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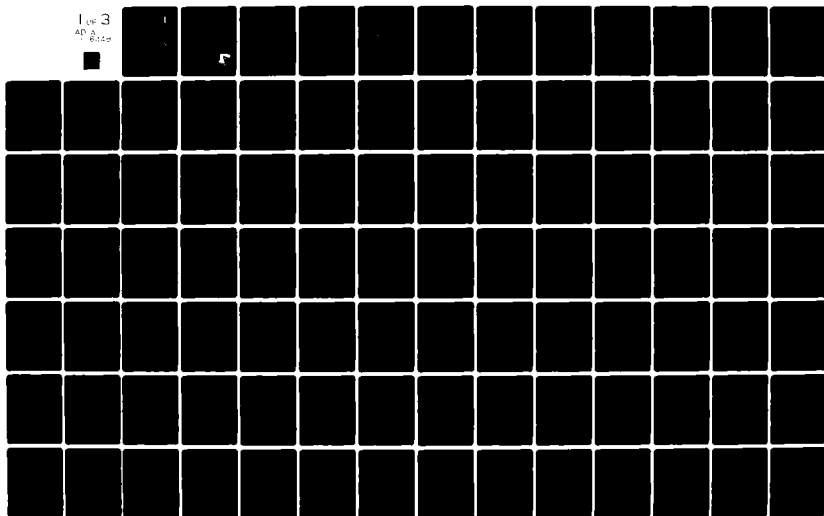
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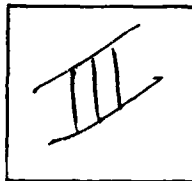
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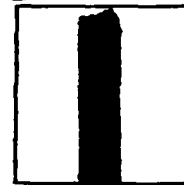
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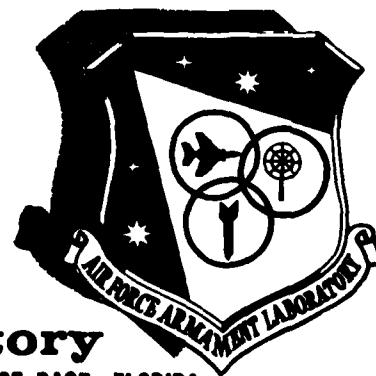
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JANUARY 1980

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20. Abstract (continued)

dielectric containing discrete scatterers. The earth terrain is then modelled as layers of such scattering media bounded by air above and a homogeneous half-space below. The development of the theoretical approach is guided by the motivation that data set obtained in a field and plotted as functions of frequency, angle, and polarization must be matched with same set of parameters characterizing the same field. In matching the theoretical results with experimental data collected from snow-ice fields, we summarize the following findings: (1) For snow-ice fields the horizontal correlation length is no less than the vertical correlation length signifying a more laminar structure. The correspondence between the continuum random medium and the discrete spherical scatterer model can be verified when the vertical correlation length is equal to the horizontal correlation length. (2) The vertically polarized backscattering cross section σ_{vv} is always greater than the horizontally polarized backscattering cross section σ_{hh} for half-space scattering media and may become small for a two-layer model. (3) To account for diurnal change exhibited by snow fields in both the active and passive remote sensing cases, a three-layer model with a thin top layer caused by solar illumination must be used.

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PREFACE

This is a final report on U.S. Air Force/Eglin Contract F08635-78-C-0115 on prediction of backscatter and emissivity of snow at millimeter wavelengths for the period covering February 1978 - September 1979. This work has been sponsored by the Air Force Armament Laboratory and performed by Massachusetts Institute of Technology, Research Laboratory of Electronics, Cambridge, Massachusetts 02139.

The Public Affairs Office has reviewed this report, and it is releasable to the National Technical Information Service (NTIS), where it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER



BARNES E. HOLDER, Jr., Colonel, USAF
Chief, Guided Weapons Division

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SECTION I INTRODUCTION

In this report the work accomplished during this program is summarized. In Section II and Section III, the completed theoretical work for active and passive remote sensing is summarized. In Section IV the work done on deriving the modified radiative transfer theory which includes the coherent effects is summarized, and the work on the rough surface effects is summarized in Section V. The experimental and ground-truth studies are summarized in Section VI. Section VII lists the computer programs with comment cards, equations used in the programs, list of symbols, and input-output formats. Publications are listed in Section VIII and the Appendices are listed in Section IX.

The comprehensive review of the remote sensing theories and the experiments pertaining to snow is included in Appendix A.

SECTION II

ACTIVE REMOTE SENSING

In the active remote sensing of earth terrain, theoretical models have been developed which can be classified under two categories: (1) wave models and (2) radiative transfer models. In both cases, the earth terrain of interest is treated as a random medium with a correlation function characterizing the size of inhomogeneities and the contrast in fluctuation strength as compared with the background dielectric constant. The model of a continuous random medium has been found to be versatile and useful in the analysis and interpretation of backscattering data collected from snow and vegetation fields (Reference 1). This model can be developed in a straightforward manner and is able to match the essential angular and spectral behavior in the collected backscattering data.

WAVE MODELS

In this approach the scattering of electromagnetic waves by a layer of random media with three-dimensional correlation functions has been solved by applying Born approximations to the wave equation. Carrying to first order in albedo, analytical results for the bistatic scattering coefficients and the backscattering cross sections have been derived (Reference 2) which account for volume scattering effects. It was found that as a result of the effect of the second boundary, the horizontally polarized return σ_{hh} can be greater than the vertically polarized return σ_{vv} , whereas for a half-space random medium σ_{vv} is always greater than σ_{hh} .

As more realistic simulation of earth terrain for active remote sensing, analytical expressions for the backscattering cross sections have been derived (Reference 3) for a stratified random medium by applying the first-order Born approximation. In the

special case of a three-layer random medium, two maxima are found in the spectral dependence of the backscattering due to resonance scattering within each random layer. The theoretical results also are found to compare favorably with data obtained from vegetation and snow-ice fields.

The Born approximation has been carried to second order in the albedo to obtain backscattering cross sections that account for depolarization effects in a two-layer random medium (Reference 4). It was found that the first- and second-order theoretical results, together with a consistent set of parameters, are able to match the essential features of like- and cross-polarized backscattering data gathered from the same target area.

RADIATIVE TRANSFER MODELS

In this approach bistatic scattering cross sections for a half space random medium are derived (Reference 5) by using the radiative transfer theory, which deals directly with radiation intensities by assuming incoherence and far-field interactions. An iterative process is applied to solve the integral equations to both first and second order in albedo. The first-order results yield backscattering cross sections which account for the like-polarized return. The second-order results, as in the case of the wave approach, exhibit depolarization effects in the backscattered power. The angular and spectral dependence of the backscattering cross sections have been illustrated numerically.

SECTION III

PASSIVE REMOTE SENSING

In the microwave remote sensing of snow, volume scattering effects play a dominant role in brightness temperature measurements. The scattering effects can be accounted for by considering the scattering to be due to either discrete scattering centers imbedded in a homogeneous medium (discrete scatterer approach) or by random inhomogeneities in a medium (random medium approach). Both the discrete scatterer approach and the random medium approach with radiative transfer theory have been used to study the effect of volume scattering. Even though the radiative transfer approach deals only with the intensities of the field quantities and neglects their coherent nature, it has an advantage in that it is simple and, more importantly, accounts for multiple scattering effects.

In the discrete scatterer approach, a Mie scattering model with radiative transfer theory was used to solve the problem of microwave thermal emission from a scattering layer on top of a homogeneous medium (Reference 6). The result was applied to the interpretation of experimental data obtained from various snow measurements. The spectral and the angular dependences of the brightness temperatures showed good agreement between theory and experiment. The brightness temperature as a function of snow depths was also interpreted. It was observed that as the snow depth increased, the brightness temperature increased when the subsurface was an aluminum plate due to the fact that the plate was cold and snow absorption induced a brightening effect. The brightness temperature decreased when the subsurface was soil, due to the fact that snow scattering induced a darkening effect.

In the process of matching the data obtained from snow fields, the phenomenon of diurnal change where the brightness temperature

decreased as a function of frequency in the morning and increased in the afternoon was encountered. In order to explain this phenomenon, the results were extended by adding a homogeneous layer on top of the scattering layer (Reference 7). The effect of a homogeneous layer was incorporated in a set of effective boundary conditions for the scattering medium. The effect of the surface layer was also illustrated by plotting the brightness temperatures as functions of frequency and viewing angle for different layer thicknesses, dielectric constants, and fractional volume of the scatterers. It was found that (1) the brightness temperature increased when the loss tangent of the surface layer was increased and when the fractional volume occupied by the scatterers was decreased, (2) in the absence of the surface layer the brightness temperature was usually decreasing as a function of frequency, and (3) the presence of the homogeneous layer might cause the brightness temperature to increase with frequency.

The random medium approach with radiative transfer theory was also used to obtain results from an N-scattering layer model with laminar structure (Reference 8). The propagation matrix formulation was used to obtain the analytical solutions. The results were illustrated with a two-scattering layer model in order to study the dependence of the brightness temperature variations on the layer thickness, variance, correlation length, and permittivity. It was found that usually the brightness temperature increased when the loss tangents increased and decreased when the variances and the correlation lengths increased. For the case of a homogeneous layer on top of a scattering layer, the fact that the brightness temperature could be increased as a function of frequency while for the case of only a scattering layer the brightness temperature decreased as a function of frequency was illustrated.

SECTION IV

MODIFIED RADIATIVE TRANSFER THEORY

The most useful theoretical approach in the active remote sensing of earth terrain is the phenomenological radiative transfer (RT) theory. The RT theory deals directly with intensities, and energy conservation is guaranteed as a consequence of the coupled first-order differential equations. However, the limitation of the RT theory is that it assumes incoherent interactions among the specific intensities. When interference effects among specific intensities become important, a modified radiative transfer (MRT) theory where coherence is included must be used. MRT equations have been developed for a two-layer one-dimensional random medium, by applying the nonlinear approximation to Dyson's equation and the ladder approximation to the Bethe-Salpeter equation. These approximations have been shown to be energetically consistent and therefore appropriate in the development of a radiative transport theory. Additional constructive interference terms not accounted for in phenomenological transport theories are found to occur due to the presence of the bottom boundary.

More recently, MRT equations have been derived (Reference 9) for active remote sensing of a half-space random medium with three-dimensional variations. The standard RT theory is shown to follow as a limiting case of the MRT theory.

SECTION V

ROUGH SURFACE EFFECTS

In passive remote sensing of geophysical surfaces, the quantity of particular interest is the emissivity which, by reciprocity and energy conservation, is equal to one minus the reflectivity. The reflectivity is calculated in terms of bistatic reflectivities as defined by Peake. Stogryn's solution for the emissivity of a rough surface with the principle of reciprocity has been in use for many years. The rough surface bistatic coefficients are calculated by using a combination of Huygen's principle and geometrical optic approach. Transmissivity of a rough surface was not considered because it is not needed in the calculation of the emissivity. The bistatic transmission coefficients for a dielectric interface were calculated using the same approaches as in the calculation of the bistatic reflection coefficients (Reference 10). It was then shown that the resultant reflectivity and transmissivity do not add to unity, indicating violation of energy conservation. This nonconservation of energy leads to a nonunique definition of emissivity calculated with this approach.

In the calculation for the emissivity, numerical integration has to be carried out for two angular variables θ_s and ϕ_s in the upper hemisphere. The computation is usually very inefficient because the integrand, for the case of small slope, is sharply peaked in the specular direction. Thus the results must be accurate enough in order to differentiate between a rough surface and a specular surface. The integral representation of the reflectivity and the transmissivity were modified in terms of the bistatic coefficients. It was then shown that the sum of the modified reflectivity and the modified transmissivity is unity. Thus conservation of energy is observed. Furthermore, the modified reflectivity and transmissivity integrals can be evaluated asymptotically and made

to exhibit the net rough surface effects as compared to a specular surface.

SECTION VI

EXPERIMENTAL AND GROUND-TRUTH STUDIES

EXPERIMENTAL STUDIES

Participation in an experiment that took place in the Rocky Mountains near Winter Park, Colorado, during March 1978 (Reference 11) was made. This was a joint effort with a team from NASA Goddard Space Flight Center and National Bureau of Standards to investigate the microwave hydrologic properties of snow. To isolate many of the electromagnetic emission characteristics of snow, a 35 GHz radio-meter was used to measure the brightness temperatures of man-made and natural snow on an aluminum plate. In particular, the following topics were investigated: (1) angular dependence of the brightness temperature as snow depth increases, (2) change in the measured brightness temperature as a target made of aluminum foil is placed on top of a snow layer, and (3) diurnal changes. The aluminum plate was used to reduce the uncertainties concerning the subsurface electromagnetic properties of the snow pack.

GROUND-TRUTH STUDIES

The ground-truth measurements for snow fields in the Rome, New York area and the Rogers City, Michigan area were obtained during the months of January and February 1979. These measurements were made in connection with the AIR FORCE SAR IMAGING flights in order to make a meaningful interpretation of the data. The ground-truth measurements for the snow fields include snow profile characteristics, free water content measurements, and depth measurements. Snow profile characteristics were obtained from a pit dug in the field, by identifying the various layers, and recording the temperature, average grain size, density, and thickness of each layer. For the free water content measurements, a freezing calorimetric technique

was used to find the percentage by weight of free water present in the snow. The depth measurements were made approximately 20 meters apart in the snow field.

In the Rome, New York area the measurements were made at four sites referred to as Rome A, Rome E, Ava B and Ava C. Two SAR imaging flights were made on January 16 and January 29, 1979. The ground-truth acquired on these two days were supplemented by the measurements made on six other days. In the Rogers City, Michigan area the measurements were made at two test sites referred to as Site E and Site F on February 7 and 8, 1979 in relation to the flight made on February 5, 1979. The detailed ground-truth measurements are included in Appendices B and C.

SECTION VII

COMPUTER PROGRAMS

PROGRAM LAMINAR

Introduction

This program is based upon the thesis by B. Djermakoye (S.M. and E.E., M.I.T., 1978). The brightness temperature from a three-layer random medium (Figure 1) with laminar structure is calculated from radiative transfer theory. The inhomogeneous temperature profiles are also included. The sky temperature is also taken into account in the program.

Two versions of this program are listed here. One is to find the brightness temperature versus angles (Version I). The other one is to find the brightness temperature versus the frequency (Version II).

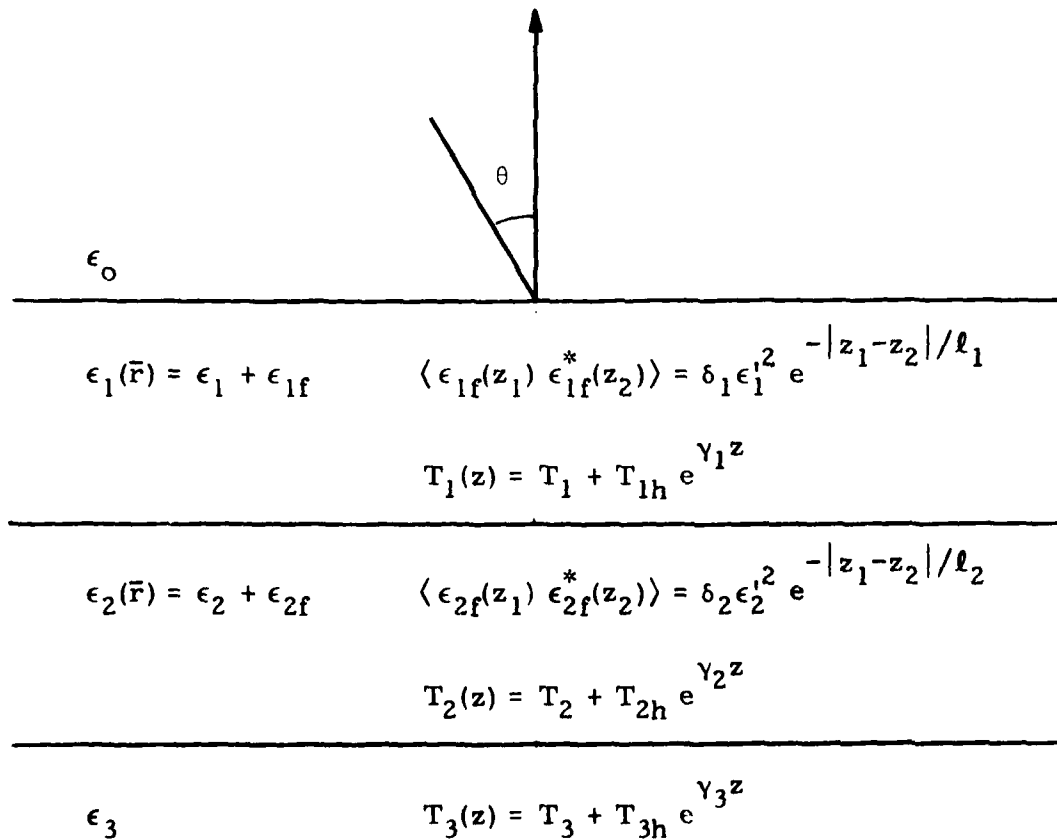


Figure 1. Geometrical Configuration of the Problem for Program LAMINAR

Equations

The radiative transfer equations governing the upward propagating intensity I_{un} and the downward propagating intensity I_{dn} in region n are

$$\frac{d}{dz} I_{un} = -\kappa_{en} I_{un} + \kappa_{an} B_n(z) + \frac{\kappa_{sn}}{2} [P_{fn} I_{un} + P_{bn} I_{dn}] \quad (1a)$$

$$\frac{d}{dz} I_{dn} = \kappa_{en} I_{dn} - \kappa_{an} B_n(z) - \frac{\kappa_{sn}}{2} [P_{fn} I_{dn} + P_{bn} I_{un}], \quad (1b)$$

where

$$B_n = \frac{K}{\lambda^2} \frac{\epsilon_n'}{\epsilon_0} T_n(z) \quad n = 1, 2, 3 \quad (2)$$

$$k_n = \omega \sqrt{\mu \epsilon_n'} \quad n = 1, 2, 3 \quad (3)$$

$$\kappa_{en} = \kappa_{an} + \kappa_{sn} \quad n = 1, 2 \quad (4)$$

$$T_1(z) = T_1 + T_{1h} e^{\gamma_1 z} \quad (5a)$$

$$T_2(z) = T_2 + T_{2h} e^{\gamma_2 z} \quad (5b)$$

$$T_3(z) = T_3 + T_{3h} e^{\gamma_3 z} \quad (5c)$$

K is the Boltzmann constant and λ is the free-space wavelength. The scattering coefficient κ_{sn} , the absorption coefficient κ_{an} , and the scattering phase functions have been determined. We have, for vertical polarization,

$$\kappa_{an} = \frac{\epsilon_n''}{\epsilon_n'} \frac{k_n}{\cos \theta_n} \quad (6)$$

$$\kappa_{sn} = \frac{k_n^2 \Delta_n \ell_n}{2 \cos^2 \theta_n} \left[\frac{1 + 4k_n^2 \ell_n^2 \cos^2 \theta_n + \cos^2 2\theta_n}{1 + 4k_n^2 \ell_n^2 \cos^2 \theta_n} \right] \quad n = 1, 2 \quad (7a)$$

$$\kappa_{sn} = 0 \quad \text{in region 3.} \quad (7b)$$

$$P_{bn} = \frac{2 \cos^2 2\theta_n}{1 + 4k_n^2 \ell_n^2 \cos^2 \theta_n + \cos^2 2\theta_n} \quad n = 1, 2 \quad (8)$$

$$P_{fn} = 2 - P_{bn} \quad n = 1, 2 \quad (9)$$

or for horizontal polarization

$$\kappa_{sn} = \frac{k_n^2 \Delta_n \ell_n}{\cos^2 \theta_n} \left[\frac{1 + 2k_n^2 \ell_n^2 \cos^2 \theta_n}{1 + 4k_n^2 \ell_n^2 \cos^2 \theta_n} \right] \quad n = 1, 2 \quad (10a)$$

$$\kappa_{s3} = 0 \quad (10b)$$

$$P_{bn} = \frac{1}{1 + 2k_n^2 \ell_n^2 \cos^2 \theta_n} \quad (11)$$

$$P_{fn} = 2 - P_{bn} \quad n = 1, 2. \quad (12)$$

The solutions:

$$I_{1u} = \eta_1 A_1 e^{a_1 z} + B_1 e^{-a_1 z} + C_1 + D_1 e^{\gamma_1 z} \quad (13a)$$

$$I_{1d} = A_1 e^{a_1 z} + \eta_1 B_1 e^{a_1 z} + C_1 + D_1' e^{\gamma_1 z} \quad (13b)$$

$$I_{2u} = \eta_2 A_2 e^{a_2 z} + B_2 e^{-a_2 z} + C_2 + D_2 e^{\gamma_2 z} \quad (14a)$$

$$I_{2d} = A_2 e^{a_2 z} + \eta_2 B_2 e^{-a_2 z} + C_2 + D_2' e^{\gamma_2 z} \quad (14b)$$

$$I_{3u} = E + G' e^{\gamma_3 z} \quad (15a)$$

$$I_{3d} = H e^{a_3 z} + E + G e^{\gamma_3 z} \quad (15b)$$

with

$$D_1' = \xi_1' D_1 \quad D_2' = \xi_2' D_2 \quad (16)$$

$$\xi_1' = \frac{a_1^2 + \gamma_1 K_{a1}}{a_1^2 - \gamma_1 K_{a1}} \quad \xi_2' = \frac{a_2^2 + \gamma_2 K_{a2}}{a_2^2 - \gamma_2 K_{a2}} \quad (17)$$

$$\eta_1 = \frac{a_1 - K_{a1}}{a_1 + K_{a1}} \quad \eta_2 = \frac{a_2 - K_{a2}}{a_2 + K_{a2}} \quad (18)$$

$$a_1 = K_{e1} \{ (1 - \tilde{\omega}_1) [1 - (\tilde{\omega}_1/2) P_{f1} + (\tilde{\omega}_1/2) P_{b1}] \}^{1/2} \quad (19a)$$

$$a_2 = K_{e2} \{ (1 - \tilde{\omega}_2) [1 - (\tilde{\omega}_2/2) P_{f2} + (\tilde{\omega}_2/2) P_{b2}] \}^{1/2} \quad (19b)$$

If we identify the scattering albedo,

$$\tilde{\omega}_1 = K_{s1}/K_{e1} \quad (20)$$

The brightness temperature is found by

$$T_B = \frac{\lambda^2 \epsilon_0}{K \epsilon_{lm}'} (1 - r_{01}) I_{1u} \Big|_{z=0} \quad (21)$$

or

$$T_B = \frac{\lambda^2 \epsilon_0 (1 - r_{01})}{K \epsilon_{lm}'} [\eta_1 A_1 + B_1 + C_1 + D_1] \quad (22)$$

With

$$B_1 = \frac{N}{D} \quad (23)$$

where

$$\begin{aligned} N = & \{ [(r_{12} - 1) C_1 a_2 a_3 + (r_{12} \xi'_1 - 1) D_1 a_2 a_3 e^{-\gamma_1 d_1} \\ & + \tilde{t}_{12} (C_2 + D_2 e^{-\gamma_2 d_1}) a_2 a_3 + \tilde{t}_{12} \eta_2 a_2 M] e^{a_2 (d_2 - d_1)} \\ & - [(r_{12} - 1) C_1 a_1 a_4 + r_{12} \xi'_1 - 1) D_1 a_1 a_4 e^{-\gamma_1 d_1} \\ & + \tilde{t}_{12} (C_2 + D_2 e^{-\gamma_2 d_1}) a_1 a_4 + \tilde{t}_{12} a_1 M] e^{-a_2 (d_2 - d_1)} \} e^{-a_1 d_1} \\ & + \tilde{t}_{12} I_1 (a_3 - \eta_2 a_4) e^{-a_1 d_1} \\ & + \{ [(r_{12} - \eta_1) \epsilon_1 a_2 a_3 + \tilde{t}_{12} \tilde{t}_{21} \epsilon_1 \eta_2 a_2] e^{a_2 (d_2 - d_1)} \\ & - [\tilde{t}_{21} \tilde{t}_{12} \epsilon_1 a_1 + (r_{12} - \eta_1) \epsilon_1 a_1 a_4] e^{-a_2 (d_2 - d_1)} \} e^{-2a_1 d_1} \end{aligned} \quad (24)$$

$$\begin{aligned} D = & \{ [(1 - r_{12} \eta_1) a_2 a_3 e^{a_2 (d_2 - d_1)} \\ & - (1 - r_{12} \eta_1) a_1 a_4 e^{-a_2 (d_2 - d_1)}] \\ & + [-\tilde{t}_{21} \tilde{t}_{12} \eta_1 \eta_2 a_2 e^{a_2 (d_2 - d_1)} \\ & + \tilde{t}_{21} \tilde{t}_{12} \eta_1 a_1 e^{-a_2 (d_2 - d_1)}] \} \end{aligned} \quad (25)$$

$$\begin{aligned} (\eta_2 - r_{23}) &= a_1 & (1 - \eta_2 r_{23}) &= a_2 \\ (1 - \eta_2 r_{12}) &= a_3 & (\eta_2 - r_{12}) &= a_4. \end{aligned} \quad (26)$$

$$\tilde{t}_{12} = t_{12} \frac{\epsilon'_{1m}}{\epsilon_{2m}} \quad \tilde{t}_{21} = t_{12} \frac{\epsilon'_{2m}}{\epsilon'_{1m}} \quad (27)$$

$$\epsilon_1 = \frac{(r_{01} - 1)C_1 + (r_{01} - \xi'_1)D_1}{(1 - r_{01}\eta_1)} \quad (28)$$

$$\epsilon_2 = -\frac{(\eta_1 - r_{01})}{(1 - r_{01}\eta_1)}$$

$$A_1 = \epsilon_1 + \epsilon_2 B_1 \quad (29)$$

$$A_2 = \frac{I_1}{a_1} e^{a_3 d_2} - \frac{a_2 B_2}{a_1} e^{2a_2 d_2}.$$

$$I_1 = (r_{23} - 1)C_2 + (\xi'_2 r_{23} - 1)D_2 e^{-\gamma_2 d_2} + \tilde{t}_{23}(E + G' e^{-\gamma_3 d_2}) \quad (30)$$

$$M = (r_{12} - 1)C_2 + D_2(r_{12} - \xi'_2) e^{-\gamma_2 d_1} + (C_1 + \xi'_1 D_1 e^{-\gamma_1 d_1}) \tilde{t}_{21} \quad (31)$$

$$C_1 = A'_1 T_1 \quad C_2 = A'_2 T_2 \quad E = A'_3 T_3 \quad (32)$$

(where the A'_1 should not be confused with the coefficient in I_{1u}).

$$(K/\lambda^2) = \frac{\epsilon'_{1m}}{\epsilon_0} = A'_1.$$

$$(K/\lambda^2) \frac{\epsilon'_{2m}}{\epsilon_0} = A'_2 \quad (33)$$

$$(K/\lambda^2) \frac{\epsilon'_{3m}}{\epsilon_0} = A'_3.$$

Symbols

<u>Fortran Symbols</u>	<u>Notation</u>	<u>Explanations</u>
TETA	θ	Incident angle (in radians)
EX1, EX2, EX3	k_1, k_2, k_3	Propagation constants
E1M, E2M, E3M	$\epsilon'_1, \epsilon'_2, \epsilon'_3$	Real part of $\epsilon_1, \epsilon_2, \epsilon_3$
QS1, QS2, QS3	$\cos \theta_1, \cos \theta_2, \cos \theta_3$	
KA1P, KA1	$\left. \begin{array}{l} 2k_1''/\cos \theta_1 \\ 2k_2''/\cos \theta_2 \\ 2k_3''/\cos \theta_3 \end{array} \right\}$	Absorption coefficients (as defined in the paper).
KA2P, KA2		
KA3P, KA3		
PFE1, PF1	P_{f1} (TE)	Equations (12), (11)
PFE2, PF2	P_{f2} (TE)	Equations (12), (11)
PBE1, PB1	P_{b1} (TE)	Equation (11)
PBE2, PB2	P_{b2} (TE)	Equation (11)
PBM1, PB1	P_{b1} (TM)	Equation (8)
PBM2, PB2	P_{b2} (TM)	Equation (8)
PFM1, PF1	P_{f1} (TM)	Equations (8), (9)
PFM2, PF2	P_{f2} (TM)	Equations (8), (9)
KSE1	κ_{s1} (TE)	Equation (10)
KSE2	κ_{s2} (TE)	Equation (10)
KSM1	κ_{s1} (TM)	Equation (7)
KSM2	κ_{s2} (TM)	Equation (7)
KE1	κ_{e1}	Equation (4)
KE2	κ_{e2}	Equation (4)
RF01	r_{01}	Reflectivities
RF12	r_{12}	"

<u>Fortran Symbols</u>	<u>Notation</u>	<u>Explanations</u>
R01TE	R_{01}	TE reflection coefficients
R12TE	R_{12}	" " "
R01TM	S_{01}	TM reflection coefficients
R12TM	S_{12}	" " "
N1	η_1	Equation (18)
N2	η_2	Equation (18)
XI1	ξ'_1	Equation (17)
XI2	ξ'_2	Equation (17)
AA1	A'_1	Equation (33)
AA2	A'_2	Equation (33)
AA3	A'_3	Equation (33)
T01	t_{01}	Transmissivities
T12	t_{12}	"
TS10	$\tilde{t}_{10}$	Equation (27)
TS12	$\tilde{t}_{12}$	Equation (27)
TS23	$\tilde{t}_{23}$	Equation (27)
TS21	$\tilde{t}_{21}$	Equation (27)
I1	I_1	Equation (30)
M	M	Equation (31)
EP1	ϵ_1	Equation (28)
EP2	ϵ_2	Equation (28)
A	A_1	Equation (29)
IU	$I_{1u} \ (z = 0)$	Equation (13a)
TB	T_B	Equation (22)

Features

1. Version I. T_B versus incident angles.

Version II. T_B versus frequency.

2. No subroutines.

Input-Output Format

1. Version I, T_B versus incident angles.

Data cards format for input:

(1) FORMAT (2F7.4, 2F7.4, 2F5.1); ϵ_1' , ϵ_1'' , ϵ_2' , ϵ_2'' , ϵ_3' , ϵ_3''

(2) FORMAT (2F6.3, 2F8.5); Δ_1 , Δ_2 , ℓ_1 , ℓ_2

(3) FORMAT (2F6.3, I2, F5.1, I2, F6.1); d_1 , d_2 , IH, Freq., NEM, T_{sky} .

IH = 0; case of two layers

IH = 1; case of three layers

NEM = 0; TM case

NEM = 1; TE case

(4) FORMAT (3F6.1, 3F4.1, 3F4.1); T_1 , T_2 , T_3 , TH1, TH2, TH3, γ_1 , γ_2 , γ_3

2. Version II, T_B versus frequency.

Data cards format for input:

(1) FORMAT (2F7.4, 2F7.4, 2F5.1); ϵ_1' , ϵ_1'' , ϵ_2' , ϵ_2'' , ϵ_3' , ϵ_3''

(2) FORMAT (2F6.3, 2F8.5); Δ_1 , Δ_2 , ℓ_1 , ℓ_2

(3) FORMAT (2F6.3, I2, I3, I2, F6.1); d_1 , d_2 , IH, ITETA(θ), NEM, T_{sky} .

ITETA is the incident angle in degrees (integer m).

(4) FORMAT (3F6.1, 3F4.1, 3F4.1); T_1 , T_2 , T_3 , T_{h1} , T_{h2} , T_{h3} , γ_1 , γ_2 , γ_3

C		LAM00010
C	PROGRAM LAMINAR NO.1	LAM00020
C		LAM00030
C	B. DJERMAKOYE (1978)	LAM00040
C	S.L.CHUANG(7,1979)	LAM00050
C	LAMINAR,THREE LAYER MODEL	LAM00060
C	RADIATIVE TRANSFER THEORY	LAM00070
C	BRITENESS TEMPERATURE VERSUS INCIDENT ANGLES.	LAM00080
C	THIS PROGRAM FOLLOWS THE PAPER 'RADIATIVE TRANSFER THEORY	LAM00090
C	FOR THE REMOTE SENSING OF LAYERED RANDOM MEDIA' BY	LAM00100
C	B. DJERMAKOYE AND J. A. KONG.	LAM00110
C	AND THE S.M. S.E.E. THESIS OF B. DJERMAKOYE,MIT,1978.	LAM00120
	REAL KA1P,KA2P,KA3P,KSE1,KSE2,KSE1P,KSE2P,KE1P,KE2P	LAM00130
	COMPLEX R01TE,R12TE,R23TE,R01TM,R12TM,R23TM	LAM00140
	COMPLEX RR1,RR2,RR3	LAM00150
	REAL G,KSM1,KSM2,KSM1P,KSM2P,KE1PP,KE2PP	LAM00160
	REAL KA1,KA2,KA3,KM1,KM2,KS1,KS2	LAM00170
	REAL KE1,KE2,N1,N2,I1,M,NUM1,NUM2,NUM3	LAM00180
	REAL NUM4,NUM5,NUM,IU,AA(500,6)	LAM00190
	COMPLEX R23,G1,G2,G3	LAM00200
	COMPLEX R01,E1,E2,E3,R12,EX1,EX2,EX3	LAM00210
	COMPLEX IX,JX	LAM00220
	NVARS=2	LAM00230
	NPT=16	LAM00240
	NORDER=0	LAM00250
	NPLOT=0	LAM00260
	IDIM=500	LAM00270
	JDIM=6	LAM00280
	IX=(1.0,0.0)	LAM00290
	JX=(0.0,1.0)	LAM00300
77	FORMAT(2F7.4,2F7.4,2F5.1)	LAM00310
10	CONTINUE	LAM00320
C	E1,E2,AND E3 ARE THE COMPLEX DIELECTRIC CONSTANTS	LAM00330
C	IN EACH REGION.	LAM00340
	READ(5,77,END=1) E1,E2,E3	LAM00350
79	FORMAT(2F6.3,2F8.5)	LAM00360
C	DEL1 AND DEL2 ARE THE VARIANCES,CL1 AND CL2 ARE THE	LAM00370
C	CORRELATION LENGTHS IN VERTICAL DIRECTION.	LAM00380
	READ(5,79,END=1) DEL1,DEL2,CL1,CL2	LAM00390
C	D1 AND D2 ARE THE DEPTHS OF THE FIRST AND SECOND LAYER,	LAM00400
C	MEASURED FROM THE TOP SURFACE. NOTE D2 IS NOT THE	LAM00410
C	THICKNESS OF THE SECOND LAYER UNLESS D1=0.	LAM00420
C	IH=0 CASE OF TWO LAYERS.	LAM00430
C	IH=1(NOT 0) CASE OF THREE LAYERS.	LAM00440
C	FREQ IS THE FREQUENCY.	LAM00450
C	NEM=0 VERTICAL POLARIZATION(TM) CASE.	LAM00460
C	NEM=1(NOT 0),HORIZONTAL POLARIZATION(TE) CASE.	LAM00470
C	TSKY IS THE SKY TEMPERATURE WHICH IS LESS THAN 7 DEGREES	LAM00480
C	GENERALLY.	LAM00490
	READ(5,78,END=1) D1,D2,IH,FREQ,NEM,TSKY	LAM00500
78	FORMAT(2F6.3,I2,F5.1,I2,F6.1)	LAM00510
C	FOR INHOMOGENEOUS TEMPERATURE PROFILES:	LAM00520
C	T1(Z)=T1+TH1*EXP(GAM1*Z),SIMILARLY FOR T2(Z) AND T3(Z),	LAM00530
C	WE ASSIGN APPROPRIATE VALUES FOR T1,TH1,GAM1 ETC.	LAM00540
C	FOR HOMOGENEOUS TEMPERATURE PROFILES:	LAM00550

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C TH1=TH2=TH3=0. GAM1=GAM2=GAM3=0. LAM00560
  READ(5,331) T1,T2,T3,TH1,TH2,TH3,GAM1,GAM2,GAM3 LAM00570
331 FORMAT(3F6.1,3F4.1,3F4.1) LAM00580
  IF(IH.EQ.0) WRITE(6,333) IH LAM00590
333 FORMAT(1H 'IH=',I2,' CASE OF TWO LAYER') LAM00600
  IF(IH.NE.0) WRITE(6,334) IH LAM00610
334 FORMAT(1H 'IH=',I2,' CASE OF THREE LAYER') LAM00620
  IF(NEM.EQ.0) WRITE(6,666) FREQ LAM00630
666 FORMAT(1H 'FREQUENCY(GHZ)=' ,F5.1,' TM CASE') LAM00640
  IF(NEM.NE.0) WRITE(6,667) FREQ LAM00650
667 FORMAT(1H 'FREQUENCY(GHZ)=' ,F5.1,' TE CASE') LAM00660
  WRITE(6,335) DEL1,DEL2,CL1,CL2,D1,D2 LAM00670
335 FORMAT(1H 'DEL1=' ,F6.4,' DEL2=' ,F6.4,' CL1=' ,F7.5,' CL2=' ,
1F7.5,' D1=' ,F6.3,' D2=' ,F6.3) LAM00680
  WRITE(6,336) E1,E2,E3 LAM00690
336 FORMAT(1H 'E1=' ,2F7.4,' E2=' ,2F7.4,' E3=' ,2F8.4) LAM00700
  WRITE(6,337) T1,T2,T3,TH1,TH2,TH3,GAM1,GAM2,GAM3 LAM00710
337 FORMAT(1H 'T1=' ,F5.1,' T2=' ,F5.1,' T3=' ,F5.1,' TH1=' ,F5.1
1,' TH2=' ,F5.1,' TH3=' ,F5.1,' GAM1=' ,F4.1,' GAM2=' ,F4.1,
1' GAM3=' ,F4.1) LAM00720
  DO 115 I=1,NPT LAM00730
C CORRESPONDING TO EACH I THE ANGLE 5*I DEGREES IS LAM00740
C THE ANGLE OF INCIDENCE. LAM00750
  TETA=FLOAT(I)*5.0 LAM00760
  EX1=20.9*FREQ*CSQRT(E1) LAM00770
  EX2=20.9*FREQ*CSQRT(E2) LAM00780
  EX3=20.9*FREQ*CSQRT(E3) LAM00790
C EX1,EX2,EX3 ARE THE PROPAGATION CONSTANTS IN EACH LAM00800
C REGION. E1M,E2M,E3M ARE THE REAL PARTS. LAM00810
  E1M=REAL(E1) LAM00820
  E2M=REAL(E2) LAM00830
  E3M=REAL(E3) LAM00840
  ARG=(3.14*TETA)/180.0 LAM00850
C IN THE FOLLOWING WE CALCULATE COS(TETA) IN EACH LAM00860
C REGION,QS1,QS2,QS3,BY SNEEL'S LAW. LAM00870
  S1=(1.-(SIN(ARG)**2)/E1M) LAM00880
  S2=(1.-(SIN(ARG)**2)/E2M) LAM00890
  S3=(1.-(SIN(ARG)**2)/E3M) LAM00900
  QS1=SQRT(S1) LAM00910
  QS2=SQRT(S2) LAM00920
  QS3=SQRT(S3) LAM00930
  CS1=(2.*S1)-1. LAM00940
  CS2=(2.*S2)-1. LAM00950
C THE ABSORPTION COEFFICIENTS IN THIS PAPER ARE DEFINED LAM00960
C AS KA1=2*(IMAGINARY PART OF K1)/COS(TETA1) LAM00970
C =E1'*K1'/(E1'*COS(TETA1)) LAM00980
C HERE E1' IS THE REAL PART AND E1'' THE IMAGINARY LAM00990
C PART OF E1. COS(TETA1) IS QS1. LAM01000
  KA1P=2.*AIMAG(EX1)/QS1 LAM01010
  KA2P=2.*AIMAG(EX2)/QS2 LAM01020
  KA3P=2.*AIMAG(EX3)/QS3 LAM01030
C THE KA'S GIVE THE VALUE OF THE ABSORPTION COEFFICIENT IN EACH LAYER. LAM01040
  KA1=KA1P LAM01050
  KA2=KA2P LAM01060
  KA3=KA3P LAM01070

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      KM1=REAL(EX1)
      KM2=REAL(EX2)
C  DEFINE RR0,RR1,RR2,RR3, TO FIND REFLECTIVITIES BETWEEN
C  TWO MEDIA: RF01,RF12,RF23.
      G0=(1.-SIN(ARG)**2)
      RR0=SQRT(G0)
      G1=(E1-SIN(ARG)**2)
      RR1=CSQRT(G1)
      G2=(E2-SIN(ARG)**2)
      RR2=CSQRT(G2)
      G3=(E3-SIN(ARG)**2)
      RF3=CSQRT(G3)
      IF (MEM.EQ.0) GO TO 111
C  THIS SECTION CONSIDERS TE WAVES AND DEFINES THE SCATTERING PARAMETERS
C  FOR THIS CASE.KSE IS THE SCATTERING EXTINCTION COEFFICIENT,PPE
C  AND PBE DEFINE THE FORWARD AND BACKWARD SCATTERING PHASE FUNCTIONS.
C  PF DEFINES THE REFLECTIVITIES AT THE DIFFERENT BOUNDARIES.
      PPE1=(1.+4.*((KM1*CL1)**2)*S1)/(1.+2.*((KM1*CL1)**2)*S1)
      PBE1=1./(1.+2.*((KM1*CL1)**2)*S1)
      KSE1=((KM1**2)*DEL1*CL1/QS1)/PPE1
      PPE2=(1.+4.*((KM2*CL2)**2)*S2)/(1.+2.*((KM2*CL2)**2)*S2)
      PBE2=1./(1.+2.*((KM2*CL2)**2)*S2)
      KSE2=((KM2**2)*DEL2*CL2/QS2)/PPE2
      KSE1P=KSE1/QS1
      KSE2P=KSE2/QS2
      R01TE=(RR0-RR1)/(RR0+RR1)
      R12TE=(RR1-RR2)/(RR1+RR2)
      R23TE=(RR2-RR3)/(RR2+RR3)
      RF01=CABS(R01TE)**2
      RF12=CABS(R12TE)**2
      RF23=CABS(R23TE)**2
      PF1=PPE1
      PB1=PBE1
      PF2=PPE2
      PB2=PBE2
      KE1P=KA1P+KSE1P
      KE2P=KA2P+KSE2P
      KE1=KE1P
      KE2=KE2P
      KS1=KSE1P
      KS2=KSE2P
      GO TO 222
C  THIS SECTION CONSIDERS TM WAVES AND DEFINES THE SCATTERING PARAMETERS
C  THE NOTATION UTILIZED IS SIMILAR TO THE TE CASE.
111  PFM1=2.*(1.+4.*((KM1*CL1)**2)*S1)/(1.+4.*((KM1*CL1)**2)*S1+
      1(CS1**2))
      PBM1=2.*(CS1**2)/(1.+4.*((KM1*CL1)**2)*S1+(CS1**2))
      KSM1=((KM1**2)*DEL1*CL1/(QS1*PFM1))
      PFM2=2.*(1.+4.*((KM2*CL2)**2)*S2)/(1.+4.*((KM2*CL2)**2)*S2+
      1(CS2**2))
      PBM2=2.*(CS2**2)/(1.+4.*((KM2*CL2)**2)*S2+(CS2**2))
      KSM2=((KM2**2)*DEL2*CL2/(QS2*PFM2))
      KSM1P=KSM1/QS1
      KSM2P=KSM2/QS2
      R01TM=((E1*RR0)-PF1)/((E1*RR0)+RR1)

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LAM01110
 LAM01120
 LAM01130
 LAM01140
 LAM01150
 LAM01160
 LAM01170
 LAM01180
 LAM01190
 LAM01200
 LAM01210
 LAM01220
 LAM01230
 LAM01240
 LAM01250
 LAM01260
 LAM01270
 LAM01280
 LAM01290
 LAM01300
 LAM01310
 LAM01320
 LAM01330
 LAM01340
 LAM01350
 LAM01360
 LAM01370
 LAM01380
 LAM01390
 LAM01400
 LAM01410
 LAM01420
 LAM01430
 LAM01440
 LAM01450
 LAM01460
 LAM01470
 LAM01480
 LAM01490
 LAM01500
 LAM01510
 LAM01520
 LAM01530
 LAM01540
 LAM01550
 LAM01560
 LAM01570
 LAM01580
 LAM01590
 LAM01600
 LAM01610
 LAM01620
 LAM01630
 LAM01640
 LAM01650

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R12TM=((E2*RR1)-(E1*RR2))/((E2*RR1)+(E1*RR2))
R23TM=((E3*RR2)-(E2*RR3))/((E3*RR2)+(E2*RR3))
RFO1=CABS(R01TM)**2
FF12=CABS(R12TM)**2
FF23=CABS(R23TM)**2
PF1=PFM1
PF2=PFM2
PB1=PBM1
PB2=PBM2
KE1PP=KA1P+KSM1P
KE2PP=KA2P+KSM2P
KE1=KE1PP
KE2=KE2PP
KS1=KSM1P
KS2=KSM2P
C THE W'S REFER TO THE SCATTERING ALBEDO.
222 W1=KS1/KE1
W2=KS2/KE2
C THE FOLLOWING SECTION COMPUTES THE BRIGHTNESS TEMPERATURE ACCORDING
C TO EQUATION 12 (PAGE 36) IN THE THESIS.
C IN THE FOLLOWING ALL THE PAGE NO.S REFER TO THE THESIS.
88 T11=SQRT(1.-PF1*(W1/2.)+PB1*(W1/2.))
T22=SQRT(1.-PF2*(W2/2.0)+PB2*(W2/2.0))
A1=KE1*T11*SQRT(1.0-W1)
A2=KE2*T22*SQRT(1.0-W2)
GF1=0.5*KS1*PF1
GB1=0.5*KS1*PB1
N1=(A1-KA1)/(A1+KA1)
C THE PARAMETERS A1,A2 ARE DERIVED IN THE APPENDIX A
C OF THE THESIS IN TERMS OF ALPHA'S.
C N1 APPEARS IN PAGE 33 OF THE THESIS.
IF (GB.LT. (.1*GF1).OR.W1.LE.0.3) N1=GB1/(A1+KE1-GF1)
GF2=0.5*KS2*PF2
GB2=0.5*KS2*PB2
N2=(A2-KA2)/(A2+KA2)
C N2 IS DEFINED IN PAGE 33.
C MOST OF THE TERMS FOLLOWING ARE DEFINED IN P.28-36.
IF (GB2.LT. (.1*GF2).OR.W2.LE.0.3) N2=GB2/(A2+KE2-GF2)
99 AA1=E1M
AA2=E2M
AA3=E3M
C XI1,XI2 ARE DEFINED IN P.33.
XI1=((A1**2)+GAM1*KA1)/((A1**2)-GAM1*KA1)
XI2=((A2**2)+GAM2*KA2)/((A2**2)-GAM2*KA2)
C HERE C1,C2,E ARE DEFINED IN P.36.
C IN THE FOLLOWING WE FIND C1,D11(D1 IN THESIS),B,A.
C FOR IU IN EQ.11.
66 C1=AA1*T1
C2=AA2*T2
E=AA3*T3
DD11=((A1**2)-GAM1*KA1)*AA1*TH1
DD12=(A1**2)-(GAM1**2)
D11=DD11/DD12
D22=0.0
IF (IH.EQ.0) GO TO 55

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LAM01660
 LAM01670
 LAM01680
 LAM01690
 LAM01700
 LAM01710
 LAM01720
 LAM01730
 LAM01740
 LAM01750
 LAM01760
 LAM01770
 LAM01780
 LAM01790
 LAM01800
 LAM01810
 LAM01820
 LAM01830
 LAM01840
 LAM01850
 LAM01860
 LAM01870
 LAM01880
 LAM01890
 LAM01900
 LAM01910
 LAM01920
 LAM01930
 LAM01940
 LAM01950
 LAM01960
 LAM01970
 LAM01980
 LAM01990
 LAM02000
 LAM02010
 LAM02020
 LAM02030
 LAM02040
 LAM02050
 LAM02060
 LAM02070
 LAM02080
 LAM02090
 LAM02100
 LAM02110
 LAM02120
 LAM02130
 LAM02140
 LAM02150
 LAM02160
 LAM02170
 LAM02180
 LAM02190
 LAM02200

	DD21=((A2**2)-GAM2*KA2)*AA2*TH2	LAM02210
	DD22=(A2**2)-(GAM2**2)	LAM02220
	D22=DD21/DD22	LAM02230
C	THE TRANSMITTIVITIES BETWEEN TWO MEDIA ARE T12,T23,T01.	LAM02240
55	T12=1.-RF12	LAM02250
	T01=1.-PF01	LAM02260
	TS10=T01*E1M	LAM02270
	EP1=((PF01-1.0)*C1+(RF01-XI1)*D11+(TS10*TSKY))/(1.0-RF01*N1)	LAM02280
	EP2=((1.0)*(N1-PF01))/(1.0-RF01*N1)	LAM02290
	G=(KA3*TH3*AA3)/(GAM3+KA3)	LAM02300
44	T23=1.-RF23	LAM02310
	TS12=(T12*E1M)/(E2M)	LAM02320
	TS23=(T23*E2M)/(E3M)	LAM02330
	TS21=(T12*E2M)/(E1M)	LAM02340
	A11=N2-RF23	LAM02350
	A22=1.0-N2*RF23	LAM02360
	A33=1.0-N2*RF12	LAM02370
	A44=N2-RF12	LAM02380
	AF1=GAM2*D2	LAM02390
	Y1=0.0	LAM02400
	IF (AR1.LT.40.0) Y1=EXP(-AR1)	LAM02410
	AR2=GAM3*D2	LAM02420
	Y2=0.0	LAM02430
	IF (AR2.LT.40.0) Y2=EXP(-AR2)	LAM02440
	I1=(RF23-1.0)*C2+((XI2*PF23)-1.0)*D22*Y1+TS23*(E+G*Y2)	LAM02450
C	I1 APPEARS IN P.36.	LAM02460
	HX3=RF12-N1	LAM02470
	HX1=RF12-1.0	LAM02480
	HX2=RF12*X11-1.0	LAM02490
	AR3=GAM2*D1	LAM02500
	AR4=GAM1*D1	LAM02510
	Y3=0.0	LAM02520
	Y4=0.0	LAM02530
	IF (AR3.LT.40.0) Y3=EXP(-AR3)	LAM02540
	IF (AR4.LT.40.0) Y4=EXP(-AR4)	LAM02550
	M=HX1*C2+(PF12-XI2)*D22*Y3+(C1+XI1*D11*Y4)*TS21	LAM02560
C	M APPEARS IN P.36.	LAM02570
	HH1=(HX1*C1)+(HX2*D11*Y4)+TS12*(C2+D22*Y3)	LAM02580
	HH2=HX3*A33+(T12**2)*N2	LAM02590
	HH3=HX3*A44+(T12**2)	LAM02600
	NUM1=((HH1*A22*A33)+(TS12*N2*A22*M))	LAM02610
	AR5=2.*A2*(D2-D1)	LAM02620
	AR6=A1*D1	LAM02630
	Y5=0.0	LAM02640
	Y6=0.0	LAM02650
	IF (AR5.LT.40.0) Y5=EXP(-AR5)	LAM02660
	IF (AR6.LT.40.0) Y6=EXP(-AR6)	LAM02670
	AR8=A2*(D2-D1)	LAM02680
	Y8=0.0	LAM02690
	IF (AR8.LT.40.0) Y8=EXP(-AR8)	LAM02700
	NUM2=(HH1*A11*A44+TS12*A11*M)*Y5	LAM02710
	NUM3=TS12*I1*(A33-N2*A44)*Y6*Y8	LAM02720
	NUM4=(HH2*EP1*A22)	LAM02730
	NUM5=(HH3*EP1*A11)*Y5	LAM02740
	AR7=2.0*A1*D1	LAM02750

Y7=0.0	LAH02760
IF (AR7.LT.40.0) Y7=EXP(-AR7)	LAH02770
NUM=(NUM1-NUM2)*Y6+NUM3+(NUM4-NUM5)*Y7	LAH02780
DN1=((A33*A22)-(A11*A44*Y5))	LAH02790
DN2=(((-1.0)*N2*A22)+(A11*Y5))	LAH02800
DEN=(1.0-EP12*N1)*DN1+N1*(T12**2)*DN2	LAH02810
DENO=DEN+((N1-EP12)*EP2*DN1+(T12**2)*EP2*DN2)*Y7	LAH02820
B=NUM/DENO	LAH02830
A=EP1+EP2*B	LAH02840
IU=(N1*A)+B+C1+D11	LAH02850
C IU IS THE UPWARD INTENSITY AT Z=0. (SEE P.35 EQ.11).	LAH02860
TB=((1.0-RF01)*IU)/E1M)+(RF01*TSKY)	LAH02870
AA(I,2)=TB	LAH02880
C AA(I,2) IS THE BRITENESS TEMPERATURE CORRESPONDING TO	LAH02890
C THE INCIDENT ANGLE 5*I DEGREES.	LAH02900
C AA(I,1) IS THE INCIDENT ANGLE 5*I DEGREES.	LAH02910
AA(I,1)=TETA	LAH02920
115 CONTINUE	LAH02930
NLINES=80	LAH02940
100 CONTINUE	LAH02950
DO 103 JI=1,NVAES	LAH02960
WRITE(6,*) W2	LAH02970
WRITE(6,*) (AA(IL,JI),IL=1,NPT)	LAH02980
103 CONTINUE	LAH02990
GO TO 10	LAH03000
1 CONTINUE	LAH03010
CALL EXIT	LAH03020
STOP	LAH03030
END	LAH03040

```

C
C      PROGRAM LAMINAR NO.2
C
C      B. DJERMAKOYE (1978)
C      S. L. CHUANG (7, 1979)
C      LAMINAR, THREE-LAYER MODEL
C      RADIATIVE TRANSFER THEORY
C      BRITENESS TEMPERATURE VERSUS FREQUENCY.
C      THIS PROGRAM FOLLOWS THE PAPER 'RADIATIVE TRANSFER THEORY
C      FOR THE REMOTE SENSING OF LAYERED MEDIA' BY
C      B. DJERMAKOYE AND J. A. KONG.
C      AND THE THESIS OF B. DJERMAKOYE 92 (SM 622 DEGREES), MIT, 1978.
      REAL KA1P, KA2P, KA3P, KSE1, KSE2, KSE1P, KSE2P, KE1P, KE2P
      COMPLEX R01TE, R12TE, R23TE, R01TH, R12TH, R23TH
      COMPLEX RR1, RR2, RR3
      REAL G, KSM1, KSM2, KSM1P, KSM2P, KE1PP, KE2PP
      REAL KA1, KA2, KA3, KM1, KM2, KS1, KS2
      REAL KE1, KE2, N1, N2, I1, M, NUM1, NUM2, NUM3
      REAL NUM4, NUM5, NUM, IU, AA (500, 6)
      COMPLEX F23, G1, G2, G3
      COMPLEX F01, E1, E2, E3, F12, EX1, EX2, EX3
      COMPLEX IX, JX
      NVAR=2
      NPT=30
      NORDAR=0
      NPLOT=0
      IDIM=500
      JDIM=6
      IX=(1.0, 0.0)
      JX=(0.0, 1.0)
77  FORMAT(2F7.4, 2F7.4, 2F5.1)
10  CONTINUE
C      E1, E2, AND E3 ARE THE COMPLEX DIELECTRIC CONSTANTS
C      IN EACH REGION.
      READ(5, 77, END=1) E1, E2, E3
79  FORMAT(2F6.3, 2F8.5)
C      DEL1 AND DEL2 ARE THE VARIANCES, CL1 AND CL2 ARE THE
C      CORRELATION LENGTHS IN VERTICAL DIRECTION.
      READ(5, *, END=1) DEL1, DEL2, CL1, CL2
C      D1 AND D2 ARE THE DEPTHS OF THE FIRST AND SECOND LAYER,
C      MEASURED FROM THE TOP SURFACE. NOTE D2 IS NOT THE
C      THICKNESS OF THE SECOND LAYER UNLESS D1=0.
C      IH=0 CASE OF TWO LAYERS.
C      IH=1 (NOT 0) CASE OF THREE LAYERS.
C      FREQ IS THE FREQUENCY.
C      NEM=0 VERTICAL POLARIZATION (TM) CASE.
C      NEM=1 (NOT 0) HORIZONTAL POLARIZATION (TE) CASE.
C      TSKY IS THE SKY TEMPERATURE WHICH IS LESS THAN 7 DEGREES
C      GENERALLY.
      READ(5, *, END=1) D1, D2, IH, ITETA, NEM, TSKY
78  FORMAT(2F6.3, I2, I3, I2, F6.1)
C      FOR INHOMOGENEOUS TEMPERATURE PROFILES:
C      T1(Z)=T1+TH1*EXP(GAM1*Z), SIMILARLY FOR T2(Z) AND T3(Z).
C      WE ASSIGN APPROPRIATE VALUES FOR T1, TH1, GAM1, ETC.
C      FOR HOMOGENEOUS CASE:

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LAF00010
LAF00020
LAF00030
LAF00040
LAF00050
LAF00060
LAF00070
LAF00080
LAF00090
LAF00100
LAF00110
LAF00120
LAF00130
LAF00140
LAF00150
LAF00160
LAF00170
LAF00180
LAF00190
LAF00200
LAF00210
LAF00220
LAF00230
LAF00240
LAF00250
LAF00260
LAF00270
LAF00280
LAF00290
LAF00300
LAF00310
LAF00320
LAF00330
LAF00340
LAF00350
LAF00360
LAF00370
LAF00380
LAF00390
LAF00400
LAF00410
LAF00420
LAF00430
LAF00440
LAF00450
LAF00460
LAF00470
LAF00480
LAF00490
LAF00500
LAF00510
LAF00520
LAF00530
LAF00540
LAF00550

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C TH1=TH2=TH3=0. GAM1=GAM2=GAM3=0. LAF00560
  READ(5,*) T1,T2,T3,TH1,TH2,TH3,GAM1,GAM2,GAM3 LAF00570
331 FORMAT(3F6.1,3F4.1,3F4.1) LAF00580
  IF(IH.EQ.0) WRITE(6,333) IH LAF00590
333 FORMAT(1H 'IH=',I2,' CASE OF TWO LAYER') LAF00600
  IF(IH.NE.0) WRITE(6,334) IH LAF00610
334 FORMAT(1H 'IH=',I2,' CASE OF THREE LAYER') LAF00620
  IF(ITETA.EQ.0) WRITE(6,89) ITETA LAF00630
  89 FORMAT(1H 'ITETA=',I2,' NADIR OBSERVATION') LAF00640
  IF(NEM.EQ.0) WRITE(6,666) ITETA LAF00650
666 FORMAT(1H 'ITETA=',I2,' TM CASE') LAF00660
  IF(NEM.NE.0) WRITE(6,667) ITETA LAF00670
667 FORMAT(1H 'ITETA=',I2,' TE CASE') LAF00680
  WRITE(6,335) DEL1,DEL2,CL1,CL2,D1,D2 LAF00690
335 FORMAT(1H 'DEL1=',F6.4,' DEL2=',F6.4,' CL1=',F7.5,' CL2=', LAF00700
  1F7.5,' D1=',F6.3,' D2=',F6.3) LAF00710
  WRITE(6,336) E1,E2,E3 LAF00720
336 FORMAT(1H 'E1=',2F7.4,' E2=',2F7.4,' E3=',2F8.4) LAF00730
  WRITE(6,337) T1,T2,T3,TH1,TH2,TH3,GAM1,GAM2,GAM3 LAF00740
337 FORMAT(1H 'T1=',F5.1,' T2=',F5.1,' T3=',F5.1,' TH1=',F5.1 LAF00750
  1,' TH2=',F5.1,' TH3=',F5.1,' GAM1=',F4.1,' GAM2=',F4.1, LAF00760
  1' GAM3=',F4.1) LAF00770
  DO 115 I=1,NPT LAF00780
    FREQ=FLOAT(I)*2.0 LAF00790
C CORRESPONDING TO EACH I WE CALCULATE BRITENESS TEMPERATURE LAF00800
C FOR FREQUENCY 2*I GHZ. LAF00810
    EX1=20.9*FREQ*CSQRT(E1) LAF00820
    EX2=20.9*FREQ*CSQRT(E2) LAF00830
    EX3=20.9*FREQ*CSQRT(E3) LAF00840
C EX1,EX2,EX3 ARE THE PROPAGATION CONSTANTS IN EACH REGION. LAF00850
C E1M,E2M,E3M ARE THEIR REAL PARTS. LAF00860
    E1M=REAL(E1) LAF00870
    E2M=REAL(E2) LAF00880
    E3M=REAL(E3) LAF00890
    AFG=(3.14*ITETA)/180.0 LAF00900
C IN THE FOLLOWING WE CALCULATE COS(TETA) IN EACH REGION, LAF00910
C I. E. QS1,QS2,QS3,ACCORDING TO SNELL'S LAW. LAF00920
    S1=(1.-(SIN(ARG)**2)/E1M) LAF00930
    S2=(1.-(SIN(ARG)**2)/E2M) LAF00940
    S3=(1.-(SIN(ARG)**2)/E3M) LAF00950
    QS1=SQRT(S1) LAF00960
    QS2=SQRT(S2) LAF00970
    QS3=SQRT(S3) LAF00980
    CS1=(2.*S1)-1. LAF00990
    CS2=(2.*S2)-1. LAF01000
C THE ABSORPTION COEFFICIENTS IN THIS PAPER ARE DEFINED LAF01010
C AS KA1=2*(IMAGINARY PART OF K1)/COS(TETA1) LAF01020
C =E1'*K1'/(E1'*COS(TETA1)) LAF01030
C HERE E1' IS THE REAL PART AND E1'' THE IMAGINARY LAF01040
C PART OF E1. COS(TETA1) IS QS1. LAF01050
    KA1P=2.*AIMAG(EX1)/QS1 LAF01060
    KA2P=2.*AIMAG(EX2)/QS2 LAF01070
    KA3P=2.*AIMAG(EX3)/QS3 LAF01080
C THE KA'S GIVE THE VALUE OF THE ABSORPTION COEFFICIENT IN EACH LAYER. LAF01090
    KA1=KA1P LAF01100

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      KA2=KA2P
      KA3=KA3P
      KM1=REAL(EX1)
      KM2=REAL(EX2)
C   DEFINE RR0,RR1,RR2,RR3 TO FIND THE REFLECTIVITIES BETWEEN
C   TWO MEDIA: RP01,RP12,RP23.
      G0=(1.-SIN(ARG)**2)
      RF0=SQRT(G0)
      G1=(E1-SIN(ARG)**2)
      RR1=CSQRT(G1)
      G2=(E2-SIN(ARG)**2)
      RF2=CSQRT(G2)
      G3=(E3-SIN(ARG)**2)
      RR3=CSQRT(G3)
      IF (NEM.EQ.0) GO TO 111
C   THIS SECTION CONSIDERS TE WAVES AND DEFINES THE SCATTERING PARAMETERS
C   FOR THIS CASE.KSE IS THE SCATTERING EXTINCTION COEFFICIENT,PPE
C   AND PBE DEFINE THE FORWARD AND BACKWARD SCATTERING PHASE FUNCTIONS.
C   RF DEFINES THE REFLECTIVITIES AT THE DIFFERENT BOUNDARIES.
      PFE1=(1.+4.*((KM1*CL1)**2)*S1)/(1.+2.*((KM1*CL1)**2)*S1)
      PBE1=1./(1.+2.*((KM1*CL1)**2)*S1)
      KSE1=((KM1**2)*DEL1*CL1/QS1)/PFE1
      PFE2=(1.+4.*((KM2*CL2)**2)*S2)/(1.+2.*((KM2*CL2)**2)*S2)
      PBE2=1./(1.+2.*((KM2*CL2)**2)*S2)
      KSE2=((KM2**2)*DEL2*CL2/QS2)/PFE2
      KSE1P=KSE1/QS1
      KSE2P=KSE2/QS2
      R01TE=(RR0-RF1)/(RR0+RF1)
      R12TE=(RR1-RR2)/(RR1+RR2)
      R23TE=(RR2-RR3)/(RR2+RR3)
      RF01=CABS(R01TE)**2
      RF12=CABS(P12TE)**2
      RF23=CABS(R23TE)**2
      PF1=PFE1
      PB1=PBE1
      PF2=PFE2
      PB2=PBE2
      KE1P=KA1P+KSE1P
      KE2P=KA2P+KSE2P
      KE1=KE1P
      KE2=KE2P
      KS1=KSE1P
      KS2=KSE2P
      GO TO 222
C   THIS SECTION CONSIDERS TM WAVES AND DEFINES THE SCATTERING PARAMETERS
C   THE NOTATION UTILIZED IS SIMILAR TO THE TE CASE.
111  PPM1=2.*(1.+4.*((KM1*CL1)**2)*S1)/(1.+4.*((KM1*CL1)**2)*S1+
      1(CS1**2))
      PBM1=2.*(CS1**2)/(1.+4.*((KM1*CL1)**2)*S1+(CS1**2))
      KSM1=((KM1**2)*DEL1*CL1/(QS1*PPM1))
      PPM2=2.*(1.+4.*((KM2*CL2)**2)*S2)/(1.+4.*((KM2*CL2)**2)*S2+
      1(CS2**2))
      PBM2=2.*(CS2**2)/(1.+4.*((KM2*CL2)**2)*S2+(CS2**2))
      KSM2=((KM2**2)*DEL2*CL2/(QS2*PPM2))
      KSM1P=KSM1/QS1

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LAF01110
 LAF01120
 LAF01130
 LAF01140
 LAF01150
 LAF01160
 LAF01170
 LAF01180
 LAF01190
 LAF01200
 LAF01210
 LAF01220
 LAF01230
 LAF01240
 LAF01250
 LAF01260
 LAF01270
 LAF01280
 LAF01290
 LAF01300
 LAF01310
 LAF01320
 LAF01330
 LAF01340
 LAF01350
 LAF01360
 LAF01370
 LAF01380
 LAF01390
 LAF01400
 LAF01410
 LAF01420
 LAF01430
 LAF01440
 LAF01450
 LAF01460
 LAF01470
 LAF01480
 LAF01490
 LAF01500
 LAF01510
 LAF01520
 LAF01530
 LAF01540
 LAF01550
 LAF01560
 LAF01570
 LAF01580
 LAF01590
 LAF01600
 LAF01610
 LAF01620
 LAF01630
 LAF01640
 LAF01650

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KSM2P=KSM2/QS2
P01TM=((E1*PF0)-RF1)/((E1*RR0)+RR1)
R12TM=((E2*RR1)-(E1*RR2))/((E2*RR1)+(E1*RR2))
R23TM=((E3*RR2)-(E2*RR3))/((E3*RR2)+(E2*RR3))
RF01=CABS(R01TM)**2
RF12=CABS(R12TM)**2
R23=CABS(R23TM)**2
PF1=PFM1
PF2=PFM2
PB1=PBM1
PB2=PBM2
KE1PP=KA1P+KSM1P
KE2PP=KA2P+KSM2P
KE1=KE1PP
KE2=KE2PP
KS1=KSM1P
KS2=KSM2P
C THE W'S REFER TO THE SCATTERING ALBEDO.
222 W1=KS1/KE1
W2=KS2/KE2
C THE FOLLOWING SECTION COMPUTES THE BRIGHTNESS TEMPERATURE ACCORDING
C TO EQUATION 12(PAGE 36) IN THE THESIS.
C IN THE FOLLOWING THE PAGE NO. REFER TO THE THESIS.
88 T11=SQRT(1.-PF1*(W1/2.)+PB1*(W1/2.))
T22=SQRT(1.0-PF2*(W2/2.0)+PB2*(W2/2.0))
A1=KE1*T11*SQRT(1.0-W1)
A2=KE2*T22*SQRT(1.0-W2)
GF1=0.5*KS1*PF1
GB1=0.5*KS1*PB1
N1=(A1-KA1)/(A1+KA1)
C THE PARAMETERS A1,A2 ARE DERIVED IN THE APPENDIX A
C OF THE THESIS IN TERMS OF ALPHA'S.
C N1 IS IN PAGE 33.
IF (GB.LT. (.1*GF1).OR.W1.LE.0.3) N1=GB1/(A1+KE1-GF1)
GF2=0.5*KS2*PF2
GB2=0.5*KS2*PB2
N2=(A2-KA2)/(A2+KA2)
C N2 IS DEFINED IN PAGE 33 AS ETA(GREEK).
C MOST OF THE TERMS FOLLOWING ARE DEFINED IN PP.28-36.
IF (GB2.LT. (.1*GF2).OR.W2.LE.0.3) N2=GB2/(A2+KE2-GF2)
99 AA1=E1M
AA2=E2M
AA3=E3M
C XI1,XI2 ARE IN PAGE 33.
XI1=((A1**2)+GAM1*KA1)/((A1**2)-GAM1*KA1)
XI2=((A2**2)+GAM2*KA2)/((A2**2)-GAM2*KA2)
C HERE C1,C2,E ARE DEFINED IN P.36.
C IN THE FOLLOWING WE FIND C1,D11(D1 IN THESIS),B,A.
C TO CALCULATE IU IN EQUATION 11.
66 C1=AA1*T1
C2=AA2*T2
E=AA3*T3
DD11=((A1**2)-GAM1*KA1)*AA1*TH1
DD12=(A1**2)-(GAM1**2)
D11=DD11/DD12

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LAF01660
LAF01670
LAF01680
LAF01690
LAF01700
LAF01710
LAF01720
LAF01730
LAF01740
LAF01750
LAF01760
LAF01770
LAF01780
LAF01790
LAF01800
LAF01810
LAF01820
LAF01830
LAF01840
LAF01850
LAF01860
LAF01870
LAF01880
LAF01890
LAF01900
LAF01910
LAF01920
LAF01930
LAF01940
LAF01950
LAF01960
LAF01970
LAF01980
LAF01990
LAF02000
LAF02010
LAF02020
LAF02030
LAF02040
LAF02050
LAF02060
LAF02070
LAF02080
LAF02090
LAF02100
LAF02110
LAF02120
LAF02130
LAF02140
LAF02150
LAF02160
LAF02170
LAF02180
LAF02190
LAF02200

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D22=0.0
IF (IH.EQ.0) GO TO 55
DD21=({A2**2}-GAM2*KA2)*AA2*TH2
DD22=({A2**2})-(GAM2**2)
D22=DD21/DD22
C THE TRANSMITTIVITIES BETWEEN ARE T12,T23,T31.
55 T12=1.-RF12
    T01=1.-RF01
    TS10=T01*E1M
    EP1=({RF01-1.0}*C1+{RF01-XI1}*D11+{TS10*TSKY})/({1.0-RF01*N1})
    EP2=((-1.0)*{N1-RF01})/({1.0-RF01*N1})
    G={KA3*TH3*AA3}/{GAM3+KA3}
44 T23=1.-RF23
    TS12={T12*E1M}/{E2M}
    TS23={T23*E2M}/{E3M}
    TS21={T12*E2M}/{E1M}
    A11=N2-RF23
    A22=1.0-N2*RF23
    A33=1.0-N2*RF12
    A44=N2-RF12
    AR1=GAM2*D2
    Y1=0.0
    IF (AR1.LT.40.0) Y1=EXP(-AR1)
    AR2=GAM3*D2
    Y2=0.0
    IF (AR2.LT.40.0) Y2=EXP(-AR2)
    I1={RF23-1.0}*C2+({XI2*FP23}-1.0)*D22*Y1+TS23*(E+G*Y2)
C I1 IS DEFINED IN P. 36.
    HX3=FP12-N1
    HX1=RF12-1.0
    HX2=FP12*XI1-1.0
    AR3=GAM2*D1
    AR4=GAM1*D1
    Y3=0.0
    Y4=0.0
    IF (AR3.LT.40.0) Y3=EXP(-AR3)
    IF (AR4.LT.40.0) Y4=EXP(-AR4)
    M=HX1*C2+{RF12-XI2}*D22*Y3+{C1+XI1*D11*Y4}*TS21
C M APPEARS IN P. 36.
    HH1={HX1*C1}+{HX2*D11*Y4}+TS12*(C2+D22*Y3)
    HH2=HX3*A33+{T12**2}*N2
    HH3=HX3*A44+{T12**2}
    NUM1=({HH1*A22*A33}+{TS12*N2*A22*M})
    AR5=2.*A2*(D2-D1)
    AR6=A1*D1
    Y5=0.0
    Y6=0.0
    IF (AR5.LT.40.0) Y5=EXP(-AR5)
    IF (AR6.LT.40.0) Y6=EXP(-AR6)
    AR8=A2*(D2-D1)
    Y8=0.0
    IF (AR8.LT.40.0) Y8=EXP(-AR8)
    NUM2={HH1*A11*A44+TS12*A11*M}*Y5
    NUM3=TS12*I1*(A33-N2*A44)*Y6*Y8
    NUM4={HH2*EP1*A22}

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LAF02210
 LAF02220
 LAF02230
 LAF02240
 LAF02250
 LAF02260
 LAF02270
 LAF02280
 LAF02290
 LAF02300
 LAF02310
 LAF02320
 LAF02330
 LAF02340
 LAF02350
 LAF02360
 LAF02370
 LAF02380
 LAF02390
 LAF02400
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 LAF02470
 LAF02480
 LAF02490
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 LAF02570
 LAF02580
 LAF02590
 LAF02600
 LAF02610
 LAF02620
 LAF02630
 LAF02640
 LAF02650
 LAF02660
 LAF02670
 LAF02680
 LAF02690
 LAF02700
 LAF02710
 LAF02720
 LAF02730
 LAF02740
 LAF02750

NUM5=(HH3*EP1*A11)*Y5	LAF02760
AR7=2.0*A1*D1	LAF02770
Y7=0.0	LAF02780
IF (AR7.LT.40.0) Y7=EXP(-AR7)	LAF02790
NUM=(NUM1-NUM2)*Y6+NUM3+(NUM4-NUM5)*Y7	LAF02800
DN1=((A33*A22)-(A11*A44*Y5))	LAF02810
DN2=(((-1.0)*N2*A22)+(A11*Y5))	LAF02820
DEN=(1.0-RF12*N1)*DN1+N1*(T12**2)*DN2	LAF02830
DENO=DEN+((N1-RF12)*EP2*DN1+(T12**2)*EP2*DN2)*Y7	LAF02840
B=NUM/DENO	LAF02850
A=EP1+EP2*B	LAF02860
IU=(N1*A)+B+C1+D11	LAF02870
C IU IS THE UPWARD INTENSITY AT Z=0. (SEE P.35,EQ.11).	LAF02880
TB=((1.0-RF01)*IU)/E1M+(RF01*TSKY)	LAF02890
AA(I,2)=TB	LAF02900
C AA(I,2) IS THE BRITENESS TEMPERATURE CORRESPONDING TO	LAF02910
C THE INCIDENT ANGLE 5*I DEGREES.	LAF02920
C AA(I,1) IS JUST THIS ANGLE 5*I DEGREES.	LAF02930
AA(I,1)=PF EQ	LAF02940
115 CONTINUE	LAF02950
NLINES=80	LAF02960
100 CONTINUE	LAF02970
DO 103 JI=1,NVARS	LAF02980
WRITE(6,*) W2	LAF02990
WRITE(6,*) (AA(IL,JI),IL=1,NPT)	LAF03000
103 CONTINUE	LAF03010
GO TO 10	LAF03020
1 CONTINUE	LAF03030
CALL EXIT	LAF03040
STOP	LAF03050
END	LAF03060

PROGRAM INVARIANT IMBEDDING

Introduction

In this program we solve the thermal microwave emission from a slab random medium with nonuniform scattering, absorption, and temperature profiles using radiative transfer theory (Figure 2). With the method of invariant imbedding, the boundary value problem of RT equations is converted to an initial value problem starting at zero thickness. The invariant imbedding technique incorporates the boundary conditions of radiative transfer equations in the new equations. They are in the form of first-order ordinary differential equations and are solved by the Runge-Kutta method in this program. The case of a laminar structure with TE polarization is considered.

Reference: "Thermal microwave emission from a random inhomogeneous layer over a homogeneous medium using the method of invariant imbedding," by L. Tsang and J.A. Kong, Radio Science, Vol. 12, No. 2, pp. 185-194, March-April 1977.

Notes: The frequency and incident angle can be changed in the program. The program we show here is for fixed angle and fixed frequency. To find T_B for different frequencies (or different angles) we just modify the DO loop (896 and 100) by changing FREQ (or DEG).

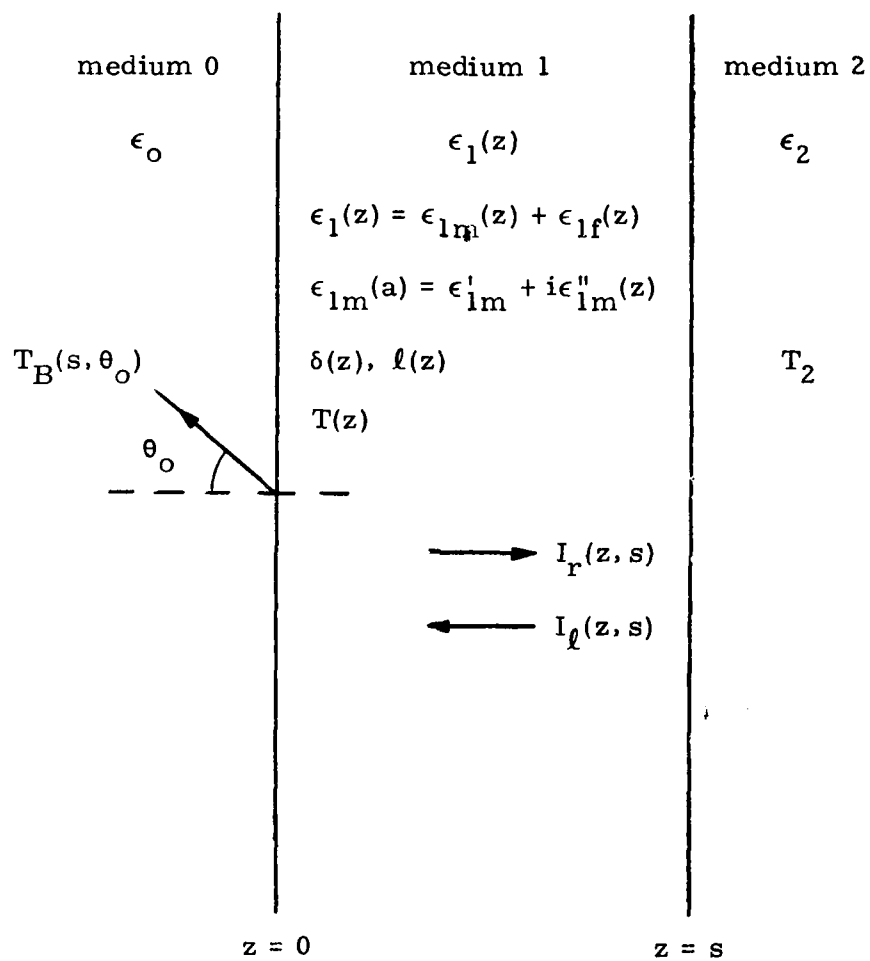


Figure 2. Geometrical Configuration of the Problem for Program INVARIANT IMBEDDING

Equations

Consider Fig. 2 with the correlation function for $\epsilon_{1f}(z)$ of the form

$$\langle \epsilon_{1f}(z_1) \epsilon_{1f}(z_2) \rangle = \delta(z) \epsilon_{2m}' \exp\left[-\frac{|z_1 - z_2|}{\ell(z)}\right], \quad (1)$$

where $z = (z_1 + z_2)/2$. The inhomogeneous scattering, absorption and temperature profiles are characterized by $\delta(z)$ and $\ell(z)$, $\kappa_{a0}(z) = (\epsilon_1''(z)/\epsilon_1')$, and $T(z)$.

In the program, we consider these cases:

$$\delta(z) = \delta_o + \delta_d e^{-\delta_r z} \quad (2)$$

$$\ell(z) = \ell_o + \ell_d e^{-\ell_r z} \quad (3)$$

$$\ell_t(z) \equiv (\epsilon_1''(z)/\epsilon_1') = \ell_{to} + \ell_{td} e^{-\ell_{tr} z} \quad (4)$$

$$T(z) = T_o + T_d e^{-T_r z}, \quad (5)$$

where $\delta_o, \delta_d, \delta_r, \ell_o, \ell_d, \ell_r, \ell_{to}, \ell_{td}, \ell_{tr}, T_o, T_d$, and T_r are all constants.

The four invariant imbedding equations obtained in the paper are

$$\frac{dR(s)}{ds} = b(s) + 2p(s) R(s) + q(s) R^2(s) \quad (6)$$

$$\frac{dt(s)}{ds} = \{p(s) + q(s) R(s)\} t(s) \quad (7)$$

$$\begin{aligned} \frac{dT_R(s)}{ds} = & [p(s) + R(s)q] T_R(s) + [pR(s) + b(s)] t_{12} T_2 \\ & + \kappa_a T(s) [1 + R(s)(1 + r_{12})] \end{aligned} \quad (8)$$

$$\frac{dT_B(s)}{ds} = t_{01}t(s)[T_R(s)q(s) + p(s)t_{12}T_2 + \kappa_a(s)T(s)(1+r_{12})] \quad (9)$$

with the initial conditions

$$R(s=0) = \frac{r_{01}}{1 - r_{01}r_{12}} \quad (10)$$

$$t(s=0) = \frac{1}{1 - r_{01}t_{12}} \quad (11)$$

$$T_R(s=0) = \frac{r_{01}r_{12}}{1 - r_{01}r_{12}} T_2 \quad (12)$$

$$T_B(s=0) = \frac{t_{01}t_{12}}{1 - r_{01}r_{12}} T_2, \quad (13)$$

where

$$p(s) = -\kappa_e(s) + f(s) + b(s)r_{12} \quad (14)$$

$$q(s) = (1+r_{12}^2)b(s) - 2r_{12}[\kappa_e(s) - f(s)]. \quad (15)$$

The total extinction coefficient profile $\kappa_e(z)$ is

$$\kappa_e(z) = \kappa_a(z) + \kappa_s(z) \quad (16)$$

where

$$\kappa_a(z) = \kappa_{a0}(z)/\cos \theta \quad (17)$$

$$\kappa_s(z) = \kappa_{s0}(z)/\cos \theta \quad (18)$$

and $f(z), b(z)$ are defined as

$$f(z) = \kappa_s(z) \frac{P_f(z)}{2} \quad (19)$$

$$b(z) = \kappa_s(z) \frac{P_b(z)}{2}. \quad (20)$$

For TE polarization considered in the program, we have

$$r_{01} = \left| \frac{\sqrt{k_o^2 - k_m'^2 \sin^2 \theta} - k_m' \cos \theta}{\sqrt{k_o^2 - k_m'^2 \sin^2 \theta} + k_m' \cos \theta} \right|^2 \quad (21)$$

$$r_{12} = \left| \frac{k_m' \cos \theta - \sqrt{k_2^2 - k_m'^2 \sin^2 \theta}}{k_m' \cos \theta + \sqrt{k_2^2 - k_m'^2 \sin^2 \theta}} \right|^2 \quad (22)$$

$$\kappa_{so}(z) = \frac{k_m'^2 \delta(z) \ell(z)}{\cos \theta} \left(\frac{1 + 2k_m'^2 \ell^2(z) \cos^2 \theta}{1 + 4k_m'^2 \ell^2(z) \cos^2 \theta} \right) \quad (23)$$

$$P_f(z) = \frac{1 + 4k_m'^2 \ell^2(z) \cos^2 \theta}{1 + 2k_m'^2 \ell^2(z) \cos^2 \theta} \quad (24)$$

$$P_b(z) = \frac{1}{1 + 2k_m'^2 \ell^2(z) \cos^2 \theta}, \quad (25)$$

where θ should be the angle in medium 1. The viewing angle θ_o for the brightness temperature $T_B(s)$ as observed by a radiometer in region 0 is related to θ by Snell's law:

$$\sin \theta_o = \frac{\epsilon_1'}{\epsilon_o} \sin \theta. \quad (26)$$

We have the set of the initial value problem, Eqs. (6)-(9), (10)-(13), which is easier to solve (than the original boundary value problem) with the numerical method.

We use the IMSL ROUTINE - DVERK to solve the differential equations (6)-(9) by the Runge-Kutta method.

Symbols

<u>Fortran Symbols</u>	<u>Notation</u>	<u>Explanations</u>
DL	ϵ_1'	Real part of permittivity in medium 1
DL2	ϵ_2'	Real part of permittivity in medium 2
LT2	ϵ_2''/ϵ_2'	Loss tangent, medium 2
TEMPO	T_o	$T(z) = T_o + T_d e^{-T_r z}$
TEMPD	T_d	
TEMPR	T_r	
TEMP	$T(z)$	
DELO	δ_o	$\delta(z) = \delta_o + \delta_d e^{-\delta_r z}$
DELD	δ_d	
DELR	δ_r	
DEL	$\delta(z)$	
CLO	l_o	$l(z) = l_o + l_d e^{-l_r z}$
CLD	l_d	
CLR	l_r	
CL	$l(z)$	
LTO	l_{to}	$l_t(z) = l_{to} + l_{td} e^{-l_{tr} z}$
LTD	l_{td}	
LTR	l_{tr}	
LT	$l_t(z)$	
DEG	θ_o	Medium 0 (in degrees)
TAI	θ_o	Medium 0 (in radians)
CTI	$\cos \theta_o$	

<u>Fortran Symbols</u>	<u>Notation</u>	<u>Explanations</u>
TAT	θ	Medium 1 (in radians)
FREQ	frequency	Frequency
WAVE	ω	
KO	k	Wave number in medium 0
KIMR	k'_1	Real part of k_1
NT	k'_1/k	
K2	k_2	Complex
T01	t_{01}	Transmissivities
T12	t_{12}	"
R01	r_{01}	Reflectivities
R12	r_{12}	"
T12P	$1 + r_{12}$	
T12P2	$1 + r_{12}^2$	
RD	$1 - r_{01}r_{12}$	
R, Y(1)	$R(s)$	Reflectivity function
T, Y(2)	$t(s)$	Transmissivity function
TRN, Y(3)	$T_R(s)/T_2$	"Reflected" temperature, normalized
TBN, Y(4)	$T_B(s)/T_2$	"Brightness" temperature, normalized
KA	$\kappa_{ao}(s)$	
KS	$\kappa_{so}(s)$	
KAP	$\kappa_s(s) = \kappa_{ao}(s)/\cos \theta$	Eq. (17)
KSP	$\kappa_s(s) = \kappa_{so}(s)/\cos \theta$	Eq. (18)

<u>Fortran Symbols</u>	<u>Notation</u>	<u>Explanations</u>
F1	$P(s)$	As defined in Eq. (14)
F12	$2 P(s)$	Eq. (14)
F2	$q(s)$	Eq. (15)
G(1)	$dR(s)/ds$	Derivative of $R(s)$
G(2)	$dt(s)/ds$	Derivative of $t(s)$
G(3)	$\frac{1}{T_2} \frac{dT_R(s)}{ds}$	Derivative of $T_R(s)/T_2$
G(4)	$\frac{1}{T_2} \frac{dT_B(s)}{ds}$	Derivative of $T_B(s)/T_2$

Features

(a) SUBROUTINE RHS(N, Z, Y, G)

This subroutine is to calculate the right-hand sides of Eqs. (6)-(9) (with Eqs. (8) and (9) normalized by T_2 , i. e., $(dT_R(z)/dz)/T_2$, $(dT_B(z)/ds)/T_2$), and evaluate at each z , the vectors $\bar{Y}(z)$ and $\bar{G}(z)$.

$$\bar{Y}(z) = \begin{pmatrix} R(z) \\ t(z) \\ T_R(z)/T_2 \\ T_B(z)/T_2 \end{pmatrix}, \quad G(z) = \frac{d\bar{Y}(z)}{dz}.$$

N is the number of equations. $N = 4$ in this program.

(b) Call DVERK(N, RHS, Z, Y, XEND, TOL, IND, C, N, W, IER)

DVERK is the IMSL ROUTINE to solve the differential equation with the RUNGE-KUTTA-VERNER fifth- and sixth-order method.

N - number of equations (=4)

Z - independent variable

- (1) On input, Z supplies the initial value.
- (2) On output, Z is replaced with XEND.

Y -

- (1) On input, Y(1) ... Y(N) supply initial values.
- (2) On output, Y(1) ... Y(N) are replaced with an approximate solution at XEND (unless error condition arises).

XEND - value of Z at which solution is desired.

TOL - tolerance for error control (input).

IND - indicator (see the manual of IMSL Library, IMSL LIB-0007).

C - communications vector of length 24.

N - row dimension of the matrix W exactly as specified in the dimension statement in the calling program.

W - workspace matrix. The first dimension of W must be (the above) N, the second must be greater or equal to 9.

IER - ERROR parameter.

(c) To run the program, use:

```
GLOBAL TXTLIB FORTMDD2 IMSL SP CMSLIB
LOAD IMBED
FILEDEF 5 DISK IMBED DATA
START
```

Input and Output Format

(1) Input: free format

The lengths are in centimeters.

```
READ(5,*) DL,DL2,LT2
```

```
READ(5,*,END=2) TEMPO,TEMPD,TEMPR,T2
```

```
READ(5,*) DELO,DELD,DELR
```

```
READ(5,*) CLO,CLD,CLR
```

```
READ(5,*) LTO,LTD,LTR.
```

This program is for fixed incident angle and fixed frequency. To vary the incident angles, just change the lines (IMB 00670, IMB 00710, IMB 00720) to:

```
DOO 896 JAK = 1, 17
```

```
DEG = FLOAT (JAK-1) * 5.0
```

(Delete "DEG = 0.0").

To vary the frequencies, change the lines (IMB 00750, IMB 00810) to:

```
NPT = 10
```

```
DO 100 I = 1, NPT
```

```
FREQ = FLOAT (I) * 5.0
```

(Delete the line "FREQ = 10.0").

(2) Output:

(1) DL,DL2,LT2

(2) TEMPO, TEMPD, TEMPR (in order)

(3) DELO, DELD, DELR (in order)

- (4) DLO, CLD, CLR (in order)
- (5) LTO, LTD, LTR (in order)
- (6) T2
- (7) DEG = (incident angle in degrees), TAI, TAT (in radians), CST($\cos \theta_0$)
- (8) FREQ (in GHZ), K1MR (k_1' cm⁻¹)
- (9) Y1234 (Y(1), Y(2), Y(3), Y(4) in this order), i. e. , R(z), t(z),
 $T_R(z)/T_2$, $T_B(z)/T_2$
- (10) Z, H, and TB.
 Z is the thickness (cm). H is the interval for each change of Z.
 TB is the brightness at thickness Z.

43

```

      WRITE(6,701)  TEMPO,TEMPD,TEMPR
701  FORMAT(1H0' TEMPO,TEMPD,TEMPR=',3E18.8)
      WRITE(6,702)  DELO,DELD,DELR
702  FORMAT(1H0' DELO,DELD,DELR=',3E18.8)
      WRITE(6,703)  CLO,CLD,CLR
703  FORMAT(1H0' CLO,CLD,CLR=',3E18.8)
      WRITE(6,704)  LTO,LTD,LTR
704  FORMAT(1H0' LTO,LTD,LTR=',3E18.8)
      WRITE(6,705)  T2
705  FORMAT(1H0' T2=',E18.8)
      DIELE2=DL2*(IX+JX*LT2)
      DO 896 JAK=1,1
C  DEG AND TAI ARE THE OBSERVATION ANGLE IN MEDIUM 0 IN DEGREES AND
C  RADIANS RESPECTIVELY. TAT IS THE CORRESPONDING ANGLE IN RANDOM MEDIUM.
C  TAI AND TAT ARE RELATED BY SNELL'S LAW.
C      DEG=FLOAT(JAK-1)*5.0
      DEG=0.0
      TAI=DEG*PI/180.
      CTI=COS(TAI)
      NPT=1
      DO 100 I=1,NPT
C  FREQ IS FREQUENCY IN GHZ
C  WAVE IS WAVELENGTH IN CENTIMETERS.
C  K0 IS FREE SPACE WAVENUMBER, K1MR IS WAVE NUMBER IN RANDOM MEDIUM, K2
C  IS WAVENUMBER OF BOTTOM MEDIUM.
      FREQ=10.0
      WAVE=30./FREQ
      K0=2.*PI/WAVE
      K1MR=SQRT(DL)*K0
      NT=K1MR/K0
      TAT=ASIN(SIN(TAI)/NT)
      CST=COS(TAT)
      WRITE(6,2369)  DEG,TAI,TAT,CST
2369  FORMAT(1H0'DEG=',F12.6,' TAI,TAT=',2F12.6,' CST=',F12.6)
      K2=CSQRT(DIELE2)*K0
      WRITE(6,711)  FREQ,K1MR
711  FORMAT(1H0'FREQ=',E18.8,' K1MR=',E18.8)
C  R01 AND P12 ARE FRESNEL REFLECTIVITY AT TOP AND BOTTOM BOUNDARIES
C  RESPECTIVELY. T01 AND T12 ARE THE CORRESPONDING TRANSMISSIVITIES.
      K2Z=CSQRT(K2*K2-(K1MR*SIN(TAT))**2)
      R01=((K0*CTI-K1MR*CST)/(K0*CTI+K1MR*CST))**2
      P12=CABS((K1MR*CST-K2Z)/(K1MR*CST+K2Z))**2
      T01=1.-R01
      T12=1.-R12
      T12P=1.+R12
      T12P2=1.+P12*R12
      RD=1.-R01*R12
C  THE UNKNOWN IN THE ORDINARY DIFFERENTIAL EQUATIONS ARE R,T,TRN,TBN
C  ACCORDING TO EQS. (6),(7),(8),AND (9).OR EQS. (6.4A),(6.4B),(6.9)AND (7.0)
C  IN CHAPTER 6 OF THE BOOK.
C  TRN AND TBN ARE NORMALIZED TO T2. FIRST WE INITIALIZE R,T,TRN,AND
C  TBN ACCORDING TO EQS. (10)-(13),OR EQS. (6.64C),(6.64D),(6.71)AND (6.72)
C  IN THE BOOK.
      R=R01/RD
      T=1./RD

```

IMB00560
 IMB00570
 IMB00580
 IMB00590
 IMB00600
 IMB00610
 IMB00620
 IMB00630
 IMB00640
 IMB00650
 IMB00660
 IMB00670
 IMB00680
 IMB00690
 IMB00700
 IMB00710
 IMB00720
 IMB00730
 IMB00740
 IMB00750
 IMB00760
 IMB00770
 IMB00780
 IMB00790
 IMB00800
 IMB00810
 IMB00820
 IMB00830
 IMB00840
 IMB00850
 IMB00860
 IMB00870
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 IMB00890
 IMB00900
 IMB00910
 IMB00920
 IMB00930
 IMB00940
 IMB00950
 IMB00960
 IMB00970
 IMB00980
 IMB00990
 IMB01000
 IMB01010
 IMB01020
 IMB01030
 IMB01040
 IMB01050
 IMB01060
 IMB01070
 IMB01080
 IMB01090
 IMB01100

```

      TRN=R01*T12/ED
      TBN=T01*T12/RD
C Z CHARACTERIZES THE THICKNESS OF SLAB. VECTOR Y ARE THE UNKNOWN, AND
C VECTOR G ARE THE DERIVATIVES OF THE UNKNOWN AND ARE GIVEN BY THE RIGHT
C HAND SIDES OF EQUATIONS (6.64A), (6.64B), (6.69), AND (6.70). VECTOR G IS
C CALCULATED IN SUBROUTINE RHS.
      Z=0.
      Y(1)=R
      Y(2)=T
      Y(3)=TRN
      Y(4)=TBN
      CALL RHS(N,Z,Y,G)
      TB=Y(4)*T2
      WRITE(6,123) (Y(II),II=1,N)
      H=ABS(Y(1)/G(1))*0.1
      WRITE(6,124) Z,H,TB
123 FORMAT(1H0'Y1234=',4E18.8)
124 FORMAT(1H0'Z=',E18.8,' H=',E18.8,' ---TB=',E18.8)
C NIN IS THE NUMBER OF TIMES WE ITERATE THE ORDINARY DIFFERENTIAL
C EQUATIONS.
      NIN=100
      DO 899 IQ=1,NIN
      DO 564 LO=1,4
C H IS THE INCREMENTAL INTERVAL IN THICKNESS AND IS CALCULATED ACCORDING
C TO THE VALUES OF Y AND G.
      PAT(LO)=1000.0
      IF (G(LO).NE.0.0.AND.Y(LO).NE.0.0) PAT(LO)=ABS(Y(LO)/G(LO))
564 CONTINUE
      H=0.2*AMIN1(PAT(1),PAT(2),PAT(3),PAT(4))
C WE WANT THICKNESS Z TO FALL ON 50 CM. AND 1000 CM.
      IF (Z.LT.49.99.AND.(Z+H).GT.50.0) H=50.0-Z
      IF (Z.LT.999.99.AND.(Z+H).GT.1000.0) H=1000.0-Z
C DVEFK IS THE SUBROUTINE SUPPLIED BY IBM IMSL MATH SOLVING ORDINARY
C DIFFERENTIAL EQUATIONS WITH RUNGE KUTTA METHOD
      IND=1
      XEND=Z+H
      CALL DVERK(N,RHS,Z,Y,XEND,TOL,IND,C,N,W,IER)
      TB=Y(4)*T2
      AA(IQ,1)=Z
      AA(IQ,2)=H
      AA(IQ,3)=TB
      IF (Z.GT.140.0) GO TO 900
899 CONTINUE
900 CONTINUE
      DO 654 IP=1,IQ
      WRITE(6,653) (AA(IP,LEUNG),LEUNG=1,3)
653 FORMAT(3X,E18.8,3X,E18.8,6X,E18.8)
654 CONTINUE
100 CONTINUE
896 CONTINUE
      GO TO 3
2 CONTINUE
      CALL EXIT
      END
      SUBROUTINE RHS(N,Z,Y,G)

```

IMB01110
 IMB01120
 IMB01130
 IMB01140
 IMB01150
 IMB01160
 IMB01170
 IMB01180
 IMB01190
 IMB01200
 IMB01210
 IMB01220
 IMB01230
 IMB01240
 IMB01250
 IMB01260
 IMB01270
 IMB01280
 IMB01290
 IMB01300
 IMB01310
 IMB01320
 IMB01330
 IMB01340
 IMB01350
 IMB01360
 IMB01370
 IMB01380
 IMB01390
 IMB01400
 IMB01410
 IMB01420
 IMB01430
 IMB01440
 IMB01450
 IMB01460
 IMB01470
 IMB01480
 IMB01490
 IMB01500
 IMB01510
 IMB01520
 IMB01530
 IMB01540
 IMB01550
 IMB01560
 IMB01570
 IMB01580
 IMB01590
 IMB01600
 IMB01610
 IMB01620
 IMB01630
 IMB01640
 IMB01650

```

C IN THIS SUBROUTINE FHS, WE CALCULATE THE DERIVATIVES OF THE UNKNOWNNS      IMB01660
C R.T,TEN,AND TBN.  THEY ARE CONTAINED IN THE RIGHT HAND SIDES OF          IMB01670
C EOS.(6.64A),(6.64B),(6.69) AND (6.70). THE UNKNOWNNS ARE STOPED IN      IMB01680
C VECTOR Y AND THE DERIVATIVES ARE STORED IN VECTOR G                      IMB01690
      REAL G(N),Y(N)                                                         IMB01700
      REAL KO,K1MP,K1MI,KA,KSD,KSN,KS,KE,KEMP,LT,LT2                       IMB01710
      REAL LTO,LTD,LTR                                                         IMB01720
      REAL KSP,KAP,KEP                                                         IMB01730
      COMMON/PARA/E01,T01,R12,T12,T12P,T12P2,K1MP,CST                     IMB01740
      COMMON/PARA1/TEMPO,TEMPOD,TEMPOD,T2                                  IMB01750
      COMMON/PARA2/DELO,DELD,DELR                                             IMB01760
      COMMON/PARA3/CLO,CLD,CLR                                              IMB01770
      COMMON/PARA4/LTO,LTD,LTR                                              IMB01780
C TEMPO,TEMPOD,TEMPOD CHARACTERISE THE TEMPERATURE PROFILE.                IMB01790
C DELO,DELD,DELR CHARACTERIZE THE SCATTERING STRENGTH PROFILE              IMB01800
C CLO,CLD,CLR CHARACTERIZE THE CORRELATION LENGTH PROFILE.                  IMB01810
C LTO,LTD,LTR CHARACTERIZE THE LOSS TANGENT PROFILE.                        IMB01820
C TEMP IS THE TEMPERATURE, CL IS THE CORRELATION LENGTH, DEL IS THE         IMB01830
C SCATTERING STRENGTH AND LT IS THE LOSS TANGENT , ALL AT POSITION Z.      IMB01840
      LT=LTO+LTD*EXP(-LTR*Z)                                                 IMB01850
      DEL=DELO+DELD*EXP(-Z*DELR)                                             IMB01860
      CL=CLO+CLD*EXP(-Z*CLR)                                                 IMB01870
      TEMP=TEMPO+TEMPOD*EXP(-Z*TEMPOD)                                       IMB01880
      TEMPN=TEMP/T2                                                           IMB01890
      F=Y(1)                                                                  IMB01900
      T=Y(2)                                                                  IMB01910
      TEN=Y(3)                                                                IMB01920
      TBN=Y(4)                                                                IMB01930
C KS IS SCATTERING COEFFICIENT, KA ABSORPTION COEFFICIENT, KE EXTINCTION    IMB01940
C COEFFICIENT, OM THE ALBEDO.  PF FORWARD PHASE FUNCTION AND PB BACKWARD    IMB01950
C PHASE FUNCTION.                                                           IMB01960
      KSD=1.+(2.*K1MP*CL*CST)**2                                             IMB01970
      KSN=1.+2.*(K1MP*CL*CST)**2                                             IMB01980
      KS=DEL*K1MP*K1MI*CL*KSN/(KSD*CST)                                     IMB01990
      PF=KSD/KSN                                                             IMB02000
      PB=1./KSN                                                             IMB02010
      K1MI=K1MP*LT*0.5                                                       IMB02020
      KA=2.*K1MI                                                             IMB02030
      KE=KS+KA                                                               IMB02040
      OM=KS/KE                                                               IMB02050
      KSP=KS/CST                                                             IMB02060
      KAP=KA/CST                                                             IMB02070
      KEP=KAP+KSP                                                            IMB02080
      F=0.5*KSP*PF                                                           IMB02090
      B=KSP*0.5*PB                                                           IMB02100
      KEMP=KEP-F                                                             IMB02110
      F1=-KEMP+B*P12                                                         IMB02120
      F12=2.*F1                                                             IMB02130
      F2=-2.*KEMP*F12+B*T12P2                                               IMB02140
      G(1)=B+R*F12+R*F*F2                                                  IMB02150
      G(2)=T*(F1+F2*R)                                                       IMB02160
      G(3)=TRN*F1+B*T12+KAP*TEMPOD+R*(TRN*F2+T12*F1+KAP*TEMPOD*T12P)    IMB02170
      G(4)=T01*T*(TRN*F2+F1*T12+KAP*T12P*TEMPOD)                         IMB02180
      RETURN                                                                  IMB02190
      END                                                                    IMB02200

```

PROGRAM BORN1

Introduction

This program computes the backscattering cross sections per unit area in the first-order Born approximation for a two-layer random medium (Figure 3) for both types of polarizations TE and TM. The program computes the backscattering cross sections as a function of angle (for a given frequency) or as a function of frequency (for a given incident angle). Two correlation functions are considered; the first is laterally Gaussian and vertically exponential, the second is spherical. This program also superimposes very rough surface effects incoherently using the model in the Radar Cross-Section Handbook, Chapter 9. The units used in this program are in the MKS system. The frequency is in Hz.

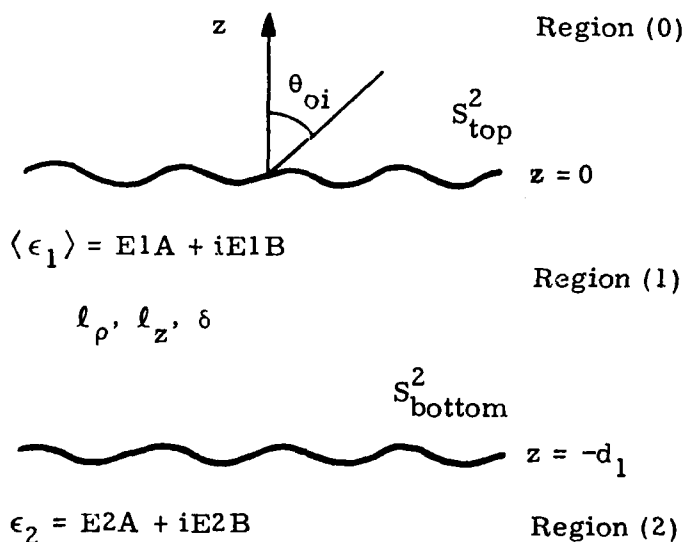


Figure 3. Geometrical Configuration of the Problem for Program BORN1

Equations

The backscattering cross sections per unit area are calculated according to the following equation:

$$\sigma_{hh} = \delta k_l^4 \pi^2 \frac{|X_{0li}|^4}{|D_{2i}|^4} \left[8d_1 \phi_1(2k_{li}, 0) |R_{12i}|^2 e^{-4k_{li}'' d_1} \right. \\ \left. + (1 + |R_{12i}|^4 e^{-4k_{li}'' d_1}) (1 - e^{-4k_{li}'' d_1}) \frac{\phi_1(2k_{li}, 2k_{li})}{2k_{li}''} \right]$$

$$\sigma_{vv} = \delta k_l^4 \pi^2 \frac{|Y_{0li}|^4}{|F_{2i}|^4} \frac{k_o^4}{|k_l|^4} \left[8d_1 \phi_1(2k_{li}, 0) |S_{12i}|^2 e^{-4k_{li}'' d_1} \right. \\ \left. + \frac{|k_{oi}^2 - k_{li}^2|^2}{|k_l|^4} + (1 + |S_{12i}|^4 e^{-4k_{li}'' d_1}) (1 - e^{-4k_{li}'' d_1}) \frac{\phi_1(2k_{li}, 2k_{li})}{2k_{li}''} \right].$$

Two correlation functions are considered in this program: The first is laterally Gaussian and vertically exponential. The corresponding spectral density is

$$\phi_1(\beta_{\perp}, \beta_z) = \frac{\ell_z \ell_{\rho}^2 e^{-\beta_{\perp}^2 \ell_{\rho}^2 / 4}}{4\pi^2 (1 + \beta_z^2 \ell_z^2)}.$$

The second is spherical. The corresponding density is

$$\phi_1(\beta) = \frac{r_o^3 / \pi^2}{[1 + \beta^2 r_o^2]^2}.$$

The rough surface effects are superimposed incoherently using the model in the Radar Cross Section Handbook, Chapter 9.

The rough surface can be either on the top or bottom surface or both.

If the rough surface is on the top layer, then

$$\sigma_{R_{hh}} = \frac{\sec^4 \theta_{oi}}{S^2} \left| \frac{k_o - k_1}{k_o + k_1} \right|^2 \exp\left(-\frac{1}{S^2} \tan^2 \theta_{oi}\right)$$

$$\sigma_{R_{vv}} = \frac{\sec^4 \theta_{oi}}{S^2} \left| \frac{\epsilon_o k_1 - \epsilon_1 k_o}{\epsilon_o k_1 + \epsilon_1 k_o} \right|^2 \exp\left(-\frac{1}{S^2} \tan^2 \theta_{oi}\right)$$

If the rough surface is on the bottom layer, then

$$\sigma_{R_{hh}} = \frac{\sec^4 \theta_t}{S^2} \left| \frac{k_1 - k_2}{k_1 + k_2} \right|^2 \exp\left(-\frac{1}{S^2} \tan^2 \theta_t\right) \exp(-4k_{1z}'' d_1)$$

$$\sigma_{R_{vv}} = \frac{\sec^4 \theta_t}{S^2} \left| \frac{\epsilon_2 k_1 - \epsilon_1 k_2}{\epsilon_2 k_1 + \epsilon_1 k_2} \right|^2 \exp\left(-\frac{1}{S^2} \tan^2 \theta_t\right) \exp(-4k_{1z}'' d_1),$$

where

$$\sin \theta_t = \frac{k_o}{k_1} \sin \theta_{oi}$$

Thus the total backscattering cross sections are given by

$$\sigma_{R_{hh}} + \sigma_{hh} \quad \text{for the TE polarization}$$

$$\sigma_{R_{vv}} + \sigma_{vv} \quad \text{for the TM polarization,}$$

where σ_R (either $\sigma_{R_{hh}}$ or $\sigma_{R_{vv}}$) is that due to the top rough surface or the bottom rough surface or both.

For $\ell, m = 0, 1, 2$,

$$k_{\ell} = \omega \sqrt{\mu \langle \epsilon_{\ell} \rangle}$$

$$k_{\ell z} = \sqrt{k_{\ell}^2 - k_{\perp}^2}$$

$$R_{\ell m} = \frac{k_{\ell z} - k_{mz}}{k_{\ell z} + k_{mz}}$$

$$S_{\ell m} = \frac{\langle \epsilon_m \rangle k_{\ell z} - \langle \epsilon_{\ell} \rangle k_{mz}}{\langle \epsilon_m \rangle k_{\ell z} + \langle \epsilon_{\ell} \rangle k_{mz}}$$

$$X_{\ell m} = 1 + R_{\ell m}$$

$$Y_{\ell m} = 1 + S_{\ell m}$$

$$D_2 = 1 + R_{01} R_{12} e^{i2k_{1z}d_1}$$

$$F_2 = 1 + S_{01} S_{12} e^{i2k_{1z}d_1}$$

A subscript "i" indicates that a quantity is to be calculated at the incident wavevector angles in the appropriate region, e.g.,

$$R_{\ell mi} = \frac{k_{\ell zi} - k_{mzi}}{k_{\ell zi} + k_{mzi}} \quad k_{\ell zi} = \sqrt{k_{\ell}^2 - k_{\perp i}^2} \quad k_{\perp i} = k_0 \sin \theta_{oi}$$

The real and imaginary parts of a quantity are denoted by a prime and double primes, respectively, e.g.,

$$k'_{1z} = \text{Re}(k_{1z}) \quad k''_{1z} = \text{Im}(k_{1z})$$

Symbols

<u>Fortran Symbol</u>	<u>Notation</u>	<u>Explanations</u>
D1	d_1	Thickness of the random layer
EPS1	$\langle \epsilon_1 \rangle$	Mean permittivity of the random layer
EPS0, EPS2	ϵ_0, ϵ_3	Permittivities of the free space region and the homogeneous ground, respectively
K0, K1, K2	k_0, k_1, k_2	Wave numbers in the air region (0-region), the first and second regions, respectively
K1Z, K2Z	k_{1z}, k_{2z}	Components of the wave numbers in the z-direction in regions (1) and (2), respectively
R01, R12	R_{01i}, R_{12i}	Reflection coefficients for the TE wave in regions (0) and (1) at the boundaries separating regions (0)-(1) and (1)-(2), respectively, evaluated at θ_{oi}
S01, S12	S_{01i}, S_{12i}	Reflection coefficients for the TM wave in regions (0) and (1) at the boundaries separating regions (0)-(1) and (1)-(2), respectively, evaluated at θ_{oi}
ZRHO	ℓ_p	Lateral correlation length of fluctuations in permittivities in the random medium
DEL	δ	Variance of fluctuations in permittivities in the random medium
RO	r_0	Spherical correlation length of fluctuations in permittivities in the random medium
E1A	$\langle \epsilon_1 \rangle' / \epsilon_0$	Real part of the mean dielectric constant in the random medium
E2A	ϵ_2' / ϵ_0	Real part of the dielectric constant in the homogeneous medium (2)
E1B	$\langle \epsilon_1 \rangle'' / \epsilon_0$	Imaginary part of the mean dielectric constant in the random medium

<u>Fortran Symbol</u>	<u>Notation</u>	<u>Explanations</u>
E2B	ϵ_2''/ϵ_0	Imaginary part of the dielectric constant in the homogeneous medium (2)
S2T, S2B	S^2	Mean square slope of the top and bottom rough surfaces, respectively
XINC, X	θ_{oi}	Fixed incidence angle and variable incidence angle, respectively
FREQC, FREQ	f	Constant and variable frequencies, respectively
RSIGH, RSIGV	$\sigma_{R_{hh}}, \sigma_{R_{vv}}$	Backscattering cross sections for the TE and TM polarizations, respectively, due to rough surface effects
SIG1, SIG2	σ_{hh}, σ_{vv}	Backscattering cross sections for the TE and TM polarizations, respectively, due to volume scattering

Input and Output Format

(1) The input parameters are:

- | | |
|----------------------|--------------------------|
| (i) ICHECK, ICHOIC | (v) APT, APB, S2T, S2B |
| (ii) FREQ, X | (vi) ZRHO, ZL, DEL |
| (iii) DX, DF, XM, FM | (vii) E1A, E1B, E2A, E2B |
| (iv) FREQC, XINC | (viii) D1 |

Sets (i), (ii), (iii), and (iv) are read from a data file named BORN1 DATA (with logical unit number 8). Sets (v), (vi), (vii), and (viii) are input at the users terminal under a free format specification. The user is prompted with a message to enter the parameters of sets (v), (vii), and (viii) in a specified order.

All input parameters are in MKS units, frequency in Hz, and angles in degrees.

<u>Fortran Symbol</u>	<u>Notation</u>	<u>Explanations</u>
ICHOIC		If ICHOIC = 1 we plot SIGMA vs frequency. If ICHOIC = 2 we plot SIGMA vs incident angle.
ICHECK		ICHECK = 1 corresponds to spherical correlation function. In this case ZRHO is set equal to ZL, and the value read for ZHRO (which is equal to that for ZL) is set equal to RO inside the program. ICHECK = 0 corresponds to Gaussian laterally, exponential vertically.
FREQ, FM		Initial and final values of the variable frequency

<u>Fortran Symbol</u>	<u>Notation</u>	<u>Explanations</u>
DF		Increment step of the variable frequency
X, XM		Initial and final values of the variable incident angle
DX		Increment step of the variable incident angle
APT		If APT = 1 top rough surface effects are included. If APT = 0 top rough surface effects are not included.
APB		If APB = 1 bottom rough surface effects are included. If APB = 0 bottom rough surface effects are not included.
S2T, S2B	S^2	Mean square slope of top and bottom rough surfaces, respectively
XINC	θ_{oi}	Fixed incident angle in degrees, if we plot σ vs frequency
FREQC	f	Fixed frequency in HZ, if we plot σ vs angle

(2) The output parameters are: SIGMA VV, SIGMA HH, INC ANGLE (DEG) or FREQUENCY (GHZ).

SIGMA VV, SIGMA HH are the backscattering cross sections per unit area for the TM and TE polarizations, respectively, in dB.

The format in which these appear is E13.7.

INC ANGLE (DEG) is the incidence angle in degrees, if ICHOIC = 2.

FREQUENCY (GHZ) is the frequency in GHZ, if ICHOIC = 1.

The format in which these appear is F6.3.

C	PROGRAM BORN1	BOR00010
C	M. ZUNIGA	BOR00020
C		BOR00030
C		BOR00040
C		BOR00050
C	PROGRAM TO COMPUTE BACK SCATTERING CROSS SECTIONS/AREA	BOR00060
C	IN THE FIRST ORDER BORN APPROXIMATION FOR A TWO LAYER RANDOM MED.	BOR00070
C	THIS PROGRAM ALSO SUPERIMPOSES VERY ROUGH SURFACE EFFECTS	BOR00080
C	INCOHERENTLY USING THE MODEL IN BARRECKS PAPER	BOR00090
C		BOR00100
C		BOR00110
C		BOR00120
C	COMPLEX EPS1,EPS2,K1,K2,K1Z,K2Z,R10,R12,S10,S12,X01,Y01	BCR00130
C	COMPLEX A12I,A10I,D2,E2,ARG,PH	BOR00140
C	REAL K0,K1R,K2R,K1ZE,K2ZE,KAZ,KZ	BOR00150
C	DATA EPS0,PI,U/8.85E-12,3.14159,1.2566E-6/	BOR00160
C		BCR00170
C	CORRELATION FUNCTION (A) IS SPHERICAL	BOR00180
C	CORRELATION FUNCTION (C) IS GAUSSIAN Laterally AND EXPONENTIAL	BOR00190
C	VERTICALLY	BOR00200
C	ICHECK=1 CORRESPONDS TO CORRELATION FUNCTION (A)	BOR00210
C	ICHECK=0 CORRESPONDS TO CORRELATION FUNCTION (C)	BCR00220
C		BOR00230
C	IF ICHOIC=1 WE PLOT SIGMA VS. FREQUENCY	BOR00240
C	IF ICHOIC=2 WE PLOT SIGMA VS. INC. ANGLE	BOR00250
C		BOR00260
C	READ(8,*) ICHECK,ICHOIC	BOR00270
C		BOR00280
C	FREQ IS THE INITIAL VALUE OF THE VARIABLE FREQ. , IN HZ.	BOR00290
C	X IS THE INITIAL VALUE OF THE VARIABLE INC. ANGLE ,IN DEG.	BOR00300
C		BCR00310
C	READ(8,*)FREQ,X	BOR00320
C	X=X*PI/180.	BCR00330
C		BOR00340
C	DX IS THE INCREMENT STEP OF THE VARIABLE INC. ANGLE,IN DEG.	BOR00350
C	DF IS THE INCREMENT STEP OF THE VARIABLE FREQ. ,IN HZ.	BOR00360
C	XM IS THE FINAL VALUE OF THE VARIABLE INC. ANGLE ,IN DEG.	BOR00370
C	FM IS THE FINAL VALUE OF THE VARIABLE FREQ. ,IN HZ.	BOR00380
C		BOR00390
C	READ(8,*) DX,DF,XM,FM	BOR00400
C		BOR00410
C	FREQC IS THE FIXED FREQ.,IN HZ.,IF WE PLOT SIGMA VS. ANGLE	BOR00420
C	XINC IS THE FIXED INC. ANGLE IN DEG.,IF WE PLOT SIGMA VS. FREQUENCY	BOR00430
C		BOR00440
C	READ(8,*)FREQC,XINC	BOR00450
C	WRITE(6,111)	BOR00460
C	111 FORMAT(3X,'ENTER APT,APB,S2T AND S2B IN THAT ORDER')	BOR00470
C		BOR00480
C	IF APT=1 TOP ROUGH SURFACE EFFECTS ARE INCLUDED	BOR00490
C	IF APT=0 TOP ROUGH SURFACE EFFECTS ARE NOT INCLUDED	BOR00500
C	IF APB=1 BOTTOM ROUGH SURFACE EFFECTS ARE INCLUDED	BOR00510
C	IF APB=0 BOTTOM ROUGH SURFACE EFFECTS ARE NOT INCLUDED	BOR00520
C		BCR00530
C	S2T DENOTES THE MEAN SQUARE SLOPE AT THE TOP SURFACE	BOR00540
C	S2B DENOTES THE MEAN SQUARE SLOPE AT THE BOTTOM SURFACE	BOR00550

C		BOR00560
	READ (5,*) APT,APB,S2T,S2B	BOR00570
	WRITE (6,2)	BCR00580
	2 FORMAT(1X,'ENTER LRHO AND LZ IN M. , ALSO ENTER DEL IN THAT ORDER'	BOR00590
	*)	BCR00600
C		BOR00610
C	ZRHO DENOTES THE LATERAL CORRELATION LENGH OF FLUCTUATION IN	BOR00620
C	PERMITTIVITY OF THE RANDOM MEDIUM,IN M.	BOR00630
C	ZL DENOTES THE VERTICAL CORRELATION LENGH ,IN M.	BOR00640
C	DEL DENOTES THE VARIANCE OF FLUCTUATION IN PERMITTIVITY IN THE	BCR00650
C	RANDOM MEDIUM	BOR00660
C		BCR00670
C	IF ICHECK=1(SPHERICAL CASE) ZRHO IS SET EQUAL TO ZL	BOR00680
C	THE VALUE READ FOR ZRHO(WHICH IS THE SAME AS THAT FOR ZL) IS SET	BCR00690
C	EQUAL TO R0 INSIDE THE PROGRAM	BOR00700
C	R0 IS THE SPHERICAL CORRELATION LENGTH OF FLUCTUATION IN	BOR00710
C	PERMITTIVITY OF THE RANDOM MEDIUM	BOR00720
C		BOR00730
	READ (5,*) ZRHO,ZL,DEL	BCR00740
	WRITE (6,3)	BOR00750
	3 FORMAT(1X,'ENTER E1A,E1B,E2A AND E2B IN THAT ORDER')	BCR00760
C		BOR00770
C	E1A IS THE REAL PART OF THE MEAN DIELECTRIC CONSTANT IN THE RANDCM	BOR00780
C	MEDIUM	BOR00790
C	E2A IS THE REAL PART OF THE DIELECTRIC CONSTANT IN THE HOMOGENEOUS	BCR00800
C	MEDIUM	BOR00810
C	E1B IS THE IMAGINARY PART OF THE MEAN DIELECTRIC CONSTANT IN THE	BOR00820
C	RANDOM MEDIUM	BOR00830
C	E2B IS THE IMAGINARY PART OF THE DIELECTRIC CONSTANT IN THE	BOR00840
C	HOMOGENECUS MEDIUM	BOR00850
C		BOR00860
	READ (5,*) E1A,E1B,E2A,E2B	BCR00870
	WRITE (6,197)	BOR00880
	197 FORMAT(3X,'ENTER D1 IN METERS')	BCR00890
C		BOR00900
C	D1 IS THE DEPTH OF THE RANDOM MEDIUM	BCR00910
C		BOR00920
	READ (5,*) D1	BOR00930
	DX=DX*PI/180.	BOR00940
	XN=XN*PI/180.	BOR00950
	R0=ZRHO	BCR00960
C		BOR00970
C	EPS1 IS THE CCMPLX MEAN PERMITTIVITY IN THE RANDOM MEDIUM (1)	BCR00980
C	EPS2 IS THE COMPLEX PERMITTIVITY IN THE HONCGENEUS MEDIUM (2)	BOR00990
C		BCR01000
	EPS1=EPS0*CMPLX(E1A,E1B)	BOR01010
	EPS2=EPS0*CMPLX(E2A,E2B)	BOR01020
C		BOR01030
C	IF ICHOIC=2 FIX FREQUENCY	BOR01040
C		BCR01050
	IF(ICHOIC.EQ.2) FREQ=FREQC	BOR01060
	ACOR=1.	BCR01070
	MSQ=2	BOR01080
C		BOR01090
C	IPOL=0 CORRESPONDS TO TE --IPOL=1 CORRESPONDS TO TM	BCR01100

C	IPOL MUST ALWAYS HAVE INITIAL VALUE=0	BOR01110
C		BOR01120
	IPOL=0	BOR01130
	IF(ICHECK.EQ.0) ACOR=0.	BOR01140
	IF(ICHECK.EQ.0) RO=ZL	BOR01150
	IF(ICHECK.EQ.0) MSQ=1	BOR01160
	IF(ICHECK.EQ.1) WRITE(6,8)	BOR01170
	IF(ICHECK.EQ.0) WRITE(6,9)	BOR01180
	8 FORMAT(3X,'CORRELATION FUNCTION A(SPHERICAL)')	BOR01190
	9 FORMAT(3X,'CORRELATION FUNCTION C(GAUSSIAN LATERALLY EXPONENTIAL	BOR01200
	*, 'VERTICALLY'))	BOR01210
	IF(APT.EQ.0..AND.APE.EQ.1.) WRITE(6,113)	BOR01220
	IF(APB.EQ.0..AND.APT.EQ.1.) WRITE(6,114)	BOR01230
	IF(APT.EQ.1..AND.APE.EQ.1.) WRITE(6,115)	BOR01240
	IF(APT.EQ.0..AND.APB.EQ.0.) WRITE(6,116)	BOR01250
	113 FORMAT(3X,'ONLY BOTTOM ROUGH SURFACE EFFECTS ARE INCLUDED')	BOR01260
	114 FORMAT(3X,'ONLY TOP ROUGH SURFACE EFFECTS ARE INCLUDED')	BOR01270
	115 FORMAT(3X,'BOTH TOP AND BOTTOM ROUGH SURFACE EFFECTS ARE INCLUDED'	BOR01280
	*)	BOR01290
	116 FORMAT(3X,'NO ROUGH SURFACE EFFECTS ARE INCLUDED')	BOR01300
	FRET=FREQC/1.0E+9	BOR01310
	IF(ICHOIC.EQ.2) WRITE(6,24) FRET	BOR01320
	24 FORMAT(3X,'FREQUENCY(GHZ)=' ,F7.3)	BOR01330
C		BOR01340
C	IF ICHOIC=1 FIX INC ANGLE	BOR01350
C		BOR01360
	IF(ICHOIC.EQ.1) X=XINC*(PI/180.)	BOR01370
	IF(ICHOIC.EQ.1) WRITE(6,25) XINC	BOR01380
	25 FORMAT(3X,'INC ANGLE(DEG)=' ,F7.3)	BOR01390
	IF(ICHOIC.EQ.1) WRITE(6,26)	BOR01400
	26 FORMAT(3X,'SIGMA VV SIGMA HH FREQUENCY(GHZ)	BOR01410
	1)')	BOR01420
	IF(ICHOIC.EQ.2) WRITE(6,27)	BOR01430
	27 FORMAT(3X,'SIGMA VV SIGMA HH INC ANGLE(DEG	BOR01440
	1G)')	BOR01450
	ICOUNT=0	BOR01460
	18 CONTINUE	BOR01470
	W=2.*PI*FREQ	BOR01480
C		BOR01490
C	K0,K1,K2 ARE THE WAVE NUMBERS IN THE AIR [(0)-REGION], THE FIRST ,	BOR01500
C	AND THE SECOND REGIONS RESPECTIVELY	BOR01510
C		BOR01520
	K0=W*SQRT(U*EPS0)	BOR01530
	K2=W*CSQRT(U*EPS2)	BOR01540
	K1=W*CSQRT(U*EPS1)	BOR01550
	K1R=REAL(K1)	BOR01560
	5 CONTINUE	BOR01570
	Y=CCS(X)	BOR01580
	YS=SIN(X)	BOR01590
	KZ=K0*Y	BOR01600
C		BOR01610
C	K1Z,K2Z ARE THE COMPONENTS OF THE WAVE NUMBER IN THE Z-DIRECTION	BOR01620
C	IN REGIONS (1) AND (2) RESPECTIVELY	BOR01630
C		BOR01640
	K1Z=CSQRT(K1*K1-K0*K0*YS*YS)	BOR01650

K2Z=CSQRT(K2*K2-K0*K0*YS*YS)
 K1ZR=REAL(K1Z)
 K2ZR=REAL(K2Z)
 KAZ=2.*AIMAG(K1Z)

R01,R12 ARE THE REFLECTION COEFFICIENTS FOR TE WAVES IN REGIONS
 (0) & (1) AT THE BOUNDARIES SEPERATING REGIONS (0)-(1) & (1)-(2)
 RESPECTIVELY
 R1C=-R01

R10=(K1Z-KZ)/(K1Z+KZ)
 R12=(K1Z-K2Z)/(K1Z+K2Z)

S01,S12 ARE THE REFLECTION COEFFICIENTS FOR TM WAVES IN REGIONS
 (0) & (1) AT THE BOUNDARIES SEPERATING REGIONS (0)-(1)
 & (1)-(2) RESPECTIVELY
 S10=-S01

S10=(EPS0*K1Z-EPS1*KZ)/(EPS0*K1Z+EPS1*KZ)
 S12=(EPS2*K1Z-EPS1*K2Z)/(EPS2*K1Z+EPS1*K2Z)
 Y01=1.-S10
 X01=1.-R10
 PHAS=2.*D1*KAZ
 ARG=COS(K1ZR*2.*D1)+CMPLX(0.,1.)*SIN(K1ZR*2.*D1)

THE FOLLOWING STEP IS TO AVOID THE UNDERFLOW RESULTING FROM THE
 LARGE NEGATIVE POWER OF THE EXPONENTIAL FUNCTION

IF(PHAS.GT.20.) PHAS=20.
 PH=ARG*EXP(-PHAS/2.)

THE FOLLOWING SECTION COMPUTES THE BACKSCATTERING CROSS SECTIONS
 PER UNIT AREA DUE TO VOLUME SCATTERING

D2=1.-R10*R12*PH
 E2=1.-S10*S12*PH
 A10I=R10
 A12I=R12
 CCEF1=DEL*(R0**3)*(K1R**4)*(CABS(X01)**4)
 COEF1=COEF1/(CABS(D2)**4)
 CCEF2=DEL*(R0**3)*(K1R**4)*(CABS(Y01)**4)
 COEF2=COEF2/(CABS(E2)**4)
 COEF2=COEF2*((CABS(K0/K1)**8))
 CCOR=ZL*ZRHO*ZRHO*EXP(-K0*K0*ZRHO*ZRHO*YS*YS)
 IF(ICHECK.EQ.1) CCOB=4.*(R0**3)
 CCEF1=CCEF1*CCOR/(4.*(R0**3))
 COEF2=COEF2*CCOR/(4.*(R0**3))
 AN=CABS((K1Z/K0)**2+YS*YS)
 AN=AN**2
 BN=CABS((K1Z/K0)**2-YS*YS)
 BN=BN**2
 IF(IPOL.EQ.0) GC TO 10
 A10I=S10
 A12I=S12

10 IF(IFCL.EQ.0) AN=1.

BOR01660
 BOR01670
 BOR01680
 BOR01690
 BCR01700
 BOR01710
 BCR01720
 BOR01730
 BCR01740
 BOR01750
 BCR01760
 BOR01770
 BOR01780
 BOR01790
 BOR01800
 BOR01810
 BOR01820
 BCR01830
 BOR01840
 BCR01850
 BOR01860
 BOR01870
 BCR01880
 BOR01890
 BCR01900
 BOR01910
 BCR01920
 BOR01930
 BOR01940
 BOR01950
 BOR01960
 BCR01970
 BOR01980
 BCR01990
 BOR02000
 BCR02010
 BOR02020
 BOR02030
 BOR02040
 BOR02050
 BOR02060
 BOR02070
 BOR02080
 BOR02090
 BCR02100
 BOR02110
 BOR02120
 BOR02130
 BOR02140
 BOR02150
 BOR02160
 BCR02170
 BOR02180
 BCR02190
 BOR02200

	IF (IPOL.EQ.0) BN=1.	BOR02210
	T1=(1.-EXP(-PHAS))/(KAZ*(1.+R0*R0*4.*K1ZR*K1ZR+4.*R0*R0*ACOR*K0*K0	BOR02220
	1*YS*YS)**BSQ)	BOR02230
	T1=T1*(1.+(CABS(A12I)**4)*EXP(-PHAS))	BOR02240
	T2=(8.*D1*EXP(-PHAS)*(CABS(A12I)**2))	BOR02250
	T2=T2/((1.+4.*R0*R0*ACOR*K0*K0*YS*YS)**2)	BOR02260
	C=COEF2	BOR02270
	IF (IPOL.EQ.0) C=CCEF1	BCR02280
	SIG=C*(T1*AN+T2*BN)	BOR02290
	IF (IPOL.EQ.0) SIG1=SIG	BOR02300
	IF (IPOL.EQ.1) SIG2=SIG	BOR02310
	IF (IPOL.EQ.1) GC TO 30	BOR02320
	IF (IPOL.EQ.0) IPOL=1	BOR02330
	IF (ICHOIC.EQ.1.AND.IPOL.EQ.1) GO TO 18	BOR02340
	IF (ICHOIC.EQ.2.AND.IPOL.EQ.1) GO TO 5	BCR02350
30	CONTINUE	BOR02360
	ZZ=X*(180./PI)	BCR02370
	IF (ICHOIC.EQ.1) ZZ=PREQ/1.0E+9	BOR02380
C		BOR02390
C	END OF BACKSCATTERING CROSS SECTIONS / AREA DUE TO VOLUME	BOR02400
C	SCATTERING	BOR02410
C		BCR02420
C	ROUGH SURFACE AT TOP CALCULATION FOLLOWS	BOR02430
C		BCR02440
	S2=S2T	BOR02450
	AP=APT	BCR02460
	XI=X	BOR02470
	RR=CABS((K0-K1)/(K0+K1))	BOR02480
	SS=CABS((EPS0*K1-EPS1*K0)/(EPS0*K1+EPS1*K0))	BOR02490
	TN2=(SIN(XI)/COS(XI))**2	BOR02500
	CHECK2=TN2/S2	BCR02510
	IF (CHECK2.GT.70.) RSIGV=0.	BOR02520
	IF (CHECK2.GT.70.) GO TO 98	BOR02530
	SC4=1./(COS(XI)*COS(XI)*COS(XI)*CCS(XI))	BOR02540
	RSIGV=(AP/S2)*SC4*SS*SS*EXP(-TN2/S2)	BOR02550
98	CONTINUE	BOR02560
	RSIGH=RSIGV*RR*RR/(SS*SS)	BOR02570
C		BOR02580
C	END TOP ROUGH SURFACE CALCULATION	BOR02590
C		BCR02600
C	ROUGH SURFACE AT BOTTOM CALCULATION BEGINS	BOR02610
C		BCR02620
	XI2=ARSIN((K0/K1B)*SIN(X))	BOR02630
	RR=CABS((K1-K2)/(K1+K2))	BOR02640
	SS=CABS((EPS1*K2-EPS2*K1)/(EPS1*K2+EPS2*K1))	BOR02650
	TN2=(SIN(XI2)/CCS(XI2))**2	BOR02660
	CHECK2=TN2/S2B	BCR02670
	IF (CHECK2.GT.70.) RSIGVB=0.	BOR02680
	IF (CHECK2.GT.70.) GO TO 107	BCR02690
	SC4=1./(COS(XI2)**4)	BOR02700
	RSIGVB=(APB/S2B)*SC4*SS*SS*EXP(-CHECK2)	BOR02710
107	CONTINUE	BOR02720
	RSIGHB=RSIGVB*RR*RR/(SS*SS)	BOR02730
	RSIGVB=RSIGVB*EXP(-PHAS)	BOR02740
	RSIGHB=RSIGHB*EXP(-PHAS)	BOR02750

C		BOR02760
C	END BOTTOM ROUGH SURFACE CALCULATION	BOR02770
C		BOR02780
	RSIGV=RSIGV+RSIGVE	BOR02790
	RSIGH=RSIGH+RSIGHB	BOR02800
	SIG1=SIG1+RSIGH	BOR02810
	SIG2=SIG2+RSIGV	BOR02820
	SIG1=10.*ALOG10(SIG1)	BOR02830
	SIG2=10.*ALOG10(SIG2)	BOR02840
	WRITE(6,19) SIG2,SIG1,ZZ	BCR02850
19	FORMAT(3X,E13.7,6X,E13.7,9X,F7.3)	BOR02860
	ICOUNT=ICOUNT+1	BOR02870
	IPOL=0	BOR02880
	IF(ICHOIC.EQ.2) X=X+DX	BCR02890
	IF(ICHOIC.EQ.1) FREQ=FREQ+DF	BOR02900
	IF(ICHOIC.EQ.2.AND.X.LT.XM) GO TO 5	BOR02910
	IF(ICHOIC.EQ.1.AND.FREQ.LT.FM) GO TO 18	BOR02920
	WRITE(6,96) ICOUNT	BOR02930
96	FORMAT(3X,'ICOUNT=',I7)	BCR02940
	STOP	BOR02950
	END	BCR02960

PROGRAM BORNM

Introduction

This program computes the backscattering cross sections per unit area in the first-order Born approximation for a three-layer random medium (Figure 4) for both types of polarizations TE and TM. The program computes the backscattering cross sections as a function of angle (for a given frequency) or as a function of frequency (for a given incident angle). The correlation function considered is laterally Gaussian and vertically exponential. This program also superimposes very rough surface effects incoherently using the model in Barrick's paper. The units used in this program are in the MKS system. The frequency is in Hz.

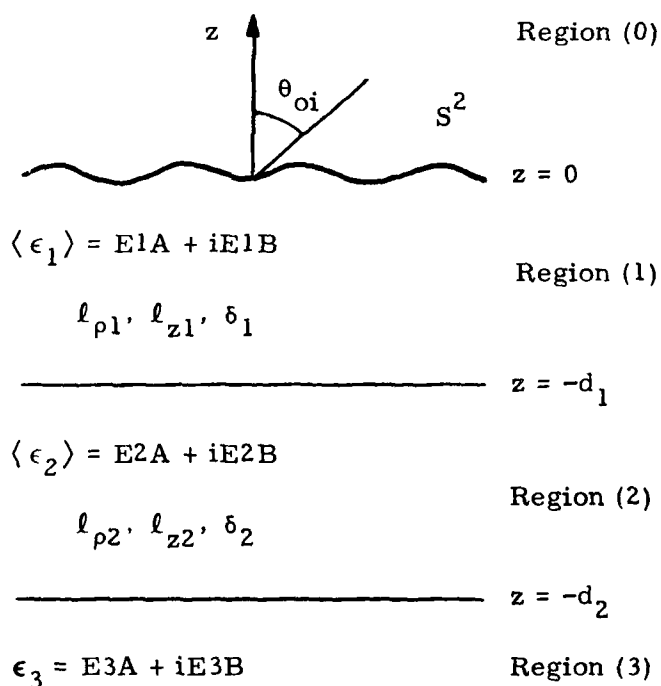


Figure 4. Geometrical Configuration of the Problem for Program BORNM

Equations

The backscattering cross sections per unit are calculated according to the following equations:

$$\begin{aligned} \sigma_{hh} = & \delta_1 k_1^4 \pi^2 \frac{|X_{01i}|^4}{|D_{2i}|^4} \left[8d_1 \phi_1(2k_{1i}, 0) \left| R_{12i} + R_{23i} e^{i2k_{2zi}(d_2 - d_1)} \right|^2 \right. \\ & \left. \left| 1 + R_{12i} R_{23i} e^{i2k_{2zi}(d_2 - d_1)} \right|^2 e^{-4k_{1zi}'' d_1} + \left(\left| R_{12i} + R_{23i} e^{i2k_{2zi}(d_2 - d_1)} \right|^4 \right. \right. \\ & \left. \left. e^{-4k_{1zi}'' d_1} + \left| 1 + R_{12i} R_{23i} e^{i2k_{2zi}(d_2 - d_1)} \right|^4 (1 - e^{-4k_{1zi}'' d_1}) \right) \right. \\ & \left. \frac{\phi_1(2k_{1i}, 2k_{1zi})}{2k_{1zi}''} \right] \\ & + \delta_2 k_2^4 \pi^2 \frac{|X_{01i}|^4 |X_{2i}|^4}{|D_{2i}|^4} \left[8(d_2 - d_1) \phi_2(2k_{1i}, 0) \left| R_{23i} \right|^2 \right. \\ & \left. e^{-4k_{2zi}''(d_2 - d_1)} e^{-4k_{1zi}'' d_1} \right. \\ & \left. + \left(\left| R_{23i} \right|^4 e^{-4k_{2zi}''(d_2 - d_1)} + 1 \right) (1 - e^{-4k_{2zi}''(d_2 - d_1)}) e^{-4k_{1zi}'' d_1} \frac{\phi_2(2k_{1i}, 2k_{2zi})}{2k_{2zi}''} \right] \end{aligned}$$

$$\begin{aligned}
\sigma_{VV} = & \delta_1 k_1^4 \pi^2 \frac{|Y_{01i}|^4}{|E_{2i}|^4} \frac{k_o^4}{|k_1|^4} \left[8d_1 \phi_1(2k_{1i}, 0) \left| S_{12i} + S_{23i} e^{i2k_{2zi}(d_2-d_1)} \right|^2 \right. \\
& \left. \left| 1 + S_{12i} S_{23i} e^{i2k_{2zi}(d_2-d_1)} \right|^2 e^{-4k_{1zi}'' d_1} \frac{|k_{pi}^2 - k_{1zi}^2|^2}{|k_1|^4} \right. \\
& + \left(\left| S_{12i} + S_{23i} e^{i2k_{2zi}(d_2-d_1)} \right|^4 e^{-4k_{1zi}'' d_1} \right. \\
& + \left. \left| 1 + S_{12i} S_{23i} e^{i2k_{2zi}(d_2-d_1)} \right|^4 (1 - e^{-4k_{1zi}'' d_1}) \frac{\phi_1(2k_{1i}, 2k_{1zi})}{2k_{1zi}''} \right) \\
& + \delta_2 k_2^4 \pi^2 \frac{|Y_{01i}|^4 |Y_{12i}|^4}{|E_{2i}|^4} \frac{k_o^4}{|k_2|^4} \left[8(d_2-d_1) \phi_2(2k_{1i}, 0) \right. \\
& \left. |S_{23i}|^2 e^{-4k_{2zi}''(d_2-d_1)} \frac{|k_{pi}^2 - k_{1zi}^2|^2}{|k_2|^4} e^{-4k_{1zi}'' d_1} \right. \\
& + \left(|S_{23i}|^4 e^{-4k_{1zi}''(d_2-d_1)} + 1 \right) (1 - e^{-4k_{2zi}''(d_2-d_1)}) e^{-4k_{1zi}'' d_1} \frac{\phi_2(2k_{1i}, 2k_{2zi})}{2k_{2zi}''} \left. \right].
\end{aligned}$$

The correlation function considered in this program is laterally Gaussian and vertically exponential. The corresponding spectral density is

$$\phi_m(\beta_z, \beta_z) = \frac{\ell_{zm} \ell_{pm}^2 e^{-\beta_z^2 \ell_{pm}^2 / 4}}{4^2 (1 + \beta_z^2 \ell_{zm}^2)}.$$

The rough surface effects which are superimposed incoherently using the model in Barrick's paper are given by the following equations (the rough surface is on the top layer):

$$\sigma_{R_{hh}} = \frac{\sec^4 \theta_{oi}}{S^2} \left| \frac{k_o - k_1}{k_o + k_1} \right|^2 \exp\left(-\frac{1}{S^2} \tan^2 \theta_{oi}\right)$$

$$\sigma_{R_{vv}} = \frac{\sec^4 \theta_{oi}}{S^2} \left| \frac{\epsilon_o k_1 - \epsilon_1 k_o}{\epsilon_o k_1 + \epsilon_1 k_o} \right|^2 \exp\left(-\frac{1}{S^2} \tan^2 \theta_{oi}\right).$$

And the total backscattering cross sections are given by

$$\sigma_{R_{hh}} + \sigma_{hh} \quad \text{for the TE polarization}$$

$$\sigma_{R_{vv}} + \sigma_{vv} \quad \text{for the TM polarization}$$

where, for $\ell, m = 0, 1, 2, 3$,

$$k_\ell = \omega \sqrt{\mu \langle \epsilon_\ell \rangle}$$

$$k_{\ell z} = \sqrt{k_\ell^2 - k_1^2}$$

$$R_{\ell m} = \frac{k_{\ell z} - k_{mz}}{k_{\ell z} + k_{mz}}$$

$$S_{\ell m} = \frac{\langle \epsilon_m \rangle k_{\ell z} - \langle \epsilon_\ell \rangle k_{mz}}{\langle \epsilon_m \rangle k_{\ell z} + \langle \epsilon_\ell \rangle k_{mz}}$$

$$X_{\ell m} = 1 + R_{\ell m}$$

$$Y_{\ell m} = 1 + S_{\ell m}$$

$$E_2 = 1 + S_{12} S_{23} e^{i2k_{2z}(d_2 - d_1)} + S_{01} [S_{12} + S_{23} e^{i2k_{2z}(d_2 - d_1)}] e^{i2k_{1z}d_1}$$

$$D_2 = 1 + R_{12} R_{23} e^{i2k_{2z}(d_2 - d_1)} + R_{01} [R_{12} + R_{23} e^{i2k_{2z}(d_2 - d_1)}] e^{i2k_{1z}d_1}.$$

A subscript "i" indicates that a quantity is to be evaluated at the incident wavevector angles in the appropriate region, e.g.,

$$R_{lmi} = \frac{k_{lzi} - k_{mzi}}{k_{lzi} + k_{mzi}} \quad k_{lzi} = \sqrt{k_l^2 - k_{li}^2} \quad k_{li} = k_o \sin \theta_{oi}$$

The real and imaginary parts of a quantity are denoted by a prime and double primes, respectively, e.g.,

$$k'_{1z} = \text{Re}(k_{1z}) \quad k''_{1z} = \text{Im}(k_{1z})$$

Symbols

<u>Fortran Symbol</u>	<u>Notation</u>	<u>Explanations</u>
D1	d_1	Thickness of first random layer
D2	d_2	Thickness of first and second random layers
EPS1, EPS2	$\langle \epsilon_1 \rangle, \langle \epsilon_2 \rangle$	Mean permittivities of the first and second random layers, respectively
EPS0, EPS3	ϵ_o, ϵ_3	Permittivities of free space region and the homogeneous ground, respectively
K0, K1, K2, K3	k_o, k_1, k_2, k_3	Wave numbers in the air region (0-region), the first, second, and third regions, respectively
K1Z, K2Z, K3Z	k_{1z}, k_{2z}, k_{3z}	Components of the wave number in the z-direction in regions (1), (2), and (3), respectively
R01, R12, R23	$R_{01i}, R_{12i}, R_{23i}$	Reflection coefficients for the TE waves in regions (0), (1), and (2) at the boundaries separating regions (0)-(1), (1)-(2), and (2)-(3), respectively, evaluated at θ_{oi}
S01, S12, S23	$S_{01i}, S_{12i}, S_{23i}$	Reflection coefficients for the TM waves in regions (0), (1), and (2) at the boundaries separating regions (0)-(1), (1)-(2), and (2)-(3), respectively, evaluated at θ_{oi}

<u>Fortran Symbol</u>	<u>Notation</u>	<u>Explanations</u>
ZRHO1, ZRHO2	$l_{\rho 1}, l_{\rho 2}$	Lateral correlation lengths of fluctuation in permittivities in first and second regions, respectively
ZL1, ZL2	l_{z1}, l_{z2}	Vertical correlation lengths of fluctuation in permittivities in first and second regions, respectively
DEL1, DEL2	δ_1, δ_2	Variances of fluctuations in permittivities in first and second regions, respectively
E1A, E2A	$\langle \epsilon_1 \rangle' / \epsilon_0, \langle \epsilon_2 \rangle' / \epsilon_0$	Real parts of the mean dielectric constant in random media (1) and (2), respectively
E3A	ϵ_3' / ϵ_0	Real part of the dielectric constant in the homogeneous medium (3)
E1B, E2B	$\langle \epsilon_1 \rangle'' / \epsilon_0, \langle \epsilon_2 \rangle'' / \epsilon_0$	Imaginary parts of the mean dielectric constant in random media (1) and (2), respectively
E3B	$\epsilon_3'' / \epsilon_0$	Imaginary part of the dielectric constant in the homogeneous medium (3)
S2	S^2	Mean square slope of the rough surface
XINC, X	θ_{oi}	Fixed incidence angle and variable incidence angle, respectively
RSIGH, RSIGV	$\sigma_{R_{hh}}, \sigma_{R_{vv}}$	Backscattering cross sections for the TE and TM polarizations, respectively, due to rough surface effects
SIG1, SIG2	σ_{hh}, σ_{vv}	Backscattering cross sections for the TE and TM polarizations, respectively, due to volume scattering
FREQC, FREQ	f	Constant and variable frequencies, respectively

Features

A subroutine function called COR(KO, X, RL, RZ, K2R) is built into the program to compute the spectral density corresponding to a correlation function which is laterally Gaussian and vertically exponential.

It computes this spectral density according to the following equation:

$$\phi_m(\beta_{\perp}, \beta_z) = \frac{l_{zm} l_{\rho m}^2 e^{-\beta_{\perp}^2 l_{\rho m}^2 / 4}}{4\pi^2 (1 + \beta_z^2 l_{zm}^2)}.$$

$l_{zm}, l_{\rho m}$ are the vertical and lateral correlation lengths in the m^{th} random layer, and the corresponding Fortran symbols are RZ, RL. The corresponding Fortran symbol for β_z is K2R.

Input and Output Format

(1) The input parameters are:

- | | |
|----------------------|---|
| (i) ICHOIC | (v) ZRHO1, ZRHO2, ZL1, ZL2,
DEL1, DEL2 |
| (ii) F, XO | (vi) E1A, E1B, E2A, E2B, E3A, E3B |
| (iii) DX, DF, XM, FM | (vii) D1, D2 |
| (iv) AP, S2 | (viii) XINC or FREQC |

Sets (i), (ii), and (iii) are read from a data file (with logical unit number 8) with the name `BORNM DATA`. Sets (iv), (v), (vi), (vii), and (viii) are input at the users terminal under a free format specification. The user is prompted with a message to enter the parameters of sets (iv), (v), (vi), (vii), and (viii) in a specified order.

All input parameters are in MKS units, frequency in Hz, and angles in degrees.

<u>Fortran Symbol</u>	<u>Notation</u>	<u>Explanations</u>
ICHOIC		If ICHOIC = 1 we plot SIGMA vs frequency. If ICHOIC = 2 we plot SIGMA vs incident angle
F, FM		Initial and final values of the variable frequency
DF		Increment step of the variable frequency
XO, XM		Initial and final values of the variable incident angle
DX		Increment step of the variable incident angle

<u>Fortran Symbol</u>	<u>Notation</u>	<u>Explanations</u>
AP		If AP = 1 rough surface effects are included. If AP = 0 rough surface effects are not included.
S2	S^2	Mean square slope of the rough surface
XINC	θ_{oi}	Fixed incident angle in degrees. If ICHOIC = 2, do not enter XINC. Instead, enter FREQC (each value of FREQC should be entered on a separate line).
FREQC	f	Fixed frequency in HZ, if we plot σ vs angle. If ICHOIC = 1, do not enter FREQC. Instead, enter XINC (each value of XINC should be entered on a separate line).

(2) The output parameters are: SIGMA VV, SIGMA HH, INC ANGLE (DEG) or FREQUENCY (GHZ).

SIGMA VV, SIGMA HH are the backscattering cross sections per unit area for the TM and TE polarizations, respectively, in dB. The format in which these appear is E13.7.

INC ANGLE (DEG) is the incident angle in degrees, if ICHOIC = 2. FREQUENCY (GHZ) is the frequency in GHZ, if ICHOIC = 1. The format in which these appear is F6.3.

```

C          *PROGRAM BORNMM*
C          M. ZUNIGA - T. HABASHY
C
C          PROGRAM TO COMPUTE BACK SCATTERING CROSS SECTIONS/AREA IN THE
C          FIRST ORDER BORN APPROXIMATION FOR A THREE LAYER RANDOM MED.
C          THIS PROGRAM ALSO SUPERIMPOSES VERY ROUGH SURFACE EFFECTS
C          INCOHERENTLY USING THE MODEL IN BARRECKS PAPER
C
C          COMPLEX EPS1,EPS2,EPS3,K1,K2,K3,K1Z,K2Z,K3Z
C          COMPLEX X01,X12,Y01,Y12,D21,E2,AN1,BN1,A12I,A23I,ARG1,ARG2,PH1,PH2
C          COMPLEX R10,R12,R23,S10,S12,S23
C          REAL K0,K1R,K2R,K1ZE,K2ZR,KAZ1,KAZ2
C          DATA EPS0,P1,U/8.85E-12,3.14159,1.2566E-6/
C
C          IF ICHOIC=1 WE PLOT SIGMA VS FREQ.
C          IF ICHOIC=2 WE PLOT SIGMA VS INC. ANGLE
C
C          READ(8,*) ICHCIC
C
C          F IS THE INITIAL VALUE OF THE VARIABLE FREQ.,IN HZ.
C          XO IS THE INITIAL VALUE OF THE VARIABLE INC. ANGLE,IN DEG.
C
C          REAL(8,*) F,XC
C
C          DX IS THE INCREMENT STEP OF THE VARIABLE INC. ANGLE,IN DEG.
C          DP IS THE INCREMENT STEP OF THE VARIABLE FREQ.,IN HZ.
C          XM IS THE FINAL VALUE OF THE VARIABLE INC. ANGLE,IN DEG.
C          FM IS THE FINAL VALUE OF THE VARIABLE FREQ.,IN HZ.
C
C          READ(8,*) DX,DP,XM,FM
C          WRITE(6,1)
C          1 FORMAT(3X,'IF APT=1 TOP ROUGH SURFACE EFFECTS ARE INCLUDED'//,3X,
C          *'IF APT=0 TOP ROUGH SURFACE EFFECTS ARE NOT INCLUDED'//,3X,
C          *'IF APB=1 BOTTOM ROUGH SURFACE EFFECTS ARE INCLUDED'//,3X,
C          *'IF APB=0 BOTTOM ROUGH SURFACE EFFECTS ARE NOT INCLUDED'//,1X,
C          *'ENTER APT,APB,S2T AND S2B IN THAT ORDER')
C
C          IF APT=1 TOP ROUGH SURFACE EFFECTS ARE INCLUDED
C          IF APT=0 TOP ROUGH SURFACE EFFECTS ARE NOT INCLUDED
C          IF APB=1 BOTTOM ROUGH SURFACE EFFECTS ARE INCLUDED
C          IF APB=0 BOTTOM ROUGH SURFACE EFFECTS ARE NOT INCLUDED
C          BY TOP ROUGH SURFACE WE MEAN ROUGH SURFACE AT THE INTERFACE
C          SEPERATING REGIONS (0) AND (1)
C          BY BOTTOM ROUGH SURFACE WE MEAN ROUGH SURFACE AT THE INTERFACE
C          SEPERATING REGIONS (2) AND (3)
C
C          S2T DENOTES THE MEAN SQUARE SLOPE AT THE TOP SURFACE
C          S2B DENOTES THE MEAN SQUARE SLOPE AT THE BOTTOM SURFACE
C
C          READ(5,*) APT,APB,S2T,S2B
C          WRITE(6,2)

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```

2 FORMAT(3X,'ENTER LRHO1,LRHO2,LZ1 AND LZ2 IN M.,ALSO ENTER DEL1', BOR00560
  *' AND DEL2 IN THAT',/,1X,'ORDER') BOR00570
C BOR00580
C ZRHO1,ZRHO2 DENOTE THE LATERAL CORRELATION LENGTHS OF FLUCTUATION BOR00590
C IN PERMITTIVITIES IN FIRST AND SECOND REGIONS RESPECTIVELY, IN M. BOR00600
C ZL1,ZL2 DENOTE THE VERTICAL CORRELATION LENGTHS, ALSO IN M. BOR00610
C DEL1,DEL2 DENOTE THE VARIANCES OF FLUCTUATIONS IN PERMITTIVITIES BOR00620
C IN FIRST AND SECOND REGIONS RESPECTIVELY BOR00630
C BOR00640
C READ(5,*) ZRHO1,ZRHO2,ZL1,ZL2,DEL1,DEL2 BOR00650
C WRITE(6,3) BOR00660
3 FORMAT(3X,'ENTER E1A,E1B,E2A,E2B,E3A AND E3B IN THAT ORDER') BOR00670
C BOR00680
C E1A AND E2A ARE THE REAL PARTS OF THE MEAN DIELECTRIC CONSTANT IN BOR00690
C RANDOM MEDIA (1) AND (2) RESPECTIVELY BOR00700
C E3A IS THE REAL PART OF THE DIELECTRIC CONSTANT IN THE HOMOGENEOUS BOR00710
C MEDIUM (3) BOR00720
C E1B AND E2B ARE THE IMAGINARY PARTS OF THE MEAN DIELECTRIC CONSTANT BOR00730
C IN RANDOM MEDIA (1) AND (2) RESPECTIVELY BOR00740
C E3B IS THE IMAGINARY PART OF THE DIELECTRIC CONSTANT IN THE BOR00750
C HOMOGENEOUS MEDIUM (3) BOR00760
C BOR00770
C READ(5,*) E1A,E1B,E2A,E2B,E3A,E3B BOR00780
C WRITE(6,4) BOR00790
4 FORMAT(3X,'ENTER D1 AND D2 IN METERS IN THAT ORDER') BOR00800
C BOR00810
C D1 IS THE DEPTH OF THE FIRST REGION BOR00820
C D2 IS THE DEPTH OF THE FIRST AND SECOND REGIONS BOR00830
C BOR00840
C READ(5,*) D1,D2 BOR00850
C DX=DX*PI/180. BOR00860
C XM=XM*PI/180. BOR00870
C BOR00880
C EPS1 AND EPS2 ARE THE COMPLEX MEAN PERMITTIVITIES IN REGIONS BOR00890
C (1) AND (2) RESPECTIVELY BOR00900
C EPS3 IS THE COMPLEX PERMITTIVITY IN THE HOMOGENEOUS MEDIUM BOR00910
C (3) BOR00920
C BOR00930
C EPS1=EPS0*CMPLX(E1A,E1B) BOR00940
C EPS2=EPS0*CMPLX(E2A,E2B) BOR00950
C EPS3=EPS0*CMPLX(E3A,E3B) BOR00960
C IF (APT.EQ.0..AND.APB.EQ.1.) WRITE(6,911) BOR00970
C IF (AEB.EQ.0..AND.APT.EQ.1.) WRITE(6,912) BOR00980
C IF (APT.EQ.1..AND.APB.EQ.1.) WRITE(6,913) BOR00990
C IF (AET.EQ.0..AND.APB.EQ.0.) WRITE(6,914) BOR01000
911 FORMAT(3X,'ONLY BOTTOM ROUGH SURFACE EFFECTS ARE INCLUDED') BOR01010
912 FORMAT(3X,'ONLY TOP ROUGH SURFACE EFFECTS ARE INCLUDED') BOR01020
913 FORMAT(3X,'BOTH TOP AND BOTTOM ROUGH SURFACE EFFECTS ARE INCLUDED' BOR01030
  *) BOR01040
914 FORMAT(3X,'NO ROUGH SURFACE EFFECTS ARE INCLUDED') BOR01050
107 CONTINUE BOR01060
C IF (ICHOIC.EQ.2) GO TO 111 BOR01070
C BOR01080
C XINC IS THE FIXED INC. ANGLE, IN DEG. IF ICHOIC = 2 DO NOT ENTER BOR01090
C XINC , INSTEAD ENTER FREQC [EACH VALUE OF FREQC SHOULD BE ENTERED BOR01100

```

C	ON A SEPERATE LINE]	BOR01110
C		BOR01120
	READ (8,*,END=106) XINC	BOR01130
	FFREQ=F	BCR01140
	GO TO 112	BOR01150
C		BCR01160
C	FREQC IS THE FIXED FREQ., IN HZ. - IF ICHCIC = 1 DO NOT ENTER FREQC	BOR01170
C	INSTEAD ENTER XINC [EACH VALUE OF XINC SHOULD BE ENTERED ON A	BOR01180
C	SEPERATE LINE]	BCR01190
C		BCR01200
	111 READ (8,*,END=106) FREQC	BOR01210
	X=XC	BOR01220
	FRET=FREQC/1.0E+9	BOR01230
	112 IF (ICHOIC.EQ.2) GO TO 61	BCR01240
	X=XINC*(PI/180.)	BOR01250
	WRITE (6,25) XINC	BOR01260
	25 FORMAT (3X, 'INC ANGLE (DEG) = ', P7.3)	BOR01270
	WRITE (6,26)	BOR01280
	26 FORMAT (5X, 'SIGMA VV', 11X, 'SIGMA HH', 9X, 'FREQUENCY (GHZ)')	BCR01290
	GO TO 18	BOR01300
	61 FREQ=FREQC	BOR01310
	WRITE (6,24) FRET	BOR01320
	24 FORMAT (3X, 'FREQUENCY (GHZ) = ', P7.3)	BCR01330
	WRITE (6,27)	BOR01340
	27 FORMAT (5X, 'SIGMA VV', 11X, 'SIGMA HH', 9X, 'INC ANGLE (DEG)')	BOR01350
	18 W=2.*PI*FREQ	BOR01360
C		BOR01370
C	K0, K1, K2, K3 ARE THE WAVE NUMBERS IN THE AIR REGION [(0)-REGION],	BOR01380
C	THE FIRST , SECOND AND THIRD REGIONS RESPECTIVELY	BOR01390
C		BOR01400
	K0=W*SQRT (U*EPSC)	BOR01410
	K1=W*CSQRT (U*EPS1)	BOR01420
	K2=W*CSQRT (U*EPS2)	BOR01430
	K3=W*CSQRT (U*EPS3)	BCR01440
	K1R=REAL (K1)	BOR01450
	K2R=REAL (K2)	BCR01460
C		BOR01470
C	IPOL=0 CORRESPONDS TO TE POLARIZATION	BCR01480
C	IPOL=1 CORRESPONDS TO TM POLARIZATION	BOR01490
C		BOR01500
	5 IFOL=0	BOR01510
	AN=1.	BOR01520
	BN=1.	BCR01530
	Y=COS (X)	BOR01540
	YS=SIN (X)	BCR01550
C		BOR01560
C	K1Z, K2Z, K3Z ARE THE COMPONENTS OF THE WAVE NUMBER IN THE	BOR01570
C	Z-DIRECTION IN REGIONS (1), (2) & (3) RESPECTIVELY	BOR01580
C		BOR01590
	K1Z=CSQRT (K1*K1-K0*K0*YS*YS)	BOR01600
	K2Z=CSQRT (K2*K2-K0*K0*YS*YS)	BOR01610
	K3Z=CSQRT (K3*K3-K0*K0*YS*YS)	BCR01620
	K1ZR=REAL (K1Z)	BOR01630
	K2ZR=REAL (K2Z)	BCR01640
	KAZ 1=2.*AIMAG (K1Z)	BOR01650

```

      KAZ2=2.*AIMAG(K2Z)
C
C      R01,R12,R23 ARE THE REFLECTION COEFFICIENTS FOR TE WAVES IN REGIONS
C      (0),(1)&(2) AT THE BOUNDERIES SEPERATING REGIONS (0)-(1),(1)-(2)
C      &(2)-(3) RESPECTIVELY
C      R10=-R01
C
      R10=(K1Z-K0*Y)/(K1Z+K0*Y)
      R12=(K1Z-K2Z)/(K1Z+K2Z)
      R23=(K2Z-K3Z)/(K2Z+K3Z)
      A12I=R12
      A23I=R23
C
C      S01,S12,S23 ARE THE REFLECTION COEFFICIENTS FOR TM WAVES IN REGIONS
C      (0),(1)&(2) AT THE BOUNDERIES SEPERATING REGIONS (0)-(1),(1)-(2)
C      &(2)-(3) RESPECTIVELY
C      S10=-S01
C
      S10=(EPS0*K1Z-EPS1*K0*Y)/(EPS0*K1Z+EPS1*K0*Y)
      S12=(EPS2*K1Z-EPS1*K2Z)/(EPS2*K1Z+EPS1*K2Z)
      S23=(EPS3*K2Z-EPS2*K3Z)/(EPS3*K2Z+EPS2*K3Z)
      X01=1.-R10
      X12=1.+R12
      Y01=1.-S10
      Y12=1.+S12
      PHAS1=D1*KAZ1
      PHAS2=(D2-D1)*KAZ2
      PHAS3=D2*KAZ2
C
C      THE FOLLOWING THREE STEPS ARE TO AVOID THE UNDERFLOW RESULTING FROM
C      THE HIGH NEGATIVE POWER OF THE EXPONENTIAL FUNCTION
C
      IF(PHAS1.GT.18.) PHAS1=18.
      IF(PHAS2.GT.18.) PHAS2=18.
      IF(PHAS3.GT.18.) PHAS3=18.
      ARG1=COS(2.*D1*K1ZR)+CMPLX(0.,1.)*SIN(2.*D1*K1ZR)
      ARG2=COS(2.*(D2-D1)*K2ZR)+CMPLX(0.,1.)*SIN(2.*(D2-D1)*K2ZR)
      PH1=ARG1*EXP(-PHAS1)
      PH2=ARG2*EXP(-PHAS2)
C
C      THE FOLLOWING SECTION COMPUTES THE BACKSCATTERING CROSS SECTIONS
C      /AREA DUE TO VOLUME SCATTERING
C
      D21=1.+R12*R23*PH2-R10*(R12+R23*PH2)*PH1
      E2=1.+S12*S23*PH2-S10*(S12+S23*PH2)*PH1
      C1=PI*PI*((CABS(X01/D21))**4)
      C2=C1*DEL2*(K2R**4)*((CABS(X12))**4)
      C1=C1*DEL1*(K1R**4)
      GO TO 10
20  AN1=((K0*YS)**2-K1Z*K1Z)
      AN=((CABS(AN1))**2)/((CABS(K1))**4)
      BN1=((K0*YS)**2-K2Z*K2Z)
      BN=((CABS(BN1))**2)/((CABS(K2))**4)
      A12I=S12
      A23I=S23

```

CONVERSATIONAL MONITOR SYSTEM

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	RSIGHB=RSIGVB*RR*RR/(SS*SS)	BOR02760
	PHAS=2.*(PHAS1+PHAS2)	BOR02770
	IF(PHAS.GT.18.)PHAS=18.	BOR02780
	RSIGVB=RSIGVB*EXP(-PHAS)	BOR02790
	RSIGHB=RSIGHB*EXP(-PHAS)	BOR02800
C		BOR02810
C	END OF BOTTOM ROUGH SURFACE CALCULATION	BOR02820
C		BOR02830
	RSIGV=RSIGV+RSIGVB	BOR02840
	RSIGH=RSIGH+RSIGHB	BOR02850
	SIG1=SIG1+RSIGH	BOR02860
	SIG2=SIG2+RSIGV	BOR02870
	SIG1=10.*ALOG10(SIG1)	BOR02880
	SIG2=10.*ALOG10(SIG2)	BOR02890
	ZZ=X*(180./PI)	BOR02900
	IF(ICHOC.EQ.1)ZZ=FREQ/1.0E+9	BOR02910
	WRITE(6,19)SIG2,SIG1,ZZ	BCR02920
19	FORMAT(3X,E13.7,6X,E13.7,9X,F7.3)	BOR02930
	IF(ICHOC.EQ.2)X=X+DX	BOR02940
	IF(ICHOC.EQ.1)FREQ=FREQ+DF	BOR02950
	IF(ICHOC.EQ.2.AND.X.LT.XM)GO TO 5	BCR02960
	IF(ICHOC.EQ.1.AND.FREQ.LT.FM)GO TO 18	BOR02970
	GO TO 107	BOR02980
106	STOP	BOR02990
	END	BOR03000
C		BOR03010
C	THE FOLLOWING IS A FUNCTION SUBROUTINE TO CALCULATE THE SPECTRAL	BOR03020
C	DENSITY CORRESPONDING TO A CORRELATION FUNCTION WHICH IS GAUSSIAN	BCR03030
C	LATERALLY AND EXPONENTIAL VERTICALLY	BOR03040
C		BOR03050
	FUNCTION COR(K0,X,RL,RZ,K2R)	BOR03060
	REAL K0,K2R	BOR03070
	Y=SIN(X)	BOR03080
	PI=3.14159	BOR03090
	TRF=K0*K0*RL*RL*Y*Y	BCR03100
	IF(TRF.GT.18.)TRF=18.	BOR03110
	COR=RZ*RI*RL*EXP(-TRF)/(4.*PI*PI*(1.+4.*K2R*K2R*RZ*RZ))	BOR03120
	RETURN	BOR03130
	END	BCR03140

SECTION VIII
PUBLICATIONS

The work performed during the period of February 1, 1978 - September 30, 1979 has been published in the categories of:

- A. referred journal articles
- B. conference papers
- C. technical reports

A. Referred Journal Articles

- A.1 L. Tsang and J. A. Kong, "Radiative transfer theory for active remote sensing of half space random media," Radio Science 13, no. 5, 763-774, Sept.-Oct. 1978.
- A.2 L. Tsang and J. A. Kong, "Radiative transfer theory for scattering by layered media," Journal of Applied Physics 50, 2465-2469, April 1979.
- A.3 L. Tsang and J. A. Kong, "Wave theory for microwave remote sensing of a half-space random medium with three-dimensional variations," Radio Science 14, no. 3, 359-369, May-June 1979.
- A.4 J. A. Kong, R. Shin, J. C. Shiue, and L. Tsang, "Theory and experiment for passive microwave remote sensing of snowpacks," Journal of Geophysical Research 84, no. B10, 5669-5673, Sept. 1979.
- A.5 M. A. Zuniga, T. M. Habashy, and J. A. Kong, "Active remote sensing of layered random media," IEEE Transactions on Geoscience Electronics GE-17, no. 4, 296-302, October 1979.
- A.6 B. Djermakoye and J. A. Kong, "Radiative-transfer theory for the remote sensing of layered random media," Journal of Applied Physics 50, no. 11, 6600-6604, November 1979.

- A.7 M. Zuniga and J. A. Kong, "Active remote sensing of random media," Journal of Applied Physics 51, 74-79, January 1980.
- A.8 L. Tsang and J. A. Kong, "Energy conservation for reflectivity and transmissivity at a very rough surface," Journal of Applied Physics 51, 673-680, January 1980.
- A.9 M. Zuniga, J. A. Kong, and L. Tsang, "Depolarization effects in the active remote sensing of random media," Journal of Applied Physics 51, 2315-2325, May 1980.

B. Conference Papers

- B.1 J. C. Shiue, J. A. Kong, H. A. Boyne, A. T. Chang, D. A. Ellerbruch, and L. Tsang, "Microwave remote sensing of snow pack characteristics," URSI/USNC Symposium, May 18, 1978.
- B.2 J. A. Kong, L. Tsang, and B. Djermakoye, "Remote sensing of a buried scattering layer," URSI/USNC Symposium, May 18, 1978.
- B.3 J. A. Kong, M. Caulfield, J. C. Shiue, R. Shin, and L. Tsang, "Single frequency microwave remote sensing of snow on an aluminum plate," International Symposium on Antennas and Propagation, Japan, August 1978.
- B.4 J. A. Kong, L. Tsang, B. Djermakoye, R. Shin, and J. C. Shiue, "Passive microwave remote sensing of snowpacks," URSI Meeting, Boulder, Colorado, November 6-9, 1978.
- B.5 J. A. Kong, L. Tsang, M. Zuniga, and R. Shin, "Theoretical models and approaches for active and passive microwave remote sensing," URSI Meeting, Seattle, Washington, June 1979.
- B.6 J. A. Kong, M. Zuniga, L. Tsang, and R. Shin, "Experimental data matching for active and passive microwave remote sensing," URSI Meeting, Seattle, Washington, June 1979.

- B.7 J. A. Kong, L. Tsang, M. Zuniga, R. Shin, J. C. Shiue, and A. T. C. Chang, "Theoretical modelling and experimental data matching for active and passive microwave remote sensing of earth terrain," Symposium on Terrain Profiles and Contours in EM Wave Propagation, AGARD/NATO Meeting, Norway, September 1979.
- B.8 J. A. Kong, M. Zuniga, T. Habashy, L. Tsang, R. Shin, and B. Djermakoye, "Random medium model applied to active and passive microwave remote sensing of earth terrain," URSI Meeting, Boulder, Colorado, November 5-8, 1979.

C. Reports

- C.1 R. T. Shing and M. A. Zuniga, "Ground-truth of snow fields in the Rome, New York area during January 1979," Technical Report, MIT, 1979.
- C.2 R. T. Shin and M. A. Zuniga, "Ground-truth of snow fields in the Rogers City, Michigan area during February 1979," Technical Report, MIT, 1979.

SECTION IX
LIST OF APPENDICES

Appendix A

"Review of remote sensing theories and experiments pertaining to snow," Report to AIR FORCE/EGLIN, Contract F08635-78-C-0115, MIT, 1978.

Appendix B

"Ground-truth of snow fields in the Rome, New York area during January 1979," R. T. Shin and M. A. Zuniga, Technical Report, MIT, 1979.

Appendix C

"Ground-truth of snow fields in the Rogers City, Michigan area during February 1979," R. T. Shin and M. A. Zuniga, Technical Report, MIT, 1979.

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1. J. A. Kong, L. Tsang, M. Zuniga, R. Shin, J. C. Shiue, and A. T. C. Chang, "Theoretical modelling and experimental data matching for active and passive microwave remote sensing of earth terrain," Symposium on Terrain Profiles and Contours in EM Wave Propagation, AGARD/NATO Meeting, Norway, September 1979.
2. M. Zuniga and J. A. Kong, "Active remote sensing of random media," J. Appl. Phys., 51, 74-79, January 1980.
3. M. A. Zuniga, T. M. Habashy, and J. A. Kong, "Active remote sensing of layered random media," IEEE Transactions on Geoscience Electronics, GE-17, no. 4, 296-302, October 1979.
4. M. Zuniga, J. A. Kong, and L. Tsang, "Depolarization effects in the active remote sensing of random media," J. Appl. Phys., 51, 2315-2325, May 1980.
5. L. Tsang and J. A. Kong, "Radiative transfer theory for active remote sensing of half space random media," Radio Science, 13, no. 5, 763-775, Sept.-Oct. 1978.
6. J. A. Kong, R. Shin, J. C. Shiue, and L. Tsang, "Theory and experiment for passive microwave remote sensing of snowpacks," J. Geophys. Res., 84, no. B10, 5669-5673, Sept. 1979.
7. L. Tsang and J. A. Kong, "Radiative transfer theory for scattering by layered media," J. Appl. Phys., 50, 2465-2469, April 1979.
8. B. Djermakoye and J. A. Kong, "Radiative transfer theory for the remote sensing of layered random media," J. Appl. Phys., 50, 6600-6604, November 1979.

9. L. Tsang and J. A. Kong, "Wave theory for microwave remote sensing of a half-space random medium with three-dimensional variations," Radio Science, 14, no. 3, 359-369, May-June 1979.
10. L. Tsang and J. A. Kong, "Energy conservation for reflectivity and transmissivity at a very rough surface," J. Appl. Phys., 51, 673-680, January 1980.
11. J. A. Kong, M. Caulfield, J. C. Shiue, R. Shin, and L. Tsang, "Single frequency microwave remote sensing of snow on an aluminum plate," International Symposium on Antennas and Propagation, Japan, August 1978.

APPENDIX A

REVIEW OF REMOTE SENSING THEORIES
AND EXPERIMENTS PERTAINING TO SNOW

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SECTION I

REMOTE SENSING THEORIES

In the remote sensing of snow it is well known that volume scattering due to medium inhomogeneity plays a dominant role. This requires that all theoretical models be accountable for the scattering properties of snow. The effects of volume scattering have been accounted for by characterizing a medium either as a random medium or as a homogeneous background medium containing discrete scatterers. Theoretical models of a vertically structured nonrandom medium (References 1-4) cannot be applied to the remote sensing of snow since the volume scattering properties of snow are not accounted for.

The active and the passive remote sensing theories of snow are reviewed separately in this report. In active sensing we are interested in the reflection coefficients, and the backscattering cross sections. In passive remote sensing we are interested in the brightness temperature and the emissivity. While the primary interest in radar studies lies in the backscattering cross sections, both the reflection coefficients and the bistatic scattering coefficients are of significance to passive remote sensing theories. However, papers on active remote sensing which may have applications in passive remote sensing are not reviewed again in the passive section unless such applications are specifically developed in those papers.

A. Active

(1) Random Medium Model.

Stogryn (Reference 5) considered the electromagnetic scattering by a bounded medium whose dielectric constant contains a small random part and a nonrandom part which can vary as a func-

tion of depth. First order perturbation theory by Karal and Keller (Reference 166) is used to derive equations satisfied by the mean fields and random components of the fields. The reflection coefficient is derived by solving the equations satisfied by the mean fields. Then the bistatic scattering coefficients are derived by first solving for the random component of the field and then taking the expected value of the product of random component of the field and its complex conjugate. The cross-polarized scattering coefficients are shown to vanish in the backscattering direction. This is expected since only the first-order terms are considered and contribution to the cross-polarized scattering coefficients in the backscattering direction comes from the higher-order terms. Also, the assumption that the correlation lengths are small compared to the wavelength is made which makes his results applicable in the low-frequency limit when such assumption is satisfied.

Tsang and Kong (Reference 6) investigated the problem of scattering by a slab random medium with a laminar structure and bounded by a different dielectric on each side for a normally incident monochromatic plane wave. The renormalization method gives rise to the Dyson equation for the mean field and the Bethe-Salpeter equation for the covariance of the field in the random medium. A two-variable expansion technique is used to solve for the zeroth-order mean Green's function from the Dyson equation under the nonlinear approximation. The mean Green's function is then used to derive modified radiative transfer (MRT) equations from the Bethe-Salpeter equation under the ladder approximation. The MRT equations are solved for a two-layer random medium and the reflectivity at normal incidence is determined.

Tsang and Kong (Reference 7) also studied scattering of electromagnetic waves by a half-space random medium with three-dimensional correlation functions. For a plane wave incident upon a random half-space, the scattered fields in nonrandom medium are obtained by employing the dyadic Green's function for a half-space medium and by

the Born approximation where the field in the random medium is replaced by the unperturbed field. Then, following Peake's (Reference 8) definition, the bistatic scattering coefficients are derived from the scattered fields. The cross-polarized scattering coefficients in the backscattering direction also vanish since the Born approximation is a single-scattering approximation which is only valid when the albedo is small.

Parashar et al. (Reference 9) considered the electromagnetic wave scattering from a slab of inhomogeneous medium with a slightly rough boundary surface. There has been much work on the electromagnetic wave scattering from a homogeneous medium with a rough surface but there is no previous work which accounts for both the volume scattering and the rough surface scattering characteristics of a medium. In the Parashar model the inhomogeneity in the medium is assumed to vary continuously in the vertical direction and has a small random variation in the horizontal direction. The scattering medium is assumed to consist of two layers where one region has increasing permittivity and the other region has decreasing permittivity in the vertical direction. Maxwell's equations are solved using the perturbation method together with Fourier transform technique. The resulting differential equations are solved by using WKB and variation of parameter methods. Field amplitudes in each medium are determined by taking boundary conditions into account and the expression for the first-order backscattering cross sections are obtained. Again the cross-polarized backscattering cross sections are zero.

Tsang and Kong (Reference 10) developed the radiative transfer theory to calculate the bistatic scattering coefficients and the backscattering cross-sections from a half-space random medium with lateral and vertical fluctuations. The radiative transfer equations without the usual emission terms are written down for the intensities in the random medium. The incident beam is taken into account by

choosing appropriate boundary conditions. Once the radiative transfer equations with the appropriate boundary conditions are solved for the intensities in the random medium, the intensities scattering into the non-random medium can be easily obtained. They solved the radiative transfer equations by an iterative process to the second order in the albedo. To the first order in the albedo, which is the same as taking the Born approximation in the wave approach, cross-polarized scattering coefficients are shown to vanish in the backscattering direction. However, in the second order they obtained cross-polarized scattering coefficients in the backscattering direction to exhibit depolarization effects of backscattered power.

(2) Discrete Scatterer Model:

Leader (Reference 11) studied the electromagnetic wave scattering from Rayleigh scatterers embedded in a dielectric slab. First the matrix doubling method developed by Twomey et al. (Reference 12) is extended to permit calculations of the polarization components of light intensities scattered in the plane of incidence from a mono-dispersive medium of Rayleigh scatterers. The technique developed by Twomey et al. provides a method for determining the scattering properties of the sum of two layers in terms of their respective properties. With this method the scattering properties of a thick scattering layer can be calculated from the knowledge of scattering properties of very thin layers whose scattering properties are approximated by the single scattering phase functions. The scattering matrix thus obtained is modified to account for dielectric discontinuities of the surfaces of a slab medium in which the scattering centers are embedded. Then the scattering cross-sections are obtained for scattered angles in the plane of incidence.

B. Passive

(1) Random Medium Model:

Gurvich et al. (Reference 13) first derived the expression for the emissivity of a half-space random medium with a laminar structure in the single scattering approximation. The emissivity is obtained by reciprocity after solving for the power coefficient of reflection from the surface and the power coefficient of scattering into the upper hemisphere. The single scattering approximation and the laminar structure of the medium are used to calculate the power coefficient of scattering.

Applying a radiative transfer approach, Tsang and Kong (Reference 14) solved the problem of microwave thermal emission from a half-space random medium with a laminar structure and nonuniform temperature distribution in the vertical direction. Because of the laminar structure of the problem considered, horizontally and vertically polarized intensities are uncoupled and the radiative transfer equations reduce from the usual integro-differential equation to a first order differential equation for each polarization. The radiative transfer equation is then solved for the intensities in the random medium, subject to the boundary conditions. After the upward intensity in the random medium is obtained, it is easily related to the brightness temperature in the upper medium. For constant absorption and scattering coefficients, the brightness temperature is determined by a simple closed-form formula. An iteration approach is also discussed for the general case when absorption and scattering coefficients are not constants.

The reflectivity of a wave at normal incidence upon a two-layer medium where top layer is a random medium with a laminar structure was derived by Tsang and Kong (Reference 6) by solving the MRT equations. This result can be applied to the passive remote sensing since by reciprocity emissivity is one minus reflectivity. They also derived the emissivity of a half-space random medium with

three-dimensional correlation functions by first calculating the bistatic scattering coefficients with the Born approximation and then obtaining emissivities following Peake's (Reference 7) definition.

Tsang and Kong (Reference 15) calculated the brightness temperature resulting from microwave thermal emission from half-space random medium with a nonuniform temperature profile in the vertical direction and a three-dimensional correlation function. The scattering phase functions and the scattering coefficients are first derived then are used in the radiative transfer equations. The radiative transfer equations for the random medium with three-dimensional correlation functions are two coupled integral-differential equations for the horizontally and vertically polarized intensities. The radiative transfer equations and the appropriate boundary conditions are cast into the integral equation form. Then by assuming a small albedo, an iterative approach is used to solve for the zeroth and the first order upward propagating intensities. Then for the general case the integro-differential radiative transfer equations are solved by a numerical approach. Following Chandrasekhar (Reference 167), the radiative transfer equations are cast into quadrature form by using the even-order Legendre polynomials. The radiative transfer equations are turned into a system of ordinary differential equations with constant coefficients. This is then solved by obtaining eigenvalues and eigenvectors and matching the boundary conditions.

Tsang (Reference 16) studied the thermal microwave emission from a scattering layer overlying a homogeneous half-space with a radiative transfer approach. The scattering layer has a nonuniform temperature profile and is characterized by three-dimensional correlation functions. The radiative transfer equations are cast into a system of first order differential equations using the Gaussian quadrature method. These equations are solved by both the classical

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MASSACHUSETTS INST OF TECH CAMBRIDGE RESEARCH LAB OF--ETC F/G 17/9
PREDICTION OF BACKSCATTER AND EMISSIVITY OF SNOW AT MILLIMETER --ETC(U)
JAN 80 J A KONG, R T SHIN F08635-78-C-0115

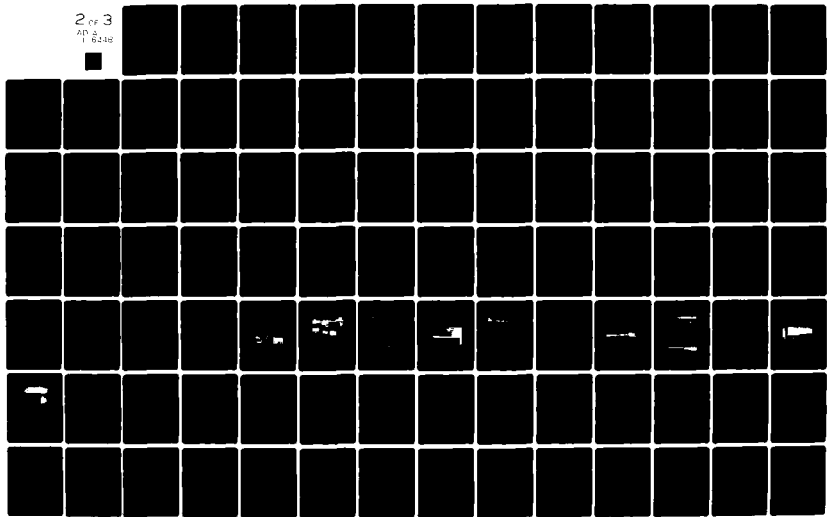
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method of calculating eigenvalues and eigenvectors, and the method of invariant imbedding.

Tsang and Kong (Reference 17) used a radiative transfer approach to study the thermal microwave emission from a inhomogeneous slab random medium bounded by different dielectrics on both sides. The random medium can have nonuniform absorption, scattering and temperature profiles and can be characterized by one-dimensional correlation functions or by three-dimensional correlation functions. With the method of invariant imbedding the boundary value problem of the radiative transfer equations is converted to a initial value problem starting at zero slab thickness. For the case of three-dimensional correlation functions, the Gaussian quadrature method is used to cast the radiative transfer equations into a system of first-order differential equations before they are solved by the method of invariant imbedding. The invariant imbedding equations so obtained are in the form of first-order ordinary equations and these equations can be solved by standard methods of initial value problems to get numerical results.

Fisher (Reference 18) also studied the thermal microwave emission from a inhomogeneous slab random medium with a radiative transfer approach. The scattering medium is characterized by three dimensional correlation functions, as well as nonrandom variations in permittivity, temperature and loss. The radiative transfer equations are solved by the Gaussian quadrature method and the invariant imbedding methods.

(2) Discrete Scatterer Model:

England (Reference 19) first studied the thermal microwave emission from a uniform half-space containing isotropic scatterers and possessing a nonuniform temperature profile with a radiative transfer approach. Isotropic scatterers are assumed to redistribute incident radiations in all directions evenly. Also assuming

that there is no exchange of energy between polarizations, resulting radiative transfer equations are cast into a system of ordinary first-order differential equations by the Gaussian quadrature method. These equations are solved by calculating the eigenvalues and eigenvectors, and by matching the boundary conditions. He then treated the case of scattering layer over a homogeneous half-space where scattering medium is characterized by a uniform layer containing Rayleigh scatterers (Reference 20). Then the resulting radiative transfer equations for the intensities in the scattering layer are solved numerically in the same way.

Chang et al. (Reference 21) studied the thermal microwave emission from a scattering layer on top of a homogeneous half-space. The scattering layer has the same background medium as the upper half-space and contains randomly spaced scattering spheres. The Mie theory is then used to calculate the extinction and scattering cross-sections of individual spheres. These quantities with the Mie-scattering phase functions are used in the radiative transfer equations. Then the radiative transfer equations are solved numerically for the intensities normal to the surface by a variation of the Gauss-Seidel method.

Tsang and Kong (Reference 22) also developed the theory of thermal microwave emission from a half-space homogeneous medium containing spherical scatterers with a radiative transfer approach using Mie-scattering phase functions. The radiative transfer equations are first solved by an iterative approach and a closed form solution is obtained. Then for the general case the Gaussian quadrature method is used to convert the radiative transfer equations into a system of ordinary first-order differential equations. The brightness temperature is solved for by calculating eigenvalues and eigenvectors and then matching the boundary conditions. Also, in addition to the monodisperse case involving only single size scatterers, they extended their result to the case involving a distribution of different size particles.

Tsang (Reference 16) also treated the more general case of thermal microwave emission from a homogeneous slab containing spherical scatterers overlying a different homogeneous half-space. The radiative transfer equations are cast into a system of ordinary first order differential equations and solved by both the classical method of calculating eigenvalues and eigenvectors and the method of invariant imbedding.

SECTION II

EXPERIMENTS

A. Active Remote Sensing

Sackinger and Byrd (References 23,24) studied the details of the electromagnetic wave backscattering at 35 GHz from snow-covered land, fresh ice and sea ice. Backscattering measurements were made as a function of angle of incidence for several different snow conditions. Both horizontal and vertical polarizations have been used, and using separate transmitting and receiving antennas, they made the backscattering measurements for horizontal, vertical, and cross-polarization cases.

Hoekstra and Spanogle (Reference 25) made measurements of the backscatterer from snow and ice surfaces for the design of a terrain avoidance system. The following two types of measurements were made on the snow surfaces:

- (1) The terrain clutter from undisturbed snow surfaces was measured at frequencies of 10, 35 and 95 GHz, at grazing angles of 1 to 0.3 degrees. At 10 GHz the measurements were made for linear, circular and cross polarizations; at 35 GHz, for linear and cross polarizations; and at 95 GHz, for linear polarization.
- (2) The terrain clutter from periodically spaced trenches in the snow surface was measured at 10 GHz and 35 GHz, at grazing angles of 1.0, 0.65 and 0.38 degrees, for linear polarization.

Currie et al. (Reference 26) made a series of radar measurements on the backscattering properties of smooth snow at 35 GHz

and 95 GHz. The bulk of the measurements were made at grazing angles between 8 and 15 degrees. The backscattering cross-sections were studied at 35 GHz and 95 GHz as functions of polarization, frequency, depression angle and time. The snowpack ground-truth data were collected in the conjunction with the radar measurements.

Ulaby et al. (Reference 27) investigated the angular, spectral, and polarization dependence of the backscattering coefficient on a select set of snow parameters-- depth, density, water equivalence, and temperature. The 1-8 GHz microwave active spectrometer (MAS) system was used to measure the backscattering response from ground covered with a relatively thin layer of snow. The scattering coefficients were measured for three linear polarization configurations (HH, VV, and HV) at angles of incident between nadir and 70 degrees. The ground data acquired in conjunction with the spectrometer measurements include soil moisture, soil temperatures at different locations and depths, air temperature, snow depth, snow density profile, and snow water equivalent profile.

B. Passive Remote Sensing

In a research conducted by the Geoscience Laboratory (References 28-30), Advanced Microwave Systems Division of Space-General Corporation, the microwave thermal emission characteristics of a number of natural surfaces including snow fields have been investigated. Both the laboratory measurements and the in-situ field measurements were made for various snow conditions at 13.5 GHz and 37 GHz as functions of angle as well as time.

Edgerton et al. (References 31, 32) also investigated the microwave thermal emission of snowpacks. Field measurements of brightness temperatures were conducted at wavelengths of 0.8, 2.2, 6 and 21 cm (37, 10.4, 4.99 and 1.42 GHz). The brightness

temperature is measured as a function of snow equivalence (water mass) for dry and wet snow on top of soil and for natural snow on top of aluminum plates.

During March of 1971, the NASA Convair 990 Airborne Observatory carrying microwave radiometers in the wavelength range of 0.8 to 21 cm was flown over dry snow fields with different substrata making brightness temperature measurements (Reference 33). At the same time the brightness temperature measurements were made on the plane, ground-truth measurements of each test site were also made.

Hofer and Schanda (Reference 34) started a long-term observational study of the microwave emission and scattering behavior of snow under quasi-controlled conditions, with five radiometers at frequencies of 4.9, 10.5, 21, 36, and 94 GHz. The brightness temperature measurements were made as a function of angle in the morning and afternoon measuring cycles. The brightness temperature measurements as a function of frequency at different angles are pointed out for morning and afternoon measuring cycles.

Another microwave remote sensing of snowpack experiment conducting in the Colorado Rocky Mountains is described by Shiue et al. (Reference 35). With four radiometers at frequencies of 5, 10, 7, 18 and 37 GHz, the brightness temperature measurements were made as a function of angle by performing both the "swath" (or "elevation") scan and the "fixed spot" scan. Also the brightness temperature measurements were made as a function of snow depth for artificial snowpile and as a function of snow water equivalence for natural snowpacks. A portable single frequency at 35 GHz was used to measure brightness temperatures, as a function of angle with "fixed spot" scan, of two different sites where the main difference between two sites was the average grain size of snow.

SECTION III

RELATED INFORMATION

A. Remote Sensing of Snow, Ice, Vegetation, and Soil Moisture

In recent years the microwave remote sensing techniques have been applied to studies of the geophysical prospection of lake, sea ice, vegetation and soil moisture. The current results in these areas of investigation offer a tantalizing glimpse of what is expected in the next few years when such remote-sensing data become generally available. Since both active and passive remote sensing have their special advantages, active and passive sensing will be discussed separately. Nevertheless, the interpretation of surface characteristics from microwave sensor outputs alone is more effective when data is available from both active (radar) and passive (radiometer) sensors. This is because both outputs are determined by the complete scattering pattern of the medium; of which one aspect (backscattering) is estimated by radar and another (brightness temperature) is estimated by the radiometer (Reference 36).

(1) Active Microwave Remote Sensing

(a) Snow:

A high resolution monocyde v.h.f. radar was developed and tested over lake ice. These tests were conducted by the US Army Cold Regions Research and Engineering Laboratory using a boom as the antenna support in 1965, and using a moving helicopter as a support in 1966. Meyer (Reference 37) discussed the results of measurements of ice thickness and snow thickness by visual data reduction. They also discussed the application of these measurements to the determination of the dielectric constant. Waite and MacDonald (Reference 38) studied snowfield mapping with K-band radar. Analysis of K-band imagery from several snowfield areas

in the United States suggests that the distribution of perennial snow results in an anomalously high signal return. In contrast to normal snow survey methods, it appears feasible to map the extent of old snow areas irrespective of most weather conditions, and even when covered with new-fallen snow. Koehler and Kavadas (Reference 39) made a study to determine if conventional radar might provide useful measurements of snow depth. In the first part of the study, they examined the various system parameters of a radar in order to determine the maximum possible resolution in snow depth. It was concluded that one might expect to get depth resolution of the order of 3 cm without going beyond the present state of the art in radar technology. In the second part of the study, they dealt with properties of snow as a radar target. At radar frequencies, snow is a dielectric with a dissipative term which depends on, among other things, the temperature and the moisture content of the snow. It was found that the character of the echo also depends on the dielectric constant of the ground beneath the snow. Very few measurements of these properties have been made at microwave frequencies. They lead to the conclusion that the technique appears to be practical but that further study of the microwave properties of snow and the earth is necessary before any final conclusions can be formed.

Linlor (Reference 40) described the snowpack water content by remote sensing, based on plane-layered models consisting of air, snow, ice, water, and earth. The reflection coefficient was computed for a plane electromagnetic wave at normal incidence with frequencies between 10^6 and 10^{10} Hz. They also gave an example of the theoretical results, showing how the water content of the snow layer and thickness of the ice can be obtained from the shape of the curve of reflection coefficient versus frequency. The paper also briefly reviews other systems for electromagnetic remote sensing and discusses the electrical properties of snow. Possible

airborne applications of the proposed electromagnetic system are outlined. Vickers and Rose (Reference 41) describe in their paper a system which can be used to derive either the snow thickness, or the average snow density by measurement of the transit time of a one nanosecond radar pulse. Their data shows that the radar system can provide an accuracy of less than 10% in the measurement of the density of the snowpack.

Kunzi and Staelin (Reference 42) derived microwave signatures for snow covered land from data obtained by the microwave spectrometer NEMS on board the Nimbus-5 satellite. The emissivity at 31.4 GHz is lower by about 10% than that at 22.2 GHz, while the emissivities for uncovered land are ≈ 0.95 at both frequencies. Maps for snow cover over land are generated for the northern hemisphere and compared with data obtained by visible light imagery. Page and Ramseier (Reference 43) present in their paper an overview of the active microwave tools becoming available to the glaciologist with emphasis on recent radar developments as applied to floating ice. They give enough theory to allow the user to understand the techniques and they discuss the side-looking radar imagery using a number of examples resulting from the use of real and synthetic aperture, single and dual polarization. Recent studies of the microwave properties of ice and snow are also reviewed, and are shown to be leading to significant advances in high-resolution radar techniques for accurate sounding of these materials. Remote sensing of freshwater ice thickness is shown to be well established and operational, with similar techniques feasible in the near future for sea ice. It is pointed out that both imaging and probing radars applied to studies of sea ice and snow usually must be used in association with data from other sensors.

Meier (Reference 44) discusses in his paper the measurement of important snow properties using electromagnetic radiation. Ulaby (Reference 45) presents a perspective on the implementation of micro-

wave sensors in future airborne and spaceborne observations of hydrologic parameters. The rationale is based on a review of the status and future trends of active (radar) and passive (radiometer) microwave research as applied to the remote sensing of soil moisture content, snowpack water equivalent, freeze/thaw boundaries, lake ice thickness, surface water area, and the specification of watershed runoff coefficients. They also include analyses and observations based on data acquired from ground based, airborne and spaceborne platforms and an evaluation of advantages and limitations of microwave sensors.

(b) Ice:

Remote sensing of the Arctic ice is an important tool for the operation of shipping in ice covered waters. The most challenging problem in the investigation of sea ice is how to predict the ice thickness, and identify sea states and ice types by remote sensing techniques. In these papers (References 46-81), we can find the studies of high altitude, side looking radar images of sea ice, radio ice-sounding technique, ice type identification by radar, ice thickness and variability by a radar approach, etc. In the paper of N. W. Guinard (Reference 49), one learns about the Four-Frequency Radar System that has been used to measure the radar returns scattered from both sea and ice surfaces for the purpose of identifying sea state and ice types and to determine effective models of the scattering processes to aid in the design of optimum sensors. J. W. Rouse (Reference 50) mentions in his paper one of the most significant results of a radar experiment which was verification of the ice type identification potential of a 2.25 cm-wavelength radar scatterometer. The results of the radar experiment are presented and the data is analyzed to determine the characteristics of radar backscatter from various Arctic ice types. A quantitative analysis of the data indicates that identifiable radar return "signatures" are obtained for each of several specific sea ice types.

The first successful radar echo sounding through glacier ice in Canada was carried out by the Dominion Observatory in 1965 on an outlet glacier of the Penny Ice Gap on Baffin Island (Reference 51). The radar soundings were generally in agreement, within the range of the reading accuracy of the oscilloscope (± 15 m), with depths obtained seismically, gravimetrically, and by the electrical resistivity method. Radio echo sounding results are also discussed in References 71, 72, 78, 79.

K. J. Campbell and A. S. Orange (Reference 62) describe in their paper an impulse radar system that provides a continuous profile of sea and fresh water ice thickness. This was put into operational use in early 1973 and it can be considered as the electromagnetic equivalent of single-trace acoustic profiling systems used in marine subbottom profiling. For the radar system, an electromagnetic pulse is generated on the ice surface and the reflections from the surface and from the ice/water interface are displayed on a continuous strip-chart recorder. Travel times of the reflected pulses can be converted directly to ice thickness. It is likely that the system also can be applied to thickness measurement of glacial ice and to crevasse detection. Airborne profiling of ice thickness by a short pulse radar is also discussed by Vickers et al. (Reference 57).

The ability of radar to discriminate sea ice types and their thickness was studied by Parashar et al. (Reference 65). Radar backscatter measurements at 400 MHz (multi-polarization) and 13.3 GHz (vv polarization) obtained from NASA Earth Resources Aircraft Program Mission 126 were analyzed in detail. The scatterometer data were separated into seven categories of sea ice according to age and thickness as interpreted from stereo aerial photographs. The variations of radar backscatter cross-section (σ^0) with sea ice thickness at various angles are presented at the two frequencies. An analytical theory of radar scatter from

sea ice was also developed in this paper. Sea ice was considered as an homogeneous medium in which the dielectric properties vary continuously in the vertical direction. In addition, a small random horizontal variation was considered. Polarized radar backscatter cross-section (σ°) was computed for six ice types at 400 MHz and 13.3 GHz by taking surface roughness into account. The results thus obtained are presented and are shown to be in general agreement with the experimental results.

Bryan and Larson (Reference 68) studied fresh-water lake ice using multiplexed imaging radar. Their analysis of ice in Whitefish Bay (Lake Superior) indicates that the combination of the ice/water interface and the ice/air interface is the major contributor to the radar backscatter as seen on the imagery. Although the ice thickness cannot be measured directly from the received signals, it is suspected that by combining the information pertaining to radar backscatter with data on the meteorological and sea-state history of the area, together with some basic ground truth data, better estimates of the ice thickness may be provided. In addition, certain ice features (e.g. ridges, ice-foot formation, areas of brash ice) may be identified with reasonable confidence. There is a continued need for additional ground work to verify the validity of imaging radars for these types of interpretations.

In the study of ice conditions and geological explorations, Side-Looking Airborne Radar (SLAR) has been used experimentally since the early 1960's. Its application and many results pertaining to ice are presented and discussed in References 46, 47, 53, 55, 56, 58, 59, 60, 64, 65, 66, 68, 69 and 74. The interpretation of ice features from the SLAR imagery was discussed, and the conclusion reached was that in spite of certain ambiguities the technique has great potential to improve with increasing resolution. Extent of coverage per distance flown and independence of light and cloud conditions make it unique among airborne sensors (Reference 74).

(c) Vegetation:

Vegetation analysis with radar imagery is discussed in References 82-96. Recent studies at Kansas University and by Raytheon Company have shown that vegetation analysis with radar imagery are possible within broad limits depending upon the geographic area being investigated. Imagery has been inspected for a wide range of climatic and topographic environments in the United States in all areas where the influence of vegetation upon radar returns was observable. There is sufficient information obtainable from this form of imagery to warrant its investigation both for use as a single sensor and for future use with other remote sensors (Reference 82). Radar imagery-- because it may be obtained through cloud cover, at night, and over large areas-- can provide valuable data for agricultural land-use mapping. Schwarz and Caspall (Reference 83) talk about the use of radar in the discrimination and identification of agricultural land use. Haralick, Caspall and Simonett (Reference 84) give a statistical study of radar imagery for crop discrimination. The influence of weather and season was also investigated by de Loor et al. (Reference 87). It was shown that if a single vegetation type is present, it behaves as a Rayleigh scatterer. The radar backscatter coefficient as a function of frequency and polarization proves to be the only usable classifier to classify vegetation with the aid of radar. Active microwave measurements of vegetation backscatter were conducted by Ulaby (Reference 91) to determine the utility of radar in mapping soil moisture through vegetation and in mapping crop types. Using a truck-mounted boom, spectral response data were obtained for four crop types (corn, milo, soybeans, and alfalfa) over the 4-8 GHz frequency band, at incidence angles of 0-70 degrees in 10 degree steps, and for all four linear polarization combinations. The results of Radar Response to Vegetation in the 8-18 GHz band were presented by Ulaby et al. (Reference 92), Bush and Ulaby (Reference 93), and Ulaby and Bush (Reference 94). Because the microwave dielectric

constant of dry vegetation matter is much smaller (by an order of magnitude or more) than the dielectric constant of water, and because a vegetation canopy is usually composed of more than 99% air by volume, it is proposed (Reference 95) that the canopy can be modeled as a water cloud whose droplets are held in place by the vegetative matter. Such a model was developed assuming that the canopy "cloud" contains identical water droplets randomly distributed within the canopy. By integrating the scattering and attenuation cross-section contributions of N droplets per unit volume over the signal path length through the canopy, an expression was derived for the backscattering coefficient as a function of three target parameters: volumetric moisture content of the soil, volumetric water content of the vegetation, and plant height. Regression analysis of the model predictions against scattering data acquired over a period of four months at several angles of incidence (0-70 degrees) and frequencies (8-18 GHz) for HH and VV polarizations yields correlation coefficients that range from 0.7 to 0.99 depending on frequency, polarization, and crop type.

(d) Soil Moisture:

The study of remote sensing of soil moisture is discussed in References 97-104. The effects of soil layering on the use of VHF radio waves for remote terrain analysis are discussed and illustrated by Nikodem (Reference 97). The radar response to soil moisture content was investigated using a truck-mounted 1-18 GHz Active Microwave Spectrometer (MAS) system (Reference 98). The sensitivity to soil moisture content and the accuracy with which it could be estimated were evaluated for both bare and vegetation-covered fields. The radar response to soil moisture was also experimentally determined (Reference 99) for each of three bare fields with considerably different surface roughness at eight frequencies

in the 2-8 GHz band for HH and VV polarizations. Analysis of the data indicates that the effect of roughness on the radar backscattering coefficient can be minimized by proper choice of the radar parameters. If, in addition, sensitivity to soil moisture content and system design constraints are considered, the following radar parameters are recommended for an operational soil moisture mapper: Radar Signal Frequency = 4 GHz. Angle of Incidence Range: $7 \sim 15$ degrees from nadir. Signal Polarization: HH or VV. The corresponding sensitivity is about 0.25 dB/0.01g/cm³. Measurements of radar backscatter from bare soil at 4.7, 5.9, and 7.1 GHz for incident angles of 0-70 degrees have been analyzed to determine sensitivity to soil moisture (Reference 95). The effect of soil moisture on the radar backscattering coefficient was investigated by measuring the 4-8 GHz spectral response from two types of bare fields: slightly rough and very rough, in terms of the wavelength (Reference 102).

(2) Passive Microwave Remote Sensing

An experimental passive microwave radiometer measurement program is described in Reference 105. That program concerns itself primarily with the nature of the experiments, the equipment used, and of course the resulting data.

(a) Snow:

Meier (Reference 106) discussed the measurement of snow cover using passive microwave radiation. The snowline mapped from air photographs of Mount Rainer on 18 June 1968, is almost identical to the 270°K brightness temperature shown on a microwave image. Microwave brightness temperature of dry snow, wet snow, and snow-free terrain are unique. Thus the snow-covered area can be calculated from an average brightness temperature for an field of view. Kunzi et al. (Reference 107) studied the signatures of various earth

surfaces measured by the Nimbus-5 microwave spectrometer. The Nimbus-5 Meteorological Satellite is equipped with a 5-Channel microwave spectrometer. The two lowest channels (22.2 and 31.4 GHz) provide information on surface brightness temperature. Distinctive microwave signatures can be observed for snow, land ice, and sea ice in both polar regions. Moore and Hooper (Reference 108) used a very sensitive K_a -band microwave radiometer to map agricultural areas during winter, spring, and summer seasons, and at various altitudes. The microwave radiometer utilized in this program employs a parametric amplifier to achieve its ultra-high sensitivity. The mapping function is accomplished by rotating parabolic antennas which scan the beam in the cross-track direction. The forward motion of the aircraft provides the other dimension. The area mapped is a strip which has a width four times the altitude of the aircraft. The system is capable of rapid installation and removal. In this paper they gave the maps obtained at 300, 750, 1500 and 3000 meters during each season. Ground-truth data includes aerial photographs taken either simultaneously with the radiometric maps or a short time after the flight tests, or 2 to 8 years before the flight tests. Agricultural information, contour maps and observer comments have also been obtained. Mooney et al. (Reference 109) summarize in their paper the main conclusions of a preliminary study carried out into the role and technological consequence of spaceborne passive microwave radiometry intended for Earth observation. The Earth's oceans, ice and snow cover and atmosphere are considered the prime areas of interest for the technique with preferred payloads being a mix of profiling and imaging devices.

Kunzi et al. (Reference 110) also discussed the snow and ice surfaces measured by the Nimbus 5 microwave spectrometer. The 22.2 GHz and 31.4 GHz channels of the microwave spectrometer on board the Nimbus 5 earth observatory satellite provide information about the global distribution and character of various types

of snow and ice. Observations for the winter and summer of 1973 are presented for both polar regions. Well defined spectral signatures are found for snow, sea ice, and land ice in Greenland and Antarctica. A simple model with subsurface temperature gradients in a lossy homogeneous dielectric does not account for the observations; internal scattering effects appear to play a dominant role.

Zwally (Reference 111) formulates in his paper the radiative transfer theory to permit a meaningful definition of emissivity for bulk emitting media such as snow. The emissivity in the Rayleigh-Jeans approximation is then the microwave brightness temperature T_B divided by an effective physical temperature $\langle T \rangle$. The $\langle T \rangle$ is an average of the physical temperature, $T(z)$, weighted by a radiative transfer function $f(z)$. Similarly, $T_B = \int_0^\infty f(z) e(z) T(z) dz$, where $e(z)$ is the local emittance. It is shown that a mean emissivity which is equal to the mean annual T_B divided by the mean annual surface temperature T_m , is a useful quantity for comparing theory and observations. Snow-crystal size measurements, $r(z)$, at seven locations in Greenland and Antarctica are used to determine the Mie Rayleigh scattering coefficient $V_s(z)$ and to calculate the mean emissivities. In that paper, Zwally (Reference 111) defines the above effective physical temperature, then uses it to define the general bulk emissivity. He also uses an approximate radiative transfer function, which is valid if the volume scattering is small relative to the absorption, to calculate the brightness temperature, the effective physical temperature, and the emissivity in order to illustrate the effects of various absorption and scattering coefficients and temperature variations. It is also used to calculate emissivities based on snow crystal size measurements for comparison with observed emissivities and to estimate the sensitivity of the emissivity to changes in the snow characteristics.

(b) Ice:

Passive remote sensing in the microwave spectral region has proved to be a useful tool for determination of oceanographic phenomena such as sea state, pollution, and sea ice characteristics. Difference in radiometric brightness temperature of the sea surface of the order of 15°K have been readily detected during airborne measurements of the Salton Sea, California and the North Atlantic using scanning phased array radiometers (Reference 113).

The problem of remotely determining the thickness of sea ice over large areas is a difficult one and the attempts have not yet proven successful (Reference 114). The techniques most widely used involve observing the surface structure and surface pattern (visually or by a radar), and attempting to infer the thickness of the ice from such information. Adey et al. (Reference 114) have developed a technique using a UHF radiometer and have recently carried out the first field trials of the technique and of the instrumentation.

Rabinovich et al. (Reference 116) studied the determination of the Meteorological characteristics of the atmosphere and the earth's surface from airborne measurements of passive microwave radiation. Radiometric investigations of the earth were started in the USSR in 1968 by launching the satellite "Cosmos 243" equipped with microwave and infrared radiometers. Basharinov et al. (Reference 117) gave the data obtained from an experiment that was conducted over the Southern hemisphere during the spring season of 1970. The data allowed them to estimate the ocean-surface temperature, the boundary of floating ice around the Antarctic continent, the temperature and the state of continental ice covers, atmospheric water vapor content, the liquid water content of clouds, characteristics of rain and some other geophysical data. A combination of remote sensing from an aircraft and simultaneous surface measurements have

confirmed the feasibility of identifying old and new sea ice according to its emission of thermal radiation at wavelengths between 0.3 and 3 cm (Reference 118). Results derived from a comparative study of surface-based 13.4 GHz passive microwave measurements with detailed surface-truth measurements concerning the physical, chemical and structural properties of Arctic sea ice illustrate distinct decreasing microwave emissions for first-year, transitional and multi-year sea ice types (Reference 120). During the spring of 1975 an extensive experiment to determine the characteristics of sea ice in the Baltic Sea by passive and active remote sensing methods was performed. Tiuri et al. (Reference 121) give a report in which the preliminary results of UHF and microwave radiometer measurements are described. The results indicate that 600 MHz and 5 GHz radiometers can be used to determine the ice thickness in the case of low salinity ice. Tooma et al. (Reference 122) gave a comparison of sea-ice type identification between airborne dual-frequency passive microwave radiometry and standard laser/infrared techniques.

(c) Soil Moisture:

Several papers (References 123-135) discuss microwave remote sensing of soil moisture. Microwave radiometric temperature measurements using both vertical and horizontal polarization were taken with fixed-view angle traverse across three sites at two locations (Reference 124). The observational wavelengths were 21 cm, 2.2 cm, and 0.8 cm. Ground truth measurements included soil moisture, soil bearing strength, electrical resistivity, and thermal temperature. Jean et al. (Reference 125) compared a theoretical expression for the total apparent temperature of a smooth surface to in situ measurements, taken from a natural terrain. Although a good correlation was observed for certain incident angles, it was impossible to separate the effects of the various environmental parameters. In order to study the effects of these various surface parameters, they

constructed a controlled test site where radiometer measurements at 31.4 GHz were made. Then they compared the data obtained to a model of the apparent temperature of a smooth surface. Blinn et al. (Reference 127) discussed the results of microwave radiometric field observations conducted at wavelengths of 21, 2.8 and 9.95 cm to determine the microwave penetration depth of a number of sands and gravels as a function of particle size and moisture content. Observations of a reflecting plate covered with varying thicknesses of test material exhibit a pronounced oscillatory behavior that is consistent with established electromagnetic theory for plane-parallel layered media. Utilization of this interference effect is proposed as a microwave radiometric technique for determining the bulk electric properties of geologic materials readily adapted to layering experiments. They proposed that the extension of the technique could lead to a method for remotely determining layer thickness in certain naturally layered systems such as sea ice. Passive microwave observations of moist soil were performed at wavelengths of 0.8 and 3.4 cm from an aircraft. The data obtained is compared with the results of direct measurements of soil moisture content (Reference 128). The dependence of brightness temperature on the value of moisture content is observed as well as the influence of vegetation cover. Newton et al. (Reference 130) discussed the feasibility of remote monitoring of soil moisture with microwave sensors. They found that the airborne measurements of radiometric temperature at monitored sites located near Chickasha, Oklahoma, and Weslaco, Texas show that vegetation cover has the effect of masking the soil moisture dependence of the microwave data. Since Peake's (Reference 8) model is inappropriate for describing emission in the presence of a vegetative cover, therefore, a new model was developed which yields emissivity directly from the material properties of the subsurface medium and from the transmission coefficient of the surface. This work was

used to develop a model for the apparent microwave temperature and radar backscatter coefficient of vegetated terrain to illustrate the effects of vegetation on the sensitivity of these parameters to variations of soil moisture. A ground measurement program was established in order to obtain data to compare the predictions of the models. Microwave radiometry has also been used for remote sensing of soil moisture in a series of aircraft flights over an agricultural test area in the vicinity of Phoenix, Arizona (Reference 131). Ground truth in the form of gravimetric measurements of the soil moisture in the top 15 cm were obtained for 200 fields. The results indicate that it is possible to monitor soil moisture variations with airborne radiometers.

Peck et al. (Reference 133) presented a comparison of concurrent measurements of estimates of soil moisture from ground sampling and from measurements of passive microwave and passive gamma radiation made by aircraft. Although the good results obtained were based on ideal conditions (minimum change in vegetative cover, excellent ground fix for aerial surveys, extensive ground truth, etc.) they do point to the possible use of microwave techniques for aerial measurement of soil moisture under selective conditions for hydrologic purposes. Kondratyev et al. (Reference 134) summarize the work accomplished in the Voyeykov Main Geophysical Observatory on passive microwave remote sensing of soil moisture and discuss the theory and calculations of microwave emission from a medium with depth-dependent physical properties. They gave a technique for determining the amount of water in the 1 m layer which can be used by plants.

Njoku and Kong (Reference 135) developed the theory of microwave thermal emission from a nonscattering half-space medium for application to regions with nonuniform subsurface soil moisture and temperature variations. A coherent stratified model valid for nonuniform temperature profiles and rapidly varying moisture profiles

was presented. For naturally occurring profiles the stratified model gives more accurate results than the other approaches at frequencies below about 4 GHz. Experimental results from ground-based radiometric observations of a controlled target area agree with the brightness temperature predicted from the theoretical model to within 10°K. By using this model the thermal microwave emission spectrum is computed for a number of representative moisture and temperature profiles in the frequency range of 0.25 to 25 GHz. A regression technique is then used to show that multifrequency data can be used to obtain moisture and temperature gradients in the soil when an estimate of the surface temperature is available. Genda and Okayama (Reference 137) describe a simulation for remote sensing to confirm the properties and meaning of remote sensed information. The simulator, suitable for the measurement of soil moisture, consists of an optical source, a polarimeter, and a sample stage. SiC and MgO and beach sand were used to represent soil. They note that the degree of polarization increases with the moisture content and particle size of the sample.

Curtis (Reference 138) discusses requirements and presents prospects in the remote sensing of soil moisture. Moore et al. (Reference 139) studied the simultaneous active and passive microwave of the earth from the skylab radscat experiment. Campbell et al. (Reference 140) discussed mesoscale and macroscale studies of floating ice for three sensor categories: visual, passive microwave, and active microwave.

Sobti et al. (Reference 141) calculated the correlations between active and passive microwave responses received by the S-193 radiometer-scatterometer on Skylab. They found that over both land and sea the correlation between polarizations is high, but that the correlation between radiometer and scatterometer response at 30 degrees incidence is negligible. This suggests that multipolarization instruments with low resolution (greater than 10 km in all

cases) are redundant while a combination of radiometer and scatterometer is useful.

B. Electrical Properties of Snow, Ice and Soil

(1) Snow and Ice

Evans (Reference 142) gives a good review of dielectric properties of ice and snow. He considers the permittivity and loss tangent of naturally occurring ice and snow. In Appendix A, he gives a chronological annotated bibliography of published measurements. Readers interested in the measurements prior to 1965 should consult this paper. We shall review papers published after 1965. Gribbon (1967) (Reference 143) studied the dielectric relaxation of neve and glacial ice on two temperate glaciers in Greenland and France. Measurement of the audio-frequency capacitance and loss tangent of thin parallel wires placed on the surface of a glacier yield ϵ' , the relative permittivity, and ϵ'' , the loss factor of the neve. The relaxation time is expressed in terms of the frequency f_m at the maximum ϵ'' value of the Cole-Cole $\epsilon'' - \epsilon'$ diagrams obtained for different wire separations.

Philberth (Reference 144) suggests a simple device to measure the permittivity of deep ice layers under the normal temperature, pressure and grain structure. The electrical properties of and electrical relaxation in saline ice were discussed by Addison (references 146, 147). Webber et al. (Reference 148) studied the VLF ground-based measurements in Antarctica, and their relationship to stratifications in the subsurface terrain. Hoekstra et al. (Reference 149) discussed the dielectric properties of sea and sodium chloride ice at UHF and microwave frequencies. Peden et al. (Reference 150) described an experiment that had been designed to yield the dielectric and loss properties of the ice cap near Byrd Station, Antarctica, in the VLF range, subsequent to the proper interpretation of the input admittance of an electrically short dipole probe.

Perry and Straiton (Reference 151) employed a quasioptical free-space technique to measure the complex dielectric constant of ice at 35.3 and 94.5 GHz. Bryan and Larson (Reference 152) discussed the application of dielectric constant measurements to radar imagery interpretation. They described several cases of radar-earth surface interaction and presented examples of radar imagery and some data on ice and snow. They concluded that the next logical step would be to quantify the radar ground truth in preparation for machine interpretation and automatic data processing of the radar imagery.

Shemelin (Reference 153) discusses the electrical and mechanical properties of ice which are of great importance in hydrology, glaciology, and meteorology. The appearance in the last 20 years of electron microscopy, neutron diffraction, and nuclear magnetic resonance has led to the broad development of physical ice and water studies. The most important results achieved in such studies in recent years are also discussed.

Campbell and Orange (Reference 154) observed sea ice electrical anisotropy in the horizontal plane with an impulse radar technique under development for profiling ice thickness. The radar technique used is the electromagnetic equivalent of the acoustic subbottom profiling method. The anisotropy is characterized by a marked change in amplitude of the vertically propagated signal reflected from the sea ice/water interface as the linearly polarized antenna was rotated in the horizontal plane on or above the ice surface. Vant et al. (Reference 155) studied the electrical properties of fresh and sea ice at 10 and 35 GHz. Addison (Reference 156) studied the electrical properties of saline ice for temperatures down to -150°C at 1 KHz. Bentley (Reference 157) provides a clear survey of advances in geophysical exploration of ice sheets and glaciers. Fitzgerald and Paren (Reference 158) studied the dielectric properties of Antarctic ice.

(2) Soil

Pearce et al. (Reference 163) developed the theory of a three component heterogeneous dielectric to provide a basis for an analytic description of the electromagnetic properties of soil systems. The theory is valid for frequencies where the electromagnetic wavelength is much greater than the soil particle size. Agreement between theory and experiments with coarse grained sand system at both audio and p-band radar frequencies is demonstrated in their paper. Leshchanskii et al. (Reference 164) used the short-circuit method based on measurement waveguides to measure the electrical parameters of sandy and loamy soils in the 0.8 to 2.26 cm range. They obtained the dependence of the permittivity and attenuation on the moisture content of the soil in the RF range. It is shown that in moist sandy soil the attenuation factor is determined by the absorption of radio waves by water molecules at all of the investigated wavelengths. In moist loamy soil the attenuation factor at centimeter wavelengths is primarily determined by the absorption of radio waves by the ions of the loamy soil. Hoekstra and Delaney (Reference 165) measured the complex dielectric constant of four types of soils, including a sand, a silt, and two clays, over the frequency range from 0.1 GHz to 26 GHz. Their results show that the relation between volumetric water content and the complex dielectric constant is relatively independent of soil types.

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APPENDIX B

GROUND-TRUTH OF SNOW FIELDS IN THE ROME, NEW YORK
AREA DURING JANUARY, 1979*

by

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SECTION I

INTRODUCTION

This report contains ground-truth measurements of snow fields performed during January 1979 at four sites in the Rome, New York area. The general locations of the sites are shown in Figure B-1 and they are referred to as Rome A, Rome E, Ava B and Ava C. The measurements were taken in connection with planned AIR FORCE SAR IMAGING flights. Two flights were made and these occurred on January 16 and January 29, 1979. The ground-truth acquired on these two days is supplemented by measurements made on six other days. This data was taken by Robert Shin and Michael Zuniga with Shun-Lien Chuang (MIT) assisting.

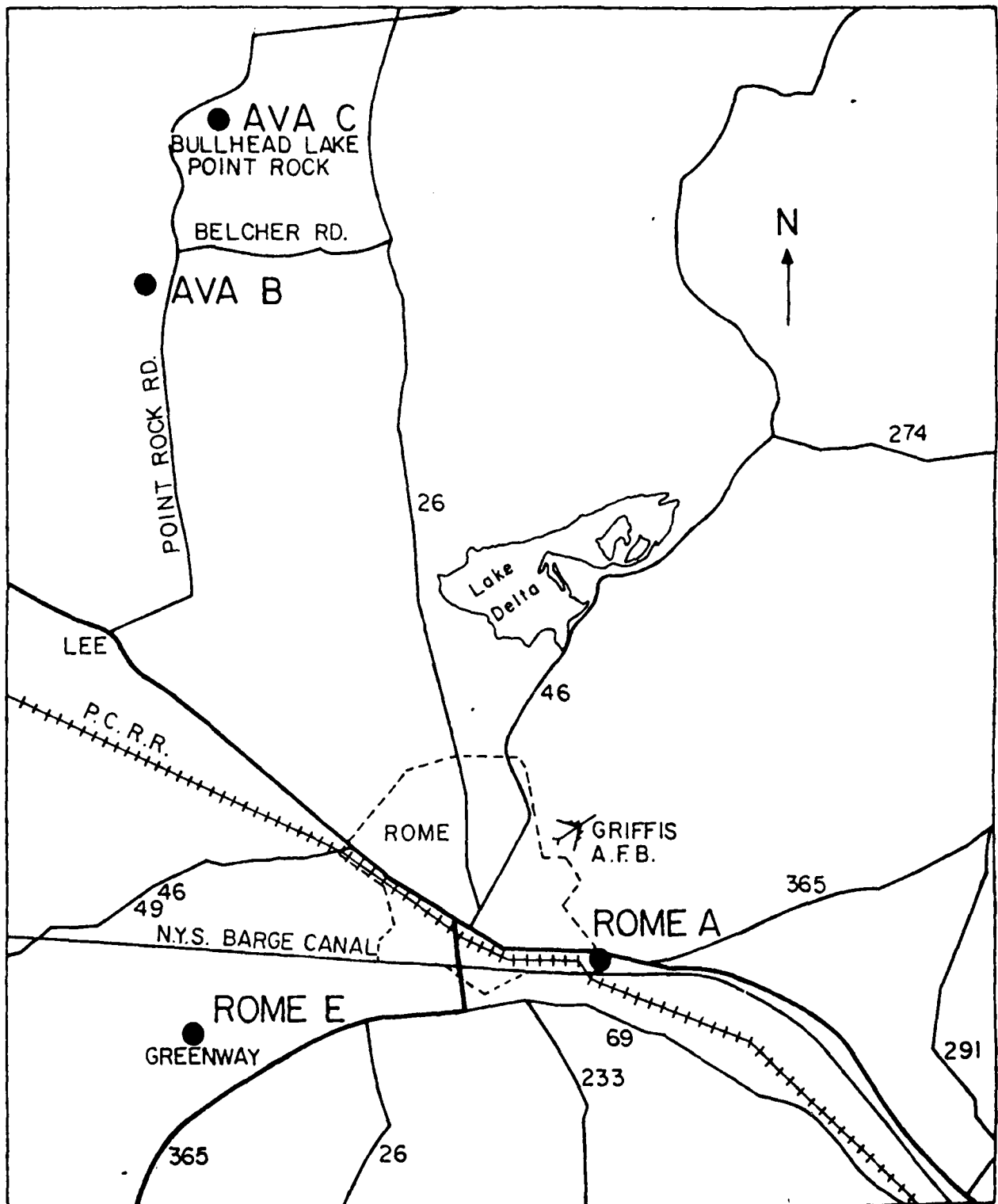


Figure B-1. General Area Map

SECTION II SITES IN ROME AREA

A. Rome A Site

Two photographs of the site are presented in Figure B-2. The site is a fuel storage area located next to Route 49 near the Rome business district. In Figure B-3 we have a map of the site with the location indicated where snow profile and associated ground-truth measurements were made.

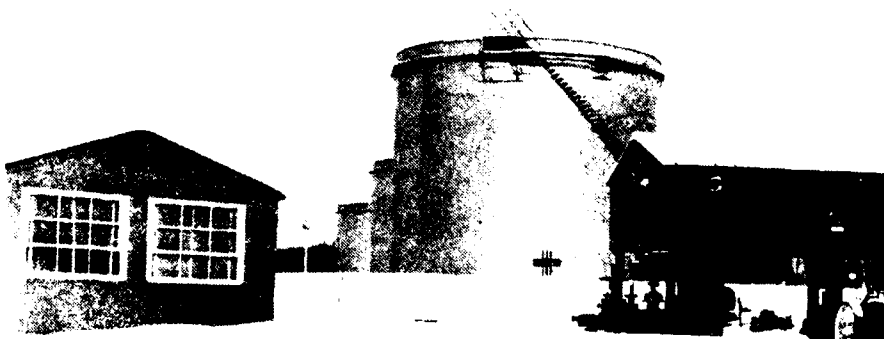


Figure B-2a. Photograph of Rome A Site.



Figure B-2b. Photograph of Rome A Site (Concluded).

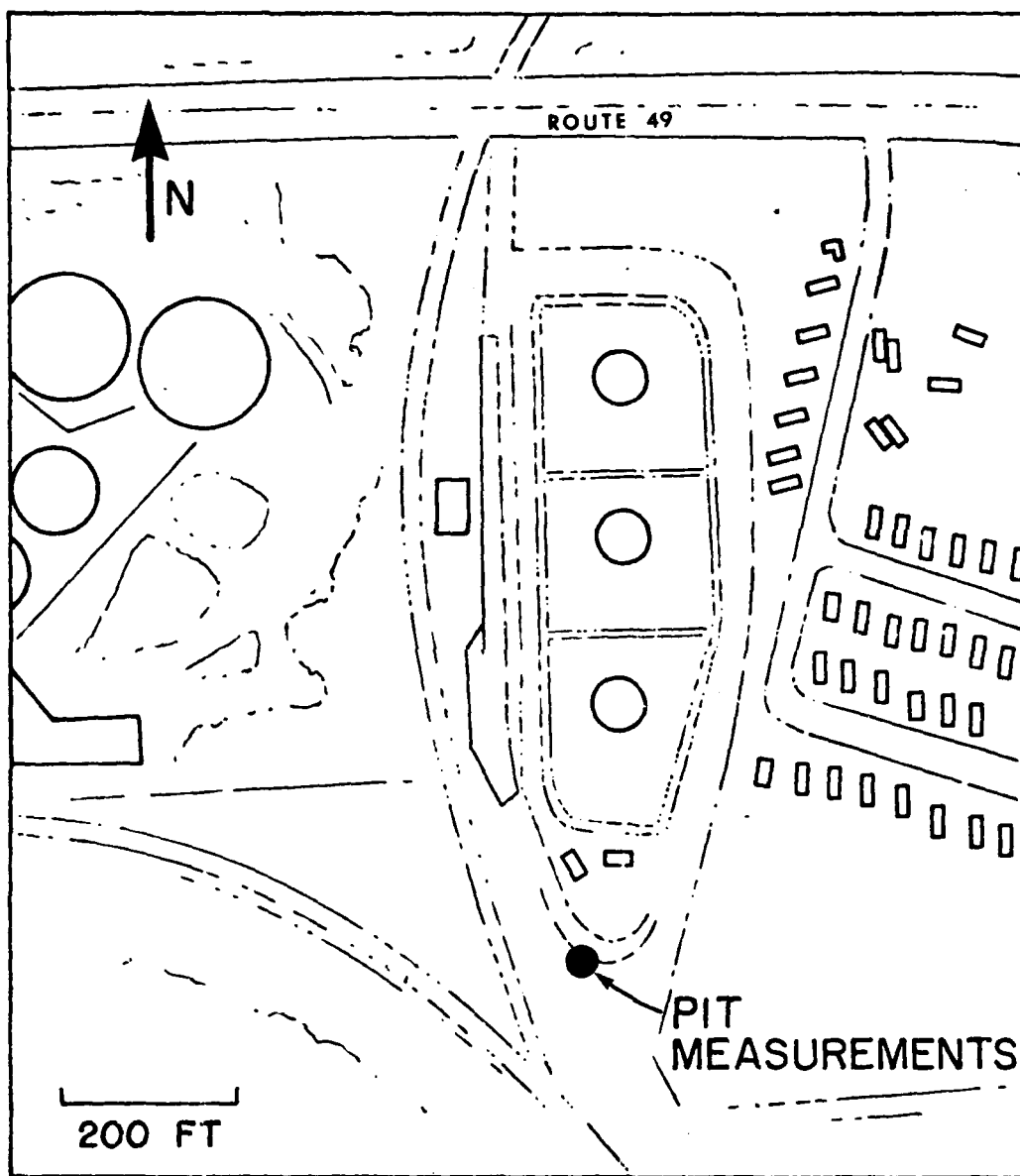


Figure B-3. Map of Rome A Site.

B. Rome E Site

This site is a flat open field located on Greenway Road next to the Greenway Cemetery in Rome. The northwest edge of the site is bounded by deciduous trees. The western and southern edges are bounded by an open field. Photographs and a map of this site are shown in Figure B-4 and Figure B-5, respectively.



Figure B-4a. Photograph of Rome E Site.



Figure B-4b. Photograph of Rome E Site (Concluded).

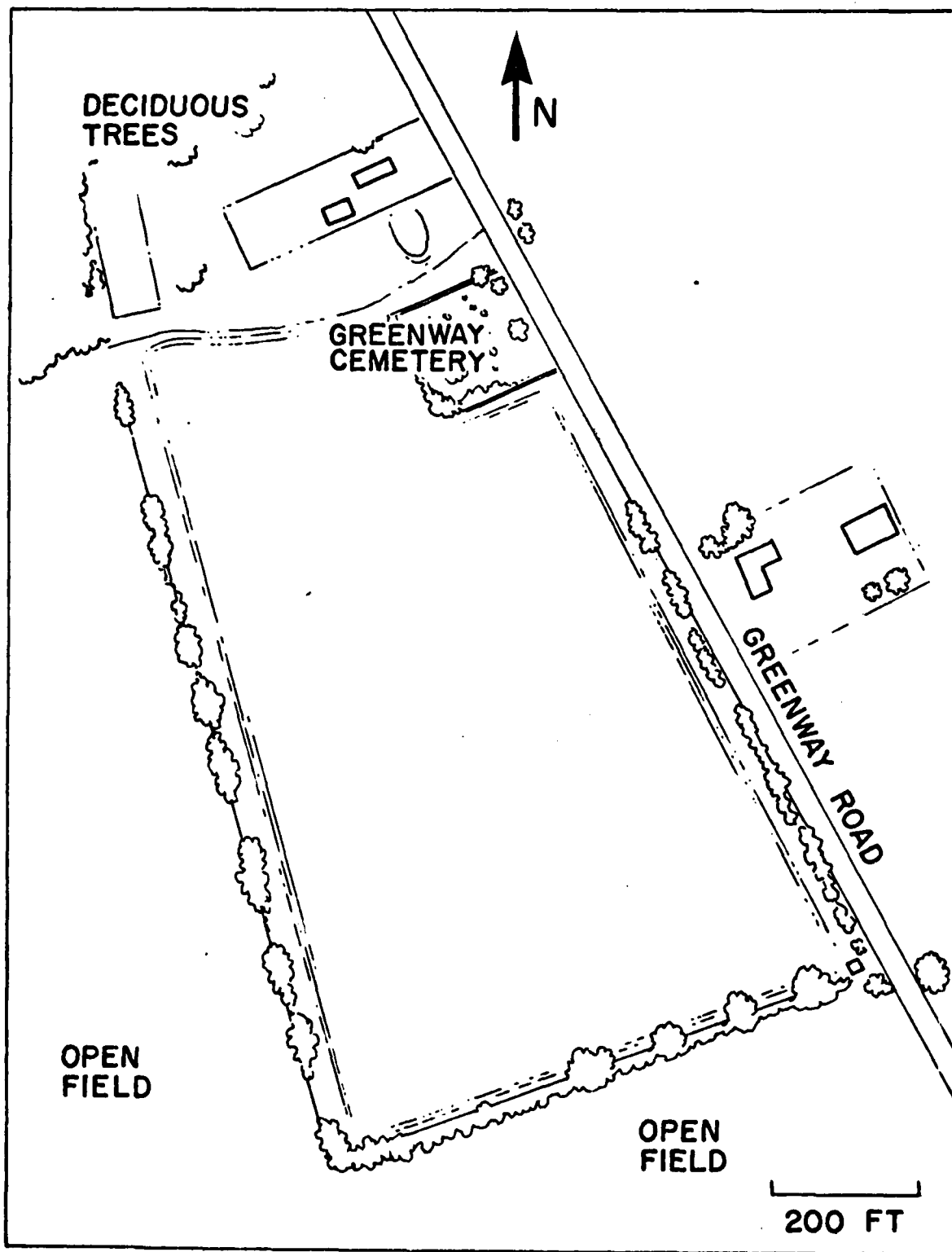


Figure B-5. Map of Rome E Site.

C. Ava B Site

This is a large open field located near the intersection of Belcher Road and Point Rock Road in the town of Lee, north of Rome. The region near the center of the site consisted of hilly terrain. The areas adjacent to Point Rock Road and to the trees in the northwest corner were flat. In Figure B-6 we have a photograph of the site and in Figure B-7 a map of the site with the features of the terrain noted.



Figure B-6a. Photograph of Ava B Site.

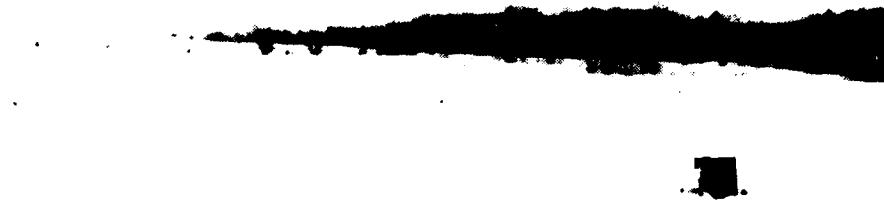


Figure B-6b. Photograph of Ava B Site (Continued).



Figure B-6c. Photograph of Ava B Site (Concluded).

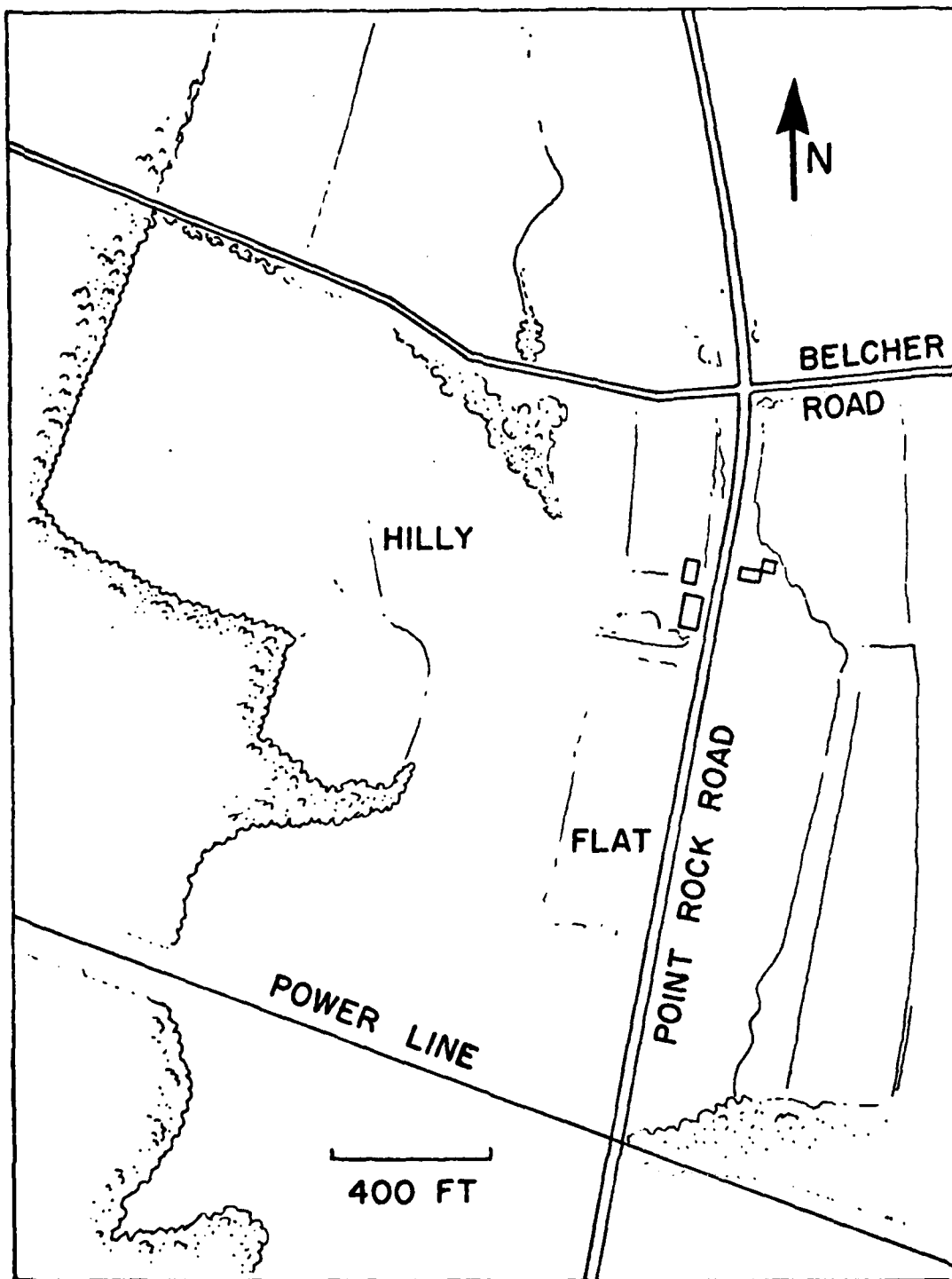


Figure B-7. Map of Ava B Site.

D. Ava C Site

This site is a lake (Bullhead Lake), situated at Kingsley Boyscout Camp in the town of Ava, north of Rome. In Figure B-8 and Figure B-9 we have photographs and a map of the site. The location where the snow profile and associated ground truth measurements were made is noted on the map.

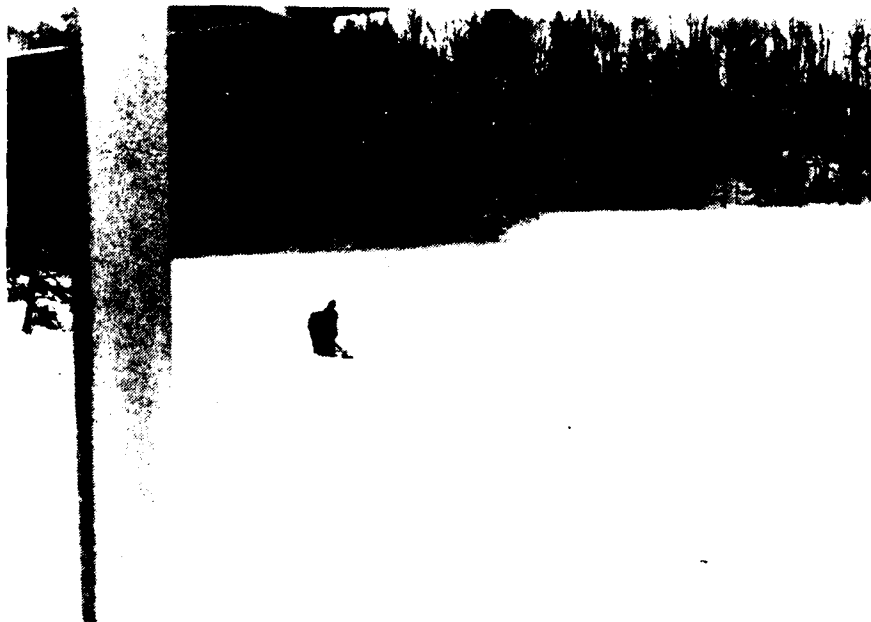


Figure B-8a. Photograph of Ava C Site.



Figure B-8b. Photograph of Ava C Site (Concluded).

SECTION III

GROUND-TRUTH MEASUREMENTS

The ground-truth data gathered at the four sites were acquired using the following procedure:

1. Snow Profile Characterization

Snow profiles were characterized by digging a pit in the snowpack and examining a selected cross sectional area of the snow layer. The various layers in the snowpack were identified and the temperature, average grain size, thickness, and density of each layer were recorded. In some cases, layer was too thin for a density measurement to be made.

2. Free Water Measurement

A freezing calorimetric technique was used to find the percentage by weight of the free water content in the snow.

3. Depth Measurement

Two snow depth measurements were made every 20 meters around the field in order to check for variability.

In Table B-1 we summarized the measurements made at the four sites.

TABLE B-1. SUMMARY OF MEASUREMENTS PERFORMED

<u>Date</u>	<u>Time</u>	<u>Sites and Measurements Made</u>	
January 9	1130 ~ 1430	Ava B:	Snow Profile and Depth Measurements
January 10	0900 ~ 1230	Rome E:	Snow Profile, Free Water, and Depth Measurements
	1500 ~ 1600	Ava C:	Snow Profile and Depth Measurements
January 12	0700 ~ 0900	Rome A:	Snow Profile and Free Water Measurements
January 16	1200 ~ 1430	Rome A:	Snow Profile and Free Water Measurements
	1515 ~ 1730	Ava B:	Snow Profile, Free Water, and Depth Measurements
	1800 ~ 1830	Ava C:	Snow Profile
January 17	0930 ~ 1030	Rome E:	Snow Profile and Depth Measurements
January 23	1115 ~ 1400	Ava B:	Snow Profile and Free Water Measurements
January 29	0900 ~ 1115	Rome A:	Snow Profile and Free Water Measurements
	1200 ~ 1400	Ava B:	Snow Profile, Free Water and Depth Measurements
	1515 ~ 1745	Rome E:	Snow Profile, Free Water and Depth Measurements
January 30	1030 ~ 1130	Ava C:	Snow Profile

A. January 9, 1979

Ava B Site (1130 ~ 1430)

TABLE B-2. SNOW PROFILE CHARACTERISTICS OF AVA B SITE

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	1	4.5	0.2	-6.0	wind blown, light snow
2	19	13	0.3 ~ 0.4	-3.0	
3	1		0.5 ~ 1.0		crusty top layer (grains frozen together)
4	6	13	0.7	-3.0	slightly frozen together, packed tightly
5	1		0.5		like third layer
6	4.5	29	0.5	-2.0	
7	3		1.0		like third layer
8	1				ice layer
9	9	32	0.7	0	tightly packed
10	7.5		0.7 ~ 0.9		like third layer
	ground			0	not frozen
<u>Total Depth:</u> 53 cm <u>Air Temperature:</u> -10°C <u>Weather:</u> Sunny See Figure B-10 for the location of the pit					

TABLE B-3. DEPTH MEASUREMENTS OF AVA B SITE

Location No.	Depth Measurements (cm)	Location No.	Depth Measurements (cm)
1	53; 54	18	61; 63
2	55; 55	19	65; 63
3	54; 53	20	65; 65
4	54; 55	21	64; 74
5	55; 54	22	67; 68
6	47; 46	23	75; 73
7	53; 49	24	61; 64
8	57; 57	25	61; 61
9	46; 46	26	60; 60
10	45; 45	27	56; 54
11	55; 53	28	58; 61
12	56; 57	29	45; 46
13	61; 63	30	51; 52
14	61; 63	31	58; 62
15	62; 63	32	53; 54
16	69; 69	33	58; 63
17	62; 64	34	51; 50
<u>Average Depth:</u> 57.9 cm See Figure B-10 for location of the measurements.			

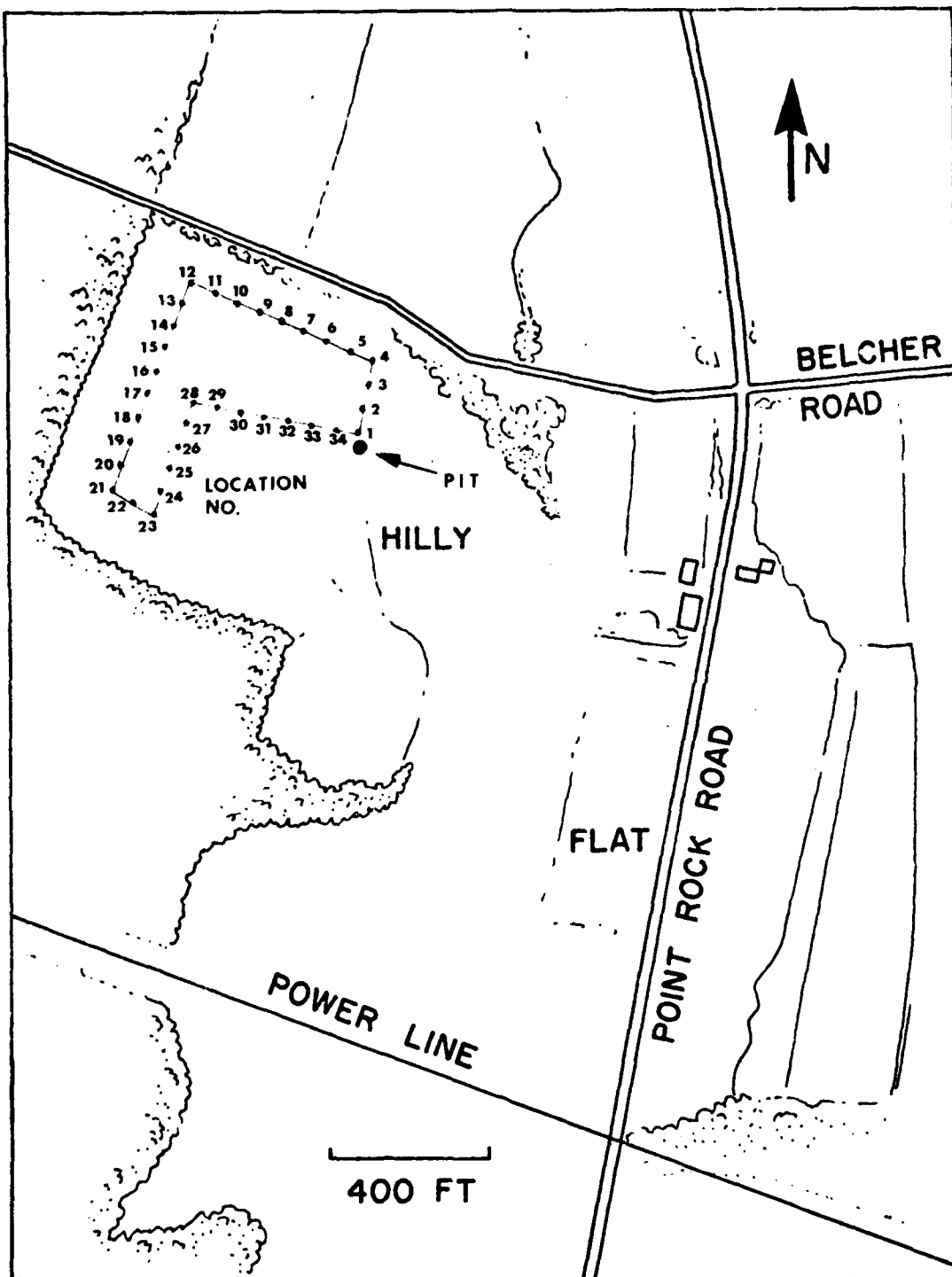


Figure B-10. Map of Ava B Site.

B. January 10, 1979

Rome E Site (0900 ~ 1230)

TABLE B-4. SNOW PROFILE CHARACTERISTICS OF ROME E SITE

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	2	7.0	0.5	-20	wind blown, light snow
2	17	18.0	0.5 ~ 0.7	-11	layer appears to be more tightly packed with depth
3	3	43.0	0.8	-4	hard, crusty, tightly packed (grains frozen together)
4	1				ice layer
5	9	32.0	1.0 ~ 1.5	-1	similar to layer three (not as tightly packed or frozen together)
ground					
<u>Total Depth:</u> 32 cm					
<u>Air Temperature:</u> -20°C					
<u>Weather:</u> Sunny, not windy					
See Figure B-11 for the location of the pit.					

TABLE B-5. FREE WATER CONTENT MEASUREMENTS AT ROME E SITE

Time	Free Water Content (% by weight)	Snow Temp. (°C)	Air Temp. (°C)	Remarks
1000 ~ 1020	2.7	-13	-13	sunny, not windy
1100 ~ 1125	2.8	-9	-9	sunny, not windy
<u>Average Free Water Content:</u> 2.8% by weight The samples were taken from the top 5 cm next to the pit.				

TABLE B-6. DEPTH MEASUREMENTS OF ROME E SITE

Location No.	Depth Measurement (cm)	Location No.	Depth Measurement (cm)	Location No.	Depth Measurement (cm)
1	35; 36	16	58; 59	31	36; 36
2	28; 23	17	38; 40	32	44; 48
3	52; 45	18	58; 63	33	38; 44
4	31; 29	19	41; 50	34	41; 52
5	36; 42	20	32; 43	35	45; 51
6	32; 40	21	40; 52	36	40; 42
7	37; 38	22	41; 38	37	53; 55
8	36; 34	23	62; 59	38	47; 49
9	36; 36	24	36; 40	39	48; 48
10	32; 32	25	34; 45	40	56; 58
11	71; 73	26	39; 40	41	56; 56
12	27; 27	27	37; 43	42	48; 44
13	70; 43	28	37; 40	43	40; 37
14	37; 67	29	36; 36		
15	63; 69	30	30; 46		
<u>Average Depth:</u> 43.7 cm See Figure B-11 for the location of the measurements.					

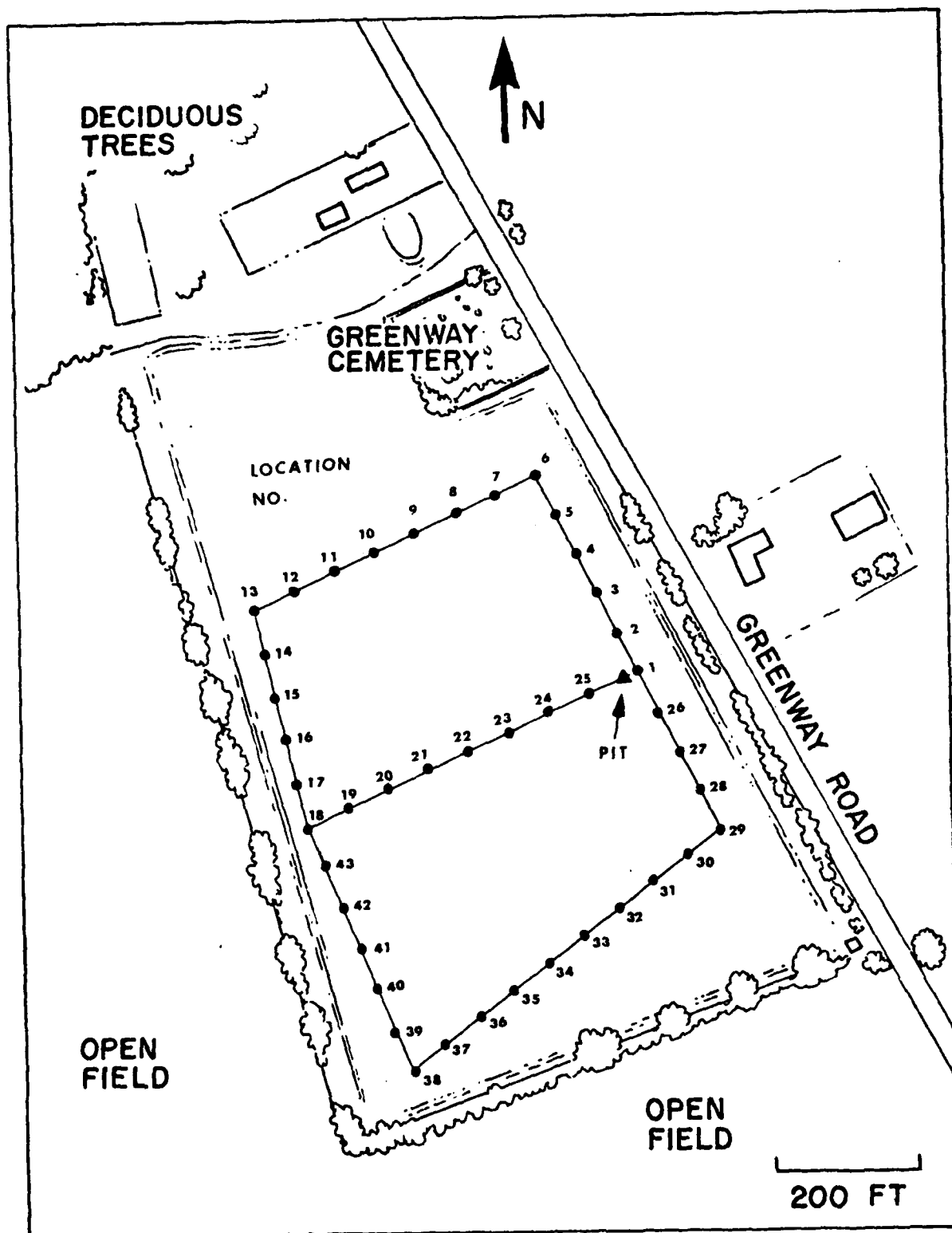


Figure B-11. Map of Rome E Site

Ava C Site (1500 ~ 1600)

TABLE B-7. SNOW PROFILE CHARACTERISTICS OF AVA C SITE

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	2	5	0.4	-9	wind blown, loosely packed
2	18.6	13.5	0.5	-7	
3	2		1.0	-1	loosely packed ice grains, not hard
4	5				ice layer
	water				

Total Depth: 22.6 cm (snow depth)

Air Temperature: -9°C

Weather: snowing lightly

See Figure B-12 for the location of the pit.

TABLE B-8. DEPTH MEASUREMENTS OF AVA C SITE

Location No.	Depth Measurements (cm)	Location No.	Depth Measurements (cm)
1	23; 23	5	24; 24
2	22; 22	6	23; 23
3	25; 25	7	23; 23
4	22; 23		
<u>Average Depth:</u> 23.2 cm See Figure B-12 for the location of the measurements. Unlike other sites the distance between the measurements is not 20 m.			

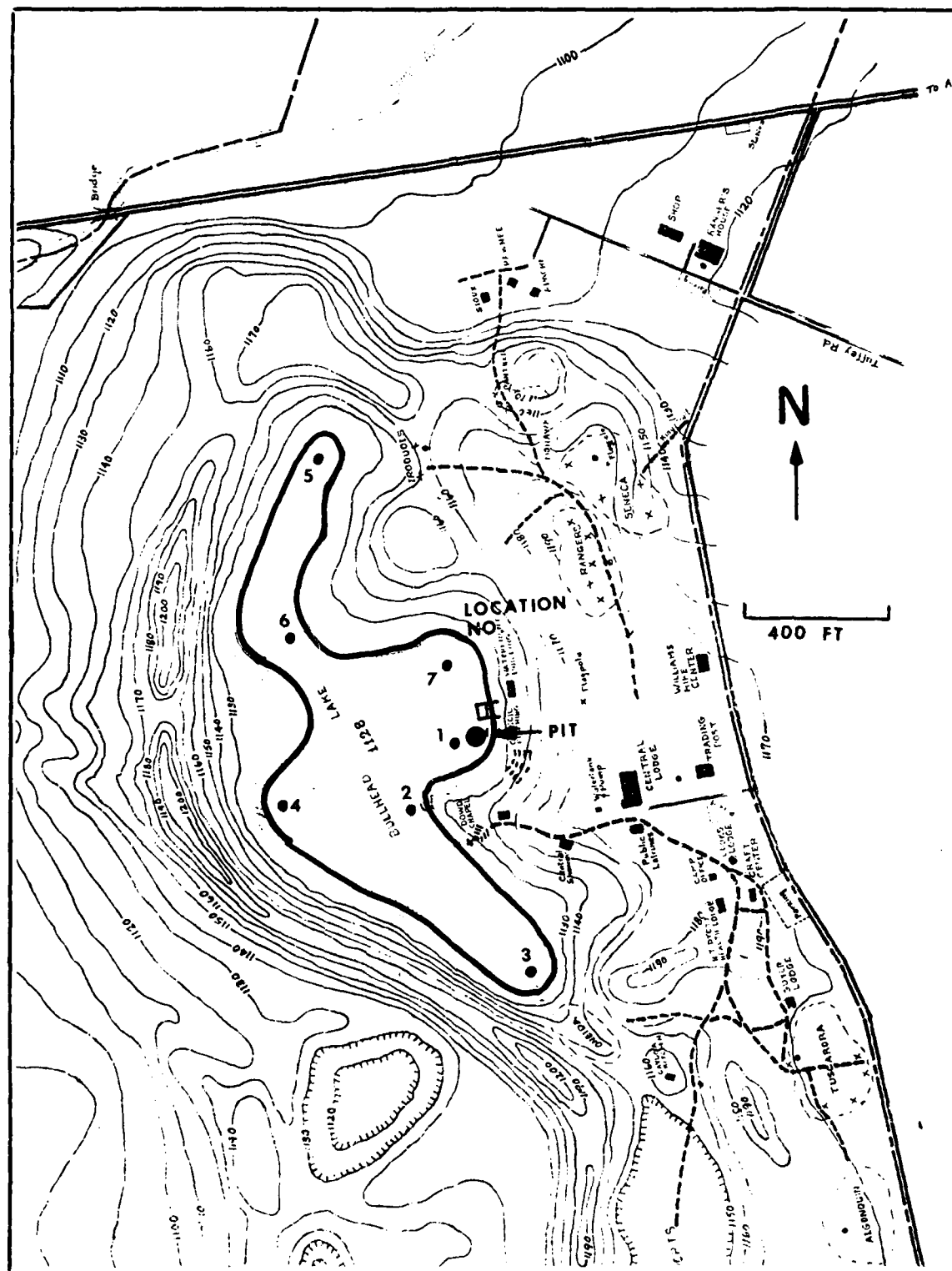


Figure B-12. Map of Ava C Site

C. January 12, 1979

Rome A Site (0700 ~ 0900)

TABLE B-9. SNOW PROFILE CHARACTERISTICS OF ROME A SITE

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	2	7	0.2 ~ 0.4		wind blown, lightly packed
2	15	17	0.8		
3	2	20	1.0		
4	5	28	1.0 ~ 1.5		crusty, tightly packed (grains frozen together)
5	1				ice layer
6	1				hard, crusty, tightly packed (grains frozen together)
7	1				ice layer
8	2				same as layer 6
Ground					
<u>Total Depth:</u> 29cm					
<u>Air Temperature:</u> -24°C					
<u>Weather:</u> Clear, sunny					
See Figure B-3 for the location of the pit.					

TABLE B-10. FREE WATER CONTENT MEASUREMENTS AT ROME A SITE

Time	Free Water Content (%) by weight)	Snow Temp. (°C)	Air Temp. (°C)	Remarks
0715 ~ 0735	3.0	-16	-24	sunny, not windy
0750 ~ 0810	1.3	-17	-21	sunny, not windy
0820 ~ 0840	1.9	-15	-21	sunny, not windy
<u>Average Free Water Content:</u> 2.1% by weight The samples were taken from the top 5 cm next to the pit.				

D. January 16, 1979

Rome A Site (1200 ~ 1430)

TABLE B-11. SNOW PROFILE CHARACTERISTICS OF ROME A SITE

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	6	10	1.0 ~ 1.5	-3	loosely packed (grains are flat in shape)
2	1				ice layer
3	3	32	0.5 ~ 1.0	-3	hard, crusty, tightly packed
4	11	22	0.5 ~ 1.0	-2	loosely packed
5	7	35	1.0 ~ 2.0		hard, crusty, tightly packed (like layer 3)
6	3				ice layer
ground					
<u>Total Depth:</u> 31 cm					
<u>Air Temperature:</u> -5°C					
<u>Weather:</u> overcast, snowing lightly					
See Figure B-3 for the location of the pit.					

TABLE B-12. FREE WATER CONTENT MEASUREMENTS AT ROME A SITE

Time	Free Water Content (% by weight)	Snow Temp. (°C)	Air Temp. (°C)	Remarks
1230 ~ 1245	6.1	-3	-5	partially sunny
1310 ~ 1330	6.0	-2	-5	snowing lightly
1340 ~ 1400	3.6	-3	-4	snowing lightly
1405 ~ 1430	4.9	-3.5	-5	snowing lightly
<u>Average Free Water Content:</u> 5.2% by weight The samples were taken from the top 5 cm next to the pit.				

Ava B Site (1515 ~ 1730)

TABLE B-13. SNOW PROFILE CHARACTERISTICS OF AVA B SITE

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	2	5	1.5 ~ 2.0 (flake size)	-8	very lightly packed (windblown flakes, flat with rib-like structure)
2	7	13	0.2 ~ 0.5	-6	lightly packed
3	7	45	0.5 ~ 1.0	-5	hard, crusty layer (spherical like grains frozen together)
4	7	21	0.5 ~ 1.0	-4	lightly packed
5	6	46	1.0	-3	similar to layer 3
6	12	25	1.0	-1	loosely packed crusty layer
7	18	unable to penetrate	1.0 ~ 2.0	0	very hard crusty layer (like ice layer) spherical grains frozen solidly together
ground					
<u>Total Depth:</u> 59 cm <u>Air Temperature:</u> -8°C <u>Weather:</u> Partially sunny to snowing moderately See Figure B-13 for the location of the pit.					

TABLE B-14. FREE WATER CONTENT MEASUREMENTS AT AVA B SITE

Time	Free Water Content (% by weight)	Snow Temp. (°C)	Air Temp. (°C)	Remarks
1525 ~ 1545	5.0	-4	-8	partially sunny
1555 ~ 1618	6.2	-6	-8	cloudy
1622 ~ 1640	3.5	-7	-9	snowing lightly
1645 ~ 1705	3.4	-7	-9	snowing moderately
<u>Average Free Water Content:</u> 4.5% by weight The samples were taken from the top 5 cm next to the pit.				

TABLE B-15. DEPTH MEASUREMENTS OF AVA B SITE

Location No.	Depth Measurements (cm)	Location No.	Depth Measurements (cm)
1 (pit)	59	7	41; 45
2	60; 59	8	63; 64
3	51; 52	9	56; 60
4	59; 58	10	53; 56
5	50; 51	11	66; 68
6	50; 54	12	63; 68
<u>Average Depth:</u> 56.8 cm See Figure B-13 for the location of the measurements.			

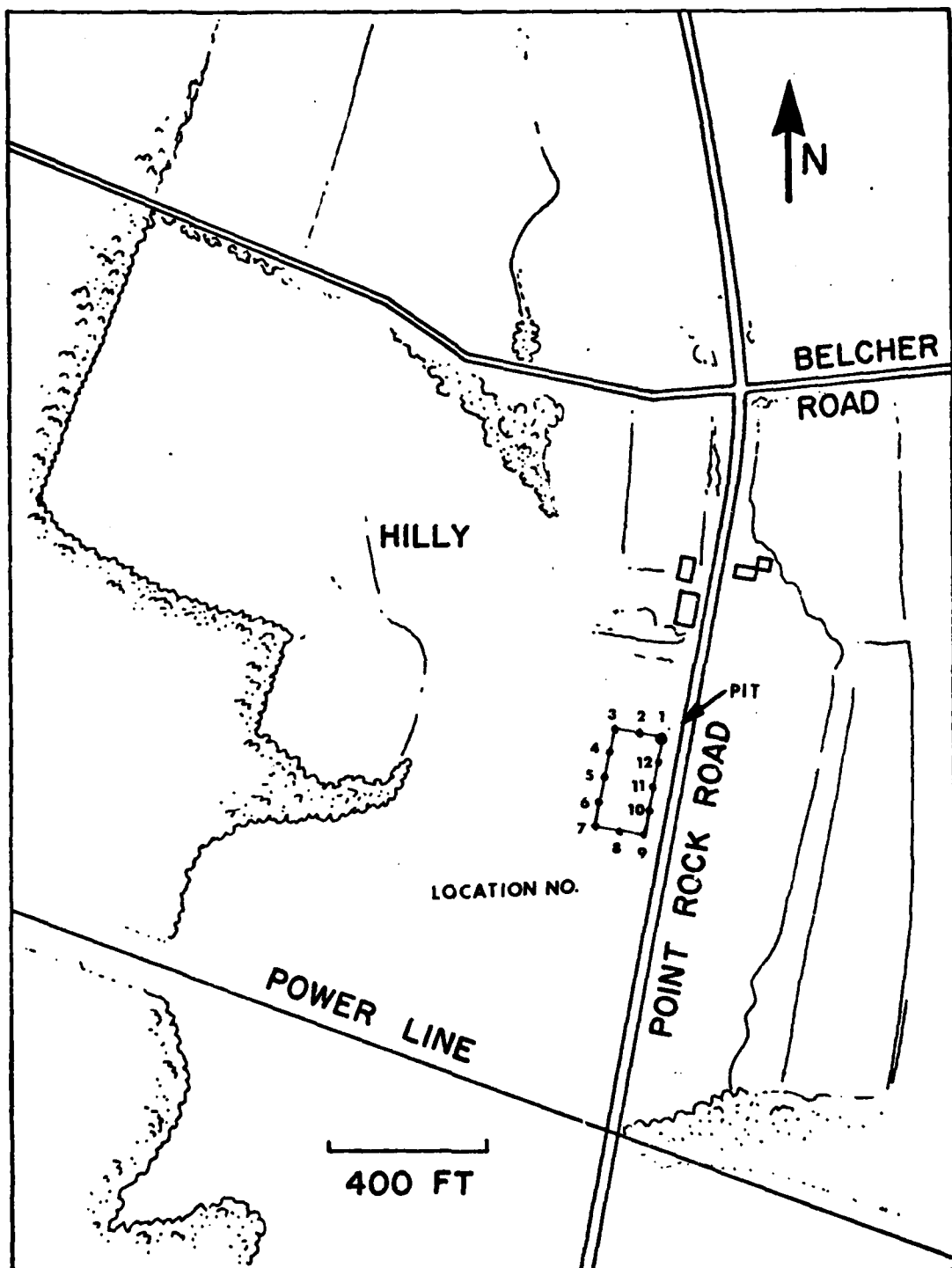


Figure B-13. Map of Ava B Site

Ava C Site (1800 ~ 1830)

TABLE B-16. SNOW PROFILE CHARACTERISTICS OF AVA C SITE

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Remarks
1	9 ~ 10	5.5	3.0 ^a	freshly fallen snow, lightly packed, rough surface ^b
2	6.5	14	0.2 ~ 0.3	
3	1.5		1.0	snow grains frozen together (hard, almost like ice)
4	4	32	0.5 ~ 0.7	crusty snow
5	1			wet slush
ice layer				
<u>Total Depth:</u> 22 ~ 23 cm <u>Weather:</u> moderately snowing a 3 mm is a size of snow flakes b rough surface-- about 1 cm fluctuations in the vertical direction and about 2 cm fluctuations in the horizontal direction. See Figure B-9 for the location of the pit.				

E. January 17, 1979

Rome E (0930 ~ 1030)

TABLE B-17. SNOW PROFILE CHARACTERISTICS OF ROME E SITE

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	4	11	0.5	-9	light, wind blown loosely packed
2	7	17.5	0.5	-8	
3	2				ice layer
4	13	21	0.5 ~ 1.0	-5	granular, slightly frozen together
5	0.5				ice layer
6	6.5	32	1.0 ~ 1.5	0	very hard crusty snow (grains frozen together)
ground					
<u>Total Depth:</u> 33 cm					
<u>Air Temperature:</u> -10°C					
<u>Weather:</u> cloudy					
See Figure B-14 for the location of the pit.					

TABLE B-18. DEPTH MEASUREMENTS OF ROME E SITE

Location No.	Depth Measurements (cm)	Location No.	Depth Measurements (cm)
1 (pit)	33	7	55; 57
2	23; 26	8	56; 58
3	33; 40	9	48; 50
4	34; 38	10	51; 50
5	46; 50	11	45; 46
6	48; 53	12	46; 43
<u>Average Depth:</u> 44.7 cm See Figure B-14 for the location of the measurements.			

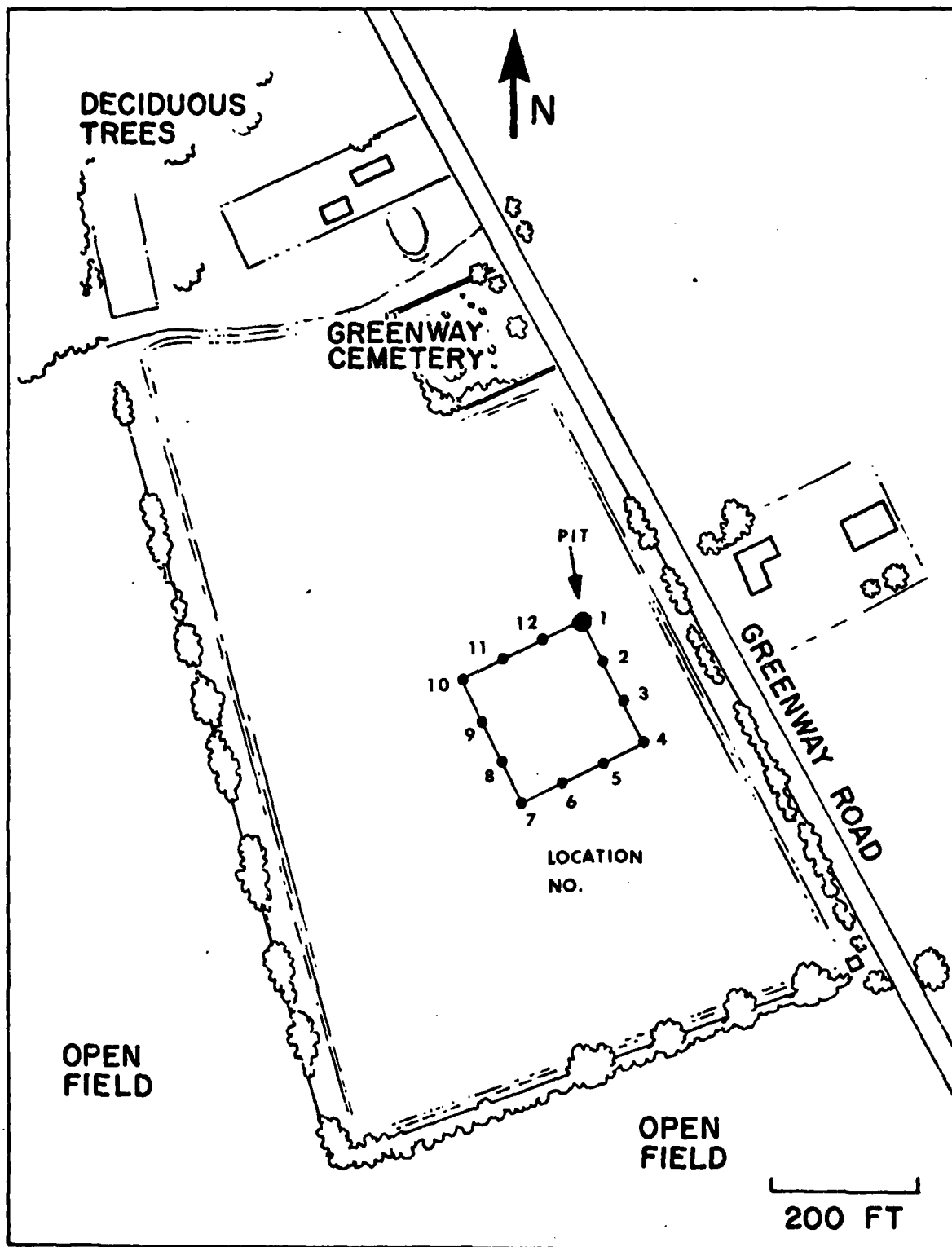


Figure B-14. Map of Rome E Site.

F. January 23, 1979

Ava B Site (1115 ~ 1400)

TABLE B-19. SNOW PROFILE CHARACTERISTICS OF AVA B SITE

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	1.5	8	0.2 ~ 0.5	0	freshly fallen snow
2	7	12.5	0.2 ~ 0.5	0	
3	2.4		0.5 ~ 1.0		snow grains frozen together
4	10	18	0.5	-1.5	tightly packed snow
5	4		0.5 ~ 1.0		snow grains frozen together solidly
6	10	21.5	0.5 ~ 0.8	0	
7	1				ice layer
8	14	27.5	0.5 ~ 1.0	0	crusty, snow grains not frozen together
9	4		0.5 ~ 1.0		snow grains frozen together solidly
10	8	30.5	1.0	0	crusty snow layer
11	4				ice layer
ground					
<u>Total Depth:</u> 65 cm <u>Weather:</u> cloudy <u>Air Temperature:</u> -1°C See Figure B-13 for the location of the pit.					

TABLE B-20. FREE WATER CONTENT MEASUREMENTS AT AVA B SITE

Time	Free Water Content (% by weight)	Snow Temp. (°C)	Air Temp. (°C)	Remarks
1135 ~ 1155	4.6	-1	-1	cloudy
1220 ~ 1240	1.9	0	0	cloudy
1255 ~ 1320	4.8	-1	-1.5	cloudy
1330 ~ 1350	5.7	0	0	cloudy
<u>Average Free Water Content:</u> 4.3% by weight The samples were taken from the top 5 cm next to the pit.				

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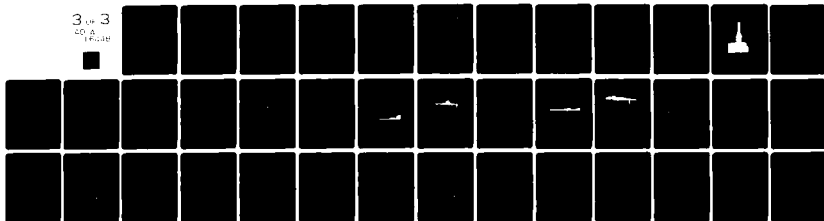
MASSACHUSETTS INST OF TECH CAMBRIDGE RESEARCH LAB OF--ETC F/6 17/9
PREDICTION OF BACKSCATTER AND EMISSIVITY OF SNOW AT MILLIMETER --ETC(U)
JAN 80 J A KONG, R T SHIN F08635-78-C-0115

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G. January 29, 1979

Rome A Site (0900 ~ 1115)

TABLE B-21. SNOW PROFILE CHARACTERISTICS OF ROME A SITE

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	4	8	1.0 ~ 2.0 ^a	0	loosely packed snow layer
2	12	39	0.8 ~ 1.0	0	crusty snow layer (grains frozen together) appears very wet
3	7	26	0.5	0	crusty snow layer, not frozen together
4	5	34	1.0	0	crusty snow (grains frozen together)
5	4				ice layer
ground					
<u>Total Depth:</u> 32 cm					
<u>Air Temperature:</u> -1°C					
<u>Weather:</u> cloudy (snow flurries on and off)					
a length measurement of needle-like ice crystals					
See Figure B-3 for the location of the pit.					

TABLE B-22. FREE WATER CONTENT MEASUREMENTS AT ROME A SITE

Time	Free Water Content (% by weight)	Snow Temp. (°C)	Air Temp. (°C)	Remarks
0925 ~ 0948	5.1	0	-1	cloudy
The sample was taken from the top layer (4 cm) of snow next to the pit.				

TABLE B-23. FREE WATER CONTENT MEASUREMENTS AT ROME A SITE

Time	Free Water Content (% by weight)	Snow Temp. (°C)	Air Temp. (°C)	Remarks
0955 ~ 1015	8.9	0	-1	light snow flurries
1020 ~ 1040	11.7	0	-1	snow flurries light snow
1045 ~ 1105	10.5	0	-1	cloudy
<u>Average Free Water Content:</u> 10.4% by weight The samples were taken from the top 10 cm (which included the wet second layer) next to the pit.				

Ava B Site (1200 ~ 1400)

TABLE B-24. SNOW PROFILE CHARACTERISTICS OF AVA B SITE

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	3	18	0.5 ~ 1.0 ^a	-3	loosely packed, wind blown
2	8	42.5	1.5 ~ 2.0	0	grains frozen solidly together (almost like an ice layer)
3	5	44	0.5 ~ 1.0	0	grains frozen together (not solidly)
4	6	39	1.5 ~ 2.0	0	like layer 2
5	16	30.5	0.5 ~ 1.0	0	like layer 3
6	2				ice layer
7	13	26	0.8 ~ 1.0	0	like layer 3
8	13		2.0 ~ 3.0		like layer 2
ground					
<u>Total Depth:</u> 66 cm <u>Air Temperature:</u> -4°C <u>Weather:</u> snowing lightly to snowing moderately a length measurement of needle-like crystals. See Figure B-15 for the location of the pit.					

TABLE B-25. FREE WATER CONTENT MEASUREMENTS AT AVA B SITE

Time	Free Water Content (% by weight)	Snow Temp. (°C)	Air Temp. (°C)	Remarks
1200 ~ 1220	4.1	-1	-4	snowing lightly
1230 ~ 1255	5.2	-2.5	-4	snowing lightly
1300 ~ 1320	8.1	-3	-4	snowing lightly
1325 ~ 1340	5.8	-3	-4	snowing moderately
<u>Average Free Water Content:</u> 5.8% by weight The samples were taken from the top wind blown layer, next to the pit.				

TABLE B-26. DEPTH MEASUREMENTS OF AVA B SITE

Location No.	Depth Measurements (cm)	Location No.	Depth Measurements (cm)
1 (pit)	66	6	60; 62
2	58; 54	7	55; 54
3	61; 62	8	55; 56
4	51; 52	9	63; 65
5	62; 57	10	62; 64
<u>Average Depth:</u> 58.9 cm See Figure B-15 for the location of the measurements.			

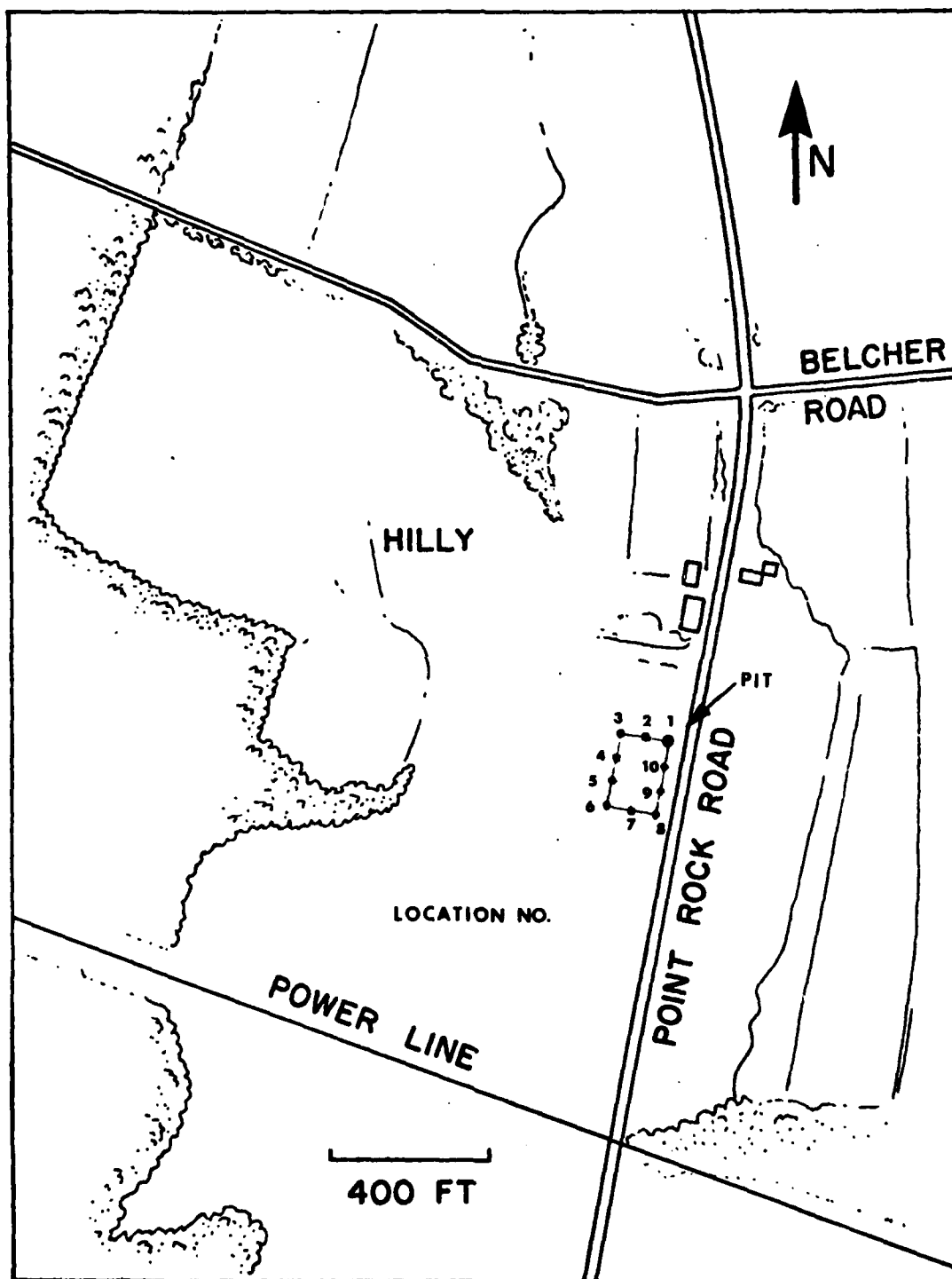


Figure B-15. Map of Ava B Site

Rome E Site (1515 ~ 1745)

TABLE B-27. SNOW PROFILE CHARACTERISTICS OF ROME E SITE

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	4	18	0.5 ^a	-2	wind blown layer
2	4	43	1.0 ~ 2.0	0	grains frozen solidly together (almost like an ice layer)
3	16	47	1.0 ~ 1.5	0	grains frozen together (not solidly), appears to be wet
4	2				ice layer
5	5	32	1.5 ~ 2.0	0	grains not frozen together (very loosely packed)
ground					
<u>Total Depth:</u> 31 cm <u>Air Temperature:</u> -2°C <u>Weather:</u> cloudy a length measurement of needle-like ice crystals See Figure B-14 for the location of the pit.					

TABLE B-28. FREE WATER CONTENT MEASUREMENTS AT ROME E SITE

Time	Free Water Content (% by weight)	Snow Temp. (°C)	Air Temp. (°C)	Remarks
1525 ~ 1545	3.8	0	-2	cloudy
1610 ~ 1625	4.8	-3	-3	cloudy
<u>Average Free Water Content:</u> 4.3% by weight The samples were taken from the top wind blown layer, next to the pit.				

TABLE B-29. FREE WATER CONTENT MEASUREMENTS AT ROME E SITE

Time	Free Water Content (% by weight)	Snow Temp. (°C)	Air Temp. (°C)	Remarks
1548 ~ 1610	16.3	0	-3	cloudy
1630 ~ 1650	15.0	0	-3	cloudy
1655 ~ 1710	4.6	0	-3	cloudy
1715 ~ 1735	10.8	0	-3	cloudy
<u>Average Free Water Content:</u> 12.9% by weight The samples were taken from the wet third layer, next to the pit.				

TABLE B-30. DEPTH MEASUREMENTS OF ROME E SITE

Location No.	Depth Measurements (cm)	Location No.	Depth Measurements (cm)
1 (pit)	31	7	47; 49
2	48; 48	8	45; 60
3	46; 47	9	58; 58
4	49; 50	10	57; 54
5	47; 49	11	52; 50
6	38; 40	12	50; 47
<u>Average Depth:</u> 48.7 cm See Figure B-15 for the location of the measurements.			

H. January 30, 1979

Ava C Site (1030 ~ 1130)

TABLE B-31. SNOW PROFILE CHARACTERISTICS OF AVA C SITE

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	1		0.5 ~ 1.0 ^a	-2	wind blown, dry
2	3	15	0.5 ~ 1.0	-1	
3	3.5	37	1.0 ~ 2.0	0	crusty, grains frozen together (not solidly)
4	0.5				ice layer
5	4		1.0 ~ 2.0	0	like layer 3
6	2			0	ice-slush mixture
water					
<u>Total Depth:</u> 14 cm					
<u>Air Temperature:</u> -6°C					
<u>Weather:</u> cloudy					
a length measurements of needle-like ice crystals					
See Figure B-9 for the location of the pit.					

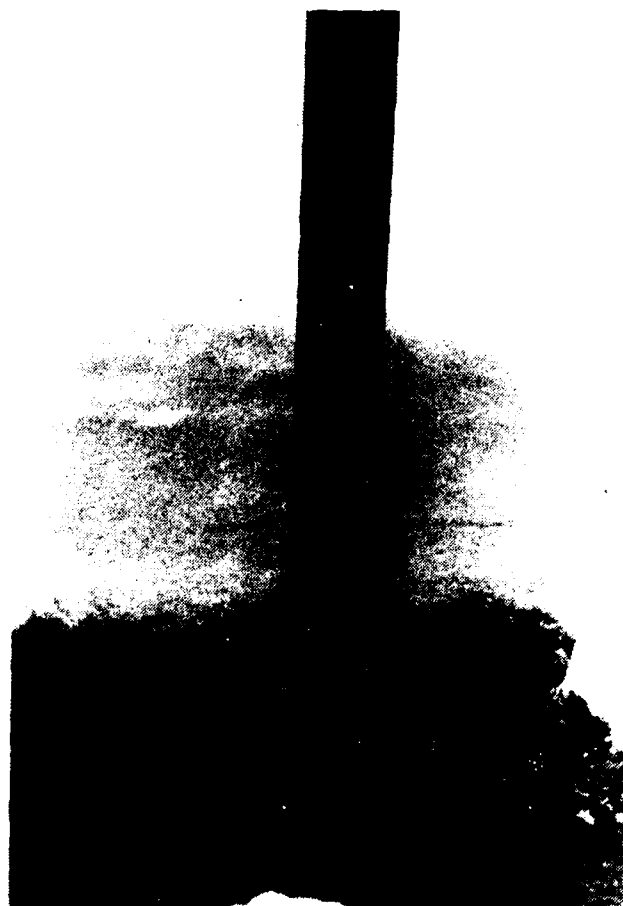


Figure B-16. Photograph of Snowpack
Cross-Section at Ava C Site.

APPENDIX C

GROUND-TRUTH OF SNOW FIELDS IN THE ROGERS CITY,
MICHIGAN AREA DURING FEBRUARY, 1979*

by

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and

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* This work was supported by NASA Contract NAS5-24139 and the AIR FORCE/EGLIN Contract F08635-78-C-0115.

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SECTION I

INTRODUCTION

This report contains ground-truth measurements performed during February 7 and 8, 1979 of snow fields at two sites in the Rogers City, Michigan area. The general locations of the sites are shown in Figure C-1 and they are referred to as Site E and Site F. The measurements were taken in region to an AIR FORCE SAR IMAGING flight of February 5, 1979. Also, the snowfall and air temperature measurements on February 5, 6, 7, 1979 were obtained from National Weather Service, Alpena Station and included in Tables C-9 through C-12. Figure C-2 shows the relative position of the sites and the Alpena National Weather Service Station.

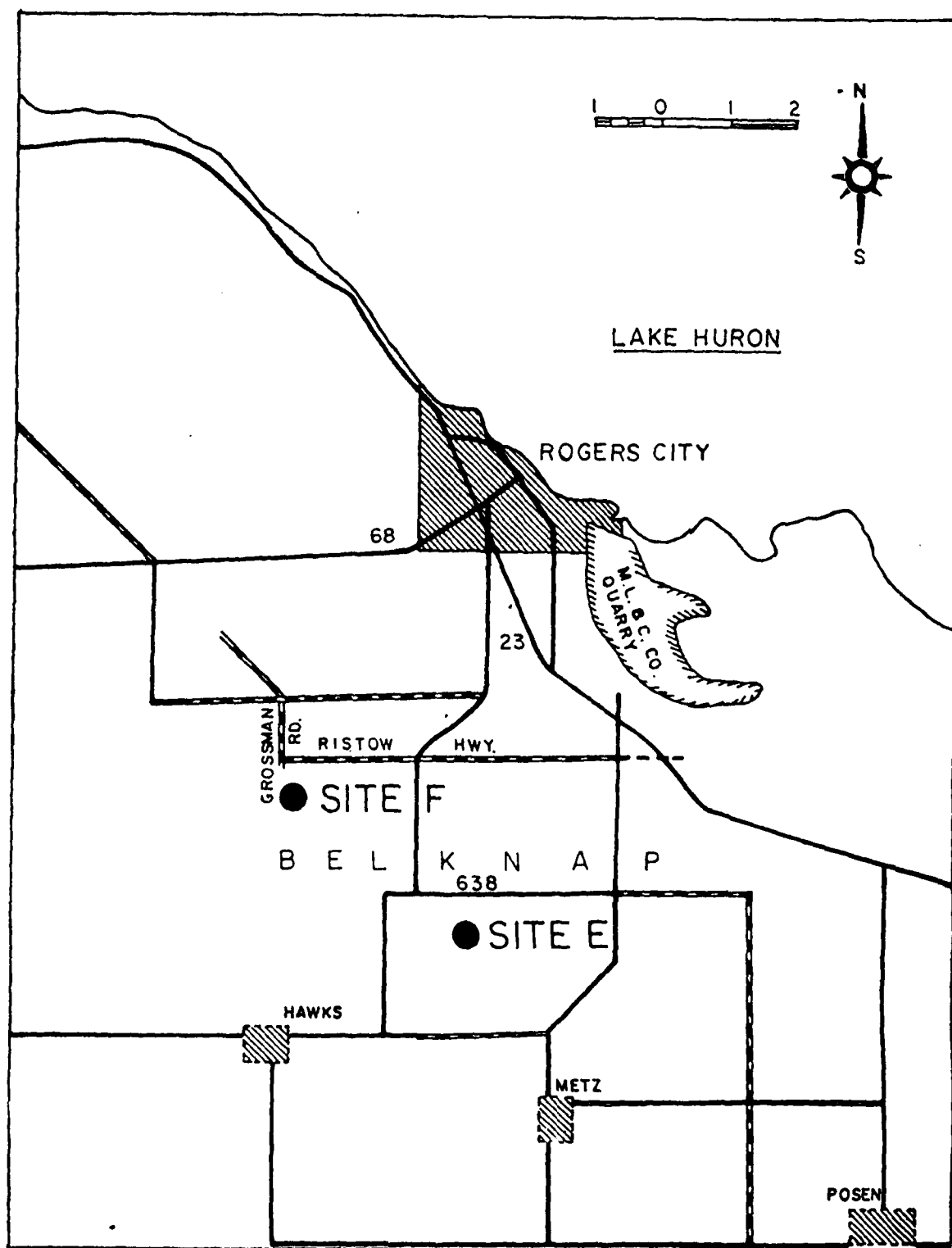


Figure C-1. General Area Map

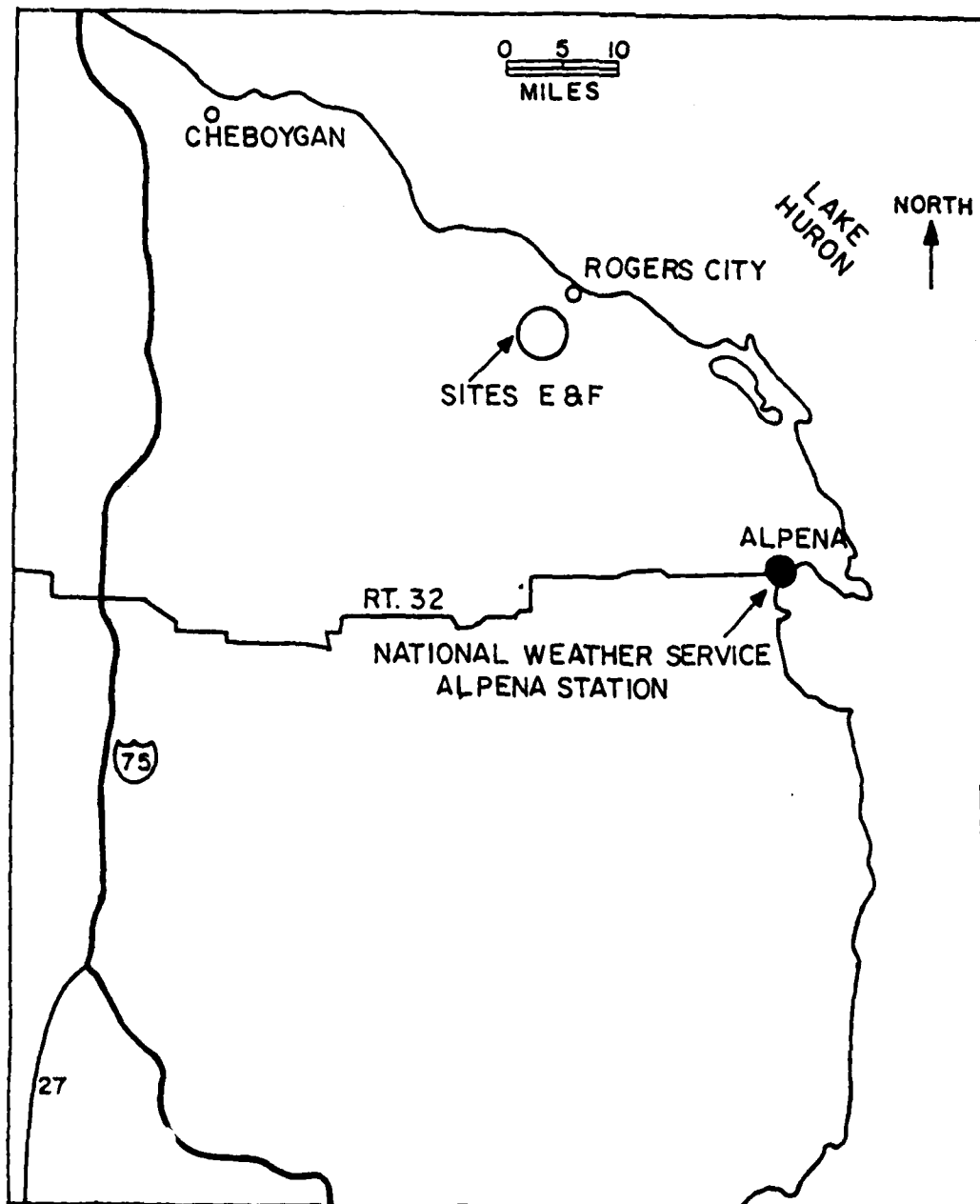


Figure C-2. Location of Alpena National Weather Service Station

SECTION II
SITES IN ROGERS CITY AREA

A. Site E

This site is a flat open field location next to the intersection of 451 Road and 638 Highway in the town of Belknap, south of Rogers City. The western edge of the site is bounded by a mixture of deciduous and pine trees. Photographs and a map of this site are shown in Figures 3 and 4, respectively.



Figure C-3a. Photograph of Site E

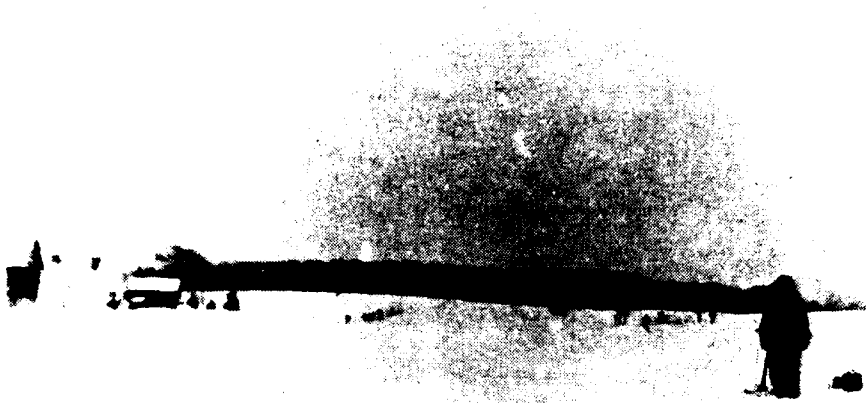


Figure C-3b. Photograph of Site E (Concluded)

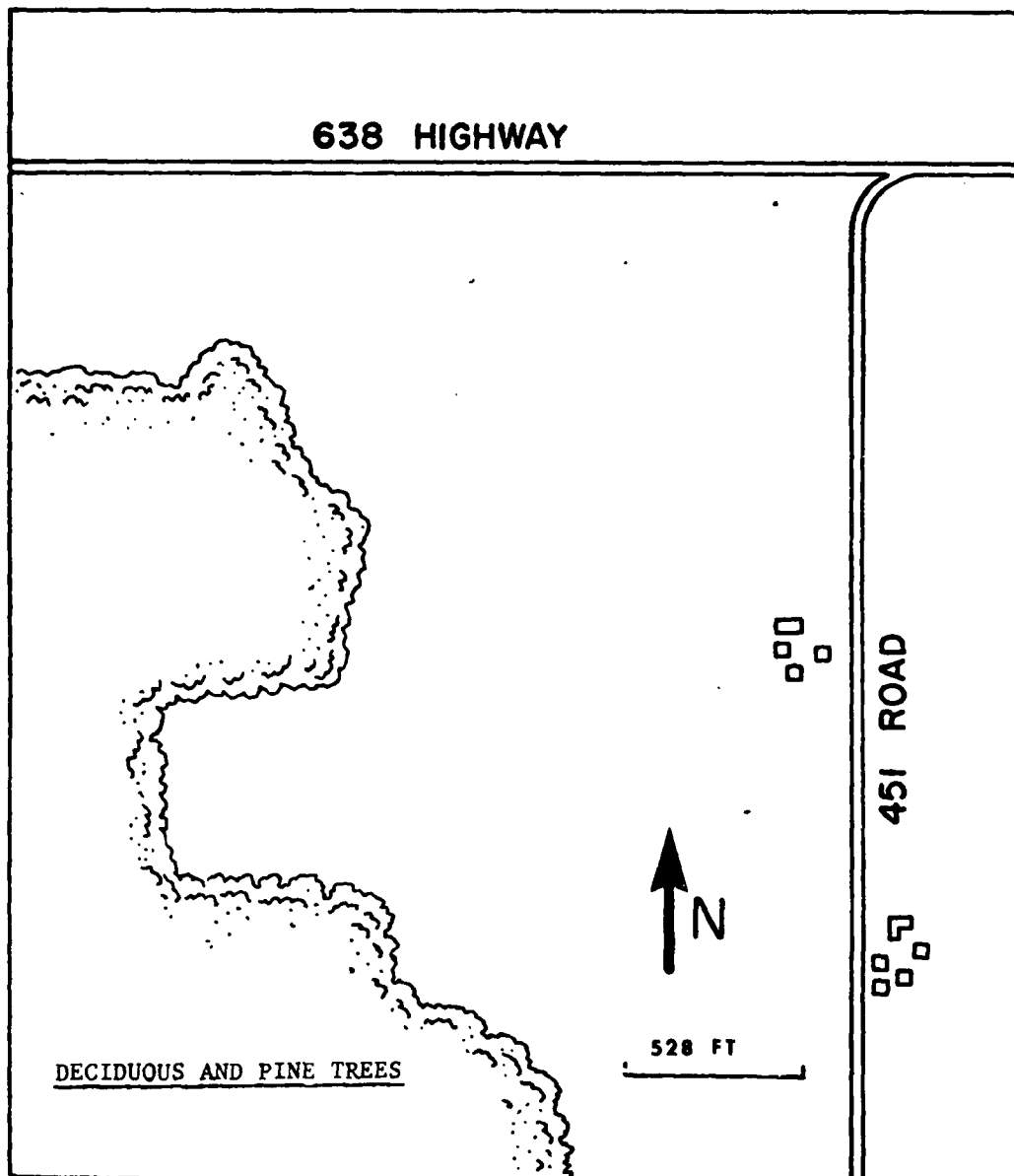


Figure C-4. Map of Site E

B. Site F

This site is a pond (Klees Pond), situated near the intersection of Grossman Road and West Ristow Highway in the town of Belknap, south of Rogers City. In Figures 5 and 6 we have photographs and a map of the site.



Figure C-5a. Photograph of Site F



Figure C-5b. Photograph of Site F (Concluded)

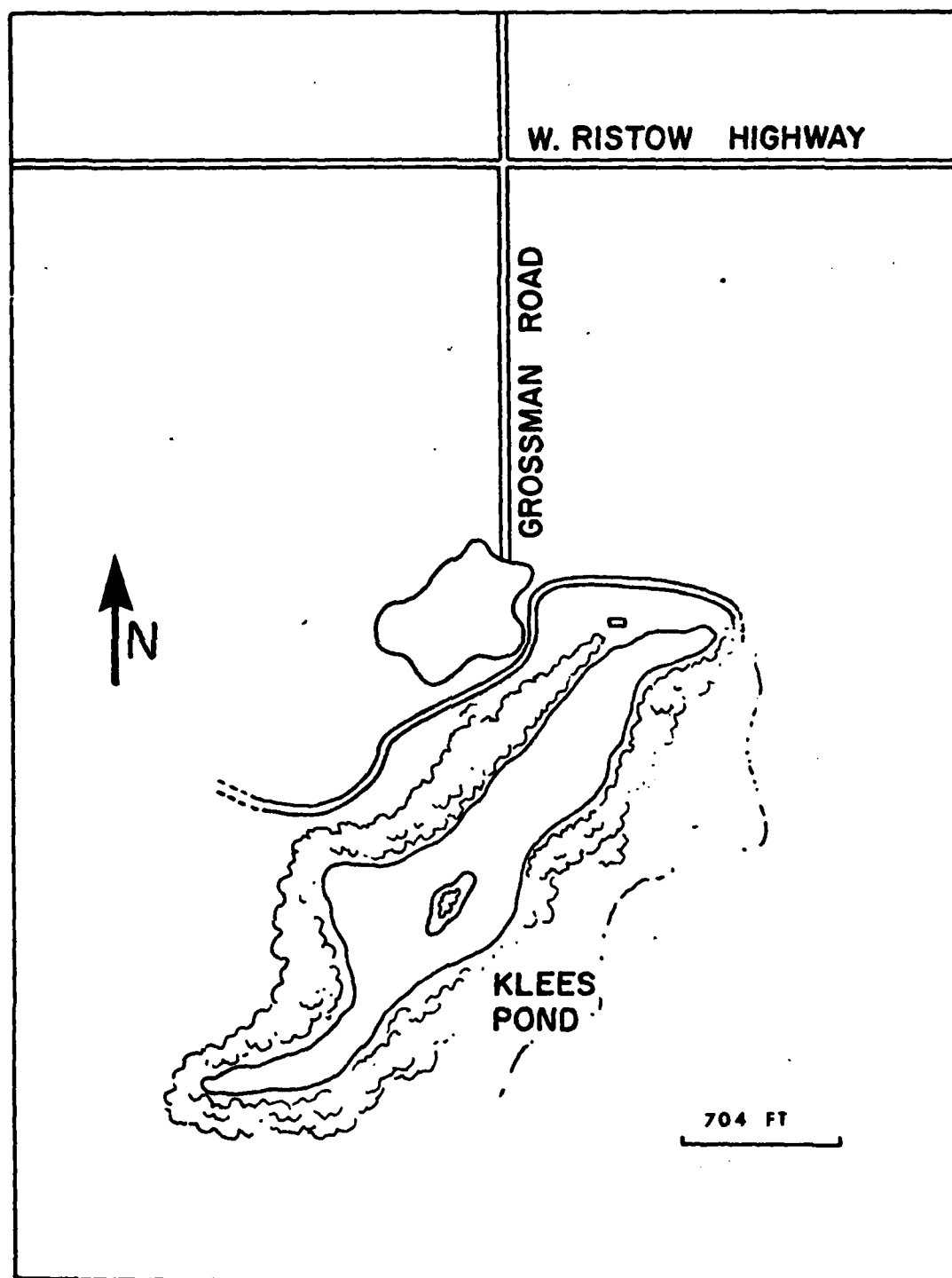


Figure C-6. Map of Site F

SECTION III

GROUND-TRUTH MEASUREMENTS

The ground truth data gathered at the two sites were acquired using the following procedures:

1. Snow Profile Characterization

Snow profiles were characterized by digging a pit in the snowpack and examining a selected cross sectional area of the snow layer. The various layers in the snowpack were identified and the temperature, average grain size, thickness, and density of each layer were recorded. In some cases, layer was too thin for a density measurement to be made.

2. Depth Measurement

Two snow depth measurements were made every 20 meters either around or across the field in order to check for variability.

Measurements on two sites, Site E and Site F, were made on both February 7 and 8, 1979.

A. February 7, 1979

Site E (1125 1400)

TABLE C-1. SNOW PROFILE CHARACTERISTICS OF SITE F

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	5	4	2 ~ 4 ^a	-3.0	freshly fallen snow rough surface, very loosely packed
2	9	21	0.5 ~ 1.0	-4.6	slightly crusty, granular
3	14	26	0.5 ~ 1.0	-5.6	same as layer 2, except this layer is more tightly packed
4	5	30	1.0	-5.0	same as layer 3
5	12	27.5	1.0	-3.7	same as layer 3
6	6	27.5	1.0 ~ 1.5	-2.0	same as layer 3
7	10	24.5	1.5 ~ 2.0	+0.4	granular, loosely packed (grains are not held together)
ground					
<u>Total Depth:</u> 61 cm					
<u>Air Temperature:</u> -5.4°C					
<u>Weather:</u> snowing lightly					
a Size of snow flakes					
See Figure C-7 for the location of the pit.					

TABLE C-2. DEPTH MEASUREMENTS OF SITE E

Location No.	Depth Measurements (cm)	Location No.	Depth Measurements (cm)
1 (pit)	61	23	56; 57
2	68; 64	24	59; 60
3	57; 59	25	62; 63
4	59; 57	26	63; 66
5	56; 56	27	64; 66
6	61; 61	28	54; 55
7	58; 60	29	66; 70
8	55; 55	30	63; 64
9	54; 56	31	62; 63
10	63; 64	32	62; 66
11	63; 60	33	59; 56
12	58; 60	34	64; 67
13	56; 57	35	64; 59
14	60; 64	36	61; 62
15	61; 63	37	65; 67
16	52; 53	38	63; 64
17	65; 63	39	72; 74
18	49; 48	40	65; 66
19	50; 50	41	56; 60
20	59; 59	42	54; 53
21	50; 54	43	57; 57
22	51; 52	44	61; 62

Average Depth: 59.9 cm

See Figure C-7 for the location of the measurements.

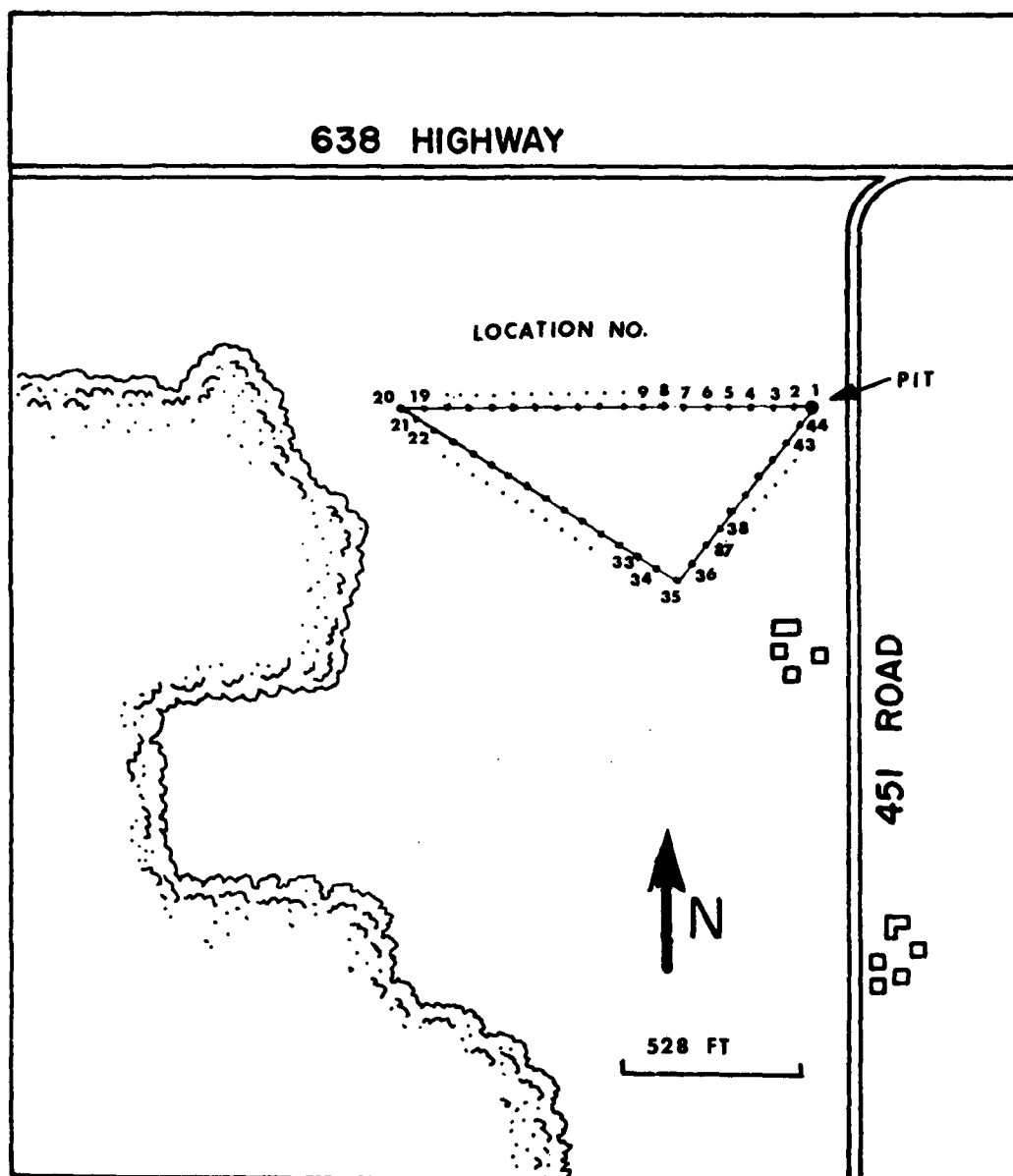


Figure C-7. Map of Site E

Site F (1630 ~ 1715)

TABLE C-3. SNOW PROFILE CHARACTERISTICS OF SITE F

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	3.5	3	2.0 ~ 4.0 ^a	-4.0	freshly fallen snow flakes
2	5.5	10	1.0 ^b	-2.0	broken flakes
3	0.5		1.0 ~ 1.5		grains frozen together
4	14.5	22.5	1.0 ~ 1.5	+1.0	granular, loosely packed
	ice				

Total Depth: 24 cm

Air Temperature: -8.0°C

Weather: cloudy

a size of snow flakes

b length measurement of needle-like broken flakes

See Figure C-8 for the location of the pit.

TABLE C-4. DEPTH MEASUREMENTS OF SITE F

Location No.	Depth Measurements (cm)	Location No.	Depth Measurements (cm)
1	19; 21	4	19; 20
2	21; 20	5	19.5; 19.5
3	20; 20		
Average Depth: 19.9 cm			
See Figure C-8 for the location of measurements.			

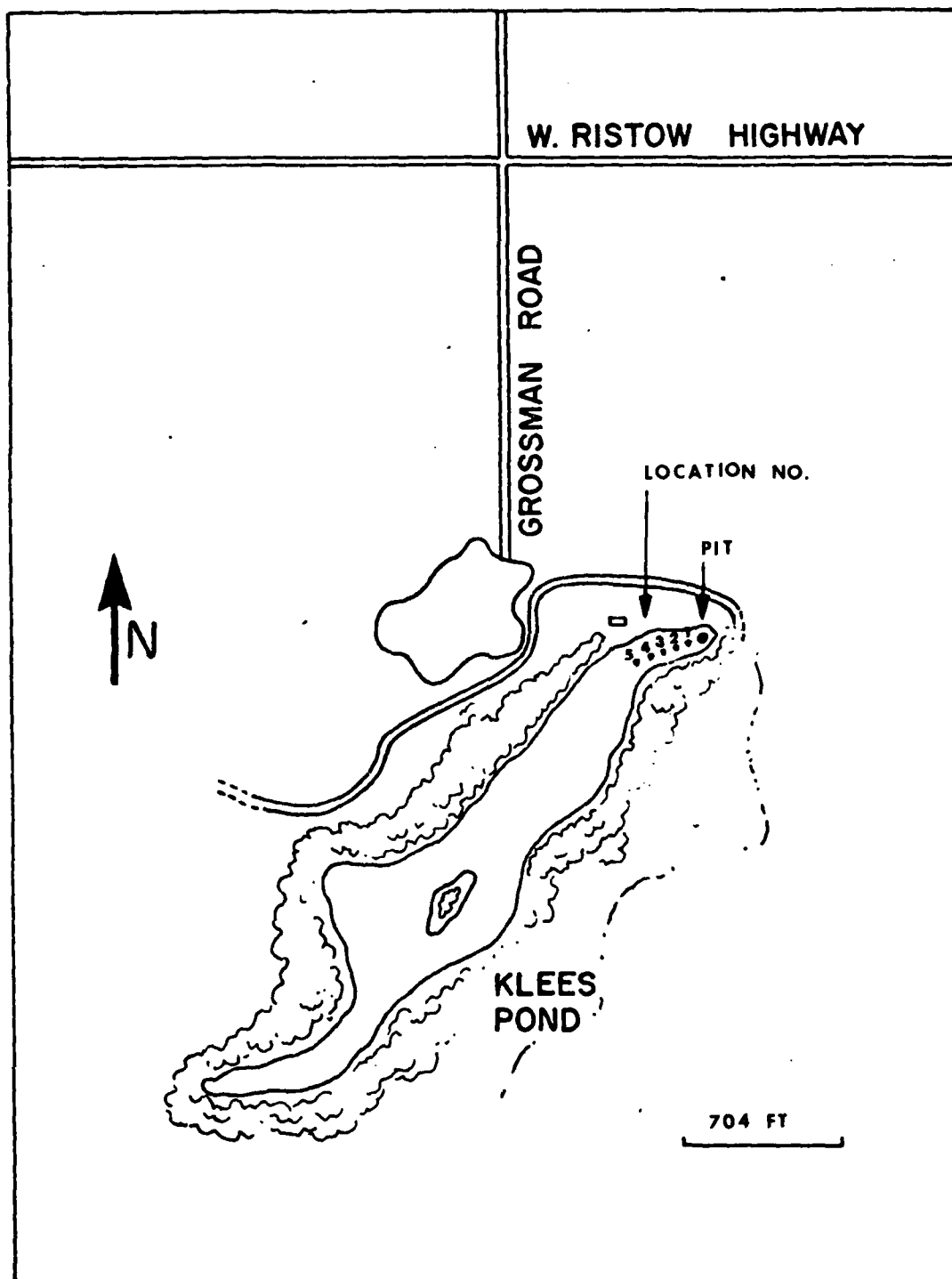


Figure C-8. Map of Site F

B. February 8, 1979

Site E (1250 ~ 1430)

TABLE C-5. SNOW PROFILE CHARACTERISTICS OF SITE E

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	1		0.3	-11.7	tightly wind packed
2	10.5	6	1.0 ~ 1.5 ^a	-9.4	broken flakes
3	0.5		0.5 ~ 1.0		crusty, grains frozen together, fractures easily
4	8.5	28.5	0.7	-6.5	granular, tightly packed (not frozen together)
5	4.5	31	0.5	-4.9	granular, packed together
6	37				granular, packed together
		27	0.7	-3.9	at 34 cm from the bottom
		28	0.7 ~ 1.0	-2.9	at 29 cm from the ground
		28	1.0	-1.8	at 23 cm from the ground
		28	1.0	-1.4	at 18 cm from the ground
		28	1.0	+0.6	at 12 cm from the ground
ground					
<u>Total Depth:</u> 61 cm <u>Air Temperature:</u> -15°C <u>Weather:</u> clear sunny					
^a Size of snow flakes. See Figure C-9 for the location of the pit.					

TABLE C-6. DEPTH MEASUREMENTS OF SITE E

Location No.	Depth Measurements (cm)	Location No.	Depth Measurements (cm)
1 (pit)	61	11	61; 63
2	50; 54	12	58; 59
3	60; 61	13	64; 65
4	61; 64	14	60; 65
5	65; 65	15	64; 70
6	68; 60	16	57; 55
7	65; 67	17	63; 67
8	59; 60	18	61; 63
9	62; 63	19	61; 59
10	60; 62		
<u>Average Depth:</u> 61.7 cm See Figure C-9 for the location of measurements.			

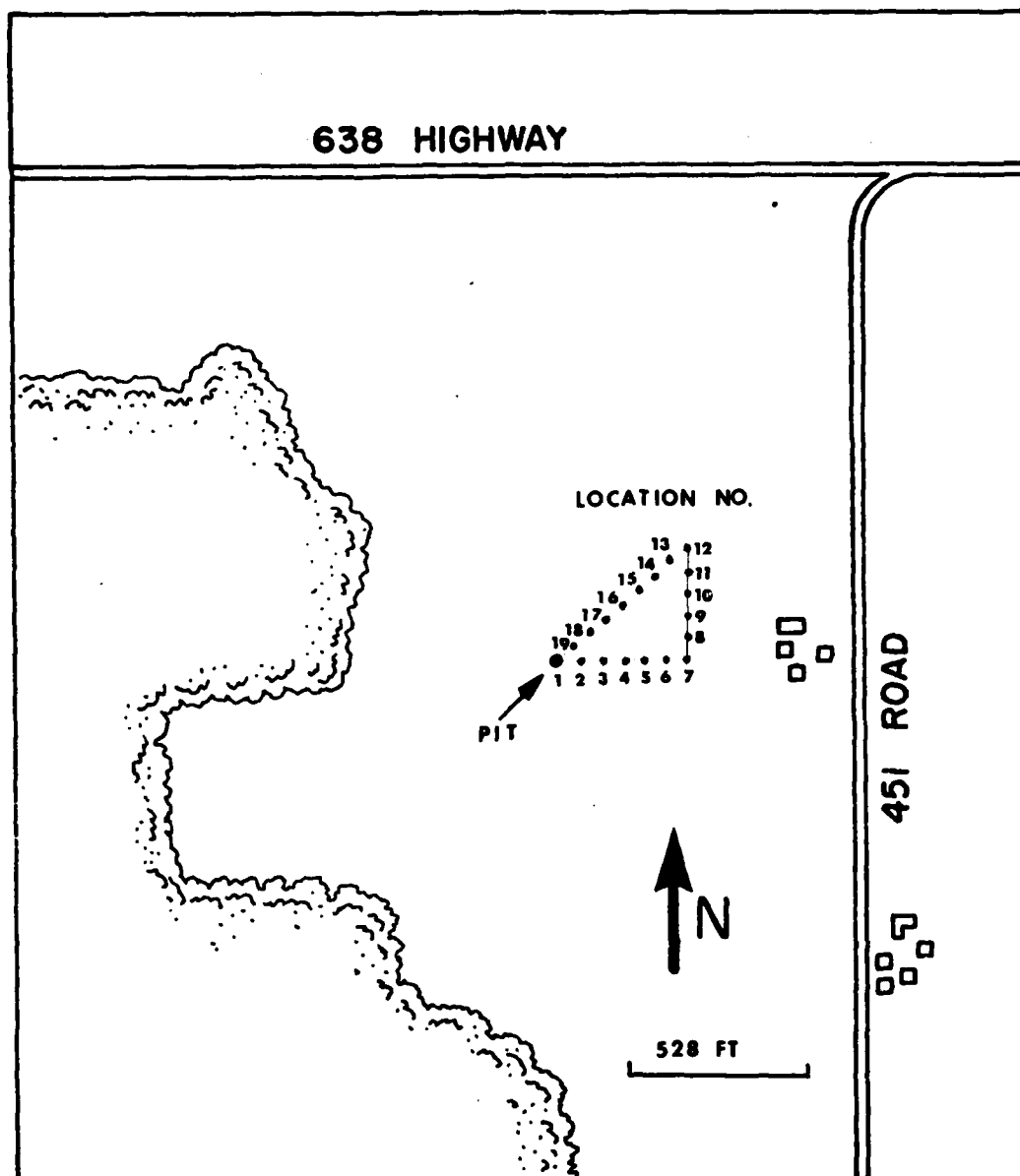


Figure C-9. Map of Site E

Site F (1617 ~ 1715)

TABLE C-7. SNOW PROFILE CHARACTERISTICS OF SITE F

Layer No.	Thickness (cm)	Density (g/100 cc)	Average Grain Size (mm)	Temperature (°C)	Remarks
1	0.5		0.3		tightly wind packed layer
2	6.5	6.5	2.0 ~ 4.0 ^a	-4.0	very light, like fresh fallen snow consists of broken snow flakes
3	0.5		0.5		crusty, granular (grains frozen together)
4	9.5	21	1.0	-1.9	granular, packed together
5	20		2.0	+0.8	granular, loosely packed together
	ice				
<u>Total Depth:</u> 19 cm <u>Air Temperature:</u> -14.5°C <u>Weather:</u> clear, sunny a Size of broken snow flakes See Figure C-10 for the location of the pit.					

TABLE C-8. DEPTH MEASUREMENTS OF SITE F

Location No.	Depth Measurements (cm)	Location No.	Depth Measurements (cm)
1	18; 19	5	19.5; 19.5
2	19; 19.5	6	21; 21.5
3	21; 21.5	7	18.5; 18.5
4	20; 21	8	18; 18.5
<u>Average Depth:</u> 19.6 cm See Figure C-10 for the location of measurements.			

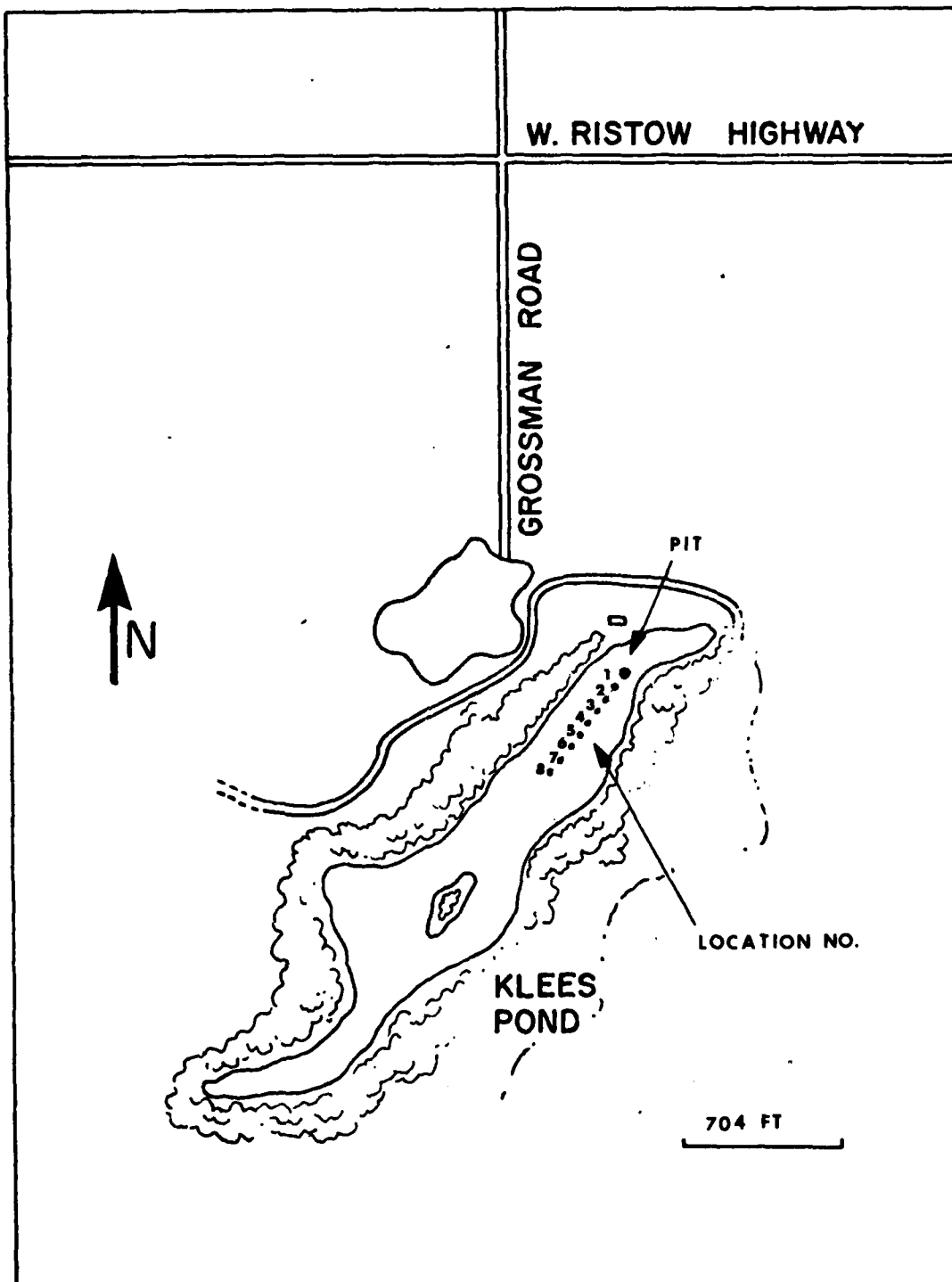


Figure C-10. Map of Site F

TABLE C-9. AIR TEMPERATURE MEASUREMENTS ON FEBRUARY 5, 1979

Time	Temperature (°F)	Time	Temperature (°F)	Time	Temperature (°F)
0057	4	0856	1	1658	9
0158	4	0955	3	1756	8
0255	4	1055	5	1857	6
0357	3	1154	6	1955	5
0458	2	1256	8	2058	2
0558	2	1354	9	2155	-1
0654	1	1455	9	2256	-1
0755	0	1555	10	2350	-1

TABLE C-10. AIR TEMPERATURE MEASUREMENTS ON FEBRUARY 6, 1979

Time	Temperature (°F)	Time	Temperature (°F)	Time	Temperature (°F)
0058	-3	0856	6	1655	14
0153	-7	0958	9	1755	14
0258	-5	1056	10	1857	14
0356	-4	1153	11	1955	15
0453	-1	1257	12	2055	16
0558	3	1353	14	2156	16
0655	5	1453	14	2255	17
0752	5	1554	14	2355	17

TABLE C-11. AIR TEMPERATURE MEASUREMENTS ON FEBRUARY 7, 1979

Time	Temperature (°F)	Time	Temperature (°F)	Time	Temperature (°F)
0058	17	0858	18	1655	17
0157	18	0957	18	1755	17
0259	18	1058	20	1857	15
0357	19	1157	22	1955	15
0457	19	1258	22	2055	14
0557	18	1358	22	2156	12
0654	18	1457	21	2255	10
0752	18	1556	20	2355	8

TABLE C-12. SNOWFALL MEASUREMENTS ON FEBRUARY 5, 6, 7, 1979

February 5, 1979		February 6, 1979		February 7, 1979	
time interval	Snow Fall (cm)	time interval	Snow Fall (cm)	time interval	Snow Fall (cm)
0000 ~ 0300	0	0000 ~ 0300	0	0000 ~ 0300	0.3
0300 ~ 0600	0	0300 ~ 0600	0.25	0300 ~ 0600	0
0600 ~ 0900	0	0600 ~ 0900	0.5	0600 ~ 0900	0
0900 ~ 1200	0	0900 ~ 1200	1.0	0900 ~ 1200	1.4
1200 ~ 1500	0	1200 ~ 1500	0.25	1200 ~ 1500	0.7
1500 ~ 1800	0	1500 ~ 1800	0.5	1500 ~ 1800	0.5
1800 ~ 2100	0	1800 ~ 2100	0	1800 ~ 2100	0
2100 ~ 2400	0	2100 ~ 2400	0.25	2100 ~ 2400	0
Total	0	Total	2.8 cm	Total	2.9 cm

