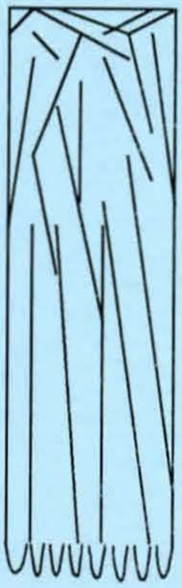
Laboratory Studies of the Electromagnetic Properties of Saline Ice

A Multi-Disciplinary Research Plan Submitted to

The Office of Naval Research



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EXECUTIVE SUMMARY

This plan describes laboratory and theoretical research to be carried out under the Sea Ice Electromagnetics Accelerated Research Initiative of the Office of Naval Research. The plan is built around three broad objectives: 1) to understand the mechanisms and processes that link the morphological/physical and the electromagnetic properties of sea ice; 2) to further develop and verify predictive models for the interaction of visible, infrared and microwave radiation with sea ice; 3) to develop and verify selected techniques in the mathematical theory of inverse scattering that are applicable to problems arising in the interaction of EM radiation with sea ice. The plan will be executed by over 30 investigators from 15 institutions. Research includes measuring and quantifying the physical properties of sea ice, collecting radiometric signatures of different ice types and morphologies, developing and testing forward models of scattering and emission from sea ice, and developing and testing inverse models to extract geophysical data about sea ice from remotely sensed data.

Experiments will begin in January of 1993 at the Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire. Work will focus around studies on the Geophysical Research Facility which is a new, concrete lined pool filled with saline water. The facility can be shielded from local fluctuations in weather by using a movable roof and refrigerated blanket.

Three measurement series are planned for the winter of 1993. These will focus on collecting data on the microwave and optical properties of an undeformed ice sheet grown from the melt. Measurements to resolve the contributions of volume and surface scattering to sea ice signatures will be performed on an artificially roughened ice sheet. A snow covered ice sheet will be created to study the effects of brine wicking and scattering from snow grains on electromagnetic signatures. Data from these measurements will be used to evaluate the performance of existing forward models. The data will also be used to begin the development of inverse models.

1. Introduction

The electrical properties of sea ice growing on the open ocean are determined by the mechanical and thermodynamical influences of the ocean and atmosphere. Winds, currents, air and water temperatures among other variables contribute to the eventual roughness, texture, chemical composition and temperature gradient through the sea ice. These latter properties tend to be inhomogeneous over relatively short length scales (10's of meters horizontally and 10s of cm vertically at best) and they tend to evolve with time as the boundary conditions and the internal composition of the ice pack changes. For these reasons, the analyses of electromagnetic data collected by spaceborne instruments over sea ice have tended to rely on empirical relationships between limited ranges of an electromagnetic variable (eg brightness temperature) and a geophysical property of the ice. Numerous papers in the literature document the success of this analysis approach for estimating sea ice concentration and sea ice motion. Yet for these same reasons, attempts to obtain a deeper understanding of the electromagnetic properties of naturally growing sea ice can be complicated. For example, it is logistically difficult to measure and sample young sea ice, some features such as the onset of flooding are transient phenomena, lateral inhomogeneity makes sampling difficult and the opportunities to view a particular type of ice or even the same piece of ice throughout the seasonal cycle have been rare. Individually, almost all of these problems can and have been overcome by field investigators. But taken together, there seemed to be a strong argument for designing a new approach to answering fundamental questions about sea ice electromagnetic properties, namely what are the important scattering and absorption mechanisms in sea ice and how are these mechanisms related to ice properties. It was felt that an approach could be found in the laboratory.

The first series of USA Cold Regions Research and Engineering Laboratory Experiments (CRRELEX), begun in 1984, were designed to confront some of the difficulties encountered in field work by growing sea ice in a carefully constrained, laboratory environment. Microwave experiments were conducted under an overarching set of principals that included: 1) a uniform ice sheet of limited and well documented physical properties could be grown and maintained; 2) multiple sensors could collect data simultaneously from the same ice; 3) there must be coordinated interpretation of the all electromagnetic observations of the ice with the measured ice physical properties. As the experiments progressed it also became apparent that two more facets needed to be added to CRRELEX. First, data must be collected that would be relevant to a range of electromagnetic models. In other words, the almost exploratory nature of the early CRRELEX experiments needed to evolve to a more rigorous cycle of hypothesis generation and evaluation. Second, time series data must be collected. This last point arose partly because of initial observations which showed that measurable changes in electrical properties occur at every stage of ice development.

Experiments completed during the first CRRELEX program demonstrated that saline ice with a predefined range of physical properties can be grown. These include thin ice with varying crystalline textures and salinity gradients, roughened ice that includes a range of roughness elements, desalinated ice and snow-covered ice. That selected ice properties can be isolated, duplicated and studied in the laboratory is an important achievement. This achievement has been exploited to better understand the relationship between particular saline-ice properties and microwave propagation phenomena. For example, there is excellent agreement between the dielectric constant of thin ice as determined from radar backscatter, radar transmission and microwave emission observations. Moreover, changes in the dielectric constant are clearly seen to be related to the complex distribution of brine and the migration of brine through the ice sheet as the ice ages. Similarly, snow cover was found to have a profound effect on both active and passive microwave observations. Again, multi-sensor data could be interpreted consistently in terms of the dielectrically rough, slushy layer that develops at the snow-ice interface.

Theoretical analysis of the CRRELEX data also revealed several factors that influence future studies. Of these, the collection of simultaneous, multi-frequency data seems to be an essential element of any measurement campaign. Obviously, multi-frequency data are critical in assessing the regimes in which either volume scatter (probably below 5 GHz) or surface scatter dominate (probably above 10 GHz). But unexpected results associated with coherent emission and scattering processes were also observed as a consequence of observations in the 6 to 10 GHz range. This frequency-dependent emissivity feature may prove valuable in sensing grey ice thickness from aircraft.

In 1991, the Office of Naval Research announced a new Accelerated Research Initiative titled "Electromagnetic properties of Sea Ice". The conceptual goal of the initiative is shown schematically in figure 1. Essentially, the program seeks to relate the electromagnetic signature of sea ice to the physical properties of the ice through forward models. In turn, the forward models will be used to define inverse models through which ice physical properties can be determined from remotely sensed electromagnetic signatures. For the reasons identified above and because of the success of the early series of CRREL experiments, it was determined that a second series of laboratory experiments would be a component of the overall ARI activity.

The ARI increases the scope of previous CRRELEX experiments in two important directions. First, the spectral range of measurements spans from UHF to visible frequencies. Consequently, a greater number and more diverse suite of instruments will be used to view the ice from above and below. Second, modeling work has assumed a significantly greater emphasis through the inclusion of additional forward modelers and the new addition of members of the inverse modelling community. Already it is clear that a successful modelling activity will require radiometric and physical property data with more stringent error bounds than were acceptable in the earlier CRRELEX experiments. This latter implication will pose a major challenge to the experimental part of the program (eg. see contribution by Ngheim and others in appendix 1).

Organization

Dr. Kenneth Jezek is responsible for overall coordination of the activity. Dr. Kenneth Golden is responsible for coordinating the theoretical component of the activity (see section entitled "Theoretical Development). Dr. Dale Winebrenner will serve as chief scientist for the thin ice growth experiment. Dr. Robert Onstott will serve as chief scientist for the ice roughening experiment and Dr. Donald Perovich will serve as chief scientist for the snow covered ice sheet experiment (see section entitled "Experimental Plan").

Science Objectives

The scientific objectives that define the experiments to be carried out at CRREL were specified as part of the development of the Accelerated Research Initiative. These

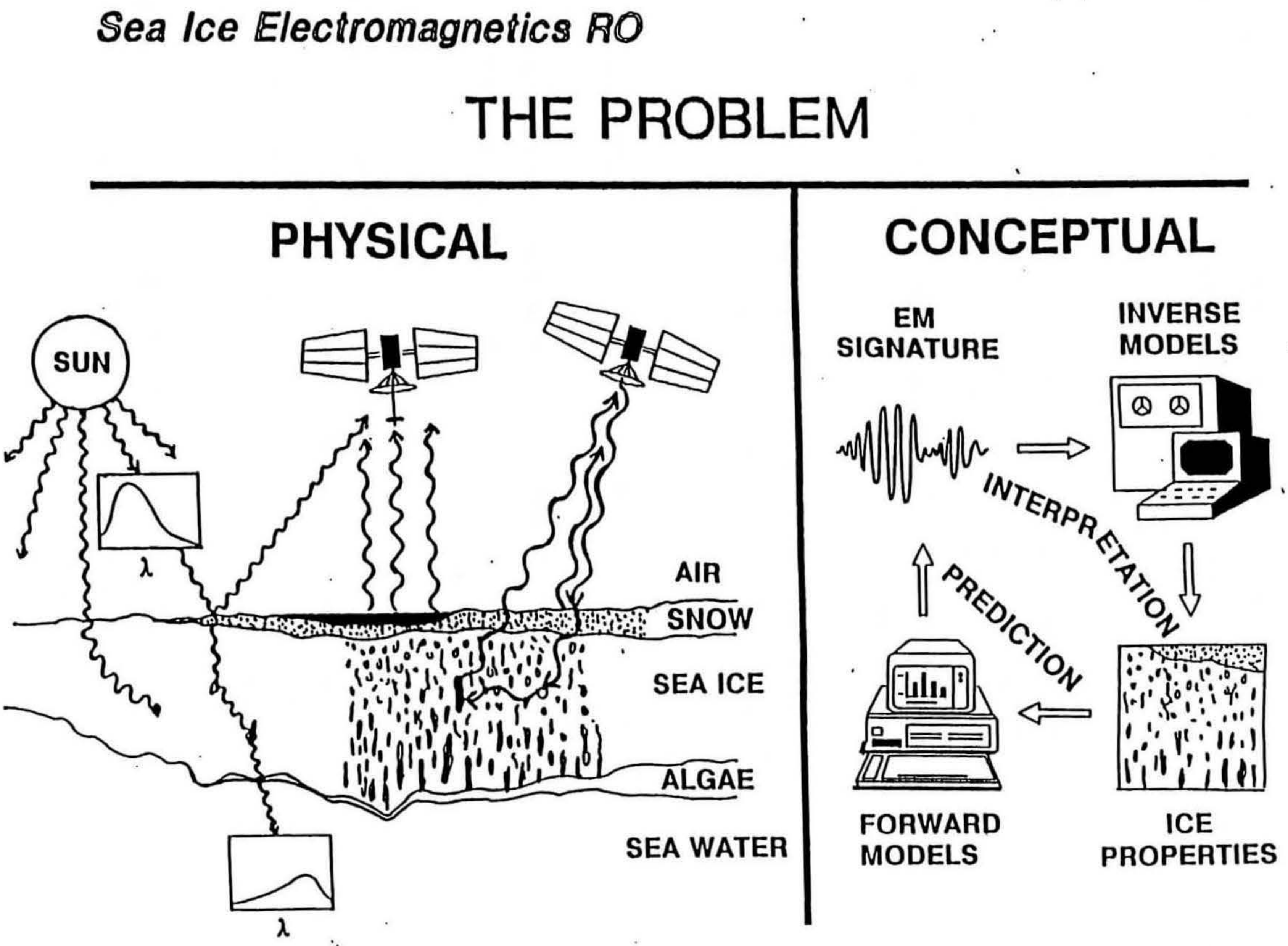
Sea Ice Electromagnetics RO
THE PROBLEM
PHYSICAL
CONCEPTUAL
SUN
λ
λ
AIR
SNOW
SEA ICE
ALGAE
SEA WATER
EM
SIGNATURE
INVERSE
MODELS
INTERPRETATION
PREDICTION
FORWARD
MODELS
ICE
PROPERTIES

Figure 1.

objectives were articulated in the white paper entitled "Electromagnetic Properties of Sea Ice" which was prepared subsequent to a workshop held at the University of Washington Pack Forest Lodge in December of 1991.

The broad objectives of the ARI are:

- to understand the mechanisms and processes that link the morphological/physical and the electromagnetic properties of sea ice,

- to further develop and verify predictive models for the interaction of visible, infrared and microwave radiation with sea ice,

- to develop and verify selected techniques in the mathematical theory of inverse scattering that are applicable to problems arising in the interaction of EM radiation with sea ice.

Specific science issues that are guiding the laboratory research program are:

- Can basic scattering mechanisms (surface, volume, types of scatterers) be identified and isolated, and can their individual effects on reflection and transmission be determined?

- Can physical models of EM scattering from sea ice be developed that are both physically realistic and mathematically tractable? To what extent can anisotropy, inclusions, discontinuities and phase changes (melting and freezing) be modeled in the equations?

- Can mathematical techniques for inverse scattering be developed so as to yield solutions for the sea ice model equations that are physically correct and computationally practicable?

- Is the variability in sea ice EM properties sufficiently quantifiable to unambiguously identify ice types and to determine deformation (ice strength) characteristics?

- To what extent is energy reflection, transmission and absorption by sea ice influenced by snow cover?

- Can correlation functions for various ice-type structures be successfully computed for modeling purposed, and can they be confirmed experimentally?
- What spectral transformations of natural light occur in sea ice, owing to the effects of Raman scattering, bottom ice algae, and snow cover?

As part of a workshop held at CRREL in October, 1992, three primary objectives were identified for measurements to be completed during 1993. These include:

- measure the microwave, optical and physical properties of an undeformed, saline ice sheet grown from the melt for subsequent use by the forward and inverse modellers;

- determine the conditions under which volume scatter or surface scatter dominates the electromagnetic signature;

- determine the role of snow cover on electromagnetic signatures.

Experiment Strategy

The experiment strategy is derived from the individual plans submitted by each principal investigator. The individual plans are included in Appendix 1.

Experiments requiring the outdoor ponds will begin on January 6 and end in mid-March. Additional experiments will continue in the indoor facilities but the nature of those experiments will largely be determined by the results of this winter's activity.

Two saline ice sheets will be grown on the outdoor pool. The first ice sheet will consist of congelation ice grown from the melt. The primary purposes of this ice sheet will be to provide the optical team an opportunity to study undeformed congelation ice and to provide broad-band microwave data to the inverse modelling team. Dr. Dale Winebrenner will serve as chief scientist for this experiment. Microwave and optical data will be acquired along with detailed physical properties as shown in Table 1. Detailed requirements include allocating a 2x2 m area near the side of the pond for optical beam spreading measurements. Ice cores retrieved at 3 cm growth intervals will be required for light scattering measurements, ice tomography experiments and dielectric constant measurements.

After the first ice sheet has reached a thickness of about 25 cm (approximately 10 days), the emphasis of research will shift to assessing the role of volume and surface scatter. Dr. Robert Onstott will serve as chief scientist for this phase. The ice thickness requirement is based on two reasons. First, we want to eliminate as nearly as possible the effect of the ice/water transition layer. Second, we want an ice sheet for which the high salinity surface layer and the signatures have stabilized. Half of the original ice sheet will remain undisturbed and serve as a control. The surface of the other half will be modified via a succession of mechanical processes designed to minimize: 1) air voids in the upper layer of the new rough surface; 2) non-Gaussianity of the surface height distribution. First, an attempt will be made to scrape a portion of the ice sheet free of small surface perturbations. If this proves successful, the entire half will be scraped and radiometric data collected. Next, a slurry of ice chips (4mm sized crushed ice) and water will be applied to the ice sheet. The objective will be to attempt and create a rough surface with a Gaussian roughness distribution and with correlation lengths on the order of several centimeters. It will be important at this stage that the lowest points of the new, rough surface lie slightly above the original congelation ice sheet. Surface roughness statistics will be characterized using several techniques including a mechanical comb gauge, photographic techniques and extraction of thick sections. At least 10 correlation lengths must be measured per azimuth angle and at least 10 azimuth angles should be measured. One or two additional slurries up to 2.5-cm thick with ice chips about 1 cm in size will be applied to increase the roughness scale and to decrease the correlation length. Data collection responsibilities are tabulated in Table 2.

TABLE 1

Experiment 1: Ice sheet 1
Objective: Investigate growth phase of a columnar ice sheet (to 25-30 cm)
Procedure: Grow a congelation ice sheet to a thickness of 25-30 cm

Measurement	Instrument	Sampling frequency	Investigator
Ice characterization			
Temperature	Thermistor Array	Every cm, every 15 min.	CRREL
Thickness	Hot wire	1/cm	Gow/Perovich
	Acoustic Pinger		Gow/Perovich
Surface Roughness	Photo	Every hour	Winebrenner
	Sample Retrieval		Onstott
Ice Samples	Corer	Every few cm of growth	Gow, Itariaga, Hunt, Onstott
Salinity	Conductivity Bridge	Every cm	Gow
		Surface layer	Grenfell
Density	Weigh Volume		Gow
Inclusion size distribution, correlation functions	Thin Sections		Perovich/Gow
Complete Met. Data	Radiometers/anemometers	Every 10 minutes	CRREL
Optical			
Albedo/reflectance	Spectroradiometer,Kipps		Perovich
Transmittance	Spectroradiometer		Perovich
Beam spread	Pulsed laser		Maffione, Tanis
Microwave			
Bulk dielectric properties	Waveguide 2-10 MHz		Onstott/Gogenini
Backscatter, polarization	35 Ghz 8510 Band Polar		UMASS
	5.3 - 13.5 1.5 Ghz		Jezek
	1-100 Ghz		Onstott
	400 Mhz		Onstott
Emissivity	6.7,10,18,37,90 IR		Grenfell
	Low freq. radiometer 1.4 Ghz		Swift
	C Band		S.N.

TABLE 2

Experiment 2: Ice sheet 1a
Objective: Investigate relative importance of surface to volume scattering
Procedure: Systematically add roughness elements to surface of ice sheet 1

Measurement	Instrument	Sampling frequency	Investigator
Ice characterization			
Temperature	Thermistor Array	Every cm, every 15 min.	CRREL
Thickness	Hot wire	1/cm	Gow/Perovich
	Acoustic Pinger		Gow/Perovich
Surface Roughness	Photo	Every hour	Winebrenner
	Sample Retrieval		Onstott
Ice Samples	Corer	Every few cm of growth	Gow, Itariaga, Hunt, Onstott
Salinity	Conductivity Bridge	Every cm	Gow
		Surface layer	Grenfell
Density	Weigh/immersion		Gow/Perovich
	Weigh/machine samples		Gow/Perovich
	Image processing		Perovich
Inclusion size distribution, correlation functions	Thin Sections		Perovich/Gow
Complete Met. Data	Radiometers/anemometers	Every 10 minutes	CRREL
Optical			
Albedo/reflectance	Spectroradiometer, Kipps		Perovich
Transmittance	Spectroradiometer		Perovich
Beam spread	Pulsed laser		Maffione, Tanis
Microwave			
Bulk dielectric properties	Waveguide 2-10 MHz		Onstott/Gogenini
Backscatter, polarization	35 Ghz 8510 Band Polar		UMASS
	5.3 - 13.5 1.5 Ghz		Jezek
	1-100 Ghz		Onstott
	400 Mhz		Onstott
Emissivity	6.7,10,18,37,90 IR		Grenfell
	Low freq. radiometer 1.4 Ghz		Swift
	C Band		S.N.

At the conclusion of the surface roughening experiments, the ice sheet will be removed and a new congelation ice sheet will be grown. Dr. Don Perovich will serve as chief scientist for this phase of the project. After about 25 cm of growth, a 1 cm thick snow layer will be applied to half of the ice sheet and radiometric data collected. Three, 5 cm thick snow layers will be successively applied and studied. It will be critical to monitor the characteristics of the snow ice interface throughout this experiment. One approach will be to carefully extract slabs of snow covered ice and move them to a -30 °C cold room. The idea will be to freeze the wicked layer expected to form in the lower portion of the snow. Once frozen, the overlying dry snow will be brushed free and the surface roughness of the wicked layer will be determined. Measurement responsibilities are listed in Table 3.

The second ice sheet will remain undisturbed and in place throughout the rest of the winter. Through natural processes of gravity drainage and melting, the sheet will desalinate. A brief period of radiometric measurements is planned for mid-March on this desalinated sheet.

Measurements on a single ice sheet grown in the lower pond will be conducted throughout the winter. The main focus of that research is to observe changes in the microwave signature of a snow-covered ice sheet. (See contribution by Lohanick, Appendix 1).

Experiments on saline ice grown in the indoor pit are planned for the summer of 1993. These will include 13.5 and 35 GHz active radar measurements. The objective of this work is similar to that proposed for the outdoor ponds but includes the added objective of studying the effects of controlled temperature cycling. (See contribution by Swift, Appendix 1).

A schedule for the principal activities is shown in Table 4 (a-d). A key element of the schedule is delivery of data to the modelling team. Data will be provided in two phases. Near real-time data will be collected during each experiment. These data will be assimilated by each chief scientist for use in assessing experiment progress. At the conclusion of the experiment, those real-time data will be forwarded into the modelling team for inspection. A refined, calibrated data set will be prepared by each team and submitted to a data base by June. (See contribution by Tanis, Appendix 1).

TABLE 3

Experiment 3: Ice sheet 2
Objective: Investigate effects of snow cover on electromagnetic signatures
Procedure: Grow 10 cm thick congelation ice, then progressively add snow to 1/2 of ice sheet

Measurement	Instrument	Sampling frequency	Investigator
Ice characterization			
Temperature	Thermistor Array	Every cm, every 15 min.	CRREL
Thickness	Hot wire	1/cm	Gow/Perovich
	Acoustic Pinger		Gow/Perovich
Ice Samples	Corer	Every few cm of growth	Gow, Itariaga, Hunt, Onstott
Salinity	Conductivity Bridge	Every cm	Gow
		Surface layer	Grenfell
Density	Weigh/immersion		Gow/Perovich
	Weigh/machine samples		Gow/Perovich
	Image processing		Perovich
Inclusion size distribution, correlation functions	Thin Sections		Perovich/Gow
Complete Met. Data	Radiometers/anemometers	Every 10 minutes	CRREL
Snow characterization			
Surface Roughness	Photo	Every hour	Winebrenner
	Sample Retrieval		Onstott
Grain size/stratigraphy	Eyepiece		Lohanick
Water content			Lohanick
Salinity	Conductivity bridge		Grenfell/Lohanick
Optical			
Albedo/reflectance	Spectroradiometer,Kipps		Perovich
Transmittance	Spectroradiometer		Perovich
Beam spread	Pulsed laser		Maffione, Tanis
Microwave			
Bulk dielectric properties	Waveguide 2-10 MHz		Onstott/Gogenini
Backscatter, polarization	35 Ghz 8510 Band Polar		UMASS
	5.3 - 13.5 1.5 Ghz		Jezek
	1-100 Ghz		Onstott
	400 Mhz		Onstott
Emissivity	6.7,10,18,37,90 IR		Grenfell
	Low freq. radiometer 1.4 Ghz		Swift
	C Band		S.N.

TABLE 4 (a)

	CRRELX 93 Winter Measurement Schedule														
	January														
	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
Investigators Arrive - Hanover		▼													
Equipment Set Up and Calibration			═												
Ice Sheet 1st Growth				═	═	═	═	═	●						
Ice Roughening									═	═	═	═	═	═	●
Snow Cover Experiment															═
Ice Cores to Optical & Dielectric Constant Invest.															▼
Desalinated Ice Experiment															
(● 'real-time' data to modelers)															

TABLE 4 (b)

	CRRELX 93 Winter Measurement Schedule														
	February														
	2	4	6	8	10	12	14	16	18	20	22	24	26	28	
Investigators Arrive - Hanover															
Equipment Set Up and Calibration															
Ice Sheet 1st Growth															
Ice Roughening															
Snow Cover Experiment	—	—	—	—	—	—	—	●							
Ice Cores to Optical & Dielectric Constant Invest.								▼							
Desalinated Ice Experiment								—	—	—	—	—	—	—	
('real-time' data to modelers)															

TABLE 4(c)

	CRRELX 93 Winter Measurement Schedule														
	March														
	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
Investigators Arrive - Hanover															
Equipment Set Up and Calibration															
Ice Sheet 1st Growth															
Ice Roughening															
Snow Cover Experiment															
Ice Cores to Optical & Dielectric Constant Invest.								▼							
Desalinated Ice Experiment							●								
('real-time' data to modelers)															

TABLE 4 (d)

	CRRELX 1993 SCHEDULE											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CRRELX 93	▭	▭	▭									
Pit Studies						▭	▭	▭				
Calibrated Data to Data Base						▼						
Summary Report to Coordinator									▼			
Investigator Meeting										▼		

As mentioned, work will begin on January 6. Starting at 0800 that morning, there will be a two-hour meeting to resolve outstanding issues concerning where instruments will be set-up and operated. Also, there will be a short group meeting on each day of the experiment. The purpose of the meeting will be data comparison.

Theoretical Development

This section summarizes the research plans of those investigators participating in the sea ice ARI whose research employs a strong theoretical or mathematical component. These plans are focused primarily on the first year of the project, yet address long range goals as well. Dr. Kenneth Golden serves as coordinator for the theoretical component of the activity.

In the plans, and at the CRREL workshop, the following issues have surfaced as primary questions which must be addressed during the first year:

1. Assessment of the relative importance of volume versus surface scattering at microwave frequencies.

2. Development of simple forward models for scattering and dielectric behavior, and a clear determination of which sea ice parameters should be used to characterize the models.

3. Analysis of what types of measurements should be made in order to recover electromagnetic parameters through inverse models, and what can, in principle, be recovered.

The above issues will be looked at individually by investigators, as well as collectively during January when many of the investigators will be at CRREL for the first series of experiments.

Below is an outline of how each research plan fits into the overall goal of the ARI, namely electromagnetic inversion of sea ice properties. For simplicity, the plans have been divided into two general categories, those which approach inversion through forward models, and those which approach the inversion directly. The plans in the first category have been further divided into those which are most concerned (at least in the first year) with volume scattering, and those concerned with surface scattering. It should be made clear that this outline is only a device used to give some overview to the broad range of theoretical work that is being undertaken, and that most investigators are engaged in work that crosses categories outlined below.

Electromagnetic Inversion for Sea Ice

I. Inversions through forward models

A. Volume Scattering

Kong	Inversion via parameter estimation in forward random medium model.
Winebrenner/Grenfell	Comparison of strong fluctuation vs. dense medium radiative transfer theory.
Golden	Analysis of how microstructure determines E-M properties, focusing on bounds for effective properties.

B. Surface Scattering

Fung	Inversion via parameter estimation in forward random surface model
Brown	Development of surface scattering models

II. Direct inverse models

Cheney/Isaacson	Analysis of recovering E-M parameters from field measurements, development of reconstruction algorithms
Sylvester/Uhlmann	Extension of isotropic impedance tomography methods to anisotropic Maxwell equations
Johnson	Development of tomographic methods for analyzing sea ice microstructure

Facilities

The expanded scope of the ARI and the more stringent data requirements demand an enhanced laboratory facility. Discussions to design and build such a facility were begun in 1989 and have led to the construction at CRREL of the geophysical research facility shown in figure 2. Essentially, a 7 foot deep, concrete lined pool filled will saline water will be the primary site of CRRELEX measurements. The pool is 25 feet wide and 60 feet long and will easily accommodate the widest imaging footprints planned for this work. A trolley with instrument gantry spans the pool and can be rolled back and forth on rails. A roof and refrigerated blanket can cover the pool to offset the effects of weather.

In addition to the primary outdoor pool, experiments can be carried out at a second outdoor concrete lined pond which is 10 m long, 10 m wide and 1 m deep. A refrigerated indoor pit (8x5x1 m) will be used for specialized active radar measurements. Finally, the CRREL test basin may be used for work on other ice types including fresh water and urea ice.

Measurements which require specialized samples or handling procedures will be carried out in one of the cold rooms at CRREL.

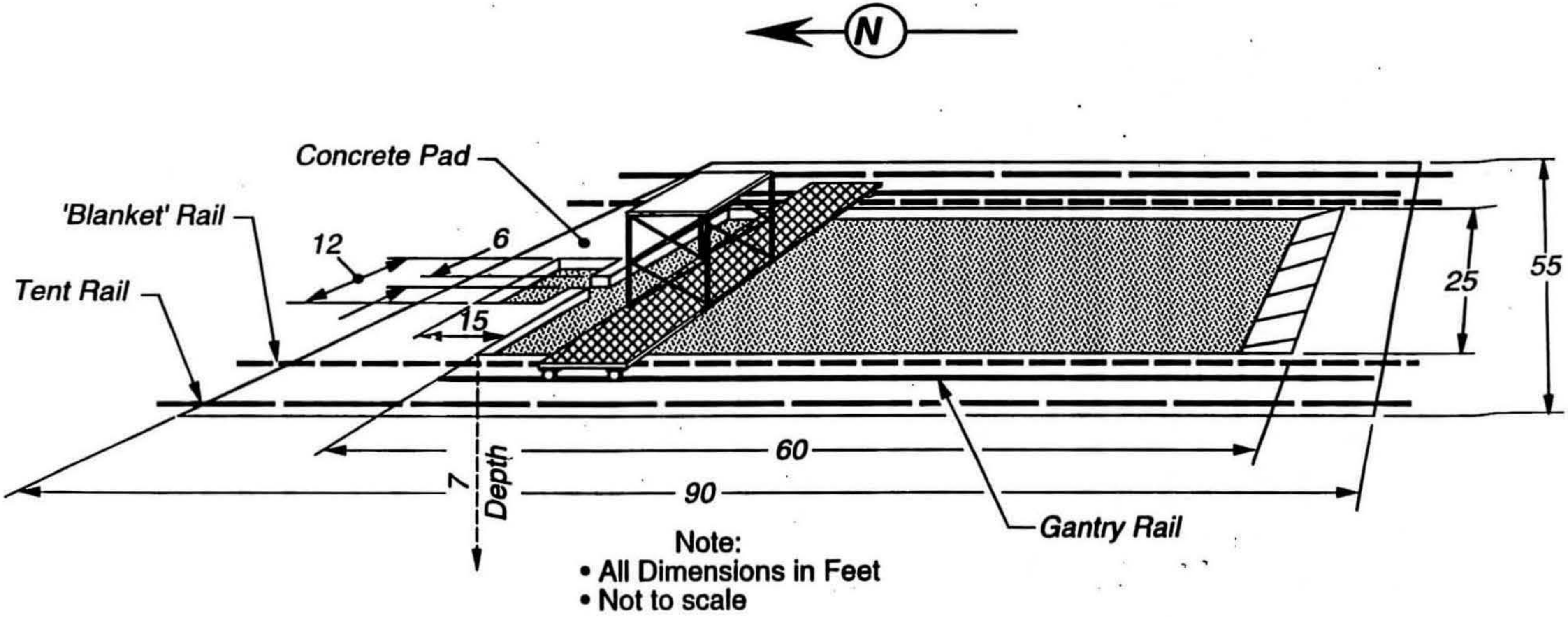
N
Concrete Pad
'Blanket' Rail
Tent Rail
12
6
15
25
55
60
90
7
Depth
Gantry Rail
Note:
• All Dimensions in Feet
• Not to scale

Figure 2.

APPENDIX 1

FUNDAMENTAL SCATTERING STUDIES APPLIED TO SEA ICE

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INTRODUCTION

The research proposed under this investigation has the goals of obtaining a more thorough understanding of the scattering of electromagnetic energy from sea ice and developing scattering models which can be used for the prediction of such scattering. To accomplish these goals, a multi-facted investigation has been proposed which includes 1) the development of an improved surface scattering model applicable to sea ice, 2) a reexamination of volumetric scattering from sea ice, 3) the incorporation of both these results into a comprehensive sea ice scattering model, and 4) the design of experiments which will permit and lead to the identification of the dominant scattering phenomenon be it volume or surface effects. In addition, this research will take advantage of the Sea Ice Electromagnetics ARI by tailoring the experimental aspects to tank and field campaigns which are planned during various phases of the ARI.

For the first year's effort, we will concentrate on the surface scattering problem and the initial design of some experiments for isolating and/or separating surface and volume scattering phenomena at microwave or millimeter wavelengths. It is not obvious that special experiments can be thought through and designed in time for the CY-93 experiments. Furthermore, the kinds of experiments which are being considered for the surface/volume problem are not easily implemented in the ice tank at CRREL which is the campaign planned for CY-93.

Our intention for the surface scattering problem is to adapt some of the ideas using the method of smoothing to penetrable surfaces which ice represents. The method of smoothing, even in its first order approximation, represents a considerable improvement over standard perturbation theory. The reason for this is its (first order smoothing's) ability to deal with surfaces having very large slopes. The price that one pays for this capability is that the height of the surface roughness must be very small. Recently, we have overcome this limitation to an extent by applying the method of smoothing to a composite surface having both large and small scales of roughness relative to a wavelength. In the lowest order of approximation, this combination of a composite surface and smoothing approxmative provides an improvement to the conventional composite scattering model because the small scale surface is not required to have small slopes. This is particularly important in the case of sea ice where slopes may indeed be large due to ice rafting and breakup. Even more important is the fact that the combination of the composite surface with smoothing leads to an integral equation which clearly shows how to improve on the basic first order scattering approximations. Classical effects such as shadowing, multiple scattering, and shadow boundary diffraction comprise the kinds of improvements that one can expect from the full integral equation.

The results summarized above were obtained for scattering from a perfectly conducting rough surface in which case it is only necessary to deal with an electric current. When the surface becomes penetrable, such as sea ice, one must deal with both electric currents and magnetic currents in order to represent the equivalent effects of the rough interface. There are a number of ways of developing the basic equations that these currents must satisfy, but perhaps the most well known is the Maue approach because he developed the equations for the perfect electric and magnetic scattering surfaces also. These equations assume the following form:

$$J = Jo + LG_{11}J + LG_{12}K \quad (1)$$

$$K + Ko + LG_{21}J + LG_{22}K \quad (2)$$

Where Jo and Ko are known functions involving the incident fields and the discontinuity in the dielectric constant and/or the magnetic permeability, L is an integral over the rough surface, the Gij are appropriate propagators for the electric current J and the magnetic current K. It is clear from (1) and (2) that the penetrable surface leads to coupled integral equations rather than single integral equations. An added complexity which is not obvious is that the Jo and Ko currents are not what one would expect them to be. That is, based on the equations for the perfectly conducting case, one would expect that the Born terms in (1) and (2) to be equal to the Kirchhoff values multiplied by an appropriate factor to represent the fraction of the energy that is reflected upwards by the penetrable surface. Unfortunately, this is not the case and it is necessary to get such behavior from the integral terms. Thus, in order to obtain the kinds of Born terms that one would expect for a penetrable surface, it will be necessary to extract this term from the integrable contributions in (1) and (2). However, before this is done, we should investigate why the Born terms in (1) and (2) are different from what we expect and is it possible that these terms actually lead to a simplified result when used in a smoothing formalism. That is, before we go trying to force the equations into a form we think that we understand, we should first seek to understand why the Born terms come out as they do. Hence, the first goal of this year's effort is to understand why these equations come out as they do and to get them into a form that is suitable for applying the techniques that we have previously used in the perfectly conducting (single equation) cases.

The second goal of this year's effort is to develop a normalized composite surface (NCS) decomposition of the coupled integral equations represented by either (1) and (2) or modified form of them. Such a decomposition will set-up the equations in a form that is appropriate for applying smoothing. However, it is very important to investigate very thoroughly the roles of both smoothing and decoupling. That is, in order to get the resulting equations into a form that is tractable, it will be necessary to apply both smoothing and to decouple the equations at some level of approximation. One of the things that is not immediately obvious is whether or not the operations of smoothing and decoupling can be interchanged with no important effects. While it may be true that in the lowest order approximation one sees no real sensitivity to the order in which these approximations are applied, this may not carry over in higher order approximations. One should expect that as long as the surface is highly lossy and the radius of curvature is not too large, there will be no great sensitivity to the order in which smoothing and decoupling are applied. The reason for this is that the surface current will be predominantly electric rather than magnetic current to play a more important role and the coupling to increase. Unfortunately, the solution cannot be based entirely on the loss properties of the subsurface material because the surface roughness also plays a critical role. For example, the loss may decrease to the point where energy enters the surface at a bulge, passes through the bulge, and reenters free space. This is an extremely complicated situation and one which we need only consider down near grazing incidence. In summary, the primary goal of the first year's research is to develop a tractable composite surface - smoothing approach to the penetrable surface scattering problem.

A secondary goal of the first year's activity is to investigate experimental methods for identifying the type of scattering mechanism, i.e., surface or volume, responsible for redirection of incident energy. We have a number of ideas for accomplishing this, but we have not done a parameter or feasibility study to determine if they are practical. This we hope to carry out with the end goal being a definitive statement of the type of experiment to be performed along with expected outcome(s). These experiments will require aircraft as they will require changes in beam footprint and variation in radar altitude.

ELECTROMAGNETIC INVERSE PROBLEMS

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OBJECTIVES

The objective of the proposed work is to develop techniques for recovering the electromagnetic parameters (permeability, conductivity, and permittivity) of a medium from measurements made outside the medium.

In the deterministic framework, the relevant parameters are the effective medium parameters, because sea ice contains inhomogeneities on the scale of millimeters, whereas the wavelength of the probing microwaves is on the order of centimeters. The reconstruction algorithms we propose to develop would provide an image of the effective medium parameters. These could then be used in conjunction with the methods to be developed by Golden and Johnson that will use such parameters to distinguish ice types.

In the stochastic framework, the relevant parameters are not the electromagnetic parameters of the medium themselves, but rather their probability distributions. From the statistical characteristics of the measured fields, it may be possible to recover only some of the statistical parameters of the medium, such as means and some of the correlation functions.

GENERAL APPROACH

A single physical model that is accepted for all types of sea ice is not yet available [W, TKS]. However, the interaction between electromagnetic fields and sea ice is governed by Maxwell's equations:

$$\nabla \wedge E = -\partial_t B$$

$$\nabla \wedge H = J + \partial_t D$$

$$\nabla \cdot D = \rho$$

$$\nabla \cdot B = 0,$$

where

$$D = \epsilon E$$

$$J = \sigma E$$

$$B = \mu H.$$

Here E is the electric field and B is the magnetic field. For ice, which is anisotropic, the permittivity ϵ and conductivity σ are real, symmetric matrices, whereas the magnetic permeability μ is nearly equal to the constant μ_0, the permeability of free space.

We plan to consider both the mathematical problems that are related to remote sensing from satellites and also those problems that are relevant to laboratory and field experiments. An example of a problem related to laboratory experiments is to find the electromagnetic parameters of a block of ice in a waveguide. An example of a problem related to field experiments is to find the electromagnetic parameters of a sheet of ice from near-surface measurements.

These laboratory and field experiments, which are done to characterize the electromagnetic parameters of the different ice types, can differ considerably from the remote sensing situation, because in the laboratory and field, we can use a much larger variety of space-time signal patterns to make our measurements. For applications involving remote sensing from satellites, we must consider the problems of measuring on only part of the boundary. In fact, one can use the idea of a boundary in both space and frequency to categorize the inverse problems that have received attention. We have developed layer-stripping algorithms for multidimensional problems in which one makes measurements over the whole spatial boundary at a single frequency. Others [BLK, CDK, CoK, K, KK] have developed layer-stripping algorithms for one-dimensional problems in which one measures for all time (i.e., on the whole frequency boundary). We plan to consider multidimensional inverse problems that are intermediate in the sense that the measured data is band-limited in space and time (or space and frequency), as is the data from frequency-modulated radar [SH, BMW].

We propose first to work out some simple cases to determine what electromagnetic parameters can in principle be found from what kind of measurements. We expect to see trade-offs between temporal and spatial resolution that will be different for different frequency ranges. These calculations may provide information about the optimal space-time patterns to use as probes.

Second, we propose to develop reconstruction algorithms for recovering the electromagnetic parameters. We will devote much of our effort to the development of layer-stripping algorithms.

LAYER-STRIPPING ALGORITHMS

Layer-stripping algorithms reconstruct the medium parameters by first using the measured data to find the parameters on the outermost edge of the medium. These parameters are then used to synthesize the measurements that would have been made if the outermost layer had been absent. Next, the process is repeated, and the medium parameters are found, layer by layer.

Our work on layer-stripping algorithms will build on the knowledge we have gained in developing such algorithms for the case in which we use electromagnetic fields to image objects much smaller than a wavelength [CI, ChK, CISI, SCII]. For example, in the infinite-wavelength case, Maxwell's equations reduce to

$$\nabla \cdot \sigma \nabla u = 0 \qquad \text{in the interior of the body } \Omega,$$

where u is the electric potential, which is related to the electric field E by $E = -\nabla u$. To construct a layer-stripping algorithm, we use the Calderón map R, which, in the case of a half-space geometry, is defined by

$$R(a)(\sigma \partial_z u)\big|_{z=a} = u\big|_{z=a},$$

Then $R(z)$ satisfies [SCII] the Riccati equation

$$\frac{dR}{dz} = \frac{1}{\sigma} + R(\partial_x \sigma \partial_x + \partial_y \sigma \partial_y)R.$$

The layer-stripping algorithm is the following.

a) Use the measured data to construct $R(0)$ and $\sigma(x, y, 0)$ for all x and y.
b) Use a finite difference approximation to the Riccati equation to find $R(\Delta)$.
c) Use $R(\Delta)$ to find $\sigma(x, y, \Delta)$.
d) Replace Δ by 2Δ and repeat, starting with step b.

We have developed codes based on the layer-stripping algorithm [SCII]. At least in our test cases, these codes outperform codes based on linearizing the inverse problem and codes that use iterative reconstruction methods. We expect the layer-stripping algorithms to work even better with shorter wavelength data because it should be easier to image objects that are larger relative to the wavelength.

Layer-stripping reconstruction algorithms may have a number of advantages over iterative reconstruction methods and approximate linearizations. First, they have no difficulty with extraneous local minima as do optimization-type methods. Second, in principle at least, they solve the full nonlinear inverse problem. Third, numerical tests suggest that layer-stripping algorithms will require fewer computations and less storage than iterative optimization-type methods. Finally, such algorithms apply equally well to various geometries and to fully three-dimensional problems. For three-dimensional problems, the computational advantages become especially important.

Much work remains to be done to develop the layer-stripping algorithms. We will first continue developing the algorithms for the model problems in which Maxwell's equations reduce to a single scalar equation. This will involve, first, theoretical work and experimentation to determine the best way to find the medium parameters on the surface where measurements are made. Second, we will investigate the question of the best way to use the measured data to construct R. In some cases, this problem is itself an ill-posed problem, one that must be understood in order to make images with the resolution that the measurement precision should allow. Third, we will investigate the question of the best basis to use in the computation. Fourth, since the inverse problem is ill- posed, we need to find the best regularization method. This is closely related to the basis used. Fifth, we will investigate the algorithm's stability, convergence, and resolution limits. This will involve a detailed analysis of how errors propagate in each step. At each stage, the analytical work will go hand-in-hand with numerical tests.

While we are continuing the development of the algorithms for the model problems, we will also continue our development of layer-stripping algorithms appropriate for the full Maxwell's equations. This work builds on our understanding of the linearized inverse problem for Maxwell's equations [SIC], on the recent work [CP, SU, OPS], and on layer-stripping formulas for the full Maxwell system that we have recently worked out with Erkki Somersalo.

OTHER APPROACHES

We will also consider other inversion methods. For example, in the infinite-wavelength case, we have obtained useful reconstructions from real data using a least-squares optimization method that uses only one step of Newton's method. Although this algorithm might not be as accurate as others, it is fast enough to work in real time. Such optimization algorithms may be useful for the laboratory and field data inversion, as well as for some of the radar applications.

In addition, we propose to investigate stochastic formulations of the inverse problem. We will study the extent to which the probability distribution of the electromagnetic parameters, or at least some of their moments, can be determined from the observed fields. In particular, we will study the case in which the electromagnetic parameters are of the form of a known background plus a random variation [TKS, W, SH]. We will investigate not only the usual integral equation methods [C, TKS], but also the applicability of layer-stripping methods.

COORDINATION WITH OTHER GROUPS

As our work proceeds, we will compare our models, methods, and results with those of other researchers [W, TKS]. We will determine the accuracy with which the complex permittivity can be recovered in simple models, and compare our results with experimental results from CRREL.

Some of this work will be carried out in collaboration with Erkki Somersalo, who has worked with us on layer-stripping methods [CISI, SCII] and on inverse problems for Maxwell's equations [SIC], and who is an expert on the use of radar to detect ice and snow cover [SH].

We intend to stay in contact with the other ONR sea ice groups; the results of their research may suggest new questions to investigate.

REFERENCES

[BLK] A.M. Bruckstein, B.C. Levy, and T. Kailath, "Differential methods in inverse scattering", SIAM J. Appl. Math. 45 (1985) 312-335.

[BMW] R.E. Blahut, W. Miler, and C.H. Wilcox, Radar and Sonar, Part I (Springer, New York, 1991).

[C] M. Cheney, "A review of inverse potential scattering", in Inverse Problems in Partial Differential Equations, ed. D. Colton, R. Ewing, and W. Rundell (SIAM, Philadelphia, 1990).

[CI] M. Cheney and D. Isaacson, "Invariant Imbedding, Layer-Stripping, and Impedance Imaging", to appear in Inverse Problems and Invariant Imbedding, SIAM volume in memory of R.E. Krueger.

[ChK] M. Cheney and G. Kristensson, "Three- dimensional inverse scattering: layer-stripping formulae and ill-posedness results", Inverse Problems 4 (1988) 625-642.

[CISI] M. Cheney, D. Isaacson, E. Somersalo, and E.L. Isaacson, "A layer-stripping approach to impedance imaging", proceedings of the Review of Progress in Computational Electromagnetics, at the Naval Postgraduate School, Monterey, California, March 1991.

[CDK] J.P. Corones, M.E. Davison, and R.J. Krueger, "Direct and inverse scattering in the time domain via invariant imbedding equations", J. Acoust. Soc. Am. 74 (1983) 1535-1541.

[CoK] J.P. Corones and R.J. Krueger, "Obtaining scattering kernels using invariant imbedding", J. Math. Anal. App. 95 (1983) 393-415.

[CP] D. Colton and L. Paivarinta, "The uniqueness of a solution to an inverse scattering problem for electromagnetic waves", preprint.

[K] R. J. Krueger, "Inverse problems for nonabsorbing media with discontinuous material properties", J. Math. Phys. 23 (1982) 396-404 and "Numerical aspects of a dissipative inverse problem", IEEE Trans. Antennas and Propagation, AP-29 (1981) 253-261.

[KK] G. Kristensson and R.J. Krueger, "Direct and inverse scattering in the time domain for a dissipative wave equation", Parts 1-4, J. Math. Phys. 27 (1986) 1667-1693; 28 (1987) 360-370; Inverse Problems 5 (1989) 375-388.

[OPS] P. Ola, L. Paivarinta, and E. Somersalo, "An inverse boundary value problem in electrodynamics", preprint.

[SCII] E. Somersalo, M. Cheney, D. Isaacson, and E.L. Isaacson, "Layer stripping: a direct numerical method for impedance imaging", Inverse Problems 7 (1991) 899- 926.

[SH] E. Somersalo and M. Hallikaninen, "A mathematical model for signal analysis of FM radar", J. Electromagnetic Waves and Appls. 4 (1990) 743-769.

[SIC] E. Somersalo, D. Isaacson, and M. Cheney, "An inverse boundary value problem for Maxwell's equations", to appear in J. Comp. and Appl. Math. (1992); an abbreviated version appears in the 7th Annual Review of Progress in Applied Computational Electromagnetics (Naval Postgraduate School, Monterey, 1991).

[SU] Z. Sun and G. Uhlmann, "An inverse boundary value problem for Maxwell's equations", preprint.

[TJ] L. Tamil and A. Jordan, "Spectral inverse scattering theory for inhomogenouse dielectric waveguides and devices", IEEE Proc. 79 (1991) 1519-1528.

[TKS] L. Tsang, J.A. Kong, and R.T. Shin, Theory of Microwave Remote Sensing (Wiley, New York, 1985).

[W] D.P. Winebrenner, J. Bredow, M.R. Drinkwater, A.K. Fung, A.J. Gow, T.C. Grenfell, H.C. Han, J.A. Kong, J.K. Lee, S. Mudaliar, S. Nghiem, R.G. Onstott, D.K. Perovich, L.Tsang, and R.D. West, "Microwave sea ice signature modeling", preprint.

Sea Ice Scattering Model

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1. INTRODUCTION

This write-up provides a scattering model formulation for sea ice in Section 2 and indicates the needed model parameters in Section 3 in terms of a first-order solution. The first-order solution is shown to indicate the major contributing terms. Algorithms for numerical solution of the exact radiative transfer equations are available and the same model parameters are called for in numerical solution.

2. RADIATIVE TRANSFER FORMULATION

The basic sea ice model assumes the sea ice to be a layered or a multi-layered medium. For simplicity only the formulation for a single layered medium with irregular boundaries is given below to illustrate what are the required parameters to represent a volume scattering medium and a rough surface boundary. The overall formulation including both the inhomogeneous volume and the rough interfaces can be written in terms of the radiative transfer equations for the upward and downward intensity matrices denoted by $\mathbf{I}^+$ and $\mathbf{I}^-$ and illustrated in Figure 1 as follows:

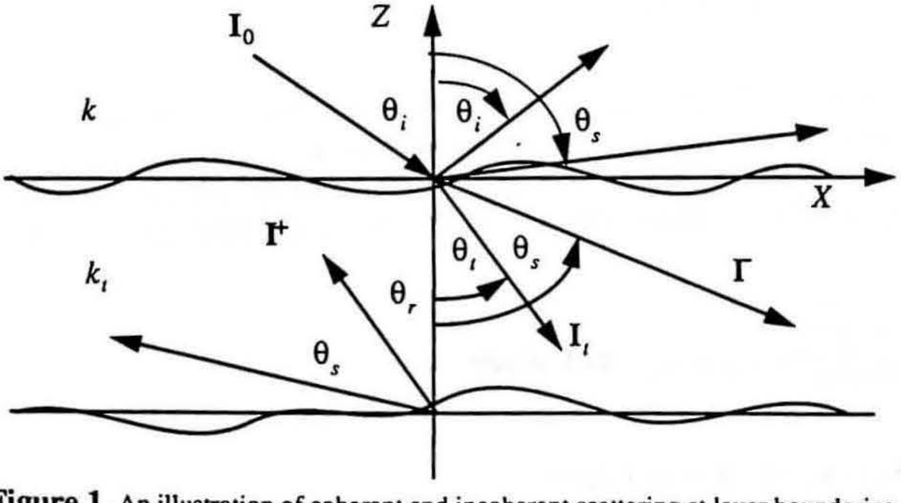

Figure 1. An illustration of coherent and incoherent scattering at layer boundaries.

$$\frac{d}{dz}\mathbf{I}^+(z) = -\kappa_{es}\mathbf{I}^+(z) + \mathbf{F}^+(z) \tag{1}$$

$$\frac{d}{dz}\mathbf{I}^-(z) = \kappa_{es}\mathbf{I}^-(z) - \mathbf{F}^-(z) \tag{2}$$

where $\kappa_{es} = \kappa_e/\cos\theta_s$

$\mu_s = \cos\theta_s$

$\mathbf{I}^+(z) = \mathbf{I}(z, \mu_s, \phi_s)$

$\mathbf{I}^-(z) = \mathbf{I}(z, -\mu_s, \phi_s)$

$$\mathbf{F}^{\pm}(z) = \frac{\kappa_{ss}}{4\pi}\int_0^{2\pi}\int_0^1 \mathbf{P}(\pm\mu_s, \mu, \phi_s - \phi)\,\mathbf{I}^+\,d\mu d\phi$$

$$+ \frac{\kappa_{ss}}{4\pi}\int_0^{2\pi}\int_0^1 \mathbf{P}(\pm\mu_s, -\mu, \phi_s - \phi)\,\mathbf{I}^-\,d\mu d\phi \tag{3}$$

In (3) κ_s, κ_e are the volume scattering and extinction coefficient matrices taken to be diagonal [Ulaby et al, 1986, Chapter 13], $\kappa_{ss} = \kappa_s/\cos\theta_s$ and $\mathbf{P}(\mu_s, \mu, \phi_s - \phi)$ is the scattering phase matrix for the inhomogeneous medium. The above differential equations given by (1) and (2) are of the first-order and have standard solutions of the form,

$$\mathbf{I}^+(z) = \mathbf{I}^+(-d)\,e^{-\kappa_{es}(z+d)} + \int_{-d}^{z}\mathbf{F}^+(z')\,e^{-\kappa_{es}(z-z')}\,dz' \tag{4}$$

$$\mathbf{I}^-(z) = \mathbf{I}^-(0)\,e^{\kappa_{es}z} + \int_{z}^{0}\mathbf{F}^-(z')\,e^{\kappa_{es}(z-z')}\,dz' \tag{5}$$

These solutions are not real solutions because $\mathbf{F}^{\pm}$ are functions of the upward and downward propagating intensities. Hence, (4) and (5) are really integral equations for these intensities. To cast them into a form suitable for iterative solution we need to incorporate the applicable boundary conditions. At the upper boundary $z = 0$ the condition is

$$\mathbf{I}^-(0) = \frac{1}{4\pi}\int_0^{2\pi}\int_0^1 \mathbf{S}(-\mu_s, \mu, \phi_s - \phi)\,\mathbf{I}^+\,d\mu d\phi$$

$$+ \frac{1}{4\pi}\int_0^{2\pi}\int_0^1 \mathbf{S}_{t1}(-\mu_s, -\mu, \phi_s - \phi)\,\mathbf{I}^i d\mu d\phi \tag{6}$$

where $\mathbf{S}(-\mu_s, \mu, \phi_s - \phi)$, $\mathbf{S}_{t1}(-\mu_s, -\mu, \phi_s - \phi)$ are the surface scattering and transmission phase matrices and $\mathbf{I}^i = \mathbf{I}_0\delta(\mu - \mu_i)\,\delta(\phi - \phi_i)$ is the intensity of the incident plane wave. At the lower boundary $z = -d$, we have the boundary condition,

$$\mathbf{I}^{+}(-d) = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{1}\mathbf{G}(\mu_s, -\mu, \phi_s - \phi)\,\mathbf{I}^{-}(-d)\,d\mu d\phi \tag{7}$$

where **G** is the scattering phase matrix for the lower surface boundary. Substituting the above boundary conditions into (4) and (5) we have

$$\mathbf{I}^{+}(z) = \left(\frac{1}{4\pi}\int_0^{2\pi}\int_0^{1}\mathbf{G}(\mu_s, -\mu, \phi_s - \phi)\,\mathbf{I}^{-}(-d)\,d\mu d\phi\right)e^{-\kappa_{es}(z+d)}$$
$$+\int_{-d}^{z}\mathbf{F}^{+}(z')\,e^{-\kappa_{es}(z-z')}dz' \tag{8}$$

$$\mathbf{I}^{-}(z) = e^{\kappa_{es}z}\left[\frac{1}{4\pi}\int_0^{2\pi}\int_0^{1}\mathbf{S}(-\mu_s, \mu, \phi_s - \phi)\,\mathbf{I}^{+}\,d\mu d\phi\right]$$
$$+e^{\kappa_{es}z}\left[\frac{1}{4\pi}\mathbf{S}_{t1}(-\mu_s, -\mu_i, \phi_s - \phi_i)\,\mathbf{I}_0\right]+\int_z^{0}\mathbf{F}^{-}(z')\,e^{\kappa_{es}(z-z')}dz' \tag{9}$$

The above two equations are the starting equations for iteration. The objective of the problem is to solve for the upward propagating intensity at $z = 0$ and then transmit it into the upper medium above the inhomogeneous layer.

2.1 Upward Scattering Intensity within the Layer

Consider the upward propagating terms. In view of (8) there are two major contributing terms to the upward propagating intensity $\mathbf{I}^{+}(0)$ at the top boundary. To the first-order in scattering, these two terms are:

1. the upward propagating intensity due to scattering from the lower boundary responding to the incoming intensity arriving at $z = -d$. From (9) the incoming intensity originated from the incident wave arriving at the lower boundary is

$$\mathbf{I}^{-}(-d) \approx e^{-\kappa_{es}d}\left[\frac{1}{4\pi}\mathbf{S}_{t1}(-\mu_s, -\mu_i, \phi_s - \phi_i)\,\mathbf{I}_0\right] \tag{10}$$

2. upward scattering within the layer due to the propagation of the incoming intensity within the layer. From (9) the incoming propagating intensity within the layer is

$$\mathbf{I}^{-}(z) \approx e^{\kappa_{es}z}\left[\frac{1}{4\pi}\mathbf{S}_{t1}(-\mu_s, -\mu_i, \phi_s - \phi_i)\,\mathbf{I}_0\right] \tag{11}$$

After substituting (10) and (11) into (8) we obtain the two contributing terms to the first-order upward intensity at $z = 0$ before transmitting out of the layer as

$$\mathbf{I}^{+}(0,\mu_s,\phi_s) \approx \frac{e^{-\kappa_{es}d}}{4^2\pi^2}\int_0^{2\pi}\int_0^{1}\mathbf{G}(\mu_s,-\mu,\phi_s-\phi)\, e^{-\kappa_e d/\mu}\mathbf{S}_{t1}(-\mu,-\mu_i,\phi-\phi_i)\,\mathbf{I}_0 d\mu d\phi$$

$$+\frac{\kappa_s}{16\kappa_e\pi^2}\int_0^{2\pi}\int_0^{1}\{1-exp[-\kappa_{es}d(\mu_s+\mu)/\mu]\}$$

$$\frac{\mathbf{P}(\mu_s,-\mu,\phi_s-\phi)}{(\mu_s+\mu)}\mu\mathbf{S}_{t1}(-\mu,-\mu_i,\phi-\phi_i)\,\mathbf{I}_0 d\mu d\phi$$

$$\equiv \mathbf{I}_g+\mathbf{I}_v \qquad (12)$$

The first term $\mathbf{I}_g$ in (12) represents contribution from the lower boundary and is controlled by lower boundary scattering and the loss in the layer. This term is important when the scattering by the lower boundary is high and the loss within the layer is low. The second term $\mathbf{I}_v$ is the contribution from the layer volume. It is important when the scattering albedo of the layer is high and the optical depth of the layer is large.

2.2 Total Scattered Intensity from an Inhomogeneous Layer

To the first-order the total scattered intensity from an inhomogeneous layer with irregular boundaries consists of three contributing terms: (1) scattering by the top rough interface; (2) scattering by the inhomogeneous volume and (3) scattering from the bottom irregular interface. The last two terms must also account for the crossing of the top interface. The mathematical representation is given by (13) below

$$\mathbf{I}(\mu_s,\phi_s) = \frac{1}{4\pi}\mathbf{S}_s(\mu_s,\mu_i,\phi_s-\phi_i)\,\mathbf{I}_0$$

$$+\frac{1}{4\pi}\int_0^{2\pi}\int_0^{1}\mathbf{S}_{1t}(\mu_s,\mu,\phi_s-\phi)\,[\mathbf{I}_v(\mu,\phi)+\mathbf{I}_g(\mu,\phi)]\,d\mu d\phi$$

$$\equiv \mathbf{I}_s+\mathbf{I}_{vt}+\mathbf{I}_{gt} \qquad (13)$$

In (13) the three types of intensity terms stated above are denoted by $\mathbf{I}_s$, $\mathbf{I}_{vt}$ and $\mathbf{I}_{gt}$ respectively. An illustration of these three terms is given in Figure 2.

3. SURFACE AND VOLUME GROUND TRUTH PARAMETERS

In this section we shall give an explicit expression for each of the three terms in (13) under the backscattering condition and then indicate the model parameters needed for model verification based on the expressions.

3.1 Backscattering from a Randomly Rough Surface

The first term in (13) represents surface scattering from the top interface. Expressed as a

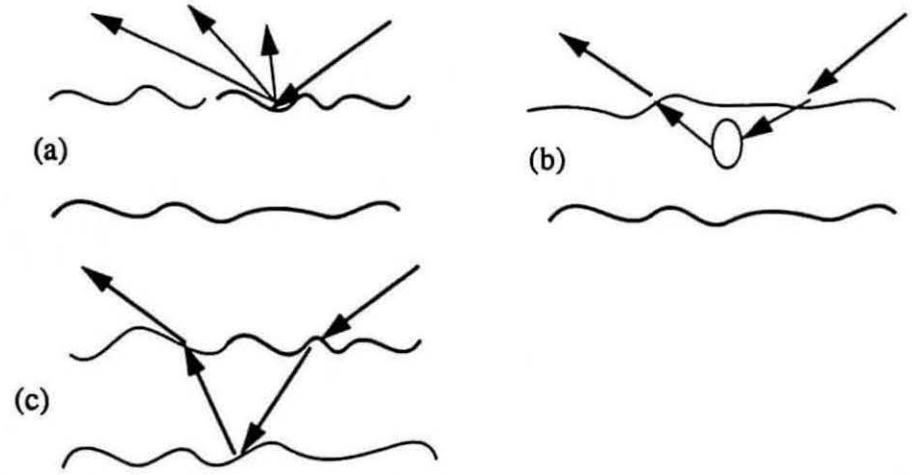

Figure 2. Scattering processes of the three terms in (13). (a) Scattering from top irregular boundary; (b) Volume scattering contribution and (c) Lower boundary contribution. In (b) and (c) transmission across the top boundary surface is involved.

backscattering coefficient for a rough surface, it is a function of the root mean square (rms) height σ and the correlation function of the surface. The correlation function contains a parameter L called the correlation length. It is convenient to normalize both σ and L to the incident wave number k i.e. we use $k\sigma$ and kL as roughness parameters. Let the incident angle be θ. Then, the surface scattering model is

$$\sigma^0_{pp} = 4\pi\cos\theta_s [I_p(\mu_s, \phi_s)/I_p]|_{\theta_s=\theta}$$

$$= \frac{k^2}{2} exp(-2k_z^2\sigma^2) \sum_{n=1}^{\infty} |I^n_{pp}|^2 \frac{W^{(n)}(-2k_x, 0)}{n!} \quad (14)$$

where $k_z = k\cos\theta$, $k_x = k\sin\theta$, and $pp = vv$ or hh,

$$I^n_{pp} = (2k_z\sigma)^n f_{pp} exp(-k_z^2\sigma^2) + \frac{(k_z\sigma)^n [F_{pp}(-k_x, 0) + F_{pp}(k_x, 0)]}{2} \quad (15)$$

and the symbol $W^{(n)}(-2k_x, 0)$ is the Fourier transform of the n^{th} power of the surface correlation coefficient.

$$f_{vv} = 2R_{\parallel}/\cos\theta;\ f_{hh} = -2R_{\perp}/\cos\theta \quad (16)$$

$$F_{vv}(-k_x, 0) + F_{vv}(k_x, 0)$$

$$= \frac{2\sin^2\theta (1 + R_{\parallel})^2}{\cos\theta}\left[(1 - \frac{1}{\varepsilon_r}) + \frac{\mu_r\varepsilon_r - \sin^2\theta - \varepsilon_r\cos^2\theta}{\varepsilon_r^2\cos^2\theta}\right] \quad (17)$$

$$F_{hh}(-k_x, 0) + F_{hh}(k_x, 0)$$
$$= -\frac{2\sin^2\theta\,(1+R_\perp)^2}{\cos\theta}\left[(1-\frac{1}{\mu_r}) + \frac{\mu_r\varepsilon_r - \sin^2\theta - \mu_r\cos^2\theta}{\mu_r^2\cos^2\theta}\right] \tag{18}$$

where $R_\perp, R_\parallel$ are the Fresnel reflection coefficients for horizontal and vertical polarizations. *These coefficients in (16) should be evaluated at normal incidence for surfaces satisfying the tangent plane approximation where kL is large* [Chapter 12, Ulaby et al, 1982]. At this time a satisfactory transition of the local angle of incidence in the Fresnel reflection coefficients from the incident angle to normal incidence is not known. It is expected that for a Gaussian correlated surface, we should evaluate the Fresnel reflection coefficients at normal incidence when kL is larger than 5. This leads to a different expression for the surface model. However, for exponentially correlated surface, a much larger kL may be used. Such a transition is not critical if the dielectric constant of the surface is large. Thus, the surface scattering model requires:

1. Surface height should be Gaussian distributed.
2. Surface rms height and correlation function should be estimated from measured surface profiles of sufficient lengths (preferred length = 400 correlation lengths).
3. Surface dielectric constant should be measured or derived from measurements.

Accuracy of measurements in length should be within 0.1 of a wavelength. Upper and lower bounds of estimated parameters will be useful.

3.2 The Volume Scattering Term

The second term in (13) is the volume scattering term. It can be converted into a backscattering coefficient as

$$\sigma^0_{vpp} = 0.5\,(\kappa_s/\kappa_e)\,T_{ll}T_{ll}\cos\theta\,[1 - exp\,(-2\kappa_e d/\cos\theta_t)]\,P_{pp}(\cos\theta_t, -\cos\theta_t;\pi) \tag{19}$$

where P_{pp} is the pp element of the volume scattering phase function and T_{ij} is the Fresnel power transmission coefficient across the top surface boundary. In (19) we have approximated the crossing of the top surface boundary by the Fresnel transmission coefficients. The model parameters are to be measured are

1. size of the scatterer.
2. dielectric constants of the scatterer and the host medium.
3. volume fraction of the scatterer.

Note that κ_e, κ_s can be computed in terms of the above information. When dielectric constants are estimated from other measurements, it is useful to indicate their upper and lower bounds.

3.3 Scattering from the Lower Boundary

The third term in (13) is dominated by noncoherent scattering from the bottom boundary surface attenuated by the layer. We approximate it by using (14) attenuated by propagation through the layer as

$$\sigma^0_{gpp} = \cos\theta T_{lt}(\theta, \theta_t) T_{tl}(\theta_t, \theta) exp(-2\kappa_e d/\cos\theta_t) \sigma^0_{pp}(\theta_t)/\cos\theta_t \quad (20)$$

where $\sigma^0_{pp}(\theta_t)$ is the surface scattering coefficient for the lower boundary evaluated using surface parameters as given in section 3.2, the dielectric constants of the layer medium and the lower half space; $\kappa_e d$ is the optical depth of the layer and θ_t is the angle of transmission from the medium above the layer into the layer. The complete backscattering model for the layer is the sum of (14), (19) and (20). In summary, the list of parameters for (20) is

1. depth of layer.
2. dielectric constants of the layer medium and the lower half space.
3. surface rms height and correlation function for the lower interface.
4. volume scattering parameters obtained in Section 3.2.

4. REFERENCE

Ulaby, F. T. Moore, R.K. and A.K. Fung, Microwave remote Sensing, Artech House, 1986

LABORATORY INVESTIGATION OF RADAR BACKSCATTER FROM SIMULATED SEA ICE

S. Gogineni and K. Jezek

1.0 INTRODUCTION

The primary objectives of the proposed experimental investigation at CRREL for 92-93 winter season are: (1) to study the effect of surface roughness on backscatter from saline ice; and (2) to investigate the effect of snow cover on radar return from saline ice.

The importance of surface and volume scatter from saline ice is a topic of considerable attention over the last few years. At present there are two models to explain backscatter from saline ice. One of these attributes scattering from saline ice to brine pockets embedded in the ice. The other explains scattering as resulting from the ice surface. It is essential to determine the basic scattering mechanism for developing forward scattering model for saline ice. We propose to conduct experiments to qualitatively determine the basic scattering process for saline ice to guide model development.

Snow modifies the thermal and scattering properties of sea ice. It acts as a thermal insulator and alters the temperature profile of an ice sheet. It also adds an additional layer of scattering particles and introduces a rough dielectric interface immediately after the first snow fall. As soon as snow falls on ice brine is wicked into the snow creating a rough dielectric interface. This causes backscatter at vertical to decrease and to increase at large incidence angles. As snow ages, grain size increases which may result enhance volume scattering from snow. This may dominate the scattering process particularly at large incidence angles. The second part of our experimental investigation is aimed at addressing this issue.

2.0 APPROACH

The experimental plans for 92-93 winter season include growing two ice sheets. The first sheet is proposed to be divided into two halves. One half is remain undisturbed and other roughened for resolving issues related to importance of volume and surface scatttering from saline ice. The second sheet is for studying the effect of snow cover on saline ice.

The approach we propose to adopt is to perform calibrated radar backscatter measurements at a minimum of two frequencies on these ice sheets. We propose to make these measurements with as detailed surface observations as possible including surface roughness and dielectric constant. We will use these surface and ice characterization data and existing surface scattering models to compute scattering from the ice surface. We will compare the theoretical predictions with experimental observations to qualitatively determine the basic scattering process.

3.0 INSTRUMENTATION

For the 92-93 winter season we propose to use step- frequency radars operating at 5.5 and 13. 5 GHz for measurements. We designed these systems for collecting data with all four linear polarizations and over incidence angles from 0 to 70 degrees. These systems are normally calibrated internally by injecting a sample of the transmitter signal into the receiver path through a lossy-transmission line. External calibration is accomplished by measuring signal backscattered by standard targets of known radar cross- section such as a sphere, Luneberg and diplane with different orientations.

The important system specifications are given in Table 1.

Table 1: System specifications

Description	C band	Ku band
Center frequency	5.5	13.5 (GHz)
RF bandwidth (MHz)	1000	1000
Antennas	Standard gain horns	Diagonal horns
Polarizations	VV, HH, VH and HV	VV, HH, VH and HV
Calibration:		
Internal	Signal injection	Signal injection
External	Sphere, Lens and diplane	Sphere, Lens and diplane
Incidence angles (degrees)	0 to 70	0 to 70

4.0 MEASUREMENTS

We propose to collect backscatter data at 5.5 and 13.5 GHz with all four linear polarizations. We will collect these data at incidence angles from about 0 to 70 degrees. We propose to measure surface roughness with a comb gauge. We will use a recently developed device to measure dielectric parameters of ice at frequencies between 2 and 10 GHz. The upper frequency at which measurements can be made is controlled by the magnitude of the dielectric constant being measured. The upper frequency, $f_h = \frac{f_r}{\sqrt{\varepsilon_r}}$ where f_r is the probe resonant frequency and er is the dielectric constant. For our probe the resonant frequency is about 17 GHz.

5.0 DELIVERABLES

We propose to supply following data to other investigators.

Backscatter data at 5.5 and 13.5 GHz
Surface roughness parameters
Dielectric parameters.

These data will be provided to other investigators within six months after the completion of the experiment.

Mathematical and Experimental Studies of the
Electromagnetic Properties of Sea Ice

Research Plan

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I. Mathematical Work

During the first year, our mathematical research will be focused on laying a rigorous foundation for analyzing the electromagnetic properties of sea ice, via bounds on its effective complex dielectric constant ϵ^*. We plan to implement a procedure [1–4] for obtaining successively tighter bounds on ϵ^* which incorporate geometrical information about the inhomogeneities in sea ice. Furthermore we shall compare these bounds with measured ϵ^* for saline ice to be grown at CRREL this winter.

In particular, we consider the sea ice to be a two component random medium with constituent permittivities ϵ_1(ice) and ϵ_2(brine). The first set of bounds includes information only about relative brine volume p_2. To obtain a tighter set we plan to incorporate information on the two point correlation function, as obtained through image processing techniques by Perovich and Gow [5]. This correlation function is sensitive to anisotropy in the crystallographic and, therefore, brine microstructure, as well as temperature, which plays a large role in determining brine geometry. Certain integrals of the correlation function enter naturally into the bounding procedure and provide a convenient way of studying anisotropy and temperature dependence of ϵ^*.

To describe the above plan in more detail, we let $\epsilon(x,\alpha)$ be the local complex dielectric constant of the sea ice, where $x \in \mathbf{R}^d$ and $\alpha \in \Omega$, the set of realizations of our random medium. We write $\epsilon(x,\alpha)$ as $\epsilon(x,\alpha) = \epsilon_1\chi_1(x,\alpha) + \epsilon_2\chi_2(x,\alpha)$, where $\chi_j(x,\alpha)$ equals 1 when medium j is at x and is zero otherwise. Let $\mathbf{E}^k(\mathbf{x},\alpha)$ and $\mathbf{D}^k(\mathbf{x},\alpha)$ be the stationary random electric and displacement fields satisfying

$$\mathbf{D}^k(\mathbf{x},\alpha) = \epsilon(\mathbf{x},\alpha)\mathbf{E}^k(\mathbf{x},\alpha) \tag{1}$$

$$\nabla \cdot \mathbf{D}^k(\mathbf{x},\alpha) = 0 \tag{2}$$

$$\nabla \times \mathbf{E}^k(\mathbf{x},\alpha) = 0 \tag{3}$$

$$< \mathbf{E}^k(\mathbf{x},\alpha) >= \mathbf{e}_k, \tag{4}$$

where $\mathbf{e}_k$ is a unit vector in the k^{th} direction, for some $k = 1,\ldots,d$. In (4), $< \cdot >$ denotes average over Ω (which is equivalent to infinite volume averaging). Equation (3) is valid as an approximation of the time dependent Maxwell equation $\nabla \times E = -\partial_t B$ in the limit when the wavelength of the applied field is long compared to the typical scale of the inhomogeneities (brine). In view of the constitutive law (1), the effective complex dielectric tensor ϵ^* is defined via

$$< \mathbf{D}^k >= \epsilon^* < \mathbf{E}^k >, \qquad k = 1,\ldots,d. \tag{5}$$

The bounding procedure described above is based on the following integral representation for a diagonal coefficient $\epsilon^* = \epsilon^*_{kk}$ of ϵ^*,

$$1 - \frac{\epsilon^*}{\epsilon_2} = \int_0^1 \frac{d\mu(z)}{s-z}, \qquad s = 1/(1-\epsilon_1/\epsilon_2), \tag{6}$$

where μ is a positive Borel measure on [0,1]. Geometrical information about the inhomogeneities is incorporated into ϵ^* via the moments $\mu_n = \int_0^1 z^n d\mu(z)$ of μ. Perturbation around a homogeneous medium yields

$$\mu_n = (-1)^n < \chi_1[(\Gamma\chi_1)^n \mathbf{e}_k] \cdot \mathbf{e}_k >, \tag{7}$$

where $\Gamma = \nabla(-\Delta)^{-1}\nabla\cdot$.

For $n = 0, \mu_0 = p_1$, the volume fraction of ice ($= 1 - p_2$, where p_2 is the brine volume fraction). For $n = 1$, μ_1 depends on the two-point correlation function $R(\mathbf{0},\mathbf{x}) =< \chi_1(\mathbf{0},\alpha)\chi_1(\mathbf{x},\alpha) >$. We plan to use information about $R(\mathbf{0},\mathbf{x})$ for sea ice provided by Gow and Perovich in order to obtain bounds on ϵ^* which are tighter than those which incorporate only volume fraction.

As a longer range goal of our mathematical work, it would be very advantageous to develop an integral representation theory analogous to that embodied in (6) which incorporates scattering effects encountered when the wavelength is comparable to the typical brine length scale. Furthermore, we wish to analyze the validity of various approximate formulas for ϵ^* and to develop formulas for ϵ^* valid in the regime where the brine inclusions percolate and classical formulas presumably are no longer valid.

References

[1] D. J. Bergman. *Phys. Rep. C*, 43:377, 1978.

[2] G. W. Milton. *J. Appl. Phys.*, 52:5294, 1981.

[3] K. Golden and G. Papanicolaou. *Comm. Math. Phys.*, 90:473, 1983.

[4] K. Golden. *J. Mech. Phys. Solids*, 34:333, 1986.

[5] D. K. Perovich and A. J. Gow. *J. Geophys. Res.*, 96(C9):16943, 1991.

II. Experimental Work

As outlined in our proposal, we plan to develop scanning tomographic methods for analyzing sea ice microstructure, which will also serve to test various inverse algorithms in a laboratory setting. The following is a detailed plan for the first year of this work.

A. Experimental Protocols for Transmission/Reflection Mode Tomographic Scanning

The construction of the 2-D mechanical scanner will be completed by the end of the second month of funding. The addition of vertical motion will be completed by the end of the third month. The completion of the 2-D, 36 antenna, electronic scanner will be completed by the end of the second month. The addition of vertical motion will be completed by the end of the fourth month. The completion of each of these scanners will allow experiments to be conducted. The first month will be used to prepare the scanners and to interface and modify inverse scattering algorithms for the experimental tasks ahead. These experiments will be conducted in the following approximate order as listed below as experimental steps.

Some of the early experiments with sea ice can be conducted with ice made in our laboratory. A small upright deep freezer will be used to make ice from fresh water and from saline solutions. Later experiments will use sea ice sent to our lab in special containers by use of overnight express mail.

Experiments steps with mechanical scanner

1. calibrate the transmitter horn for electric field distribution and receiver horn for sensitivity pattern
   This will be done the first month. This information is essential for using the inverse scattering algorithm. There are two ways of doing this: (1) direct calculation from horn geometry; (2) measurement in an antenna range using test objects or probes. We will use the first method initially but later will check and refine the calculations with measurements.
2. scan rotationally symmetric, cylindrical ice objects
   This step can be started in the third month. The simple shape will only require one view with the scanner. The algorithm will be studied for its ability to image moderate contrast between air and ice.
3. scan cylindrical ice objects
   Non-rotational symmetric objects will be scanned and imaged in this step. This step will require the rotation of the ice object as well as the receiver horn. This step will open the way for seeing arbitrary inhomogeneous objects.
4. add air pockets
   Adding air pockets will test the ability to see voids in the ice and to image average dielectric constant for voids less than 1/2 wave length.
5. add water pockets
   Adding water pockets will test the algorithm for its ability to image high contrast in dielectric constant between air and water. The number of iterations required for the algorithms to converge will increase. We will be investigating various acceleration methods to compensate for this effect. In early experiments the water will be held in rubber balloons to stabilize the volume of water (stop melting or freezing of water pockets).
6. add sea water (brine) pockets
   Adding brine pockets will test the algorithm for its ability to image high contrast in both dielectric constant and conductivity between brine and water. The number of iterations required for the algorithms to converge will increase again. Again, we will be investigating various acceleration methods to compensate for this effect. In early experiments the brine

will be held in rubber balloons to stabilize the volume of brine (stop melting or freezing of brine pockets).

7. add combined air and brine pockets
   This will test the ability to image the most general case of sea ice. In early test balloons will be used to hold air and brine.

8. scan or time at temperature that promote increases or decreases in size of brine pockets
   By controlling the temperature of the sample of ice with brine, it is possible to promote increases or decreases in size of brine pockets. This will be done by use of a thin plastic container surrounding the sea ice sample on the scanner rotation stage. When a large amount of dry ice is placed above the sample the convection currents will freeze the brine. When When a small amount of dry ice is placed above the sample the weak convection currents will allow the ice to thaw and the brine pockets to grow.

9. change frequency
   Changing frequency will serve several ends. First, it will confirm the trade-off between spatial resolution and penetration. Second, it will allow one-sided (as an aircraft would see) and two-sided (as with the use of cross bore-hole ice sampling) geometries to be explored for future data collection.

10. repeat above steps with vertical motion of sea ice sample
    By repeating the above experiments with vertical motion, the realism for modeling real 3-D sea ice will be enhanced.

Experimental steps with 36 element, horn array scanner

1. calibrate the transmitter horn for electric field distribution and receiver horn for sensitivity pattern
   This will be done the first month in parallel with the horns for the mechanical scanner. See above.

2. scan rotationally symmetric, cylindrical objects
   This step can be started in the third month. The simple shape will only require one view with the scanner. The scanner and algorithm will be studied for its ability to image moderate contrast objects. An important part of this test is to determine the degree to which cross coupling between receiver horns is a problem.

3. initiate the solution of cross coupling between receiver horns
   This step will last as long as necessary. If simple solutions are adequate, then we may proceed to step 4 below. If a simple solution is not adequate, then we will begin the task of finding an analytical solution such as a new Green's function. If the problem yields to solution very slowly, then more emphasis will be placed on using the mechanical scanner for studies beyond step 3.

4. scan cylindrical ice objects
   Non-rotational symmetric objects will be scanned and imaged in this step. This step will require the rotation of the test object as well as the receiver horn. This step will open the way for seeing arbitrary inhomogeneous objects.

5. use horn array to speed scanning in conjunction with mechanical scanner.
   If a robust solution to cross coupling is found quickly, then this method will become an important supplement to the mechanical scanner.

B. Optional Experimental Protocols for Reflection Mode Tomographic Scanning

The above protocols were included in the original proposal. Since the time the original proposal was submitted, the Advanced Imaging Methods Laboratory (AIM Lab) at the University of Utah has obtained a contact from the Idaho National Engineering Laboratory (INEL), Idaho Falls, Idaho, to develop an advanced prototype ground penetrating radar (GPR) system using inverse scattering methods. As part of this work, a scale model laboratory scanner will be be constructed that will operate at about 1/10 the wave length of the field mode. The laboratory model will operate in the frequency range of 0.7 to 20 GHz. It will be computer controlled with x-y scan axes and one rotation axis separately for the transmitter and receiver. Wide bandwidth, logperiodic antennas will be used to give the wide system bandwidth. Like the mechanical scanner and the horn array, the transmitter and receiver functions will be supplied by the use of the HP-9510B network analyzer. The disadvantage of this scanner is that is can not make the high spatial resolution images that the mechanical scanner can (since a smaller numerical aperture is used in a complete scan). The advantages are that this scanner does not require the rotation of a specimen. A further advantage is that it can scan layered ice and water. Thus, we can use this scanner to measure the thickness of snow and ice over a water layer. In this way the techniques for measuring the thickness of snow and ice over water can be studied and perfected using scaled layer thicknesses and frequencies. Later the techniques can be extended to lower frequencies and applied to field studies with real sea ice.

Clearly, the above scanner is a bonus to this sea ice program. However, its use is optional since no funds have been supplied by the Navy for this study. Nevertheless, we will attempt to schedule this equipment for some studies related to sea ice. When the full scale, field model GPR unit is delivered in the spring of 1993, it may also be possible to prepare it for use in some sea ice simulation studies in the winter of 1993. Thus, we suggest the following optional, voluntary protocol.

<u>Studies with 0.7 to 20 GHz laboratory GPR scanner.</u>

1. <u>calibrate the logperiodic antennas for electric field distribution and sensitivity patterns</u>
   This step is similar to that of the horns, except no accurate analytic model is known, so test range calibration will be necessary.
2. <u>perform experiments to measure thickness of ice over fresh water.</u>
   This step will be performed in January of 1993.
3. <u>perform experiments to measure thickness of snow and ice over fresh water.</u>
   This step will be performed in January of 1993.

<u>Studies with 50 to 500 GHz field GPR scanner.</u>

1. <u>calibrate scanner</u>
   This step will be done during spring and summer of 1993 under the INEL contract.
2. <u>perform experiments to measure thickness of ice over fresh water.</u>
   This step will be performed in January of 1994.
3. <u>perform experiments to measure thickness of ice over sea water.</u>
   This step will be performed in January of 1993 subject to arrangements with the Navy and would be done at CRELL. Extra funding for travel would have to be provided.

ELECTROMAGNETICS AND OPTICS ADVANCED RESEARCH INITATIVE

LABORATORY INVESTIGATIONS INTO THE STRUCTURAL AND PHYSICAL CHARACTERISTICS OF SALINE ICE SHEETS AND THEIR ELECTROMAGNETIC PROPERTIES

Co PI's
Anthony J. Gow
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INTRODUCTION

Since FY 1984, as part of the highly productive CRRELEX Program, we have successfully fabricated a variety of saline ice types ranging from first-year ice stimulants to thermally modified ice sheets exhibiting the physical and structural characteristics that closely simulated those found in arctic second-year ice. These and additional ice types including snow-covered and rubbled ice sheets and pancake ice were successfully documented with respect to their physical property characteristics, in conjunction with active and passive microwave imaging.

The original outdoor tank or pool has now been replaced by a much larger more sophisticated structure. A new concrete pool measuring 18 m x 7.5 m x 2 m deep has been constructed; a portable roof structure and gantry, designed to be moved on rails installed beside the pool are in the process of construction. The pool will be filled with water in mid December and raised to the desired salinity with sea salt in readiness for experiments to begin in January 1993. Additional testing facilities available at CRREL include the lower pond, an indoor refrigerated pit that was recently converted for use with sea water and the Ice Engineering Facilities towing basin, while not set up for saline ice work, has been used extensively for freshwater and urea ice testing.

OBJECTIVES

In furthering the objectives of the ARI, our main scientific focus at CRREL will be on rendering a complete physical, thermal and structural characterization of ice sheets grown in support of the electromagnetic and modelling initiatives.

There are three major objectives:

1. Determining the physical and structural properties of the various ice types to be investigated. These could include frazil/pancake ice types that characterize the earliest stages of arctic sea ice growth, columnar congelation ice and its evolution to mature first-year ice, and multi-year ice variants resulting from thermal modification and desalination of first-year ice. This description will include a statistical characterization of the volume scatters (i.e. brine and vapor inclusions) in the ice.

2. Determining, through controlled laboratory experiments, small scale changes in ice structure due to repeated thermal cycling, with particular emphasis on changes accompanying the transformation of first-year ice to second-year and older ice types.

3. Investigating the development and evaluation of surface forms at various roughness scales, focusing particularly on frost flowers. salty surface skins the salt-wicking properties of thin surface snow covers and artificially rubbled surfaces. Assist in determining quantitative measures of the surface roughness of the various ice types.

APPROACH

Ice sheets will be fabricated via the same techniques that proved so successful during CRRELEX. Techniques to be used will include (a) spray seeding of the water to initiate growth of columnar-congelation ice, b) the use of submersible pumps to nucleate growth of granular frazil and c) the operation of a wave generator to convert thin sheets of semi-consolidated frazil into pancake ice. Ice thickness changes as a function of time will be monitored, as appropriate, against such factors as surface air temperature, wind chill and radiation fluxes. Throughout the ice growth process we will conduct vertical profile measurements of temperature, salinity, and density and their derived properties, brine volume and porosity. The structural examination of the ice will be made via thin sections and will include detailed studies of the ice plate/brine inclusion relationships. Changing growth rate of the ice and its effect on such substructure of the crystals is of intrinsic importance in assessing both the qualitative and quantitative nature of salt entrapment. In conjunction with ice growth we will closely monitor changes in ice surface characteristics, especially those affecting the distribution of brine. Changes due to brine expulsion and frost flower formation and "wicking up" of brine by snow seems to result in a dielectric roughening of the interface between the snow and the ice. This effect needs to be examined in detail in light of the importance of even thin layers of snow in promoting this process. In the event of heavier snow loads the ice surface may be depressed below the free-board causing flooding, permeation and freezing of seawater to occur within the snow cover. In the case of multiyear ice such flooding can lead to EM signatures with typically first-year characteristics. Thermal modification of ice sheets, including pooling of surface water to simulate the process of brine flushing, can be undertaken to evaluate the various desalinating mechanisms contributing to the transformation of first-year ice to second-year and older ice types.

Using photographs of thin sections we will endeavor, with image processing techniques, to statistically describe volume scattering characteristics via correlation functions (microwave) and inclusion size distribution statistics (microwave and optical) of the various ice types. In this regard we hope to be able to grow columnar ice with aligned c-axes by imposing a constant direction current flow across the ice/water interface. This would facilitate a three dimensional brine inclusion analysis essential to obtaining a complete description of sea ice correlation functions.

The characterization of ice surface conditions should be augmented with data from a surface roughness measuring device. In this fashion the surface roughness can be defined with the quantitative detail necessary for active and passive microwave models. Surface roughness statistics, such as the mean roughness height and the roughness autocorrelation, can then be computed.

All stages of the growth and modification of ice sheets will be carefully coordinated with ongoing measurements of microwave signatures.

INSTITUTIONAL SUPPORT

CRREL will provide support for all visiting scientists in the Electromagnetic Properties of Sea Ice ARI. This support will include office and work space for the set-up and testing of equipment. In addition visiting researchers will have access to workshop facilities, a fully-equipped cold room complex, a comprehensive library specializing in cold regions literature and a competent staff of professional researchers and support personnel.

MICROWAVE EMISSION FROM POLAR SURFACES

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INTRODUCTION

In addition to providing benchmark cases to test the EM models over a range of physical conditions as inclusive as we can come to that encountered in the field, we also want to investigate certain pressing remote sensing science questions which have arisen directly from our previous investigations. Our observational plans are slanted to satisfy both objectives subject to the ice types we can grow in the outdoor pond. These problems are described first, and the observations we plan to carry out to address them are given.

During CEAREX, LEADEX and previous CRREL pond experiments we have identified several physical processes associated with ice formation and growth that give rise to significant features in the development of new and young ice signatures which suggest that such ice may be identifiable in satellite imagery. The behavior of the passive microwave signature of congelation ice [in PR(19) GR(19,37) space for example] has been observed to evolve through a rather circuitous path arriving at a definite region which appears to correspond to young ice in SMM/I satellite data. Presently we need more congelation ice observations at sampling rates of 1-2 per hour to see how robust the evolutionary sequence we have observed is and to see how much the sequence is influenced by random forcing due to local weather patterns. We presently think we are detecting changes which are directly associated with the ice structure evolution, in particular with growth processes which involve the vertical redistribution of brine in the upper cm or two of the ice. For example, initial consolidation of new ice appears to be followed by expulsion of brine onto the surface which causes the brightness temperatures - particularly at millimeter wavelengths (18 -90 GHz) - to decrease after their initial rise. We also know that natural sea ice signatures ultimately evolve to the familiar values for thick first year ice, but we have neither observational nor theoretical explanation of what gives rise to this change. In recent pond experiments we have achieved the needed sampling rate, but we have not been able to follow the ice evolution long enough to determine what occurs as the thickness approaches 30 cm.

With growth of frost flowers or the introduction of snow, brine from the surface layer is wicked up and causes metamorphism of a portion of the overlying ice crystals affecting the surface scattering as well as the salinity profile. In another experiment, we found that the growth of pancake ice gave rise to a very different dependence of TB versus ice thickness. We know that these two modes of growth are common in various regions of the polar oceans. Both frost flower and pancake ice formation will give rise to direct modification of the surface and volume scattering, but the indirect effects - new scattering regimes arising from near surface metamorphism - will also play an important role in ice signatures.

A further question which has also arisen from previous pond experiments and resulting modeling studies is what are the physical changes which give rise to the depolarization [an increase in TB(H-Pol) relative to TB(V-Pol)] resulting from the transition from young ice to thick FY ice? The transition may to be due to surface roughening, impedance matching or some other factor; and the physical changes are clearly observed but as yet unexplained. Related to this may be the effects of pressure ridges for which initial studies suggest a distinct signature with polarization ratios near zero.

We have observed examples of most of the above phenomena during the CRREL pond experiments, and the initial investigations resulted in their identification. Often, however, for lack of experience about what to look for, the structural changes were not characterized in sufficient detail to understand the physics and to constrain the theoretical models available. Thus, although partial quantitative descriptions were obtained, a rigorous physical understanding of the emissivity and TB variations was not possible. Still, the results we did obtain have allowed us to formulated new passive microwave satellite algorithms for thin ice and they suggest further enhancements may be possible.

In view of recent advances in both theoretical modeling and observational capabilities, we are now in a much better position to obtain both the radiative and physical measurements needed to specify the models. Our measurements are designed to improve our expertise in both areas. They will require both close cooperation between the groups making electromagnetic observations, physical measurements, and the groups doing modeling. In particularly, we need dense time sequences during all aspects of the measurements and improved techniques for investigating surface roughness and near surface salinity variations.

SCIENTIFIC OBJECTIONS

We plan to carry out specific tasks described below although we will rely heavily on other groups to provide complementary ice characterization data. The cooperation of several groups is essential to carry out these experiments. In particular we would make radiometric observations and measure the surface temperature, ice thickness, snow thickness density and salinity.

The types of ice we would propose to investigate are given below along with a brief motivation for looking at each type. The order for observing these types will require appropriate scheduling, and the years in which they are done will be decided at planning meetings prior to each observing season.

FIRST YEAR

In the first year we plan to investigate a congelation sheet from initial formation until it reaches at least 20 cm in thickness making both radiometric and physical observations every half hour until the ice signatures have stabilized. After this the surface of the sheet will be roughened by adding ice cubes and observations will cover the transitions as the ice cubes fuse to the surface.

The second ice sheet will involve growth of a congelation sheet to about 10 cm which will then be covered with increasing thicknesses of snow. The ice thickness should be great enough to avoid flooding the ice surface until we are ready to do that specifically. Observations will be carried out s the snow metamorphoses on the surface.

We also anticipate that the ice harvested from the first and perhaps second sheets will be piled up near the pond and will be available for our continuing study of pressure ridges. These observations would be made at intervals of opportunity between the pond ice runs. We want to measure the changes in signatures as the "ridged" ice undergoes brine drainage.

TWO TO FIVE YEARS

In subsequent years we would carry out the same basic set of measurements subject to improvements suggested by our experiences. Listed below are ice types which we would investigate in subsequent years in order of importance weighted by feasibility of producing them at CRREL. Also given are the basic properties they represent.

a. Frazil and pancake ice - natural roughness over a range of spatial scales from millimeters to tens of centimeters.

b. Young pressure ridges - meter scale roughness and desalination under cold conditions.

c. Frost flower covered ice - small scale surface roughness and surface metamorphism.

d. Rafted ice - the influence of brine drainage and layering effects.

e. Drained/desalinated ice - effects of melt freeze cycling on desalination giving enhanced volume scattering.

f. Others - Artificial Surface Roughness,

B-B ice - Cases with strongly enhanced volume scattering to approximate cases which are difficult to represent by natural processes.

Snow cover on all of these surfaces will probably have varying effects and will be investigated for selected cases. Of primary importance would be the differences between the effects of snow on highly salty versus desalinated surfaces.

RADIOMETRIC OBSERVATIONS

The radiation observations for each of the experiments described above would be essentially the same. They would consist of brightness temperatures of the ice at 6.7, 10, 18.7,37, and 90 GHz over a range of nadir angles together with sky scans to give a low temperature calibration point and provide sky brightness for emissivity determination. With our recently upgraded system, we can make a full set of frequency, angle (20-70°). and polarization (vertical and horizontal) measurements at a given site including calibrations in about 10 to 15 minutes which allows us to observe rapidly enough to measure the details of the temporal development of TB and emissivity even for rapidly growing new ice.

A need has been identified by the theoretical community to obtain fully polarimetric radiometric data. We have at each frequency in conjunction with our present linearly polarizing antennas, and we plan to modify our instruments accordingly. At the moment we have a prototype for use at 10 GHz and we have tested it successfully during LEADEX. Over the next two years we plan to construct similar units for each of the remaining radiometers for use at CRREL.

THERMAL INFRARED OBSERVATIONS

To facilitate monitoring the ice surface temperature and to determine the infrared emissivity of the ice we will include in our set of instruments a PRT-5 thermal radiometer. This operates at a wavelength of 10 microns and the measurements will be nonpolarimetric.

We also intend to carry out a set of Vis/IR observations in conjunction with our radiometric studies. We will measure special albedo, transmissivity, and bidirectional reflectance in the visible and near infrared (350-1100 nm). At selected orientations and wavelengths we would also measure the full Stokes vector of the scattered radiances. The Visible/IR versus microwave comparison would be somewhat limited because daylight is required for the optical observations. Based on past experience, however, we can expect significant intervals when both set of measurements can be made together.

This work will be carried out jointly with Dr. D.K. Perovich whose spectrophotometer would be used and who would be primarily responsible for carrying out the optical observations. Our principal contributions would be to assist in the observations and to provide and operate a dual filter polarimeter which we built to make fully polarimetric optical observations at 560 and 800 nm. We would also use our radiative transfer model to analyze the visible and infrared data in conjunction with the microwave analysis.

PHYSICAL PROPERTIES

We also plan to contribute to the measurements of the physical characteristics of the various ice types. We will concentrate on those properties needed specifically for reduction and interpretation of the passive microwave data. Specifically these include surface and air temperatures at the instrument sites; Salinity profiles S(z) at 1 to 3 mm resolution in top 5 to 10 mm using core sectioning devices we are constructing with an optical salinometer; and the thicknesses of the ice and overlying layers such as snow or frost flowers using a ruler or caliper.

We have developed a method for measuring the salinity profile in the upper 5 mm of consolidated ice at 1 mm resolution using a series of ice shaving planes. This technique would be applied at regular intervals to monitor the surface salinities which together with the temperature profile to be measured by CRREL personnel would specify the brine volume near the surface. Core samples, also to be obtained by CRREL, would be used to investigate the brine pocket size distribution.

This information would be put into the general database and would be available for general use.

FIELD EXPERIMENT

We also plan to carry out an Arctic field experiment taking advantage of logistical support for the ice mechanics experiment in 1994. This would give us access to first-year (FY) and multiyear (MY) surface types as well as pressure ridges of differing ages. These are the cases for which volume scattering is strongest, and which have proved most difficult to simulate in the pond.

We would also obtain data from the Beaufort Sea which, in conjunction with prior field work, would allow us to investigate regional differences in MY ice signatures. We would also have access to thin ice types on a site of opportunity bases, and we will attempt to monitor the transition from young ice into the FY regime.

We plan to carry out the same set of radiometric measurements as described for the CRREL pond. We will be prepared to obtain our own bulk properties data such as temperature and salinity profiles, ice and snow thickness, and snow grain size and densities. We presume that an equivalent set of ice characterization data will be obtained.

The work described here depends strongly on cooperative interaction with both D.P. Winebrenner and D.K. Perovich and the other principal investigators on the project to provide theoretical analysis, ice characterization, and logistics support. We will also be working with Winebrenner under funding from another E&M ARI grant on applying microwave theory to the above observations.

LIGHT SCATTERING POLARIZATION MEASUREMENTS IN CRRELEX

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PARTICIPATION

In conjunction with growing artificial sea ice sheets at CRREL, Lawrence Berkeley Laboratory (LBL) will carry out measurements at LBL on samples prepared from core samples taken during ice growth. There are no plans to carry out measurements at CRREL in the winter of 1992-1993.

SCIENTIFIC OBJECTIVE

The scientific objective of the first phase of the project is to measure the polarized scattering properties of ice samples using an existing nephelometer (scattering instrument) at LBL. The nephelometer will be modified to control the temperature of the ice sample and provide a low moisture environment for the optical elements of the instrument. Facilities will be established at LBL to machine ice samples into appropriate shapes and sizes. Experimental data of the angular dependent scattering and polarization parameters will be used to understand and model the polarization dependent interaction between natural and artificial light and the ice. The results will also determine the design of a portable instrument that will be built for the use in tank ice measurements at CRREL the following winter.

INSTRUMENTATION

Scattering measurements on the samples of artificial sea ice grown at CRREL will be made using the polarization-modulated angle scanning polar nephelometer. The instrument uses light from an argon-ion laser, which is linearly polarized and passes through a acousto-optic birefringence modulator before entering the scattering sample. Light scattered as a function of angle is detected by a photomultiplier tube mounted on a rotatable arm carrying the collection optics, polarization analyzers and spectral filters. The initial polarizer and modulator produce alternating left and right circular polarization at a frequency of 50 kHz. Interaction of the polarization-modulated light with the scattering system and with the final polarizing filters produces an alternating light intensity detected by the photomultiplier tube. The ac signal from the photomultiplier tube is synchronously detected by a lock-in amplifier at 50 kHz or 100 kHz. The dc component is measured separately.

REQUIREMENTS

Ice cores taken at growth intervals of approximately 3 centimeters and shipped in dry ice will be required. In addition to the date of the cores, other pertinent information available regarding temperature, growth rates, surface melting, etc. would be helpful in reproducing the laboratory conditions and interpreting the measurements. If water circulation is carried out, the orientation of the fores with respect to the general water flow direction should be included. In addition to the artificial ice from the slab, we would also like to obtain sections of cores from other ice types from the arctic for measurements.

COLLABORATIONS AND ANTICIPATED RESULTS

Comparisons will be made with phase function data taken earlier by Grenfell and discussed with him. Other CRRELEX investigators will be contacted regarding the optical and radar properties of the ice and their relationship to the results of the laboratory measurements at LBL. Discussions will be carried out with Iturriaga to coordinate measurements of core properties made in his laboratory with those at LBL. Polarization and phase function data will be made available for the modeling effort for a range of results.

The results of the measurements will be essential to design the field instrument because the ice nephelometer will necessarily to limited to measuring only a few of the 16 elements of Mueller scattering matrix. The choice of matrix elements to measure in the field is likely to be from the first column of the matrix since it represents the polarization properties of ice for non-polarized incident light (sunlight).

FUTURE

In the next available winter season (1993-1994) the prototype of the ice nephelometer will be constructed and be deployed for experiments at CREEL. If instrumental testing and measurements results at CRREL are successful, arrangements will be made for field measurements of various types of sea ice in the arctic.

ANALYSIS OF ICE CORES

R. Iturriaga
C. Roesler

APPROACH

We will analyze ice cores that Don Perovich will send to us. Following information will be provided:

1. Science objective: To determine inherent optical properties of the dissolved and particulate components in ice.
2. Measurements:
   a) Spectral absorption of bulk and individual particulates.
   b) Spectral absorption of dissolved matter present.
   c) Scattering properties of particulates
   d) Size of particulates
3. Instruments: Spectrophotometer, microphotometer, particle analyzer and scattering meter (available at the labs).
4. Data deliverable 2 - 4 months after sample is received.
5. Physical property: Optical properties of particulates present in the ice such as, attenuation coefficient, absorption coefficient, and scattering coefficient.

INVERSION OF ELECTROMAGNETIC DATA TO RECONSTRUCT SEA ICE PARAMETERS

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The objective of the proposed program is to develop practical inversion algorithms to reconstruct sea ice parameters using active and passive microwave measurements. The first step of the program will be to obtain a theoretical model for the physical system under consideration. Initially, a layered random medium model will be used. The ice layer will be described as a host ice medium embedded with randomly distributed inhomogeneities overlaying a homogeneous halfspace of sea water. The radiative transfer theory will be used to obtain solutions for experimentally measurable quantities. Hence the random medium model and the radiative transfer theory will constitute the initial solution for the forward scattering problem. The solution of the forward scattering problem will be used to invert electromagnetic data to reconstruct sea ice parameters by optimization methods.

1. Introduction

Layered random medium models have been successfully used to describe sea ice. Within the framework of such a model, electromagnetic wave-sea ice interactions can be described by several different approaches. The radiative transfer theory is a popular choice and have been used and validated for various physical configurations. Therefore, the random medium model and the radiative transfer approach will initially be used for developing inversion algorithms. For the inversion of sea ice parameters, such as scatterer permittivity, fractional volume, size, and shape, a parameter estimation scheme will be used. This scheme will be based on the solution of the forward scattering problem. For a given measurement data, the forward calculation will be carried out with a set of estimated input parameters. If the predicted result of the forward model does not match the measurement data, the input parameters will be adjusted. The procedure will then be repeated until the calculated result matches the measurement data. During the iteration, the process of adjusting the input parameters is critical for rapid convergence. The optimization will be carried out according to an appropriate nonlinear programming scheme. Since this inversion algorithm depends on the solution of the forward scattering problem, it is crucial to have forward models that explain experimental data accurately. Therefore improvement of forward models is included in the research program.

The following is a more detailed description of the research work to be carried out:

1. Investigation of the feasibility of data inversion for different combinations of sea ice parameters. In this study we will try to determine the type of data necessary to invert for a given set of unknown parameters. For example we will consider questions of the following kind: Is the backscattering coefficient as a function of incident angle at a single frequency sufficient to estimate the correlation lengths of the random medium? What if we have that data at a number of frequencies? How much additional information is

obtained with the bistatic scattering coefficient data?

2. Investigation of the possibility of parameter reconstruction by using passive measurements. This study will be an extension of item (1). Passive measurements constitute an alternative to active remote sensing and is included in the research programs of several groups. Therefore it is crucial to consider the information content of these measurements and this will be given special attention.

3. Determination of the sensitivity of the measurable quantities (backscattering coefficients, bistatic coefficients, Mueller matrices, etc.) on physical sea ice parameters. This study will complement the work described in items (1) and (2). The objective is to determine various ice conditions and measurable quantities such that the sensitivity is large enough to allow for inversion in a noisy environment. In each sensitivity calculation, only one sea ice parameter will be allowed to change. Measurable quantities at different frequencies, look angles, and polarizations will be simulated by varying the parameter of interest to find the configuration which gives the largest dynamic range. This information will be useful in determining the optimal measurement for sea ice parameter retrieval.

4. Incorporation of *a priori* information into the inversion scheme. Often *a priori* information about the parameters to be invert for is available from other considerations. Intelligent use of this information can reduce the degree of nonuniqueness of the inverse problem and can make possible otherwise impossible inversion problems. We will investigate different methods of utilizing *a priori* information and determine the effects on the inversion schemes.

5. Improvement of forward scattering and emission models. Since the inversion schemes depend strongly on the solutions of the forward models, it is crucial to have forward models that explain experimental data accurately. Therefore, improvement of forward models for both active and passive remote sensing is included in the research program and this will be carried out in parallel with the development of the inversion algorithms.

2. CRREL Experiments

The following experimental data will be useful in our investigation of the sea ice parameter inversion algorithms:

1. The active measurement data that can be used to reconstruct sea ice parameters include backscattering and bistatic scattering coefficients. To determine and compare the information content of different data types, measurements at different angles, frequencies, and polarizations will be desirable. With the available measurement data, we will try to determine the optimal measurement variables to reconstruct a given set of sea ice parameters. For the validation and improvement of the forward and inverse models, the ground truth for the following physical properties of sea ice is needed.

a. Temperature, salinity and density profiles.

b. Direct measurement of permittivities

c. Correlation functions in horizontal and vertical directions

d. Dimensions and fractional volumes of brine inclusions

e. Ice thicknesses

f. Surface roughness spectrums To isolate the effects of rough surface scattering, a measurement data set with flat sea ice boundaries will be desirable.

2. The sea ice parameter inversion study will be repeated with passive data. Also, the complementarity of passive and active measurements will be investigated. This necessitates the active and passive measurements to be performed on the same ice. Therefore, the same ground truth will be used with the passive data which consists of brightness temperatures at different angles, frequencies and polarizations.
3. It is possible to incorporate information about measurement uncertainities into the optimization scheme. Therefore, a knowledge of percent error in the measurements will be desirable as a part of the experimental database. A description of measurement procedures and calibration techniques will be useful in modifying certain optimization parameters for better reconstruction of sea ice parameters.

3. Proposed Work for the Following Years

1. Inversion of Effective Permittivity Profile

We will improve and apply the newly developed renormalized STIE method to retrieve the complex effective permittivity profiles of sea ice. Under the renormalized STIE approach, an exact equation for inversion is derived from the integral equation relating electromagnetic fields and the equivalent current characterizing the complex permittivity profile. The integral equation can be solved by employing the Fourier transform and the eigenfunction expansion of the Green's function. The approximation comes in when only finite number of the eigenmodes are used in the numerical calculation. One source of the non-uniqueness of the inversion result is due to the non-radiating source inside the unknown region. Another source of non-uniqueness is from the multiple solutions of the simultaneous nonlinear equations. More eigenmodes we use in the expansion, more solutions will occur. This restricts the maximum number of expansion modes that can be used, which consequently restricts the accuracy of the final result. However, this can be overcome by increasing the number of measurements at different positions on the surface, at different frequencies, or by a better initial guess suggested by *a priori* information of the unknown profile. The iterative inversion method based on Green's function formulation and the Born approximation will also be studied. In this approach, the Green's function integral for the coherent reflected field will be evaluated iteratively until the convergence test between the calculated results and the measurements has been satisfied. The excitation field will be used to evaluate the induced current initially.

One other approach to the inversion of the effective permittivity profiles is to make use of the Riccati differential equation for reflection coefficients in one-dimensional inhomogeneous media. In this approach, we will derive inversion schemes based on both Schelkunoff's and Redheffer's Riccati equations to reconstruct the effective permittivity profiles from measured reflection coefficients on ice surfaces.

2. Sea Ice Parameter Estimation

We will continue the development of inversion schemes for sea ice parameters such as scatterer permittivities, fractional volume, size, shape, and orientation distributions based on our forward theoretical models and simulation algorithms. Different multi-dimensional numerical optimization schemes will be investigated to maximize the efficiency of the method. As in other parameter estimation problems, the initial guess is critical in achieving accurate results. Hence, this method has to be used with some *a priori* information regarding the true values of the inverted parameters. Therefore methods of incorporating *a priori* information into the optimization scheme will be studied.

3. Inversion of Ice Types with Neural Network Approach

Recently the neural network algorithms have been successfully applied to classification of radar images of sea ice. In this program, we propose to employ this new technique to the inversion of ice types. First, polarimetric active and passive sea ice images will be classified by unsupervised neural network classifiers, such as combined LVQ and ML algorithm, into regions of different polarimetric features. Then, for each region, the average covariance matrix or the brightness temperature Stokes vector for active and passive cases, respectively, will be further processed by another neural network trained with data generated theoretically or empirically for different ice types. The output of this final step will be the ice type for the region under consideration.

4. Applications of Polarimetric Passive Techniques

It has been shown that if geophysical media are not azimuthally symmetric, in either deterministic or statistical sense, the complex correlation between the brightness temperatures measured at the horizontal and vertical polarization channels contains significant information regarding the structure of the media. Therefore, we propose to apply polarimetric passive remote sensing techniques to determine the symmetric axes of sea ice. Reciprocity and energy conservation principles will be used to relate active bistatic scattering coefficients to polarimetric emissivities. In order to derive the complete set of polarimetric parameters, we need the emissivities of four different polarizations, namely, horizontal, vertical, right-hand circular, and 45° linear. The reflectivities and hence the emissivities of these polarizations can be obtained through solving the corresponding forward surface and volume scattering problems with the active polarimetric scattering models . The orientations of surface asymmetric features and directional volume structures can be determined with fully polarimetric passive measurements.

5. Improvement of Polarimetric Active Remote Sensing Models

5.1 Model with scatterer size and shape distributions

Sea ice contains a mixture of multi-species scatterers, such as brine inclusions and air bubbles of different sizes and shapes. The scatterer fractional volume is also a function of temperature. We propose to extend our existing forward multi-layer random medium model to account for sea ice with scatterer size and shape distributions. First we will identify the probability density functions characterizing the size and shape distributions of the inhomogeneities of sea ice based on experimental observations. The strong fluctuation theory will be applied to calculate the effective permittivity. The distorted Born approximation as well as the radiative transfer theory will be used to formulate the polarimetric backscattering coefficients.

5.2 Composite volume and surface scattering model

There are two important scattering mechanisms for sea ice: volume scattering from internal inhomogeneities and surface scattering from rough interfaces. The interaction between the two types of scattering mechanisms provides a source of depolarization. In the composite volume and surface scattering model, the scattering effects due to volume inhomogeneities, rough interfaces, and interactions between the two will be treated rigorously. The radiative transfer theory will be used to model the volume scattering from the inhomogeneous layers with boundary conditions characterizing the rough interfaces. Both numerical and iterative methods will be examined to solve for the polarimetric radar scattering coefficients.

6. Sensitivity Analyses

We will apply our forward theoretical models to study the sensitivity of backscattering coefficients with respect to each physical parameter. The purpose is to evaluate various ice conditions under which the sensitivity is large enough to allow inversion of interested physical parameters. In each calculation, only one ice parameter is allowed to change, whereas all other parameters are fixed. Radar backscattering coefficients at different frequencies, looking angles, and polarizations will be simulated by varying the ice parameter of interest. Then the calculation will be repeated for a different set of fixed parameters. Finally, the values of the fixed parameters and the radar configurations corresponding to the largest backscattering dynamic range for the parameter of interest will be identified. This information will be useful in selecting parameters for ground truth measurements and in determining the optimal sensor configuration for sea ice parameters retrieval.

7. Validation of Theoretical Models

We will collaborate with other research institutions in future experiments to validate our inversion algorithms and other theoretical findings in active and passive remote sensing of sea ice. We will also participate in experimental studies of sea ice characterization, such as composition, permittivity, salinity, correlation length, and S-parameter measurements. Sea ice parameter inversion will be performed with measured polarimetric data as well as forward simulation results as input. The retrieved ice parameters will be compared with measured ice characterization data and the input of the forward calculations, correspondingly.

LABORATORY PASSIVE MICROWAVE MEASUREMENTS OF SEA ICE IN SUPPORT OF EM/ARI

Alan W. Lohanick (PI)

INTRODUCTION

Most of our portion of the ARI effort will be conducted at the CRREL facility known as the "lower pond", a concrete-lined pool with movable roof, equipment gantry, and heated instrument/data reduction shelter. We will be using instruments and other equipment on loan from the Naval Research Laboratory (NRL) specifically for use in ARI data gathering and reduction.

We will also be making radiometer measurements at the CRREL GRF if necessary, and providing snow characterization during the snow-cover phases of the experiments there. If any adjunct experimental sites are set up in the vicinity of CRREL, such as small tanks for special measurements (e.g., recent suggestions by U. Texas, Arlington), we will be available to participate.

INSTRUMENTS

-Passive microwave radiometers:

Our primary data collection instruments are three NRL radiometers. The characteristics of these instruments are listed in the following table:

frequency (GHz)	antenna type	polarization	3-dBbeamwidth	calibration
10	rect. horn	H or V	30 deg	2K
37	lens horn	H or V	3 deg	2K
85	lens horn	H or V	3 deg	2K

The 10 GHz and 85 GHz instruments are rotated in their mounts to take near-simultaneous brightness temperatures in either polarization. The 37 GHz instrument gathers both polarizations simultaneously through the same antenna. (This instrument is on loan from NRL, SSC, Mississippi.)

Calibration of the instruments is achieved by frequently taking sky and blackbody absorber readings. Sky readings (brightness temperatures) are taken at 30, 40, 50, and 60 deg from zenith, allowing for extrapolation to zero atmospheric thickness. Since the brightness temperature of the sky with no atmosphere is the 3 K background radiation, we thus obtain the voltage outputs of the instruments for 3K. The brightness temperature of the blackbody absorber is its physical temperature (emissivity approximately 1.0), giving the voltage outputs of the instruments at the high and of the scale (250-273 K). The instruments have linear response between these extremes, and we thus have our calibration. Instrument drift is minimal, but its effect is virtually eliminated by the frequent calibrations.

-RADAR

We also plan to borrow a Ku-band (13 GHz) FM/CW radar from the University of Kansas for readings of radar backscatter from the same surfaces. This instrument has the capability to resolve depth of the dominant backscatter return for thicker snowpacks. We thus gain the ability not only to take near-simultaneous active and passive readings (backscatter and brightness temperature), but to determine the relative strength of the backscatter from the snow/ice interface, which is our primary focus.

MEASUREMENTS

In each winter season (December to March), we will grow one ice sheet to a thickness of about 20 cm. (in winter '92/93, the sheet will be allowed to grow in quiet water, forming congelation ice. In winter '93/94, the water in the pond will be agitated, so that a frazil ice sheet will form.) The ice sheet will be protected from precipitation during growth to the chosen thickness.

(Although we are interested primarily in snow-covered ice, we will monitor brightness temperature as a function of ice thickness from zero ice thickness to the chosen thickness. We will provide the CRREL physical properties characterization team with ice cores for ice characterization.)

SNOW CASE 1 - POSITIVE FREEBOARD

When natural snowfall is anticipated, the roof will be moved from the pond. Snow will be allowed to accumulate to about half the thickness of the ice sheet. The ice will be weighted down by the snow to a point at which its top surface is yet above water level (i.e, positive freeboard). This will prevent the case in which hydrostatic pressure causes brine to infiltrate the lower snow layers. The roof will be replaced over the pond whenever either further precipitation or solar melting are anticipated, thus preventing internal layering in the snow until we are ready for case 2.

SNOW CASE 2 - NEGATIVE FREEBOARD

When case 1 is completed, and further natural snowfall is anticipated, the roof will again be moved from the pond, allowing further snowfall sufficient to weight the ice sheet to negative freeboard (total snow water equivalent greater than 0.92 of ice sheet thickness). This will cause the case in which hydrostatic pressure causes brine to infiltrate the snow. The roof will continue to be used to prevent further unwanted precipitation or solar melting.

PHYSICAL PROPERTIES MEASUREMENTS

For a period of time which depends on the changes in observed conditions, we will monitor the physical character of the entire column of surface: air, snow, ice, and water, with particular emphasis on the changes at the snow/ice interface.

Measurements (not including the samples we will provide for physical properties) will include the following [accuracy is confidence in final value, reporting is earliest availability of reduced data]:

vertical temp. profile	instrument	3 lead thermistor array
	accuracy	1 K
	data interval	15 min (continual)
	vertical spac.	0.5 to cm (smallest interval at snow/ice interface)
	reporting	same day

salinity distribution (above ice surface)	instrument	hand-held refractometer
	accuracy	1 ppt
	sampling	approx. 0.1 cc volume of brine, slush, ice, and snow.
	data interval	1 day
	reporting	one to two days
snow grain characterization	instrument	35mm camera, with field microscope (10X) or macro lens.
	measurements	-descriptive grain shape -grain size to .1mm -estimated grain size distribution
	data interval	1 day
	reporting	visual - immediate photos - one or more days
snow/ice interface roughness (visual	Instruments	35 mm camera pc digitizing pad
	measurements	rms height, correlation length
	data interval	several days
	reporting	1-2 days
snow density	instrument	snow density kit
	accuracy	1 kg/cu. meter
	data interval	daily
snow moisture (liquid water content by percent)	instrument	-photometer (using dye dilution technique) and/or -resometer (borrowed from Dave Barber, ISTS, Waterloo, Canada)
	accuracy	2-3 percent (?)
	data interval	hourly, when indicated by ambient conditions (i.e., snow temperature near 0 c).
	reporting	one hour

microwave measurements		
brightness temperatures	instruments	10GHz radiometer 37 GHz radiometer 85 GHz radiometer (specifications above
	Incidence angles	10 to 70 deg, 10 deg interval
	data interval	1 sec to 1 hour, depending on purpose
	reporting	same day
radar backscatter	instrument	13 GHz FM/CW radar (borrowed from KU)
	range resolution	5 cm (?)
	data interval	1 hour or longer, depending on purpose and conditions
	reporting	?

Data Deliverables

Preliminary data reports linking microwave data to surface physical properties, can be produced within one week of initial data taking. Lag time for photography of snow grains, and for reduction of the active microwave data, are the limiting factors.

Brightness temperatures:

Microwave brightness temperatures as function of frequency, incidence (nadir) angle, polarization and time, at intervals listed above.

Backscatter cross sections:

Radar backscatter as a function of depth in snow and ice, and incidence angle at four polarization combinations.

Surface characterizations:

Snow density, grain size, thickness, moisture, salinity distribution, and temperature profile. Optical thickness can be calculated using Stogryn model.)

Snow/ice interface density, grain size, thickness, moisture, salinity distribution and

microwave measurements		
brightness temperatures	instruments	10GHz radiometer 37 GHz radiometer 85 GHz radiometer (specifications above
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	reporting	?

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Snow density, grain size, thickness, moisture, salinity distribution, and temperature profile. Optical thickness can be calculated using Stogryn model.)

Snow/ice interface density, grain size, thickness, moisture, salinity distribution and temperature profile, plus some measure of the roughness. RMS roughness and correlation length (of dielectric constant ?) will be estimated by means to be developed in cooperation with the CRREL ice characterization team and other PI's.

SCIENCE OBJECTIVES

Determine the dominant region in the snow-ice column of the microwave signal for a particular set of snow-on-ice conditions for an initially small set of circumstances (two thicknesses of snow each year, two initial underlying ice types). Since the entire snow-ice column will be well characterized, the snow and the ice can be modeled with some accuracy. Their composite modeled microwave signature can be compared to the measured signature to check the contribution of the snow/ice interface, which is difficult to model because of its physical complexity. Estimates of the dielectric roughness of the snow/ice interface will help to guide the modeling of this interface.

Determine the time variation of the microwave signal, to learn if time series can be used to maintain knowledge of underlying ice type. Since the underlying ice and the snow do not change rapidly in most instances, any more rapid changes at the snow/ice interface could lead to better understanding of the signal. Also, since surface brine infiltration is regulated by the weight and thermal insulation of the snow, time series may afford a method of determining snow water equivalent (density times thickness).

Physical property measurements required from CRREL team, and suggested accuracies.

Ice samples:

The following physical properties measurements can be done by the CRREL characterization team, from ice cores provided by us. Because of the disruptive nature of coring to our surface, which we would have undisturbed for as long as possible, we will take the smallest possible number of cores which still characterizes the ice well. A few cores will be obtained during initial ice sheet growth (approximately one every two days). One full core will be obtained before each snowfall, and near the end of the final snow metamorphosis. The character of the main ice column is not expected to change appreciably after 20 cm growth and with a snow cover.

ice structure	descriptive
ice salinity profile	1 ppt, minimum possible interval for top 2 cm
ice surface roughness	RMS height or correlation length

near-surface thick sections	crossed-Polaroid photos (for identification of near-surface layers and roughness measures.)

Dielectric constant:

In addition to the ice characterizations above, we have bee discussing with V. Lytle the possibility of making dielectric constant measurements of snow and ice surfaces at the lower pond. These would serve as a confirmation of numerical models of the surfaces. Reasonable required accuracies might be about 0.1 for real part and 0.001 imaginary part.

ACTIVE MEASUREMENTS OF SEA ICE OPTICAL PROPERTIES

Jacob Longacre (PI)
Carl Lindstrom (Co-PI)

Naval Undersea Warfare Center (NUWC)

ABSTRACT

The objective of this research is to analyze the mechanisms and processes that link the morphological/physical and the electromagnetic properties of sea ice. By characterizing these relationships, we can determine the extent to which electromagnetic measurements can be used to nonintrusively investigate physical properties of the ice. The results of this research will also significantly enhance information databases on electromagnetic (EM) detectability, vulnerability, and communications capabilities under ice.

Later sources will be used to generate an in situ observational database of optical properties of sea ice. We will utilize collimated, polarized, narrow bandwidth laser sources in order to effectively characterize the optical properties of the ice. We will use short pulse length lasers to determine the temporal as well as spatial effects of propagation through ice. We will work with researchers at universities and other laboratories to correlate these measured optical properties with known ice physical and structural characteristics for various ice types. These correlations will be used to further validate, and refine predictive models for describing the interaction of optical radiation with sea ice.

TECHNICAL APPROACH

NUWC will work with the Cold Regions Research and Engineering Laboratory (CRREL) and other researchers to conduct studies on simulated sea ice samples grown at the CRREL facility. Laboratory work will include measuring optical properties of small, homogeneous, well-characterized samples and of young ice types grown under controlled environmental conditions. To avoid changes that occur in optical characteristics of inhomogeneous natural ice when removed from its environment, we will also conduct downwelling laser propagation experiments in situ. Spatial profiles will be measured by using a downward-looking laser on the surface and deploying an optical detection system under the ice. Optical detectors will also be deployed above the ice to measure backscatter. Optical transmission, beam spreading, and backscattering measurements will be made for different laser incident angles and polarizations. Structural characteristics such as air bubbles, brine pockets, ice crystal size and orientation, salt crystals, and inorganic impurities, will be quantified and documented. Physical characteristics of the ice, such as temperature and mechanical stress, will also be measured.

We are interested in making measurements on the simulated sea ice sheet (first ice sheet grown in the outdoor pond) for the duration of its growth cycle. We plan to make spatial and temporal measurements of the light forward scattered and backscattered from the ice as a function of ice thickness, snow cover (if it occurs) and laser polarization. We also plan to make measurements of light scattered from the ice as a function of incident laser angle to determine the advantages and disadvantages of a bistatic configuration.

In order to conduct these investigations, we will need to cut a square meter hole in the ice at the edge of the pool. Our equipment will be deployed from this hole and could be removed after each day's testing. Most of our testing will be conducted after dark in order to minimize ambient noise.

EXPECTED NEW UNDERSTANDING

The objective of this research is to analyze the mechanisms and processes that link the morphological/physical and the electromagnetic properties of sea ice. By characterizing these relationships, we can determine the extent to which electromagnetic measurements can be used to nonintrusively investigate physical properties of the ice. Results of this research will also significantly enhance information databases on electromagnetic (EM) detectability, vulnerability, and communications capabilities under ice.

FACILITIES AVAILABLE

The FY93 research will be conducted at NUWC Marine Optics Research Laboratory and at CRREL. We plan to use the following blue-green lasers for the CRREL pool ice experiments:

- argon ion laser (cw, air-cooled, 100 mW average power @ 514 and 488 nm)
- pulsed diode-pumped 2XNd:YAG laser (10 μJ/pulse, 1 kW peak power, 20 mW average power @532 nm)

In addition, we have packaged several detectors in underwater housings, including picowatt power detectors, avalanche photodiodes (APD), photomultiplier tubes (PMT), and NUWC-built ultrasensitive optical receivers based on PMT technology. We also have supporting optical test equipment, such as red (660 nm) and green (532 nm) transmissometers, etc. that will be required for this field test.

MEASUREMENTS OF THE COMPLEX DIELECTRIC CONSTANT OF SEA ICE

AT FREQUENCIES FROM 26.5 TO 40 GHz

Dr. Victoria I. Lytle (PI)
Stephen F. Ackley (Co-PI)

INTRODUCTION

During 1992, we will experimentally measure the complex dielectric permittivity and the losses due to scattering from the ice grown at CRREL, at frequencies from 26.5 to 40GHz (Ka-Band).For sea ice, a non-magnetic material, the dielectric constant is the link between Maxwell's Equations and the measured electromagnetic fields. Because sea ice is a heterogeneous mixture of brine and air pockets within an ice matrix, the permittivity will depend not only on the relative percentage of each of these components, but also the size and location of the inclusions (Vant et al 1974). During these experiments, the measured dielectric constant will be correlated to detailed information about the ice microstructure from the same core. This will allow us to identify the effects of brine volume, and inclusion size on the dielectric properties.

OBJECTIVES

1. Experimentally measure the complex dielectric constant of different sea ice types at frequencies from 26.5 to 40GHz.

2. Determine degree of anisotropy in the dielectric constant of sea ice.

3. Determine the penetration depth of the electromagnetic waves, and hence the depth to which the physical properties of the ice can influence the measured backscatter.

4. Estimate the total volume scattering losses, by reducing the temperature, and consequently the losses associated with the liquid brine.

A technique has be developed at CRREL (Rennie 1991), to measure the complex dielectric constant of sea ice cores using a reflection-transmission technique. It utilizes a Hewlett Packard 8510 network analyzer to accurately measure the time and magnitude of a simulated pulse as it reflects off the front and back face of the core sample. Using the results, the real part of the permittivity can be estimated as well as the losses. This technique will be applied to cores extracted from the outdoor pond this winter. The experiments will be conducted indoors in temperature controlled room, allowing us to vary the temperature, and hence the brine content of the samples.

Detailed microstructural data will also be collected on the specific cores measured (collaboratively with Gow and Perovich of CRREL). This will include measurements of inclusion size distributions, and correlation functions.

We will collect several cores from each ice sheet that is grown, to be used for the dielectric measurements. The experimental work will be conducted inside a cold room, and is not dependent on the out side temperatures, or the specific timing of the outdoor experiments.

SPECIFICALLY, DURING THE 1992 EXPERIMENT WE WILL:

1. Experimentally measure the complex dielectric constant from 26.5 to 40GHz of ice cores collected from an ice sheet grown in the outdoor pond. These measurements will be performed at several different temperatures and different electric field orientations.

2. Analyze the microstructure of the samples using thin sectioning, and image processing techniques (in collaboration with Gow and Perovich at CRREL) to understand the correlation between the microstructure and the dielectric properties.

The results of these measurements will be used to develop scattering models to verify these results, and to contribute to the development of the inverse models (in collaboration with Golden, Univ. of Utah, and Cheney, RPI).

REFERENCES

Rennie, R. (1991) Dielectric Measurements of Sea Ice in the Frequency Range 26.5 to 40GHz using a Quasi-Optical Technique, Master of Engineering Thesis, Thayer School of Engr., Dartmouth College, Hanover, NH.

Vant, M.R., R.O. Ramseler, V. Makios (1978) The Complex Dielectric Constant of Sea Ice at Frequencies in the Range 0.1-40GHZ, J. Appl. Phys., Vol. 49, No.3, p. 1264-1280.

Polarimetric Remote Sensing of Sea Ice

S. V. Nghiem, R. Kwok, S. H. Yueh, and J. A. Kong

To understand electromagnetic scattering and emission from sea ice and their relationship to physical and morphological characteristics, accurate active polarimetric backscatter measurements are proposed to be made at C-band frequency, which will provide complementary data to passive emission measurements. The experiments will be designed to collect well calibrated data for the validation and further development of forward and inverse models. Specifically, the measurements will be conducted to study volume scattering, surface scattering, combined volume-surface scattering, effects of temperature and other characterization parameters of sea ice, and layering effects due to snow and slush on sea ice. With the characterizing data in terms of profiles and bulk parameters, the measured electromagnetic signatures provide the experimental basis for physical interpretation with theoretical models. The research plan for this project is described in this report.

1. OBJECTIVES

The objectives of this research on Sea-ice Electromagnetics Accelerated Research Initiative (ARI) are to understand the electromagnetic properties of sea ice and their relationship to physical and morphological characteristics. For this purpose, accurate active polarimetric measurements are proposed to be carried out at C-band to provide complemetary data in an integrated manner with passive data of sea ice. The proposed experiments are designed to provide physical insights into the scattering and emission mechanisms from sea ice and validation of forward and inverse models. The experimental results will then be further fed back into the models for iterative refinement of theory and experiments that eventually close the experiment-model loop for understanding of electromagnetic interactions in sea ice. Specifically, the measurements will be conducted to study volume scattering, surface scattering, combined volume-surface scattering, effects of temperature and other characterization parameters of sea ice, and layering effects due to snow and slush on sea ice. These active and passive electromagnetic signatures together with sea ice characterization data provide the experimental basis for physical interpretation with forward and inverse models. In the effort to relate electromagnetic responses to the physical and morphological properties of sea ice, the accuracy of measurements, coupled with an understanding of the sensitivity required to validate forward and inverse models, is an important factor for the success of the program.

The plan for the research approach is to: (1) define the data quality requirements, which are then translated into the requirements on measurement procedures for data collection and the requirements on calibration measurements; (2) develop the data calibration algorithms for removing the system errors; (3) carry out a program for acquisition of fully polarimetric scattering measurements, which is coordinated with emission measurements and characterization of the sea ice, with focus on the parameters and hypotheses to be tested; and (4) process the data including calibration, reduction, coordination, and dissemination. Through this process, error sources can be identified and calibration data will be collected to remove these errors. The research plan to carry out these tasks are described in the following sections.

2. DATA QUALITY REQUIREMENTS

The data accuracy requirements will be analyzed by carrying out a sensitivity study, the number of measurement samples required in order to reduce statistical uncertainties, and calibration requirements for improving the accuracy of sensors.

The sensitivity study will be conducted prior to every experiment based on our up-to-date theoretical models, to determine the accuracy required for sensor measurements and also for characterization measurements. From available theoretical models, ice characterization parameters are used as input to calculate sea ice signatures. The sensitivity of the theoretical signatures on the input parameters will then be translated into the accuracy required for the instruments and experimental procedures. The accuracy requirement on measurements for forward models is determined based on acceptable tolerance for model testing.

Polarimetric scattering coefficients from sea ice, which contains random scatterers, are only meaningful in the statistical average sense, meaning that enough independent samples of the scatter data from many realizations of the ice configuration have to be collected in order to reduce the inherent statistical uncertainties when estimating the covariance matrix of the polarimetric backscattered data. Based on the statistical sampling and estimation theory, the number of independent samples, which need to be taken for each specified accuracy, will be calculated for the coefficients of interest. On the other hand, the uncertainties of the limited number of measurements will be estimated to assess statistically the accuracy of the measured data. This information will be important in data interpretation with forward and inverse models.

Besides the uncertainty due to finite sampling, the errors caused by the imperfection of the sensors used for data collection should be minimized by data calibration. The results of the sensitivity analysis or the data accuracy requirements will be translated into the requirements for the calibration experiments designed to infer the system parameters, including the gain due to the system and antenna, the antenna pattern, the target range, and the illuminated area.

3. CALIBRATION ALGORITHMS

To obtain useful polarimetric data for the validation of theoretical models and inversion of sea ice parameters or profiles, accurate calibration has to be carried out. Point targets for calibration will be deployed in scene and the responses from these targets will be used to estimate the parameters for polarization cross-talk or channel isolation, channel imbalance, antenna pattern, and the absolute radar gain.

According to the reciprocity theorem in electromagnetics, the complex backscattering element f_{hv} measured with horizontal polarization while transmitting vertical polarization is the same as f_{vh} measured with vertical polarization while transmitting horizontal polarization. However, due to the asymmetry of the transmitting and receiving ports of polarimetric radars, the measured HV and VH responses will not be identical in general and therefore need to be calibrated by a symmetrization method. The data symmetrization will be carried out by an exact algorithm based on the principle of reciprocity, which symmetrizes the measured scattering matrix by a two-by-two matrix derived from the polarimetric covariance matrix of measurements.

Because of the imperfect isolation (cross-talk) between the horizontal and vertical channels, the powers from the co-polarized channels will be coupled into the cross-polarized channels thereby contaminating the actual cross-polarized responses from sea ice. Cross-talks will be removed by using an algorithm which is based on the symmetry theory, valid for all scattering mechanisms to all orders, for the decorrelation between cross- and co-polarized components of the scattering matrix with reflection symmetry.

Due to the different losses and path lengths experienced by the signals in the horizontal and vertical channels, the relative gain and phase shift between these two channels will not be balanced. This channel imbalance, if not removed, will cause errors in the polarization amplitude ratio and the relative phase between HH and VV responses of sea ice, and thus distorts the signatures of sea ice. This channel imbalance complex factor will be estimated from the HH and VV responses of the trihedral reflector deployed during and experiment.

From the radar equation, it can be seen that in order to invert the backscattering coefficients from the power measured by the instruments, a factor accounting for the transmit power, antenna gain, receiver gain, range loss, and illuminated area, has to be determined by the radiometric calibration. To this end, the response of the trihedral reflector with known theoretical backscattering cross section will be used to infer this factor at every incident angle.

4. EXPERIMENTAL MEASUREMENTS

The experimental measurements are to provide new understanding of electromagnetic scattering and emission in relation to ice characteristics with quantitative interpretations from theoretical models. For this purpose, the measurement program, as described below, encompasses fully polarimetric measurements, active-passive interlacing, controlled experiments, and calibration measurements.

Fully polarimetric radar measurements are proposed to be made at C-band with incident angle up to 60 degrees. The fully polarimetric measurements of backscattering include both magnitude and phase of all combinations of linear horizontal (h) and vertical (v) polarizations. First, the full scattering matrix elements are obtained by transmitting h and receiving h and v, and then transmitting (v) and receiving v and h. The covariance matrix is formed from ensemble averages of measured scattering matrices. Mueller matrices will be derived from covariance matrices to obtain polarization signatures of sea ice. Experiments for understanding the volume, surface, and volume-surface scatterings will be carried out at the outdoor facility at CRREL, which allows both active and passive integrated measurements, and in the CRREL indoor pit, where the temperature is controllable.

Polarimetric active and passive measurements will provide complementary information for validation of forward and inverse models. However, the measurements must be made on the same sea ice, under the same physical and morphological conditions to obtain the active/passive data complementary. The active-passive interlacing is carried out by integrating an active system with a passive system to allow the same observation direction and the same sensor foot-print; then, the active data are taken, for example, while the passive sensor is on standby; and then, the active is on standby for the passive measurement during the integration time. This active-passive measurement interlacing will provide complementary data with time and space correlations for more rigorous testing of forward and inverse models. This effort promotes the coordination between active and passive data collection.

In the laboratory environment, some sea ice parameters or profiles can be controlled or partially controlled to carry out an experiment focused on isolating the effect of a characterizing parameter or a scattering mechanism. Important controllable effects, due to the unique laboratory facilities at CRREL, are temperature and layering. Temperature is an important parameter in governing sea ice characteristics due to thermodynamic phase change and permittivity variations in the sea ice constituents. This is especially relevant for new ice which will be grown at CRREL. Temperature effects can be investigated with experiments carried out at the outdoor ponds in CRREL by exploiting diurnal variations in temperature. In this case, remote sensing data need to be correlated with local weather data. Layering effects of snow or slush can also be studied at the outdoor pond with both active and passive sensors by using the removable roof, subject to the local snow condition. In the indoor pit, where the temperature is completely controllable, experiments are conducted to study ice growth and morphological conditions under controlled temperatures. Experiments to study scattering mechanisms and layering effects can also be carried out at the indoor pit, however, the measurements are limited to active radar since a radiometer cannot be used indoors due to thermal radiation contamination.

Calibration measurements will provide data for removing system errors and corrections on sea ice signatures to achieve the necessary accuracy established by the Data Quality Requirements. The calibration procedures will be performed as specified by the calibration algorithms before and after an experiment to assure long-term system stability. During the experiments, calibration measurements will be carried out periodically in order to account for the change of system parameters due to the variation of temperatures and other physical factors. The calibration data will include measurements of the radar cross-sections of a trihedral reflector, along with the measurements of the target range and the illuminated area.

5. DATA PROCESSING

The measured calibration data will be used in the calibration algorithms to calibrate the scattering data from sea ice. First, the data are symmetrized with a method developed based on exact solutions from the principle of reciprocity. After the data symmetrization, a series of procedures will be applied to the data to correct for cross-talks and channel imbalance both in terms of magnitude and phase. These algorithms are developed based on exact solutions for the calibrations. Finally, the radiometric calibration algorithm is used to obtain the fully calibrated data for accurate sea ice signatures. The calibration algorithms will be documented to explain how the calibration procedures are carried out.

When more information regarding sea ice scattering, emission, and characterization are obtained simultaneously, the validation and further development of forward and inverse models can be done on a more rigorous basis and, thereby, clearer understanding of electromagnetic interaction with sea ice can be reached. Correlated polarimetric active and passive data can be obtained from the proposed active-passive interlacing to be coordinated with other sensor measurements and sea ice characterization measurements to form a complete data set on the sea ice under investigation.

From the data base of active, passive, and characterization measurements, remote sensing data can be obtained for deriving relationships to ice parameters and extracting trends in the complementary active and passive signatures revealing the electromagnetic responses of sea ice. For this purpose, the data are reduced as functions of incident angles, ice characterization parameters, and other relevant variables. The reduced data can then be used to illustrate the trends for data interpretation, model validation, and directions for new experiments.

After measurement activities, data are formatted for users with a header in each data file for data notation and description. Algorithms are developed to extract the covariance matrix in a polarimetric backscattering format and also in a normalized format. For Mueller matrix, a computer program is written to obtain the complete set of the elements in the four-by-four matrix and polarization signatures from the measured data. In the data dissemination, collaboration from all institutions will be necessary to form the complete data sets to create a data library and the corresponding data catalog.

6. PLAN FOR 93 AND INPUT FOR CRREL EXPERIMENTS

For Sea Ice Experiment in the Cold Regions Research and Engineering Laboratory (CRREL) during next year (1993), our available models are used to determine which sea ice parameters need to be measured and to estimate the necessary accuracy of the parameters. The models calculate (1) effective permittivities, (2) volume scattering, and (3) surface scattering from sea ice chracterization parameters to obtain polarimetric active and passive signatures. For example, our model for calculation of effective permittivity estimates that at the temperature of $-10°C$, a 20% error in the measurements of axial ratios of ellipsoidal brine inclusions can lead to 20% error in the imaginary part; while similar error can be caused by only 5% in the sea ice bulk density measurements. In the followings, the parameters and their accuracies are suggested for ARI groups related to the measurements. These suggestions can be considered together with the inputs from other groups to define the overall ARI measurement program. For sea ice characteristics, the parameters are summarized as:

1. Temperature profile (10% accuracy) at surface and at 1cm intervals in depth
2. Salinity profile (10%) at surface and at 1cm intervals in depth
3. Density profile and bulk sea ice density (2%)
4. Horizontal thin sections at 1cm increment in depth
5. Vertical thin sections at 30° increments in azimuth
6. C-axis orientation angle with respect to horizontal plane within 5° accuracy
7. Linear dimensions of ellipsoidal brine inclusions (5%)
8. Correlation functions from horizontal and vertical thin sections
9. Size distributions for brine inclusions and air bubbles
10. Ice thickness (10% for ice less than 10cm thick, within 1cm for thicker ice)
11. For thin ice, measure salinity, density, and thickness of brine layer on top of sea ice

For the boundaries of the sea ice layer with other media, the surface roughness spectrum needs to be characterized by measuring the surface profiles. The rough surface scattering is dominant at smaller incident angle and the angular response can be very sensitive to the roughness spectrum. For example, a Gaussian surface gives rise to an exponential dependence of the backscattering coefficients on mean square surface slope in the geometric optic limit. Thus, the two-dimensional surface needs to be characterized with as much sample as possible. Followed are some suggestions:

1. For upper surface (air/ice interface), measure profile of more than 10 correlation lengths with highest possible resolution. For each azimuth direction, measure 10 profiles. Collect data for 10° azimuth steps.
2. For lower surface (ice/water interface), measure average thickness of the dendritic growth layer, average thickness of the knife-edge ice platelets in this layer, and the average area in which the horizontal c-axes are locally aligned in the same azimuth direction.

For polarimetric radar measurements, the radar needs to be calibrated to remove system errors due non-reciprocal effects, imperfect channel isolation, amplitude and phase imbalances. We are developing algorithms for applications to the calibration of ground-based polarimetric data. Thes algorithms include

1. Symmetrization of scattering matrix based on the principle of reciprocity
2. Cross-talk removal with exact solution based on symmetry theory
3. Algorithms for removal of amplitude and phase imbalances
4. Radiometric calibration to account for the transmit power, antenna gain, receiver gain, range loss, and illuminated area.

For the indoor pit in CRREL during summer 93, experiments are designed to monitor sea ice growth at cold temperatures with polarimetric radar at C-band. This experiment is to observe the variation the polarimetric signatures with respect to sea ice characteristic parameters during the ice growth. This process simulates the thin ice growth in the Artic under winter temperature and will help in the development of inversion models for sea ice parameters such as thickness. The experiments are also for studying volume/surface scattering effects with measurements on rough and smooth surfaces of the ice layer. The experimental data will provide the basis to test availble models and further development for more sophisticated theoretical models.

ELECTROMAGNETIC STUDY OF ARCTIC SEA ICE

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SUMMARY OF SCIENCE OBJECTIVES

Objectives of this program include the characterization and exploitation of the electromagnetics properties of sea ice with the ultimate goal to improve the retrieval of geophysical information using remote sensors. This activity will be accomplished through further documentation of the microwave signatures of sea ice in conjunction with and in support of a larger study of the relationship between the physical structure of ice and snow, and their electromagnetic properties in the sub-microwave, microwave, and millimeter-wave regions. Efforts will be coordinated and coupled with physical property characterizations, passive microwave observations, and theoretical modeling studies. Scattering measurements will be conducted to document the microwave response of specially prepared (laboratory) or selected (field) sea ice scenes. An important aspect of this work is to provide empirical measurements and guidance in support of the modeling and measurement aspect of the proposed program. Additionally, support will be provided in the measurement of physical and electrical properties using techniques established for the laboratory and field.

In both the microwave and optical remote sensing cases, it is important to further refine our knowledge as to what is being sensed. Questions include:

What are the sensors responding to?

How much of the signal is dominated by the snow/ice interface, the brine pockets within the ice sheet, the gas bubbles within the ice sheet, the snowpack, the wicking of brine into the snow on ice, and the ice/water interface (particularly of interest in the thin ice case)?

MEASUREMENT APPROACH TO MICROWAVE STUDY OF SEA ICE

It is believed that an improvement in and validation of forward scattering models and the development of inverse models will provide an enhanced ability to retrieve sea ice geophysical information. This will be promoted through a series of controlled laboratory experiments. The approach proposed concentrates on the examination of specific scattering behaviors. Scenes which yield dominant surface and volume scattering behaviors will be considered independently. The investigation then expands to include simulants comprised of mixtures of volume and surface scattering behaviors. A key aspect in the validation process is the determination of sensitivities to controlling parameters (sensor and scene). The characterization of the distribution of physical and electrical properties, both vertically and horizontally, is critical. The measurement suite of instruments and investigation approach will be assessed and evaluated to insure that the scattering and physical property measurements are of the required precision, sampling-frequency, accuracy, and detail. The portion of the electromagnetic spectrum (microwave) of principal interest extends from 0.5-to-94 GHz.

Measured data and focussed experiments will be used to identify the dominant and second-order scattering mechanisms and to detail the response of ice and snow to environmental forcing etc. These measurements are also important in identifying and understanding the key physical properties and processes (i.e., presence of a brine and slush, and ice-sheet state transitions). Data will be generated and prepared for use in model development and validation.

Sea Ice Features

There are a variety of sea ice features and forms of interest. Special consideration will be given to the following:
1) sensitivity to various surface roughness regimes;
2) interior-ice discrete-scatterers or permittivity fluctuations;
3) snow on ice;
4) collection of brine or slush at the air-ice or snow-ice interface; and
5) ambient temperature and solar heating effects.

Physical Property Characterizations

Sea ice is a crystalline material composed principally of freshwater ice in which brine, salt particulates, and gaseous inclusions are embedded systematically and non-systematically. Characterization measurements (provided as a group) will include
1) high-resolution (vertical and horizontal) salinity, porosity, and temperature profiles,
2) 3-dimensional interior ice permittivity parameters,
3) surface roughness mean, fluctuation, and correlation lengths,
4) crystallography, and brine geometry and distributions, and
5) snow crystal shapes, sizes, bonding, and density.

INSTRUMENTATION AND MEASUREMENT APPROACH

The acquisition of scattering coefficients which are highly accurate is critical to this program. Sensor calibration and intercalibration will be addressed rigorously and documented. Procedures will be developed to insure complete sensor characterization. This will prove useful in the utilization of these data and for the development of techniques to extract sensor effects, if necessary. Efforts will be pursued to promote the coordination of the many measurement aspects of this program. These includes the observations of the ice physics, meteorology, microwave measurement (scattering coefficient, emission, and electrical property), and optics measurements.

Acquired data to be provided to the ARI are summarized in the tables which follow. Microwave measurements will be conducted from 0.5-to-94 GHz utilizing an instrumentation-type radar which is polarimetrically capable. The heart of the radar includes a vector network analyzer (HP8510) for use as the IF processor, a frequency synthesizer for phase-locked IF signal control, RF and antenna array modules, and a system control and data acquisition computer.

On-site data processing will be incorporated to allow near real-time assessment of the backscatter response. This will facilitate the detection of transitions in physical properties, changes in ice sheet state, the formation of brine on the ice surface, or the freezing of brine at the snow-ice interface, among others.

MICROWAVE SENSOR MEASUREMENT MATRIX FOR YEAR 1 OF ARI

SYSTEM	FREQUENCY	POLARIZATION	INCIDENCE ANGLE
POLRAD	0.5 & 1.25 GHz 5.25, 9.38, 35 & 94 GHz	VV & HH Fully Polarimetric	40° 0°-to-50°

Electrical Property Measurements

Electrical property measurements will be acquired by using the scatterometer operated at 0° incidence to obtain a measure of the coherent response which is dominated by the bulk dielectric constant of the scene. In addition, a small reflectometer which operates at 10 GHz will be positioned at the side of the ice tank for baseline measurements.

Surface Roughness Measurements

Surface roughness measurements will be provided using the "sample-retrieval vertical-photographic method" developed by Onstott. Slabs (> 3 cm x 30 cm) of ice will be retrieved (for thicknesses greater than about 1 cm). A vertical thick-section (wafer with a thickness of about 2 mm) is then prepared and photographed with a camera with a flat field-of-view and oriented normal to the air-ice interface. Photographs will be mosaiced and digitized. Statistics will then be calculated. This measurement technique is optimum when surfaces are very-smooth to rough and when roughness statistics are to be used at millimeter frequencies (i.e. where very fine height and length resolutions are required). An additional advantage is provided in the delineation between the ice surface and overburden layer (i.e. snow and frost flowers) is often greatly facilitated.

ELECTRICAL AND SURFACE ROUGHNESS MEASUREMENT MATRIX

Property	Description
Electrical	Radar Reflectivity: (1) $\lvert\epsilon_r^*\rvert$: spaced temporally in time at 5-to-94 GHz. (2) $\lvert\epsilon_r^*\rvert$: continuously measured in time at 10 GHz.
Surface Roughness	Sample-Retrieval Vertical-Photographic Method: $\sigma_{surface}$ $\ell_{surface}$ $Slope_{surface}$ $PDF_{surface.height}$

OBJECTIVES AND PLAN FOR THE LABORATORY OBSERVATIONS OF YEAR 1

PURPOSE

- Determine the magnitude of the contributions of surface and volume scattering for new and young first-year ice.
- Examine the ability to model first-year ice with variable (small) scales of air-ice roughness.

APPROACH

A thick (>20 cm) sheet of congelation ice will be grown to produce a scene with a slow time-varying microwave signature and one where scattering is limited to within the ice sheet (for one not too thin), and one for which the influence of surface brine expulsion is minimal.

This ice sheet will be observed for various surface roughness conditions (i.e. for $\sigma \approx$ 0.05-to-0.4 cm rms). A section of the ice sheet will be maintained in its natural state ($\sigma \approx 0.05$ cm rms) and will be intercompared with the modified portion of the ice sheet. A goal is to maintain ice in the two target areas (perturbed and undisturbed) which are identical, except for differences in surface height properties of the air-ice interface (i.e. the top 0.2-to-1.2 cm of the ice sheet) . All other properties associated with permittivity, brine, and air will be maintained. This approach is taken to argue that if signature differences arise between these two scenes they will only be attributable to changes in surface-height properties and not to properties within the ice interior. If scattering is driven solely by volume scattering from within the ice interior, the effects due to a perturbed air-ice interface will be small. If, however, the air-ice interface dominates the process than the scattering behavior will be comparable to that predicted by surface scattering theory. In some portions of the frequency range used in this study both surface and volume scattering may be required for signature prediction, especially if during the investigation the ice undergoes too high of a degree of desalination and porosity enhancement.

Two adjacent regions on the ice sheet will be utilized and measurements will be conducted in pairs (i.e. natural and perturbed). This allows (a) for the temporal intercomparison of a smooth and rough ice sheet, (b) the monitoring of changes in the ice sheet (i.e. short term desalination effects, T_{air}, solar radiation etc) which effect the microwave signatures, and (c) an ability to insure that all roughness regimes may be intercompared.

Ice Roughness Regimes

Four ice regimes will be created and studied. The air-ice interface will be perturbed by depositing particles composed of fresh water on the ice sheet. The natural response of young ice is to release a quantity of brine when a particle is deposited. If brine fills in at the particle-ice interface, melting of the particle will occur. In time this liquid will refreeze, bonding the particle to the ice sheet and filling in about the particle. The four roughness regimes proposed include:

(a) naturally smooth ($\sigma \approx 0.05$ cm rms),
(b) perturbation due to 2 mm snow crystals ($\sigma \approx 0.1$ cm rms),
(c) perturbation due to 4 mm crushed ice pellets ($\sigma \approx 0.2$ cm rms), and
(d) perturbation due to 1 cm ice cubes ($\sigma \approx 0.4$ cm rms).

Surface Modification Goals

Goals in preparing a rough surface scene include providing:

(a) a uniform distribution of surface elements with a Gaussian distribution considered the ideal,

(b) minimal air voids in the surface layer and a surface discontinuities with a fine spray of fresh water used to fill air voids an reduce surface discontinuities, and

(c) a perturbed ice sheet is allowed to temperature stabilize (> 1 hour) before a measurement session proceeds.

Surface Roughness Characterization

The characterization of surface-height properties is paramount in the surface roughness parametric study. Measurements are needed to document the surface-height distribution, the correlation-length function, and anisotropy. Multiple techniques will be applied in accomplishing this objective. A visual assessment and "mechanical comb method" (Gogineni) will be made to establish the uniformity of surface elements during surface construction. The "light-projection photographic-method" (Winebrenner and Perovich) will be used to provide the large areal survey of roughness. Numerous radial profiles will be required throughout the perturbed scene for each of the roughness regimes. The "sample-retrieval photographic-method" (Onstott) will be used to describe the roughness of the smoothest ice scenes and for a reference from which to compare the results of the other two methods.

Ice Sheet Characterization

The "standard set" of ice physical property measurements is required. Additional emphasis is needed to characterize the voids and air bubbles in the surface roughness layer, the layer structure, and the bubbles and brine features found in the immediate vicinity of the air-ice interface. This examination will be based on thin-section assessments (Gow and Perovich). Measurement of the upper layer density is important in monitoring changes in porosity.

Electrical Property Characterization

Multifrequency radar reflectivity measurements will be made of both the natural and perturbed ice sheets to monitor and measure the bulk dielectric constant.

PROPOSED MEASUREMENT SCHEDULE

Series	Dates	Comments
Installation Preparation	6-11 January	System Installation and Calibration
Growth Study	11-21 January	Observation of undisturbed congelation ice growth for ice 0-to-20 cm.
Air-Ice Interface Perturbation Study	21-27 January	Study of thick saline ice with 4 roughness regimes. One will be naturally smooth and provide a temporal reference insuring precise inter-data intercomparison. Case 1: Smooth Thick Ice ($\sigma \approx 0.05$ cm rms) Case 2: Slightly Rough ($\sigma \approx 0.1$ cm rms) Case 3: Moderately Rough ($\sigma \approx 0.2$ cm rms) Case 4: Rough ($\sigma \approx 0.4$ cm rms)

DELIVERABLES AND EXPECTED NEW UNDERSTANDING

A laboratory-based measurement program is planned because it allows the requisite detail needed in performing a full validation of forward scattering models. Accurate forward models are required to facilitate the development of inverse methods. Achievement of high precision and a full range in all contributory parameters in all facets of this investigation will be required. Systematic variation in these parameters allow the exercise of models over a wide array of potential parameter combinations. *In situ* arctic trials are also planned to provide an additional basis for the evaluation of program success in improving the retrieval of geophysical properties.

These measurements will be made in conjunction with measurements in other portions of the electromagnetic spectrum. Synergisms are anticipated in both the characterization of the scattering properties in ice and snow, as well as in the utilization of multiple sensors to improve information retrieval. These data will be available to support all aspects of the ARI.

This program will also have as a principal thrust the theme of developing an improved understanding of the evolution of sea water into ice and the aging of sea ice. The change in physical and electrical properties (salinity, surface temperature, surface and bulk dielectric constant, penetration depth, and surface roughness statistics), and the corresponding change in the microwave signature is of great interest in the desire to improve the ability to discriminate sea ice from water and to relate $\sigma°$ with a continuum of ice thicknesses for young and old sea ice forms.

The role of surface and volume scatter in the generation of backscatter from new and young ice will be examined in Year 1 through a perturbed air-ice interface experiment.

RELATIONSHIPS OF OPTICAL PROPERTIES AND ICE STRUCTURE

1993 CRRELEX PLANS

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INTRODUCTION

An understanding of how shortwave radiation interacts with a sea ice cover is important to a number of problems. Shortwave radiation plays a critical role in the heat balance of a sea ice cover. Spectral reflectance and polarization data for different ice types are necessary in the interpretation of visible and near-infrared remote sensing imagery. Information on light transmission and scattering in sea ice has naval operational significance. The amount and spectral composition of light transmitted through the ice cover are important factors in primary productivity under the ice. The transmission of ultraviolet light through the ice may influence the health of marine organisms.

Sea ice exhibits a great degree of temporal and spatial variability in its structure. This variability strongly impacts the optical properties of the medium. In particular, there are large changes in optical properties associated with the initial formation and growth of new ice. The microstructure of sea ice is intricate and highly variable consisting of ice platelets, air bubbles, and brine pockets and channels. All of these inclusions are potential absorbers and scatterers of light. Since sea ice is always at or near its salinity determined freezing point, changes in ice temperature result in changes in the brine volume and the ice structure, changes which impact the optical properties of the ice. Relating ice structural changes to changes in ice optical properties is the primary objective of our CRRELEX observational program.

SCIENTIFIC OBJECTIVES

The overall long term objective of this project is to determine quantitative relationships between the optical properties of sea ice and its physical state and structure and then implement this information into a theoretical framework which relates the ice optical properties to the ice structure. Achieving the long term objective of this project entails addressing several specific short term goals including:

1. Measure spectral values from 280-1100 nm of apparent optical properties such as albedo, transmittance, bidirectional reflectance function, and polarization for a wide variety of first year and multi-year ice types.

2. Couple radiative transfer models with the observations of apparent properties to calculate inherent properties such as extinction coefficient, single scattering albedo, and phase function from 280-1100 nm.

3. Relate seasonal changes in optical properties to changes in ice structure.

4. Examine the effectiveness of polarization data in distinguishing among various surface types.

APPROACH

Our 1993 observational studies will concentrate on insitu measurements of the optical properties of ice sheets grown under controlled conditions at the CREEL Geophysical Research Facility. The optical measurements will consist of a) measurements of spectral irradiance and radiance of selected ice types, ice thicknesses, and surface conditions and b) routine recording of bulk irradiances. These measurements will be performed during daylight hours on all three of the proposed ice sheets.

Field portable spectro-radiometers with fiber optic probes (e.g Spectron Engineering 590, Analytical Spectral Devices PS-11) will be used to make spectral measurements from 280-100 nm as the ice sheets grow and evolve. The observational program will include periodic spectral measurements of a) incident, reflected, and transmitted irradiance, b) the angular distribution, in both azimuth and elevation, of reflected and transmitted radiance, and c) the polarization of reflected radiance. These data will be used to compute spectral albedos, transmittances, bidirectional reflectance functions, and polarization levels for the ice studied.

The focus in this season's CRREL pond experiments will be on the congelation growth phase experiment. We will also perform measurements during the artificially roughened ice and snow-covered ice experiments. The optical dataset from these experiments will be used to elucidate differences in the optical properties between these snow and ice conditions and also to examine changes in the optical properties as the ice evolves. Areas of particular interest include monitoring variations in the optical properties as the ice grows thicker, as the brine volume changes, and as the physical properties of the surface layer changes.

In addition to the spectral measurements, wavelength integrated values of incident, reflected, and transmitted irradiance will be routinely measured using shortwave radiometers (Eppley; International Light 1700). These data will be recorded every few minutes on a Campbell Scientific datalogger to provide information on short-term variations in the bulk optical properties. These bulk observations will be correlated with data on ice temperatures and brine volumes.

The proposed optical measurements will be made in close coordination with other optical and microwave programs and will be complemented by a detailed physical characterization of these ice sheets characterization of these ice sheets (Gow and Perovich, 1992). The physical characterization will provide information on the ice structure, as well as the vertical distribution of salinity, temperature, brine volume, and air volume. Information on the size distribution of air and brine inclusions will be particularly useful in interpreting the optical observations and relating the optical properties to the ice structure. Finally, all pertinent results will be made available to the other ARI participants. Particular care will be taken to provide a comprehensive dataset to the inverse modelers.

SEA ICE CHARACTERIZATION WITH MILLIMETER WAVE RADARS AND LOW FREQUENCY MICROWAVE RADIOMETERS

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Robert E. McIntosh (Co-PI)

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PROPOSED PROGRAM AND APPROACH

The following presents details on our proposed research, which is experimentally intensive. The discussion can be summarized if we consider our research to be addressing the following hypotheses:

- Remote sensing laboratory facilities offer great value in the understanding of electromagnetic interaction with natural surfaces, such as sea ice in its various forms
- Novel electromagnetic system techniques and judicious choice of operating characteristics can be used to independently infer various sea ice and snow parameters, such as volume inclusions and surface roughness
- Extended electromagnetic frequency bands will provide new ice products
- Valid theoretical models can be developed to explain the experimental results. As a corollary, simple algorithms can be developed to explain first order interactions.

We propose a three year research program, and a preliminary schedule is presented as Table I. We believe that three years is needed to report data, and certify that the program will leave behind a useful facility that can be routinely used to check out future remote sensing concepts and technology that are sure to develop.

INDOOR FACILITY MEASUREMENT PROGRAM

There are two facilities at CRREL that we propose to use in studying the electromagnetic properties of sea ice. One of the facilities is commonly referred to as "the pit". This is a refrigerated room which contains a relatively deep pool which can be filled with either fresh or saline water, and frozen to obtain ice thicknesses exceeding one foot. The temperature can be lowered to -20 degrees Centigrade, and regulated to within a degree or two. A second facility which we plan to use will be one of the conventional cold rooms, where we will conduct backscattering measurements on smaller prepared ice slabs. The advantages of using indoor facilities are evident. Measurements can be done during any season and on any particular day. In addition, there is considerable amount of control over

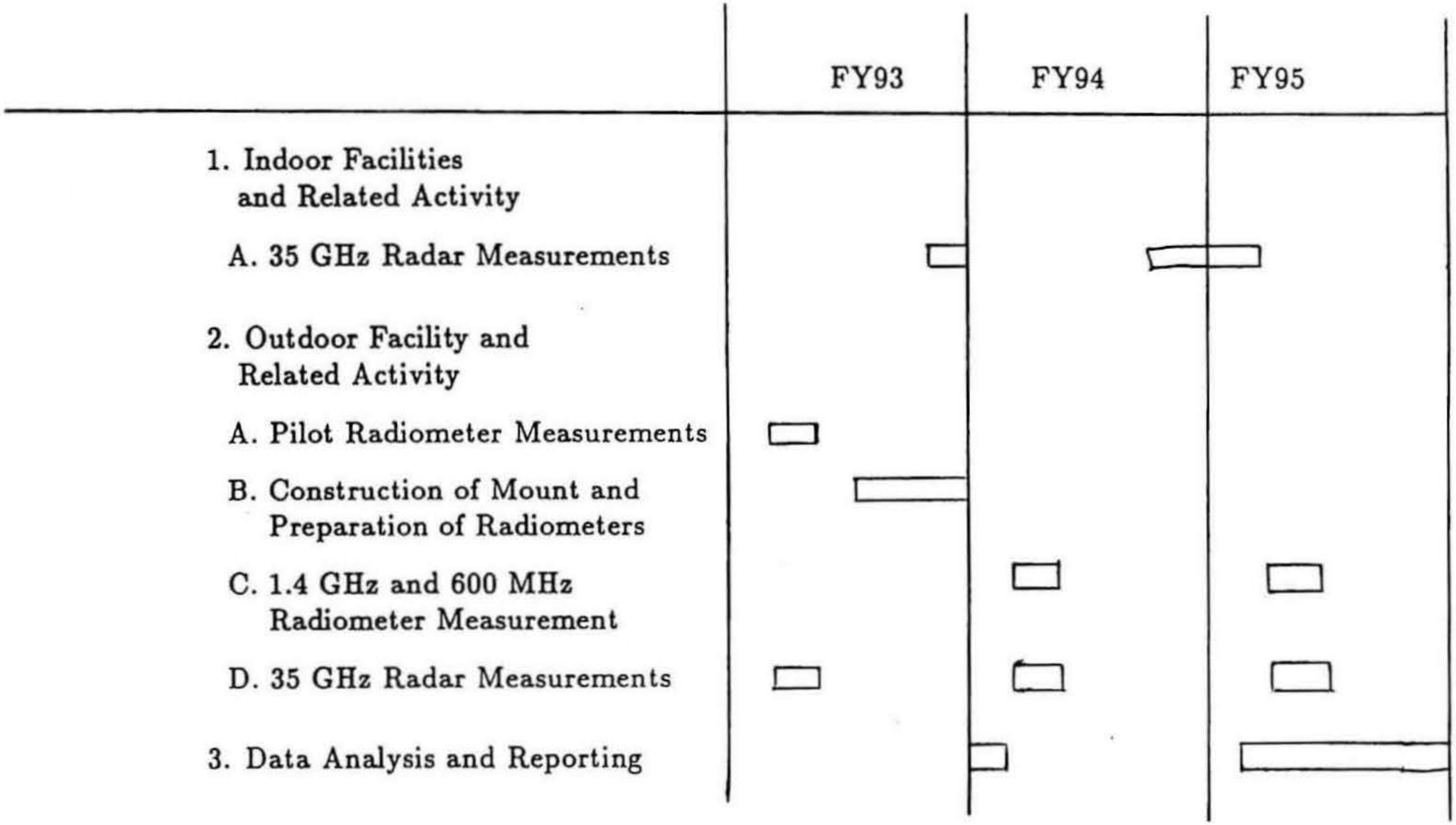

Table I. Work Plan and Events

the situation to reduce the experiment to its essence. For example, the temperature can be driven low enough to prevent surface melting and its effect on the microwave signature.

Equipment

Because an inside facility is relatively isothermal (i.e., no large contrast between the target and the "sky"), passive microwave measurements are difficult to implement. As a result, all of our indoor measurements will utilize active techniques. Our specific plan is to use Hewlett-Packard 8510 Network Analyzer based radar systems. The 8510 is a wide band system which allows us to time-gate the radar backscatter signal in order to reject errors associated with multiple reflections from walls and other obstacles. The 8510 is also a coherent system, which is needed to conduct polarimetric radar studies. The only disadvantage of the 8510 is that it requires time to cycle through the broad band of frequencies needed to transform to time domain reflectometry. Fortunately, time scales are relatively long relative to ice growth, which presents us with no problems. We have already constructed a 35 GHz radar to be used in conjunction with the 8510 system. This radar has the potential of achieving full polarimetric capability. A block diagram of this system is shown in Figure 1. This system has performed in an evolutionary mode over the past 2 - 3 years, and can now efficiently provide polarimetric data.

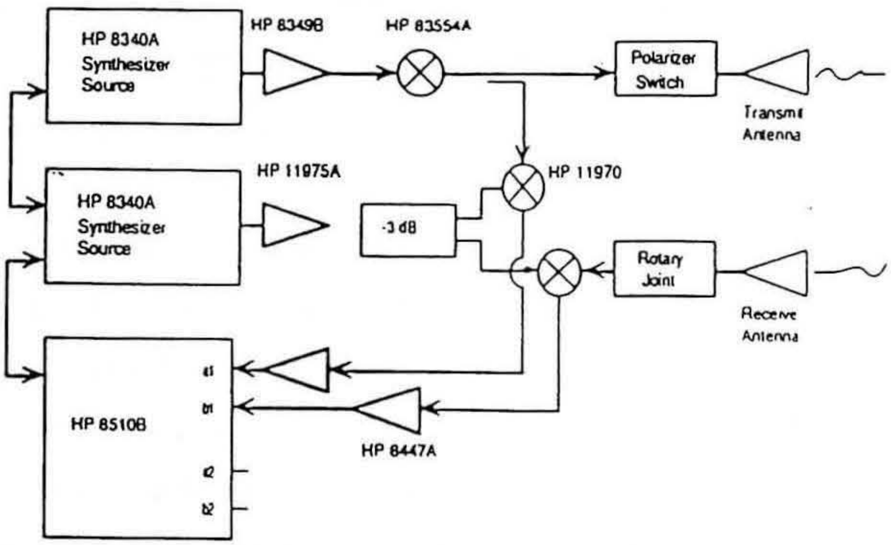

Figure 1. University of Massachusetts' polarimetric scatterometer

Measurements Using the "Pit" Facility

As we mentioned above, two indoor facilities will be used at CRREL. The first facility that we will use will be the pit. We plan to do a series of measurement which relate to baseline measurements, rough surface scattering measurements, and volume scattering measurements. In the category of baseline measurements, our first priority is to measure the polarimetric signature of ice during the growth phase at 35 GHz. The purpose here is identify and remove instrument imperfections associated with antenna cross-polarization, component phase errors, gain drifts, etc. A corner reflector will be deployed for calibration, and a metal sheet will be placed over the ice at the conclusion of the growth phase experiment to establish a reference that is completely devoid of volume or rough surface scatterers. We anticipate that the difference between the flat plate and thick smooth ice signature will establish a volume scattering level for inclusions within the ice. After the ice has assumed a stable thickness, backscattering measurements will be done as a function of ice temperature as the room temperature is allowed to cycle from an extremely low value towards the melting point without actually allowing the ice to melt and produce surface water. Pilot experiments have been done at 35 GHz, and we observed that the radar cross section generally increased as the ice temperature became warmer. We would like to redo these experiments to check repeatability and to extend the observational wavelength. However, of a more fundamental nature, we would like to identify whether the change in radar cross section is due to changes in the dielectric constant with temperature, or if it is due to brine being flushed out. In order to pin down the latter possibility, we will work with CRREL scientists to assure that ice sampling will be done to establish the salinity level within the ice. Various methods have been used in past CRRELEX experiments to generate surface roughness including raking the surface and deploying ice cubes and spraying water to make the cubes adhere to the surface. One of the better methods of generating a rough surface has been to use a mechanical paddle at the edge of the tank to generate waves while the ice freezes. This is equivalent to the ice rafting process in the natural environment. We would propose to use the paddle to generate several ice surfaces, each characterized by a different scale of roughness. We can conceive of changing the scale of roughness by controlling the mechanical frequency of the paddle.

The last series of experiments that we immediately anticipate relate to snow over ice. We are very interested in these experiments because they will provide an in depth study of the volume scattering process. Snow is an extremely low loss dielectric, and electromagnetic waves can penetrate considerable distance within snow. It is also known that free water content within snow creates a volume scattering situation, which we do not expect to see within the ice layer as a result of the high bulk attenuation. If we therefore place a few tens of centimeters of snow on top of the ice, we can use time gating to positively identify a volume scattering situation. The utility of time gating was illustrated by Beaven et al., whose unpublished results are shown in Figure 2. The importance of these results is that it illustrates that range gating can be effectively used to separate volume scattering from surface scattering. Without time gating, there is no other unique way to separate these two scattering processes. Therefore, if we wish to use combinations of wavelength, polarization, and viewing angle to separate volume and surface effects, we will need range gating as a control parameter. For example, if we place snow over a roughened ice surface, observations plotted vs. viewing angle for a particular range gate will clearly provide a separation mechanism for surface vs. volume scatter. Snow over ice will also provide a basis for a number of comprehensive measurements. Snow surface roughness can be changed in order to see if the weak reflecting boundary will support significant scattering from the snow air interface. Temperature cycling can be used to control the free water content and therefore the degree of volume scattering. Extreme temperature cycling can be done to significantly alter the snow density and grain size which should also impact the back scattering.

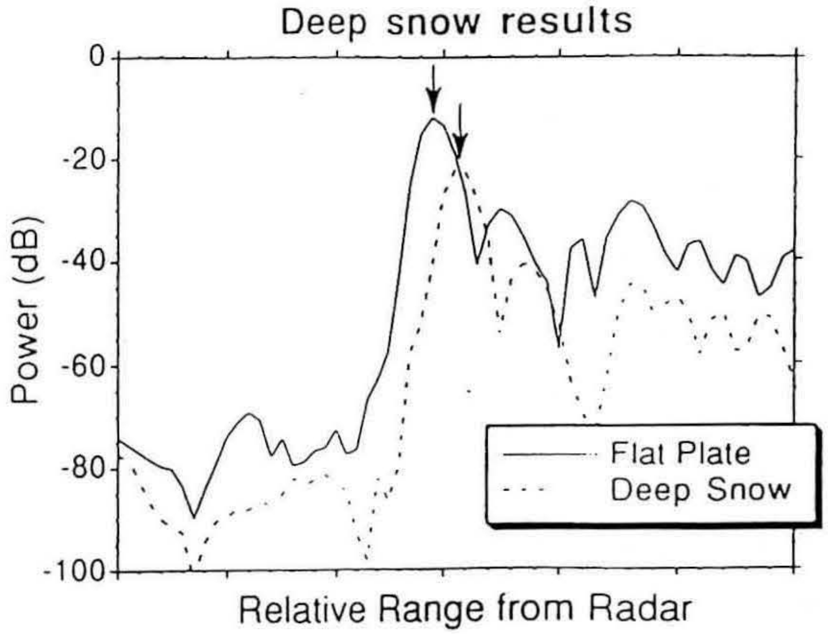

Figure 2. Results from the deep snow experiment demonstrate that the return from snow-covered saline ice is from the ice-snow interface. The snow depth is 21 cm

We emphasize that we are looking for experimental combinations of viewing angle, polarization, and wavelength to arrive at a reasonable basis of concluding whether we have volume or surface scattering in a particular experiment. In this vein, we will also be looking carefully at the statistical data collected as a part of the experimental procedure. For example, the radar must be physically translated to collect independent radar samples; low roughness and correlated volume scatterers will require larger distances between independent data samples. This decorrelation distance will show up in the data reduction process. As another example, a short temporal decorrelation should be indicative of significant volume scattering.

Measurements Using Cold Room Facilities

The more conventional cold room facilities were used for the first time this year to evaluate a new experiment to test the validity of volume scattering theories. Specifically, small spherical pellets, or "bb"s were frozen into a slab of fresh water ice to set up a controlled experiment. These pellets have a known constant diameter, and a known number were frozen into a known volume of ice to fix the number density of scatterers. This experiment has an additional advantage of potentially allowing the radar system to be stationary, and rotating the loaded slab to achieve independent samples. In this case, target rotation can be used in addition to translation in order to obtain a very large number of independent samples. The fact that the radar will be stationary will reduce systematic measurement error; the large number of independent samples will reduce random error.

The overall purpose of this experiment is not to simulate actual sea ice, but to provide a well defined geometry whose scattering properties can be modeled and compared with carefully done experiments. We can envision fabricating a number of these slabs, each having a significant perturbation of its electromagnetic description; such as a change in volume density and diameter of the inclusions. It would also be possible to introduce elliptical inclusions in order to introduce an anisotropy in the scattering measurements.

Outdoor Facility Measurement Program

An out of doors facility is presently under construction at CRREL as a replacement to one that was funded by the Office of Naval Research. The construction costs for this new facility will borne by the Army, and will introduce a number of advancements including a greater depth needed to grow and support a thicker ice sheet. This facility will be built in stages to introduce improvements to preserve the integrity of the ice sheet during winter thaws. Although the facility will not be able to operate all year long, a movable roof and cooling units will hopefully be added at a later date to overcome effects of rain and thawing periods during the winter months.

Equipment

We also plan to use the 8510 based radar system for the out of doors experiments. However, one of the principal advantages of conducting the experiments outside is the fact that it is now possible to conduct passive microwave measurements. Thus, we will be able to emphasize the radiometer measurements in these series of experiments. In particular, we will concentrate on the lower microwave frequencies for the passive microwave measurements. Specifically, we plan to evaluate 1.4 GHz and 600 MHz for sea ice measurement applications. The 1.4 GHz channel is already being explored by NASA to conduct soil moisture measurements from space. Because of the large penetrating capability of long wavelengths into lossy dielectrics, 1.4 GHz may find applications in the remote sensing of sea ice; particularly in deriving thickness and identifying thin ice types. The 1.4 GHz radiometer is on indefinite loan from NASA Langley Research Center, and has recently been overhauled and will collect ocean-related data from a ship in connection with TOGA COARE. This instrument will therefore be ready to participate in experiments once a suitable mounting platform has been constructed. The 600 MHz radiometer, also on loan from Langley, has already been used to observe sea ice from a ship on a cruise to Antarctica; however, some modernization will be necessary to improve data collection.

Although our passive microwave measurements will concentrate on low frequency radiometry, we are presently developing a 35 GHz passive polarimeter which will be used to measure the entire Stokes' matrix. This device will have a four channel output which will allow reconstruction of any polarization state.

Measurements Using the Outdoor Facility

We will initially focus on installing a suitable structure to mount our equipment. This may not be a trivial task, since we will concentrate on making passive microwave measurements at longer than traditional electromagnetic wavelengths. For example, our 1.4 GHz radiometer utilizes a 1m x 1m antenna aperture. Our 600 MHz radiometer has an antenna with much larger antenna dimensions and the unit weighs several hundred pounds. The utility of the long electromagnetic wavelengths exhibited their usefulness during the early CRREL experiments when the UMass C-Band Stepped Frequency Microwave Radiometer (SFMR) was used to collect data over the first outdoor facility. Results were published which indicated that microwaves provide observations over a depth corresponding to approximately one free space wavelength into the ice. By adding L-Band and UHF, we can expect to probe as deep as 20 cm and 50 cm with the respective new instruments, and hopefully learn more about the bulk properties of the saline ice. In addition, dry snow cover becomes more transparent as the wavelength increases. Therefore, the long wavelengths, when used in concert with the more conventional wavelengths (which we assume will be provided by other investigators, such as Grenfell and Lohanick) will provide a multispectral data base for future multi-sensor discrimination of snow covered ice. Another unique measurement that was made by the SFMR was the deduction of changes that occurred in the dielectric constant of sea ice during the immediate growth. Our observations indicated that during immediate freeze-up the dielectric constant assumed a rather large value of 15 for the first few millimeters of growth and then began to decrease toward the nominal value of 4 with continued growth. Additional longer wavelengths are needed to better define the temporal characteristics of the dielectric constant, and the results will be of great value in establishing the electromagnetic properties during growth with the idea of eventually characterizing thin ice types with remote sensing instruments. Controlled experiments will also shed some insight on the changing characteristics of snow as a result of wicking of the surface brine. We are convinced that the surface brine determines the high dielectric constant associated with the initial growth. Up to this point, all of our 8510 radar measurements have been done indoors in the pit and in cold rooms. After the outdoor facility is completed, we will also conduct radar measurements. The radar will have full polarimetric capability, and will complement the more traditional radar frequencies, which we anticipate will be provided by other investigators, such as Onstott or Gogenini. We fully anticipate that our radars will be extremely sensitive to backscatter introduced by volume scatterers. We therefore anticipate that our millimeter wave radars will be a powerful tool for characterizing the signature of snow over the ice surface. The range gating capability will also allow us to locate the sources of volume scattering. We believe that in time, millimeter wave radars will be operating in space, and backscatter from snow will be evident in the data. These experiments will open a preliminary data base to enable future investigators to interpret the spacecraft results.

Another exciting area that is beginning to emerge is radiometric polarimetry. The polarimetric signature may give clues on the relative importance of surface vs. volume scattering. In addition, and polarization state can be synthesized to optimize parameter extraction and to provide all polarization combinations to test modeling results. This represents a relatively new capability, and initial experimentation is needed to determine its full utility as a concept.

Modeling

Intensive modeling, as is done by investigators such as Brown, Fung, Kong, and Winebrenner is not our forte; however, we recognize its value, as well as our development of first order theory. We do intend to interpret our own data on a first-order basis, and to keep the approach as physically based as possible. Within limitations, the first order results gives excellent insight into the processes. For example, geometric optics and small perturbation theory connect quite well to the dominant radar scattering processes; however, neither approach succeeds in predicting the proper level for the cross-polarized component. We would relegate this more involved analysis to others who have geared up their research programs to address problems such as this. Other examples of first order analyses would be to ignore multiple volume scattering and to assume an incoherent interaction between boundaries of different dielectric media. Other avenues of modeling that we have pursued in the past has been the development of easy to use regression formulas to calculate an electromagnetic parameter which may be a function of several variable. One such example is the expression for the dielectric constant of sea water as a function of temperature and salinity. This work has been widely referenced, and was a relatively straightforward task to do as a consequence of the homogeneity of the physical properties of sea water. This is an example where it is difficult to arrive at an expression starting from absolute fundamentals, and it may be expeditious to develop such empirical models to account for higher order effects.

INVERSE PROBLEMS FOR MAXWELL'S EQUATIONS

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Our proposal deals with the theoretical and numerical aspects of inverse problems for Maxwell's equations. The problems we consider are all concerned with probing the internal structure of any inhomogeneous medium (e.g sea ice) from electromagnetic measurements which are made in the exterior.

The main thrust of the proposal is to extend methods developed by the proposers for the isotropic impedence tomography problem so that they may be used to treat inverse problems for Maxwell's equation. There are two main difficulties which must be dealt with: the first is the extension of results from the scalar conductivity equation to a system of equations; the second difficulty is anisotropy. Both of these difficulties have been dealt with to a limited extent already by the proposers and others.

We will elaborate on the previous paragraphs in more detail below. For now we make a brief summary of what we expect to do within the next three years:

FIRST YEAR PLAN

1) Completely characterize the obstructions to solving the linerarized inverse boundary value problems and inverse scattering problems for

Maxwell's equations (i.e. determine what parts of the full permittivity, permeability, and conductivity tensors can possibly be recovered from exterior measurements). We will begin to address the following specific situations which are special to sea ice:

a) How is the uniqueness question affected by the priori knowledge that the magnetic permeability is constant and isotropic? are the the remaining electromagnetic parameters uniquely determined by scattering or boundary measurements?

b) Does uniqueness for the linearized problem still hold in the case where the only data is monostotic (i.e. backscattering)?

c) If the dielectric coefficients depend only on depth, can a one-dimensional inversion procedure succeed in recovering the coefficients? Could observations of waves that are normally incident be sufficient data for such an inversion?

EXTENDED PLANS FOR YEARS TWO AND THREE

2) Solve the identifiability problem for the anisotropic inverse scattering problems for Maxwell's equations when the medium has special symmetries. This is an extension of 1.c above.

3) Develop a High frequency "Born approximation" for anisotropic Maxwell's equations under suitable hypotheses.

4) Develop and implement methods for stabilizing layer stripping algorithms for the inverse conductivity problem as well as investigating the applicability of such methods

to Maxwell's equations. We expect to apply such methods to the problem of recovering the depth of the ice from scattering data.

Inverse Boundary Value Problems for Maxwell's Equations Let $\Omega \subseteq \mathbb{R}^3$ be a bounded domain in $\mathbb{R}^3$. For an inhomogenous anisotropic medium, the electric permittivity, electric conductivity and magnetic permeability are positive definite tensors denoted by $\varepsilon(x)$, $\sigma(x)$ and $\mu(x)$ respectively. For an isotropic medium these tensors are scalar functions. The problem is to determine as much as possible about these parameters from measurements of the electric and magnetic fields at the boundary.

The electric field $\mathcal{E}$ and the magnetic field $\mathcal{H}$ satisfy the time-dependent Maxwell equations

$$\text{(1)} \qquad \begin{aligned} \text{curl } \mathcal{E} + \mu \frac{\partial \mathcal{H}}{\partial t} &= 0 \quad \text{in } \Omega, \\ \text{curl } \mathcal{H} - \varepsilon \frac{\partial \mathcal{E}}{\partial t} &= \sigma \mathcal{E}. \end{aligned}$$

If we consider time harmonic waves of the form

$$\text{(2)} \qquad \mathcal{E}(x,\ t) = E(x)e^{-i\omega t},\ \mathcal{H}(x,\ t) = H(t)e^{-i\omega t}, \omega > 0.$$

with frequency ω, then the space-dependent E and H satisfy the harmonic part of Maxwell's equations

$$\text{(3)} \qquad \text{curl } E - i\omega H = 0,\ \text{curl } H + i\omega n E = 0,\ \text{in } \Omega$$

with

$$\text{(4)} \qquad n(x) = \varepsilon(x) + i\frac{\sigma(x)}{\omega}.$$

Let ν denote the unit outer normal to $\partial\Omega$. We denote by Λ the map that assigns the tangential component of $E|_{\partial\Omega}$ to that of $H|_{\partial\Omega}$, i.e.,

$$\text{(5)} \qquad \Lambda(\nu \wedge E) = \nu \wedge H.$$

The inverse boundary problem is then to determine $\varepsilon(x), \mu(x),\ \sigma(x)$ from knowledge of the map Λ.The map Λ summarizes the results of all possible boundary measurements. The medium is identifiable if Λ contains sufficient information to determine the internal parameters of the medium.

This problem was proposed by Cheney, Isaacson and Somersalo in [S-I-C] in the isotropic case. They considered the linearized problems at a constant background.

If the time variation of the electromagnetic field is slow (i.e. steady state direct current or low frequencies) then this becomes the impedence tomography problem proposed by Calderón ([C]): to determine the conductivity of a body by making voltage and current measurements at the boundary. There has been considerable progress in dealing with this problem in recent years both in the theoretical and applied aspects of the problem (see the surveys [C-I] and [S-U V]). The system (1) in this case is replaced by the scalar equation (we use the letter γ instead of σ to denote the conductivity in this case).

$$\text{div }(\gamma \nabla u) = 0 \text{ in } \Omega,\ (\gamma > 0 \text{ in } \overline{\Omega}) \tag{6}$$

and the map Λ_γ, referred to as the Dirichlet to Neumann map, is given by

$$\Lambda_\gamma(u|_{\partial\Omega}) = (\gamma \frac{\partial u}{\partial \nu})|_{\partial\Omega}. \tag{7}$$

In the isotropic case, fundamental progress was obtained by the proposers ([S-U, I-IV]) by constructing exponentially growing solutions of (6) of the form

$$u = e^{x\cdot\rho}\gamma^{\frac{-1}{2}}(1 + \Psi_\gamma(x,\rho)) \text{ in } \Omega \tag{8}$$

with ρ in $\mathbb{C}^n$, $\rho \cdot \rho = 0$ and $\Psi_\gamma \to 0$ as $|\rho| \to \infty$ uniformly in $\overline{\Omega}$.

The analog of (8) for the system (3). has already been constructed by Sun and Uhlmann [Su-U] in the isotropic case under the additional assumption that the parameters are close to constants, by Colton and Paivarinta ([C-P]) under the assumption that the magnetic permeability is constant in Ω, and more recently for the general isotropic case by Ola, Paivarinta, and Somersalo ([O-P-S]).

Inverse Problems for Anisotropic Maxwell's Equations The case of anisotropic materials presents additional difficulties. In general, it is not possible to recover an anisotropic conductivity from its Dirichlet to Neumann map. Given any γ and any diffeomorphism Ψ which fixes the boundary of Ω, we can construct a (generally) different conductivity, $\Psi_*\gamma$, with the same voltage to current map. The formula reads

$$(\Psi_*\gamma(y))^{\ell m} = \frac{\frac{\partial \Psi^\ell}{\partial x^i}\gamma^{ij}\frac{\partial \Psi^m}{\partial x^j}}{\det(\frac{\partial \Psi}{\partial x})} \circ \Psi^{-1}(y). \tag{9}$$

Hence it is possible to recover γ from Λ_γ only up to the action of the group of diffeomorphisms Ψ which fix $\partial\Omega$ (this was first observed in [K-V]).

The obvious conjecture is that any two conductivities with the same voltage to current map are related by such a diffeomorphism.

There are two main difficulties in proving such results: the first is the construction of the special complex exponential solutions which played the dominant role in all the isotropic problems, and the second is the construction of the diffeomorphism.

The proposers have shown that this is the only obstruction to the linearized problem at constant background at either high or low frequencies ([S-U IV]).

The same diffeomorphism action provides an obstruction to identifiability for Maxwell's equations as well, and the proposed work 1) from the first page of the project description is to decide whether the diffeomorphism action is the only such obstruction to solving the same inverse problem for Maxwell's equations. There are now three symmetric tensors to be reconstructed form the data, and there may be more obstructions to identifiability. The same methods as in the conductivity problem reduce this to an algebraic calculation, but one whose solution is not yet clear.

For the full nonlinear problem, the fact that the diffeomorphism invariance is the only such obstruction has been proved in two dimensions for C^3 conductivities which are close to constants in [S I] and in dimensions ≥ 3 for analytic conductivities on strictly convex domains in [L-U].

The methods introduced in [S I] should extend to the axially symmetric inverse problem for Maxwell's equations, while the methods from [L-U] may extend to the Maxwell system with real analytic coefficients. This is the work proposed in 2) on the first page.

Inverse scattering problems

In the inverse scattering problem, one attempts to determine the parameters $\varepsilon(x)$, $\mu(x)$, $\sigma(x)$ in (3) from measuring the far-field pattern of the electromagnetic field . If the frequency is fixed (and low), the inverse scattering problem is equivalent to the inverse boundary value problem discussed in the proposal. In particular the results of Sun and Uhlmann ([Su-U]) , Colton and Paivarinta ([C-P]) and Ola, Paivarinta and Somersalo ([O-P-S]) apply to determine the electromagnetic parameters in the isotropic case.

The case of high frequency behavior is also of considerable interest for the determination of the medium parameters of sea ice; the scale of the inhomogenieties is large compared to the wavelenghts.

We plan to extend the geometrical optics construction from the isotropic to the anisotropic case in order to obtain the analog of the Born approximation. The main difficulty is the complicated structure of this system. For example if we consider Maxwell equations in a biaxial crystal, i.e. the case where the electric permittivity has 3 different eigenvalues, the magnetic permeability is constant and the conductivity is zero,the system has characteristics speeds that coalesce, i.e. double characteristics ([M-U], [U]). In this case, the geometrical optics construction is available for scalar equations having the same characteristic speeds as Maxwell equations ([M-U], [U]). The proposers plan to extend this construction to the system: to construct geometrical optics solutions as well as find the analog of the Born approximation.

Layer Stripping and the Ricatti Equation

Probably the most important problem is to develop algorithms to reconstruct the electromagnetic parameters. The work proposed in 4) on the first page is to develop a stable version of such an algorithm.

A detailed description of the algorithm was included in our original proposal and will not be repeated here.

The main point is that the naive layer stripping algorithm is extremely unstable ; however, knowledge of a partial (and perhaps complete) characterizations of the data serves to stabilize the method.

The proposed research involves 1) studying the stability properties (at both high and low frequencies) of this algorithm in both the layered and radially symmetric cases in two and three dimensions, 2) attempting some naive extensions of the stabilized method to the non-layered case, and 3) extending the methods to Maxwell's equations.

The proposers plan to consider the case of a layered medium and extend the algorithm constructed by Sylvester ([S II]) for radial conductivities. This algorithm is related to layer-stripping methods which have been developed by Cheney et al. ([C-I-S-I]) for the impedance tomography problem. It is different in that it uses a theoretical characterization of the data to stabilize the algorithm

References

[C] Calderón, A.P., *On an inverse boundary value problem*, Seminar on Numerical Analysis and its Applications to Continuous Physics, Soc. Brazileira de Matemática, Rio de Janeiro, (1980), 65-73.

[C-I] Cheney, M. and Isaacson, D., *Current problems in impedence imaging*, SIAM Proceedings Series List, Inverse Problems in Partial Differential Equations, (1990), 141-149, D. Colton, R. Ewing and W. Rundell, editors.

[C-I-S-I] Cheney, M., Isaacson, D., Somersalo, E., and Isaacson, E., *A layer stripping approach to impedence imaging*, 7th Annual Review of Progress in Applied Computational Electromagnetics, Naval Postgraduate School, Monterrey, (1991).

ACTIVE OPTICAL MEASUREMENTS DURING CRRELEX '93

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SCIENCE OBJECTIVES

1. Determine the connectivity between microwave volume backscatter and optical transmission and beam spreading for smooth young ice as a function of ice layer thickness, freeboard, and microwave frequency.

2. Determine the impact of ice roughness conditions on ice layer optical transmission and beam spreading measurements and relationship to changes in the surface roughness induced backscatter signature.

LONG-TERM OBJECTIVE

Exploit combined optical and microwave remote sensing to provide additional information on sea ice and snow geophysical parameters.

MEASUREMENTS AND APPROACH

A thick ice sheet will be growned to produce slow changes in the optical properties due primarily to changes in ice sheet thickness and brine expulsion. Beam spreading functions and ice layer transmission losses will be measured by placing a Nd:YAG laser source beneath the ice sheet and direct the beam upward through the ice sheet. The resulting beam spreading pattern will be measured just above the ice surface. Measurements will include both radiance and irradiance along a transect through the beam center axis. Measurements will be made with a vertical beam although an off-axis beam pattern may also be investigated if time permits. Passive irradiance above and below the ice sheet at the laser wavelength with irradiance sensors which are coupled into the same instrumentation package. The beam spreading measurements will require an area which can be accessed from the side of the pond of four square meters (2m X 2m). Laboratory measurements of transmission and beam spreading will be made on small ice samples coincident with the *in situ* experiments.

[L-U] Lee, J. and Uhlmann, G., *Determining anisotropic real-analytic conductivities by boundary measurements* , Comm. Pure Appl. Math., XLII, (1989), 1097-1112.

[Na J] Nachman, A., *Reconstructions from boundary measurements* , Annals of Math, 128, (1988), 531-576.

[N I] ________, *Inverse scattering at a fixed energy*, to appear Proceedings of the 10th International Congress on Math. Physics, (1991).

[No] Novikov, R.G., *Multidimensional inverse spectral problems* , Funct. Anal. and Appl. 22, 263-272 (1988).

[R] Ramm, A., *Recovery of the potential from fixed energy scattering data*, Inverse problems 4, (1988), 877-886.

[S I] Sylvester, J., *An anisotropic inverse boundary value problem* , Comm. Pure Appl. Math, XLIII (19–), 201-23-.

[S II] ________, *A convergent layer stripping algorithm for the radially symmetric impedence tomography problem*, to appear Comm. P.D.E.

[S-C-I] Somersalo, E., Isaacson, D. and Cheney, M., *A linearized inverse boundary value problem for Maxwell's equations* , preprint.

[Su-U] Sun, Z. and Uhlmann, G., *An inverse boundary value problem for Maxwell's equations* , to appear Archive for Rat. Mech.

[S-U I] Sylvester, J. and Uhlmann, G., *A uniqueness theorem for an inverse boundary value problem in electrical prospection* , Comm. Pure Appl. Math., XXXIV, (1986), 91-112

[S-U II] ________, *A global uniqueness theorem for an inverse boundary value problem*, Ann. of Math., 125, (1987), 153-16-.

[S-U III] ________, *Inverse boundary value problems at the boundary-continuous dependence*, Comm. Pure Appl. Math., XLI, (1988), 197-221.

[S-U IV] ________, *Inverse problems in anisotropic media* , Contemp. Math., 122, 105-117 (1991).

[S-U-V] ________, *The Dirichlet to Neumann map and applications*, SIAM Proceeding Series List, Inverse Problems in Partial Differential Equations, (1990), 141-149, D. Colton, R. Ewing and W. Rundell

INSTRUMENTATION

Instrumentation will include the (1) the ERIM laboratory sea ice transmissometer unit which will require cold tent space (7'X7'), (2) the *in situ* laser transmissometer which will be operated from the pond apron with a detector track unit extended over the pond ice (see attached figure). The detector unit will be movable along the track to record the upward beam spreading pattern. The scanner platform will contain an upward and downward looking irradiance sensors and a downward looking radiance detector. The track/scanner structure will be portable and can be removed to support other experiments. The Ne:YAG (532nm) laser source will be positioned from a temporary fixture which will be attached to the hard-points located on the sidewalls. This installation will be made prior to filling the pond with saltwater. This laser source unit can then be attached to this fixture while the pond is filled. Our intention is to leave the source unit in place during both the ice growth and ice roughness experiments. If it becomes necessary to remove the laser source unit for repairs a 2' diameter ice hole will be required. Space is needed in the hut structure to be located along side the pond for data logging. The PC recording system and table will require a 7' X 7' space.

MEASUREMENT PLAN

Optical measurements will be made for each of the experiments described above. The present expectation is that the laser measurements will be supported for a seven day period during each experiment. It is essential that these beam spreading/transmission measurements be conducted on the same ice sheet and times as the Onstott/ERIM microwave measurements. At present these microwave measurement experiments are planned to be more extensive and time coordination of these measurements is not expected to be a problem. For the ice growth experiment, when the sheet surface is smooth and protected from the weather the optical measurements can be made on the opposite end of the pond from the microwave measurements. During the ice roughness experiments it may be necessary to move the optical transmission measurements to the same portion of the ice sheet. The most desirable scenario is to perform the same physical surface roughness experiments on two sections of the pond and likely separated by the gantry. The proposed schedule follows.

Besides the microwave measurements (Onstott) the laser transmission measurements will need a complete set of ice physical property measurements. Emphasis is needed on characterization of voids and air bubbles in the surface layer and the brine features found in the lower ice layers (Gow and Perovich).

The surface roughness modifications described by Onstott must be implemented in the surface area designated for optical measurements. Alternatively the laser beam transmission and spreading measurements could be perform on the same portion of the sheet provided that interference and obstructions imposed by the detector/scanner operations is not a problem.

PROPOSED MEASUREMENT SCHEDULE

Activity	Dates	Description
Installation	6-11 January	System setup and calibration
Smooth Ice Sheet Growth Study	11-18 January	Measurements of the undisturbed ice growth for 0-20cm with protection and maintenance of a smooth surface (<0.05cm rms)
Surface Roughness Study	21-28 January	Maintain ice sheet at a constant thickness and change surface roughness from smooth (undisturbed) to rough in controlled steps

DELIVERABLES

The optical data will be integrated with both the physical data and microwave data sets to yield time series of coincident measurements of upward optical beam transmission and spreading, diffuse transmission, bottom reflectivity, microwave backscatter measurements (Onstott) at selected wavelengths and incidence angles, ice physical properties (Gow and Perovich) such as temperature and ice thickness measurements as a function of time and ice sheet thickness. For the growth study the time series will not likely be continuous but rather consist of a series of hourly ten minutes series. If coincident downward spreading measurements made by NUWC (Longacre) are available they will also be integrated into the deliverable. Quality of daytime beam transmission and spreading measurements will inherently be less because of the interference of ambient light. The best day to day time series will be collected during nighttime hours. During the surface roughness experiments optical, microwave, and physical measurement data will be gathered at each roughness step. A written data report will follow the CRRELEX experiments describing the datasets collected and instrumentation and procedures.

DATABASE DEVELOPMENT

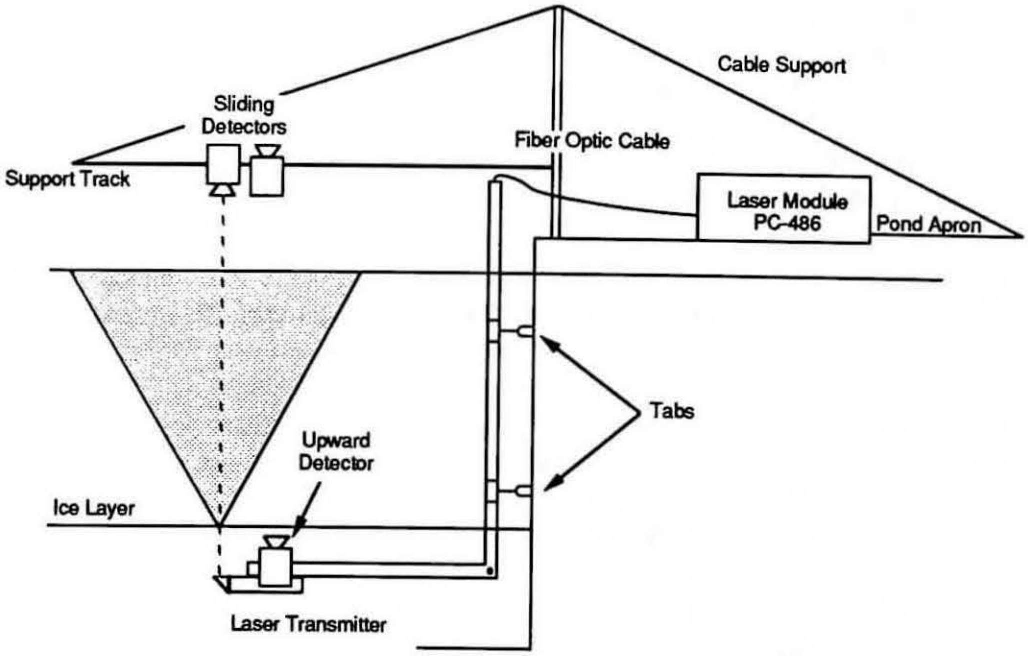
A database is being developed at ERIM to support the entire community of scientists working on the Electromagnetic Properties of Sea Ice ARI. Plans call for the structural portion of the database to be ready in early Spring of '93. The database will span visible, infrared, millimeter, and microwave portions of the electromagnetic spectrum. A system of three separate databases is presently envisioned. (1) The investigator's meta database will contain descriptive information on experimental data, instruments, data collection times, data identifiers, status of processing, modeler's data needs, etc. This database will be essentially a catalog of available data and anticipated entries and will be organized by investigator. The meta database could become a source for preparation of periodic status reports. (2) The modeler's database will contain datasets used as input to forward and inverse models and also possibly the model prediction results. The modeler's database can be visualized as the interface between the modelers and the experimenter's. The experimenter's can place specific datasets (e.g.dielectric and temperature profiles) into this database to support modelling activities. This latter database will be organized by wavelength group with indicators included to show sources (investigators) and relative time marks for of coverage for each entry. The modeler's database is the one that will be updated as new results are obtained and the one that would likely get published in a electromagnetic properties of sea ice monograph published during the last year of the ARI. (3) The experimenter's database will contain processed datasets and will be organized by experimenter, experiment, time mark, and parameter. Initially the layering might look something like Ken Jezek's measurements chart he presented at the ARI workshop.

The database can be supported through INTERNET requiring minimal user costs and ease of data entry and retrieval operations. The recommended approach is to develop an E-MAIL database server which can be accessed by all investigators and ONR management. Other possible approaches include wide area information servers and anonymous FTP. With the E-MAIL approach a database use can simply send an E-MAIL message containing a series of data requests and data entries. Help files will be installed to guide use of each of the three databases. The database requests will be served automatically from a request que and return E-MAIL messages will contain the desired requests. If very large data requests(entries) are made it may be more appropriate to receive (send) the data on 8mm tape cassette. E-MAIL data entries will be held until they can be reformatted for entry in the database.

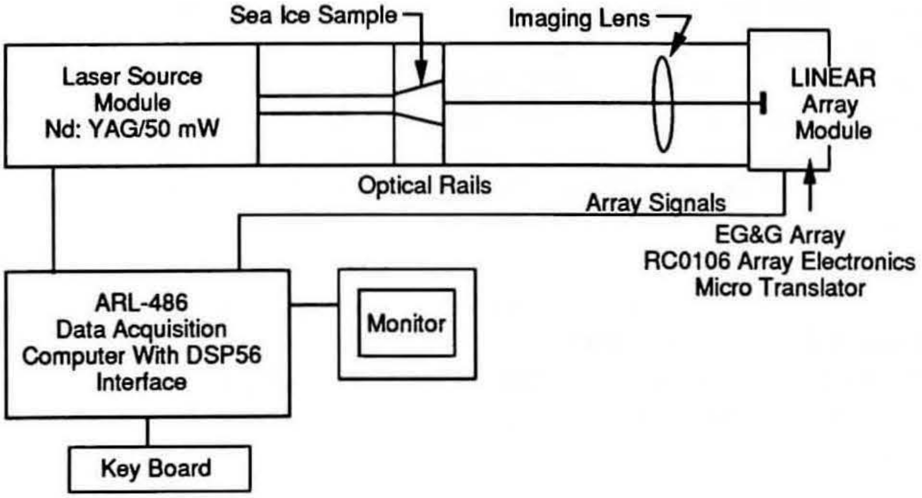
This database can be up and running by April or May. This database is recognized to be an important component in the ARI. Suggestions for the structure are needed. It is vital that an agreed upon format be put into this plan. I would think it appropriate to begin populating the investigator's database as early as next April.

SET UP FOR CRREL UPWARD LASER TRANSMISSION MEASUREMENTS

CES-91-084a-1-R1



LABORATORY SEA ICE TRANSMISSOMETER



Research Plan for CRRELEX 93 and Later Years

Scattering Physics in Microwave Signatures of Sea Ice: A Focussed Investigation
Dale Winebrenner, PI, and T.C. Grenfell and L. Tsang, co-I's

Prologue: Basic Theoretical Expressions and Characterization Requirements

The theoretical part of our proposal is based on (1) intercomparisons of two quite different volume scattering theories, many-layer strong fluctuation theory (SFT) and dense medium radiative transfer (DMRT), against an extensive common data set of characterization observations and scattering and emission observations, and (2) an examination of interactions between volume and rough surface scattering effects. Thus our work requires characterization of both the inhomogeneities in sea ice as well as surface roughness. Following is a brief and simplified overview of the fundamental equations for SFT, DMRT, and two classes of rough surface scattering models, together with specifications on accuracies needed in characterization for meaningful tests of scattering models, such as can be given based on current knowledge of model sensitivities.

Note the following model summaries are by no means derivations; the reader should not expect that the results quoted are obvious from the background given. The summaries are given just to illustrate the main elements of the theory and results in some particularly simple cases. Learning these theories from the ground up still requires a substantial effort with the literature. Note also that the notation is not constant or consistent between subsections below; rather, we have in each case used notation consistent with the original papers on each theory in the hope that this would cause the least confusion in further study.

(Stogryn's) Many-Layer SFT Model

Stogryn's SFT model computes (bistatic) scattering cross sections for sea ice , and from these the emissivity , assuming that the ice is isothermal, using Kirchhoff's law:

$$e_j(\theta_o) = 1 - |R_j(\theta_o,\phi_o)|^2 - \frac{1}{4\pi\cos\theta_o}\int_0^{\pi/2}\int_{-\pi}^{\pi} \sin\theta\, d\theta\, d\phi \left[\sigma^o_{jh}(\theta,\phi;\theta_o,\phi_o) + \sigma^o_{jv}(\theta,\phi;\theta_o,\phi_o)\right],$$

where $e_j(\theta_o,\phi_o)$ is the emissivity for polarization $j = h$ or v, at nadir and azimuthal angles of observation θ_o and ϕ_o, respectively, $|R_j|^2$ is the Fresnel power reflection coefficient for the same polarization, and $\sigma^0_{jv}(\theta,\phi;\theta_o,\phi_o)$ and $\sigma^0_{jh}(\theta,\phi;\theta_o,\phi_o)$ are the incoherent (bistatic) differential scattering cross sections in the scattering direction θ, ϕ for h- and v-polarized radiation incident from the direction θ_o, ϕ_o, respectively.

Sea ice as a scattering medium is idealized by the model in the following way:

(1) Microscopically, sea ice is pictured as consisting of pure ice in which prolate-spheroidal brine pockets and spherical air bubbles appear spatially randomly-occurring

inhomogeneities. All brine pockets are assumed to be of the same size and shape parameters, and all air bubbles are assumed to be of identical radius. These parameters are to be supplied from ice characterization measurements. Any dry snow on top the ice is thought as a collection of spherical ice particles embedded in air, each with the same radius. (We will consider only dry snow here.) This radius is also to be set according to independent characterization information. Typical brine pocket sizes are tenths of millimeters wide by roughly 1 millimeter long. Typical air bubble radii range from tenths of millimeters for first-year ice to millimeters for multi-year ice, whereas typical snow particle radii are on the order of a millimeter.

(2) Brine pockets are sandwiched between ice platelets and thus aligned in individual sea ice crystals (which have dimensions of roughly 1 cm). This results in in a local tensor permittivity within each crystal. The orientation of crystals, however, is random, and thus the local tensor permittivity varies randomly from place to place in the sea ice. This fluctuation in the tensor permittivity is the source of volume scattering in the sea ice in this model. Volume scattering in snow is due to the spatial fluctuations in permittivity between ice- and air-filled spaces.

(3) The macroscopic properties of the ice and any overlying snowcover are assumed constant in any horizontal plane, but may vary arbitrarily in the z-(i.e., depth-) direction. This allows realistic treatment of measured depth profiles of ice salinity. and other properties. The current implementation of the model treats as may as 30 distinct layers, each with differing ice or snow properties (but within which properties are assumed constant). It is assumed, however, that the macroscopic properties display no horizontal anisotropy -- that is, there is no preferred horizontal direction associated with or defined by the ice or snow properties. Thus, for example, the prolate-spheroidal brine pockets generally have their major axes tilted away from vertical, all in a given direction within a given crystal. However, the random orientation from crystal to crystal causes a macroscopic azimuthal isotropy. Note, though, that the vertical elongation of the brine pockets does lead to a dielectric anisotropy (i.e. a mean dielectric tensor), with a vertical preferred direction.

(4) Scattering from rough interfaces above or within the ice and snow can be neglected -- at least, the the model does not treat any such scattering.

The spatial and angular distributions of the electric field vector, $\overline{E}$, are determined from the following wave equation for $\overline{E}$ within the random medium:

$$\nabla\times\nabla\times\overline{E} - k^2\overline{\overline{K}}\,\overline{E} = 0 \tag{2}$$

Both the electric field and dielectric tensor $\overline{\overline{K}}$ are expressed as the sum of mean and (spatially) fluctuating parts, $\overline{E} = \overline{E}_m + \overline{E}_r$ and $\overline{\overline{K}} = \overline{\overline{K}}_o + \overline{\overline{K}}_r$.

The essential tasks are to compute the mean (coherent) electric field and the incoherently scattered field. The bilocal approximation is used to compute the mean field, which, under this approximation satisfies the wave equation:

$$\nabla\times\nabla\times\overline{E}_m - \left[k^2\overline{\overline{K}}_o + \int_{z'<0} d^3r' <\overline{\overline{\xi}}(\overline{r})\overline{\overline{G}}(r-r')\overline{\overline{\xi}}(r')>\right]\overline{E}_m = 0 \tag{3}$$

The tensor Green's function $\overline{\overline{G}}$ is specified by requiring that it satisfy the wave equation

$$\nabla \times \nabla \times \bar{\bar{G}}(\bar{r}-\bar{r}') - k^2 \bar{\bar{K}}_o \bar{\bar{G}}(\bar{r}-\bar{r}') = \delta(\bar{r}-\bar{r}') \ . \tag{4}$$

Note that the mean field depends on position (and, in particular, on depth) within the ice and snow. ξ is a second rank tensor related to the randomly varying (most generally, tensor) permittivity, $\bar{\bar{K}}(\bar{r})$, at a point $\bar{r}$ in the random medium by the relation:

$$\bar{\bar{\xi}}(\bar{r}) = k^2[\bar{\bar{K}}_o(\bar{r}) - \bar{\bar{K}}(\bar{r})] \left[1 + \bar{\bar{S}}\, k^2[\bar{\bar{K}}_o(\bar{r}) - \bar{\bar{K}}(\bar{r})] \right]^{-1} \ , \tag{5}$$

where $\bar{\bar{S}}$ is a tensor that depends on the shape of the correlation function for permittivity fluctuations, that is, on the so-called exclusion volume (e.g., $\bar{\bar{S}} = -[\ 3\ k^2 \bar{\bar{K}}_o]^{-1}$ in the case of a medium with spherically symmetric correlation of permittivity, such as the collection of jumbled ice spheres used as an idealization for snow in this model). This relation is a consequence of the defining relation for $\bar{\bar{\xi}}$, namely

$$<\bar{\bar{\xi}}> = \bar{\bar{0}} \ . \tag{6}$$

For plane wave illumination of the kind of random medium specified above, the mean field also turns out to be a plane wave with an effective propagation constant (depending only on depth, z)

$$\bar{\bar{K}}_{eff}(z) = \bar{\bar{K}}_o(z) + k^{-2} \int_{z'<0} d^3r' \int dx \int dy < \bar{\bar{\xi}}(\bar{r}) \bar{\bar{G}}(r - r') \bar{\bar{\xi}}(\bar{r}') > \tag{7}$$

The ensemble averages indicated above are averages over different configurations of the scattering medium. For media with spherically symmetric permittivity correlation functions (e.g., snow), this means just averaging over different positions of inhomogeneities. For sea ice, however, this averaging also includes an averaging over the orientations of the equi-correlation surfaces to model the large scale azimuthal isotropy, even in the presence of elongated brine pockets tipped away from the vertical direction.

Computation of the correlations between elements of $\bar{\bar{\xi}}$ indicated in equation 7 boils down to to a computation in terms of correlation functions (as functions of spatial lag) between elements of $\bar{\bar{K}}$. These may be inferred from direct measurements of the correlation function of the spatial pattern of ice and brine, such as those obtained by D. Perovich of CRREL. In Stogryn's model, however, these correlation functions are themselves calculated based on the ice temperature, salinity and density at a given depth, together with assumptions about the geometric configurations of brine pockets and air bubbles in the ice, and ice grains and water inclusions in (generally wet) snow. Thus independent information about brine pocket sizes, shapes, inclinations and so on can be used 1) to set these parameters directly in Stogryn's model, and 2) to check the correlation functions for elements of $\bar{\bar{K}}$ computed by Stogryn's model.

Note that Equation 6 in fact determines $\bar{\bar{K}}_o$, the quasi-static dielectric tensor of the random medium. For snow, this formula retrieves the Polder-van Santen formula for dielectric mixtures.

It remains then to compute the incoherent scattered field. This version of strong fluctuation theory accomplishes this via the distorted Born approximation, i.e., by assuming that the incoherently scattered field is made up predominantly of contributions scattered directly out of the coherent field (but subsequently re-scattered -- this limits the strength of scattering that can be treated using SFT, but the severity of the limit is difficult to estimate theoretically).

$$\bar{E}_r(\bar{r}) = -\int_{z'<0} d^3r' \bar{\bar{G}}(\bar{r}-\bar{r}')\bar{\bar{\xi}}(\bar{r}')\bar{E}_m(\bar{r}') \tag{8}$$

Various ensemble averages of the scattered electric field for certain choices of illumination then determine the reflection coefficients and scattering cross sections.

In the most general cases treated so far by Grenfell, the effective permittivity takes the form

$$\bar{\bar{K}}_{eff} = \begin{bmatrix} K_{11} & 0 & K_{13} \\ 0 & K_{11} & 0 \\ K_{13} & 0 & K_{33} \end{bmatrix} . \tag{9}$$

For snow, the off-diagonal terms in this tensor are zero.

With $\bar{\bar{K}}_{eff}$ in hand, the reflection coefficients for horizontal- and vertical-polarization can be computed. In the special case where $\bar{\bar{K}}_{eff}$ is not a function of depth, these are given by

$$R_h(\theta_o) = \frac{\cos\theta_o - (K_{11}-\sin^2\theta_o)^{1/2}}{\cos\theta_o + (K_{11}-\sin^2\theta_o)^{1/2}} \tag{10a}$$

and

$$R_v(\theta_o) = \frac{(K_{11}/K_{33})^{1/2} B\cos\theta_o - \left[(K_{33}-\sin^2\theta_o)^{1/2} + \dfrac{\sin\theta_o\cos\theta_o K_{13}}{(K_{33}-\sin^2\theta_o)^{1/2}}\right]}{(K_{11}/K_{33})^{1/2} B\cos\theta_o + \left[(K_{33}-\sin^2\theta_o)^{1/2} - \dfrac{\sin\theta_o\cos\theta_o K_{13}}{(K_{33}-\sin^2\theta_o)^{1/2}}\right]} , \tag{10b}$$

respectively, where

$$B \equiv \left[1 + \frac{K_{13}^2/K_{11}}{K_{33}-\sin^2\theta_o}\right]^{1/2} . \tag{10c}$$

The general form for the scattering cross sections according to this model is given by an integral expression of the form

$$\sigma^0_{ab}(\theta,\phi;\theta_o,\phi_o) = C(k,\theta,\phi,\theta_o,\phi_o)\cdot \tag{11}$$

$$\int_{-\infty}^{0}\int_{-\infty}^{0} dz'dz'' f_a(z')f_a^*(z'')A_{bb}(z')A_{bb}^*(z'')W(k_{ox}-k_x,k_{oy}-k_y,z',z'')$$

where a and b denote the receive and transmit polarizations, respectively, the f's are associated with the mean electric field, the A's with the Green's tensor $\bar{\bar{G}}$, and W is a Fourier transform of the a correlation function associated with $\bar{\bar{K}}$. The wavenumbers in the argument of W are given by $k_x = k\sin\theta\cos\phi$, $k_y = k\sin\theta\sin\phi$, and $k_{ox} = k\sin\theta_o\cos\phi_o$, $k_{oy} = k\sin\theta_o\sin\phi_o$.

The most illustrative case is that of a single, optically thick (i.e, effectively infinitely thick) layer of snow for hh-polarization. In this case, the quasi-static and effective permittivities collapse into scalars K_o and K_1, respectively. Then we have

$$\sigma^0_{hh}(\theta,\phi,\theta_o,0) = \left| \frac{1+R_h(\theta_o)}{[K_o - \sin^2\theta]^{1/2} - \cos\theta} \right|^2 \cdot \qquad (12)$$

$$RE\left\{[-\alpha(K_o,\theta) - g(K_1,\theta_o)]^{-1}\right\} \sum_{n=1}^{3} H(v_n,\rho(l_n)) J_1[\alpha^*(K_o,\theta), g^*(K_1,\theta_o), \rho(l_n)]$$

where v_n is the volume fraction of component n and n=1 denotes pure ice, n=2 denotes water, and n=3 denotes air, l_n is the correlation length of the spatial pattern of inclusions of material n, and where

$$\rho(l_n) = l_n^{-1}(1+l_n^2k^2\sin^2\theta_o)^{1/2} \qquad (13a)$$

$$J_1(\alpha^*,g^*,\rho) = RE\left\{[\alpha^* + g^* + \rho]^{-1} + \frac{\rho}{[\alpha^* + g^* + \rho]^2}\right\} \qquad (13b)$$

$$H_n = \frac{v_n(1-v_n)}{l_n\rho^3(l_n)} \sum_{i,j} \xi_i A_{ij} \xi_j \qquad (13c)$$

$$g(K_1,\theta_o) = -ik(K_1 - \sin^2\theta_o)^{1/2} \qquad (13d)$$

and

$$\alpha(K_o,\theta) = -ik(K_o - \sin^2\theta)^{1/2} \quad . \qquad (13e)$$

As for which of these parameters really matter (under what circumstances), the reflection coefficients are primarily determined by the elements of $\overline{\overline{K}}_{eff}$ and their depth dependence, except when scattering is strong, as in very bubbly multi-year ice. The backscattering cross section, however, is very sensitive to the size of brine and air inclusions in the ice and ice grains in the snow. The cross section goes approximately like l^3, where l is the characteristic scatterer size. This means that if scatterers cover a range of sizes, the larger scatterers are much more important in determining the amount of microwave scattering. Note that brine pocket sizes in particular depend strongly on temperature, and perhaps on salinity. Information on their size and geometric characteristics, as functions of depth and the ice growth history, is sorely lacking.

Dense Medium Radiative Transfer Theory (DMRT)

Dense Medium Radiative Transfer theory is derived directly from Maxwell's equations by way of a well-defined, self-consistent set of approximations (unlike classical radiative transfer, which is heuristically derived). The final form of the theory is identical to that of classical radiative transfer except that the extinction coefficient and single-scattering albedo are related to the physical properties of the scattering medium differently than are the analogous quantities in the classical theory.

The key physical effect addressed by DMRT is the following: in snow and sea ice, the fractional volume of the scatterering material occupied by the scatters themselves (i.e., ice grains in snow, air bubbles in sea ice) is typically large, ranging from a few percent to 40%. In such cases, the positions of neighboring scatterers are no longer independent (as they are in the sparsely populated random media to which classical radiative transfer applies), but rather crowd each other into correlated positions. At microwave frequencies, where the correlation length of particle positions is typically small compared to the wavelength, this correlation leads to interference between scattered field contributions due to different scatterers, even in the ensemble average over scatterer positions. This interference typically reduces scattering below what would be expected if each scatterer contributed independently. Thus the extinction and albedo in DRMT depend on the pair correlation function of particle positions (the dependence will be shown explicitly momentarily). Because the form of the theory is identical to that of classical radiative transfer, for which several solutions of the multiple scattering problem are known, we can solve DRMT including multiple scattering of the incoherent field. This turns out to be important in high albedo cases and stands in contrast to the restriction on SFT due to the distorted Born approximation. DRMT is also fully polarimetric.

The price for these advantages is a set of restrictions on scatterer size and shape and the geometric configuration of the scattering medium. The theory is limited to spherical scatterers; this means that we can realistically treat scattering in snow with reasonably spherical or irregular crystals, but perhaps not very dendritic crystals, and scattering the air bubbles in multi-year sea ice, which are roughly spherical, but not from elongated brine pockets in first-year ice. This suggests that the strengths of DRMT will prove to be complementary to those of SFT. This limitation is fairly fundamental.

The present implementation of the theory is limited to Rayleigh scatterers -- the spheres must be smaller than about a sixth of the radiation wavelength -- but accounts for a distribution in the sizes of such scatterers. The present implementation is also limited to scattering media that can be realistically idealizes as consisting of two or fewer plane-parallel scattering layers. We are presently working to ease both these restrictions.

With that said, the fundamental equation in DMRT is

$$\cos\theta \frac{\partial \bar{I}(z;\theta,\phi)}{\partial z} = -\kappa_e \bar{I}(z;\theta,\phi) + \frac{\kappa_e \tilde{\omega}}{4\pi} \int_0^{\pi} d\theta' \sin\theta' \int_0^{2\pi} d\phi' \bar{\bar{P}} \cdot \bar{I}(z;\theta',\phi') \quad , \tag{14}$$

where I is the Stokes vector

$$\bar{I}(z;\theta,\phi) = \begin{bmatrix} I_v \\ I_h \\ U \\ V \end{bmatrix} \quad . \tag{15}$$

The phase matrix $\bar{\bar{P}}$ is identical to the classical Rayleigh scattering phase matrix (appropriately normalized). The extinction coefficient, κ_e, is related to the effective propagation constant of the coherent wave, K, according to

$$\kappa_e = 2IM\left\{K\right\} \tag{16}$$

and the effective propagation constant is found according to the quasi-crystalline approximation with coherent potential (QCA-CP); in practice these means solving a non-linear algebraic equation for K numerically. For the case of scatterers of a single size, this equation is

$$K^2 = k^2\varepsilon_r + f\,k^2(\varepsilon_s-\varepsilon_r)\left[1+\frac{k^2(1-f)(\varepsilon_s-\varepsilon_r)}{3K^2}\right]^{-1} \tag{17}$$

$$\times\left\{1+i\,\frac{2}{9}K\,a^3k^2(\varepsilon_s-\varepsilon_r)\left[1+\frac{k^2(1-f)(\varepsilon_s-\varepsilon_r)}{3K^2}\right]^{-1}\left[1+4\pi n_o\int_0^\infty dr\, r^2(g(r)-1)\right]\right\}$$

where a is the (spherical) scatterer radius, n_o is the number of scatterers per unit volume, and $f = n_0 4\pi a^3/3$ is the fractional volume of the scattering medium occupied by scatterers. *These quantities must be specified by independent characterization measurements to test the model.*

The quantity g in equation 16 is the pair correlation function, defined as the conditional probability of finding a scatterer at radius r provided a scatterer is located at r=0, per unit volume of scatterer material. In practice, we use the Percus-Yevick approximation for g and non-interpenetrating, but otherwise non-interacting particles (this approximation was first developed in the study of molecular physics of fluids -- we regard it as a reasonable approximation to the pair correlation functions in snow and sea ice in the absence of better approximations based on observations). In this approximation,

$$1+4\pi n_o\int_0^\infty dr\, r^2(g(r)-1) = \frac{(1-f)^4}{(1+2f)^2} \quad . \tag{18}$$

Having solved for the coherent field effective propagation constant, the single scattering albedo ϖ in equation 15 is given by

$$\varpi = \frac{2}{9}\,\frac{a^3 f}{\kappa_e}\left|\,k^2(\varepsilon_s-\varepsilon_r)\left[1+\frac{k^2(1-f)(\varepsilon_s-\varepsilon_r)}{3K^2}\right]^{-1}\right|^2\left[1+4\pi n_o\int_0^\infty dr\, r^2(g(r)-1)\right] \quad . \tag{19}$$

The transport equation 15 must be solved numerically for the vector of Stokes parameters of radiation emerging from the scattering medium. Thus there is no closed form expression for the scattering cross sections or brightness temperatures. However, once the transport equation has been solved for a specified incident polarization, the scattering cross sections can be expressed in terms of the Stokes parameters according to

$$\sigma^0_{iv}(\theta,\phi,\theta_o,\phi_o) = 4\pi\cos\theta\, I_i(\theta,\phi) \quad , \tag{20a}$$

where $i = h$ or v for vertical polarization incident in the direction (θ_o,ϕ_o), and

$$\sigma^0_{ih}(\theta,\phi,\theta_o,\phi_o) = 4\pi\cos\theta\, I_i(\theta,\phi) \quad , \tag{20b}$$

for horizontal polarization incident in the direction (θ_o, ϕ_o). The reflection coefficients are computed via the usual Fresnel formulae from the effective propagation constants in the scattering media. The emissivity of the medium can then be computed according to Kirchhoff's law (equation 1).

This scattering model is, like SFT, highly sensitive to scatterer size. Because Rayleigh scattering is so size dependent, even just a few large particles (per hundred in a size distribution of particles) can dominate the scattering response of the medium. Thus it is especially important that ground truth measurements characterize the sizes and relative abundances of even the largest, though rare, particles (ice grains in snow, air bubbles in sea ice). The total fractional volume occupied by scatterers, which is proportional to ice or snow density, is also important, but is a less sensitive parameter. Snow wetness and salinity in the upper layers of multi-year ice are also sensitive parameters. Unfortunately our knowledge of model sensitivities is insufficient to make these statements quantitative at this time.

Rough Surface Scattering Models

The classical rough surface scattering models are based on the following idealized physical picture of sea ice -- the ice is assumed to be equivalent to an infinitely-thick slab of dielectric material with some (effective) scalar, relative dielectric constant (derived in some unspecified way from the actual, tensor permittivity profile in the ice).

With these assumptions, the classical Bragg-scattering (i.e., lowest-order perturbation theory) for the backscattering cross section is given by

$$\sigma_{ij}^{0} = 16\pi k^4 \cos^4\theta \, | \alpha_{ij}(\theta) |^2 W(2k \sin\theta, 0) \quad , \tag{21}$$

where θ the angle of incidence, W is the power spectrum of surface roughness defined in terms of the correlation function of surface heights $\rho(x,y) = \langle f(x_0+x, y_0+y) f(x_0, y_0) \rangle$,

$$W(K_x, K_y) = (2\pi)^{-2} \int\int_{-\infty}^{\infty} dx\, dy\, \exp(-iK_x x - iK_y y)\, \rho(x,y) \tag{22}$$

(we have for simplicity chosen the coordinate system such that the plane of incidence coincides with the x-z plane), and where

$$\alpha_{HH}(\theta) = \frac{\varepsilon_r - 1}{[\cos\theta + (\varepsilon_r - \sin^2\theta)^{1/2}]^2} = -R_h(\theta) \quad , \tag{23a}$$

$$\alpha_{VV}(\theta) = \frac{(\varepsilon_r - 1)[(\varepsilon_r - 1)\sin^2\theta + \varepsilon_r]}{[\varepsilon_r \cos\theta + (\varepsilon_r - \sin^2\theta)^{1/2}]^2} \quad , \tag{23b}$$

and

$$\alpha_{HV}(\theta) = \alpha_{VH}(\theta) = 0 \quad . \tag{23c}$$

Note that this lowest order result does not depend on the form of the probability density function for surface height -- it holds as well for Gaussian surfaces as for non-Gaussian surfaces. However, higher order perturbation, which is needed to compute cross-polarized backscattering and changes in emission due to surface scattering, does rely on an assumption that the surface height statistics are Gaussian.

Because the surface roughness spectrum is central in all perturbation theory results, the essential characterization input needed for testing surface scattering models is this spectrum. Perturbation theory typically predicts significant backscattering for standard deviations of surface height even 1/20th of the radiation wavelength, so the height profiles used to estimate the spectrum should be accurate to at least $\lambda/20$. The relevant spectral wavenumber in the equations above is roughly $2k$ (or less), so we need horizontal sampling sufficient to resolve spectral components of spatial wavelength $\lambda/2$ or better. This requires (for Nyquist sampling) a horizontal resolution in our height profiles of $\lambda/4$ or better. For λ = 3 cm (corresponding to X-band), these requirements come out to a height accuracy of 0.6 mm or better and a horizontal resolution of 7.5 mm or better. Obviously in connection with higher-order perturbation theory and the other models mentioned below, we should also collect a sufficient number of independent sample of surface height to test the assumption of a Gaussian surface height distribution.

The classical physical optics models (of which there are several, all slightly different, in the electromagnetic case), all assume similar forms for the like-polarized scattering cross sections:

$$\sigma^0_{ii}(\theta,\phi,\theta_o,\phi_o{=}0) = F(\theta,\theta_o,\varepsilon_r)\cdot \qquad (24)$$

$$\int_0^\infty\!\!\int_0^\infty dxdy\, \cos^2(k\,x\,\sin\theta\cos\phi + k\,y\,\sin\theta\sin\phi)\cdot$$

$$\left[\exp\left\{-(kh)^2(\cos\theta_o+\cos\theta)^2\left[1-h^{-2}\rho(x,y)\right]\right\} - \exp[-(kh)^2\cos^2(kx\sin\theta\cos\phi + ky\sin\theta\sin\phi)]\right]$$

where ii = hh or vv, ρ is the same surface height correlation given above and h is the standard deviation of the surface height variations. Note that F depends only the incidence and scattering angles, polarization, and dielectric properties of the surface. This form holds only for Gaussian surface height statistics. Analogous forms for a few special cases of non-Gaussian height statistics are known but have not been widely used. Sampling requirements for adequate estimation of ρ in this case are comparable to those given above for sampling to test conventional perturbation theory.

More modern models typically assume Gaussian stats for analytical averaging. In these cases, the spectrum (or correlation function) is is the only additional surface characterization needed. Since such theories must reduce in appropriate limits, requirements should be same, at least approximately.

Outline of Theoretical Work for FY93 (CRRELEX 93)

I. Generalize many-layer SFT to compute fully polarimetric signatures

II. Begin work to extend DMRT into Mie scattering (i.e., the larger scatterer or, equivalently, higher frequency) regime, using both analytical and Monte Carlo simulation methods

III. Compute rough surface boundary condition matrices for use with DMRT, according to 4th order conventional perturbation theory (in preparation to study surface/volume scattering interaction)

IV. Carry out a detailed comparison of SFT predictions with observations for flat congelation ice grown in CRRELEX 93

V. Carry out a detailed comparison of signature observations for roughened ice surfaces created in CRRELEX 93 with available theory

VI. NEW ITEM SINCE THE PLANNING MEETING: Investigate possible inversion of L-band reflection coefficient observations for flat, grey ice to directly estimate the permittivity tensor as a function of depth in the ice, together with Margaret Cheney, Dave Isaacson, and Ken Golden -- Initial effort will focus on numerical experiments using a forward signature model by Winebrenner and various inversion methods. Our aim is to show feasibility and likely usefulness of an actual, physical experiment that could be performed as part of CRRELEX 94.

Outline of Theoretical Work for FY94 and FY95

I. Detailed intercomparison of SFT and DMRT, including especially snow-covered grey ice.

II. Study of interaction of surface and volume scattering effects on signatures, with the aim of developing tests for relative importance of each.

III. Investigate alternative ways to include roughness effects in SFT

IV. Compare roughness scattering model predictions with observations for pancake ice

V. Possible work on inversion of reflection coefficient and polarimetric backscattering observations using inverse theory (Joint with Cheney, Isaacson and Golden)