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A PHYSICAL OPTICS APPROACH TO THE ELECTROMAGNETIC FIELD SCATTER--ETC(U)

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Contract No. N60530-76-C-0186, Dtd. Nov. 1977

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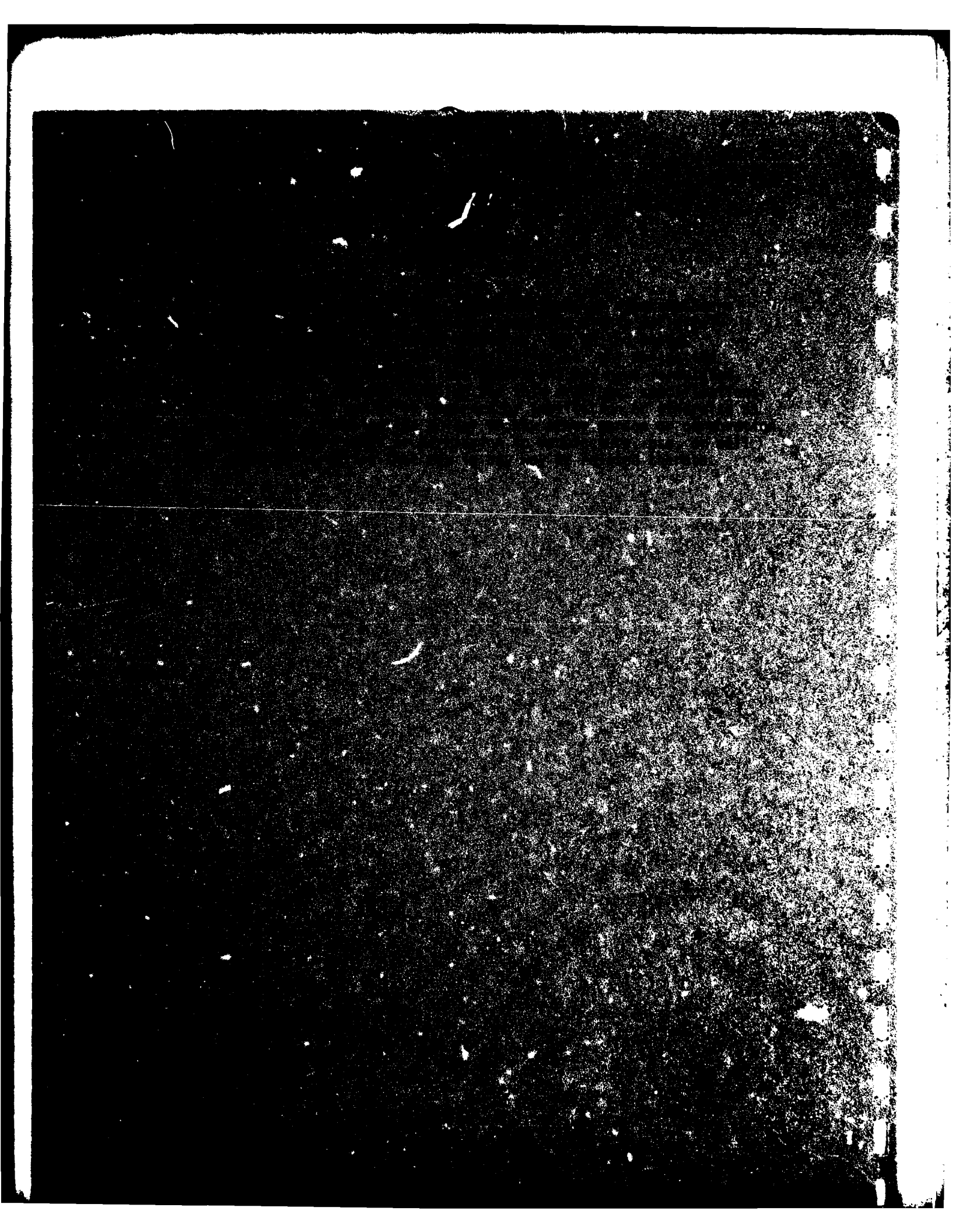
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1 REPORT NUMBER	2 GOVT ACCESSION NO	3 RECIPIENT'S CATALOG NUMBER
4 TITLE (and Subtitle) A PHYSICAL OPTICS APPROACH TO THE ELECTRO- MAGNETIC FIELD SCATTERED BY SIMPLIFIED SHIP-SEA MODELS		5 TYPE OF REPORT & PERIOD COVERED Technical
7 AUTHOR(s) Daniel J. Ryan		6 PERFORMING ORG. REPORT NUMBER ESL (78)4428-2
9 PERFORMING ORGANIZATION NAME AND ADDRESS The Ohio State University ElectroScience Laboratory, Department of Electrical Engineering Columbus, Ohio 43212		8 CONTRACT OR GRANT NUMBER(s) N60530-76-C-0186
11 CONTROLLING OFFICE NAME AND ADDRESS Department of the Navy, Supply Officer, Code 2524 Naval Weapons Center China Lake, California 83555		10 PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project 3310-0421-76
14 MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12 REPORT DATE November 1977
		13 NUMBER OF PAGES 63
		15 SECURITY CLASS. (of this report) Unclassified
		15a DECLASSIFICATION/DOWNGRADING SCHEDULE
16 DISTRIBUTION STATEMENT (of this Report)		
<div style="border: 1px solid black; padding: 5px; width: fit-content; margin: auto;"> <p>DISTRIBUTION STATEMENT A Approved for public release; Distribution Unlimited</p> </div>		
17 DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18 SUPPLEMENTARY NOTES		
19 KEY WORDS (Continue on reverse side if necessary and identify by block number)		
Composite model	Backscattered field	Geometrical Theory
Physical optics	Gravity waves	of Diffraction
One-dimensional model	Capillary waves	
Ship-sea corner	Cylindrical surface	
20 ABSTRACT (Continue on reverse side if necessary and identify by block number)		
<p>A technique is presented to calculate the backscattered field from a simplified ship-sea model with the sea represented by a one-dimensional composite surface, and the ship by a flat plate. The physical optics approximation was used to obtain an expression for the received voltage as a single integral over the profile of the surface. Four principle scattering mechanisms of the model were examined independently to show their effect on the radar return. A composite signature was then</p>		

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calculated for several model geometries. The calculated signatures were compared with measured signatures and good agreement was obtained. In all signatures the ship model return could be distinguished from the return due to the other scattering mechanisms.

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ACKNOWLEDGMENTS

The author wishes to express his sincere gratitude to Professor William H. Peake, the author's graduate advisor and project supervisor, for his help and guidance throughout this work. Special thanks are also extended to Dr. W. D. Burnside and Mr. John Huang for their patience and helpful suggestions and to Dr. L. Peters, Jr. for his reading of the manuscript. The assistance and cooperation of all the people at the ElectroScience Laboratory is greatly appreciated.

The work reported in this thesis was supported in part by Contract N60530-76-C-0186 between Naval Weapons Center, China Lake, California, and The Ohio State University Research Foundation.

The material contained in this report is also used as a thesis submitted to the Department of Electrical Engineering, The Ohio State University as partial fulfillment for the degree Master of Science.

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CHAPTER I INTRODUCTION

In past years, research has provided a great deal of information about the mechanics of scattering of an electromagnetic field from the sea surface. Much of this work has been motivated by the problem of detection of ships at sea. This report uses a simplified ship-sea model to obtain some insight into the interaction between the sea and a ship when they are illuminated with a radar signal.

The simplified sea model used in this report is a one-dimensional composite model developed during a previous study [1,2], in which the method of moments and physical optics were used to calculate the scattering from the surface.

This report expands on this previous work by adding a metal flap to represent a simplified model for the ship. Since this combined ship-sea model is too large for the method of moments approach, this report further develops the physical optics approach to study the scattered fields. The first section describes the surface and sets up the geometry of the model. Then a general equation for bistatic scattering from the composite surface is developed. The subsequent sections treat in detail the principal scattering mechanisms, namely; scattering directly back from the composite surface; scattering from the surface-flap corner; and scattering from the edge of the flap. In this report, only horizontal polarization is considered.

CHAPTER 11
COMPOSITE SEA SURFACE - SHIP MODEL

The purpose of this section is to describe a simplified one-dimensional model for a ship on the ocean. The ocean is represented by a composite surface made of aluminum roofing. A large scale sinusoid is used to model the gravity waves, and small trapezoids superimposed on the sinusoid are used to model the capillary waves. The ship is modeled by a flat metal plate placed at one end of the model sea surface, (see Figure 1-1).

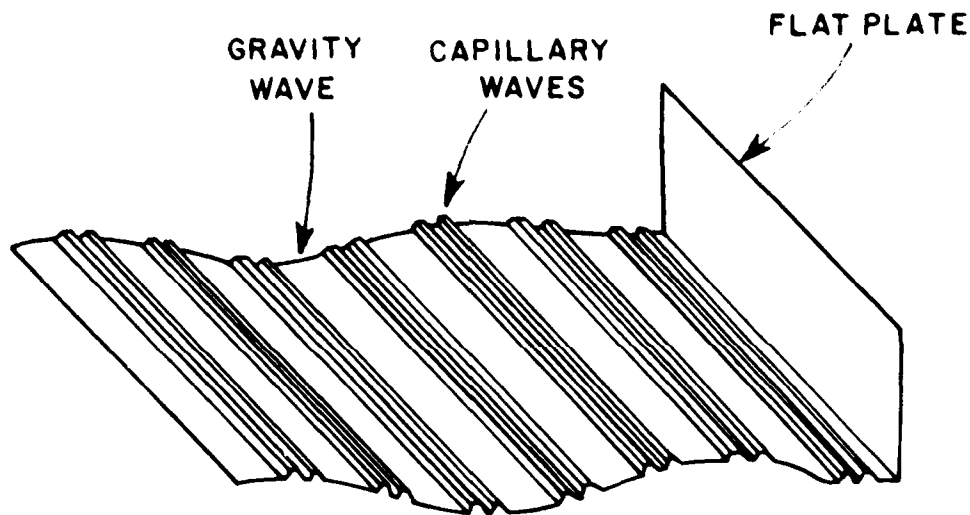


Figure 1-1. Composite sea surface-ship model.

For the actual surface, designed to simulate the sea surface at S-band, the sinusoidal gravity waves have a peak-to-peak height of 3.5 in., and a mechanical wavelength of 4.1 ft. This provides a mean square slope of about 10° , representing a relatively calm sea (Figure 1-2). The modeled capillary waves are double trapezoids each one 3 cm long and separated by 1 cm (see Figure 1-3), recurring every 20 cm along the sinusoids. This composite surface model can be easily represented mathematically, facilitating the theoretical analysis of the scattered fields.

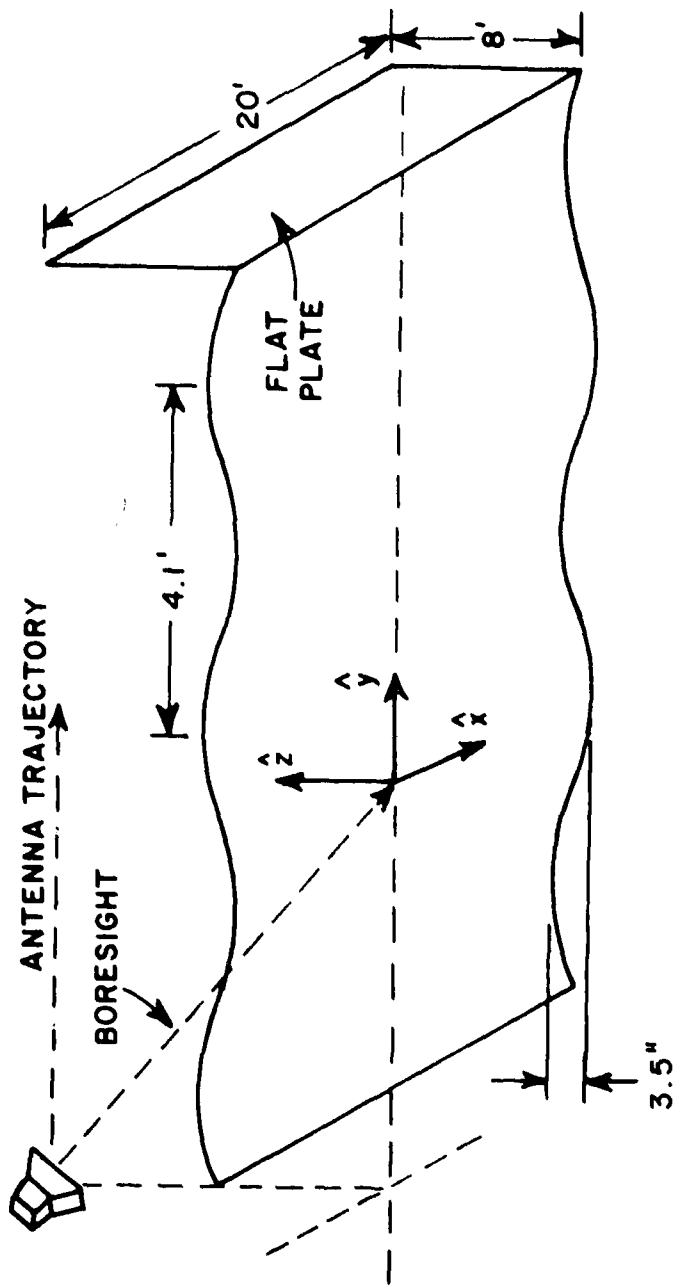


Figure 1-2. Geometry of the cylindrical surface with flat plate.

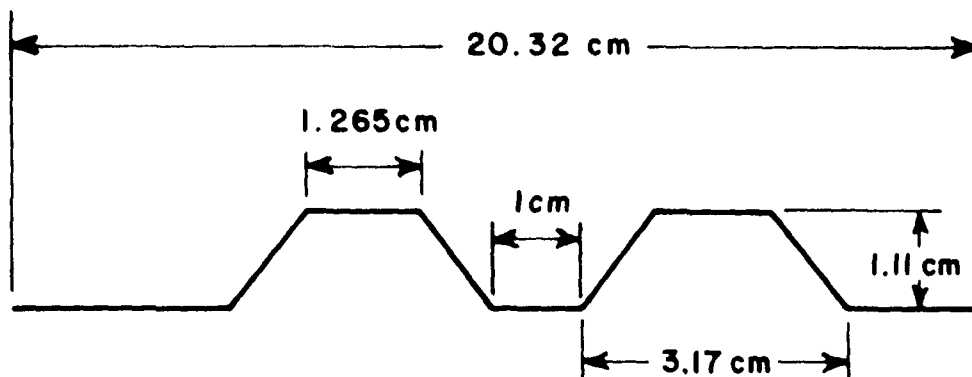


Figure 1-3. Geometry of double trapezoid capillary wave profile.

At one end of the surface model is an eight foot high metal plate representing the ship. This metal plate makes an angle with the surface such that a corner, not necessarily right-angled, is formed. The major contribution to the backscattering from such a configuration is the double-bounce reflection from this corner. For an actual ship at sea, there are a multitude of double and triple bounce corners on the structure of the ship itself. Even so, the largest single contribution to the return signature will probably still be the corner where the ship meets the sea surface.

The ship-sea model described here has four principal mechanisms which give significant contributions to the backscattered field. These are the backscatter from gravity waves, backscatter from the trapezoids, backscatter from the ship-sea double bounce region, and the diffracted field from the plate edge. First we shall consider the general physical optics formulation for this one-dimensional geometry, and then investigate the scattering from each of the four mechanisms. The calculated scattered fields will be compared with the experimental results obtained at the Encounter Simulation Laboratory, where the ship-sea model shown in Figure 1-1 was constructed.

CHAPTER III
 PHYSICAL OPTICS EXPRESSION FOR SCATTERING
 FROM A CYLINDRICAL SURFACE

The first step in obtaining the scattered fields is to calculate the scattering from an arbitrary cylindrical surface. The approach taken here is to use the physical optics currents generated by the incident field and then find the far field radiated by these current generators.

The general equations for the physical optics currents, given the incident field, were summarized in Reference [1]. The scattered electric field, dE_s , at a point in the far-field of a current element J_s is given by

$$dE_s = jkZ_0 \frac{e^{-jkR'_n}}{4\pi R'_n} (J_s \times \hat{r}'_n) \times \hat{r}'_n ds \quad (1)$$

where \hat{r}'_n is the unit vector describing the direction for R'_n , the distance from the surface element ds to the field point, k is the wave number and $Z_0 = 120\pi$ ohms. The surface current J_s , in the physical optics approximation, is

$$J_s = 2\hat{n} \times H_i \quad (2)$$

where \hat{n} is the normal to the surface element ds (see Figure 3-1) and is given by

$$\hat{n} = -\sin\phi \hat{y} + \cos\phi \hat{z} \quad (3)$$

The angle between the normal \hat{n} and the vertical is defined to be ϕ .

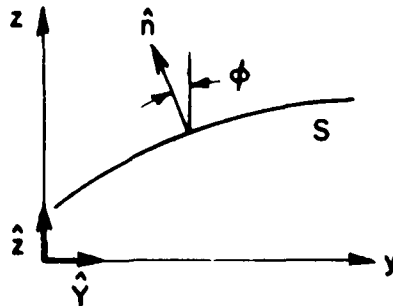


Figure 3-1. Geometry of the normal to the surface.

The magnetic field \vec{H}_i incident upon the surface can be written as

$$\vec{H}_i = I_0 (f_v f_h)^{1/2} \vec{p}_h \frac{e^{-jkR_n}}{R_n} \quad (4)$$

where I_0 is a nominal current strength, and f_v, f_h are antenna pattern factors, to be discussed later. For an antenna of maximum gain, G_T , which radiates power P_T

$$I_0 = (P_T G_T / 4\pi Z_0)^{1/2} \quad (5)$$

The polarization state of the transmitted field is characterized by a polarization factor \vec{p}_h . For horizontal (perpendicular) polarization the electric field \vec{E}_0 , in the aperture, is in the x_0 direction (see Figure 3-2). For the geometry of the sea-ship model, the unit vector x_0 is parallel to the coordinate unit vector \hat{x} . The polarization factor can be expressed as

$$\vec{p}_h = - \frac{\hat{x}_0 \times \hat{r}_n}{|\hat{x}_0 \times \hat{r}_n|} \quad (6)$$

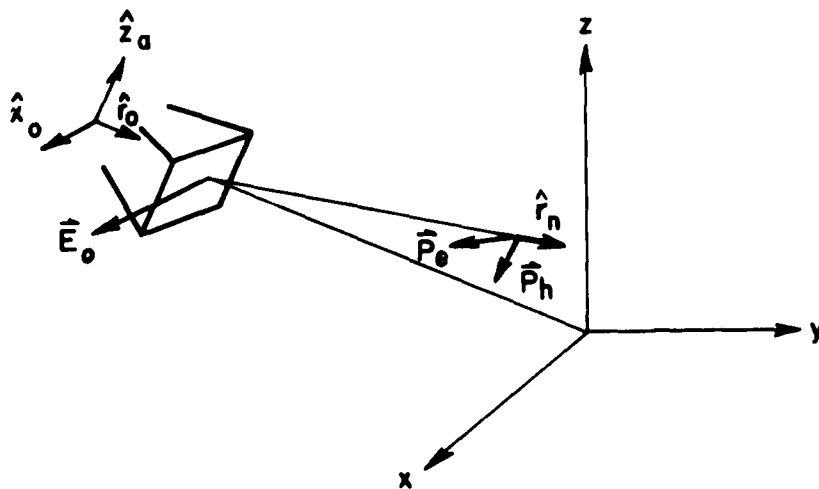


Figure 3-2. Polarization state for the transmitted field.

The one way antenna power pattern, $F(\xi, \eta)$, is assumed to be a product pattern with one principal plane in the x-y plane (pattern angle η) and the other principal plane containing the z axis (pattern angle ξ) (see Figure 3-3), so that $F(\xi, \eta)$ can be written as

$$f(\xi, \eta) = f_v(\xi) f_h(\eta) \quad (7)$$

By assuming that $f_h(\eta)$ is Gaussian, it will later be possible to reduce the two dimensional surface integration to a one dimensional integration.

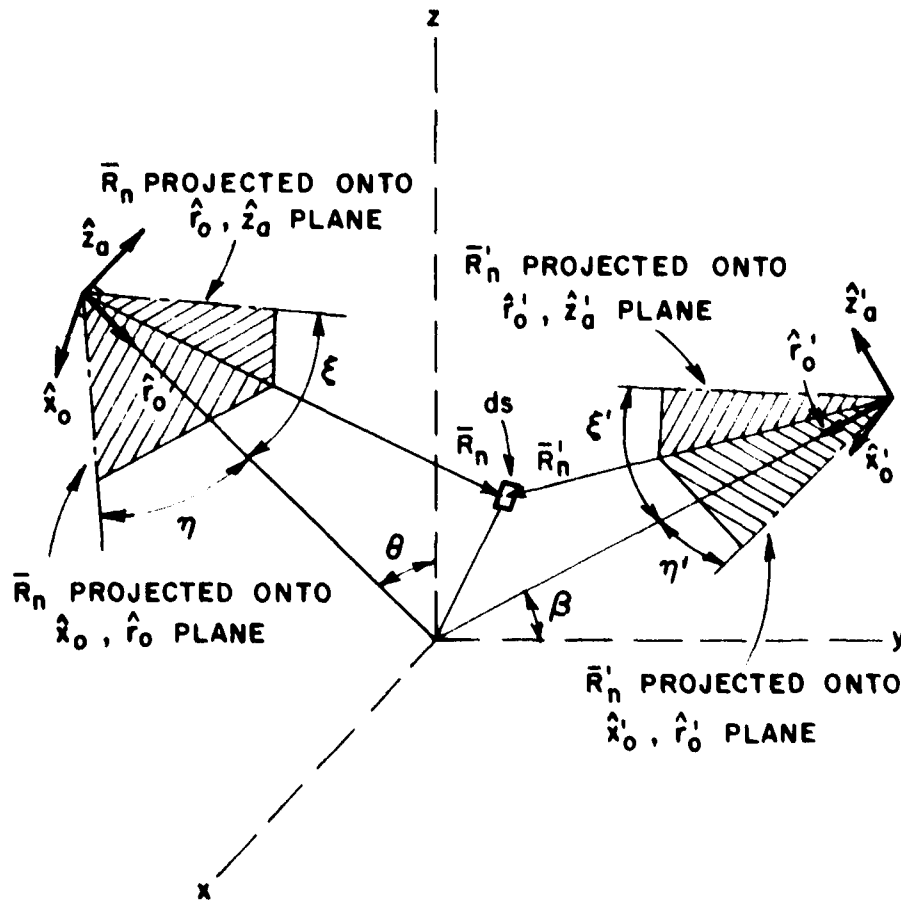


Figure 3-3. Transmitter and receiver coordinate angles.

Combining Equations (2) and (4) gives an expression for the physical optics currents.

$$\vec{J}_s = 2 I_0 f(\xi, \eta)^{1/2} e^{-jkR_n} (\hat{n} \times \vec{P}_h) \quad (8)$$

Substituting the equations for \hat{n} (Equation (3)) and \vec{P}_h (Equation (6)) into Equation (8) gives

$$\vec{J}_s = 2 I_0 f(\xi, \eta)^{1/2} e^{-jkR_n} \left[(-\sin\phi \hat{y} + \cos\phi \hat{z}) \times \frac{-(\hat{x} \times \hat{r}_n)}{|\hat{x} \times \hat{r}_n|} \right] \quad (9)$$

From Figure 3-4 we have that

$$\hat{r}_n = \frac{1}{R_n} (R_0 \hat{r}_0 + y\hat{y} + h\hat{z} + x\hat{x}) \quad (10)$$

where

$$\hat{r}_0 = \sin\theta \hat{y} - \cos\theta \hat{z} \quad .$$

Substituting Equation (10) back into the equation for the physical optics current (Equation (9)) and simplifying, we obtain

$$\vec{J}_s = 2 I_0 f(\xi, \eta)^{1/2} e^{-jkR_n} \frac{(R_0 \cos(\theta-\phi) + y \sin\phi - h \cos\phi)}{R_n [(R_0 \cos\theta - h)^2 + (R_0 \sin\theta + y)^2]^{1/2}} \hat{x} \quad (11)$$

For the antenna polarization chosen here, the physical optics currents are in the x-axis direction.

Using the expression (11) for \vec{J}_s , in Equation (1), and expanding the triple cross product

$$(\hat{x} \times \hat{r}'_n) \times \hat{r}'_n = \left(\frac{x^2}{R'_n{}^2} - 1 \right) \hat{x} + \frac{x}{R'_n{}^2} (y - R'_0 \cos \beta) \hat{y} - \frac{x}{R'_n{}^2} (h - R'_0 \sin \beta) \hat{z} \quad (12)$$

where the unit vector \hat{r}'_n is defined in Figure 3-4,

$$\hat{r}'_n = \frac{1}{R'_n} [(y - R'_0 \cos \beta) \hat{y} + (h - R'_0 \sin \beta) \hat{z} + x \hat{x}] \quad (13)$$

we obtain

$$d\vec{E}_s = \frac{2jkZ_0}{4\pi} I_0 f(\xi, \eta)^{1/2} \frac{e^{-jk(R_n + R'_n)}}{R_n R'_n} \quad (14)$$

$$* \frac{(R_0 \cos(\theta - \phi) + y \sin \phi - h \cos \phi)}{[(h - R_0 \cos \theta)^2 + (R_0 \sin \theta - y)^2]^{1/2}}$$

$$* \left\{ \left(\frac{x^2}{R'_n{}^2} - 1 \right) \hat{x} + \frac{x}{R'_n{}^2} (y - R'_0 \cos \beta) \hat{y} - \frac{x}{R'_n{}^2} (h - R'_0 \sin \beta) \hat{z} \right\}$$

$$* \frac{d_x d_y}{\cos \phi}$$

So far, only the transmitting antenna pattern has been accounted for. The receiver, at the point where the field is being measured, must also have a power pattern and a polarization direction. We shall assume in this case that the receiving antenna has the same pattern as the transmitting antenna. Also, to find the horizontally polarized component of the scattered field, we assume that the receiving antenna polarization is in the x-direction. Equation (14) can be changed to take into account the receiving antenna by multiplying by the one way power pattern, given by (see Figure 3-3)

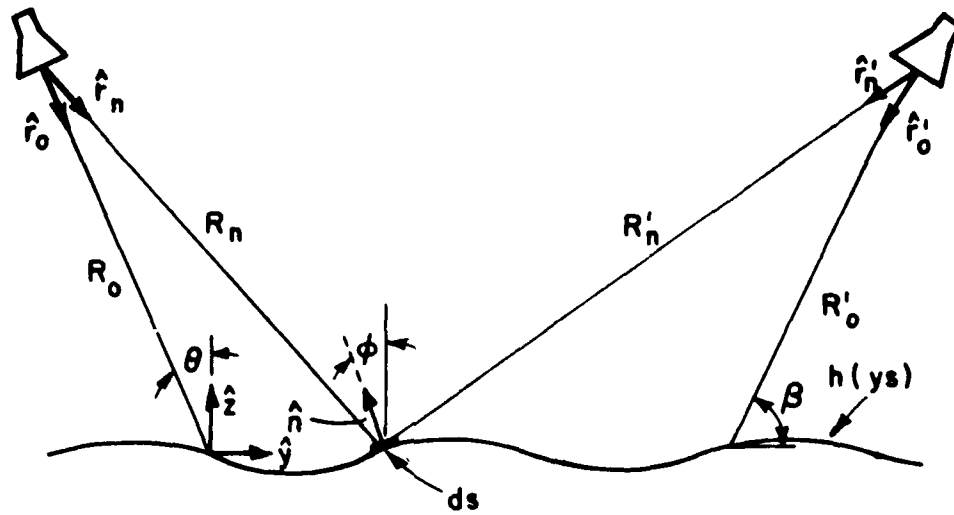


Figure 3-4. Incident and reflected ray geometry.

$$f(\epsilon', \eta')^{1/2} = f_v(\epsilon')^{1/2} f_n(\eta')^{1/2} \quad (15)$$

and by taking the dot product with the receiver polarization

$$\hat{a}_r = \hat{x} \quad .$$

Furthermore, if the maximum receiving aperture of the antenna is given by A_e , the receiver voltage, i.e., the voltage at the receiver due to the scattered field from ds , is found to be

$$dV_r = \frac{2jV_0}{4\pi} f(\epsilon, \eta)^{1/2} f(\epsilon', \eta')^{1/2} \frac{e^{-jk(R_n + R'_n)}}{R_n R'_n} \quad (16)$$

$$\left(\frac{x^2}{R_n'^2} - 1 \right) \frac{(R_0 \cos(\theta - \phi) + y \sin \phi - h \cos \phi)}{[(h - R_0 \cos \theta)^2 + (y + R_0 \sin \theta)^2]^{1/2}} \frac{d_x d_y}{\cos \phi}$$

where

$$V_0 = Z_0 I_0 (A_e k^2)^{1/2}$$

Equation (16) gives an expression for the horizontally polarized component of the electric field at a point, scattered from an incremental area of the total surface. To obtain the total field at any point, a double integration over the entire surface is required.

Assuming that both the receiver and the transmitter have a Gaussian product pattern, then

$$f(\xi, \eta)^{1/2} = e^{-\frac{1}{2} A \tan^2 \eta} e^{-\frac{1}{2} B \tan^2 \xi}$$

$$f(\xi', \eta')^{1/2} = e^{-\frac{1}{2} A \tan^2 \eta'} e^{-\frac{1}{2} B \tan^2 \xi'} \quad (17)$$

where A and B are beamwidth parameters. The angles ξ, η, ξ' and η' (shown in Figure 3-3) can be expressed analytically in terms of dot products.

$$\tan \xi = \frac{\vec{r}_n \cdot \vec{z}_a}{\vec{r}_n \cdot \vec{r}_o} = \frac{y \cos \theta + h \sin \theta}{R_o + y \sin \theta - h \cos \theta} \quad (18)$$

$$\tan \eta = \frac{\vec{r}_n \cdot \vec{x}}{\vec{r}_n \cdot \vec{r}_o} = \frac{x}{R_o + y \sin \theta - h \cos \theta} \quad (19)$$

$$\tan \xi' = \frac{\vec{r}'_n \cdot \vec{z}'_a}{\vec{r}'_n \cdot \vec{r}'_o} = \frac{h \cos \theta - y \sin \theta}{R'_o - y \cos \theta - h \sin \theta} \quad (20)$$

$$\tan \alpha' = \frac{r_n' \cdot x'}{r_n' \cdot r_o'} = \frac{x}{R_o' - y \cos \beta - h \sin \beta} \quad (21)$$

Substituting these angle definitions back into Equation (16) gives the following expression for the received voltage.

$$V_r = \frac{2jV_o}{4\pi} \int_y \int_x \frac{(R_o \cos(\theta - \phi) + y \sin \phi - h \cos \phi)}{\cos \phi [(h - R_o \cos \theta)^2 + (y + R_o \sin \theta)^2]^{1/2}} \left(\frac{x^2}{R_n'^2} - 1 \right) e^{-jk(R_n' + R_n)} \frac{1}{R_n' R_n} \quad (22)$$

$$\star e^{-\frac{A}{2} x^2 \left(\frac{1}{R_2^2} + \frac{1}{R_2'^2} \right) - \frac{B}{2} (y \cos \theta + h \sin \theta)^2 / R_2^2 - \frac{B}{2} (h \cos \beta - y \sin \beta)^2 / R_2'^2} d_x d_y$$

where

$$R_2 = R_o + y \sin \theta - h \cos \theta$$

$$R_2' = R_o' - y \cos \beta - h \sin \beta$$

Because of the choice of the two principal planes defining the power patterns, we are able to separate the x and y integrations. By integrating from minus infinity to infinity in the x direction, we can integrate analytically the x dependent part of the double integral so that

$$V_r = \frac{2jV_o}{4\pi} \int_y \bar{x} \frac{(R_o \cos(\theta - \phi) + y \sin \phi - h \cos \phi)}{\cos \phi [(h - R_o \cos \theta)^2 + (y + R_o \sin \theta)^2]^{1/2}} \quad (23)$$

$$\star e^{-\frac{B}{2} (y \cos \theta + h \sin \theta)^2 / R_2^2 - \frac{B}{2} (h \cos \beta - y \sin \beta)^2 / R_2'^2} dy$$

where

$$\bar{X} = \int_{-\infty}^{\infty} \left(\frac{x^2}{R_n'^2} - 1 \right) \frac{e^{-jk(R_n + R_n')}}{R_n R_n'} e^{-\frac{A}{2} \left(\frac{1}{R_2^2} + \frac{1}{R_2'^2} \right) x^2} dx$$

and

$$R_n^2 = R_1^2 + x^2 \tag{24}$$

$$R_n'^2 = R_1'^2 + x^2$$

with

$$R_1^2 = (h - R_0 \cos \theta)^2 + (y + R_0 \sin \theta)^2 \tag{25}$$

$$R_1'^2 = (h - R_0' \sin \beta)^2 + (y - R_0' \cos \beta)^2$$

Using the Fresnel approximation in expanding the exponential phase terms

$$e^{-jkR_n} = e^{-jk(R_1^2 + x^2)^{1/2}} \cong e^{-jk(R_1 + \frac{x^2}{2R_1})} \tag{26}$$

$$e^{-jkR_n'} = e^{-jk(R_1'^2 + x^2)^{1/2}} \cong e^{-jk(R_1' + \frac{x^2}{2R_1'})}$$

and approximating the denominator terms as

$$\frac{1}{R_n} = \frac{1}{(R_1^2 + x^2)^{1/2}} \cong \frac{e^{-\frac{x^2}{2R_1^2}}}{R_1}$$

$$\frac{1}{R_n'^3} = \frac{1}{(R_1'^2 + x^2)^{3/2}} \cong \frac{e^{-\frac{3x^2}{2R_1'^2}}}{R_1'^3} \tag{27}$$

the evaluation of the \bar{X} integral in Equation (23) gives

$$\bar{X} = \frac{-R_2 R_2' \sqrt{2\pi} e^{-jk(R_1 + R_1')}}{[AR_1^2 R_1'^2 R_2^2 + AR_1^2 R_1'^2 R_2'^2 + jkR_1 R_1' R_2^2 R_2'^2 + jkR_1^2 R_1'^2 R_2^2 R_2'^2 + R_1^2 R_2^2 R_2'^2 + 3R_1^2 R_2^2 R_2'^2]^{1/2}}$$

(28)

Further evaluation of the integral, Equation (23), would require a computer. Notice also that if Equation (23) is evaluated by computer, any desired vertical plane antenna patterns, $f_V(\xi)$ and $f_V(\xi)$, may be used in place of the gaussian patterns of Equation (17).

CHAPTER IV BACKSCATTER FROM A MODEL SEA SURFACE

As pointed out in Section II, there are four principal mechanisms contributing to the total field scattered by the simplified ship-sea model. We consider first the backscatter from the large-scale (gravity) waves.

A. Geometry of the Wave Models

To calculate this direct backscatter from the gravity waves, we first define the surface. The gravity wave model lies in the x - y_s plane. The surface height is a function of y_s only, so that

$$h(y_s) = H_{ei} + H_{ei} * \sin(w_m * y_s + \text{Phase}) \quad (29)$$

and the surface is uniform in the x direction. The constant H_{ei} is the peak amplitude of the sinusoid, $w_m = \frac{2\pi}{\lambda_m}$ is the mechanical wave-number of the surface. The surface itself is 40 feet in length, with $\lambda_m = 4.1$ feet and $H_{ei} = 1.75$ inches. In implementing the computations of the scattered field, the surface is assumed to occupy the range $-40 < y_s < 0$ with the flat plate position at $y_s = 0$.

The capillary waves, modeled by small trapezoids, are superimposed on the surface of the gravity waves. Each trapezoid is made up of plane segments as shown in Figure 2-3. The upper three segments represent the actual surface. The other two segments are straight line approximations to the original sinusoid.

The scattering from such a composite surface could be computed from Equation (23) since the profile $h(y_s)$ of the surface is known. However, in order to simplify subsequent calculations, the three upper segments of each trapezoid are considered to be individual scatterers. That is, instead of integrating over the surface of the trapezoid, we consider the current density, J_s , concentrated at the center of each of the segments. These current densities are then used to determine the field scattered from the segments. If any trapezoids are positioned such that a face is in the shadow region of the incident field, then the current density on that segment is taken to be zero. In addition, since the field scattered from the sinusoidal component alone (i.e., no trapezoids) is computed first, in order to illustrate the effect of the gravity waves, the total field may be found by adding the field scattered by the trapezoids to this gravity

wave field. Thus the fields scattered by the two lower segments of the individual trapezoid must be subtracted from the total field to account for the fact that the interval of the sinusoidal profile, $h(y_s)$, occupied by the trapezoid has already been computed in the gravity wave program.

B. Discussion of Computer Code for Backscatter from the Sinusoidal Surface (Gravity Waves)

Since the profile of the surface is known, the voltage at the receiver due to the field scattered from the model surface is found by a numerical integration of Equation (23). The Equation then takes the form

$$V_r = \frac{-jV_0}{2\pi} \sum_{y=y_{s1}}^{y_s2} \frac{R_2 R_2' R_0}{R_1} (\cos\theta + \sin\theta \tan\phi + y/R_0 \tan\phi - h(y_s)/R_0) \quad (30)$$

$$\cdot g^{-1/2} e^{-jk(R_1 + R_1')} e^{-\frac{B}{2} (\tan^2 \xi + \tan^2 \xi')} \Delta y$$

where

$$g = AR_1^2 R_1'^2 R_2'^2 + AR_1'^2 R_1^2 R_2^2 + jkR_1 R_1'^2 R_2^2 R_2'^2 + jkR_1' R_1^2 R_2^2 R_2'^2 + R_1^2 R_2^2 R_2'^2 + 3R_1^2 R_2^2 R_2'^2$$

The variables in Equation (30) are shown in Figure 4-1, and are defined as follows.

The boresight distance, R_0 , is the distance from the radar to the y-axis, measured along the radar axis. R_0 is given by

$$R_0 = zz/\sin(\pi/2 - \theta)$$

where zz is the perpendicular height of the radar above the y-axis. The return boresight distance R_0' is equal to R_0 since the radar is monostatic. The incremental value, Δy , is the width (measured horizontally) of the portion of the surface contributing to the sum in Equation (30). There is just one physical optics current element per increment. In the program of the Appendix, y is taken to be 0.01.

By taking the origin of the x,y,z coordinate system to be at the intersection of the boresight with the y-axis, the distance between the radar and the surface point at Δy , R_1 , can be written as

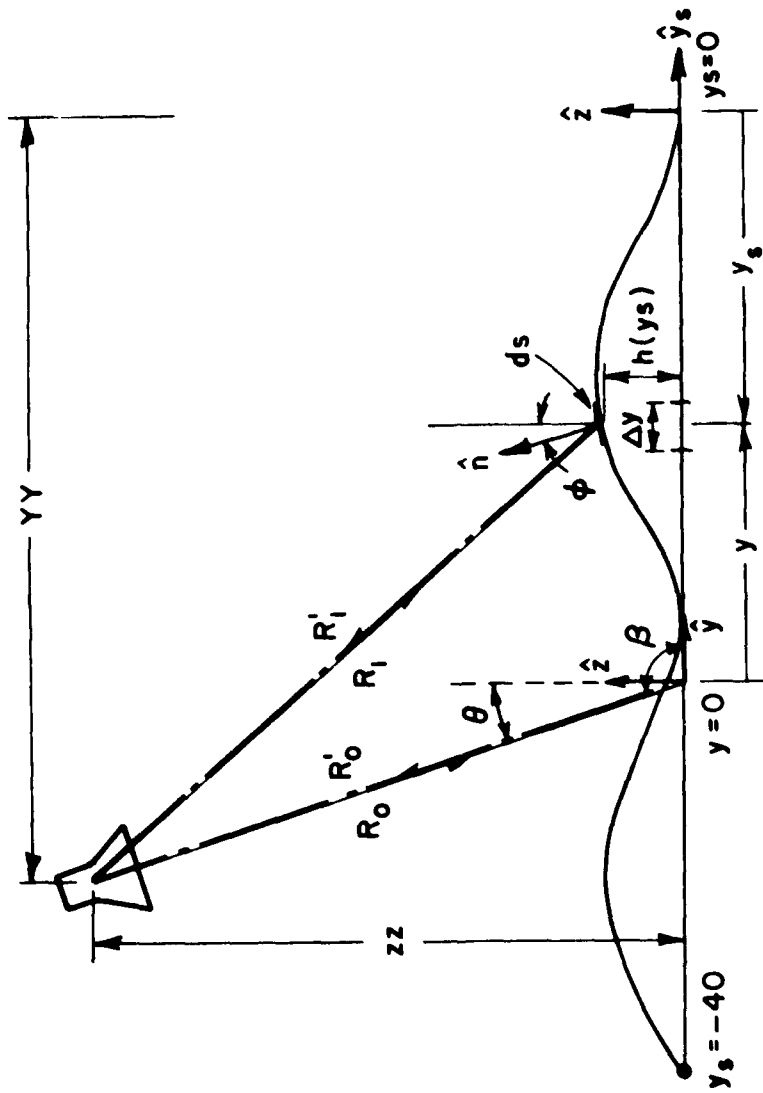


Figure 4-1. Geometry for backscatter from gravity waves.

$$\begin{aligned}
 R_1^2 &= (y + R_0 \sin\theta)^2 + (h(y_s) - R_0 \cos\theta)^2 \\
 &= (y - y_0)^2 + (h(y_s) - h_0)^2
 \end{aligned}
 \tag{31}$$

where θ is the angle between the vertical (z) axis and the boresight, and

$$y_0 = -R_0 \sin\theta$$

$$h_0 = z_0 = R_0 \cos\theta$$

The return distance between the radar and Δy is R_1' and is equal to R_1 for direct backscatter. The quantity R_2 is the projection of R_1 onto R_0 and is defined as

$$R_2 = R_0 + y \sin\theta - h(y_s) \cos\theta \tag{32}$$

R_2' is the projection of R_1' onto R_0' and is given by

$$R_2' = R_0' - y \cos\beta - h(y_s) \sin\beta \tag{33}$$

where the angle β is measured between the horizontal (y) axis and the return boresight. The quantities R_2 and R_2' are also equal for a monostatic radar.

The portion of the surface contributing to the sum is defined by the limits $y=Y_{S1}$ and $y=Y_{S2}$. These limits are determined by the angles at which the incident field is 20 dB down from the boresight level. Since we have defined the point $y=0$ to be at the intersection of the boresight with the y -axis, the value of Y_{S1} will be negative and Y_{S2} positive. The surface profile function $h(y_s)$ is always evaluated with respect to the origin of the x, y_s, z coordinate system, that is $y_s=0$ at the end of the surface model (see Figure 4-2). We then have for the limits of integration

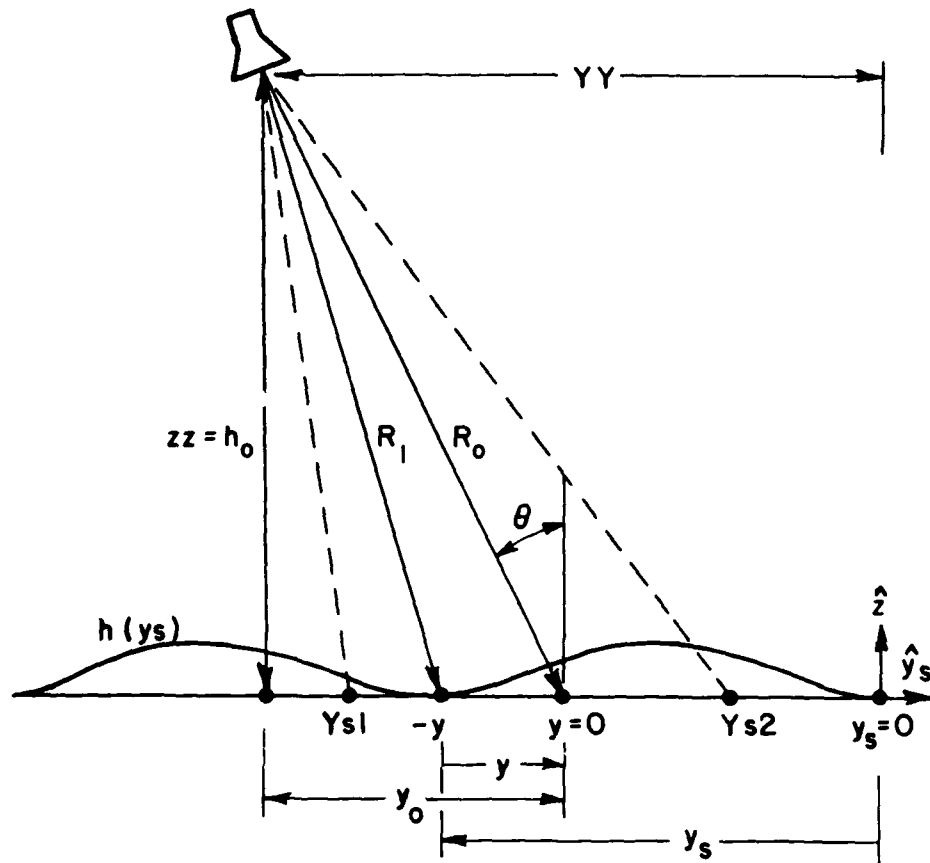


Figure 4-2. Geometry defining the limits of integration.

$$Y_{s1} = y_0 + h_0 \cdot \tan(\theta - 1.3 \cdot \theta_{3dB})$$

$$Y_{s2} = y_0 + h_0 \cdot \tan(\theta + 1.3 \cdot \theta_{3dB})$$

(34)

where θ_{3dB} is the 3dB beamwidth in degrees, which for our gaussian pattern has been taken to be 15° .

The specified section of the computer code in the Appendix utilizes Equation (30) with $h(y_s)$ defined by Equation (29) to calculate the receiver voltage due to the backscattered field from the sinusoidal surface model, as the radar moves from the end of the surface at $y_s = -40$ to the flat plate at $y_s = 0$. This portion of the code

requires input values of; the height, $D1$ in feet, of the radar above the y axis at $y_s=0$, the look angle, α , of the radar as measured from the trajectory to boresight in degrees, and the dive angle, ψ , of the radar in degrees from the horizontal. The output is the voltage at the receiver (complex valued) in units of volts (see Figure 4-3).

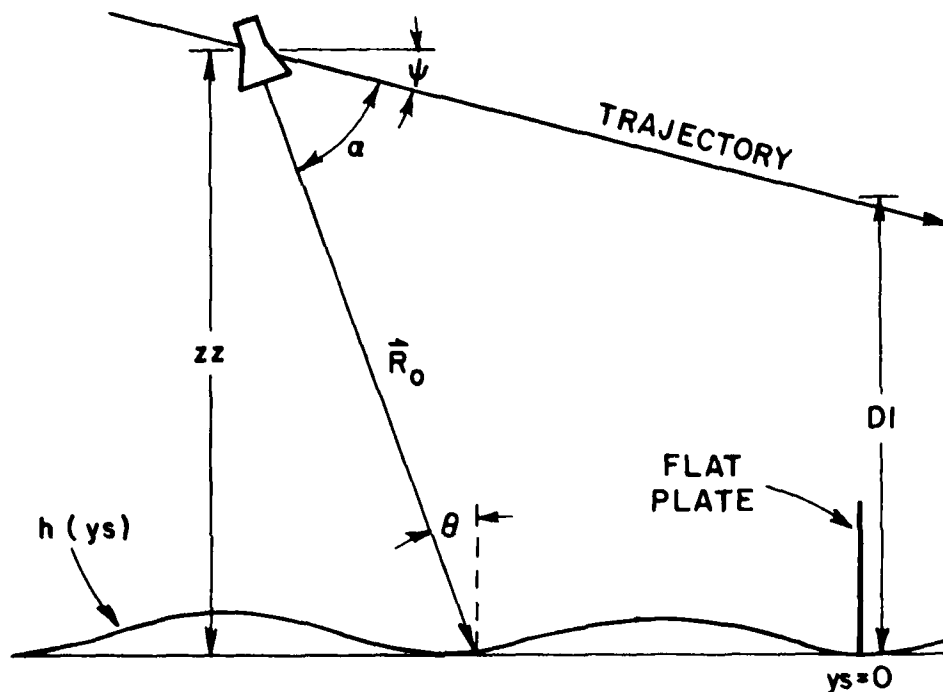


Figure 4-3. Geometry of input variables.

C. Discussion of Computer Code for Backscatter from Trapezoids (Capillary Waves)

The most direct way to include the physical optics scatter from the trapezoids would be to superimpose their profile on the profile given by $h(y_s)$ for the gravity waves, and apply Equation (30). However, it is possible to generate a set of equations that adequately describe the scattering from a single, arbitrarily placed trapezoid, so that one set of equations could be used in a computer code to calculate the backscatter from all of the trapezoids.

The field scattered from an arbitrary trapezoid is found by considering each segment of the trapezoid separately. The field contributions from the three upper segments are added together. Because the field from the entire sinusoidal surface has already been calculated, the scattering from those portions which are now covered must be subtracted from the total field. For this reason the field contribution from the bottom two segments is subtracted from the field of the upper three segments. The net field contribution from the five segments is added to the field scattered from the gravity wave. This process is repeated for each trapezoid on the surface. When the radar is moved to a new position a new value for the received complex voltage is calculated. In this manner, a backscattering signature for the model sea surface is obtained for the specified radar trajectory.

To find the net backscattered field due to a trapezoid, we consider first the field scattered from one side of the trapezoid by using a simplified form of Equation (23). Because each side of the trapezoid profile is only a small fraction of a wavelength long, we can further simplify the calculation of the scattered field by considering the entire physical optics current to be concentrated in the center of the segment. Thus, no integration in the y-direction along the segment is needed. Instead we simply multiply by the effective width of the segment. Also, since we are dealing with a monostatic radar, the transmitted and received distances are equal, eliminating the primes on variables which denote the scattered distances, and doubling the transmitted distances. Equation (23) can now be written in a form suitable for calculations of the field scattered from the trapezoids.

$$\begin{aligned}
 V_r(n) = & -\frac{jV_0}{2\pi} \frac{L(n)\sin\theta(n)(y+R_0\sin\theta) + \cos\theta(n)(h-R_0\cos\theta)}{\cos\theta(n)[(h-R_0\cos\theta)^2 + (y+R_0\sin\theta)^2]^{1/2}} dwy(n) \\
 & * e^{-B(y\cos\theta+hs\sin\theta)^2/R_2^2} \\
 & * \int_{-\infty}^{\infty} \frac{e^{-j2kR_1}}{R_1^2} e^{-\left(\frac{2}{R_1^2} + \frac{A}{R_2^2} + j\frac{k}{R_1}\right)x^2} dx \quad (35)
 \end{aligned}$$

where $n=1, \dots, 5$ depending on which segment of the trapezoid is being considered (see Figure 4-4); $L(n)$ is either +1 or -1, depending on the normals n_i

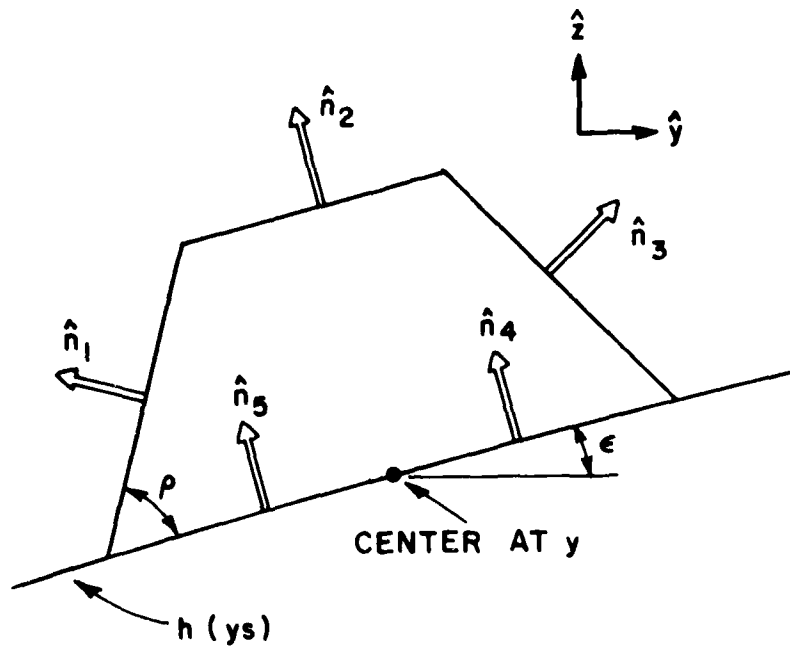


Figure 4-4. Profile of trapezoid showing normals.

$$\hat{n}_i = L(n) \sin \sigma(n) \hat{y} + \cos \sigma(n) \hat{z} \quad (36)$$

$$L(n) = -1 \text{ for } n = 1, 2, 4, 5$$

$$L(n) = +1 \text{ for } n = 3$$

The parameter $\sigma(n)$ is also a function of the segments of the trapezoid.

$$\sigma(1) = \rho + \epsilon$$

$$\sigma(2) = \epsilon$$

$$\sigma(3) = \rho - \epsilon$$

$$\sigma(4) = \epsilon$$

$$\sigma(5) = \epsilon$$

(37)

Here, ρ is the angle describing the slope of the surface $h(y_S)$ at the midpoint of the trapezoid, and σ is the angle that defines the slope of the sides of the trapezoid (see Figure 4-4). Since σ_i defines the slope of the i -th segment of the trapezoid, the width of the i -th segment projected along the y -axis will be a function of σ_i , so that

$$\begin{aligned} dwy(1) &= 0.048 \cdot \cos(\rho + \sigma) \\ dwy(2) &= 0.415 \cdot \cos(\sigma) \\ dwy(3) &= 0.048 \cdot \cos(\rho - \sigma) \\ dwy(4) &= 0.052 \cdot \cos(\sigma) \\ dwy(5) &= 0.052 \cdot \cos(\sigma) \end{aligned} \quad (38)$$

By carrying out the integration over x in Equation (35) and summing over the five faces of the trapezoid, an equation for the received voltage contributed from a trapezoid centered at position y can be written

$$\begin{aligned} V_r = & - \frac{jV_0}{2\pi} \sum_{n=1}^5 (\pm) \frac{L(n) \sin(n)(y+R_0 \sin \sigma) + \cos(n)(h-R_0 \cos \sigma)}{\cos(n) [(h-R_0 \cos \sigma)^2 + (y+R_0 \sin \sigma)^2]^{1/2}} \\ & + \frac{dwy(n) e^{-2jkR_1} e^{-R(y \cos \sigma + h \sin \sigma)^2 / R_1^2}}{R_1^2 (\pi / R_1^2 + A / R_1^2 + jk / R_1)^{1/2}} \quad (v) \quad (39) \end{aligned}$$

where the choice of sign (\pm) is such that the top segments ($n=1,2,3$) are (+) and the bottom two segments ($n=4,5$) are (-). In this equation y is defined to be the position of the mid-point of the trapezoid on the surface $h(y_S)$. All other terms are as defined for the gravity wave calculations.

The portion of the computer code that calculates the field scattered from the trapezoids is a subroutine in the gravity wave code. This subroutine requires the position of the radar, and returns the voltage at the receiver due to the field scattered from the trapezoid superimposed on $h(y_S)$. This complex voltage is added to the voltage due to scattering from the gravity waves so that the program gives, at each position of the radar, the receiver voltage due to the field scattered from the composite surface model. The following section gives the results of some typical calculations.

D. Results for Backscatter from Surface Model

The signature for the sea-surface model, (i.e., the receiver voltage as a function of the distance YY) as calculated using the physical optics current approximation, is shown in Figure 4-5 for two different trajectory geometries. Two signatures are shown for each configuration, one modeling the sea as a gravity wave alone (i.e., as $h(y_s)$) and the other as the composite surface including the trapezoidal capillary waves. In all signatures, the magnitude of the receiver voltage is in dB below reference voltage V_0 , which has been taken to be unity. All signatures are plotted so that they are normalized to the highest value in the signature.

Note that the radar system used to obtain the measured signatures includes a range gate (short or long) to eliminate wall reflections. The effect of this range gate has been included in the calculated signatures by inserting a gating function $C(R_1, l)$ in, e.g. Equations (30) and (39). The argument l in $C(R_1, l)$ denotes that the short range gate was used.

Figure 4-5a shows clearly the effects of the periodicity of the sinusoidal surface model. When the contribution of the trapezoids is added in, the signatures take on a more random appearance, but the underlying periodicity is still noticeable (Figure 4-5b). The lobe at the end of the signatures of Figure 4-5a is the result of terminating the surface at $y_s=0$.

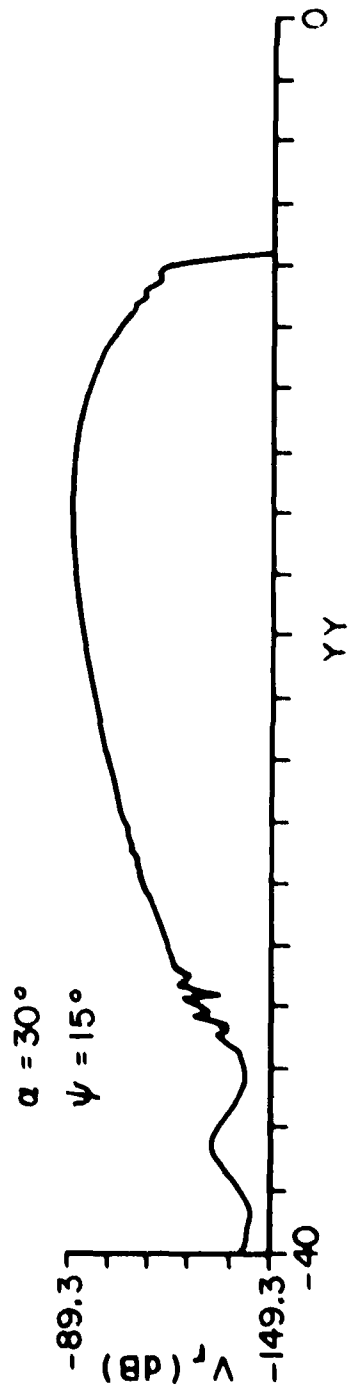
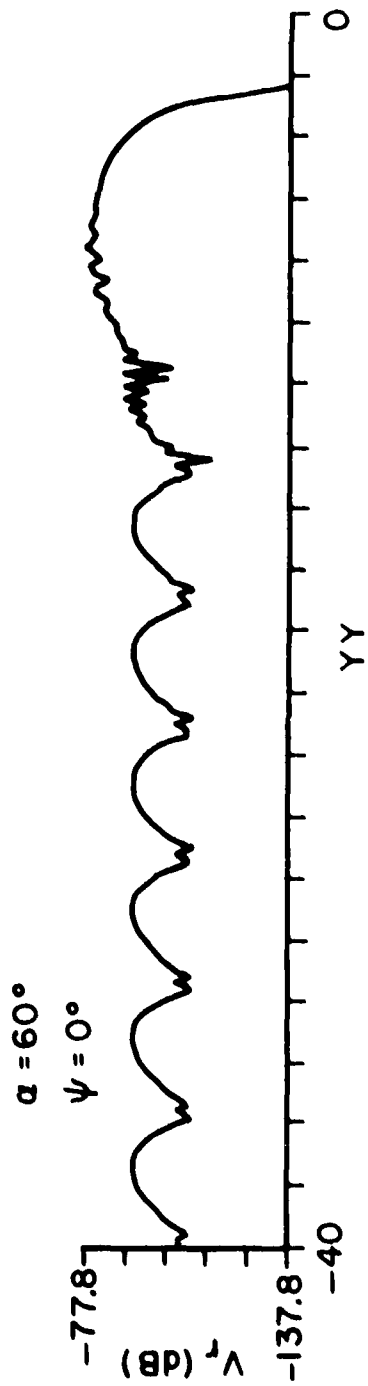


Figure 4-5a. Directivities for scatterer for grazing waves at 90° .

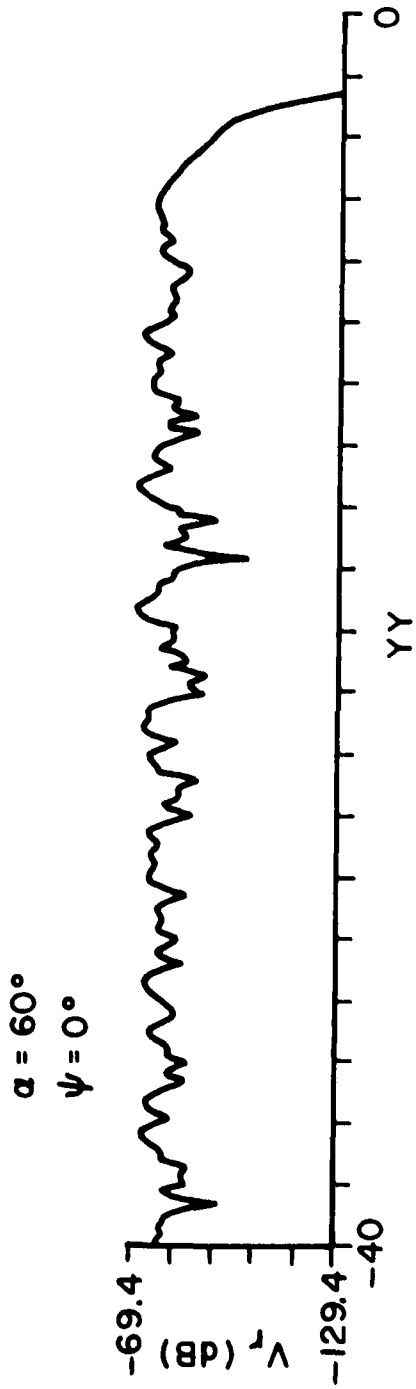


Figure 4-5b. Signatures for backscatter from composite surface.

CHAPTER V
DOUBLE-BOUNCE SCATTER FROM A SHIP MODEL

A. Geometry of the Ship Model

The next scattering mechanism to be considered is the double-bounce corner formed by the intersection of the ship and the sea surface. In the Encounter Simulation Laboratory experiment [3], the ship is modeled by the 8' high plate. To simulate different roll angles for the ship the plate angle μ can be varied. The radar approaches in the yz plane from the negative y direction along a trajectory defined by the dive angle ψ (see Figure 5-1).

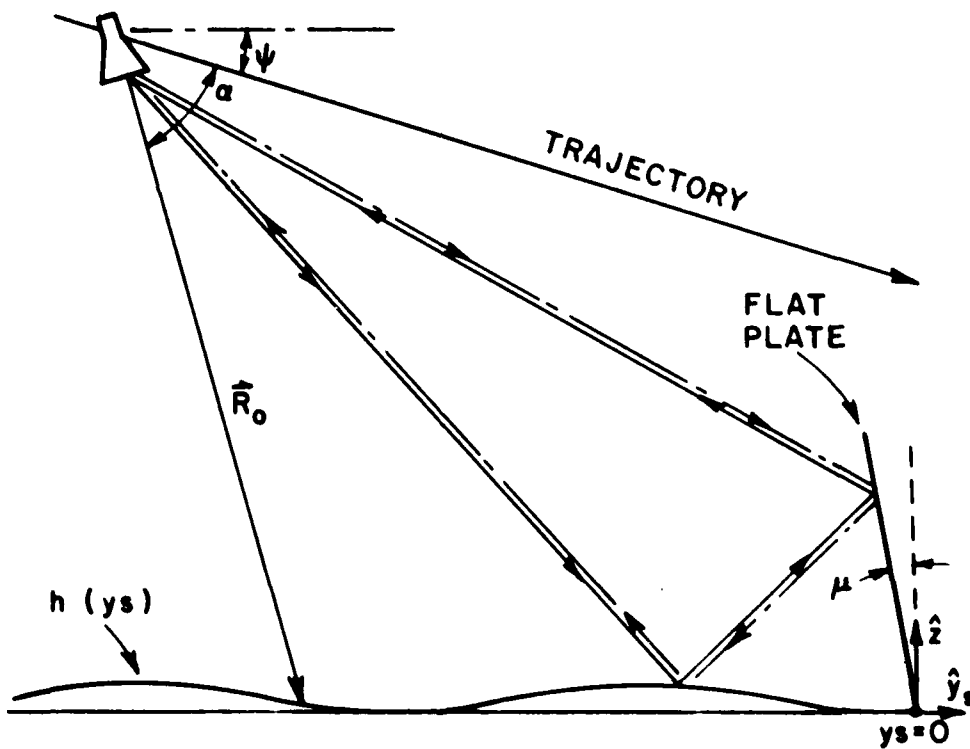


Figure 5-1. Geometry for double-bounce scatter.

B. Simplifications to Model

There are, in fact, two double-bounce paths, one in the direction transmitter-sea surface-plate-receiver and the other in the direction transmitter-plate-sea surface-receiver. In both cases the scatter from the sea surface is in the forward direction. Because the dominant scattering effect from the sea surface is the forward scatter from the large scale structure, $h(y_s)$, we can neglect the effects of the capillary waves in calculating the double-bounce effect. This will greatly simplify the field calculations and the computer code.

Even after neglecting the capillary waves, a direct calculation of the scattered fields would take an unreasonable amount of computer time. Instead we may take advantage of certain symmetries of the problem to further simplify the calculations.

For any configuration of the sea-plate-transceiver positions, the geometry can be made symmetric about the flat plate by using image theory. That is, since the plate is an ideal reflector, we may image the surface and transceiver. By appropriately defining the limits of integration, we can then effectively remove the plate (see Figure 5-2). This can be done, of course, only if the sea surface behind the plate can be neglected. For the study of the double-bounce scatter this is indeed the case. Reflection off the plate is taken into account by multiplying the field passing through the plane of the plate by a minus sign (for horizontal polarization).

Another simplification is that the two ray paths from transmitter to receiver through any point C on the plate are of equal length. Therefore, by reciprocity, we may calculate the field due to a first reflection off the sea, and multiply it by two to account for the ray hitting the plate first. The resulting configuration is shown in Figure 5-3.

Thus, by image theory and reciprocity, the problem has been reduced to a simple application of the equation derived in Section III for bistatic scattering. For a horizontally polarized field

$$V_r = - \frac{2jV_0}{2\pi} \int_Y \frac{R_2 R_2'}{R_1} (R_0 \cos\theta + R_0 \sin\theta \tan\phi + y \tan\phi - h(y_s))$$

$$\star g^{-1/2} e^{-jk(R_1 + R_1')} e^{-\frac{B}{2} (\tan^2 \epsilon + \tan^2 \epsilon')} dy \quad (40)$$

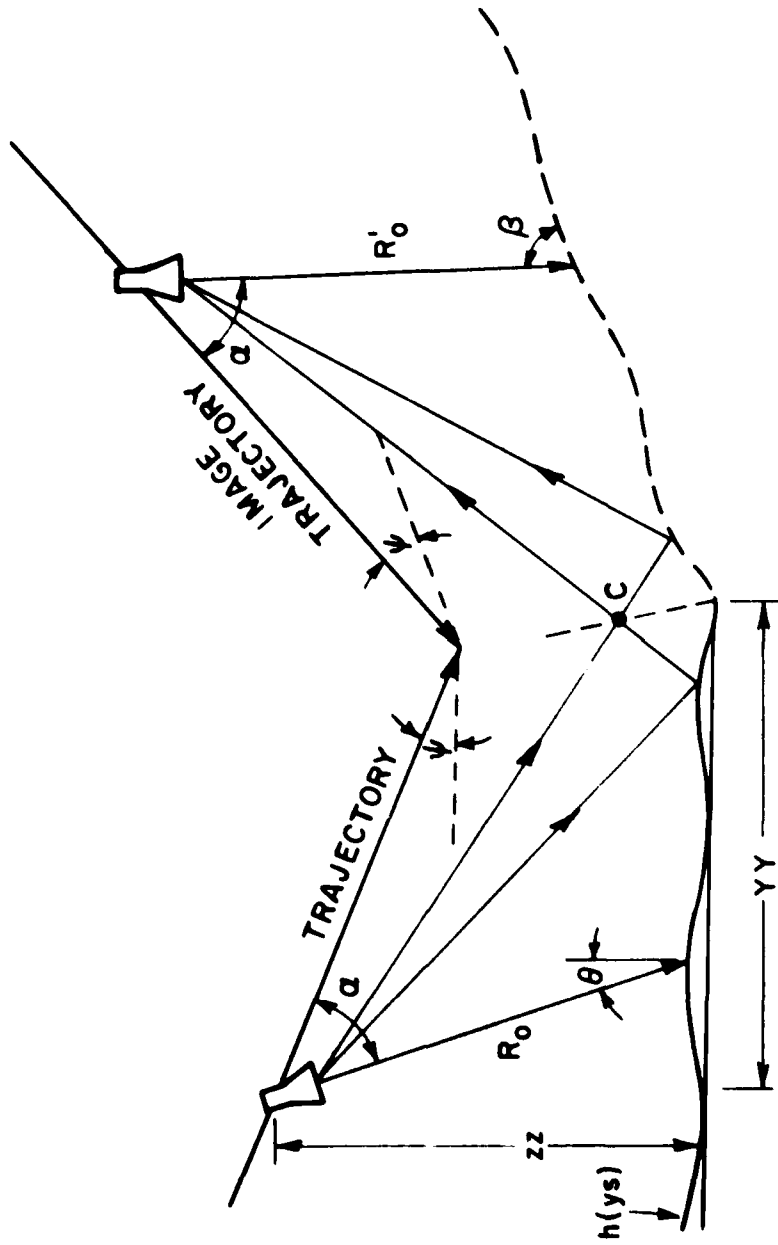


Figure 5-2. Geometry resulting from image theory.

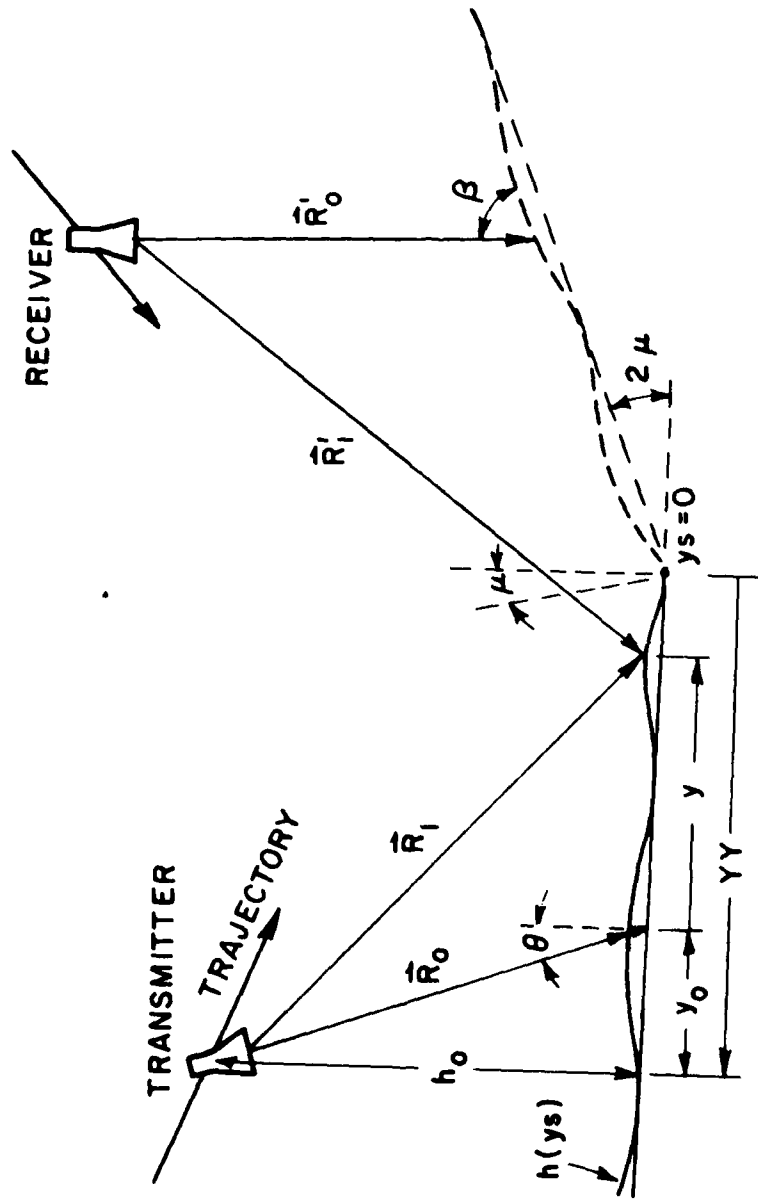


Figure 5-3. Simplified geometry of double-bounce scatter.

where

$$g = AR_1^2 R_1'^2 R_2'^2 + AR_1^2 R_1'^2 R_2^2 + R_1'^2 R_2^2 R_2'^2 + 3R_1^2 R_2^2 R_2'^2 + jkR_2^2 R_1'^2 (R_1' R_1^2 + R_1 R_1'^2)$$

and $h(y_s)$ is the sinusoid defined by Equation (29). The appropriate limits of integration will be discussed in the next section.

C. Discussion of Computer Code for Double-bounce Scatter

The field which is reflected back to the radar by the presence of the plate can be calculated by a numerical integration of Equation (40). By reducing the integral to a finite summation over small increments, Δy , we have

$$V_r = \frac{2jV_0}{2\pi} \frac{Y_{s2}}{Y_{s1}} \frac{R_2 R_1'}{R_1} (R_0 \cos \theta + R_0 \sin \theta \tan \theta + y \tan \theta - h(y_s)) \\ * g^{-1/2} e^{-jk(R_1 + R_1')} e^{-\frac{B}{2} (\tan^2 \theta + \tan^2 \theta')} \Delta y \quad (41)$$

where g is defined in Equation (40). Unlike the formulation of Equation (30) for the scattering due to the gravity waves alone, the primed variables and the unprimed variables are not equal. This is because of the simplifications introduced by the image theory. Figure 5-3 defines the variables for this scattering equation. The terms R_1 and R_1' are the distances from the incremental segment, Δy , on the surface $h(y_s)$ to the transmitter and receiver, respectively. These distances are given by

$$R_1^2 = (y - y_0)^2 + (h - h_0)^2 \\ R_1'^2 = \left(yy - y + \frac{(yy + y_0) \sin \theta}{\sin(\frac{\pi}{2} - 2\mu + \theta)} \right)^2 + (h(y_s) - R_0' \sin \theta)^2 \quad (42)$$

where the angles θ, μ, θ and the quantities y, y_0, yy and h_0 are as shown in Figure 5-3. The receiver boresight distance R_0' is

$$R'_0 = R_0 + (yy+y_0)\sin 2\mu / \sin(\pi/2 - 2\mu + \theta) \quad (43)$$

where R_0 is the boresight distance to the transmitter. The antenna pattern angles ξ and ξ' are as defined in Section III. The projections R_2 and R'_2 are given by

$$R_2 = R_0 + y \sin \xi - h(y_s) \cos \theta$$

$$R'_2 = R'_0 - (y - 2y_0 - 2yy) \cos \xi - h(y_s) \sin \xi \quad (44)$$

The limits of this numerical integration, Y_{S1} and Y_{S2} are determined by the 20 dB points of the antenna pattern, as for the gravity wave integration, with one additional constraint. The integration must take into account only those ray paths for which either the transmitted ray or the reflected ray passes through the plate. The limits of integration must satisfy both conditions simultaneously (see Figure 5-4).

The calculations of the double-bounce scatter are made in the subroutine DBS. The subroutine requires as input the position of the radar, and size and position of the plate. The subroutine returns to the main program the complex voltage at the receiver due to the reflections from the ship-sea corner back to the radar. The following pages show typical signatures of several double-bounce geometries.

D. Results for Double-bounce Scatter from the Ship Model

The signatures for the double-bounce scatter contribution, as calculated using Equation (41), are shown in Figure 5-5 for several different model geometries. The magnitude of the receiver voltage, in dB below the reference voltage V_0 , is plotted as a function of the position yy of the radar. As before, a range gate function $C[(R_1+R'_1)/2, 1]$ must be included in Equation (41).

The effect of the depression angle α can be seen by comparing the signatures of Figure 5-5a or 5-5b. Note that for near-grazing incidence angles the double-bounce contribution extends over a greater range. The effect of the dive angle μ can be seen by comparing the signature with $\alpha=60^\circ$ and $\mu=5^\circ$ in Figure 5-5b with the signature in Figure 5-5c that has the same α and μ . A larger dive angle results in a signature less extended in range and shifted in position towards $yy=0$.

Comparing the signatures of Figure 5-5c illustrates the effect of the plate angle μ . The radar return becomes stronger over a wider range for obtuse corner angles ($\mu < 0$), and decreases in magnitude with compressed range for acute corner angles ($\mu > 0$).

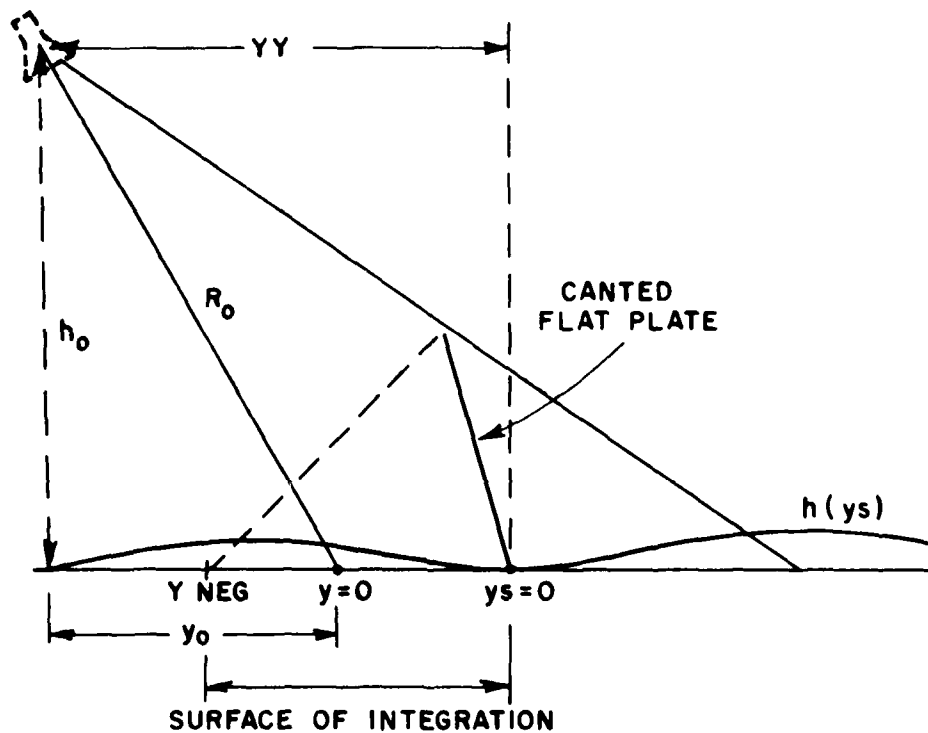


Figure 5-4. Geometry for defining the surface of integration.

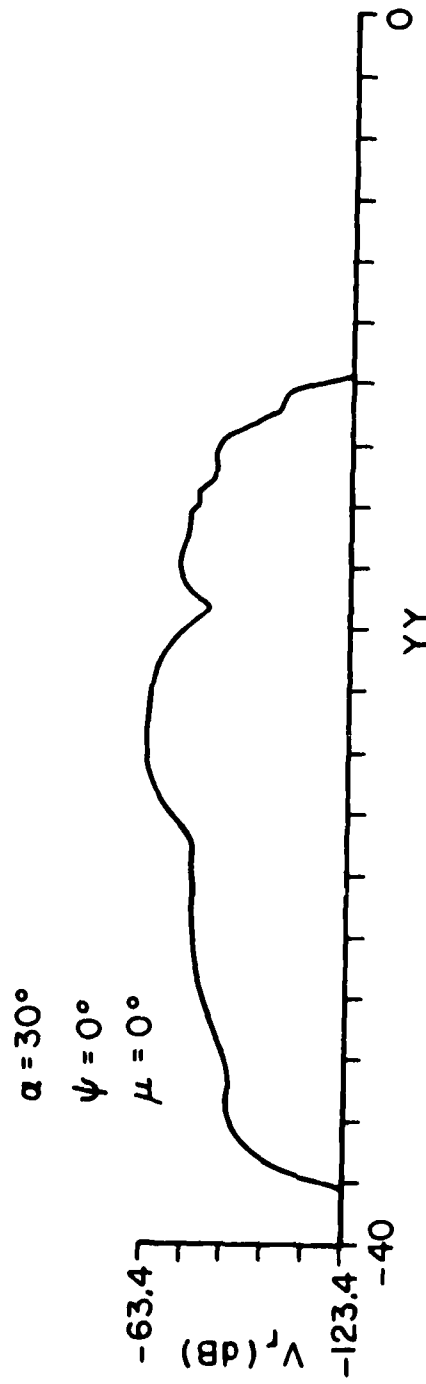
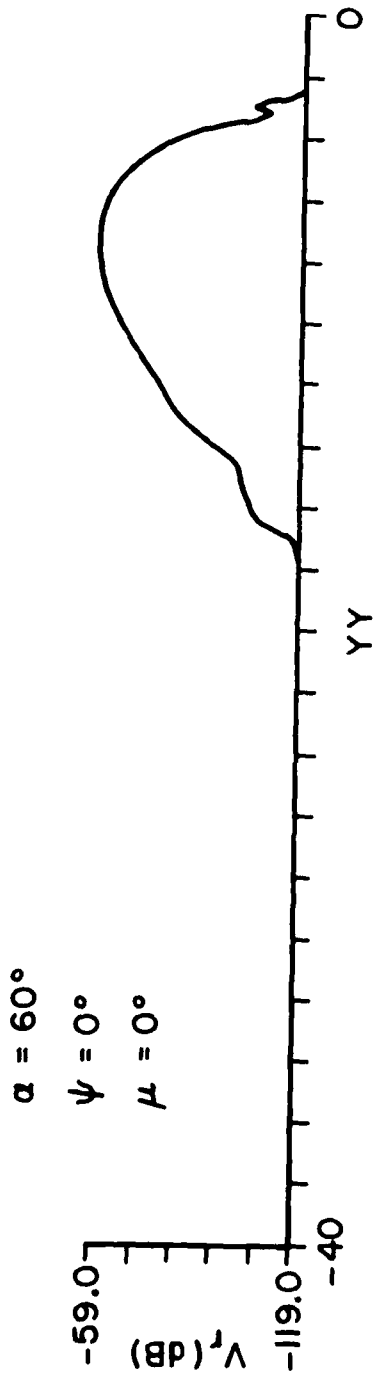


Figure 5-5a. Signatures for double-bounce scatter from a ship model.

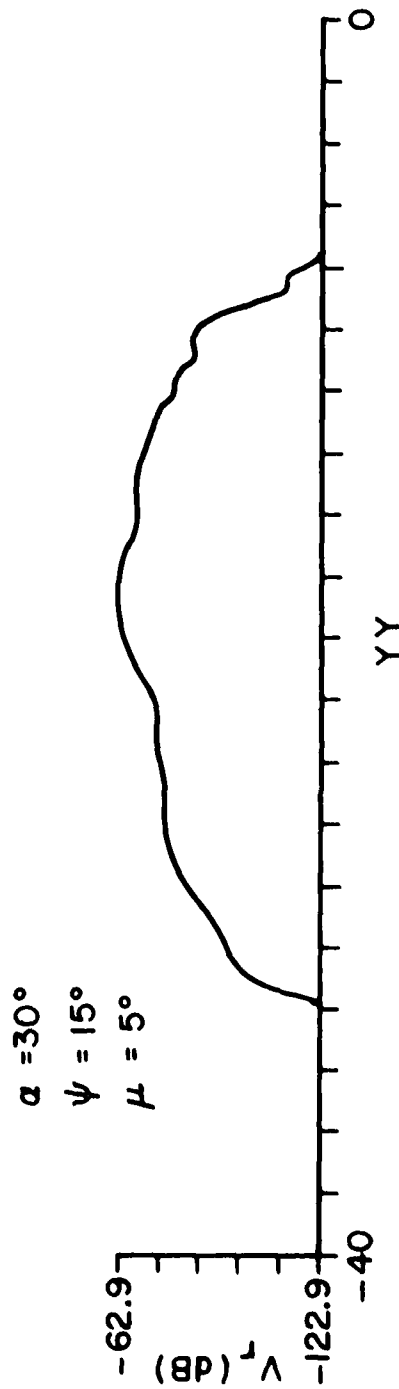
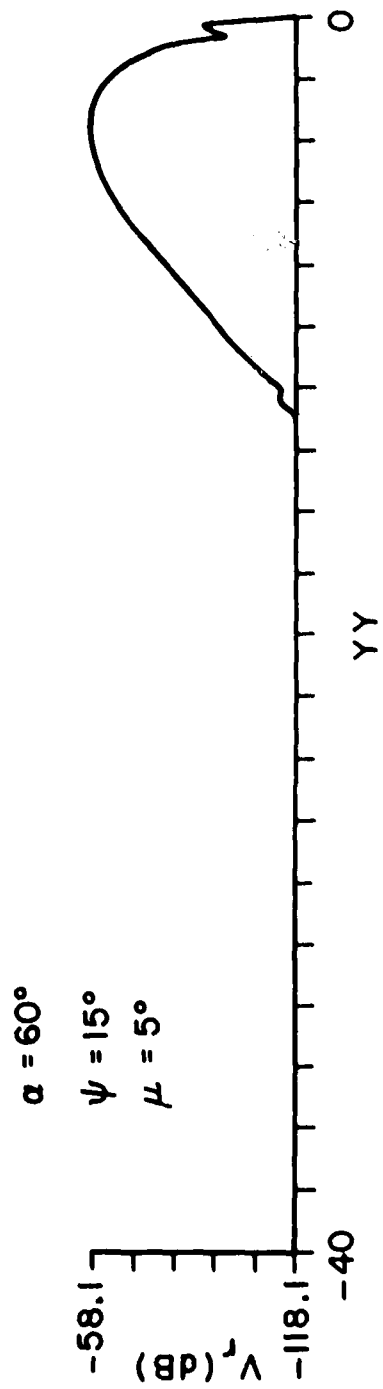


Figure 5-5b. Signatures for double-bounce scatter from a ship model.

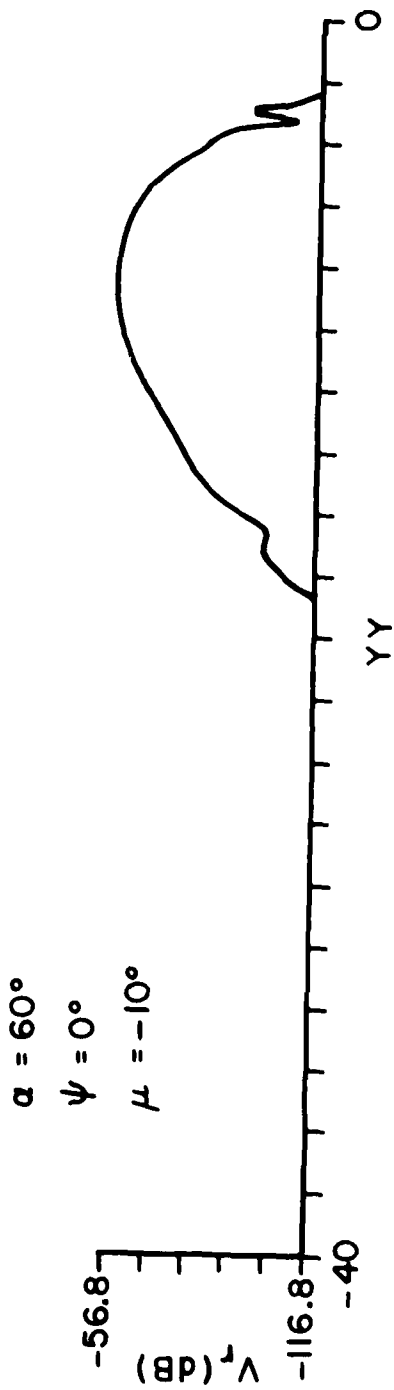
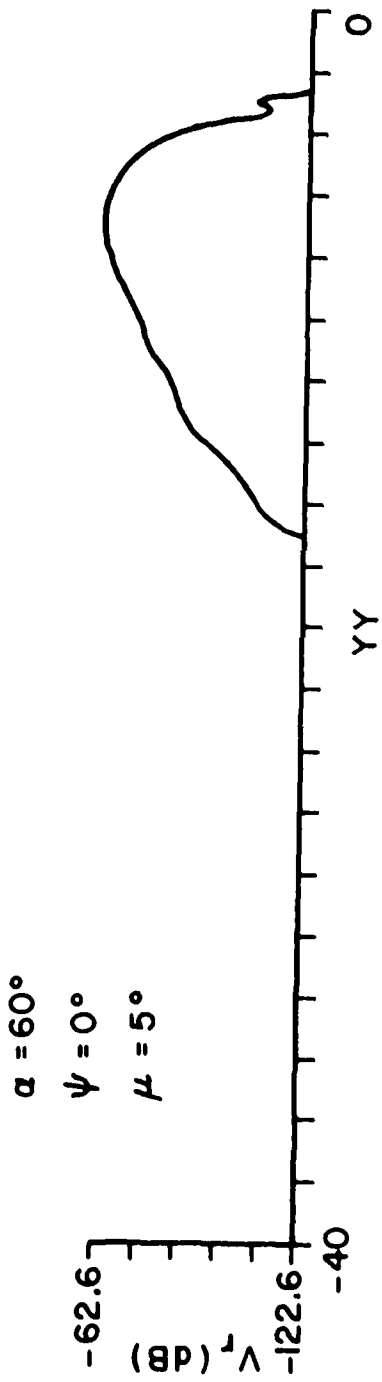


Figure 5-5c. Signatures for double-bounce scatter from a ship model.

CHAPTER VI
BACKSCATTER FROM THE PLATE EDGE

In the previous section it was found that a significant return can be expected from the double-bounce mechanism. There may also be a contribution due to diffraction from the edge of the plate. When an incident or reflected field interacts with the edge of the plate, there is a field diffracted in all directions. Because of the method of solving for the double-bounce scattering, the edge-sea surface interactions have been accounted for. Hence, the only field contribution that has not been considered is that which is diffracted directly back to the radar. The Geometrical Theory of Diffraction (GTD) is used to study this contribution.

A. Geometry

The GTD solution requires only a knowledge of the plate and radar positions; the sea surface does not affect the direct diffraction from the plate edge. As before, the radar approaches from the negative y-direction, with the distance from the radar to the plate edge defined as R_g . The geometry of the plate and radar is shown in Figure 6-1.

B. Equation for Backscatter

Since here we are only concerned with the edge diffraction, the flat plate can be considered as the limiting case of the wedge, for which much work has already been done. In reference [4] an expression is given for the diffracted field from a wedge. For receiver distances R from the edge which are approximately equal to the distance R_0 of the source from the edge, this diffracted field is given as

$$u^d = \frac{e^{-jk(R+R_0)}}{(R+R_0)} e^{jk\left(\frac{RR_0}{R+R_0}\right)} \left[V_B\left(\frac{RR_0}{R+R_0}, \psi' - \psi'_0\right) \pm V_B\left(\frac{RR_0}{R+R_0}, \psi' + \psi'_0\right) \right] \quad (45)$$

where the choice of sign (\pm) is determined by the polarization of the field. The minus sign applies for an electric field polarized parallel to the edge, and the plus sign for perpendicular to the edge. V_B is the diffraction function and is defined in Reference [4]. The angles ψ' and ψ'_0 are defined in Figure 6-1, and are equal for a monostatic radar. Similarly, the distances R and R_0 are equal and are defined in Figure 6-1 to be the distance R_g . Equation (45) then simplifies to

$$u^d = \frac{e^{-j2kR_g} e^{jkR_g/2}}{2R_g} [V_B(R_g/2, 0) - V_B(R_g/2, 2\psi_0')] \quad (46)$$

Here we have chosen the minus sign since we are dealing only with horizontal polarization.

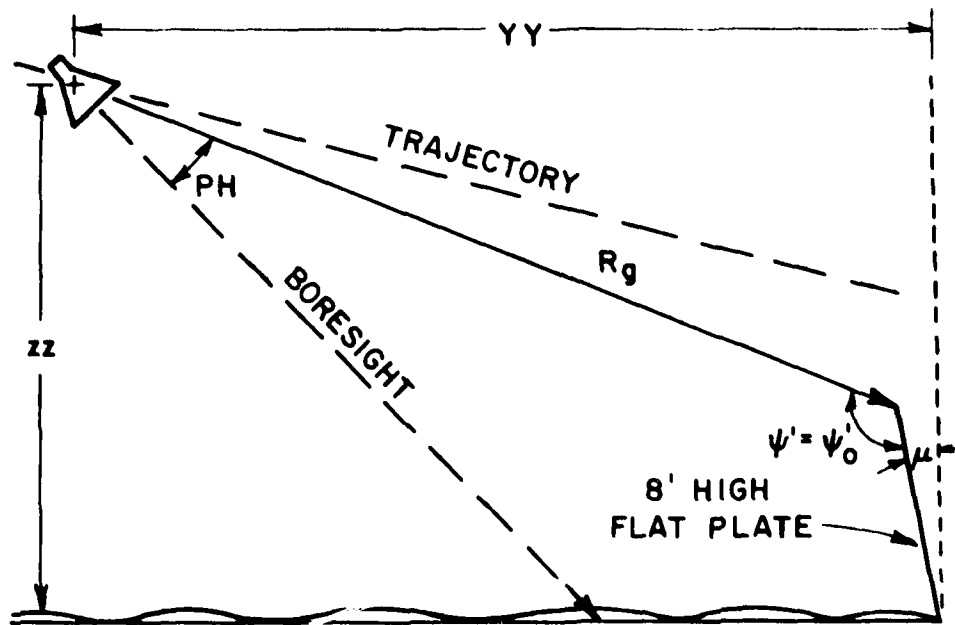


Figure 6-1. Geometry for edge diffraction.

C. Discussion of Edge Diffraction Computer Code

The calculation of the field due to diffraction from the plate edge from Equation (46) is straight forward. This calculation is made in subroutine GTDFP. The subroutine uses a computer code already available at the ElectroScience Laboratory for the computation of the diffraction function V_B . The inputs required for the subroutine are the position of the radar, and size and position of the plate. The subroutine returns the voltage at the receiver due to the diffracted

field. The calculation is made for each new position of the radar. Some diffraction signatures are shown in the following section.

D. Results for Edge Diffraction From Plate

The signatures for the field diffracted from the plate edge are shown in Figure 6-2. The model geometries that are shown for the diffraction mechanism are some of the same geometries shown for the double-bounce mechanism, Figure 5-5. Again, the range gate function $C(R_g, l)$ must be included in Equation (46).

Note that as in the double-bounce backscatter (Figure 5-5), the diffraction signatures extend over a greater range but are smaller in magnitude for near grazing incidence angles. Tilting the plate results in a shift of the position of the maximum return. Increasing the dive angle also results in a signature extended over a greater range.

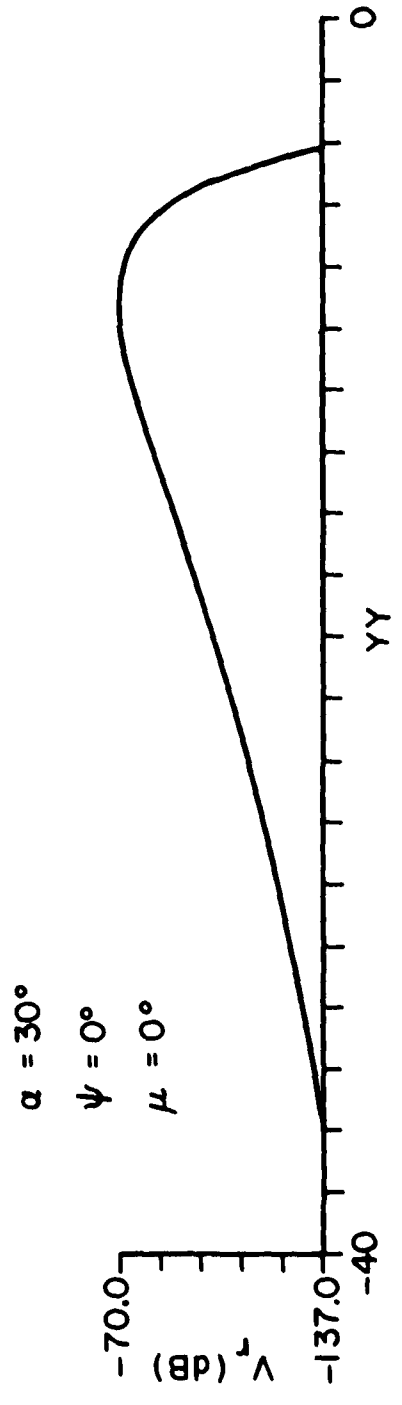
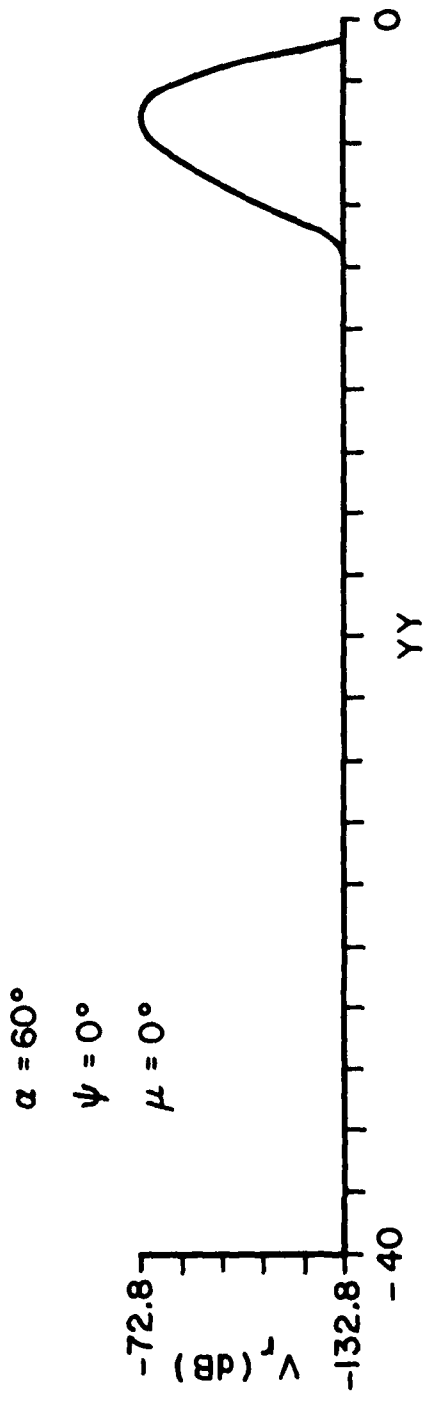


Figure 6-2a. Signatures for diffraction from plate edge.

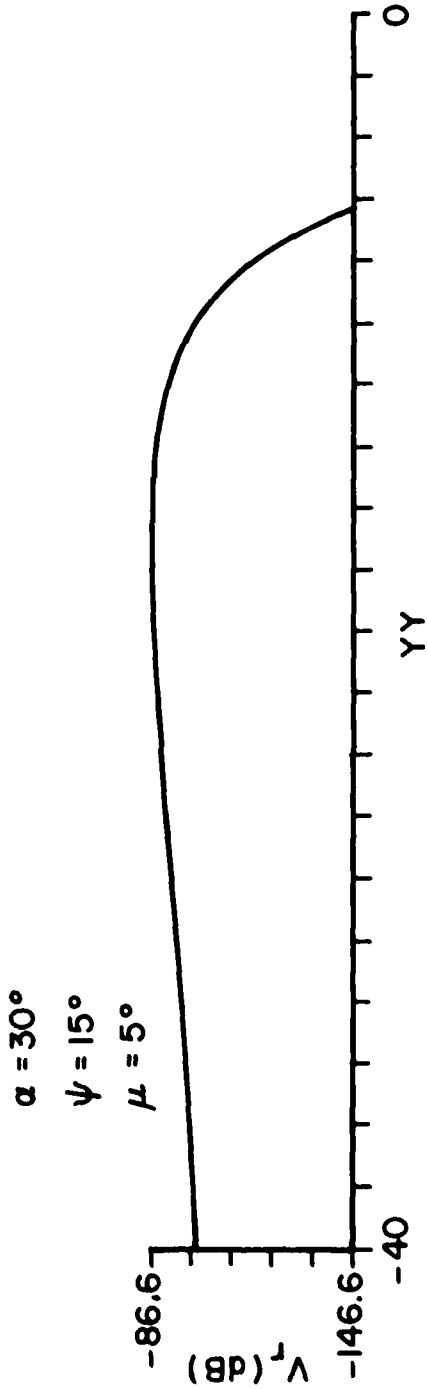


Figure 6-2b. Signatures for diffraction from plate edge.

CHAPTER VII COMPLETE MODEL FOR SHIP-SEA SCATTERING

The previous sections illustrated the four principal mechanisms for backscattering. Each mechanism was considered independently of the others to show how each contributed to the total ship-sea backscattering problem. Since we are measuring the voltage at the receiver, superposition allows us to sum the voltages due to each of the independent scattering mechanisms. The result is the measured receiver voltage due to scattering from the complete ship-sea model (Figure 1-1).

A. Comparison with Measured Results

Figure 7-1 shows the comparison between a signature calculated by superposition, and the signature for the corresponding geometry as measured at the Encounter Simulation Laboratory. A check of the accuracy of the absolute level of the calculated receiver voltage can be obtained by using the return from a calibration sphere as a reference. The sphere return was calculated using the radar range Equation [5] for a 14" diameter sphere placed 18'7" from the trajectory of the radar. From Figure 7-1 it is clearly seen that the calculated and measured magnitudes of the scattering signatures are at the same level relative to the calibration sphere return. In all of the signatures in Figure 7-2, the level of the experimental signature relative to the calculated signature was determined by superimposing the calculated and measured sphere responses. The measured signatures are also identified by the experimental run number [3].

Figure 7-2 shows the comparison between the complete model signatures and the experimental data for a variety of model geometries. In all signatures the short range gate was used. Note that in most of the signatures the double-bounce contribution is easily identifiable as a change in the magnitude of the signature. In the geometries of Figures 7-2a through 7-2c, the contribution from edge diffraction can be seen as the last lobe on the signature. In all of the signatures the quasi-random return from the trapezoids is modulated by the gravity wave (sinusoidal) contribution in the "clutter" region of the signature.

$\alpha = 60^\circ$
 $\psi = 0^\circ$
 $\mu = 0^\circ$
----- EXPERIMENTAL RUN # 38

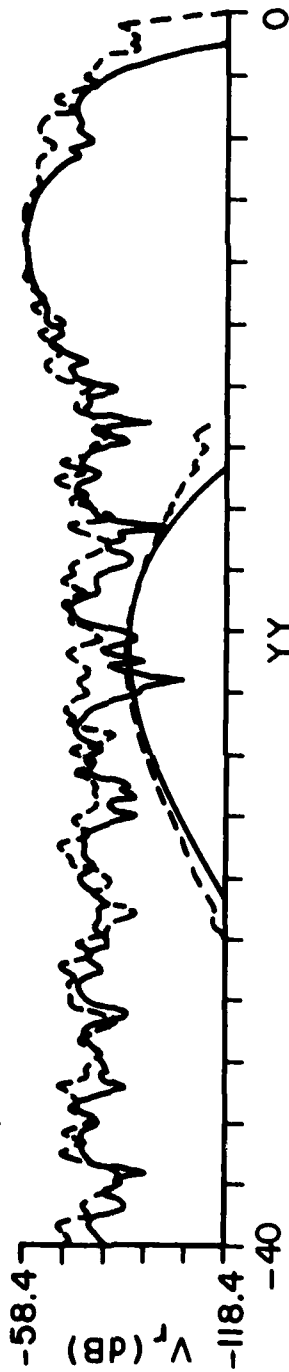


Figure 7-1. Comparison of experimental and calculated signatures showing calibration sphere response.

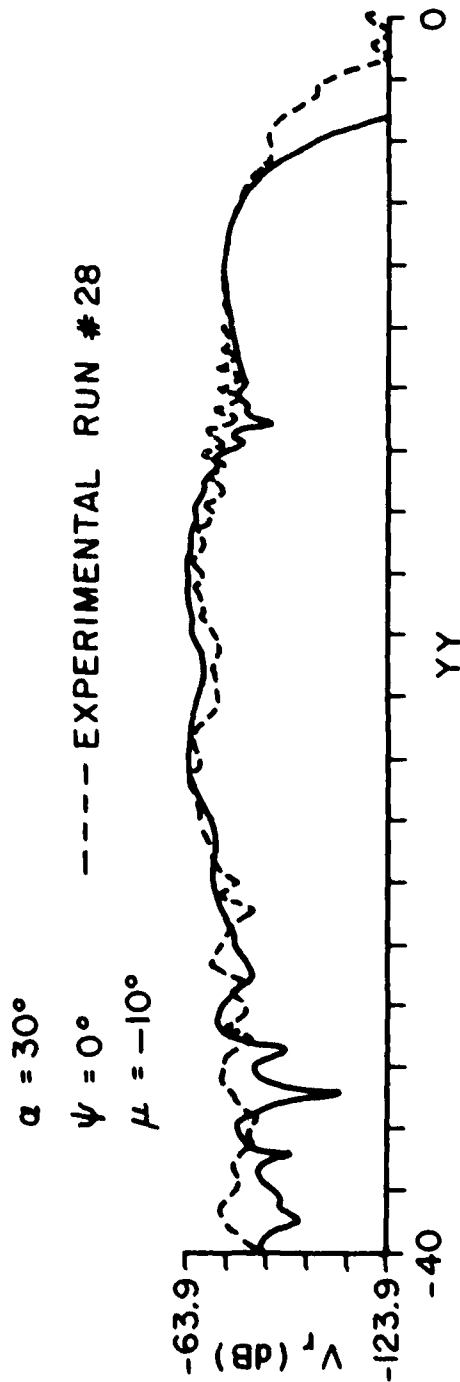
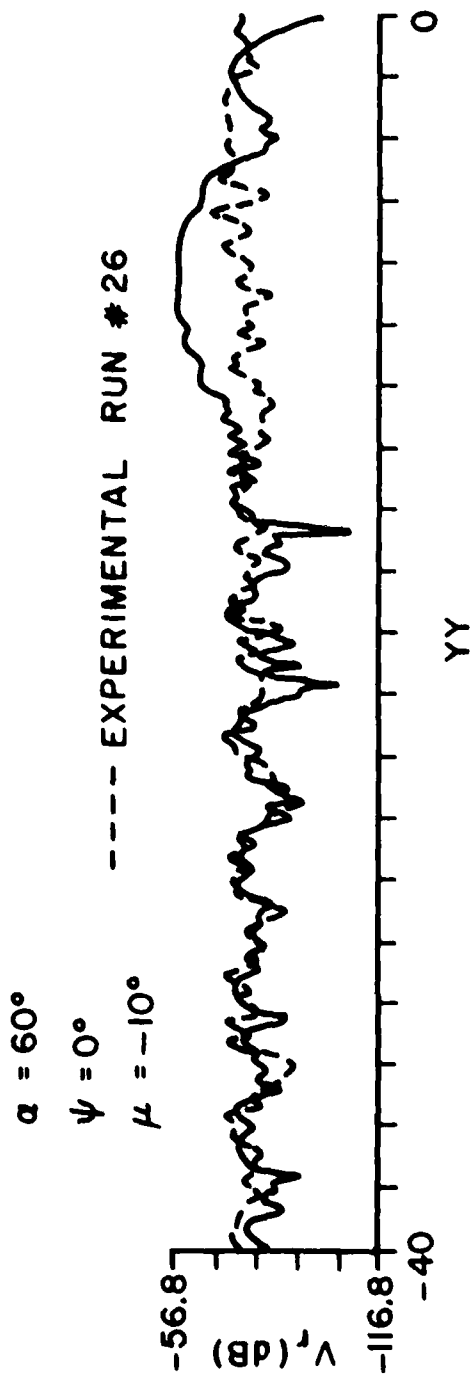


Figure 7-2a. Comparison of calculated and experimental signatures.

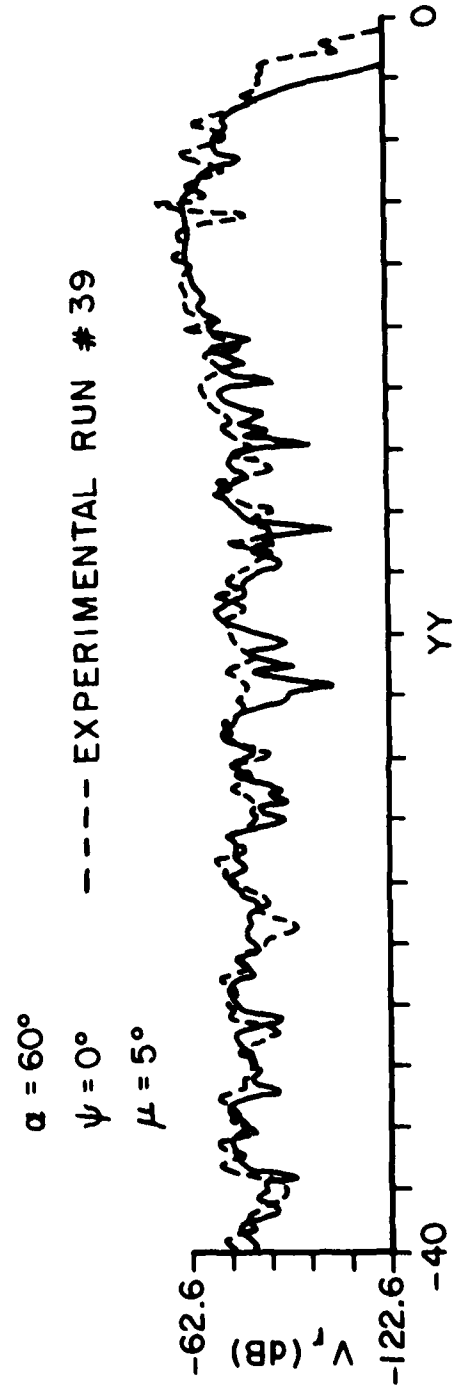
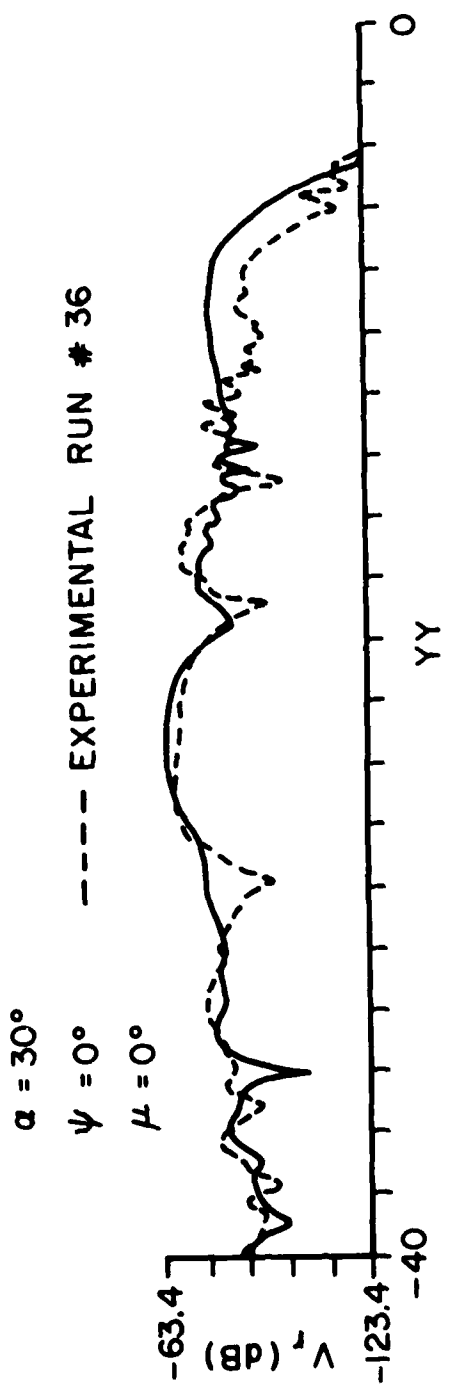


Figure 7-2b. Comparison of calculated and measured signatures.

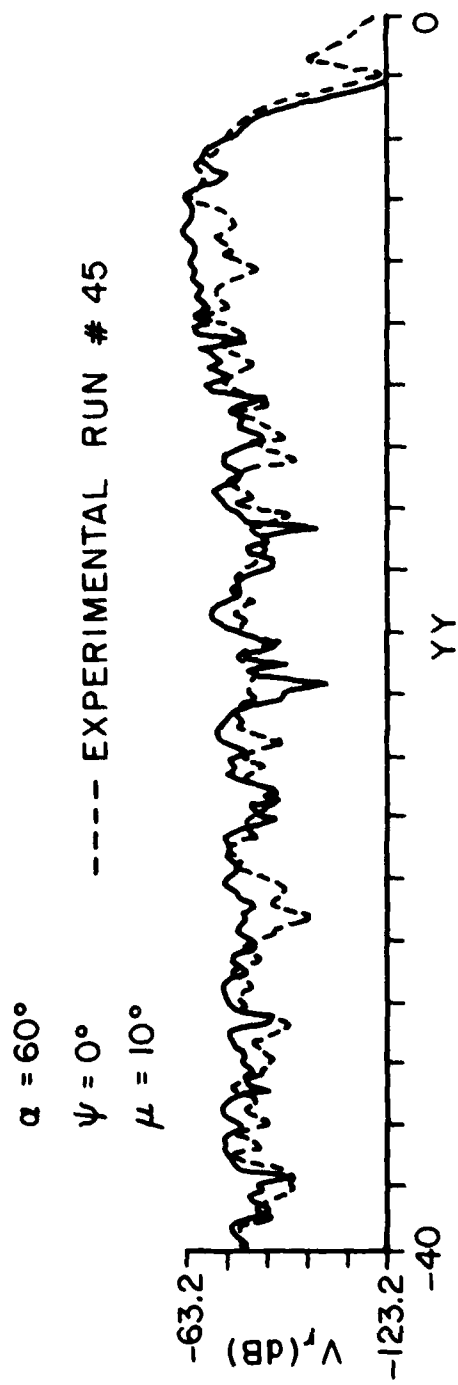
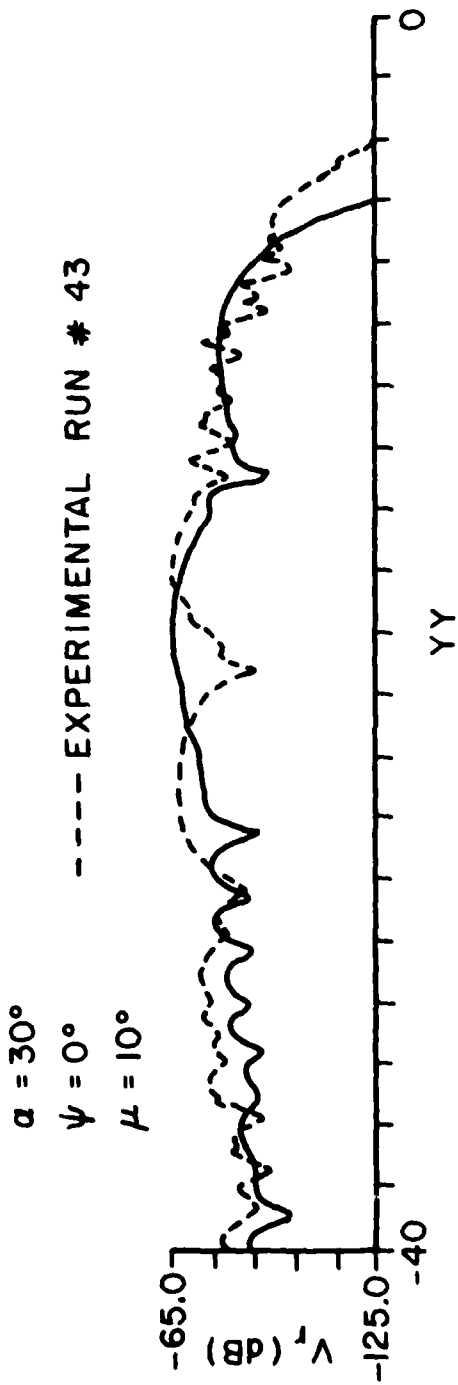


Figure 7-2c. Comparison of calculated and measured signatures.

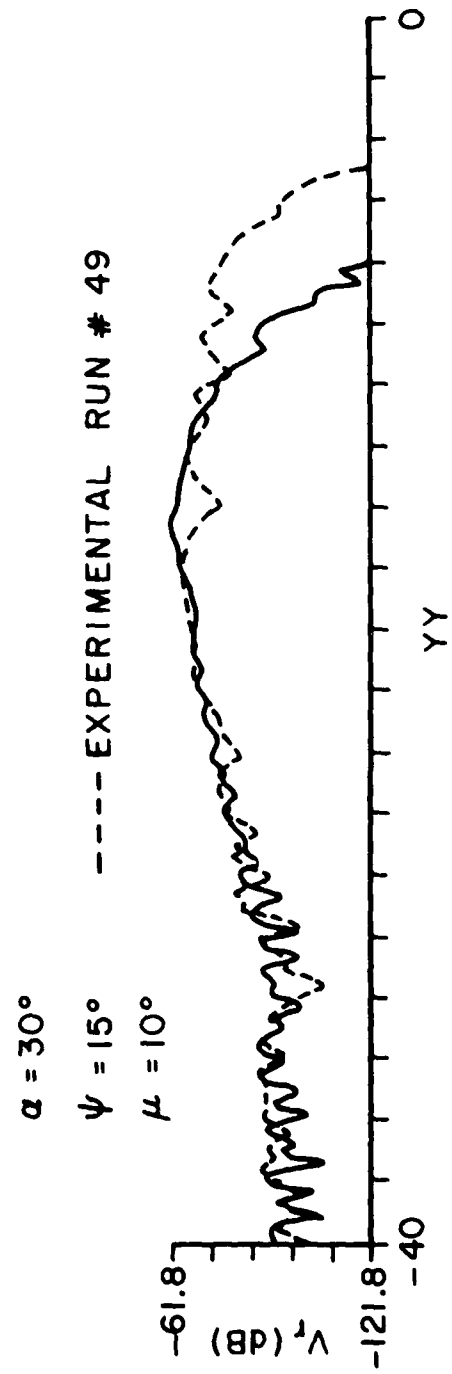
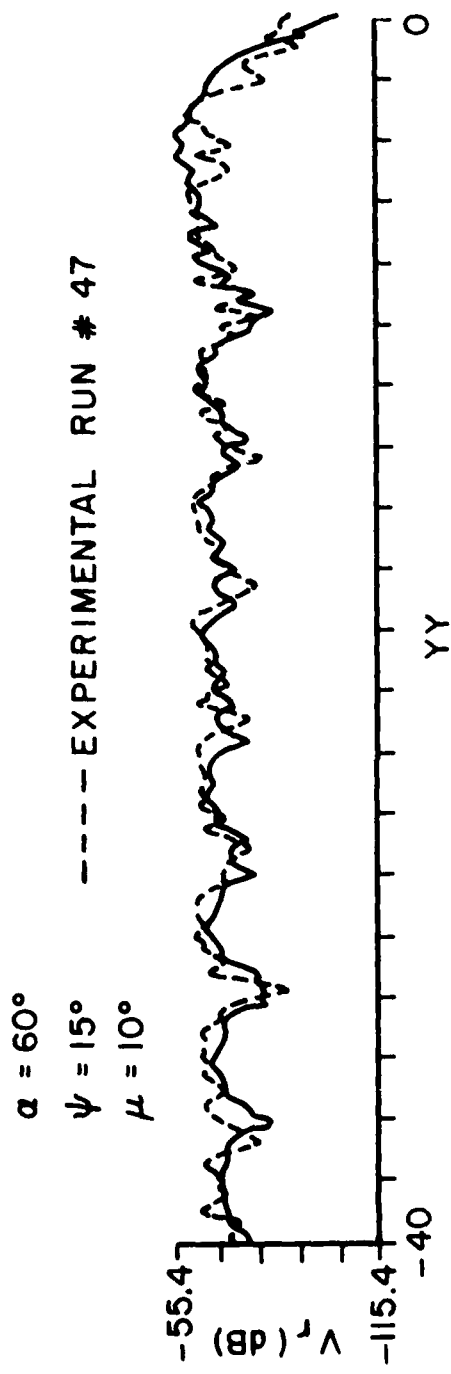


Figure 7-2d. Comparison of calculated and experimental signatures.

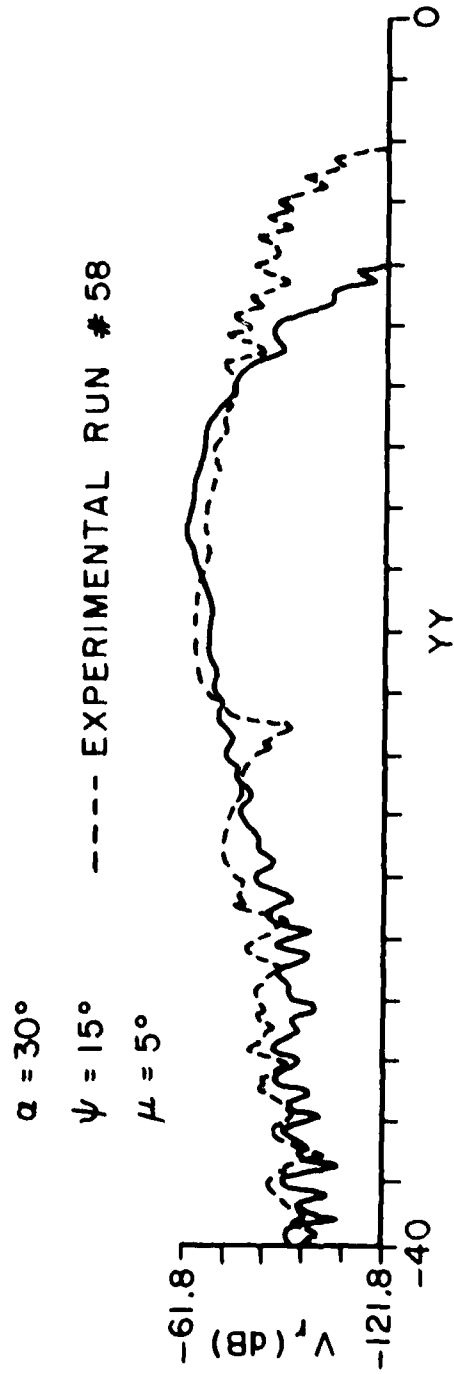
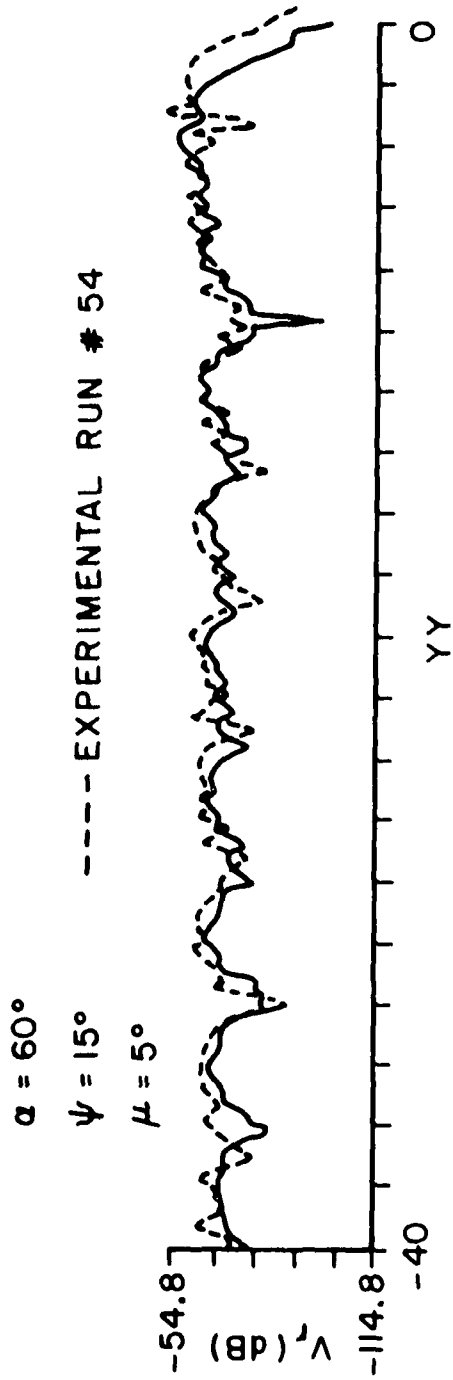


Figure 7-2e. Comparison of calculated and experimental signatures.

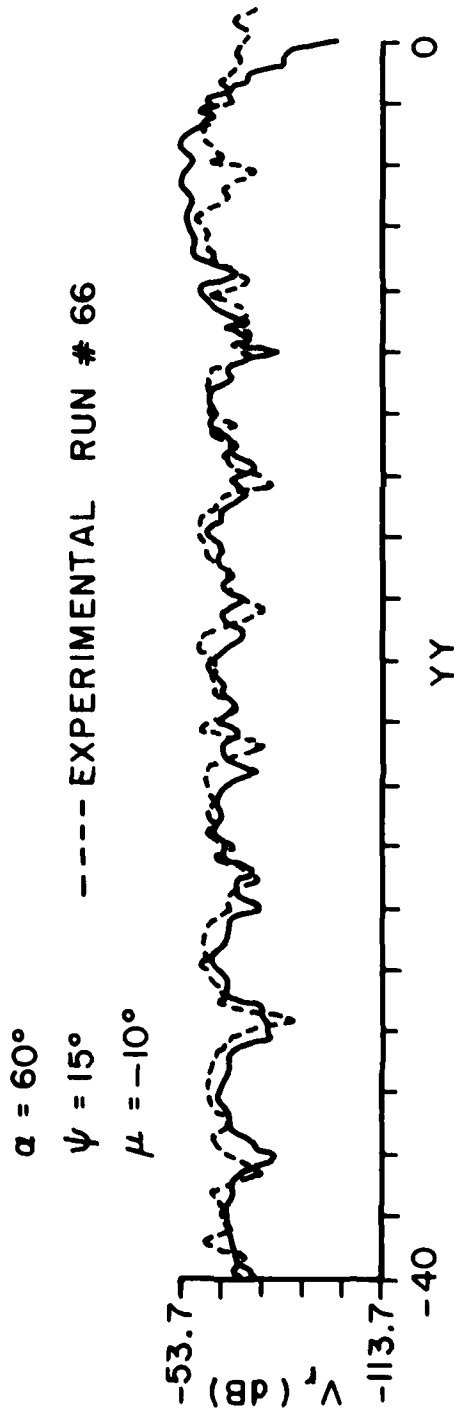
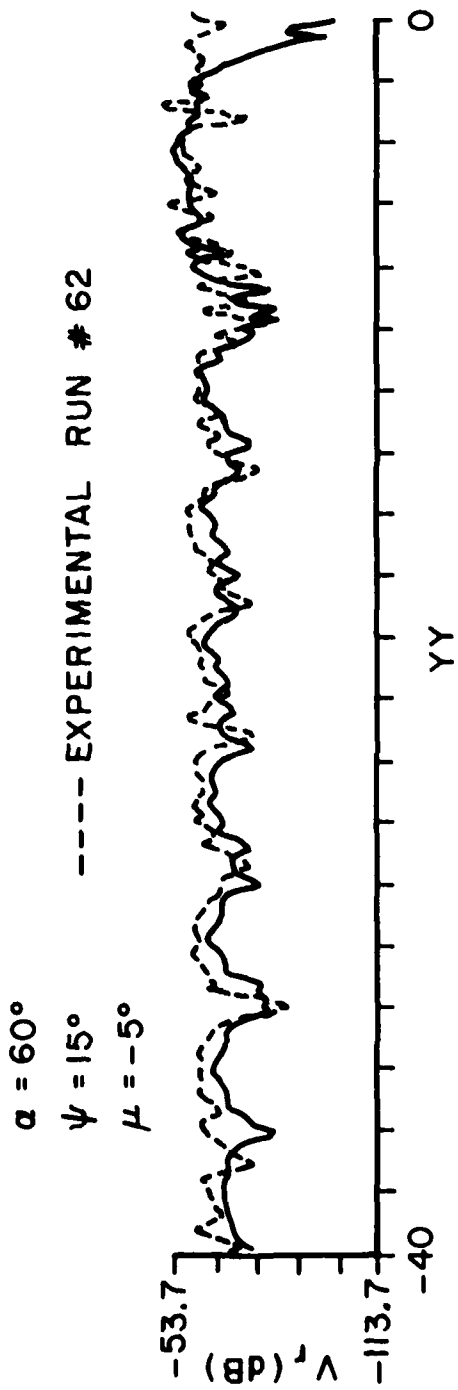


Figure 7-2f. Comparison of calculated and experimental signatures.

CHAPTER VIII SUMMARY AND CONCLUSIONS

The purpose of this report was to develop a method for numerically calculating the backscatter from a simple one-dimensional sea-ship model. The surface was a "composite" model of the sea surface with the large scale gravity waves modeled by a sinusoid and the capillary waves modeled by trapezoids periodically superimposed on the sinusoidal surface. The ship model was composed of a metal flap mounted on the surface model.

For this ship-sea model there are four principal scattering mechanisms that contribute to the backscattered signature; namely, backscatter from the gravity waves, backscatter from the capillary waves, double-bounce scatter from the ship-sea corner, and diffraction from the edge of the plate. Since the surface model was too large to employ the more exact moment method, the first three of these mechanisms were analyzed using the physical optics approximation, while the last mechanism was calculated by a direct application of the Geometrical Theory of Diffraction. The voltage received at the antenna terminals was calculated for each of the scattering mechanisms.

The results were presented in a form showing the contribution from each of the individual scattering mechanisms, and these were then combined to produce the total received voltage as a function of radar position. The resulting signatures compared favorably with the measured data from the Naval Weapons Center, both in absolute level and in the spatial variation of the signature.

Thus, the technique presented here provides an accurate and efficient method of determining the backscatter from simple one-dimensional ship-sea models. The accuracy of the results were limited mainly by the use of the physical optics approximations. The running time of the one-dimensional surface programs could be reduced by employing a faster integration scheme, since no special effort was made to produce an efficient computer code.

It should also be noted that the physical optics technique can be applied to a wide variety of surface structures and experimental configurations provided the integration increments are properly chosen. For example, the antenna power pattern or polarization of the radar system can be easily changed from those used in this study. The ability to separate the contributions of the four scattering mechanisms, and to associate a range and doppler shift with each point on the surface, provides a convenient method for investigating the effects of a variety of range gates, doppler filters, polarizations, etc. on system performance.

APPENDIX
COMPUTER CODE SSSCAT

A listing of the computer code discussed in the text is presented here. To facilitate the understanding of the code, the symbols used in the program have been used in the text whenever possible. Note that the code may employ programming features not universal to all computer systems.

```

1 C PROGRAM USSCAT *** BY DAN RYAN
2 C PROGRAM CALCULATES THE FIELD SCATTERED FROM A
3 C SHIP-SFA MODEL FOR A HORIZONTALLY POLARIZED INCIDENT
4 C FIELD. THE MODEL IS COMPOSED OF A FLAT PLATE MOUNTED
5 C ON A SINUSOIDAL SURFACE.
6 C THE MAIN PROGRAM CALCULATES THE FIELD SCATTERED
7 C FROM THE GRAVITY WAVE MODEL. SUBROUTINE SPPS CALCULATES
8 C THE FIELD SCATTERED FROM THE CAPILLARY WAVE MODEL.
9 C SUBROUTINE DBSGTO CALCULATES THE DOUBLE SOURCE
10 C SCATTER FROM THE CORNER CREATED BY THE SURFACE AND PLATE.
11 C DBSGTO CALLS SUBROUTINE ATOPR WHICH CALCULATES
12 C THE DIFFRACTED FIELD FROM THE PLATE EDGE.
13 C *****
14 C SSSOUT = OUTPUT FILE WHERE DATA IS STORED
15 C ALPHA = ANGLE HOURSIGHT MAKES WITH TRAJECTORY(DEG)
16 C PHID = TRAJECTORY ANGLE MEASURED FROM HORIZONTAL(DEG)
17 C YU = ANGLE PLATE MAKES WITH VERTICAL(DEG)
18 C THETA = ANGLE HOURSIGHT MAKES WITH VERTICAL(DEG)
19 C HEII = PEAK AMPLITUDE OF SURFACE(FT)
20 C HP = HEIGHT OF PLATE(FT)
21 C RI = ALTITUDE OF RADAR ABOVE SURFACE AT YSE=0.(FT)
22 C BWH = HORIZONTAL 3DB BEAMWIDTH(DEG)
23 C VWH = VERTICAL 3DB BEAMWIDTH(DEG)
24 C PHASE = PHASE SHIFT OF SINUSOIDAL SURFACE(DEG)
25 C FL = ELECTRICAL WAVELENGTH(FT)
26 C KP = ELECTRICAL WAVE NUMBER
27 C KM = MECHANICAL WAVE NUMBER
28 C VXYX = COMPLEX VOLTAGE AT RADAR DUE TO FIELD SCATTERED
29 C FROM SEA-SHIP MODEL(VOLTS)
30 C DT = DISTANCE ALONG TRAJECTORY(FT)
31 C TSP = STARTING POINT OF RADAR
32 C DTMZ = INCREMENT ALONG TRAJECTORY(FT)
33 C *****
34 C
35 C
36 C INCLUDE 'FSSB.SYS'
37 C DIMENSION VXYX(200),DT(200)
38 C COMMON/PI/PI,THI,CPH
39 C COMMON/FOUR/YU,ZZ,YU,RO
40 C COMMON/ANG/THETA,THI,PHID,PHI,ALPHA,ALP,YU,MUR
41 C COMMON/SINE/PHASE,HEII,HP,DC,BWH
42 C COMMON/VA/RI,VWH,BWH,AR,EL,VC,M,KP
43 C COMPLEX DENZ,DFVI,PEP
44 C COMPLEX PEI,XI,VR,VXI,VSTP
45 C COMPLEX VXYX,VORS
46 C REAL DT,KP,U,MUR
47 C CALL GETCF(CO)
48 C CALL ASSIGN('SSSOUT',5H3266P,1)
49 C CALL ASSIGN('MESSG',0.,3)
50 C HEII = .146
51 C HEI = HEII
52 C HP = 3.0
53 C RI = 0.00125
54 C BWH = 15.0
55 C VWH = 15.0

```

```

56 PHASE = 10.
57 FL =
58 WM = 4.99736*.3048
59 KP = 2.*PI/EL
60 A = .6931472/(TAN(RWH/114.59))**2
61 P = .6931472/(TAN(RWV/114.59))**2
62 CALL SUPERR(3)
63 VU = 1.0
64 WRITE(8,10)
65 READ(9,-101)
66 10 FORMAT(' TYPE DI=? ')
67 WRITE(8,11)
68 READ(8,-)ALPHA,PHID,MU
69 11 FORMAT(' TYPE ANGLES ALPHA; PHID; MU=? ')
70 WRITE(8,12)
71 READ(8,-)M
72 13 FORMAT(' TYPE 1/2*LONG/SHORT; M=? ')
73 CALL DEASSN
74 THETA = 90.-ALPHA-PHID
75 THI = THETA/DPR
76 PHI = PHID/DPR
77 ALP = ALPHA/DPR
78 MUR = MU/DPR
79 TM2 = 39.4167/COS(PHI)
80 NIM2 = TM2/200.
81 DU = (31-00)/COS(PHI)
82 KKK = 200
83 DO 41 I = 1,KKK
84 WRITE(3,111)M
85 111 FORMAT(' PROGRAM IS IN M=?;I3.' LOOP')
86 CLOSE 3
87 N(N) = N-1
88 TM2 = TM2-NIM2
89 DUP = TM2*SIN(PHI)
90 Z2 = DU+THI
91 YY = TM2*COS(PHI)
92 STA = PI/2.+THI
93 C
94 C THE FOLLOWING SETS UP THE BOUNDARIES OF INTEGRATION
95 C AS DEFINED BY THE BEAMWIDTH.
96 C
97 DU = Z7/SIN(PI/2.-THI)
98 RPO = R0
99 RRO = R0**2
100 RHO = RPO**2
101 CTH = COS(THI)
102 CSH = SIN(THI)
103 RU = Z7
104 YU = -R0*STH
105 YPOS = YU+YU
106 YS1 = YU+R0*TAN(THI-1.3*RWV/DPR)
107 P1 = THI+1.3*RWV/DPR
108 IF(P1.GT.1.55)P1=1.55
109 YS2 = YU+R0*TAN(P1)
110 YS1B = YS1-Y0

```

REF. NOT

```

111      IF (YS2.GT.YPOS)YS2=YP0S
112 C
113 C
114 C      THIS SECTION INTEGRATES OVER THE ANTENNA FOOTPRINT.
115 C      THE RESULT IS THE VOLTAGE RECEIVED BACK AT THE
116 C      POINT OF TRANSMISSION. (VOLTS)
117 C
118 C
119      VAY = (0.0,0.0)
120      IF (YS10.GE.YY)GO TO 31
121      DY = 0.01
122      Y = YS1
123 31     YS = -Y0+YY+Y
124      H2I = HEI1
125      IF (YS.GE.-.08333)H2I=0.
126      H = HEI+HEI*SIN(W*YS+PHASE*PI/180.)
127      YK = YS+.005
128      HK = HEI*SIN(W*YK+PHASE*PI/180.)
129      R2 = H0+Y*STH-H*CLTH
130      RK2 = R2**2
131      RY1 = (Y-Y0)**2+(H-H0)**2
132      RY1 = SQRT(RY1)
133      RRP1 = RK1
134      RP1 = SQRT(RRP1)
135      TNE = (Y*CTH+H*STH)/R2
136      TNE2 = TNE**2
137      RP2 = RPO-Y*DCOS(BTA)-H*STN(BTA)
138      RRP2 = RP2**2
139      TNF2 = H*LOS(BTA)/RP2-Y*SIN(BTA)/RP2
140      IF (TNF2.GT.1.5)TNF2=1.5
141      TNF2 = TNF2**2
142      IF (TNF2.GT.2.)TNF2=2.
143      T = -R1*(R1+RRP1+RR2+RRP2+RR2+RRP2+RR1+R01)
144      S = -(T*RR1+RRP1+RRP2+RR2+RRP1+RRP2+3.*RR1+RR2+RRP2)
145      S = S-RRR1+RRP1+RR2
146      HEN2 = CMPLX(S,T)
147      CLF1 = CSQRT(HEN2)
148      RE = -R0*(1+RP1)+PI/2.
149      RE0 = P.0
150      REP = CMPLX(RE0,RE)
151      REP1 = CLXP(REP)
152      Y1 = R0+R2**2.*RRP2*REP1/DFN1
153      PH = ATAN(W*HEI*DCOS(W*YS+PHASE*PI/180.))
154      AJ1 = CTH+STH*TAN(PH)+Y/P0*TAN(PH)-H/H0
155      ABF = AB1/H1
156      CLE0 = EXP(-H/2.*TNE2)
157      CLE0P = EXP(-H/2.*TNF2)
158      CLE0P = CLE0
159      P = (H1+RP1)/2.
160      VX = -1.*X1*DY*ARL*CLE0*CLE0P*V0*C(R.*PI)/SQRT(PI*P.)
161      VAY = VXY+VX
162      Y = Y+DY
163      IF (Y.LE.YS2) GO TO 31
164      DO B1 UU=1,40
165      DO B1 W=1,2

```

THIS PROGRAM IS NOT PRACTICABLE.
 THE PROGRAM IS ONLY A
 SIMULATION OF THE THEORY WHICH DO NOT
 INCLUDE THE EFFECTS OF

```

166      YN=JN*0.46667+0.125
167      TF(K,LC,2)Y=YM-0.14567
168      CALL SPHS(VSTP,YM)TN1)
169      VAY=VXY+VSTP
170      81 CONTINUE
171      51 CALL D3SGTD(VCRS,YY,ZZ)
172      VXY(N) = VXY+VCRS
173      41 CONTINUE
174      WRITE(1) (VXY(N),N=1,KKK)
175      CALL GETCP(NCP)
176      CP = (NCP-NC0)/IUN.
177      WRITE(3,600)CP
178      800 FORMAT('0',10X,'TOTAL CPIS=',F8.2)
179      CALL EXIT
180      END
181 C
182 C
183      BLOCK DATA
184      LOGICAL LTEST,(DEBUG
185      DIMENSION P(5),L(5)
186      REAL L
187      COMMON/TEST/LTEST,DEBUG
188      COMMON/PIS/PI,TPI,TPR
189      COMMON/PIS/P,L
190      DATA PI,TPI,TPR/3.1419265,6.2831531,57.29577950/
191      DATA LTEST,DEBUG/.FALSE.,.FALSE./
192      DATA P/0.04069,0.026460,0.04059,0.021,0.026/
193      DATA L/-1.0,-1.0,1.0,-1.0,-1.0/
194      END
195 C
196 C
197 C
198 C
199      RANGE GATE.
200      FUNCTION C(R,M)
201 C
202 C
203 C
204 C
205 C
206 C
207 C
208 C
209 C
210 C
211      4 CONTINUE
212      RETURN
213      END
214 C
215 C
216 C
217 C
218 C
219 C
220 C

```

SUBROUTINE SPHS CALCULATES THE SCATTERING FROM THE SMALL TRAPEZOIDAL PERTURBATIONS THIS IS A BRAGG SCATTER CONTRIBUTION

```

221 SUBROUTINE SPHS(VSTP,YP4,THI)
222 DIMENSION H(5),L(5),HS(5),YP(5),DWT(5),SIG(5)
223 COMMON/SURF/PHASE,HEII,HP,DD,WM
224 COMMON/ANT/RWV,BWH,A,R,FL,VO,M,KP
225 COMMON/PIS/PI,TM1,OPR
226 COMMON/ELNE/YY,ZZ,YJ,RO
227 COMMON/PIS/M,L
228 COMPLEX U,VSTP,DEI2,DEI1,VS,ANB,CARR
229 REAL L,KP,NU
230 U=(0.,1.0)
231 NU=ATAN(.35563/1.10677)
232 RHO=49.3496/OPR
233 CTH = SIN(THI)
234 CTH = COS(THI)
235 YSEYM
236 HET = HEII
237 YP(YSEYM,--,.28333)HET=0.
238 H=HEII+HET*SIN(WM*YS+PHASE*PI/180.)
239 NU=ZZ
240 DHE=H*HEII*COS(WM*YS+PHASE*PI/180.)
241 EPS=ATAN(DHE)
242 C
243 C
244 C THE FOLLOWING DEFINES THE GEOMETRY OF THE
245 C TRAPEZIODS. HS AND YP DEFINE THE POSITION OF THE
246 C CURRENT ELEMENT IN EACH SEGMENT.
247 C
248 C
249 HS(1)=H(1)*SIN(NU-EPS)
250 HS(2)=H(2)*COS(EPS)
251 HS(3)=H(3)*SIN(NU+EPS)
252 HS(4)=H(4)*SIN(-EPS)
253 HS(5)=H(5)*SIN(-EPS)
254 C
255 YP(1)=H(1)*COS(NU-EPS)
256 YP(2)=H(2)*SIN(EPS)
257 YP(3)=H(3)*COS(NU+EPS)
258 YP(4)=H(4)*COS(EPS)
259 YP(5)=H(5)*COS(EPS)
260 C
261 SIG(1)=RHO+EPS
262 SIG(2)=EPS
263 SIG(3)=RHO-EPS
264 SIG(4)=EPS
265 SIG(5)=EPS
266 C
267 DWT(1)=.046*COS(RHO+EPS)
268 DWT(2)=.041*COS(EPS)
269 DWT(3)=.044*COS(RHO-EPS)
270 DWT(4)=.152*COS(EPS)
271 DWT(5)=.052*COS(EPS)
272 C
273 C THIS SECTION CALCULATES THE VOLTAGE AT THE
274 C RECEIVER DUE TO THE FIELD SCATTERED FROM
275 C EACH SEGMENT OF THE TRAPEZOID. (VOLTS)

```

```

276 C      VSTP=(0.,0.)
277      RU 70 N=1.5
278      HH=HS(N)+H
279      YT=YD+YY+YM+YP(N)
280      RZ=RO+YT*STH-HH*CTH
281      RR2=R2**2
282      RR1=(YT-YO)**2+(HH-HO)**2
283      R1=SQRT(RR1)
284      TN=(YI*CTH+HH*STH)/R2
285      TMT=TN**2
286      IF(TMT.GE.2.)TMT=2.
287      S=2./R1+A/RR2
288      TEMP/R1
289      DEN2=CMPLX(S,T)
290      DEN1=CSQRT(DEN2)
291      REC=LN(1)*SI(SIG(N))*(YT+RO*STH)+COS(SIG(J))*(HH-RO*CTH)
292      RLU=(HH-RO*CTH)**2+(YT+RO*STH)**2
293      RLU=SQRT(RLU)
294      CLFO=EXP(-R*TMT)
295      ARH=-2.*J*P*RR1
296      CARH=CEXP(ARH)
297      VS=-V0*J*REL/RLU*QWY(N)*CLFO*CARH/DEN1/2./R1/SQRT(R1)
298      VS=VS*(N1,1)
299      IF(N.GE.4)VS=-VS
300      VSTP=VSTP+VS
301      CONTINUE
302 70      RETURN
303      END
304
305 C
306 C
307 C
308 C
309 C      THIS SUBROUTINE CALCULATES THE DOUBLE BOUNCE
310 C      SCATTER FROM A FLAT PLATE AT A SPECIFIED ANGLE TO A
311 C      COMPOSITE SINUSOIDAL SURFACE. THE SOLUTION ALSO
312 C      CONTAINS THE EDGE DIFFRACTION FROM THE TIP OF
313 C      THE PLATE. THE FIELD IS HORIZONTALLY POLARIZED.
314 C
315 C
316 C      SUBROUTINE HBSGT(DVDP,YY,ZZ)
317 C      COMMON/ANG/THETA,THI,PHI,PHI,ALPHA,ALP,MU,MUR
318 C      COMMON/SURF/PHASE,HEI,HP,UR,WR
319 C      COMMON/ANT/HW,SWH,A,R,EL,V0,KP
320 C      COMPLEX LEM2,DFN1,PEP
321 C      COMPLEX PEP1,XI,V1,VXY,VDS
322 C      COMMON/PIS/PI,TPI,DPR
323 C      COMPLEX EXY,UD
324 C      REAL AP,MU,MUR
325 C      HEI = HEI
326 C      RTA = PI/2.-THI+2.*MUR
327 C
328 C      THE FOLLOWING SETS UP THE BOUNDARIES OF INTEGRATION
329 C      AS DEFINED BY THE BEAMWIDTH.
330 C

```



```

441      PH02 = 2.*PH00
442      CALL VP(RUH1,VUH1,RGH,PH00,FV)
443      CALL VP(RUH2,VUH2,RGH,PH02,FV)
444      VBC1 = CMPLX(RUH1,VUH1)
445      VBC2 = CMPLX(RUH2,VUH2)
446      VBC = VBC1-VBC2
447      DU = ANTE*(AP*VBC/(2.*RG))/KP
448      RETURN
449      END

451 C
452 C
453 C
454 C
455 C      SUBROUTINE FRESNEL(C,S,XS)
456 C!!!
457 C!!! THIS IS THE FRESNEL INTEGRAL SUBROUTINE WHERE THE INTEGRAL IS FROM
458 C!!! X=0 TO XS, THE INTEGRAND IS EXP(-U*PI/2,0.001), AND THE OUTPUT IS
459 C!!! C(XS)-J0S(XS).
460 C!!!
461      DIMENSION A(12),B(12),CC(12),D(12)
462      LOGICAL LTEST,LOEBUG
463      COMMON /PIS/PI,TP1,UPR
464      COMMON /LST/LTEST,LJBUG
465      DATA A/1.295769140,-0.000001702,-6.808544854,-0.000576361,6.920691
466      0902,-0.0118796657,-3.050465640,-0.075752419,0.250463781,-0.02563904
467      01,-0.150230960,0.034404779/
468      DATA B/0.000000033,4.255387524,-0.000092410,-7.750020400,-0.00952
469      0099,5.075161296,-0.138341947,-1.363724124,-0.403349276,0.70222,01
470      06,-0.21195929,0.010547001/
471      DATA CC/0,-0.024933975,0.000003036,0.005770056,0.000689692,-0.009
472      497135,0.011948099,-0.006748873,0.000246420,0.002102967,-0.0012179
473      030,0.000233939/
474      DATA D/0.109471140,0.000000023,-0.000351341,0.00023006,0.00485146
475      06,0.001903218,-0.017122014,0.024064067,-0.027225555,0.016497308,-0
476      005594515,0.000833386/
477      IF(XS.LE.0.0) GO TO 414
478      Y=XS
479      Z = PI*X*X/2.0
480      FR=0.0
481      FI=0.0
482      K=13
483      IF(X=4.0) 10,40,40
484 10      Y=X/4.0
485 20      K=K-1
486      FR=(FR+A(K))*Y
487      FI=(FI+B(K))*Y
488      IF(K=2) 30,30,20
489 30      F=(FR+A(1))
490      FI=FI+B(1)
491      C=(FR*COS(X)+FI*SIN(X))*SQRT(Y)
492      S=(FI*SIN(X)-FR*COS(X))*SQRT(Y)
493      GO TO 1
494 40      Y=4.0/X
495 50      K=K-1

```

```

496      FR=(FR+CC(K))*Y
497      FI=(FI+Q(K))*Y
498      IF(K=2) GO,60,50
499  60   FR=FR+CC(1)
500      FI=FI+Q(1)
501      C=0.5*(FR*COS(X)+FI*SIN(X))*SQRT(Y)
502      S=0.5*(FR*SIN(X)-FI*COS(X))*SQRT(Y)
503      GO TO 1
504  414  C=-0.0
505      S=-0.0
506  1    IF(.NOT.LTEST)GO TO 2
507  2    RETURN
508      END
509  -----
510  SUBROUTINE VR (RVS,UVH,P,ANGLE,FN)
511  C!!!
512  C!!! THIS SUBROUTINE IS FOR THE VR CALCULATIONS WHERE RVS IS THE REAL
513  C!!! PART, UVH IS THE IMAGINARY PART, K IS THE DISTANCE IN WAVELENGTHS.
514  C!!! ANGLE IS IN DEGREES, AND FN IS N DEFINED BY THE WEDGE ANGLE.
515  C!!!
516      COMPLEX UEA, TOP*COM*EXP(I*PPI,0),PT
517      LOGICAL LTEST, LDEBUG
518      COMMON /FIS/PI, TPI, DPR
519      COMMON /TEST/ LTEST, LDEBUG
520      ANGE=ANGLE/DPR
521      UY=CMPLX(0.0, FN*SQRT(TPI))
522      TOP=CEXP(CMPLX(0.0, -(TPI*FN+PI/4.0)))
523      COM=TOP/UEA
524      CNS=(PI+ANGE)/(2.0*FN*PI)
525      SGN=SIGN(1., CNS)
526      N=IFIX(ABS(CNS)+0.5)
527      DN=SGN*FLOAT(N)
528      A=1.0+COS(ANGE-2.0*FN*PI*DN)
529      BOTL = 2.0*SQRT(ABS(A))
530      CAP=CEXP(CMPLX(0.0, TPI*A))
531      CALL FNMPLS (C,S,BOTL)
532      C=SQRT(PI/2.0)*(0.5-C)
533      S=SQRT(PI/2.0)*(S-0.5)
534      RAG=(PI+ANGE)/(2.0*FN)
535      TSIN= SIN(RAG)
536      TS=ABS(TSIN)
537      X=10.)
538      Y=1.0/X**5
539      IF(TS,GT,Y) GO TO 442
540      COMPE=SQRT(2.0)*FN*SIN(ANGE/2.0-FN*PI*DN)
541      IF(COS(ANGE/2.0-FN*PI*DN).LT,0.0) COMPE=-COMPE
542      GO TO 443
543  442   DN=SQRT(A)*COS(RAG)/TSIN
544      COMPE=0
545  443   UPI=COM*EXP*COM*CMPLX(C,S)
546      CNS=(PI+ANGE)/(2.0*FN*PI)
547      SGN=SIGN(1., CNS)
548      N=IFIX(ABS(CNS)+0.5)
549      DN=SGN*FLOAT(N)
550      A=1.0+COS(ANGE-2.0*FN*PI*DN)

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551      POTL = 2.0*SQRT(COS(SIN(A)))
552      X=EXP(COMPLEX(CO.C,PI*ON*A))
553      CALL FPMPLS (C,S,POTL)
554      C=SQRT(C/2.0)*(0.5-C)
555      SE=SQRT(C/2.0)*(S-0.5)
556      P=SQRT(C/2.0)*(2.0*E)
557      TSIN=SIN(A)
558      TSE=ABS(TSIN)
559      IF (TS.GT.E) GO TO 562
560      COMP= SQRT(2.0)*E*N*SIN(A*E/2.0-E*PI*ON)
561      TE(COS(A*E/2.0-E*PI*ON),E,T,0.0) COMP=COMP
562      GO TO 125
563 560  OP=SQRT(C)*COS(A*E)/2*TSIN
564      COMP=TE(C)
565 125  COMP=COMP*E*COMP*COMPLEX(C,S)
566      R=REAL (COMP)
567      I=AIMAG (COMP)
568      IF (DABS(I)GT.E) GO TO 1
569 1      RETURN
570      END

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