.4183E-06	-19.57	25	1	0.0	0.9
26	0.0	7.92	47.92	33.92	0.5542	0.0403	1.0876E-04	3.2231E 00	6.1994E-06	-18.10	26	1	0.0	0.7
27	0.0	5.32	45.32	32.32	0.5775	0.0242	1.0174E-04	3.8914E 00	8.2812E-06	-16.84	27	1	0.0	0.4
28	0.0	2.58	42.58	30.58	0.5995	0.0105	9.5727E-05	4.4854E 00	1.0598E-05	-15.77	28	1	0.0	0.2
29	0.0	-0.28	39.72	28.71	0.6202	0.0010	9.0677E-05	4.8795E 00	1.2962E-05	-14.93	29	1	0.0	0.0
30	0.0	-3.30	36.70	26.70	0.6395	0.0109	8.5383E-05	4.9488E 00	1.4460E-05	-14.42	30	1	0.0	0.3
31	0.0	-6.44	33.56	24.56	0.6573	0.0192	7.9832E-05	4.6105E 00	1.4817E-05	-14.31	31	1	0.0	0.5
32	0.0	-9.72	30.28	22.28	0.6735	0.0262	7.5110E-05	3.8757E 00	1.3788E-05	-14.63	32	1	0.0	0.8
33	0.0	-13.14	26.86	19.86	0.6880	0.0323	7.0705E-05	2.8715E 00	1.1324E-05	-15.48	33	1	0.0	1.1
34	0.0	-16.69	23.31	17.31	0.7008	0.0376	6.5718E-05	1.8156E 00	7.8486E-06	-17.07	34	1	0.0	1.4
35	0.0	-20.37	19.63	14.63	0.7117	0.0422	6.2218E-05	9.3345E-01	4.5155E-06	-19.47	35	1	0.0	1.8
36	0.0	-24.15	15.85	11.85	0.7206	0.0464	5.8849E-05	3.5898E-01	1.9475E-06	-23.13	36	1	0.0	2.1
37	0.0	-28.02	11.98	8.98	0.7277	0.0503	5.4906E-05	8.4646E-02	5.1006E-07	-28.94	37	0	0.0	2.5
38	0.0	-31.97	8.03	6.03	0.7328	0.0540	5.1929E-05	1.7671E-03	1.2050E-08	-45.21	38	0	0.0	3.0
39	0.0	-35.97	4.03	3.03	0.7359	0.0578	4.8743E-05	-6.2004E-03	4.7789E-08	-36.23	39	0	0.0	3.5

```
C     NEAR ZONE SOLUTION OF THE TIME-AVERAGE POWER PROBABILITY                  10
C     DISTRIBUTION BELOW THE OCEAN OF A LASER BEAM INCIDENT ON SURFACE          20
C                                                                               30
C                                                                               40
C     NOMENCLATURE:                                                             50
C                                                                               60
C          PSI=ANGLE OF INCIDENT BEAM WITH RESPECT TO VERTICAL AXIS             70
C          CHI=ANGLE OF WIND WITH RESPECT TO THE INCIDENT BEAM IN               80
C            THE XY-PLANE                                                       90
C          ALPHA=ANGLE OF MAX WAVE SLOPE WITH RESPECT TO THE INCIDENT          100
C               BEAM IN THE XY-PLANE                                           110
C          B=MAX SLOPE OF WAVE FACET                                           120
C          NU=NUO=ANGLE BETWEEN REFRACTED RAY PROJECTED ONTO XY-PLANE          130
C               AND THE Y AXIS                                                 140
C          MU=MUO=ANGLE BETWEEN REFRACTED RAY AND THE Z AXIS                   150
C          Z=DEPTH BELOW OCEAN SURFACE (METERS)                                160
C          RAD=INCIDENT RAY SPOT RADIUS AT WAVE FACET (MINOR AXIS OF           170
C              ELLIPSE WHEN PSI IS NON-ZERO)                                   180
C          BB=MAJOR AXIS OF SPOT INCIDENT ON WAVE FACET                        190
C          W=WIND VELOCITY (M/SEC)                                             200
C          WI=RAY INCIDENCE ANGLE                                              210
C          WR=RAY REFRACTION ANGLE                                             220
C          CTF=DIFFUSE TRANSMITTANCE FUNCTION                                  230
C          BS=BACKWARD SCATTERING COEFFICIENT                                  240
C          AC=ABSORBTION COEFFICIENT                                           250
C          T=FRESNEL'S TRANSMITTANCE FUNCTION                                  260
C          AN=INDEX OF REFRACTION                                              270
C          PSLOPE=SLOPE PROBABILITY FUNCTION                                   280
C          DAREA=AREA INCREMENT                                                290
C          JACOB=JACOBIAN                                                      300
C          PWRDEN=POWER DENSITY (DECIBELS)                                     310
C                                                                              320
C                                                                              330
      INTEGER VALID                                                            340
      REAL NUO,JMUO,JACOB,MUO,NUORUN                                           350
      REAL MUU,MUL,NUU,NUL                                                     360
      COMMON MUO,NUO,PSI,AN,PSIRUN,NUORUN,PI,Z,RAD,BB,JK                       370
      DIMENSION W(4), CHI(3), NCHI(3), RG(4), JMUO(90), PWRDEN(90), PSIN       380
     1(10)                                                                     390
C                                                                              400
CC    INPUT PARAMETERS FOR THIS RUN                                            410
C                                                                              420
      DATA W,CHI,NCHI/14.,10.,5.,1.,0.,1.5708,3.14159,0,90,180/                430
      DATA PSIN/0.,10.,20.,30.,40.,50.,60.,70.,80.,84./                        440
      DATA ETA1,ETA2,XI1,XI2/.577350269,-.577350269,.577350269,-.5773502       450
     169/                                                                      460
      Z = 10.                                                                  470
      RAD = .2                                                                 480
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```
      NUORUN = 0.                                                        490
      NUC = NUORUN/57.2958                                               500
      AN = 1.33                                                          510
      PI = 3.141592654                                                   520
C                                                                        530
C     DIFFUSE TRANSMITTANCE FUNCTION (DTF)                               540
C     REF 11: PG 65                                                      550
      BS = .065                                                          560
      AC = .044                                                          570
      FK = SQRT(AC*(AC+2.*BS))                                           580
      DTF = FK/((AC+BS)*SINH(FK*Z)+FK*COSH(FK*Z))                        590
C                                                                        600
C     PSI=40 DEG                                                         610
      LM = 5                                                             620
      PSIRUN = PSIN(5)                                                   630
      PSI = PSIRUN/57.2958                                               640
      BE = RAD*(1./COS(PSI))                                             650
C                                                                        660
C     CHI=0 DEG                                                          670
      L = 1                                                              680
C                                                                        690
C     WIND=14 M/SEC                                                      700
      I = 1                                                              710
C                                                                        720
C     OUTPUT PRINTING INSTRUCTIONS                                       730
      WRITE (6,105) Z,DTF,W(I),PSIRUN,RAD,NUORUN,CHI(L)                  740
  105 FORMAT (1H1,10X,'NEAR ZONE SOLUTION',5X,'DEPTH=',F6.2,' M',5X,     750
     1 'DTF=',F8.5,5X,'WIND=',F4.1,' M/SEC'/11X,'PSI=',F4.1,' DEG',11X,  760
     2 'RAD=',F5.1,' M',8X,'VALID=1'/11X,'NUO=',F4.1,' DEG',11X,'CHI=',  770
     3 F4.1,' DEG',7X,'INVALID=0'///)                                    780
C                                                                        790
      WRITE (6,110)                                                      800
  110 FORMAT (1X,'MUO',2X,'ALPHA',4X,'B',7X,'WI',6X,'WR',6X,'T',5X,      810
     1 'JACOB',6X,'PSLOPE',5X,'PRATIO',5X,'PWRDEN',1X,                   820
     2 'MUO',2X,'VALIDITY',2X,'XI',2X,'ETA'/)                            830
C                                                                        840
C     MUO VARIED FROM 1 TO 90 DEG MAX FOR PSI LESS THAN OR EQUAL         850
C     TO 30 DEG, AND FROM 15 TO 90 DEG MAX FOR PSI GREATER THAN 30 DEG:  860
C     MUO IN RADIANS; JMUO IN DEGREES                                    870
C     REF 3: EQNS 50,54,55,82,83                                         880
C                                                                        890
      DO 115 J=1,90                                                      900
      PWRDEN(J) = 0.                                                     910
  115 CONTINUE                                                           920
C                                                                        930
      IF (PSIRUN.GT.30.) GO TO 120                                       940
      INT = 1                                                            950
      GO TO 125                                                          960
```

```
  120 INT = 15                                                                  970
C                                                                               980
  125 DO 195 J=INT,90                                                           990
      JMUO(J) = FLOAT(J)                                                       1000
      MUO = JMUO(J)/57.2958                                                    1010
      JK = J                                                                   1020
      JJ = J-6                                                                 1030
C                                                                              1040
C     ALPHA,B,WI,WR ARE COMPUTED IN SUBROUTINE ANGLES:                         1050
      CALL ANGLES (ALPHA,B,WI,WR)                                              1060
C     REFS 2,3&4                                                               1070
C                                                                              1080
C     T=FRESNEL'S TRANSMITTANCE                                                1090
C     REFS 9&10                                                                1100
      TPER = (2.*COS(WI)*SIN(WR)/SIN(WI+WR))**2                                1110
      TPAR = (2.*COS(WI)*SIN(WR)/SIN(WI+WR)*COS(WI-WR))**2                     1120
      T = (TPAR+TPER)/2.                                                       1130
C                                                                              1140
C     JACOBIAN COMPUTED IN SUBROUTINE JACO,                                    1150
      CALL JACO (ALPHA,B,JACOB)                                                1160
C     REF 3: EQNS 48-52                                                        1170
C                                                                              1180
C     PSLOPE=SLOPE PROBIBILITY FUNCTION                                        1190
C     REF 5: EQNS 5-9,12-18                                                    1200
      SIGC = SQRT(.003+1.92E-03*W(I))                                          1210
      SIGU = SQRT(3.16E-03*W(I))                                               1220
      C21 = .01-.0086*W(I)                                                     1230
      C03 = .04-.033*W(I)                                                      1240
      C40 = .4                                                                 1250
      C22 = .12                                                                1260
      C04 = .23                                                                1270
      AP = ALPHA-CHI(L)                                                        1280
      ZXP = TAN(B)*SIN(AP)                                                     1290
      ZYP = TAN(B)*COS(AP)                                                     1300
      XI = ZXP/SIGC                                                            1310
      ETA = ZYP/SIGU                                                           1320
      FACT1 = (1./(2.*PI*SIGC*SIGU))*EXP(-.5*(XI**2+ETA**2))                   1330
      FACT2 = 1.-.5*C21*(XI**2-1.)*ETA-(1./6.)*C03*(ETA**3-3.*ETA)             1340
      FACT3 = (1./24.)*C40*(XI**4-6.*XI**2+3.)+.25*C22*(XI**2-1.)*(ETA**       1350
     12-1.)                                                                    1360
      FACT4 = (1./24.)*C04*(ETA**4-6.*ETA**2+3.)                               1370
      PSLOPE = FACT1*(FACT2+FACT3+FACT4)                                       1380
C                                                                              1390
C     VALIDITY CHECK (VALID=1; INVALID=0) ON SLOPE PROBABILITY                 1400
      AXI = ABS(XI)                                                            1410
      AETA = ABS(ETA)                                                          1420
      VALID = 1                                                                1430
      IF ((AXI.GT.2.5).OR.(AETA.GT.2.5)) VALID=0                               1440
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C                                                                       1450
C     DETERMINE IF THE SURFACE PROJECTION OF THE POINT OF OBSERVATION   1460
C     IS INSIDE OR OUTSIDE THE BEAM:                                    1470
C     REF 3: EQNS 68-70,75-77                                           1480
      Y1 = -(Z*TAN(MUO))/SQRT((TAN(NUO))**2+1.)                         1490
      IF (NUO.NE.0.) GO TO 130                                          1500
      SUMCK1 = Y1+BB                                                    1510
      IF (SUMCK1.LT.0.) GO TO 135                                       1520
      IF (SUMCK1.GE.0.) GO TO 170                                       1530
  130 X1 = -(Z*TAN(MUO)*TAN(NUO))/SQRT((TAN(NUO))**2+1.)                1540
      CTNU = COTAN(NUO)                                                 1550
      CA = CTNU*(X1*CTNU-Y1)                                            1560
      CB = SQRT(BB**2*CTNU**2-(BB**2/RAD**2)*(Y1**2-BB**2+X1*CTNU*(X1*CT1570
     1NU-2.*Y1)))                                                       1580
      CC = CTNU**2+BB**2/RAD**2                                         1590
      SUMCK2 = ABS(X1)-((CA-(SIN(NUO)/ABS(SIN(NUO)))*CB)/CC)            1600
      IF (SUMCK2.GT.0.) GO TO 135                                       1610
      IF (SUMCK2.LE.0.) GO TO 170                                       1620
C                                                                       1630
C     CALCULATION OF INTEGRATION LIMITS FOR THE SURFACE PROJECTION      1640
C     OF THE POINT OF OBSERVATION OUTSIDE THE BEAM:                     1650
C     REF 3: EQNS 13,14,21-26,34-39,60-70                               1660
  135 IF (PSIRUN.EQ.0.) GO TO 155                                       1670
C                                                                       1680
C     OBLIQUE INCIDENCE, OUTSIDE BEAM:                                  1690
      X1 = -(Z*TAN(MUO)*TAN(NUO))/SQRT(1.+TAN(NUO)**2)                  1700
      Y1 = -(Z*TAN(MUO))/SQRT(1.+TAN(NUO)**2)                           1710
C     INTERMEDIATE EQNS: ABX,AYS,BXAY                                   1720
      ABX = (RAD**2)*(BB**2)*X1                                         1730
      AYS = (RAD**2)*Y1*SQRT((BB**2)*(X1**2)-(RAD**2)*(BB**2)+(RAD**2)*(1740
     1Y1**2))                                                           1750
      BXAY = (BB**2)*(X1**2)+(RAD**2)*(Y1**2)                           1760
      X21 = (ABX-AYS)/BXAY                                              1770
      X22 = (ABX+AYS)/BXAY                                              1780
      IF (X1.LT.RAD) GO TO 140                                          1790
      Y21 = BB*SQRT(1.-X21**2/RAD**2)                                   1800
      Y22 = BB*SQRT(1.-X22**2/RAD**2)                                   1810
      GO TO 145                                                         1820
  140 Y21 = -BB*SQRT(1.-X21**2/RAD**2)                                  1830
      Y22 = -BB*SQRT(1.-X22**2/RAD**2)                                  1840
  145 IF (NUO.NE.0.) GO TO 150                                          1850
      X4 = 0.                                                           1860
      X5 = 0.                                                           1870
      Y4 = -BB                                                          1880
      Y5 = BB                                                           1890
      GO TO 165                                                         1900
  150 CTNU = COTAN(NUO)                                                 1910
      CA = CTNU*(X1*CTNU-Y1)                                            1920
```

```
      CB = SQRT(BB**2*CTNU**2-(BB**2/RAD**2)*(Y1**2-BB**2+X1*CTNU*(X1*CT      1930
     1NU-2.*Y1)))                                                             1940
      CC = CTNU**2+BB**2/RAD**2                                               1950
      X4 = (CA-(SIN(NUO)/ABS(SIN(NUO)))*CB)/CC                                1960
      X5 = (CA+(SIN(NUO)/ABS(SIN(NUO)))*CB)/CC                                1970
      YY4 = BB*SQRT(1.-X4**2/RAD**2)                                          1980
      Y4SG = (X4-X1)*CTNU+Y1                                                  1990
      Y4 = SIGN(YY4,Y4SG)                                                     2000
      YY5 = BB*SQRT(1.-X5**2/RAD**2)                                          2010
      Y5SG = (X5-X1)*CTNU+Y1                                                  2020
      Y5 = SIGN(YY5,Y5SG)                                                     2030
      GO TO 165                                                               2040
C                                                                             2050
C     NORMAL INCIDENCE, OUTSIDE BEAM:                                         2060
  155 X1 = 0.                                                                 2070
      Y1 = -Z*TAN(MUO)                                                        2080
      X21 = -(RAD*SQRT(Y1**2-RAD**2)/Y1)                                      2090
      X22 = -X21                                                              2100
      Y21 = -RAD*SQRT(1.-X21**2/RAD**2)                                       2110
      Y22 = -RAD*SQRT(1.-X22**2/RAD**2)                                       2120
      IF (NUO.NE.0.) GO TO 160                                                2130
      X4 = 0.                                                                 2140
      X5 = 0.                                                                 2150
      Y4 = -RAD                                                               2160
      Y5 = RAD                                                                2170
      GO TO 165                                                               2180
  160 CTNU = COTAN(NUO)                                                       2190
      CNA = -Y1*CTNU                                                          2200
      CNB = SQRT(RAD**2*CTNU**2-Y1**2+RAD**2)                                 2210
      CNC = CTNU**2+1.                                                        2220
      X4 = (CNA-(SIN(NUO)/ABS(SIN(NUO)))*CNB)/CNC                             2230
      X5 = (CNA+(SIN(NUO)/ABS(SIN(NUO)))*CNB)/CNC                             2240
      YY4 = BB*SQRT(1.-X4**2/RAD**2)                                          2250
      Y4SGN = X4*CTNU+Y1                                                      2260
      Y4 = SIGN(YY4,Y4SGN)                                                    2270
      YY5 = BB*SQRT(1.-X5**2/RAD**2)                                          2280
      Y5SGN = X5*CTNU+Y1                                                      2290
      Y5 = SIGN(YY5,Y5SGN)                                                    2300
  165 B1 = SQRT((Y4-Y1)**2+(X4-X1)**2)                                        2310
      B2 = SQRT((Y5-Y1)**2+(X5-X1)**2)                                        2320
      DNU1 = ARCOS((Y1*(Y1-Y21)+X1*(X1-X21))/SQRT((X1**2+Y1**2)*((Y1-Y21      2330
     1)**2+(X1-X21)**2)))                                                     2340
      DNU2 = ARCOS((Y1*(Y1-Y22)+X1*(X1-X22))/SQRT((X1**2+Y1**2)*((Y1-Y22      2350
     1)**2+(X1-X22)**2)))                                                     2360
      MLL = ATAN(B2/Z)                                                        2370
      MLL = ATAN(B1/Z)                                                        2380
      NLL = NUO+DNU1                                                          2390
      NLL = NUO-DNU2                                                          2400
```

```
      GC TO 185                                                          2410
C                                                                        2420
C     CALCULATION OF INTEGRATION LIMITS FOR THE SURFACE PRCJECTION       2430
C     OF THE POINT OF OBSERVATION INSIDE THE BEAM:                       2440
C     REF 3: EQNS 13,14,43-45,71-77                                      2450
  17C X1 = -(Z*TAN(MUO)*TAN(NUO))/SQRT(1.+TAN(NUO)**2)                   2460
      Y1 = -(Z*TAN(MUO))/SQRT(1.+TAN(NUC)**2)                            2470
      IF ((NUO.EQ.0.).OR.(NUO.EQ.PI)) GC TO 175                          2480
      X6 = (COTAN(NUO)*(X1*COTAN(NUO)-Y1)+SQRT(BB**2*COTAN(NUO)**2-(BB** 2490
     12/RAD**2)*(Y1-BB**2+X1*COTAN(NUO)*(X1*COTAN(NUO)-2.*Y1))))/(CCTAN( 2500
     2NLC)**2+BB**2/RAD**2)                                              2510
      YY6 = BB*SQRT(1.-X6**2/RAD**2)                                     2520
      Y6SG = Y1+(X6-X1)*COTAN(NUO)                                       2530
      Y6 = SIGN(YY6,Y6SG)                                                2540
      GC TO 180                                                          2550
  175 Y6 = 0.                                                            2560
  18C B3 = SQRT((Y6-Y1)**2+(X6-X1)**2)                                   2570
      MUU = ATAN(B3/Z)                                                   2580
      MLL = 0.                                                           2590
      NLL = 2.*PI                                                        2600
      NUL = 0.                                                           2610
C                                                                        2620
C     PRATIO=POWER DENSITY RATIO                                         2630
C     CCMPUTED USING A TWO-POINT GAUSS-LEGENDRE QLADRATURE               2640
C     NUMERICAL INTEGRATICN SCHEME                                       2650
C     REF 3: EQN 53                                                      2660
C     REFS 14&15                                                         2670
C     CINT=CONSTANT DURING INTEGRATION                                   2680
  185 CINT = T*COS(WI)*(1./COS(WR))*PSLOPE*TAN(B)*(1./COS(B))**2*(1./JAC 2690
     1CB)*(((MUU-MUL)*(NUU-NUL))/4.)*CTF                                 2700
      ETAMU1 = ((MUU-MUL)*ETA1+MUU+MUL)/2.                               2710
      ETAMU2 = ((MUU-MUL)*ETA2+MUU+MUL)/2.                               2720
      XINU1 = ((NUU-NUL)*XI1+NUU+NUL)/2.                                 2730
      XINU2 = ((NUU-NUL)*XI2+NUU+NUL)/2.                                 2740
      FXT1 = COS(ETAMU1)*COS(MUO)+SIN(ETAMU1)*SIN(MUO)*COS(ABS(XINU1-NUO 2750
     1))                                                                 2760
      FXT2 = COS(ETAMU1)*COS(MUO)+SIN(ETAMU1)*SIN(MUO)*CCS(ABS(XINU2-NUO 2770
     1))                                                                 2780
      FXT3 = COS(ETAMU2)*COS(MUO)+SIN(ETAMU2)*SIN(MUO)*CCS(ABS(XINU2-NUO 2790
     1))                                                                 2800
      FXT4 = COS(ETAMU2)*COS(MUO)+SIN(ETAMU2)*SIN(MUO)*CCS(ABS(XINU1-NUO 2810
     1))                                                                 2820
      PRATIO = ABS(CINT*(FXT1+FXT2+FXT3+FXT4))                           2830
C                                                                        2840
      PWRDEN(J) = 10.*ALOG10(PRATIO*Z**2)                                2850
C     REF 2: PGS 65-67; FIG 34                                           2860
C                                                                        2870
C     CUTPUT INSTRUCTIONS                                                2880
```

```
C       CONVERT ALPHA,B,WI,WR FROM RADIANS TO DEGREES                          2890
        RDEG = 57.2958                                                         2900
        ALPHAD = ALPHA*RDEG                                                    2910
        BD = B*RDEG                                                            2920
        WID = WI*RDEG                                                          2930
        WRD = WR*RDEG                                                          2940
        WRITE (6,190) J,ALPHAD,BD,WID,WRD,T,JACOB,PSLOPE,PRATIO,PWRDEN(J),     2950
       1J,VALID,AXI,AETA                                                       2960
  190 FORMAT (1X,I2,1X,F7.2,1X,F7.2,1X,F7.2,1X,F7.2,1X,F7.4,1X,F7.4,1X,1      2970
       1PE11.4,1X,1PE11.4,1X,0PF8.2,2X,I2,5X,I2,3X,F4.1,1X,F4.1)               2980
C                                                                              2990
C       LOOP EXIT FOR LOW SLOPE PROBABILITY                                    3000
        IF ((PSLOPE.LT.1.E-20).AND.(PWRDEN(J).LT.PWRDEN(JJ)).AND.(J.GT.5))     3010
       1 GO TO 200                                                             3020
  195 CONTINUE                                                                 3030
C                                                                              3040
  200 CONTINUE                                                                 3050
        END                                                                    3060
```

```
C     FAR ZONE SOLUTION OF THE TIME-AVERAGE POWER PROBABILITY                  10
C     DISTRIBUTION BELOW THE OCEAN OF A LASER BEAM INCIDENT                    20
C     ON THE SURFACE                                                           30
C                                                                              40
C                                                                              50
C     NOMENCLATURE:                                                            60
C                                                                              70
C          PSI=ANGLE OF INCIDENT BEAM WITH RESPECT TO VERTICAL AXIS            80
C          CHI=ANGLE OF WIND WITH RESPECT TO THE INCIDENT BEAM IN              90
C              THE XY-PLANE                                                   100
C          ALPHA=ANGLE OF MAX WAVE SLOPE WITH RESPECT TO THE INCIDENT         110
C                BEAM IN THE XY-PLANE                                         120
C          B=MAX SLOPE OF WAVE FACET                                          130
C          NU=NUO=ANGLE BETWEEN REFRACTED RAY PROJECTED ONTO XY-PLANE         140
C                AND THE Y AXIS                                               150
C          MU=MUO=ANGLE BETWEEN REFRACTED RAY AND THE Z AXIS                  160
C          Z=DEPTH BELOW OCEAN SURFACE (METERS)                               170
C          RAD=INCIDENT RAY SPOT RADIUS AT WAVE FACET (MINOR AXIS OF          180
C              ELLIPSE WHEN PSI IS NON-ZERO)                                  190
C          BB=MAJOR AXIS OF SPOT INCIDENT ON WAVE FACET                       200
C          W=WIND VELOCITY (M/SEC)                                            210
C          WI=RAY INCIDENCE ANGLE                                             220
C          WR=RAY REFRACTION ANGLE                                            230
C          CTF=DIFFUSE TRANSMITTANCE FUNCTION                                 240
C          BS=BACKWARD SCATTERING COEFFICIENT                                 250
C          AC=ABSORBTION COEFFICIENT                                          260
C          T=FRESNEL'S TRANSMITTANCE FUNCTION                                 270
C          AN=INDEX OF REFRACTION                                             280
C          PSLOPE=SLOPE PROBABILITY FUNCTION                                  290
C          DAREA=AREA INCREMENT                                               300
C          JACOB=JACOBIAN                                                     310
C          PWRDEN=POWER DENSITY (DECIBELS)                                    320
C                                                                             330
      INTEGER VALID                                                           340
      REAL NUO,JMUO,JACOB,MUO,NUORUN                                          350
      COMMON MUO,NUO,PSI,AN,PSIRUN,NUORUN,PI,Z,RAD,BB,JK                      360
      DIMENSION W(3), CHI(3), NCHI(3), RG(4), JMUO(90), PWRDEN(90), PSIN      370
     1(10)                                                                    380
C                                                                             390
C     INPUT PARAMETERS:                                                       400
      DATA W,CHI,NCHI/14.,10.,5.,0.,1.5708,3.14159,0,90,180/                  410
      DATA PSIN/0.,10.,20.,30.,40.,50.,60.,70.,80.,84./                       420
      Z = 50.                                                                 430
      RAD = .2                                                                440
      PI = 3.141592654                                                        450
      AN = 1.33                                                               460
      NUORUN = 0.                                                             470
                                                                              480
```

```
      NLC = NLORUN/57.2958                                                    490
C                                                                             500
C     DIFFUSE TRANSMITTANCE FUNCTION (DTF)                                    510
C     REF 11: PG 65                                                           520
      BS = .065                                                               530
      AC = .044                                                               540
      FK = SQRT(AC*(AC+2.*BS))                                                550
      DTF = FK/((AC+BS)*SINH(FK*Z)+FK*COSH(FK*Z))                             560
C                                                                             570
C     PSI = 40 DEG                                                            580
      PSIRUN = PSIN(5)                                                        590
      PSI = PSIRUN/57.2958                                                    600
      BE = RAD*(1./COS(PSI))                                                  610
C                                                                             620
C     WIND DIRECTION CHI = 0 DEG                                              630
      L = 1                                                                   640
C                                                                             650
C     WIND=14 M/SEC                                                           660
      I = 1                                                                   670
C                                                                             680
C     OUTPUT PRINTING INSTRUCTIONS                                            690
C                                                                             700
      WRITE (6,105) Z,DTF,W(I),PSIRUN,RAD,NUORUN,CHI(L)                       710
  105 FORMAT (1H1,10X,'FAR ZONE SOLUTION',5X,'DEPTH=',F6.2,' M',5X,           720
     1 'DTF=',F8.5,5X,'WIND=',F4.1,' M/SEC'/11X,'PSI=',F4.1,' DEG',10X,       730
     2 'RAD=',F5.1,' M',8X,'VALID=1'/11X,'NUO=',F4.1,' DEG',10X,'CHI=',       740
     3 F4.1,' DEG',7X,'INVALID=0'///)                                         750
C                                                                             760
      WRITE (6,110)                                                           770
  110 FORMAT (1X,'MUO',2X,'ALPHA',5X,'B',6X,'WI',6X,'WR',6X,'T',5X,           780
     1 'JACOB',5X,'DAREA',6X,'PSLOPE',7X,'PRATIC',5X,'PWRDEN',1X,             790
     2 'MUO',2X,'VALIDITY',1X,'XI',3X,'ETA'/)                                 800
C                                                                             810
C     MUO VARIED FROM 1 TO 90 DEG MAX FOR PSI LESS THAN OR EQUAL              820
C     TO 30 DEG, AND FROM 15 TO 90 DEG MAX FOR PSI GREATER THAN 30 DEG:       830
C     MUO IN RADIANS; JMUO IN DEGREES                                         840
C     REF 3: EQNS 50,54,55,82,83                                              850
C                                                                             860
      DO 115 J=1,90                                                           870
      PWRDEN(J) = 0.                                                          880
  115 CONTINUE                                                                890
C                                                                             900
      IF (PSIRUN.GT.30.) GO TO 120                                            910
      INT = 1                                                                 920
      GO TO 125                                                               930
  120 INT = 15                                                                940
C                                                                             950
  125 DO 135 J=INT,90                                                         960
```

```
      JMLO(J) = FLOAT(J)                                                    970
      MLC = JMUO(J)/57.2958                                                 980
      JK = J                                                                990
      JL = J-6                                                             1000
C                                                                          1010
C     ALPHA,B,WI,WR ARE COMPUTED IN SUBROUTINE ANGLES:                     1020
C     REFS 2,3&4                                                           1030
      CALL ANGLES (ALPHA,B,WI,WR)                                          1040
C                                                                          1050
C     T=FRESNEL'S TRANSMITTANCE                                            1060
C     REFS 9&10                                                            1070
      TPER = (2.*COS(WI)*SIN(WR)/SIN(WI+WR))**2                            1080
      TPAR = (2.*COS(WI)*SIN(WR)/SIN(WI+WR)*COS(WI-WR))**2                 1090
      T = (TPAR+TPER)/2.                                                   1100
C                                                                          1110
C     JACOBIAN COMPUTED IN SUBROUTINE JACO                                 1120
C     REF 3: EQNS 48-52                                                    1130
      CALL JACO (ALPHA,B,JACOB)                                            1140
C                                                                          1150
C     AREA INCREMENT (DAREA) COMPUTED IN SUBROUTINE AREA                   1160
C     REF 3: EQNS 13,14,21-24,38,39,79,80                                  1170
      CALL AREA (DAREA)                                                    1180
C                                                                          1190
C     PSLOPE=SLOPE PROBIBILITY FUNCTION                                    1200
C     REF 5: EQNS 5-9,12-18                                                1210
      SIGC = SQRT(.003+1.92E-03*W(I))                                      1220
      SIGU = SQRT(3.16E-03*W(I))                                           1230
      C21 = .01-.0086*W(I)                                                 1240
      C03 = .04-.033*W(I)                                                  1250
      C40 = .4                                                             1260
      C22 = .12                                                            1270
      C04 = .23                                                            1280
      AP = ALPHA-CHI(L)                                                    1290
      ZXP = TAN(B)*SIN(AP)                                                 1300
      ZYP = TAN(B)*COS(AP)                                                 1310
      XI = ZXP/SIGC                                                        1320
      ETA = ZYP/SIGU                                                       1330
      FACT1 = (1./(2.*PI*SIGC*SIGU))*EXP(-.5*(XI**2+ETA**2))               1340
      FACT2 = 1.-.5*C21*(XI**2-1.)*ETA-(1./6.)*C03*(ETA**3-3.*ETA)         1350
      FACT3 = (1./24.)*C40*(XI**4-6.*XI**2+3.)+.25*C22*(XI**2-1.)*(ETA**   1360
     12-1.)                                                                1370
      FACT4 = (1./24.)*C04*(ETA**4-6.*ETA**2+3.)                           1380
      PSLOPE = FACT1*(FACT2+FACT3+FACT4)                                   1390
C                                                                          1400
C     VALIDITY CHECK (VALID=1; INVALID=0) ON SLOPE PROBABILITY             1410
      AXI = ABS(XI)                                                        1420
      AETA = ABS(ETA)                                                      1430
      VALID = 1                                                            1440
```

```
      IF ((AXI.GT.2.5).OR.(AETA.GT.2.5)) VALID=0                        1450
C                                                                       1460
C     PRATIO=POWER DENSITY RATIO                                        1470
C     REFS 2,3&4                                                        1480
      PRATIO = ABS(DTF*T*TAN(B)*((1./CCS(B))**2)*COS(WI)*(1./CCS(WR))*PS 1490
     1LCPE*CAREA/JACOB)                                                 1500
C                                                                       1510
      PWRDEN(J) = 10.*ALOG10(PRATIO*Z**2)                               1520
C     REF 2: PGS 65-67; FIG 34                                          1530
C                                                                       1540
C     CUTPUT INSTRUCTIONS                                               1550
C     CONVERT ALPHA,B,WI,WR FROM RADIANS TO DEGREES                     1560
      RDEG = 57.2958                                                    1570
      ALPHAD = ALPHA*RDEG                                               1580
      BD = B*RDEG                                                       1590
      WID = WI*RDEG                                                     1600
      WRD = WR*RDEG                                                     1610
      WRITE (6,130) J,ALPHAD,BD,WID,WRD,T,JACOB,CAREA,PSLCPE,PRATIO,PWRD 1620
     1EN(J),J,VALID,AXI,AETA                                            1630
  130 FORMAT (1X,I2,1X,F7.2,1X,F7.2,1X,F7.2,1X,F7.2,1X,F7.4,1X,F7.4,1X,1 1640
     1PE11.4,1X,1PE11.4,1X,1PE11.4,1X,0PF8.2,2X,I2,5X,I2,3X,F4.1,1X,F4.1 1650
     2)                                                                 1660
C                                                                       1670
C     LOOP EXIT FOR LOW SLOPE PROBABILITY                               1680
      IF ((PSLCPE.LT.1.E-40).AND.(PWRDEN(J).LT.PWRDEN(JJ)).AND.(J.GT.5)) 1690
     1 GO TO 140                                                        1700
  135 CONTINUE                                                          1710
C                                                                       1720
  140 CONTINUE                                                          1730
      END                                                               1740
```

```
      SUBROUTINE ANGLES (ALPHA,B,WI,WR)                                    10
C                                                                          20
C     SUBROUTINE ANGLES SOLVES FOR ALPHA,B,WI&WR GIVEN PSI,NUO,MUO&AN      30
C                                                                          40
      EXTERNAL FINDAB,FINDB                                                50
      REAL NUO,MUO,NUORUN                                                  60
      COMMON MUO,NUO,PSI,AN,PSIRUN,NUORUN,PI,Z,RAD,BB,JK                   70
      DIMENSION Q(2), Y(1)                                                 80
      IF (PSIRUN.EQ.0.) GO TO 230                                          90
      IF (NUORUN.EQ.0.) GO TO 215                                         100
C                                                                         110
C     SOLUTION FOR PSI&NUO NON-ZERO:                                      120
C     ALPHA & B FOR A GIVEN MUO & NUO ARE OBTAINED BY SOLVING             130
C     SIMULTANEOUS NON-LINEAR EQNS 82&83 OF REF 3 USING IBM SOURCE        140
C     LIB SUBROUTINE (NLNSYS)                                             150
C                                                                         160
C     FIRST ESTABLISH INITIAL GUESS FOR NLNSYS                            170
      IF ((JK.EQ.1).OR.((JK.EQ.15).AND.(PSIRUN.GT.30.))) GO TO 205        180
      Q(1) = ALPHA                                                        190
      Q(2) = B                                                            200
      GO TO 210                                                           210
  205 Q(1) = .1                                                           220
      Q(2) = .1                                                           230
  210 CALL NLNSYS (2,10,4,ISING,1,FINDAB,Q)                               240
      ALPHA = Q(1)                                                        250
      B = Q(2)                                                            260
      WI = ARCOS(COS(PSI)*COS(B)-SIN(PSI)*COS(ALPHA)*SIN(B))              270
      WR = ARCOS((1./AN)*SQRT(COS(WI)**2+AN**2-1.))                       280
      GO TO 235                                                           290
C                                                                         300
C     SOLUTION FOR PSI NON-ZERO & NUO=0.0:                                310
  215 ALPHA = 0.                                                          320
C     B SOLVED FROM NON-LINEAR EQN 82 OF REF 3 USING IBM SOURCE LIB       330
C     SUBROUTINE (NLNSYS);  FIRST ESTABLISH INITIAL  B GUESS              340
      IF ((JK.EQ.1).OR.((JK.EQ.15).AND.(PSIRUN.GT.30.))) GO TO 220        350
      Y(1) = B                                                            360
      GO TO 225                                                           370
  220 Y(1) = .1                                                           380
  225 CALL NLNSYS (1,10,4,ISING,1,FINDB,Y)                                390
      B = Y(1)                                                            400
      WI = ARCOS(COS(PSI)*COS(B)-SIN(PSI)*SIN(B))                         410
      WR = ARCOS((1./AN)*SQRT(COS(WI)**2+AN**2-1.))                       420
      GO TO 235                                                           430
C                                                                         440
C     SOLUTION FOR PSI=0.0:                                               450
  230 ALPHA = NUO                                                         460
      B = ATAN((AN*SIN(MUO))/(AN*COS(MUO)-1.))                            470
      WI = B                                                              480
```

```
      WR = ARSIN((1./AN)*SIN(B))                                        490
C                                                                       500
  235 RETURN                                                            510
      END                                                               520
```

```
      SUBROUTINE FINDAB (Q,F,K)                                                 10
C                                                                               20
C     SUBROUTINE USED BY NLNSYS FOR COMPUTING THE (ALPHA&B) PAIR                30
C                                                                               40
C                    Q(1)=ALPHA                                                 50
C                    Q(2)=B                                                     60
C                                                                               70
      REAL MUO,NUO,NUORUN                                                       80
      COMMON MUO,NUO,PSI,AN,PSIRUN,NUORUN,PI,Z,RAD,BB,JK                        90
      DIMENSION Q(2)                                                           100
      IF (K.EQ.1) GO TO 305                                                    110
      GO TO 310                                                                120
C                                                                              130
  305 F = -COS(MUO)+(1./AN)*(COS(PSI)+(SIN(PSI)*COS(Q(1))*SIN(Q(2))-COS(       140
     1PSI)*COS(Q(2))+SQRT((SIN(PSI)*COS(Q(1))*SIN(Q(2))-COS(PSI)*COS(Q(2      150
     2)))**2+AN**2-1.))*COS(Q(2)))                                             160
      GO TO 315                                                                170
C                                                                              180
  310 F = -COTAN(NUO)+COTAN(Q(1))-SIN(PSI)/(SIN(Q(1))*SIN(Q(2))*(SIN(PSI       190
     1)*COS(Q(1))*SIN(Q(2))-COS(PSI)*COS(Q(2))+SQRT((SIN(PSI)*COS(Q(1))*       200
     2SIN(Q(2))-COS(PSI)*COS(Q(2)))**2+AN**2-1.)))                             210
C                                                                              220
  315 RETURN                                                                   230
      END                                                                      240
```

```
      SUBROUTINE FINDB (Y,F,K)                                                  10
C                                                                               20
CC    SUBROUTINE FINDB USED BY NLNSYS FOR COMPUTING B;   B=Y(1)                 30
C                                                                               40
      REAL MUO,NUO,NUORUN                                                       50
      COMMON MUO,NUO,PSI,AN,PSIRUN,NUORUN,PI,Z,RAD,BB,JK                        60
      DIMENSION Y(1)                                                            70
      SPSI = SIN(PSI)                                                           80
      CPSI = COS(PSI)                                                           90
C                                                                              100
      F = -COS(MUO)+(1./AN)*(CPSI+(SPSI*SIN(Y(1))-CPSI*COS(Y(1))+SQRT((S       110
     1PSI*SIN(Y(1))-CPSI*COS(Y(1)))**2+AN**2-1))*COS(Y(1)))                     120
C                                                                              130
      RETURN                                                                   140
      END                                                                      150
```

```
      SUBROUTINE JACO (ALPHA,B,JACOB)                                          10
C                                                                              20
C     SUBROUTINE JACO COMPUTES THE JACOBIAN FOR NORMAL & OBLIQUE               30
C     INCIDENCE.                                                               40
C                                                                              50
      REAL JACOB,MUO,NUO,NUORUN                                                60
      COMMON MUO,NUO,PSI,AN,PSIRUN,NUORUN,PI,Z,RAD,BB,JK                       70
      IF (PSIRUN.EQ.0.) GO TO 505                                              80
C                                                                              90
C     JACOBIAN FOR OBLIQUE INCIDENCE:                                         100
      AKK = SQRT((SIN(PSI)*COS(ALPHA)*SIN(B)-COS(PSI)*COS(B))**2+AN**2-1      110
     1.)                                                                      120
      SK = (SIN(PSI)*COS(ALPHA)*SIN(B)-COS(PSI)*COS(B))+AKK                    130
      DKDA = ((SIN(PSI)*SIN(ALPHA)*SIN(B)*(COS(PSI)*COS(B)-SIN(PSI)*COS(      140
     1ALPHA)*SIN(B)))/AKK)-SIN(PSI)*SIN(ALPHA)*SIN(B)                         150
      DKDB = (((SIN(PSI)*COS(ALPHA)*SIN(B)-COS(PSI)*COS(B))*(SIN(PSI)*CO      160
     1S(ALPHA)*COS(B)+COS(PSI)*SIN(B)))/AKK)+(SIN(PSI)*COS(ALPHA)*COS(B)      170
     2+COS(PSI)*SIN(B))                                                       180
      D = ((SK*SIN(ALPHA)*SIN(B))**2+(SK*COS(ALPHA)*SIN(B)-SIN(PSI))**2)      190
     1*SQRT(AN**2-(COS(PSI)+SK*COS(B))**2)                                    200
      JACOB = ABS((1./D)*((COS(B)*SIN(ALPHA)*SIN(PSI)*DKDA)*(DKDB*SIN(B)      210
     1+SK*COS(B))+(DKDB*COS(B)-SK*SIN(B))*((SK*SIN(B))**2-(SIN(PSI)*SIN(      220
     2B))*(DKDA*SIN(ALPHA)+SK*COS(ALPHA)))))                                  230
      GO TO 510                                                                240
C                                                                              250
C     JACOBIAN FOR NORMAL INCIDENCE:                                           260
  505 AK = -COS(B)+SQRT(COS(B)**2+AN**2-1.)                                    270
      DKDB = SIN(B)*(1.-(COS(B)/SQRT(COS(B)**2+AN**2-1.)))                     280
      JACOB = ABS((1./SQRT(AN**2-(1.+AK*COS(B))**2))*(DKDB*COS(B)-AK*SIN       290
     1(B)))                                                                   300
C                                                                              310
  510 RETURN                                                                   320
      END                                                                      330
```

```
      SUBROUTINE AREA (DAREA)                                                  10
C                                                                              20
C     SUBROUTINE AREA COMPUTES THE AREA INCREMENT (DAREA) FOR                  30
C     NORMAL & OBLIQUE INCIDENCE.                                              40
C                                                                              50
      REAL MUO,NUO,NUORUN                                                      60
      COMMON MUO,NUO,PSI,AN,PSIRUN,NUORUN,PI,Z,RAD,BB,JK                       70
      CALL ERRSET (251,500,-1,1)                                               80
      IF (PSIRUN.EQ.0.) GO TO 625                                              90
C                                                                             100
C     DAREA FOR OBLIQUE INCIDENCE:                                            110
      X1 = -(Z*TAN(MUO)*TAN(NUO))/SQRT(1.+TAN(NUO)**2)                        120
      Y1 = -(Z*TAN(MUO))/SQRT(1.+TAN(NUO)**2)                                 130
C     INTERMEDIATE EQNS: ABX,AYS,BXAY                                         140
      ABX = (RAD**2)*(BB**2)*X1                                               150
      AYS = (RAD**2)*Y1*SQRT((BB**2)*(X1**2)-(RAD**2)*(BB**2)+(RAD**2)*(      160
     1Y1**2))                                                                 170
      BXAY = (BB**2)*(X1**2)+(RAD**2)*(Y1**2)                                 180
      X21 = (ABX-AYS)/BXAY                                                    190
      X22 = (ABX+AYS)/BXAY                                                    200
      IF (X1.LT.RAD) GO TO 605                                                210
      Y21 = BB*SQRT(1.-X21**2/RAD**2)                                         220
      Y22 = BB*SQRT(1.-X22**2/RAD**2)                                         230
      GO TO 610                                                               240
  605 Y21 = -BB*SQRT(1.-X21**2/RAD**2)                                        250
      Y22 = -BB*SQRT(1.-X22**2/RAD**2)                                        260
  610 IF (NUO.NE.0.) GO TO 615                                                270
      X4 = 0.                                                                 280
      X5 = 0.                                                                 290
      Y4 = -BB                                                                300
      Y5 = BB                                                                 310
      GO TO 620                                                               320
  615 CTNU = COTAN(NUO)                                                       330
      CA = CTNU*(X1*CTNU-Y1)                                                  340
      CB = SQRT(BB**2*CTNU**2-(BB**2/RAD**2)*(Y1**2-BB**2+X1*CTNU*(X1*CT      350
     1NU-2.*Y1)))                                                             360
      CC = CTNU**2+BB**2/RAD**2                                               370
      X4 = (CA-(SIN(NUO)/ABS(SIN(NUO)))*CB)/CC                                380
      X5 = (CA+(SIN(NUO)/ABS(SIN(NUO)))*CB)/CC                                390
      YY4 = BB*SQRT(1.-X4**2/RAD**2)                                          400
      Y4SG = (X4-X1)*CTNU+Y1                                                  410
      Y4 = SIGN(YY4,Y4SG)                                                     420
      YY5 = BB*SQRT(1.-X5**2/RAD**2)                                          430
      Y5SG = (X5-X1)*CTNU+Y1                                                  440
      Y5 = SIGN(YY5,Y5SG)                                                     450
  620 C1 = SQRT((Y5-Y1)**2+(X5-X1)**2)/Z                                      460
      C2 = SQRT((Y4-Y1)**2+(X4-X1)**2)/Z                                      470
      C3 = (Y1*(Y1-Y21)+X1*(X1-X21))/SQRT((X1**2+Y1**2)*((Y1-Y21)**2+(X1      480
```

```
     1-X21)**2))                                                                490
      C4 = (Y1*(Y1-Y22)+X1*(X1-X22))/SQRT((X1**2+Y1**2)*((Y1-Y21)**2+(X1        500
     1-X21)**2))                                                                510
      IF (C3.GT.1.0) C3 = 1.0                                                   520
      IF (C4.GT.1.0) C4 = 1.0                                                   530
      CAREA = ((PI/4.)*(ATAN(C1)-ATAN(C2)))*(ARCOS(C3)+ARCOS(C4))               540
      GO TO 640                                                                 550
C                                                                               560
C     CAREA FOR NORMAL INCIDENCE:                                               570
  625 X1 = 0.                                                                   580
      Y1 = -Z*TAN(MUO)                                                          590
      X21 = -(RAD*Y1*SQRT(Y1**2-RAD**2))/Y1**2                                  600
      X22 = -X21                                                                610
      Y21 = -RAD*SQRT(1.-X21**2/RAD**2)                                         620
      Y22 = -RAD*SQRT(1.-X22**2/RAD**2)                                         630
      IF (NUO.NE.0.) GO TO 630                                                  640
      X4 = 0.                                                                   650
      X5 = 0.                                                                   660
      Y4 = -RAD                                                                 670
      Y5 = RAD                                                                  680
      GO TO 635                                                                 690
  630 CTNU = COTAN(NUO)                                                         700
      CNA = -Y1*CTNU                                                            710
      CNB = SQRT(ABS(RAD**2*CTNU**2-Y1**2+RAD**2))                              720
      CNC = CTNU**2+1.                                                          730
      X4 = (CNA-(SIN(NUO)/ABS(SIN(NUO)))*CNB)/CNC                               740
      X5 = (CNA+(SIN(NUO)/ABS(SIN(NUO)))*CNB)/CNC                               750
      YY4 = BB*SQRT(1.-X4**2/RAD**2)                                            760
      Y4SGN = X4*CTNU+Y1                                                        770
      Y4 = SIGN(YY4,Y4SGN)                                                      780
      YY5 = BB*SQRT(1.-X5**2/RAD**2)                                            790
      Y5SGN = X5*CTNU+Y1                                                        800
      Y5 = SIGN(YY5,Y5SGN)                                                      810
  635 C1 = SQRT((Y5-Y1)**2+(X5-X1)**2)/Z                                        820
      C2 = SQRT((Y4-Y1)**2+(X4-X1)**2)/Z                                        830
      C3 = (Y1*(Y1-Y21)+X1*(X1-X21))/SQRT((X1**2+Y1**2)*((Y1-Y21)**2+(X1        840
     1-X21)**2))                                                                850
      C4 = (Y1*(Y1-Y22)+X1*(X1-X22))/SQRT((X1**2+Y1**2)*((Y1-Y21)**2+(X1        860
     1-X21)**2))                                                                870
      IF (C3.GT.1.0) C3 = 1.0                                                   880
      IF (C4.GT.1.0) C4 = 1.0                                                   890
      CAREA = ((PI/4.)*(ATAN(C1)-ATAN(C2)))*(ARCOS(C3)+ARCOS(C4))               900
C                                                                               910
  640 RETURN                                                                    920
      END                                                                       930
```

```
      SUBROUTINE NLNSYS(N,MAXIT,NUMSIG,ISING,IPRINT,EVALUT,X)          NLNS1430
C                                                                      NLNS1440
C     NLNSYS SOLVES A SYSTEM OF SIMULTANEOUS NON-LINEAR EQUATIONS
C     NLNSYS IS FROM THE IBM SYSTEM 360 SUBROUTINE LIBRARY
C
      DIMENSION X(1)                                                   NLNS1450
      INTEGER CONVRG,TALLY,PONTER                                      NLNS1460
      COMMON/SSSS/ISUB(19),COE(20,21),PONTER(20,20)                    NLNS1470
      EXTERNAL EVALUT                                                  NLNS1480
      DIMENSION TEMP(20),PART(20)                                      NLNS1490
C                                                                      NLNS1500
      CONVRG=1                                                         NLNS1510
C        INITIALIZE CONVERGENCE AND TOLERANCE DETERMINERS.             NLNS1520
      ISING=0                                                          NLNS1530
      RELCON=10.**(-NUMSIG)                                            NLNS1540
C        ITERATION LOOP.                                               NLNS1550
      DO 55 M=1,MAXIT                                                  NLNS1560
C        PROGRAM WILL PRINT OUT SUCCESSIVE APPROXIMATIONS OF X IF      NLNS1570
C        IPRINT IS 0.                                                  NLNS1580
      IF (IPRINT.EQ.0) WRITE (6,1000) M,(X(I),I=1,N)                   NLNS1590
 1000 FORMAT(1X,12HON ITERATION,I4,17HTHE X ESTIMATE IS,5F15.7/7F15.7/ NLNS1600
     1       7F15.7///)                                               NLNS1610
C        INITIALIZE FIRST ROW OF ARRAY WHICH ENABLES INDEXING TO PIVOT NLNS1620
C        THROUGH THE VARIABLES WITHOUT INTERCHANGING ROWS OR COLUMNS.   NLNS1630
      DO 5 J=1,N                                                       NLNS1640
    5 PONTER(1,J)=J                                                    NLNS1650
C        ONE K FOR EACH EQUATION.                                      NLNS1660
      DO 40 K=1,N                                                      NLNS1670
C        IF K IS GREATER THAN 1 BACK-SUBSTITUTION IS NECESSARY.        NLNS1680
      IF (K.GT.1) CALL BAKSUB(K,N,X)                                   NLNS1690
      CALL EVALUT(X,F,K)                                               NLNS1700
      FACTOR=.001                                                      NLNS1710
    7 TALLY=0                                                          NLNS1720
      DO 10 I=K,N                                                      NLNS1730
      ITEMP=PONTER(K,I)                                                NLNS1740
      HOLD=X(ITEMP)                                                    NLNS1750
C        GET INCREMENT TO OBTAIN ITEMP'TH PARTIAL.                     NLNS1760
      H=FACTOR*HOLD                                                    NLNS1770
      IF (H.EQ.0.) H=.001                                              NLNS1780
      X(ITEMP)=HOLD+H                                                  NLNS1790
C        IF K IS GREATER THAN 1, A NEW X(ITEMP) VALUE WILL AFFECT X'S  NLNS1800
C        WHICH ARE EXPRESSED IN TERMS OF IT AS A RESULT OF PREVIOUS    NLNS1810
C        EQUATION STEPS.                                               NLNS1820
      IF (K.GT.1) CALL BAKSUB(K,N,X)                                   NLNS1830
      CALL EVALUT(X,FPLUS,K)                                           NLNS1840
C        GET ITEMP'TH PARTIAL.                                         NLNS1850
      PART(ITEMP)=(FPLUS-F)/H                                          NLNS1860
      X(ITEMP)=HOLD                                                    NLNS1870
```

```
C          IF PARTIAL IS TOO SMALL, INCREASE TALLY.'                          NLNS1880
      IF(ABS(PART(ITEMP)).EQ.0) GO TO 9                                       NLNS1890
      IF(ABS(F/PART(ITEMP)).GT.1.0E20) TALLY=TALLY+1                          NLNS1891
      GO TO 10                                                                NLNS1892
    9 TALLY=TALLY+1                                                           NLNS1893
   10 CONTINUE                                                                NLNS1910
      IF (TALLY.LE.(N-K)) GO TO 15                                            NLNS1920
      FACTOR=FACTOR*10.0                                                      NLNS1930
C          IF SURFACE IS TOO FLAT, THE SINGULARITY INDICATOR IS SET TO        NLNS1940
C          ZERO AND RETURN IS EXECUTED.                                       NLNS1950
      IF (FACTOR.GT..5) GO TO 65                                              NLNS1960
      GO TO 7                                                                 NLNS1970
   15 IF(K.LT.N) GO TO 20                                                     NLNS1980
C          IF LAST PARTIAL IS ZERO, A SINGULARITY IS INDICATED AND A          NLNS1990
C          RETURN EXECUTED.                                                   NLNS2000
      IF (ABS(PART(ITEMP)).EQ.0.) GO TO 65                                    NLNS2010
      COE(K,N+1)=0                                                            NLNS2020
      KMAX=ITEMP                                                              NLNS2030
      GO TO 40                                                                NLNS2040
   20 KMAX=PONTER(K,K)                                                        NLNS2050
      DERMAX=ABS(PART(KMAX))                                                  NLNS2060
      KPLUS=K+1                                                               NLNS2070
C          GET INDEX FOR LARGEST PARTIAL IN K'TH EQUATION.                    NLNS2080
      DO 30 I=KPLUS,N                                                         NLNS2090
      JSUB=PONTER(K,I)                                                        NLNS2100
      TEST=ABS(PART(JSUB))                                                    NLNS2110
      IF (TEST.LT.DERMAX) GO TO 25                                            NLNS2120
      DERMAX=TEST                                                             NLNS2130
C          DEFINE PIVOT TO SWIVEL ABOUT THE VARIABLE WITH MAXIMUM PARTIAL     NLNS2140
C          WHEN WE GET TO THE NEXT EQUATION.                                  NLNS2150
      PONTER(KPLUS,I)=KMAX                                                    NLNS2160
C          IF THIS PARTIAL IS BIGGER, WE HAVE A NEW MAXIMUM.                  NLNS2170
      KMAX=JSUB                                                               NLNS2180
      GO TO 30                                                                NLNS2190
   25 PONTER(KPLUS,I)=JSUB                                                    NLNS2200
   30 CONTINUE                                                                NLNS2210
C          IF THAT PARTIAL IS 0, INDICATE A SINGULARITY AND RETURN.           NLNS2220
      IF (ABS(PART(KMAX)).EQ.0) GO TO 65                                      NLNS2230
      ISUB(K)=KMAX                                                            NLNS2240
      COE(K,N+1)=0                                                            NLNS2250
      DO 35 J=KPLUS,N                                                         NLNS2260
      JSUB=PONTER(KPLUS,J)                                                    NLNS2270
C          SAVE THESE CONSTANTS FOR FUTURE USE.                               NLNS2280
      COE(K,JSUB)=-PART(JSUB)/PART(KMAX)                                      NLNS2290
C          GET PART OF EXPRESSION FOR THE NEW X(KMAX) VALUE                   NLNS2300
   35 COE(K,N+1)=COE(K,N+1)+PART(JSUB)*X(JSUB)                                NLNS2310
   40 COE(K,N+1)=(COE(K,N+1)-F)/PART(KMAX)+X(KMAX)                            NLNS2320
C          IF N IS 1, WE HAVE OUR SOLUTION IN THE NEXT STEP WITHOUT ANY       NLNS2330
```

```
C          BACK-SUBSTITUTING.                                                    NLNS2340
      X(KMAX)=COE(N,N+1)                                                        NLNS2350
C          FOR N GREATER THAN 1, WE PERFORM A FINAL BACK-SUBSTITUTION TO         NLNS2360
C          GET OUR NEW X-VECTOR.                                                 NLNS2370
      IF (N.GT.1) CALL BAKSUB(N,N,X)                                            NLNS2380
      IF (M.EQ.1) GO TO 50                                                      NLNS2390
      DO 43 I=1,N                                                               NLNS2400
C          TEST FOR CONVERGENCE.                                                 NLNS2410
      IF (ABS((TEMP(I)-X(I))/X(I)).GT.RELCON) GO TO 45                          NLNS2420
   43 CONTINUE                                                                  NLNS2430
      CONVRG=CONVRG+1                                                           NLNS2440
C          IF IT CONVERGES, RETURN WITH LAST VECTOR.                             NLNS2450
      IF (CONVRG.GE.3) GO TO 60                                                 NLNS2460
      GO TO 50                                                                  NLNS2470
   45 CONVRG=0                                                                  NLNS2480
C          SAVE CURRENT X-VECTOR FOR TESTING WITH NEXT X-VECTOR.                 NLNS2490
   50 DO 55 I=1,N                                                               NLNS2500
   55 TEMP(I)=X(I)                                                              NLNS2510
C          IF M IS THE ITERATION LIMIT, RETURN.                                  NLNS2520
      GO TO 70                                                                  NLNS2530
   60 MAXIT=M                                                                   NLNS2540
      GO TO 70                                                                  NLNS2550
   65 ISING=1                                                                   NLNS2560
   70 RETURN                                                                    NLNS2570
      END                                                                       NLNS2580
```

```
      SUBROUTINE BAKSUB(K,N,X)                                          BKSB2600
C
C        THIS SUBROUTINE BACK-SUBSTITUTES OR UPDATES VARIABLES WHICH ARE BKSB2610
C        FUNCTIONS OF CURRENT X ENTRY VALUES.                           BKSB2620
C     BAKSUB IS PART OF THE NLNSYS ROUTINE.
C
      DIMENSION X(1)                                                    BKSB2630
      INTEGER PONTER                                                    BKSB2640
      COMMON/SSSS/ISUB(19),COE(20,21),PONTER(20,20)                     BKSB2650
C                                                                       BKSB2660
      DO 10 KMM=2,K                                                     BKSB2670
      KM=K+2-KMM                                                        BKSB2680
      KMAX=ISUB(KM-1)                                                   BKSB2690
      X(KMAX)=0.                                                        BKSB2700
      DO 5 J=KM,N                                                       BKSB2710
      JSUB=PONTER(KM,J)                                                 BKSB2720
C        SEE (3) FOR THE EXPRESSION FOR X(KMAX).                        BKSB2730
    5 X(KMAX)=X(KMAX)+COE(KM-1,JSUB)*X(JSUB)                            BKSB2740
   10 X(KMAX)=X(KMAX)+COE(KM-1,N+1)                                     BKSB2750
      RETURN                                                            BKSB2760
      END                                                               BKSB2770
```

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