On the Dielectric Properties and Normalized Radar Cross-Section of Crude Oil-Contaminated Sea Ice

Thomas David Neusitzer

A Thesis submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirements of the degree of

Master of Science

Department of Electrical and Computer Engineering University of Manitoba Winnipeg, Manitoba, Canada

Copyright ©2017 by Thomas David Neusitzer

Abstract

This thesis explores the effects of crude oil spilled beneath young sea ice on the dielectric properties and normalized radar cross-section of the ice at microwave (C-band) frequencies. The dielectric profile, also referred to as the complex permittivity profile, of sea ice is a governing factor in how the ice scatters incident electromagnetic waves, thus affecting its associated normalized radar cross-section. The dielectric profile of sea ice is dependent on both the geophysical and thermal properties of the ice. Crude oil contained beneath, within, or on the surface of young sea ice was expected to change these properties, thus impacting both the dielectric profile and normalized radar cross-section of the ice. Differences between the dielectric profile and normalized radar cross-section of uncontaminated and oil-contaminated sea ice is expected to facilitate detection of oil-contaminated sea ice through active microwave remote sensing technologies. As such, a discussion of the geophysical, thermodynamic, and electromagnetic properties of sea ice is presented, as well as an overview of the behaviour of oil in ice infested environments and the efforts undertaken to detect crude oil-contaminated sea ice. Following this, the details of a preliminary laboratory experiment conducted to explore the differences in the dielectric profiles of uncontaminated and contaminated sea ice are presented. Next, a comprehensive description of the meso-scale crude oil-in-sea ice experiment and the results, including the modelled dielectric profiles and measured normalized radar cross-sections of uncontaminated and oilcontaminated sea ice, is provided. Finally, a simulation study comparing the normalized radar cross-section for the uncontaminated and oil-contaminated cases is presented. Based on the experimental and simulation work conducted, the observed differences in the temperature profiles and normalized radar cross-sections of uncontaminated and oil-contaminated sea ice suggest that differentiation between uncontaminated and oil-contaminated young sea ice using microwave remote sensing technologies may be possible.

Acknowledgement

I would like to thank my advisors Drs. Puyan Mojabi and David Barber for their support and guidance throughout this endeavor. I would also like to thank Dr. Dustin Isleifson and Dr. Feiyue Wang for their role in helping to evaluate and improve this work as part of my M.Sc. examination committee.

As well, I would like to thank Dave Babb and Dave Binne for their assistance and expertise in conducting the experiments at the Sea-ice Environmental Research Facility.

In addition, I would like to thank my friends and colleagues for their support throughout this process, namely Philip Lafrance, Trevor Brown, Chai Narendra, Chen Niu, Tyler Tiede, and Nozhan Bayat.

I would like to thank the Natural Science and Engineering Research Council (NSERC) for their financial support, and Tundra Oil & Gas Ltd. for donating the crude oil for this research.

Finally, I would like to thank my family for all of their love, support, and encouragement. Without them, this would not have been possible.

"For every piece to fall in place, forever gone without a trace, your horizon takes its shape, no turning back, don't turn that page"

Dave Grohl - Foo Fighters

Long Road to Ruin Echoes, Silence, Patience & Grace

To my parents and my sister

In loving memory of Corey

Contributions of Authors

This thesis contains a manuscript that has been accepted for publication in *IEEE Transactions on Geoscience and Remote Sensing*, which comprises Chapter 4 herein. The paper has several authors, but T. D. Neusitzer is the first author. The following describes the contribution of each author for the paper.

T. D. Neusitzer, N. Firoozy, T. M. Tiede, D. S. Desmond, M. J. L. Lemes, G. A. Stern, S. Rysgaard, P. Mojabi and D. G. Barber, "Examining the impact of a crude oil spill on the permittivity profile and normalized radar cross-section of young sea ice," *IEEE Transactions on Geoscience and Remote Sensing*, 2017

- T. D. Neusitzer: Collection of experimental data, data analysis, dielectric modelling, x-ray microtomography of samples, manuscript preparation
- N. Firoozy: Collection of experimental data, radar cross-section simulation
- T. M. Tiede: Collection of experimental data
- D. S. Desmond: Collection of experimental data
- M. J. L. Lemes: X-ray microtomography of samples
- G. A. Stern: Academic advisor to D. S. Desmond
- S. Rysgaard: Supervisor to M. J. L. Lemes
- P. Mojabi: Academic advisor to T. D. Neusitzer, N. Firoozy, T. M. Tiede; manuscript editing
- D. G. Barber: Academic co-advisor to T. D. Neusitzer, N. Firoozy, T. M. Tiede, and D. S. Desmond

Contents

1.	Introduction					
	1.1 Motivation					
	1.2	Thesis	Outline			
	Refe	rences .				
2.	Back	kground				
	2.1	Geophy	ysical Properties of Snow-Covered Sea Ice			
		2.1.1	Sea Ice Formation			
		2.1.2	Salinity of Sea Ice			
		2.1.3	Snow			
	2.2	Thermo	odynamic Properties of Snow-Covered Sea Ice			
		2.2.1	General Thermodynamic Model for Snow-Covered Sea Ice 18			
		2.2.2	Thermal Conductivity of Ice and Snow			
	2.3	Electro	magnetic Properties of Snow-Covered Sea Ice			
		2.3.1	Electromagnetic Theory			
		2.3.2	Relative Complex Permittivity of Sea Ice			
		2.3.3	Relative Complex Permittivity of Snow			
		2.3.4	Microwave Scattering			
		2.3.5	Active Microwave Remote Sensing of Snow-Covered Sea Ice 35			
	2.4	ntaminated Sea Ice				
		2.4.1	Behaviour of Oil in Ice-Infested Environments			
		2.4.2	Current Detection Efforts			
	Refe	rences .				
3.	Expe	erimenta	1 Preparation			
	3.1	Cold L	aboratory Experiment			
	3.2	Dielect	ric Modelling			
		3.2.1	Dielectric Measurement of Crude and Corn Oils			
		3.2.2	Cold Room Experiment Dielectric Profiles			
	References					

Contents

4.	Examining the Impact of a Crude Oil Spill on the Permittivity Profile and Normalized						
	Rada	Radar Cross-Section of Young Sea Ice 65					
	4.1	Introdu	uction		66		
	4.2	Experi	iment and Observations		69		
		4.2.1	Oil-in-Sea Ice Mesocosm Experiment		69		
		4.2.2	Evolution of the Ice		71		
		4.2.3	Temperature Profile		74		
		4.2.4	Salinity Profile		75		
		4.2.5	<i>x</i> -ray Microtomography		79		
		4.2.6	Normalized Radar Cross-Section (NRCS)		80		
			4.2.6.1 NRCS observations for the uncontaminated case		83		
			4.2.6.2 NRCS observations for the contaminated case		83		
	4.3	Compl	lex Permittivity		85		
		4.3.1	Permittivity Modelling Using Physical Measurements		86		
		4.3.2	Permittivity Modelling Using x-ray Microtomography		89		
		4.3.3	Normalized Radar Cross-Section Simulation		94		
		4.3.4	Evaluation of Permittivity Models		95		
	4.4	Conclu	usion		96		
	Refe	erences.		•••	103		
5	Nor	malized	Radar Cross-Section Simulation Studies		104		
5.	5 1	Monos	static NRCS Simulation	•••	104		
	5.1	Ristati	ic NRCS Simulation	•••	105		
	53	Comm	$\begin{array}{c} \begin{array}{c} \begin{array}{c} \\ \end{array} \\ $	•••	112		
	J.J Refe	rences		•••	112		
	Keit	ichees .		•••	114		
6.	Con	clusions	and Future Work		115		
Δr	nend	iv			110		
Δŀ	penu	IA			11)		
Α.	Brin	e Permi	ttivity Formulas		120		
	Refe	erences .			122		
B	Add	itional (Contributions to the Literature		123		

List of Tables

3.1	The relative dielectric constant of corn oil and crude oil as measured through the cavity perturbation technique	59
4.1	Volume fractions determined through <i>x</i> -ray microtomography of the oil-contaminated ice	80
4.2	Comparison of Calibrated Measured and Simulated NRCS for Oil-Contaminate Sea Ice generated using the Three-Phase Polder-van Santen/de Loor (3- PvS/dL) and Quasi Two-Phase Tinga-Voss-Blossey (2-TVB) Mixture Mod- els Assuming Spherical Inclusions	ed 94
5.1	Roughness parameters used for NRCS simulation assuming a Gaussian correlation function.	106
5.2	Assumed permittivities for the half-space for NRCS simulation modelled us- ing the two-phase Polder-van Santen/de Loor (2 PvS/dL) mixture model for uncontaminated sea ice, and the three-phase Polder-van Santen/de Loor (3 PvS/dL) and quasi two-phase Tinga-Voss-Blossey (q2 TVB) mixture models for oil-contaminated sea ice.	106

List of Figures

2.1	The freezing point and the temperature of maximum density of sea water versus salinity, adapted from [1].	10
2.2	Flow chart of sea ice growth, adapted from [3]	11
2.3	Schematic of the one-dimensional snow-covered sea ice heat flux and energy transfer model, adapted from [17].	18
3.1	Schematic of the tank systems utilized for experiments in the cold laboratory, with the ice growth tank shown on the left and the pressure release tank shown on the right.	50
3.2	The insulated tank systems used to grow artificial sea ice for the cold labo- ratory experiments.	51
3.3	The measured temperature profiles for (a) uncontaminated sea ice and (b) corn oil-contaminated sea ice grown in the cold laboratory experiment	53
3.4	The measured bulk salinity profiles for (a) uncontaminated sea ice and (b) corn oil-contaminated sea ice grown in the cold laboratory experiment. Note that the sample pertaining to the top 3 cm of one of the contaminated samples taken at -15 °C was lost and as such does not have a measured salinity.	53
3.5	The measured corn oil volume fraction profiles for the contaminated sea ice grown in the cold laboratory experiment. Note that the sample pertaining to the top 3 cm of one of the contaminated samples taken at -20 °C was lost and as such does not have an associated corn oil volume fraction.	54

3.6	Schematic of the Resonant Cavity used for Dielectric Measurement	56
3.7	The magnitudes of the (a) real and (b) imaginary parts of the permittivity of the uncontaminated sea ice grown in the cold laboratory experiment calculated using the two-phase Polder-van Santen/de Loor mixture model for spherical inclusions at a frequency of 5.5 GHz.	60
3.8	The magnitudes of the (a) real and (b) imaginary parts of the permittivity of the corn oil-contaminated sea ice grown in the cold laboratory experiment calculated using the three-phase Polder-van Santen/de Loor mixture model for spherical inclusions at a frequency of 5.5 GHz.	61
3.9	The magnitudes of the (a) real and (b) imaginary parts of the permittivity of the corn oil-contaminated sea ice grown in the cold laboratory experiment calculated using the quasi two-phase Tinga-Voss-Blossey mixture model for spherical inclusions at a frequency of 5.5 GHz	61
4.1	The insulated fibreglass tank used for the oil-in-ice mesocosm experiment at the University of Manitoba Sea-ice Environmental Research Facility during the winter of 2016 prior to freezing.	70
4.2	Diagram of the injection of crude oil into the water column beneath the ice. To avoid excess pressure buildup, water was simultaneously drained from the tank as the oil was injected.	71
4.3	The surface of the oil-contaminated ice (a) February 10 at 10:45 am, (b) February 11 at 10:50 am after substantial oil migration up through the ice, (c) February 16 at 9:30 am after a period of snowfall, (d) February 18 at 10:50 am with evidence of crude oil percolating up through the snow layer, (e) February 19 at 9:30 am after partial melting of the snow/oil layer due to warm weather, (f) February 23 at 11:50 am after an additional snowfall, and (g) March 1 at 11:20 am after upward percolation of crude oil through the snow.	73
4.4	Data for the uncontaminated ice growth period from January 15 to 21, 2016: (a) ambient air temperature in Winnipeg, MB, Canada [20], (b) measured ice/water column temperature profile, and (c) measured normalized radar cross-section of the uncontaminated sea ice at an incidence angle of 56° in the VV polarization	76

4.5	Data for the oil-contaminated ice growth period from February 8 to March 1, 2016: (a) ambient air temperature in Winnipeg, MB, Canada [20], (b) measured ice/water column temperature profile, and (c) calibrated measured normalized radar cross-section of oil-contaminated sea ice in the VV polarization at an incidence angle of 57°. Note that the dashed line indicates when oil-injection was performed, and the dash-dotted line indicates when evidence of the oil migrating up through the ice was first observed. The NRCS data from the afternoon of February 10 to the morning of February 12 was lost due to software issues with the scatterometer's data collection unit, and the data from the evening of February 17 to the morning of February 18 was lost due to a power-outage.	77
4.6	The measured bulk salinity profiles for (a) uncontaminated ice grown from January 15 to 21, 2016 and (b) from February 8 to March 1, 2016. Note that the horizontal axes are not to scale, and any unlabeled tick has the same time-stamp as the closest labelled tick to its left.	78
4.7	Distribution of crude oil within sections of the contaminated ice cores. Note that the horizontal axis is not to scale, and any unlabeled tick has the same time-stamp as the closest labelled tick to its left.	79
4.8	Horizontal cross-sections of oil-contaminated ice cores obtained through x -ray microtomography. In these images, air is shown in black, brine is shown in white, ice is shown in light grey, and oil is shown in dark gray. Three- dimensional analysis of the x -ray microtomography scans concluded that oil content by volume was 3.82% in core (a), 3.19% in core (b), 1.43% in core (c), 1.81% in core (d), and 0.864% in core (e). Each sample is approximately 3 cm in diameter, and each sample was contained within a polypropylene tube during scanning to minimize contamination of the instrument. The polypropylene tubes are visible in each image as the ring surrounding each sample, and have similar shading to the oil in the samples	81
4.9	Vertical cross-sections of oil-contaminated ice cores obtained through x -ray microtomography. In these images, air is shown in black, brine is shown in light blue/white, ice is shown in blue, and oil is shown in red. The polypropylene tubes are visible in each image in red, bounding the sample within. These cross-sections correspond to the horizontal cross-sections in Fig. 4.8.	82
4.10	The magnitudes of the (a) real and (b) imaginary parts of the permittivity of the uncontaminated sea ice grown from January 15 to 21, 2016 calculated using the two-phase Polder-van Santen/de Loor mixture model for spherical inclusions at a frequency of 5.5 GHz.	90

4.11	The magnitudes of the (a) real and (b) imaginary parts of the permittivity of the oil-contaminated sea ice grown from February 8 to March 1, 2016 calculated using the three-phase Polder-van Santen/de Loor mixture model for spherical inclusions at a frequency of 5.5 GHz. Note that the horizontal axes are not to scale, and any unlabeled tick has the same time-stamp as the closest labelled tick to its left.	90
4.12	The magnitudes of the (a) real and (b) imaginary parts of the permittivity of the oil-contaminated sea ice grown from February 8 to March 1, 2016 calculated using the quasi two-phase Tinga-Voss-Blossey mixture model for spherical inclusions at a frequency of 5.5 GHz. Note that the horizontal axes are not to scale, and any unlabeled tick has the same time-stamp as the closest labelled tick its left.	91
4.13	The modelled permittivity of an oil-contaminated ice sample using volume fraction data obtained through <i>x</i> -ray microtomography, utilizing the quasi two-phase Polder-van Santen/de Loor mixture model (PvS/dL) and the quasi two-phase Tinga-Voss-Blossey mixture model (TVB), both at a frequency of 5.5 GHz. The sample was taken at 3:30 pm on March 1, 2016	93
4.14	Comparison of the performance of the permittivity mixture models for oil- contaminated sea ice. Top: Complex permittivity of oil-contaminated sea ice at 1 GHz evaluated at temperatures of -20 , -10 , and -1.8 °C. Bottom: Complex permittivity of oil-contaminated sea ice at a temperature of -1.8 °C evaluated at frequencies of 1, 4, and 10 GHz. Mixture models as listed in the plot legends: (a) three-phase Polder-van Santen/de Loor, (b) quasi two-phase Tinga-Voss-Blossey, (c) quasi two-phase Polder-van Santen/de Loor with air inclusions, (d) quasi two-phase Tinga-Voss-Blossey with air inclusions, (e) the linear mixture model presented in [14]. All models were evaluated assuming a bulk salinity of 6 psu, an oil permittivity of 2.2332 – j0.0373 (which is assumed to be constant across the entire frequency range), and an air volume fraction of 1.5% when applicable.	97
5.1	Simulated monostatic NRCS of both uncontaminated and oil-contaminated sea ice in the (a) VV, (b) HH, and (c) HV polarizations	107
5.2	Differences between the simulated monostatic NRCS of uncontaminated and oil-contaminated sea ice in the (a) VV, (b) HH, and (c) HV polarizations.	109

5.3	Simulated bistatic NRCS for the (a) VV and (b) HH polarizations of uncon-	
	taminated sea ice, the (c) VV and (d) HH polarizations of oil-contaminated	
	sea ice modelled using the three-phase Polder-van Santen/de Loor mixture	
	model, and the (e) VV and (f) HH polarizations of oil-contaminated sea ice	
	modelled using the quasi two-phase Tinga-Voss-Blossey mixture model	111
5.4	The difference between the simulated bistatic NRCS of uncontaminated sea	
	ice and oil-contaminated sea ice modelled using (a) the three-phase Polder-	
	van Santen/de Loor and (b) the quasi two-phase Tinga-Voss-Blossey mixture	
	models in the VV polarization.	112

Nomenclature

Abbreviation	Description
GPR	Ground Penetrating Radar
$\mathbf{I}^2 \mathbf{E} \mathbf{M}$	Improved Integral Equation Model
NMR	Nuclear Magnetic Resonance
NRCS	Normalized Radar Cross-Section
PPT	Parts Per Thousand
PSU	Practical Salinity Units
PvS/dL	Polder-van Santen/de Loor
SAR	Synthetic Aperture Radar
SERF	Sea-ice Environmental Research Facility
SLAR	Side-Looking Airborne Radar
TE	Tranverse Electric
TVB	Tinga-Voss-Blossey
UUV	Unmanned Underwater Vehicle
UV	Ultraviolet
VNA	Vector Network Analyzer

Introduction

The Arctic is one of the few places on the planet that has been relatively untouched by humanity's expansion throughout the ages. This isolation is largely due to the inhospitable nature of the frozen desert, as well as the ever present sea ice making Arctic waters treacherous to navigate by ship. In the last half century it has become clear that the climate in the Arctic is changing, and thus changing the topography of the sea ice in the region. These changes being observed in the Arctic are widely considered to be the result of natural variations accelerated by increased human industrial activity, and may have lasting impacts on the rest of the world. As the Arctic is changing, it is becoming increasingly more accessible to humanity and may soon see increased activity amongst several industries, thus there has been increased interest in improving the understanding of the potential impacts industrialization may have on the environment and enabling humanity to minimize these impacts. To this end, this thesis focuses on exploring the changes in the dielectric profile and normalized radar cross-section of young sea ice exposed to a crude oil spill in an effort to enable detection of such oil spills in the Arctic through remote sensing technologies.

1.1 Motivation

It is becoming increasingly evident that the landscape of the Arctic is changing as a result of global warming. The amount of thick multi-year ice in the Arctic Ocean has been declining, and is being replaced by thinner first-year ice [1–3]. First-year ice is significantly more vulnerable to variations in the Arctic climate than its multi-year counterpart, and as such, is liable to melt during the summer months, which has contributed to decreased ice extent during Arctic summers [4, 5]. Perhaps the most prevalent evidence of the shrinking sea ice cover are the then-record minimum sea ice extent that was observed in September 2007 [6], and the record minimum observed five years later in 2012 [7]. The Arctic Ocean, which was once treacherous to navigate due to vast amounts of thick ice, now exhibits substantial regions of thin ice and open water annually, making conditions much more favourable for industrialization of the Arctic than in the past.

The primary industries that are expected to expand operations into the Arctic as a result of the shrinking ice cover are the petroleum industry and marine shipping industry. Recently, cruise tourism through Arctic waters has increased in popularity [8], which would also share several of the environmental challenges as marine shipping through the Arctic. The potential of developing the petroleum resources of the Arctic, including crude oil, has been studied since the latter half of the 20th century [9], and has recently received renewed interest [10, 11]. Currently, it is speculated that roughly 13% of the remaining undiscovered oil reserves on the planet exist in the Arctic [12], and some of the discovered Arctic oil and gas reserves are among the largest single fields in the world [9]. Ultimately, the future development of Arctic crude oil resources is dependent on a combination of several economic, political, and environmental factors [13–15], although such development may soon become a reality [15]. Marine shipping through Arctic waters is perhaps a more immediate form of industrialization, as it does not require the same infrastructure as the petroleum industry.

Current trends indicate that ship traffic through the Canadian Arctic has been increasing in the last thirty years, mainly between the months of July and October inclusive [16]. As well, the decline of the sea ice cover in Arctic waters is projected to open up new shipping routes, which will have been previously unnavigable, by the middle of the 21st century [17, 18]. Thus, there is the potential for marine shipping through the Arctic to further increase in the years to come, and as such, a potential framework for responsible shipping through the Canadian Arctic has been proposed [19]. Both the development of Arctic oil resources and increased marine shipping through the Arctic carry with them the inherent risk of releasing crude oil and/or bunker fuels into the ice-infested waters of the Arctic, which could have potentially devastating consequences for the environment. Therefore, it is crucial that humanity begin to responsibly prepare for the industrialization of the Arctic.

As the world transitions into the age of an industrialized Arctic, it is necessary to determine how crude oil spilled in ice-infested Arctic waters would impact the properties of the sea ice for both detection and remediation purposes, since open water spill detection methods are expected to be ineffective in the Arctic and current technologies are in the early stages of development. The research presented in this thesis was conducted in an attempt to develop an understanding of how the electromagnetic properties of young sea ice, namely the dielectric profile and normalized radar cross-section of the ice, would be impacted by the presence of crude oil beneath, within, and on top of the ice. Understanding how these properties are affected by the presence of crude oil is expected to lay the foundation for the development of oil-contaminated sea ice detection schemes using microwave remote sensing technologies, and as such, better prepare the world for protecting the environment in conjunction with the industrialization of the Arctic.

1.2 Thesis Outline

This thesis is composed of six chapters, including this introduction. The second chapter provides a synopsis of the geophysical, thermodynamic, and electromagnetic properties of Arctic sea ice, as well as an overview of the current knowledge on crude oil-contaminated sea ice as it pertains to this research. Following this, the third chapter details the preliminary experimentation that was conducted in preparation for the oil-in-sea ice mesocosm experiment. Chapter 4 presents a manuscript accepted for publication in *IEEE Transactions on* Geoscience and Remote Sensing entitled "Examining the impact of a crude oil spill on the permittivity profile and normalized radar cross-section of young sea ice" which describes the oil-in-sea ice mesocosm experiment performed at the University of Manitoba Sea-ice Environmental Research Facility in the winter of 2016. Included within this chapter are the experimental observations of the geophysical and electromagnetic properties of the oilcontaminated sea ice that was grown, as well as models for the permittivity profile of the contaminated sea ice. Following this, the fifth chapter presents a simulation study of the normalized radar cross-section of oil-contaminated sea ice. Finally, the sixth chapter concludes this thesis by summarizing the conclusions drawn from the research presented herein, and providing suggestions for future extensions of the work presented in this thesis. Please note that the references cited in each chapter are presented immediately following the end of the chapter.

References

- D. A. Rothrock, Y. Yu, and G. A. Maykut, "Thinning of Arctic sea-ice cover," *Geophysical Research Lett.*, vol. 26, no. 23, pp. 3469–3472, Dec. 1999.
- Y. Yu, G. A. Maykut, and D. A. Rothrock, "Changes in the thickness distribution of Arctic sea ice between 1958-1970 and 1993-1997," *J. Geophysical Research*, vol. 109, no. C08, Aug. 2004.
- [3] J. C. Comiso, "Large decadal decline of the Arctic multiyear ice cover," J. Climate, vol. 25, pp. 1176–1193, Jul. 2011.
- [4] J. C. Comiso, C. L. Parkinson, R. Gertsen, and L. Stock, "Accelerated decline in the Arctic sea ice cover," *Geophysical Research Lett.*, vol. 35, no. 1, Jan. 2008.
- [5] J. C. Stroeve, M. C. Serreze, M. M. Holland, J. E. Kay, J. Malanik, and A. P. Barrett, "The Arctic's rapidly shrinking sea ice cover: A research synthesis," *Climatic Change*, vol. 110, no. 3-4, pp. 1005–1027, Jun. 2012.
- [6] D. K. Perovich, J. A. Richter-Menge, K. F. Jones, and B. Light, "Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007," *Geophysical Research Lett.*, vol. 35, no. 11, Jun. 2008.

- [7] C. L. Parkinson and J. C. Comiso, "On the 2012 record low Arctic sea ice cover: Combined impact of preconditioning and an August storm," *Geophysical Research Lett.*, vol. 40, no. 7, pp. 1356–1361, Apr. 2013.
- [8] J. Dawson, E. J. Stewart, M. E. Johnston, and C. J. Lemieux, "Identifying and evaluating adaptation strategies for cruise tourism in Arctic Canada," *J. Sustainable Tourism*, vol. 24, no. 10, pp. 1425–1441, Nov. 2016.
- [9] W. F. Weeks and G. Weller, "Offshore oil in the Alaskan Arctic," *Sci.*, vol. 225, no. 4660, pp. 371–378, Jul. 1984.
- [10] D. W. Houseknecht and K. J. Bird, "Oil and gas resources of the Arctic Alaska Petroleum Province," U.S. Geological Survey Professional Paper, no. 1732-A, 2006.
- [11] National Petroleum Council, "Arctic potential: Realizing the promise of U.S. Arctic oil and gas resources," *National Petroleum Council Rep.*, 2015.
- [12] D. L. Gautier, K. J. Bird, R. R. Charpentier, A. Grantz, D. W. Houseknecht, T. R. Klett, T. E. Moore, J. K. Pitman, C. J. Schenk, J. H. Schuenemeyer, K. Sørensen, M. E. Tennyson, Z. C. Valin, and C. J. Wandrey, "Assessment of undiscovered oil and gas in the Arctic," *Sci.*, vol. 324, no. 5931, pp. 1175–1779, May 2009.
- [13] N. E. Flanders, R. V. Brown, Y. Andre'eva, and O. Larichev, "Justifying public decisions in Arctic oil and gas development: American and Russian approaches," *Arctic*, vol. 51, no. 3, pp. 262–279, Sep. 1998.
- [14] J. R. Hasle, U. Kjellén, and O. Haugerud, "Decision on oil and gas exploration in an Arctic area: Case study from the Norwegian Barents Sea," *Safety Sci.*, vol. 47, no. 6, pp. 832–842, Jul. 2009.
- [15] Ø. Harsem, A. Eide, and K. Heen, "Factors influencing future oil and gas prospects in the Arctic," *Energy Policy*, vol. 39, no. 12, pp. 8037–8045, 2011.

- [16] L. Pizzolato, S. E. L. Howell, C. Derksen, J. Dawson, and L. Copland, "Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012," *Climatic Change*, vol. 123, no. 2, pp. 161–173, Jan. 2014.
- [17] L. C. Smith and S. R. Stephenson, "New trans-Arctic shipping routes navigable by midcentury," in *Proc. Nat. Academy Sci.*, vol. 110, no. 13, Jan. 2013, pp. E1191– E1195.
- [18] S. R. Stephenson, L. C. Smth, and J. A. Agnew, "Divergent long-term trajectrories of human access to the Arctic," *Nature Climate Change Lett.*, vol. 1, no. 3, pp. 156–160, May 2011.
- [19] Oceans North Canada, "The integrated Arctic corridors framework: Planning for responsible shipping in Canada's Arctic waters," *PEW Charitable Trust Rep.*, Apr. 2016.

Background

In order to sufficiently address the study of oil-contaminated sea ice from an electromagnetic remote sensing perspective, it is important to develop an understanding of sea ice as a medium as well as how crude oil interacts with sea ice. As such, this chapter discusses the geophysical, thermodynamic, and electromagnetic properties of uncontaminated sea ice; and the behaviour of crude oil exposed to sea ice and current efforts to detect oil-contaminated sea ice. While sea ice can be found naturally in both Arctic and Antarctic waters, the discussion herein is limited to sea ice in the Arctic Ocean.

2.1 Geophysical Properties of Snow-Covered Sea Ice

Perhaps the most appropriate place to begin the discussion of Arctic sea ice is to examine the geophysical properties of the ice and the snow cover that is commonly observed on top of the ice. From a microwave remote sensing point of view, these properties play a critical role in how electromagnetic radiation interacts with the snow-cover and sea ice, thus it is necessary to thoroughly explore such properties within the context of this thesis. As such, this section explores the formation process of sea ice, the salinity of sea ice, as well as the snow layer that is common on top of sea ice.

2.1.1 Sea Ice Formation

Sea ice forms naturally in the Arctic Ocean as a product of frigid air cooling the surface of the sea water, in conjunction with a convection process within the top layers of the ocean. This process begins as the ocean surface is cooled to the freezing point of sea water. The freezing point of sea water is generally lower than that of fresh water, and is inversely proportional to the salinity of the water, as illustrated in Fig. 2.1 [1]. For typical salinities of Arctic sea water of 30 to 35 practical salinity units $(psu)^1$, the freezing point is between -1.8 and -2 °C. As the surface water is cooled by the air, it becomes more dense than the underlying water and sinks, forcing the warmer sea water to the surface and causing convective mixing of the upper ocean which transfers heat between the surface and underlying waters, counter-acting the cooling process. As such, the top layer of the ocean becomes supercooled prior to the formation of sea ice. At salinities above 24.7 psu, the freezing point of sea water is greater than the temperature at which the density of sea water is maximum, thus this convection process will continue as the upper ocean layer is supercooled to the point where ice begins to form [2]. When the top ocean layer is sufficiently supercooled, tiny disks and needles of ice form within this layer and subsequently float to the ocean surface, as ice is less dense than sea water. As this process continues, the accumulation of these disks and needles of ice results in the formation of a thin layer of randomly oriented ice crystals referred to as frazil

¹ Certain regions of the Arctic Ocean have salinities below 24.7 psu, including the Baltic, Kara, and Laptev-East Siberian Seas [2]. Due to the low salinity in these regions, the ice formation process more closely resembles that of fresh water.



Fig. 2.1: The freezing point and the temperature of maximum density of sea water versus salinity, adapted from [1].

ice. From this point onward, the ice growth process largely depends on the ocean conditions during formation, as illustrated by the flow-chart adapted from [3] shown in Fig. 2.2.

Under calm conditions where there is little wind, the frazil ice crystals freeze together to form a layer of grease ice on the surface of the ocean, which gives the surface of the ocean a similar appearance to an oil slick. As this ice evolves into a continuous thin, layer of ice known as nilas, it begins to transition from being transparent to grey, with the nilas becoming white in colour once sufficiently thick. Rafting of different nilas sheets can occur if light winds and/or currents slide the nilas sheets on top of each other, forming a larger layer of ice. Following the formation of nilas, ice growth is primarily in the vertical direction since the convective mixing that allowed frazil ice to form no longer occurs in the water beneath the nilas. This growth process is known as congelation growth, and is primarily driven by the freezing of water molecules to the bottom of the existing ice, which results in a crystalline structure with horizontal crystal axes [2]. As congelation growth continues, the ice evolves from nilas to first-year sea ice. Conversely, if turbulent currents and strong winds



Fig. 2.2: Flow chart of sea ice growth, adapted from [3].

are present during the formation of the frazil layer, the ice will accumulate into circular disks and become pancake ice. Due to the turbulent conditions, the disks are unable to freeze together uniformly, and collisions between disks push frazil ice onto the edges of the disks, which freezes and raises the edges of the ice disk. As with the growth of nilas, rafting can occur in pancake ice formation. Alternatively, if the pancake ice is thick enough ridging may occur, in which the ice is deformed or fractured as a result of the surrounding ice compressing it. The ice pancakes will eventually consolidate and freeze together as consolidated pancake ice, a form of sheet ice formed from congelation ice. Regardless of the ocean conditions, the sheet ice formed will continually grow thicker, provided the sea water beneath the ice reaches its freezing point. As air temperature warms up, the ice sheet will begin to melt. If ice is sufficiently thick, it can survive the summer melt and become multiyear ice. Otherwise, the ice sheet will melt and the ocean surface will return to open water until the following winter.

The structure of sea ice can be divided into several separate layers which relate to the dominant ice growth processes required for formation. The frazil layer consists of the uppermost part of the ice which was formed through the freezing of the frazil ice crystals [1]. This layer generally has no dominant crystal plane due to the random orientations of the individual crystals when they freeze together. Below the frazil layer is the transition or transitional layer, in which the ice shifts from a randomly oriented crystal structure to one in which the columnal crystal structure begins to dominate. The section of the ice formed through congelation growth is referred to as the columnar layer of the ice due to the column-like nature of ice growth as the crystals become vertically elongated. In general, the columnar layer is the largest of the three layers within the sea ice. The bottom portion of the ice at the sea ice/water interface is known as the skeletal layer. In this layer, the width of the elongated crystals grown through congelation growth has narrowed, and sea water can more easily penetrate up into the ice [1, 2]. Typically, the skeletal layer is only a few centimetres thick.

2.1.2 Salinity of Sea Ice

The salinity of sea ice is one of the primary geophysical parameters of interest in the study of sea ice from a remote sensing point of view. The amount of dissolved salts within water entrapped within the ice contributes to the permittivity and effective electromagnetic conductivity of the sea ice, and is a determining factor of how far within the ice electromagnetic waves can penetrate. Due to the formation processes of sea ice, as well as the brine dynamics within the ice, the salinity of the ice varies with depth [4]. Typically, the salinity of young sea ice follows a c-shape with depth, which is to say that the top of the ice has a higher salinity, the middle section of the ice has a lower salinity, and the bottom of the ice again has a higher salinity.

The salinity of sea ice is primarily due to the brine entrapped within the ice, and precipitated salts within the ice may also contribute. As sea water freezes, brine is expelled from the growing ice sheet. During the initial formation of the ice cover, some of this brine is rejected towards the surface of the ice, which contributes to the higher salinity of the top portion of sea ice. Once congelation ice has begun to form, brine can be expelled into the openings within the dendritic structure of the ice, and may become entrapped within the sea ice if the ice dendrites surrounding the brine freeze together [1, 2]. The trapped brine within sea ice is commonly referred to as the brine pockets or brine inclusions within the ice. As the ice continues to freeze, the entrapped brine is further concentrated, increasing the salinity of the brine included within the ice. As a result of the temperature gradient of the sea ice system, and subsequently the entrapped brine, the brine pockets can migrate downwards towards the ice/water interface. As this occurs, the pockets of brine increase in size [1, 2], as they are exposed to increasingly warmer temperatures. Alternatively, a brine pocket may rupture if the internal pressure in the pocket becomes too great, in which the brine is ejected from the pocket through cracks in the ice [2]. This process is known as brine expulsion. It is important to note that the brine ejected from the pocket in this process will travel outward from the pocket, which can include both upwards and downwards through cracks in the ice.

While both the migration of brine pockets and the expulsion of brine into cracks in the ice contribute to the overall movement of brine within the ice, the primary mechanism for brine movement within the sea ice is gravity drainage [2]. As a consequence of the higher density of the brine included within the ice relative to the sea water beneath the ice, brine will drain out of the sea ice through brine channels into the sea water below. This process is driven by the increase in height of the surface of the sea ice relative to the ocean surface as ice growth continues, which forces the brine downwards as a result of the pressure head within the channels [1, 2]. Since the uppermost portion of the ice is the coldest during the growth period, some of the brine channels may completely freeze and prevent entrapped brine from draining. At the same time, brine in the middle and lower portions of the ice may be free to drain downwards through the brine channels. The combination of these affirms the c-shape of the salinity gradient that is generally observed in sea ice.

It is often difficult to determine the salinity of the brine entrapped within the ice through direct physical measurements. Instead, the brine salinity for each section of an ice core is generally determined from ice temperature measurements using the following empirical formula [5]

$$S_{b} = \begin{cases} 1.725 - 18.756T - 0.3964T^{2}, & -8.2 \leq T \leq -2 \text{ °C} \\ 57.041 - 9.929T - 0.16204T^{2} - 0.002396T^{3}, & -22.9 \leq T \leq -8.2 \text{ °C} \\ 242.94 + 1.5299T + 0.0429T^{2}, & -36.8 \leq T \leq -22.9 \text{ °C} \\ 508.18 + 14.535T + 0.2018T^{2} & -43.2 \leq T \leq -36.8 \text{ °C} \end{cases}$$
(2.1)

where S_b and T denote brine salinity in psu and temperature in °C respectively. The brine volume fraction, which is a measure of the volume of brine within the ice relative to the total volume of the sea ice sample, can be determined from the brine salinity and the bulk salinity of the ice as [6, 7]

$$v_b = \frac{S_i}{S_b} \frac{\rho_i}{\rho_b} \tag{2.2}$$

where S_i , ρ_i , and ρ_b are the bulk salinity of the sea ice, the density of pure ice, and the density of brine respectively. The densities of pure ice and brine can be calculated using the following empirical equations [6]

$$\rho_i = 0.917 - 1.403 \times 10^{-4} T \tag{2.3}$$

$$\rho_b = 1 + 8 \times 10^{-4} S_b. \tag{2.4}$$

Alternatively, the brine volume fraction of a sea ice sample may be calculated from bulk salinity and temperature measurements using the following empirical model developed by [8]²

$$v_{b} = \begin{cases} 10^{-3}S_{i} \left(-\frac{52.56}{T} - 2.28\right), & -2.06 \le T \le -0.5 \ ^{\circ}\text{C} \\ 10^{-3}S_{i} \left(-\frac{45.917}{T} + 0.930\right), & -8.2 \le T \le -2.06 \ ^{\circ}\text{C} \\ 10^{-3}S_{i} \left(-\frac{43.795}{T} + 1.189\right), & -22.9 \le T \le -8.2 \ ^{\circ}\text{C} \end{cases}$$
(2.5)

A second, but less accurate model for the brine volume fraction of sea ice was also presented in [8], which provides a single expression for the brine volume fraction across the same range of temperatures

$$v_b = 10^{-3} S_i \left(-\frac{49.185}{T} + 0.532 \right), \quad -22.9 \le T \le -0.5 \,^{\circ}\text{C}.$$
 (2.6)

 $^{^{2}}$ The empirical models for brine volume fraction presented in [8] were developed using experimental data reported in [5].

In this work, the brine volume fraction as determined by (2.6) is utilized for simplicity.

2.1.3 Snow

The discussion of the geophysical properties of Arctic sea ice would be incomplete without exploring the properties of the snow layer that is commonly found on the surface of sea ice. Snow is generally considered to consist of individual ice grains and air, and can include both liquid pure water and brine depending on conditions [7, 9–11]. A complete characterization of a snow layer on sea ice would include measurements of the temperature, thickness, density, salinity, grain size and structure, and liquid content of the snow. After snow is deposited on the surface of sea ice, it undergoes metamorphism in response to becoming wetted or from naturally compressing itself [4]. In this process, the individual snowflakes of the initial snowfall merge together to become ice grains as a result of vapor diffusion caused by a large temperature gradient across the snow layer [4, 12]. The effects of this process are usually greater at the snow/ice interface, leading to larger grain sizes at the bottom of the snow layer. The size of the ice grains at the surface of the snow layer are generally smaller and more rounded than the grains at the base of the snow. Another mechanism for the formation of snow grains is simply the refreezing of previously wetted snow.

The differences in grain size and shape, as well as density and salinity³, between different depths in the snow layer during the winter have prompted the classification of horizontal sublayers within the snowpack [13, 14]. The first of these is the basal layer, which is the deepest layer within the snow and generally has the largest grain sizes and the highest salinity. Above the basal layer is the so-called original snow layer, which generally has a lower salinity and

 $^{^{3}}$ The salinity of the snow on top of sea ice in the winter is largely due to brine wicking resulting from capillary action on the surface brine skim of the ice [4].

grain size, but can also have a higher density. The uppermost part of the snow is said to be the new snow layer, which is generally not saline, less dense than the original snow layer, and has the smallest grain size.

For situations where there is liquid water or brine content within the snow, the wet snow can also be classified based on its liquid content into two regimes. If the liquid content of the snow is less than 7% of the total snow volume, the snow is said to be in the pendular regime, whereas snow with a liquid content above 7% of the total volume is said to be in the funicular regime [15]. The transition between these two regimes occurs when 11 to 15% of the pore volume within the snow is filled with liquid water or brine [15, 16]. Both the pendular and funicular regimes of wet snow generally exhibit faster growth of ice grains than in dry snow, with the funicular regime seeing the fastest growth. One of the characteristics of the funicular regime is that the liquid content is free to move within the structure of the snow layer, whereas in the pendular regime, the water or brine tends to replace the air between grains to form interconnected grain clusters.

2.2 Thermodynamic Properties of Snow-Covered Sea Ice

Sea ice in the Arctic is part of a complex thermodynamic system that includes both the atmosphere, snow cover on the surface of the ice, and the ocean beneath the ice, thus there are several factors that influence its temperature. The temperature of sea ice is one of the primary properties of interest in Arctic microwave remote sensing, and is often used to determine the salinity of the brine within the ice in lieu of physical measurements. Typically, the temperature of the ice varies with depth, as the ocean waters beneath the ice are comparatively warm, and the surface of the ice is exposed to cold air and/or snow. As such it is often more suitable to speak in terms of the temperature profile of the ice. This section discusses the general thermodynamic model for snow-covered sea ice as well as the thermodynamic properties of sea ice and snow.

2.2.1 General Thermodynamic Model for Snow-Covered Sea Ice

The thermodynamics of sea ice is generally modelled as a one-dimensional system by parameterizing the factors that affect the temperature of the ice into several heat fluxes, as shown in Fig. 2.3 [17]. This model assumes that both the snow and ice layers are homogeneous and infinitely long in the horizontal direction, such that heat transfer only occurs in the vertical direction.



Fig. 2.3: Schematic of the one-dimensional snow-covered sea ice heat flux and energy transfer model, adapted from [17].

At the surface of the of the snow layer, the balance of heat fluxes is given by [17]

$$(1-\alpha)F_{r} - I_{0} + F_{L} - F_{\epsilon L} + F_{s} + F_{l} + k\left(\frac{\partial T}{\partial z}\right)_{0} = \begin{cases} 0 & T_{0} < 273 \text{ K} \\ -q_{s}\frac{d(h+H)}{dt}\Big|_{z=0} & T_{0} = 273 \text{ K} \end{cases}.$$
(2.7)

Here, F_r denotes the incoming short wave radiation, αF_r is the reflected or outgoing short wave radiation, where α is the surface albedo (or reflection coefficient for solar radiation) of the interface, I_0 is the flux of radiative energy transmitted into the system, and F_L is the incoming long-wave radiation. The outgoing long-wave radiation is denoted by F_{EL} , such that $F_{EL} = \epsilon_L \sigma T_0^4$, where ϵ_L is the long-wave emissivity, σ is the Stefan-Boltzmann constant, and T_0 is the temperature at the air-snow interface. Additionally, F_s represents the sensible heat flux, F_l is the latent heat flux in the air, and F_c is the conduction flux in the snow (or ice) layer, q_s is the latent heat of fusion within the snow layer, and h and H are the thicknesses of the snow and ice layers respectively. It is important to note that in (2.7) the positive terms denote incoming fluxes while the negative terms denote outgoing fluxes, each flux is time-dependent, and the units for each flux are watts per square meter, or [W/m²]. The right hand side of (2.7) is set to zero for surface temperatures below 273 K (0 °C), as the snow will not melt at these temperatures. When the temperature at the interface between the air and the snow is above 273 K, the right hand side of (2.7) becomes non-zero to describe the melting of the snow at the interface.

Within the snow layer, the transfer of heat in the vertical direction is given by [17]

$$\rho_s c_s \frac{\partial T}{\partial t} = k_s \frac{\partial^2 T}{\partial z^2} + \kappa_s I_0 e^{-\kappa_s z}.$$
(2.8)

Here ρ_s is the density of the snow in kg/m³, c_s is the specific heat of the snow in J/kgK, while k_s and κ_s represent the thermal conductivity and the radiation extinction coefficient of snow respectively in W/mK and m⁻¹. As per convention, T denotes temperature and t denotes time, which are in kelvin and seconds respectively. Since (2.8) only describes the conduction of heat within the snow layer, it is only valid for $0 \le z \le h$.

The snow-ice interface represents a boundary within the thermodynamic system of snowcovered sea ice, and is accounted for within the model by two boundary conditions. The first of these conditions is the assumption that temperature is continuous across the interface (i.e. $T_s(z = h^-) = T_i(z = h^+)$), and the second is the requirement that heat conduction be continuous across the interface, which is shown by [17]

$$k_s \frac{\partial T_s}{\partial z}\Big|_{z=h} = k_i \frac{\partial T_i}{\partial z}\Big|_{z=h}.$$
(2.9)

The transfer of heat within the ice itself is significantly more complicated than that of the snow layer due to the presence of brine pockets within the ice. These brine pockets are said to reduce temperature changes within the ice due to shifts in the equilibrium between the brine pockets and the surrounding ice. Thus, the heat conduction within the ice is a function of the salinity of the brine encapsulated within the ice. As a result, the model for heat transfer within the ice contains several differential terms, however several of these terms can be ignored without a significant reduction in accuracy. The simplified model for heat transfer within the ice is shown by [17]

$$\rho_i c_i \frac{\partial T}{\partial t} = k_i \frac{\partial^2 T}{\partial z^2} + \kappa_i I_0 e^{-\kappa_i z}.$$
(2.10)

As in (2.8), ρ_i , c_i , k_i and κ_i represent the density, specific heat, thermal conductivity and the bulk radiation extinction coefficient of the ice respectively. However, in (2.10) ρ_i , c_i and k_i are functions of both the salinity and temperature of the ice. Similarly to the heat transfer within the snow layer, (2.10) is only valid for $h \le z \le H + h$. The last component of the one-dimensional thermodynamic model for snow-covered sea ice is the boundary condition at the ice-water interface. As was the case for the snow-ice interface, the heat conduction across the ice-ocean interface is required to be continuous. This condition is illustrated in the following [17]

$$k_i \frac{\partial T_i}{\partial z} \bigg|_{z=h+H} - F_W = q_i \frac{d(h+H)}{dt} \bigg|_{z=h+H}.$$
(2.11)

Here F_W denotes the turbulent heat flux from the water beneath the ice and q_i is the latent heat of fusion within the ice. The right hand side of (2.11) is not explicitly zero, which indicates that the fluxes on either side of the interface do not always balance out. Therefore, the right hand term indicates whether the ice is growing or melting depending on whether its positive or negative.

2.2.2 Thermal Conductivity of Ice and Snow

There is a significant difference in the thermal conductivities of both snow and the sea ice, and the presence of a layer of snow on top of sea ice can drastically affect the temperature of the ice. Snow is typically considered a poor thermal conductor compared to sea ice, and as such, a layer of snow on top of sea ice tends to insulate the ice from the cold Arctic air. As a result of the insulating effect of snow, heat transfered into the ice from the ocean waters beneath it will largely remain within the ice, which causes the temperature of snow-covered sea ice to generally be higher than its bare ice counterpart. The thermal conductivity of snow is dependent on both the density and the temperature of the snow, and is described by [18]

$$k_s = 2.845 \times 10^{-6} \rho_s^2 + 2.7 \times 10^{-4} \times 2^{(T_s - 233)/5}.$$
(2.12)
As a consequence of the brine content in sea ice, the thermal conductivity of sea ice is a function of the thermal conductivity of pure or freshwater ice, the salinity of the ice, and the ice temperature. This is shown by [17, 18]

$$k_i = k_{i, pure} + \frac{\beta S}{T_i - 273}.$$
(2.13)

Here $\beta = 0.1172$ W/m·ppt and S denotes the bulk salinity of the ice. Since the melting point of pure ice is 273 K, this equation is only valid for $T_i < 273$ K.

2.3 Electromagnetic Properties of Snow-Covered Sea Ice

Microwave remote sensing technologies have proven to be useful for environmental monitoring applications for a wide range of terrains, including in the Arctic. The principles of Arctic microwave remote sensing are founded upon the fundamentals of how sea ice behaves in an electromagnetic sense. In general, microwave remote sensing technologies can be categorized as either active or passive sensor systems. The distinction between active and passive technologies lies in how they operate. Passive microwave remote sensing systems, such as radiometers, simply measure the electromagnetic radiation naturally emitted from materials, such as sea ice. Conversely, active microwave remote sensing systems interrogate the sea ice by emitting electromagnetic waves towards the ice and measuring the scattered or reflected radiation. As the focus of this thesis pertains to active microwave remote sensing, this section discusses the underlying electromagnetic theory involved, the relevant electromagnetic properties of both sea ice and snow, as well as the theory behind microwave scattering of objects and a brief overview of active microwave remote sensing of snow-covered sea ice.

2.3.1 Electromagnetic Theory

In order to understand how sea ice interacts with electromagnetic waves, it is useful to examine the basics of the underlying electromagnetic theory for generic media. In general, the propagation of electromagnetic waves in any medium is governed by Maxwell's equations, which form the mathematical basis for describing how electric and magnetic fields within a given material are related. The differential form of Maxwell's equations is given as [19]

$$\nabla \cdot \mathbf{D} = \rho \tag{2.14a}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{2.14b}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{2.14c}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}.$$
 (2.14d)

In these equations, **D** represents the electric flux density in C/m^2 , ρ is the electric charge density in C/m^3 , **B** represents the magnetic flux density in Wb/m², **E** and **H** are the electric and magnetic field intensities in V/m and A/m respectively, and **J** is the electric current density in A/m². In general, following the assumption of no external sources, the electric and magnetic flux densities, as well as the electric current density, are related to the electric and magnetic field intensities following

$$\mathbf{D} = \hat{\varepsilon}(\omega)\mathbf{E} \tag{2.15a}$$

$$\mathbf{B} = \hat{\mu}(\omega)\mathbf{H} \tag{2.15b}$$

$$\mathbf{J} = \sigma \mathbf{E}.\tag{2.15c}$$

Here $\hat{\varepsilon}(\omega)$, $\hat{\mu}(\omega)$, and σ are the permittivity, permeability and conductivity of the material in which the wave is propogating respectively, and ω is the angular frequency such that $\omega = 2\pi f$ where f denotes frequency. The permittivity, permeability, and conductivity are intrinsic properties to the material, and determine quantities such as the speed at which the waves propagate through the material and the intrinsic impedance of the material. Both the permittivity and permeability for a given material are defined relative to that of free space, as shown by

$$\hat{\varepsilon}(\omega) = \varepsilon_0 \hat{\varepsilon}_r(\omega) \tag{2.16}$$

$$\hat{\mu}(\omega) = \mu_0 \hat{\mu}_r(\omega). \tag{2.17}$$

In these equations the subscript r denotes the relative permittivity and permeability of the material. The permittivity and permeability of free space are constants defined as $\varepsilon_0 \cong 8.85419 \times 10^{-12}$ F/m and $\mu_0 = 4\pi \times 10^{-7}$ H/m. In general, the relative permittivity and permeability are complex quantities and functions of frequency, and are tensor quantities. However, materials are often approximated as being isotropic, thus the permittivity and permeability can be taken as scalar values. For non-magnetic materials, such as sea ice and snow, the relative permeability is taken to be $\mu_r = 1$.

Often, the conductivity of the material is included within the imaginary part of the permittivity as a consequence of evaluating Maxwell's equations in the complex domain for time-harmonic plane waves. Assuming the waves have a $e^{j\omega t}$ dependence, where j is the imaginary number and t is time, (2.14) can be re-written in the complex domain as

$$\nabla \cdot \hat{\varepsilon}(\omega) \mathbf{E} = \rho \tag{2.18a}$$

$$\nabla \cdot \hat{\mu}(\omega) \mathbf{H} = 0 \tag{2.18b}$$

$$\nabla \times \mathbf{E} = -j\omega\hat{\mu}(\omega)\mathbf{H} \tag{2.18c}$$

$$\nabla \times \mathbf{H} = j\omega \left(\hat{\varepsilon}(\omega) - j\frac{\sigma}{\omega}\right) \mathbf{E}.$$
 (2.18d)

For the purpose of symmetry between (2.18c) and (2.18d), the effective permittivity of the

material is defined as

$$\hat{\varepsilon}_{eff} = \hat{\varepsilon}(\omega) - j\frac{\sigma}{\omega}.$$
(2.19)

As per convention, the complex permittivity is of the form $\hat{\varepsilon}(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega)$. Therefore, the effective relative permittivity of a material can be written as

$$\hat{\varepsilon}_{r\ eff} = \varepsilon'_{r}(\omega) - j\left(\varepsilon''_{r}(\omega) + \frac{\sigma}{\omega\varepsilon_{0}}\right).$$
(2.20)

For the purposes of this thesis, the permittivities considered are effective relative permittivities, and do not include the dielectric constant of free space, ε_0 .

2.3.2 Relative Complex Permittivity of Sea Ice

The complex permittivity of sea ice is often difficult to measure in-situ, and is generally determined from bulk salinity and ice temperature measurements, which are significantly easier to perform. From an electromagnetic point of view, sea ice itself is generally considered to be a heterogeneous mixture of brine and air inclusions within a pure ice background, and due to the heterogeneity of sea ice, the permittivity is not constant with depth, and to a lesser extent with horizontal distance. As such, it is appropriate to consider the permittivity of sea ice to be a tensor quantity. However, for simplicity, the horizontal variations are often neglected and the vertical dielectric profile, also called the complex permittivity profile, of the ice is considered.

The dielectric constant of pure ice, denoted herein as ε_i , is dependent on both the temperature of the ice and frequency in the microwave region of the electromagnetic spectrum, as shown in the following equations [7, 20, 21]

$$\varepsilon'_{i} = 3.1884 + 9.1 \times 10^{-4} T, \quad -40 \le T \le 0 \,^{\circ} \mathrm{C}$$
 (2.21)

$$\varepsilon_i'' = \frac{\alpha_0}{f} + \beta_0 f \tag{2.22a}$$

$$\alpha_0 = (0.00504 + 0.0062\theta) e^{-22.1\theta} \quad \text{GHz}$$
 (2.22b)

$$\beta_0 = \frac{B_1}{T_K} \frac{\mathbf{e}^{b/T_K}}{(\mathbf{e}^{b/t_K} - 1)^2} + B_2 f^2 + \mathbf{e}^{-9.963 + 0.0372(T_K - 273.16)} \quad \text{GHz}^{-1} \tag{2.22c}$$

$$\theta = \frac{300}{T_K} - 1.$$
 (2.22d)

Here T and T_K denote temperature in °C and K respectively, and f denotes frequency in GHz, while $B_1 = 0.0207$ K/GHz, b = 335 K, and $B_2 = 1.16 \times 10^{-11}$ GHz⁻³. As can be seen from (2.21), at microwave frequencies, the real part of the permittivity of pure ice only depends on temperature. At microwave frequencies, the imaginary part of the permittivity of pure ice is small and as such may be neglected.

The permittivity of brine, which is denoted as ε_b , is generally taken to follow the Debye relaxation model, as illustrated by [7, 22]

$$\varepsilon_b' = \varepsilon_{W\infty} + \frac{\varepsilon_{b0} - \varepsilon_{W\infty}}{1 + (2\pi f \tau_b)^2}$$
(2.23)

$$\varepsilon_b'' = (2\pi f \tau_b) \frac{\varepsilon_{b0} - \varepsilon_{W\infty}}{1 + (2\pi f \tau_b)^2} + \frac{\sigma_b}{2\pi f \varepsilon_0}$$
(2.24)

In these equations, the dc permittivity (ε_{b0}), relaxation time constant (τ_b), and conductivity (σ_b) of brine are all functions of temperature and the normality of the brine solution, N_b , which is a function of the salinity of the brine⁴. Please see Appendix A for the equations

⁴ It is worth noting that the real part of the permittivity of brine or sea water is less than that of fresh water. The real part of the permittivity of fresh water is large due to the strong dipole moment resulting from the natural polarization of water molecules. The dissolution of salts in fresh water decreases the effective dipole moment of the water since the ions from the salts attract the water molecules, disrupting their preferred natural orientation, thus causing the real part of the permittivity to decrease [23]. Conversely, the imaginary part of the permittivity of water is increased by the dissolution of salts since the ions increase the conductivity of the mixture.

for ε_{b0} , τ_b , σ_b , and N_b . The salinity of the brine included within the ice is generally determined from the temperature of the ice using the empirical model shown by (2.1), and the permittivity of brine as frequency tends to infinity, $\varepsilon_{W\infty}$, is taken to be 4.9.

Due to the fact that sea ice is a mixture of pure ice and brine, it is necessary to apply a mixture model to determine the effective permittivity of the sea ice. There are several dielectric mixture models available in the literature, however there are three mixture models which are the most commonly applied to sea ice. The first of these models is given as [7]

$$\varepsilon_{mix}^{\alpha} = \varepsilon_i^{\alpha} + v_b (\varepsilon_b^{\alpha} - \varepsilon_i^{\alpha}). \tag{2.25}$$

In this model α can take on numerous values, with $\alpha = 1$ yielding the linear mixture model, $\alpha = 1/2$ being the refractive mixture model, and $\alpha = 1/3$ being the cubic mixture model. The second of these mixture models is the two-phase Polder-van Santen/de Loor mixture model, which considers the geometry of the inclusions within the host material to be ellipsoidal in nature. Specifically, the Polder-van Santen/de Loor mixture model assumes that the mixture is comprised of randomly oriented ellipsoidal inclusions surrounded by the host material. In its general form, the Polder-van Santen/de Loor mixture model for randomly oriented brine inclusions within a pure ice background is given by [7, 24, 25]

$$\varepsilon_{mix} = \varepsilon_i + \frac{v_b}{3} (\varepsilon_b - \varepsilon_i) \sum_{u=x,y,z} \left(\frac{1}{1 + N_u \left(\frac{\varepsilon_b}{\varepsilon^*} - 1 \right)} \right), \quad \varepsilon^* = \begin{cases} \varepsilon_i, & v_b \le 0.1 \\ \varepsilon_{mix}, & v_b > 0.1 \end{cases}$$
(2.26)

where N_u is the depolarization factor for the ellipsoidal inclusions in the u axis. The depolarization factor is a geometric factor used to relate the electric field intensities internal and external to the inclusions, the value of which may be calculated using [7, 26]

$$N_u = \frac{a_x a_y a_z}{2} \int_0^\infty \frac{ds}{(s + a_u^2)\sqrt{(s + a_x^2)(s + a_y^2)(s + a_z^2)}}$$
(2.27)

for each axis of an ellipsoidal inclusion, where a_x , a_y , and a_z are the semiaxes of the ellipsoid. It is important to note that the depolarization factors for each axis must add up to unity (i.e. $\sum_{u=x,y,z} N_u = 1$). For inclusions with spherical geometry, the depolarization factors for each axis of the inclusion are equal (i.e. $N_x = N_y = N_z = 1/3$) and (2.26) reduces to [7, 24, 25]

$$\varepsilon_{mix} = \varepsilon_i + 3v_b \varepsilon^* \frac{\varepsilon_b - \varepsilon_i}{\varepsilon_b + 2\varepsilon^*}, \quad \varepsilon^* = \begin{cases} \varepsilon_i, & v_b \le 0.1 \\ \varepsilon_{mix}, & v_b > 0.1 \end{cases}.$$
(2.28)

The third dielectric mixture model commonly utilized to determine the effective relative permittivity of sea ice is the two-phase Tinga-Voss-Blossey mixture model. As was the case with the Polder-van Santen/de Loor mixture model, the Tinga-Voss-Blossey model is formulated for ellipsoidal inclusions. However, this model assumes that the ellipsoidal inclusions are contained within a fictitious confocal ellipsoidal shell consisting of the host material, and that beyond the boundaries of the shell of the host material, the permittivity is that of the mixture. The general form of the Tinga-Voss-Blossey mixture model for randomly oriented ellipsoidal brine inclusions within a pure ice host is given by [7, 27]

$$\varepsilon_{mix} = \varepsilon_i + \frac{v_b}{3} (\varepsilon_b - \varepsilon_i) \sum_{u=x,y,z} \left(\frac{1}{1 + (N_{u1} - N_{u2}v_i) \left(\frac{\varepsilon_b}{\varepsilon_i} - 1\right)} \right).$$
(2.29)

Here N_{u1} and N_{u2} correspond to the depolarization factors of the host and inclusion ellipsoids respectively, and can be determined using (2.27). For the case of spherical inclusions,

the depolarization factors for both the inclusion and fictitious host ellipsoids become equal to 1/3, and (2.29) reduces to

$$\varepsilon_{mix} = \varepsilon_i + \frac{3v_b\varepsilon_i(\varepsilon_b - \varepsilon_i)}{2\varepsilon_i + \varepsilon_b - v_b(\varepsilon_b - \varepsilon_i)}.$$
(2.30)

Each of these models is a function of the relative permittivities of pure ice and brine, which are both functions of temperature and frequency. In addition, in each model, the contribution of the permittivity of brine is weighted by the brine volume fraction of the sea ice, which can be calculated using (2.2), (2.5), or (2.6).

It is important to note that these models which approximate mixtures of different materials as a single material with an equivalent effective relative permittivity perform well for low frequencies. At higher frequencies, there is the potential that the inclusions within the host material could have a size comparable to the wavelength within the host material, at which point modelling a mixture as having an effective relative permittivity in this manner may introduce inherent error since such models do not account for the effects of spatial dispersion in the medium [28].

2.3.3 Relative Complex Permittivity of Snow

The determination of the complex permittivity of the snow layer that is often present on top of sea ice is generally more complicated than that of sea ice. As stated in Section 2.1.3, depending on conditions, snow can be a mixture of pure ice and air; pure ice, air, and pure water; or pure ice, air, and brine [7, 9–11]. These different compositions of the snow layer are commonly referred to as dry snow, wet snow, and brine-wetted dry snow respectively. Note that the pure ice here is granular in nature, and as such behaves differently in an electromagnetic sense than in sea ice.

There are several empirical models which have been developed to account for specific compositions of the snow layer, the first and most basic of which is that of dry snow. Since the real part of the permittivity of pure ice is essentially independent of frequency and minimally dependent on temperature, the real part of the permittivity for dry snow is primarily dependent on the density of the snow. Accounting for this, the real part of the permittivity of dry snow can be modelled as [9]

$$\varepsilon_{ds}' = \begin{cases} 1 + 1.9\rho_{ds}, & \rho_{ds} < 0.5 \text{g/cm}^3 \\ 0.51 + 2.88\rho_{ds}, & \rho_{ds} > 0.5 \text{g/cm}^3 \end{cases}$$
(2.31)

where ρ_{ds} represents the density of the dry snow. Alternatively, ε'_{ds} can be modelled in terms of the volume fraction of pure ice through applying the two-phase Tinga-Voss-Blossey mixture model for spherical inclusions and assuming the snow layer consists of pure ice grains within a background medium of air using [7]

$$\varepsilon_{ds}' \approx \frac{1 + 0.84v_i}{1 - 0.42v_i}.\tag{2.32}$$

Yet another alternative is presented in [29], and provides an empirical model for the real part of the permittivity of dry snow in terms of the volume fraction of pure ice. This model is shown by

$$\varepsilon'_{ds} = \begin{cases} 1 + 1.4667v_i + 1.435v_i^3, & 0 \le v_i \le 0.45\\ (1 + 0.4759v_i)^3, & v_i \ge 0.45 \end{cases}$$
(2.33)

The magnitude of the imaginary part of the permittivity of dry snow can be calculated using the following equation [7, 9]

$$\varepsilon_{ds}'' \approx \frac{0.34 v_i \varepsilon_i''}{(1 - 0.42 v_i)^2}$$
 (2.34)

and is generally on the order of 10^{-3} .

Modelling the permittivity of wet snow is somewhat complicated by the presence of pure water in the mixture. Since pure water has a dielectric constant which is relatively large (having approximate value in the ranges of $50 \le \varepsilon'_r \le 80$ and $30 \le \varepsilon''_r \le 40$ for Cband frequencies at temperatures near 0 °C [30, 31]), the permittivity of wet snow is largely governed by the volume of pure water included within the snow. A modified Debye-like empirical model developed by [9] for the relative permittivity of wet snow is given by

$$\varepsilon_{ws} = A + \frac{Bm_v^x}{1 + \left(\frac{f}{f_0}\right)^2} - j \frac{C\left(\frac{f}{f_0}\right)m_v^x}{1 + \left(\frac{f}{f_0}\right)^2}.$$
(2.35)

Here, A, B, C, and x are model parameters, f_0 is the effective relaxation frequency of wet snow, and m_v is the volume fraction of liquid water contained within the snow (also called the snow wetness). From the model fit presented in [9], it was determined that x = 1.31 and $f_0 = 9.07$ GHz, and the remaining model parameters can be calculated using the following equations⁵

$$A = A_1(1.0 + 1.83\rho_s + 0.02m_v^{1.015}) + B_1$$
(2.36a)

$$B = 0.073A_1 \tag{2.36b}$$

$$C = 0.073A_2$$
 (2.36c)

$$A_1 = 0.78 + 0.03f - 5.8 \times 10^{-4} f^2$$
(2.36d)

$$A_2 = 0.97 - 3.9 \times 10^{-3} f + 3.9 \times 10^{-4} f^2$$
 (2.36e)

$$B_1 = 0.31 - 0.05f + 8.7 \times 10^{-4} f^2.$$
(2.36f)

This model is valid for the frequency range from 3 to 37 GHz, snow densities between 0.09 and 0.38 g/cm³ inclusive, and snow water volume fractions between 1 and 12%.

⁵ In the calculation of the model parameters in (2.36), it is required that f be in GHz.

A dielectric model for brine-wetted dry snow has been put forth by [10], and is given by the following equation

$$\varepsilon_{mix} = XV_b \frac{\varepsilon_b - \varepsilon_{ds}}{1 + N_0 \left(\frac{\varepsilon_b}{\varepsilon_{ds}} - 1\right)}.$$
(2.37)

Here, X is a coupling factor, N_0 is the dominant depolarization factor, and V_b is the so-called *true* brine volume fraction, which is calculated as [10]

$$V_b = \frac{v_b \rho_b}{(1 - v_b)\rho_i + v_b \rho_b} \frac{\rho_s}{\rho_b}.$$
(2.38)

For the case in which the brine contained within the snow-layer can be represented as isotropically oriented spheroids, the value of the coupling factor X is taken to be 2/3 [10]. The value of the dominant depolarization factor is dependent on the saturation of the snow, and can be taken to be approximately 0.053 for snow in the pendular regime and approximately 0.076 for snow in the funicular regime [10, 16].

2.3.4 Microwave Scattering

Within the context of microwave scattering of sea ice, it is useful to discuss the radar crosssection of the ice as well as the underlying theory. The radar cross-section of an object or region of interest is a far-field quantity with respect to antenna theory, and is a measure of the ratio between the scattered and incident electromagnetic power for the target of interest. A target's radar cross-section is defined to be the cross-sectional area of a sphere made of a perfect electric conductor which would hypothetically provide the same scattering response as the target of interest [32]. In general, the radar-cross section of a target is a function of frequency, angle of incidence, and polarization. For a given target, the linearly polarized transmitted and received electric field intensities of the incident and reflected plane wave can be decomposed into their vertical and horizontal components as [32]

$$\mathbf{E}_{t} = |\mathbf{E}_{t}|\cos\gamma_{t}\hat{\mathbf{v}} + |\mathbf{E}_{t}|\sin\gamma_{t}\hat{\mathbf{h}}$$
(2.39a)

$$\mathbf{E}_r = |\mathbf{E}_r| \cos\gamma_r \hat{\mathbf{v}} + |\mathbf{E}_r| \sin\gamma_r \hat{\mathbf{h}}$$
(2.39b)

where γ_t and γ_r are the angles between the vertical axis and the transmitted and received electric field intensities respectively, and $\hat{\mathbf{v}}$ and $\hat{\mathbf{h}}$ are unit vectors in the vertical and horizontal directions. The received electric field intensity is related to the transmitted electric field intensity by [32]

$$\begin{bmatrix} E_{vr} \\ E_{hr} \end{bmatrix} = \begin{bmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{bmatrix} \begin{bmatrix} E_{vt} \\ E_{ht} \end{bmatrix}$$
(2.40)

where S_{pq} are the elements of the scattering matrix with the subscripts p and q denoting the received and transmitted polarizations. In general, S_{pq} is a complex quantity. Since the radar cross-section of a target is defined mathematically as [7, 32]⁶

$$\sigma_{pq} = \lim_{R \to \infty} 4\pi R^2 \frac{p|\mathbf{S}_s|}{q|\mathbf{S}_i|} = \lim_{R \to \infty} 4\pi R^2 \frac{p|\mathbf{E}_s|^2}{q|\mathbf{E}_i|^2}$$
(2.41)

where S denotes the Poynting vector, and the subscripts s and i denote the scattered and incident quantities respectively, the scattering matrix can be rewritten in terms of the radar cross-sections in each polarization as

$$\frac{1}{|\mathbf{E}_i|} \begin{bmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{bmatrix} = \begin{bmatrix} \sqrt{\sigma_{vv}} & \sqrt{\sigma_{vh}} \\ \sqrt{\sigma_{hv}} & \sqrt{\sigma_{hh}} \end{bmatrix}$$
(2.42)

where the square of the amplitude of element $\sqrt{\sigma_{pq}}$ is equal to the radar cross-section in that polarization.

⁶ Note that the requirement that $R \to \infty$ in (2.41) denotes the far-field zone with respect to the interrogating antenna.

For distributed targets or regions of interest, the radar cross-section is normalized by the area illuminated by the radar, which is given by

$$\sigma_{pq}^{0}(\theta_{i},\phi_{i},\theta_{obs},\phi_{obs}) = \lim_{R \to \infty} \frac{4\pi R^{2}}{A} \frac{\langle^{p} |\mathbf{S}_{s}(\theta_{i},\phi_{i},\theta_{obs},\phi_{obs})|\rangle}{|\mathbf{S}_{i}|}.$$
(2.43)

This dimensionless quantity is commonly referred to as the normalized radar cross-section, or NRCS, and is a function of the angle of incidence θ_i and the azimuth angle ϕ_i at which the radar system transmits the interrogating wave, as well as the elevation and azimuth angles of the observation point, θ_{obs} and ϕ_{obs} . In (2.43), the ensemble average of the power density of the scattered wave, denoted here as $\langle |\mathbf{S}_s| \rangle$, is taken to reduce large fluctuations of the non-averaged NRCS observed for regions which are otherwise uniform. Embedded within (2.41) and (2.43) is the fact that the scattered fields are dependent on both the permittivity of the target, as well as the roughness of the target's surface. Thus, attempts to model the NRCS of a target region must consider both the dielectric and surface properties.

There are several classifications of radar systems employed in active microwave remote sensing. Some systems are only capable of measuring in one polarization (either HH or VV), while others are capable of measuring the co-polarized components as well as the cross-polarized components and are said to be polarimetric. Another distinction is made based on the location of the receiver relative to the transmitter. Systems are said to be monostatic if the transmitter and receiver share a location, in which case the observation angles for the NRCS become $\theta_{obs} = \theta_i$ and $\phi_{obs} = \phi_i + \pi$. For all other locations of the receiver, the radar system is said to be bistatic.

2.3.5 Active Microwave Remote Sensing of Snow-Covered Sea Ice

Active microwave remote sensing of sea ice has been employed in Arctic research endeavours since 1956, and has proven to be effective in differentiating between ice types as well as various surface features of the ice [33]. In addition, the radar technology utilized has proven to be versatile, as measurements can be conducted using surface-based sensors, airborne sensors, and most recently, satellite-based spaceborne sensors. Surface-based measurements are typically conducted using scatterometers, while air-craft based measurements have utilized scatterometers, side-looking airborne radar (SLAR), and synthetic aperture radar (SAR). In general, satellite-based systems utilize SAR.

Microwave scattering in young and first year sea ice tends to be dominated by the scattering which occurs at the air-ice interface in what is referred to as surface scattering [33, 34]. Volume scattering due to the interactions of the penetrating wave with air bubbles and brine inclusions within the ice can contribute to the overall scattering response of the ice, however the relatively high salinity of the ice causes significant attenuation in the penetrating wave as well as the scattered wave within the sea ice. Therefore, the contribution of volume scattering to the overall scattering response of young and first year sea ice is generally minimal. Conversely, the scattering response of multi-year sea ice tends to be dominated by volume scattering due to the microstructure of the ice, as the lower salinity of the ice reduces the attenuation of the penetrating wave [33, 34]. Surface scattering does contribute to the overall scattering response of multiyear ice, but to a lesser extent than for young and first year sea ice. Typical values for the NRCS in the VV polarization at C-band frequencies and an incidence angle of 23° for thick first year and multi-year sea ice during the winter months are -14 ± 2 dB and -10 ± 1 dB respectively [34].

The scattering behaviour of the snow layer that may form on the surface of sea ice demon-

strates some dependence on the classification of the snow (i.e. dry/wet snow). For the case of dry snow, the primary scattering mechanism is volume scattering from the random orientation of the ice grains, as the NRCS of a dry snow layer is virtually independent of surface roughness [4, 7]. In contrast, the NRCS of wet snow is dependent on the roughness of the air-snow interface, which is due in part to the higher effective relative permittivity of wet snow compared to dry snow [7]. As such, wet snow can exhibit both surface and volume scattering, with the magnitude of the volume scattering component dependent on the location of the water within the snow layer relative to the ice grains [11]. The scattering behaviour of brine-wetted dry snow is also higher than that of dry snow. However, the volume scattering contribution of brine-wetted dry snow decreases as the brine volume fraction increases, as the conductivity of brine tends to attenuate the penetrating wave [4]. In addition the scattering response of snow would tend to change as the snowpack undergoes metamorphosis, as the density and grain shape of the ice crystals would be changed.

2.4 Oil-Contaminated Sea Ice

In the context of this thesis, crude oil-contaminated sea ice refers to sea ice which has crude oil directly beneath it in the water column, crude oil included within the ice, crude oil on the surface of the ice and/or in the snowpack, or some combination of these scenarios. In this section, the behaviour of oil in the presence of sea ice is considered as it pertains to these scenarios, and the current efforts to detect oil-contaminated sea ice are explored.

2.4.1 Behaviour of Oil in Ice-Infested Environments

Due to the difference in density between crude oils and sea water, oil which is introduced into the system in the water column beneath the ice will rise to the sea ice/water interface. As the crude oil ascends through the water column, it will generally separate into minute droplets as it rises, and will gather on the underside of the ice [35]. The manner in which the oil collects at the ice/water interface is dependent on both the topography of the bottom of the ice and the properties of the oil itself, including its viscosity. As the bottom of the sea ice is generally soft and porous, oil that has gathered beneath it can penetrate upwards several centimetres [35]. For sea ice that is sufficiently thick, the oil generally will not penetrate beyond the skeletal layer at the bottom of the ice. Sea ice growth may continue below the oil collected at the bottom of the ice, which can encapsulate the oil as a layer within the ice and trap oil that has penetrated into the skeletal layer as inclusions [35]. Since crude oils generally have a thermal conductivity which is 15 to 20 times lower than that of sea ice [35], the presence of the oil can significantly impede further growth of the contaminated sea ice.

The rate at which the oil spreads beneath the ice, and subsequently the distance to which it spreads from the initial spill, is governed by several factors. These can include the currents in the sea water beneath the ice, as well as the type of ice and the topography of the underside of the ice. In general, oil spilled beneath sea ice tends to be naturally prevented from spreading by the presence of the ice, unlike an oil spill in open water [36]. This is particularly true for ice with significant depressions at the ice/water interface, as the oil will tend to pool within the depressions. If the oil is contained under drift or pack ice, the oil will tend to travel with the floes and remain largely contained until the floes begin to break up [36, 37]. In the event of the break up of a floe with oil trapped beneath it, the oil will continue to spread at an increasing rate as the ice concentration decreases.

Oil that has pooled under the ice can be prevented from spreading further by continued growth of the ice adjacent to the pool. Sufficient additional ice growth beside the pool can result in the formation of an ice lip, which impedes the ability of the oil to spread [35]. As the ice continues to grow, and the oil continues to be pooled and contained by the ice lip, the sea water surrounding the oil can freeze, encapsulating the pooled oil within the sea ice itself. Such an oil pool or encapsulation has been observed to cause an increase in salinity in the ice directly above it, resulting from either the oil preventing brine drainage from this portion of the ice or the change in the temperature gradient caused by the presence of oil [35]. Migration of oil which has pooled beneath or has been encapsulated within sea ice is largely dependent on the season in which the spill occurs. Upward oil migration is restricted in the winter by the freezing of the brine channels as the ice cools [35]. During the fall freeze-up and the spring melt, the oil can move relatively freely up through the brine channels to the surface of the ice, decreasing the albedo of the ice [35]. In addition, oil has been observed to migrate into the snow layer on the surface of the ice, with the snow absorbing 20 to 25% of the oil [36, 38]. As crude oil is exposed to Arctic environments, it may also undergo several changes at a chemical level. Oil which has been spilled in the water column beneath sea ice can undergo emulsification [39], and weathering of such spills can vary with the type and coverage of the ice [37, 40].

2.4.2 Current Detection Efforts

There have been several works published on potential technologies to detect crude oilcontaminated sea ice in preparation for industrialization of the Arctic, however many of these technologies are still in development [41, 42]. One of the technologies which has seen recent advances is that of laser fluorosensors [41, 43]. These sensors are generally mounted on aircraft, and operate by directing ultraviolet (UV) radiation at the target, which in this case is sea ice, and detecting the visible light emitted from the target through fluorescence. While sea ice itself does not fluoresce when exposed to UV radiation, several compounds within crude oils exhibit fluorescence at these wavelengths, including aromatic compounds [41, 44]. Although algae, which can grow at the bottom of sea ice during the spring melt, will also fluoresce when excited by UV radiation, the polarization of the fluorescence can be used to differentiate between oil-contaminated ice and an ice algal bloom [44]. Due to the utilization of the visible region of the electromagnetic spectrum, laser fluorosensors are less effective in detecting oil-contaminated ice during precipitation events, and through fog and cloud cover.

Oil-in-ice detection using surface-contacting acoustic sensors has been shown to be possible [41, 45], however there are several logistical issues which have prevented the technology from developing further. The primary operating principle of such acoustic sensors is that oil behaves as a quasi solid at higher acoustic frequencies, which causes it to reflect both longitudinal and transverse acoustic waves (i.e. both types of acoustic waves). Provided the acoustic attenuation within the ice, which is proportional to the salinity of the ice, is sufficiently low, the presence of oil can be identified by the wave reflections [41, 45]. For the surface-contacting acoustic sensors to operate effectively in an oil-in-ice detection situation, they must be placed in direct contact with a snow-free ice surface [41, 45]. As such, deployment of the sensors requires not only personnel on location to configure the detection system, but also significant labour to dig through the snowpack to deploy the sensors unless the ice is bare. Due to the need to deploy the sensors locally, some prior knowledge of the location of the oil-contamination would also be required for these sensors to be effective.

Due to the limitations of surface-contacting acoustic sensors, there has been some research conducted on the application of upward looking acoustic sensors (sonar) mounted on an unmanned underwater vehicle (UUV) for oil-in-ice spill detection [46]. The UUV-based sensor suite also included upward looking optical sensors with a sheet laser system for low light conditions. In the experiment presented, the sea ice was sufficiently thick that the majority of the crude oil pooled in an artificially created hollow at the ice/water interface, and the rate at which the oil spread was determined using the optical sensors. The sonar sensor, which in this case had a direct line of sight to the crude oil unlike its surface mounted counterparts, allowed quantification of the thickness of the oil layer beneath the ice based on the acoustic waves reflected from the oil/water interface and the ice/oil interface. In using a UUV-based sensor suite for mapping oil spilled beneath sea ice, the measurements taken are independent of the weather and sea ice conditions, however prior knowledge of the general location of a spill is required for a UUV-based system to be deployed and utilized effectively. Since the experiment presented in [46] was performed in a tank with the UUV mounted on rails on the bottom of the tank, it remains unclear how such a system would perform if mounted on a submersible in the Arctic Ocean in the presence of ocean currents.

Another technology that has shown potential for applications in oil spill detection in ice infested waters is synthetic aperture radar [47]. Although radar measurements were initially thought to be unsuited for Arctic oil spill detection as the presence of sea ice dampens the wave action of the unfrozen portions of the Arctic Ocean, and the damping of wave action by an oil slick in open water is one of the characteristics utilized in open water spill detection, the research presented in [47] suggests that polarimetric SAR measurements can be used to differentiate between oil slicks and young sea ice in the marginal ice zones. This ability to discriminate between the two stems from the difference in the co-polarization ratio⁷ observed for crude oil and sea water mixtures and young sea ice. Simulation results for modelling of the co-polarization ratio assuming a Bragg scattering model suggest that the co-polarization ratio assuming a Bragg scattering model suggest that of an oil and sea water

⁷ The co-polarization ratio is sometimes defined to be $\frac{S_{vv}}{S_{hh}}$. In radar measurements where the NRCS is obtained, the magnitude of the co-polarization ratio may be calculated as $\frac{\sigma_{vv}^0}{\sigma_{hh}^0}$.

mixture, and differentiation between the two would be more effective at larger incidence angles [47]. However, the work presented in [47] does not include radar measurements of oil-contaminated sea ice, thus further development is needed for SAR detection of Arctic oil spills.

Ground penetrating radar (GPR) has also shown promise for detecting oill spilled beneath sea ice, and quantifying the amount of oil present. In particular, one-dimensional inversion of GPR data collected from a tank experiment in which crude oil was spilled beneath bare sea ice facilitated the quantification of the thickness of the oil layer beneath the ice [48]. In the experiment presented in [48], plastic sheeting was frozen into the ice to create a containment loop to form a localized area for the oil to pool beneath the ice, and GPR data was collected for both the uncontaminated ice outside the containment loop and the oil-contaminated ice. Within the oil-contaminated ice grown in this experiment, there was a thin encapsulated layer of oil within the ice as a result of an smaller-scale introduction of oil at an early stage of the ice growth, and the inversion algorithm successfully recovered the thickness of the encapsulated layer if and only if an initial guess was given for the location and thickness of the layer. Conversely, the inversion algorithm was successful in determining the thickness of the oil layer at the bottom of the sea ice even when the initial guess was that there was no oil layer beneath the ice. Similar to other surface-based technologies, the application of this GPR technique in the event of an Arctic oil spill would be limited by the ability to deploy systems and personnel to the spill location, and as such would require prior knowledge of where the spill occurred. As well, it may be necessary to expand the inversion algorithm to two- or three-dimensions to reflect the spatial heterogeneity of Arctic sea ice, as well as to account for snow cover, if this method is to be utilized in an actual spill scenario.

Other technologies which have been considered for Arctic oil spill detection applications include optical and infrared sensors, microwave radiometers, and magnetic resonance spec-

troscopy. However, optical detection of oil spilled beneath sea ice using the visible spectrum of electromagnetic radiation requires the ice to be transparent [41, 45], which is rarely, if at all, the case, and melt ponds with significant sediment can have a similar appearance to crude oil, which further complicates detection [45, 49]. Therefore, optical methods in the visible spectrum do not appear to be useful for applications pertaining to the detection of oil in an ice infested environment. Some consideration has been given to utilizing passive UV sensors and hyperspectral sensors, however UV sensors can be limited by cloud cover, and hyperspectral sensors have yet to be field tested [45, 49]. Similarly, the viability of using radiometers for Arctic oil spill detection is currently inconclusive [41, 45]. Finally, nuclear magnetic resonance (NMR) spectroscopy technology is currently being developed for detection of oil beneath sea ice, and improvements to increase the signal to noise ratio and decrease the dead time of the sensor are being pursued to increase the feasibility of utilizing this technology for Arctic oil spill detection [45].

In summary, the technologies being explored for the detection of crude oil in ice-infested environments are largely in the early stages of development, and several require personnel to be in the vicinity of the spill site to operate. While radar-based techniques including spaceborne SAR are being evaluated for such applications, the work thus far has been largely simulation based and there has yet to be measured radar data for oil-contaminated sea ice published in the literature. In addition, the electromagnetic based detection methods may benefit from an improved understanding of how the presence of crude oil will affect the temperature, salinity, and dielectric profiles of the sea ice. Therefore, the research presented in the following chapters was conducted to address these issues and improve the current state of knowledge of oil-contaminated sea ice to further facilitate the development of remote sensing technologies for the purposes of Arctic oil-spill detection.

References

- W. F. Weeks and S. F. Ackley, "The growth, structure, and properties of sea ice," in *The geophysics of sea ice*. Berlin, Germany: Springer, 1986, pp. 9–164.
- [2] P. Wadhams, *Ice in the Ocean*. Philadelphia, PA: Gordon and Breach Science Publishers, 2000, ch. 2.
- [3] National Snow and Ice Data Center. "All about sea ice". [Online]. Available: https://nsidc.org/cryosphere/seaice/index.html
- [4] M. Shokr and N. K. Sinha, Sea Ice: Physics and Remote Sensing. New York, NY: Wiley, 2015.
- [5] A. Assur, "Composition of sea ice and its tensile strength," in *Arctic Sea Ice*. Washington, DC: National Academy of Sciences - National Research Council, 1958, pp. 106–138.
- [6] G. F. N. Cox and W. F. Weeks, "Equations for determining the gas and brine volumes in sea ice samples," *J. Glaciology*, vol. 29, no. 102, 1983.
- [7] F. T. Ulaby and D. G. Long, *Microwave Radar and Radiometric Remote Sensing*. Ann Arbor, MI: University of Michigan Press, 2014.

- [8] G. Frankenstein and R. Garner, "Equations for determining the brine volume of sea ice from -0.5 to -22.9 °C," J. Glaciology, vol. 6, no. 48, 1967.
- [9] M. Hallikainen, F. T. Ulaby, and M. Abdelrazik, "Dielectric properties of snow in the 3- to 37-GHz range," *IEEE Trans. Antennas Propag.*, vol. 34, no. 11, pp. 1329–1340, 1986.
- [10] M. R. Drinkwater and G. B. Crocker, "Modelling changes in the dielectric and scattering properties of young sow-covered sea ice at GHz frequencies," *J. Glaciology*, vol. 34, no. 118, pp. 274–282, Feb. 1998.
- [11] A. Langlois and D. G. Barber, "Passive microwave remote sensing of seasonal snowcovered sea ice," *Progress in Physical Geography*, vol. 31, no. 6, pp. 539–573, 2007.
- [12] D. G. Barber and S. V. Nghiem, "The role of snow on the thermal dependence of microwave backscatter over sea ice," *J. Geophysical Research*, vol. 104, no. C11, pp. 25 789–25 803, Nov. 1999.
- [13] D. G. Barber, S. P. Reddan, and E. F. LeDrew, "Statistical characterization of the geophusical and electrical properties of snow on landfast first-year sea ice," *J. Geophysical Research*, vol. 100, no. C2, pp. 2673–2686, Feb. 1995.
- [14] M. Sturm, J. Holmgren, and D. K. Perovich, "Winter snow cover on the sea ice of the Arctic Ocean at the Surface Heat Budget of the Arctic Ocean (SHEBA): Temporal evolution and spatial variability," *J. Geophysical Research*, vol. 107, no. C10, 2002.
- [15] S. C. Colbeck, "An overview of seasonal snow metamorphism," *Reviews of Geophysics and Space Physics*, vol. 20, no. 1, pp. 45–61, Feb. 1982.
- [16] A. Denoth, "The pendular-funicular liquid transition in snow," J. Glaciology, vol. 25, no. 91, pp. 93–97, Jan. 1980.

- [17] G. A. Maykut and N. Untersteiner, "Some results from a time-dependent thermodynamic model of sea ice," J. Geophysical Research, vol. 76, no. 6, Feb. 1971.
- [18] E. E. Ebert and J. A. Curry, "An intermediate one-dimensional thermodynamic sea ice model for investigating ice-atmosphere interactions," *J. Geophysical Research*, vol. 98, no. C6, pp. 10 085–10 109, Jun. 1993.
- [19] S. Ramo, J. R. Whinnery, and T. Van Duzer, *Fields and waves in communication electronics*, 3rd ed. New York, NY: Wiley, 1994, ch. 3.
- [20] C. Mätzler and U. Wegmüller, "Dielectric properties of fresh-water ice at microwave frequencies," J. Physics D: Appl. Physics, vol. 20, no. 12, pp. 1623–1630, 1987.
- [21] G. Hufford, "A model for the complex permittivity of ice at frequencies below 1 THz," *Int. J. Infrared and Millilmeter Waves*, vol. 12, no. 7, pp. 677–682, 1991.
- [22] A. Stogryn, "Equations for calculating the dielectric constant of saline water," *IEEE Trans. Microw. Theory Tech.*, vol. 19, no. 8, pp. 733–736, Aug. 1971.
- [23] J. B. Hasted, D. M. Ritson, and C. H. Collie, "Dielectric properties of aqueous ionic solutions: Parts I and II," J. Chemical Phys., vol. 16, no. 1, Jan. 1948.
- [24] D. Polder and J. H. van Santen, "The effective permeability of mixtures of solids," *Physica*, vol. 12, no. 5, pp. 257–271, 1946.
- [25] G. P. de Loor, "Dielectric properties of heterogeneous mixtures containing water," J. *Microwave Power*, vol. 3, no. 2, pp. 67–73, 1968.
- [26] A. Sihvola, "Dielectric polarization and particle shape effects," *J. Nanomaterials*, May 2007.
- [27] W. R. Tinga, W. A. G. Voss, and D. F. Blossey, "Generalized approach to multiphase dielectric mixture theory," J. Applied Physics, vol. 44, no. 9, pp. 3897–3902, 1973.

- [28] S. Tretyakov, Analytical modelling in applied electromagnetics. Norwood, MA: Artech House, 2003.
- [29] C. Mätzler, *Thermal microwave radiation: Applications for remote sensing*. Stevenage, Hertfordshire, U.K.: The Institution of Engineering and Technology, 2006, ch. 5.
- [30] J. B. Hasted, "Liquid water: dielectric properties," in *Water, A comprehensive treatise, Vol. 1*, F. Franks, Ed. New York, NY: Plenum Press, 1972, ch. 7, pp. 255–309.
- [31] R. Buchner, J. Barthel, and J. Stauber, "The dielectric relaxation of water between 0°C and 35°C," *Chemical Physics Lett.*, vol. 306, pp. 57–63, Jun. 1999.
- [32] E. F. Knott, *Radar Cross Section Measurements*. New York, NY: van Nostrand Reinhold, 1993, ch. 1.
- [33] R. G. Onstott, "SAR and scatterometer signatures of sea ice," in *Microwave remote sensing of sea ice*, F. D. Carsey, Ed. Washington, DC: American Geophysical Union, 1992, ch. 5, pp. 73–104.
- [34] D. Lubin and R. Massom, *Polar Remote Sensing: Volume I: Atmospheres and oceans*.Berlin, Germany: Springer, 2006.
- [35] NORCOR Engineering & Research Limited, "The interaction of crude oil with Arctic sea ice," *Beaufort Sea Project Tech. Rep. No.* 27, Dec. 1975.
- [36] D. Dickins, "Behaviour of oil spills in ice and implications for Arctic spill response," in *Proc. Arctic Technology Conf.*, Houston, TX, Feb. 2011.
- [37] L.-G. Faksness, P. J. Brandvik, R. L. Daae, F. Leirvik, and J. F. Børseth, "Large-scale oil-in-ice experiment in the Barents Sea: Monitoring of oil in water and MetOcean interactions," *Marine Pollution Bulletin*, vol. 62, no. 5, pp. 976–984, 2011.

- [38] M. F. Fingas and B. P. Hollebone, "Review of behaviour of oil in freezing environments," *Marine Pollution Bulletin*, vol. 47, no. 9, pp. 333–340, 2003.
- [39] W. J. Campbell and S. Martin, "Oil and ice in the Arctic ocean: Possible large-scale interactions," *Sci.*, vol. 181, no. 4094, pp. 160–166, Jul. 1973.
- [40] P. J. Brandvik and L.-G. Faksness, "Weathering processes in Arctic oil spills: Mesoscale experiments with different ice conditions," *Cold Regions Sci. and Technology*, vol. 55, no. 1, pp. 160–166, Jun. 2009.
- [41] M. Fingas and C. E. Brown, "Detection of oil in ice and snow," J. Marine Sci. and Eng., no. 1, pp. 10–20, 2013.
- [42] M. Fingas and C. Brown, "Review of oil spill remote sensing," *Marine Pollution Bulletin*, vol. 83, Apr. 2014.
- [43] C. E. Brown and M. F. Fingas, "Review of the development of laser fluorosensors for oil spill applications," *Marine Pollution Bulletin*, vol. 47, no. 9, pp. 477–484, 2003.
- [44] W. S. Pegau, J. Garron, and L. Zabilansky, "Detection of oil in and under ice," Arctic Response Technology: Oil Spill Preparedness Final Rep., 2016.
- [45] C-Core, "Oil spill dectetion and mapping in low visibility and ice: Surface remote sensing," C-Core Rep. R-12-081-1001, ver. 5.1, 2013.
- [46] J. P. Wilkinson, T. Boyd, B. Hagen, T. Maksym, S. Pegau, C. Roman, H. Singh, and L. Zabilansky, "Detection and quantification of oil under sea ice: The view from below," *Cold Regions Sci. and Technology*, vol. 109, pp. 9–17, 2015.
- [47] C. Brekke, B. Holt, C. Jones, and S. Skrunes, "Discrimination of oil spills from newly formed sea ice by synthetic aperture radar," *Remote Sensing of Environment*, vol. 145, Feb. 2014.

- [48] J. H. Bradford, E. L. Babcock, H.-P. Marshall, and D. F. Dickins, "Targeted reflectionwaveform inversion of experimental ground-penetrating radar data for quantification of oil spills under sea ice," *Geophysics*, vol. 81, no. 1, pp. WA59–WA70, 2015.
- [49] D. Dickins and J. H. Andersen, "Remote sensing technology review and screening," Oil in Ice - JIP Rep. No. 22, SINTEF Materials and Chemistry, Marine Environment Technology, 2009.

Experimental Preparation

In preparation for the oil-in-sea ice experiment that was performed from January to March 2016 which is presented in Chapter 4, a tank experiment was conducted in the University of Manitoba Centre for Earth Observation Science cold laboratory. Due to the health and safety concerns surrounding working with crude oil in the laboratory, corn oil was chosen as a substitute as it was expected to have a similar dielectric constant at C-band frequencies to crude oil, as well as a similar density to crude oil. This chapter presents the details of the cold laboratory experiment, as well as the measured temperature, bulk salinity, and corn oil volume fraction data for the samples collected. In addition, this chapter discusses dielectric modelling of the uncontaminated and contaminated sea ice grown in the cold laboratory experiment, as well as the dielectric measurement of the corn and crude oils used in this research.



Fig. 3.1: Schematic of the tank systems utilized for experiments in the cold laboratory, with the ice growth tank shown on the left and the pressure release tank shown on the right.

3.1 Cold Laboratory Experiment

The cold laboratory experiment consisted of the growth of both uncontaminated and corn oil-contaminated artificial sea ice under controlled ambient temperatures. To conduct the experiment, a set of two identical tank systems, based on the tank design of [1], were fabricated using 50 gallon polyethylene tanks. A schematic of the tank system design is shown in Fig. 3.1. The tank systems consisted of an ice growth tank, which was insulated on all sides except the top, and a pressure release tank which was insulated on all sides. The tanks were connected at the bottom by $1 \frac{1}{4}$ " threaded vinyl tubing, which was also insulated, and PVC ball valves were connected at the output ports of the tanks to isolate the tanks from each other if necessary. Fig. 3.2 shows the fully assembled tank systems in the cold laboratory.

Throughout the experiment, the ice temperature profile was measured in-situ with thermocouples¹ frozen into the ice with a 1 cm spacing. The measured temperature profile was collected using a Campbell Scientific CR1000 data logger with a measurement interval of

¹ Omega Engineering Inc. PR-T-24-SLE Type-T thermocouple wire was used. When used in conjunction with a Campbell Scientific CR1000 datalogger, the thermocouples allow for temperature measurement accurate to within 0.3 °C for temperatures in the range of -25 to 50 °C. For temperatures ranging from -55 to -25 °C and 50 to 85 °C, temperature measurements are accurate to within 0.8 °C [2].



Fig. 3.2: The insulated tank systems used to grow artificial sea ice for the cold laboratory experiments.

5 minutes. The ice growth tanks each had heating cables wrapped around the bottom half of the tanks beneath the insulation to prevent the brine in the tanks from freezing to the bottom. The operation of the heating cables was controlled using electrically controllable outlets connected to the CR1000 such that the heating cables would be powered when the thermocouple at the lowest depth in the sea water reached the freezing point. Initially, the experiment was to be conducted with the uncontaminated and corn oil-contaminated sea ice grown simultaneously using the two separate tank systems. However, during the initial freeze-up of the experiment, one of the tank systems experienced catastrophic failure and leaked the majority of its artificial sea water onto the floor of the cold laboratory. The experiment was then adjusted such that it would be conducted in two stages using a single tank system: the first stage was for uncontaminated ice growth, while the second stage was for the corn oil-contaminated ice growth. Since the cold laboratory allows precise ambient temperature control, it was expected that there would be minimal difference in the results between the revised and original experimental plans, aside from the time required to conduct the experiment.

For each stage of the experiment, the 33 psu artificial sea water in the ice growth tank was allowed to freeze in an ambient temperature of -20 °C for a period of one week to allow significant initial ice growth. Following this growth period, the ambient temperature was held at -20 °C and one 3" by 3" rectangular ice core was taken every second day using a power drill with an auger bit. Following the final sampling at -20 °C, the ambient temperature in the cold laboratory was set to -15 °C and the system was allowed to stabilize for approximately half a week. With the ambient temperature held at -15 °C, ice cores were again collected every second day. Following this, the cold laboratory temperature was adjusted to -10 °C and the system was again allowed to stabilize. Several ice cores were taken simultaneosly at this temperature in each stage, however in each case only one sample was not lost to the water beneath the ice. Between the two stages of the experiment, the tank system was removed from the cold laboratory and allowed to melt, after which the sea water was re-mixed to dissolve any salts that had precipitated at the bottom of the tanks. For the corn oil-contaminated stage of the experiment, approximately 2.2 L of corn oil was injected into the water column via a hole drilled through the ice roughly halfway through the initial growth period.

Each ice core taken was subsequently cut into horizontal sections with the top section being 2 to 3 cm thick and the lower sections varying in thickness, and were allowed to melt at room temperature. This difference in thickness stemmed purely from the limited number of sample containers available for the experiment. For the melted uncontaminated samples, bulk salinity was measured directly using a conductivity probe. For the melted corn oil-contaminated samples, the corn oil and salt water were separated through gravimetric means to determine the volume of corn oil within each subsection of the ice cores, and the bulk salinity of the separated sea water was measured using the conductivity probe. The temperature and bulk salinity profiles for each core sample are shown in Figs. 3.3 and 3.4 respectively. In addition, the corn oil volume fraction profiles for the contaminated samples



Fig. 3.3: The measured temperature profiles for (a) uncontaminated sea ice and (b) corn oilcontaminated sea ice grown in the cold laboratory experiment.



Fig. 3.4: The measured bulk salinity profiles for (a) uncontaminated sea ice and (b) corn oilcontaminated sea ice grown in the cold laboratory experiment. Note that the sample pertaining to the top 3 cm of one of the contaminated samples taken at -15 °C was lost and as such does not have a measured salinity.

are shown in Fig. 3.5.

As can be seen from Fig. 3.3, there is minimal difference in the temperature profiles of the sea ice grown in both the uncontaminated and contaminated stages of the experiment.



Fig. 3.5: The measured corn oil volume fraction profiles for the contaminated sea ice grown in the cold laboratory experiment. Note that the sample pertaining to the top 3 cm of one of the contaminated samples taken at -20 °C was lost and as such does not have an associated corn oil volume fraction.

The most notable difference between the temperature profiles of the two stages is that the bottom of the ice appears to have been slightly colder in the contaminated stage. There does appear to be a more significant difference between the bulk salinity profiles of the uncontaminated and corn oil-contaminated ice cores shown in Fig. 3.4, as the lower sections of the contaminated cores generally have a lower salinity. From the corn oil volume fraction profiles plotted in Fig. 3.5, it is clear that there was minimal corn oil content within the ice sampled, except for the sample taken at an ambient temperature of -10 °C which has an oil volume fraction of approximately 4.2% in the top 3 cm of the core. Finally, it should be noted that these differences between the contaminated and uncontaminated cases are fundamental to the development of appropriate remote sensing techniques.

3.2 Dielectric Modelling

In order to link the measured geophysical and thermal properties of the artificial sea ice grown during the cold laboratory experiment to the electromagnetic properties of sea ice relevant to active microwave remote sensing, the dielectric profiles of the ice samples collected were modelled accordingly. Prior to the modelling of the permittivity profiles, it was crucial to determine the permittivity of the corn oil used in the cold laboratory experiment through measurement. The permittivity of the crude oil which was used in the oil-in-sea ice mesocosm experiment described in Chapter 4 was also determined for the dielectric modelling that was done with that experiment, as well as to confirm that corn and crude oils had similar permittivities at microwave frequencies. As such, this section presents the procedure used to measure the permittivity of the corn and crude oils used as well as the results of the measurements, and the modelled dielectric profiles of the corn oil-contaminated sea ice from the cold laboratory experiment.

3.2.1 Dielectric Measurement of Crude and Corn Oils

The permittivity of the corn oil used in the cold laboratory experiment, as well as that of the crude oil used for the mesocosm experiment detailed in Chapter 4, was measured using the cavity perturbation technique [3, 4]. While it was possible to measure the permittivity of these two fluids using other methods (e.g. the open-ended co-axial dielectric probe technique) the cavity perturbation method was utilized as measurements could be performed on a small volume sample of crude oil which was sealed within a glass tube, thus ventilation and personal protection equipment was not required and the measurement apparatus was not contaminated. The cavity that was used to perform the measurements was made of copper, and was rectangular with the dimensions 86 mm by 43 mm by 262 mm (which correspond to the x, y, and z directions), as shown in Fig. 3.6, and was excited such that TE_{mnp} modes would propagate. For the purposes of dielectric measurement only TE_{m0p} modes were considered, and the perturbations were located within the cavity at (43 mm, y, 100 mm), such that the electric field intensity would only have a y-directed component at that point and thus

be tangential to the perturbation, regardless of the TE mode being excited.



Fig. 3.6: Schematic of the Resonant Cavity used for Dielectric Measurement.

The procedure for measuring the dielectric constant of a material through cavity perturbation when the size of the perturbation is small relative to the size of the cavity is as follows [3, 5]: first, the reflection coefficient, S_{11} , of the cavity is measured using a vector network analyzer (VNA) when the cavity is unperturbed, and then again when the cavity is perturbed by the material of interest. The loaded quality factor of the perturbed cavity is then determined from the change in resonant frequency in the $|S_{11}|$ data and the shape of the resonant peak as

$$Q_L = \frac{f_S}{\Delta f_{\text{xdB}}} \tag{3.1}$$

where f_S is the resonant shifted frequency of interest in the perturbed cavity and Δf_{xdB} is the width of the shifted resonant peak at the level where $|S_{11}| = x \, dB$. From this, the unloaded quality factors for the perturbed cavity are calculated as

$$Q_U = Q_L \left(\frac{2}{\xi} \sqrt{\frac{|S_{11}|^2_{\text{xdB}} - |S_{11}|^2_{f_s}}{1 - |S_{11}|^2_{\text{xdB}}}} \right)$$
(3.2)

where the value of ξ was dependent on whether the cavity was over- or undercoupled, which can be determined by plotting the local S_{11} for the peak on a Smith chart using the VNA. The determination of whether the cavity was over- or undercoupled, or critically coupled is made based on whether the local S_{11} plotted on the Smith chart encircles the origin or not: if the origin falls within the circle produced by plotting the local S_{11} on a Smith chart, the cavity is overcoupled; if the origin is outside the circle, then the cavity is undercoupled; if the circle passes directly through the origin of the Smith chart, then the cavity is said to be critically coupled and the unloaded and loaded quality factors were equal. The value of ξ in (3.2) is calculated as

$$\xi = \begin{cases} 1 - |S_{11}|_{f_s}^2, \text{ if overcoupled} \\ 1 + |S_{11}|_{f_s}^2, \text{ if undercoupled} \end{cases}$$
(3.3)

In (3.2) and (3.3), $|S_{11}|_{xdB}$ and $|S_{11}|_{f_S}$ are the magnitude of the reflection coefficient at the x dB level and at the resonant frequency respectively, both of which are in linear units (i.e. $|S_{11}|_{xdB} = 10^{\frac{xdB}{20}}$). The permittivity of the perturbing material can then be calculated using the shift in the resonant frequency and the change in the unloaded quality factor of the cavity due to the perturbation as

$$\varepsilon_r' = 1 - 2\frac{f_s - f_0}{f_0} \frac{V_c}{4\psi V_S}$$
(3.4a)

$$\varepsilon_r'' = \frac{V_c}{4\psi V_S} \left(\frac{1}{Q_S} - \frac{1}{Q_0}\right) \tag{3.4b}$$

Here the subscripts S and 0 denote the values determined from perturbing the cavity with the material of interest and the unperturbed cavity respectively, and V_C and V_S denote the volume of the cavity and the volume of the perturbation respectively. In (3.4), ψ is a correction factor that accounts for the relative intensity of the electric field for the TE_{m0p} mode at
the location of the perturbation (x = 43 mm, z = 100 mm) determined by

$$\psi = \left| \sin\left(\frac{m\pi}{a}x\right) \sin\left(\frac{p\pi}{d}z\right) \right|^2 \tag{3.5}$$

Note that this procedure assumes that the size of the perturbation is sufficiently small that the electric field internal to the perturbation can be approximated as being equal to the electric field immediately external to the perturbation.

For the purposes of measuring the dielectric constant of fluids such as corn oil and crude oil, the samples had to be contained within a suitable structure during cavity perturbation measurements in this manner. As such, the oils were sealed inside glass tubes with an outer diameter of 3 mm and an inner diameter of 1.65 mm prior to the measurements. In order to remove the effect of the glass on the measurements, the unperturbed measurement was performed with an empty (or air-filled) glass tube, identical to the ones that contained the corn and crude oils, placed in the cavity. The measured relative dielectric constants for the corn oil and crude oil samples are summarized in Tab. 3.1. The results of the TE_{103} , TE_{105} , and TE_{106} measurements were found to be inaccurate, either due to low magnitudes of the electric field intensity at the perturbation location or interference from neighbouring resonant modes, and as such are not shown here. As can be seen from these results, the relative permittivity of the corn and crude oils analyzed through the cavity perturbation method do not vary significantly for frequencies between approximately 1.8 and 4.5 GHz, and the permittivities are close enough that corn oil may be used as a substitute for crude oil for laboratory experiments. The measured values for the relative permittivity of the corn and crude oils analyzed appear to be consistent with the trends in the lower frequency data that has been published [6, 7].

Tab. 3.1: The relative dielectric constant of corn oil and crude oil as measured through the cavity perturbation technique

Resonant Mode	Frequency (GHz)	$\varepsilon_{r,\ corn\ oil}$	$\varepsilon_{r,\ crude\ oil}$
TE_{101}	1.8357	3.0356 - j0.1816	2.4145 - j0.0237
TE_{102}	2.0865	2.8478 - j0.1606	2.3072 - j0.0156
TE_{104}	2.8767	2.9177 - j0.1760	2.3679 - j0.0229
TE_{107}	4.3707	2.6269 - j0.1509	2.2332 - j0.0373

3.2.2 Cold Room Experiment Dielectric Profiles

The dielectric or relative complex permittivity profiles for the uncontaminated ice from the cold laboratory experiment were modelled using the two-phase Polder-van Santen/de Loor mixture model for spherical inclusions, as given by (2.28). The plots of the magnitudes of the real and imaginary components of the relative complex permittivity of the uncontaminated sea ice are shown in Fig. 3.7. For the purposes of modelling the permittivity for the corn oil-contaminated sea ice samples, two mixture models were applied: the three-phase Polder-van Santen/de Loor mixture model, and the quasi two-phase Tinga-Voss-Blossey mixture model, both assuming spherical inclusions. These two models were proposed for modelling the permittivity of crude oil-contaminated sea ice in [8], which comprises Chapter 4 herein. The three-phase Polder-van Santen/de Loor mixture model is given by

$$\varepsilon_{mix} = \varepsilon_{ice} + 3v_{brine}\varepsilon_{mix}\frac{\varepsilon_{brine} - \varepsilon_{ice}}{\varepsilon_{brine} + 2\varepsilon_{mix}} + 3v_{oil}\varepsilon_{mix}\frac{\varepsilon_{oil} - \varepsilon_{ice}}{\varepsilon_{oil} + 2\varepsilon_{mix}}$$
(3.6)

and the quasi two-phase Tinga-Voss-Blossey mixture model is given as

$$\varepsilon_{mix} = \varepsilon_{sea\,ice} + \frac{3v_{oil}\varepsilon_{sea\,ice}(\varepsilon_{oil} - \varepsilon_{sea\,ice})}{2\varepsilon_{sea\,ice} + \varepsilon_{oil} - v_{oil}(\varepsilon_{oil} - \varepsilon_{sea\,ice})}.$$
(3.7)

Note that in the evaluation of the quasi two-phase Tinga-Voss-Blossey mixture model in (3.7), the permittivity of sea ice must first be calculated using (2.30). For further details on these



Fig. 3.7: The magnitudes of the (a) real and (b) imaginary parts of the permittivity of the uncontaminated sea ice grown in the cold laboratory experiment calculated using the two-phase Polder-van Santen/de Loor mixture model for spherical inclusions at a frequency of 5.5 GHz.

mixture models, please see Chapter 4. The resulting permittivity profiles for the corn oilcontaminated sea ice are shown in Figs. 3.8 and 3.9. Both the uncontaminated and contaminated profiles were calculated for a frequency of 5.5 GHz, which is the center frequency of the scatterometer used to measure the normalized radar cross-section of the sea ice in the mesocosm experiment described in Chapter 4. In lieu of higher frequency data for the relative permittivity of the corn oil used for the experiment, the measured value of 2.6269 - j0.1509 at 4.3707 GHz was used.

In comparing the permittivity profiles of the uncontaminated and corn oil-contaminated sea ice, it is evident that the uppermost section of the uncontaminated ice had permittivity values of $3.70 \le \varepsilon'_r \le 5.00$ and $0.050 \le \varepsilon''_r \le 0.360$. For the top sections of the contaminated ice, permittivity values were in the ranges of $3.60 \le \varepsilon'_r \le 5.10$ and $0.180 \le \varepsilon''_r \le 0.385$ for the three-phase Polder-van Santen/de Loor mixture model, and $3.60 \le \varepsilon'_r \le 4.60$ and $0.05 \le \varepsilon''_r \le 0.160$ for the quasi two-phase Tinga-Voss-Blossey mixture model. The permittivity profiles calculated using the quasi two-phase Tinga-Voss-



Fig. 3.8: The magnitudes of the (a) real and (b) imaginary parts of the permittivity of the corn oilcontaminated sea ice grown in the cold laboratory experiment calculated using the threephase Polder-van Santen/de Loor mixture model for spherical inclusions at a frequency of 5.5 GHz.



Fig. 3.9: The magnitudes of the (a) real and (b) imaginary parts of the permittivity of the corn oilcontaminated sea ice grown in the cold laboratory experiment calculated using the quasi two-phase Tinga-Voss-Blossey mixture model for spherical inclusions at a frequency of 5.5 GHz

Blossey mixture model are more conservative than those calculated with the three-phase Polder-van Santen/de Loor mixture model, which is to be expected based on the different model formulations. Aside from a few exceptions, the permittivity profiles of the corn oilcontaminated sea ice tend to have lower values of both the real and imaginary parts compared to the uncontaminated sea ice. Although there is a visible difference between the modelled permittivity profiles for uncontaminated and contaminated sea ice, it remains to be seen if the difference is sufficient enough to be detectable using microwave remote sensing technologies. As crude oil was measured to have a lower permittivity than corn oil at L-, S-, and C-band frequencies, it would suggest that the difference between the permittivity profiles of uncontaminated sea ice and crude oil-contaminated sea ice would be even greater than the difference seen here. In addition, since crude oil is a poorer thermal conductor than its corn oil counterpart, the presence of crude oil may also significantly affect the temperature profile of the sea ice, thus further impacting the permittivity profile. An outdoor meso-scale crude oil-in-sea ice experiment was also conducted to examine the impact of crude oil on the permittivity profile of the ice, amongst other properties, which is detailed in the following chapter.

References

- [1] A. Diaz, (personal correspondence), 2015.
- [2] Campbell Scientific, "CR1000 Measurement and Control Datalogger," 2015.
- [3] L. F. Chen, C. K. Ong, C. P. Neo, V. V. Varadan, and V. K. Varadan, *Microwave electronics: Measurement and materials characterization*. New York, NY, U.S.A.: Wiley, 2004, ch. 6.
- [4] M. S. Venkatesh and G. S. V. Raghavan, "An overview of dielectric properties measuring techniques," *Canadian Biosystems Eng.*, vol. 47, no. 7, pp. 15–30, 2005.
- [5] G. Bridges, "Dielectric measurement using cavity perturbation," course notes for ECE 7440 *Microwave Materials Measurement Techniques*, Department of Electrical and Computer Engineering, University of Manitoba, 2015.
- [6] H. Lizhi, K. Toyoda, and I. Ihara, "Dielectric properties of edible oils and fatty acids as a function of frequency, temperature, moisture and composition," *J. Food Eng.*, vol. 88, pp. 151–158, 2008.
- [7] T. Friisø, Y. Schildberg, O. Rambeau, T. Tjomsland, H. Førdedal, and J. Sjøblom, "Com-

plex permittivity of crude oils and solutions of heavy crude oil fractions," *J. Dispersion Sci. and Technology*, vol. 19, no. 1, pp. 93–126, 1998.

[8] T. D. Neusitzer, N. Firoozy, T. M. Tiede, D. S. Desmond, M. J. L. Lemes, G. A. Stern, S. Rysgaard, P. Mojabi, and D. G. Barber, "Examining the impact of a crude oil spill on the permittivity profile and normalized radar cross-section of young sea ice," *IEEE Trans. Geosci. Remote Sens.*, 2017 (in press).

Examining the Impact of a Crude Oil Spill on the Permittivity Profile and Normalized Radar Cross-Section of Young Sea Ice

This paper has been accepted for publication in *IEEE Transactions on Geoscience and Remote Sensing* and is copyright ©2017 by IEEE. Reprinted with permission, from [T. D. Neusitzer, N. Firoozy, T. M. Tiede, D. S. Desmond, M. J. L. Lemes, G. A. Stern, S. Rysgaard, P. Mojabi and D. G. Barber, "Examining the impact of a crude oil spill on the permittivity profile and normalized radar cross-section of young sea ice," *IEEE Transactions on Geoscience and Remote Sensing*, 2017].

Abstract

An oil-in-sea ice mesocosm experiment was conducted at the University of Manitoba Seaice Environmental Research Facility from January to March 2016 in which geophysical and electromagnetic parameters of the ice were measured and general observations about the oilcontaminated ice were made. From the experimental measurements, the presence of crude oil appears to affect the temperature and bulk salinity profiles as well as the normalized radar cross-section (NRCS) of the contaminated young sea ice. The measured temperature and bulk salinity profiles of the ice, as well as the crude oil distribution within the ice, were used to model the permittivity profile of the oil-contaminated ice by adapting two mixture models commonly used to describe sea ice to account for the presence of oil. Permittivity modelling results were used to simulate the NRCS of the oil-contaminated sea ice in an effort to determine the accuracy of the models. In addition, the application of x-ray microtomography in modelling the dielectric profile of oil-contaminated sea ice was examined. The sensitivity of the permittivity models for oil-contaminated sea ice to changes in temperature, frequency, and oil volume fraction was also examined.

4.1 Introduction

The Arctic Ocean is a highly dynamic environment, with the annual formation, transport, and melting of sea ice constantly changing the topography of the region. In recent years, the advent of climate change has begun to affect the Arctic, most notably in the reduction of multiyear sea ice and the shrinking sea ice extent in the summer months [1–4]. As a result of the reduction of sea ice cover, there are significant regions of open water in the Arctic Ocean during the summer, which have renewed interest from industry in both shipping goods through the Arctic [5] and developing the untapped Arctic oil resources [6]. As

a consequence of these renewed interests, it is critical that appropriate methods for detection and remediation of oil spills in the Arctic be developed.

While some research has been conducted to develop methods for detecting oil spilled beneath sea ice, many of the applicable technologies are still in their infancy [7, 8]. Currently, the technologies that have been explored for oil spill detection in sea ice infested environments include optical sensors, infrared sensors, radiometers, synthetic aperture radar, ground penetrating radar, laser fluorosensors, acoustic sensors, and nuclear magnetic resonance spectroscopy [7, 9, 10]. Of these technologies, recent advances in under-ice oil spill detection using laser fluorosensors [11], underwater acoustic and optical sensors [12], and ground penetrating radar [13] have been made. Radar-based techniques, such as synthetic aperture radar, appear to have been dismissed as ineffective in detecting oil spills under sea ice, as the methods employed in open water spill detection are not as useful in ice-infested environments. However, recent work indicates that active microwave measurements may have the potential to be of use in the detection of oil spills in sea ice infested environments [14]. Furthermore, the presence of oil both underneath and within sea ice has the potential to affect the thermodynamics (via being a poorer thermal conductor) and salinity (e.g. through the replacement of brine within the sea ice) of the sea ice, thus affecting dielectric profile of the sea ice, and in turn its radar cross-section. Crude oil spilled beneath sea ice has been observed to migrate up through the ice and/or become encapsulated within the ice [15, 16], and oil pooled beneath the ice can insulate the ice from the ocean and interfere with brine drainage [15]. As the thermodynamics and brine content of the ice are governing factors for the dielectric profile of the ice, as well as the surface roughness, detection of under-ice oil spills through radar-based methods may be possible. In other words, oil spills in a sea ice infested environment have the potential to affect the dielectric profile of sea ice, thus affecting its corresponding radar cross-section. The presence or absence of oil spills can then be potentially inferred via processing (inverse scattering algorithms) of radar cross-section data. Within this framework, we have performed a preliminary investigation of an inversion strategy to determine the presence of crude oil in sea ice on a yes/no basis using a subset of the normalized radar cross-section (NRCS) data presented in this paper [17]. Finally, it should be noted that developing a good understanding of the effects that oil spills might have on the dielectric properties of sea ice can potentially be used to detect oil spills from its *side* effects in active microwave remote sensing technologies. This can be advantageous since *direct* detection can be challenging due to the lack of sufficient measured scattering data and the limited penetration depth of microwaves into the ice.

In this paper, the effects of crude oil spilled underneath young sea ice on the thermodynamics, salinity, and NRCS of the ice are explored within the framework of examining the electromagnetic properties of oil-contaminated sea ice. The aim of the research presented herein is to compare the temperature, bulk salinity, dielectric profiles, and NRCS of uncontaminated and oil-contaminated young sea ice grown under similar conditions in an effort to differentiate between the respective complex permittivity profiles and radar cross-sections. In doing so, the research presented in this paper is contributing to the development of Arctic oil spill detection schemes that rely on identification of the changes in the complex permittivity profile of sea ice arising from the presence of crude oil beneath, within, and/or on top of young sea ice. While there have been several publications pertaining to the interactions of crude oil and sea ice (e.g. [15, 16, 18, 19]), there has been less research published on the effect of oil on the permittivity of sea ice (e.g. [14]). Since the complex permittivity profile governs the electromagnetic scattering of the ice, it is critical that the effects of crude oil contamination on the complex permittivity profile are thoroughly examined if microwave remote sensing technologies are to be employed effectively in Arctic oil spill detection. Sufficient differences in the complex permittivity profiles of uncontaminated and oil-contaminated ice have the potential to affect active microwave measurements collected from sea ice (e.g. the NRCS), which could allow discrimination between uncontaminated and oil-contaminated sea ice based on active microwave remote sensing. This differentiation could prove useful to various stakeholders interested in environmental management, including the oil and gas industries, the marine shipping industry, various levels of government, regulators, and indigenous organizations. To this end, this paper presents measurements and observations from an oil-in-sea ice mesocosm experiment performed at the University of Manitoba Sea-ice Environmental Research Facility during the winter of 2016, as well as models for the permittivity profile of oil-contaminated sea ice and a potential framework in which to evaluate the accuracy of the models.

4.2 Experiment and Observations

The following sections describe the oil-in-sea ice mesocosm experiment conducted. As such, measured data on the ice grown, the temperature and salinity profiles of the ice, x-ray microtomography, and the NRCS associated with the profile are presented.

4.2.1 Oil-in-Sea Ice Mesocosm Experiment

An oil-in-ice mesocosm experiment was carried out at the University of Manitoba Sea-ice Environmental Research Facility (SERF) in Winnipeg, MB, Canada from January 15 to March 1, 2016. As can be seen in Fig. 4.1, artificial sea ice was grown from open water with a salinity of 32 psu in an insulated fibreglass tank (3 m diameter, 1 m height, which corresponds to $55\lambda_0$ diameter and a height of $18.\overline{3}\lambda_0$, where λ_0 is the wavelength in free space at 5.5 GHz, the frequency of operation for the scatterometer used in this experiment), during two periods in the course of the experiment: January 15 to 21 and February 8 to March 1. In the first of these growth periods, the ice was grown without any crude oil contamination; during the second growth period, approximately 20 L of crude oil was injected into the water



Fig. 4.1: The insulated fibreglass tank used for the oil-in-ice mesocosm experiment at the University of Manitoba Sea-ice Environmental Research Facility during the winter of 2016 prior to freezing.

column beneath the ice after the ice thickness had reached approximately 6.5 cm, as illustrated in Fig. 4.2. The crude oil used in the experiment was a sour mixture of aromatic and paraffinic hydrocarbons containing 100 ppm toluene, 10 ppm benzene, 100 ppm xylene, and 10 ppm hydrogen sulfide. Throughout the course of the ice growth, the temperature profile of the ice was measured in-situ by thermocouples frozen into the ice, and physical sampling of the ice was performed to determine the bulk salinity profile and oil distribution within the ice. In addition, *x*-ray microtomography was used to analyze sections of oil-contaminated ice cores in order to examine the geometry and distribution of oil inclusions within the ice. To this end, a Bruker SKYSCAN 1174 Compact Micro-CT system was utilized to analyze the ice microstructure.

Sampling of the sea ice was conducted using a Kovacs Enterprise Mark II coring system, which facilitated the collection of 9 cm diameter cores. In the first phase of the experiment, the collected cores were cut by hand into horizontal sections roughly 2.5 cm thick, placed into plastic sample bags, and stored in a freezer until they could be processed. In the second phase of the experiment, the collected cores were cut by hand into two or three



Fig. 4.2: Diagram of the injection of crude oil into the water column beneath the ice. To avoid excess pressure buildup, water was simultaneously drained from the tank as the oil was injected.

sections based on the thickness of the core at hand and placed in sterilized glass sample jars, and stored in a freezer until they were processed. This difference stemmed from the requirements of the chemical analysis component of the experiment, which is not presented herein. Samples taken during the periods in which the NRCS was measured were limited to the outer edge of the tank to avoid significantly impacting the NRCS, and samples taken after NRCS measurement had concluded were taken from several locations across the entire tank. It should be noted that a number of precautions were taken to mitigate the health and safety risks associated with exposure to crude oil. These included requiring personnel to wear chemical protective coveralls, nitrile gloves, and respirators with face shields during the sampling of the oil contaminated ice.

4.2.2 Evolution of the Ice

The evolution of the uncontaminated ice grown from January 15 to 21 occurred under calm environmental conditions, as there was little to no wind during the formation of the ice. In addition, there was minimal snowfall during this period, so the ice surface was largely exposed to the ambient environment. The ice appeared to be relatively uniform in thickness, growing to approximately 22 cm thick within the week-long period. On the other hand, winds were substantially stronger during the initial freeze-up for the oil-contaminated ice experiment, however conditions subsequently calmed down, leading to the formation of ice comparable to that of the first phase of the experiment. The surface of the ice was relatively featureless prior to the injection of oil beneath the ice on February 9, 2016, after which the ice surface underwent several changes due to upward migration of the oil and snowfall, illustrated in Fig. 4.3.

Approximately five hours after the introduction of crude oil into the water column, some oil had migrated through the ice to the surface. On the day after the introduction of the oil, there was a moderate amount of oil that had migrated up through the ice, either through cracks in the ice or brine channels, and some oil had come up over the side of the ice at the edge of the pool (Fig. 4.3a). Almost two days after the addition of oil to the water column, a significant amount of crude oil had migrated to the ice surface (Fig. 4.3b). Following the observed oil migration, there was significant snowfall on February 13 and 14 which covered the majority of the ice surface with a layer of snow (Fig. 4.3c). The oil that had migrated to the ice surface was observed to percolate upwards into the snow layer (Fig. 4.3d), and the snow layer was partially melted by warm temperatures (Fig. 4.3e). In the last week of the experiment, a new layer of snow was deposited on the surface (Fig. 4.3f), and the oil again percolated up through the snow (Fig. 4.3g).

Physical sampling of the oil-contaminated ice revealed that the crude oil was unevenly distributed throughout the ice. As such, some ice cores appeared to have very little oil-contamination while others had significant oil content, therefore there was some degree of spatial heterogeneity in the ice grown. In some of the samples, a thin encapsulated layer of oil was observed roughly 6.5 cm below the ice surface, which corresponds to the ice thickness when oil was introduced into the system. Core samples collected in different locations of the tank throughout the second phase of the experiment had thicknesses varying from 4 cm to 25 cm, further indicating that the oil-contaminated ice grown was heterogeneous. It



(a)

(b)





(d)

(e)

(f)



Fig. 4.3: The surface of the oil-contaminated ice (a) February 10 at 10:45 am, (b) February 11 at 10:50 am after substantial oil migration up through the ice, (c) February 16 at 9:30 am after a period of snowfall, (d) February 18 at 10:50 am with evidence of crude oil percolating up through the snow layer, (e) February 19 at 9:30 am after partial melting of the snow/oil layer due to warm weather, (f) February 23 at 11:50 am after an additional snowfall, and (g) March 1 at 11:20 am after upward percolation of crude oil through the snow.

is speculated that the heterogeneity of the ice was due to an uneven distribution of the crude oil beneath, within, and on top of the sea ice throughout the second phase of the experiment.

4.2.3 Temperature Profile

The temperature profile of the ice was measured in-situ with a measurement interval of fifteen minutes. The measured temperature profiles of the uncontaminated and oil-contaminated ice grown are shown in Figs. 4.4 and 4.5. In addition, the air temperature data for both periods of the experiment [20] are included in these figures. From the temperature profiles shown in Figs. 4.4b and 4.5b it is clear that there was more diurnal variation in the temperature profile of the oil-contaminated ice for the period of February 8 to 14 than in that of the uncontaminated ice for its entire growth period. While the air temperature from February 8 to 14 was warmer on average than from January 15 to 21, as illustrated in Figs. 4.4a and 4.5a, this alone was likely not the cause of the increased diurnal variation. Further examination of the air temperature data for both periods reveals that the air temperatures in January tended to increase throughout the entire day, whereas those from February 8 to 14 tended to increase until mid-day and then decrease. This cyclical trend in the ambient temperature, combined with the presence of the oil on and within the ice, may have been the driving force behind the exaggerated diurnal variation in the temperature profile of the oil contaminated ice. After February 14, the diurnal variation in ice temperature was dampened by the snow layer that had formed on top of the ice until the warm ambient temperatures melted the oil/snow mixture on the surface of the ice on February 18 and 19. Afterwards, the diurnal variation in the ice temperature profile resumed, although the degree of variation was lower, likely due to the relatively warmer ambient temperatures and additional snowfall. On February 26 and 27, warm air temperatures again partially melted the oil-wetted snow and warmed up the ice. Subsequently, the air temperatures returned to more seasonal levels, there was

additional snowfall, and the temperature profile of the oil-contaminated ice continued to demonstrate diurnal variations until the end of the experiment. It is worth noting that some of the upward oil migration occurred at the location where the thermocouples were frozen into the ice, which may have introduced additional uncertainty into the ice temperature measurements. It is speculated that the presence of the oil around the thermocouples may have caused the surrounding ice to have a decreased albedo relative to other parts of the ice, so the thermocouples closest to the ice surface may have measured temperatures higher than the true ice temperature during periods of intense solar radiation. This would account for the thermocouple 2.5 cm below the ice surface registering temperatures (February 19, 26, 27), despite the ice not being melted. These anomalous temperature measurements also correspond to mid-day in each case, which is the point where the intensity of sunlight would be greatest. The ice core samples analyzed for the purposes of this work were obtained during periods where the measured ice temperatures were well within the expected range for sea ice, thus the impact of these anomalies on the results herein was minimized.

4.2.4 Salinity Profile

The bulk salinity profiles measured from the ice samples taken throughout the uncontaminated and oil-contaminated phases of the experiment are shown in Fig. 4.6. Examination of the bulk salinity profile of the uncontaminated ice, shown in Fig. 4.6a, illustrates that the top 2.5 cm of the ice had a higher salt content than the lower sections, which indicates that there was brine rejection during the formation of the ice. In addition, the bottom of the ice generally had a similar salinity to that of the middle sections, which would indicate that there was substantial brine drainage into the water beneath the ice. It is evident in Fig. 4.6b that the ice was less saline in the second phase of the experiment when the ice was oil-contaminated, and





Fig. 4.4: Data for the uncontaminated ice growth period from January 15 to 21, 2016: (a) ambient air temperature in Winnipeg, MB, Canada [20], (b) measured ice/water column temperature profile, and (c) measured normalized radar cross-section of the uncontaminated sea ice at an incidence angle of 56° in the VV polarization.



Fig. 4.5: Data for the oil-contaminated ice growth period from February 8 to March 1, 2016: (a) ambient air temperature in Winnipeg, MB, Canada [20], (b) measured ice/water column temperature profile, and (c) calibrated measured normalized radar cross-section of oil-contaminated sea ice in the VV polarization at an incidence angle of 57°. Note that the dashed line indicates when oil-injection was performed, and the dash-dotted line indicates when evidence of the oil migrating up through the ice was first observed. The NRCS data from the afternoon of February 10 to the morning of February 12 was lost due to software issues with the scatterometer's data collection unit, and the data from the evening of February 17 to the morning of February 18 was lost due to a power-outage.



Fig. 4.6: The measured bulk salinity profiles for (a) uncontaminated ice grown from January 15 to 21, 2016 and (b) from February 8 to March 1, 2016. Note that the horizontal axes are not to scale, and any unlabeled tick has the same time-stamp as the closest labelled tick to its left.

the top 5 cm of the ice generally had the lowest bulk salinity. This reduced salinity may have been due to the relatively higher ice temperatures observed throughout the oil-contaminated phase of the experiment, which would have potentially allowed more brine drainage compared to the uncontaminated phase of the experiment. As well, the lower bulk salinity of the oil-contaminated ice may have been a result of the crude oil replacing the brine within the ice as it migrated upward towards the surface.

In addition to temperature and bulk salinity, the vertical distribution of the crude oil in the contaminated samples was measured through the separation of oil and brine after melting the samples, and the distribution of oil is shown for each core sample in Fig. 4.7. The majority of the oil within the ice was contained within the top 5 cm, as the ice was 6.5 cm thick when the oil was introduced into the system.



Fig. 4.7: Distribution of crude oil within sections of the contaminated ice cores. Note that the horizontal axis is not to scale, and any unlabeled tick has the same time-stamp as the closest labelled tick to its left.

4.2.5 *x*-ray Microtomography

x-ray microtomography scans were taken for five core sections from three separate oilcontaminated ice core samples in an effort to examine the microstructure of oil-contaminated ice. These samples were cut from 9 cm diameter core sections to be cylindrical in shape with a sub-core diameter of approximately 3 cm and a height of no more than 3 cm. To minimize oil-contamination of the *x*-ray instrument, these samples were placed inside polypropylene tubes prior to the measurements. In the analysis of these scans, the constituent components of the oil-contaminated ice (air, brine, crude oil, ice) were differentiated based on their relative densities. Horizontal and vertical cross-sections of the samples were obtained and are shown in Figs. 4.8 and 4.9 respectively, which illustrate the geometry and distribution of the oil inclusions within the sections of the ice analyzed. As can be seen in these cross-sections, the oil included within the ice (dark grey in Fig. 4.8 and red in Fig. 4.9) tended to surround the air inclusions, yet there were some small pockets of exclusively oil observed. From these figures it can also be seen that the brine (shown in white and light blue in Figs. 4.8 and 4.9 respectively) was somewhat separate from the oil within the ice. It is speculated that this

Sample	v_{air}	v_{brine}	v_{oil}
а	0.0390	0.0622	0.0382
b	0.0142	0.0450	0.0319
С	0.0122	0.0131	0.0143
d	0.00902	0.0348	0.0181
e	0.00801	0.0256	0.00864

Tab. 4.1: Volume fractions determined through x-ray microtomography of the oil-contaminated ice

isolation may be the result of the natural separation of oil and water due to differences in density and molecular polarity. In addition to the vertical and horizontal cross-sections of the samples, the volume fractions of air, brine, and oil within the samples were determined from quantitative analysis of the *x*-ray microtomography scans, the values for which are listed in Table 4.1. Samples a and b correspond to middle sections of ice cores (2.5 to 7.5 cm and 5 to 10 cm beneath the ice surface respectively), while samples c through e correspond to the top, middle, and bottom sections of a single ice core (0 to 5 cm, 5 to 10 cm, and 10 to 21.3 cm beneath the ice surface respectively).

It should be noted that since the samples analyzed through x-ray microtomography are only a small portion of a core sample, the volume fraction results do not necessarily reflect the true volume fractions of the whole sample. As such, the volume fractions obtained from this analysis appear to under-estimate the amount of brine and over-estimate the amount of crude oil included within the ice compared to the volume fractions obtained from the physical measurements.

4.2.6 Normalized Radar Cross-Section (NRCS)

A frequency-modulated continuous wave polarimetric C-band scatterometer based on the design presented in [21] was mounted approximately 3.8 m above the surface of the ice and



Fig. 4.8: Horizontal cross-sections of oil-contaminated ice cores obtained through x-ray microtomography. In these images, air is shown in black, brine is shown in white, ice is shown in light grey, and oil is shown in dark gray. Three-dimensional analysis of the x-ray microtomography scans concluded that oil content by volume was 3.82% in core (a), 3.19% in core (b), 1.43% in core (c), 1.81% in core (d), and 0.864% in core (e). Each sample is approximately 3 cm in diameter, and each sample was contained within a polypropylene tube during scanning to minimize contamination of the instrument. The polypropylene tubes are visible in each image as the ring surrounding each sample, and have similar shading to the oil in the samples.

used to measure the normalized radar cross-section of the ice in the VV, HH, and HV polarizations. Due to the small size of the tank, measurements were limited to incidence angles between 55° and 58°, and azimuth angles from -5° to 5°. For the duration of both measurement periods, the scatterometer was configured to perform continuous measurements of the polarimetric normalized radar cross-section to produce a time-series evolution of the NRCS. To reduce the effect of horizontal inhomogeneity of the ice, the scans for each azimuth angle were averaged to determine the normalized radar cross-section at each angle of incidence. All NRCS measurements were calibrated using a metal trihedral calibration target. In ad-



Fig. 4.9: Vertical cross-sections of oil-contaminated ice cores obtained through x-ray microtomography. In these images, air is shown in black, brine is shown in light blue/white, ice is shown in blue, and oil is shown in red. The polypropylene tubes are visible in each image in red, bounding the sample within. These cross-sections correspond to the horizontal cross-sections in Fig. 4.8.

dition, the measured NRCS values for the oil-contaminated sea ice were calibrated through post-processing in an identical manner to that which was done in [17]. This so-called data calibration was utilized to reduce the modeling error between the simulated and the actual system [17], specifically for the NRCS simulation analysis presented in Section 4.3.3 of this paper.

The time-series evolution of the normalized radar cross-section for the uncontaminated ice grown from January 15 to 21, 2016 and the oil-contaminated ice grown from February 8 to March 1, 2016 are shown in Figs. 4.4c and 4.5c for incidence angles of 56° and 57° respectively. Note that the NRCS at an incidence angle of 57° was not measured for the uncontaminated ice, thus the NRCS at 56° is used here. The HH and HV polarizations for the NRCS measured in both phases of the experiment are not shown, as they were found

to be incorrect. Therefore, only the VV component of the NRCS is presented herein. It is believed that connection issues, for the uncontaminated case, with the cable connected to the horizontal-polarized antenna caused the HH and HV signals to be attenuated to the point where the measured NRCS was approximately flat.

4.2.6.1 NRCS observations for the uncontaminated case

In examining the trend of the measured NRCS of the uncontaminated ice grown during the first phase of the experiment, it is evident that the NRCS dropped by roughly 10 dB from the start of measurements to the early morning of January 16 as the pool transitioned from open water to ice that was less than 7.5 cm thick. Such a reduction in the NRCS is consistent with the decrease in magnitude of the electromagnetic reflection coefficient corresponding to a transition from an interface between media with a large dielectric contrast (i.e. air and brine) to an interface with a lower contrast (i.e. air and sea ice). As the ice growth continued, the measured NRCS tended to increase until approximately mid-day on January 18, after which changes in the NRCS became significantly less pronounced as the measured NRCS fluctuated between values roughly 2.5 dB apart until the end of the first phase of the experiment. These fluctuations appear to correspond to fluctuations in the ice temperature profile during this period, which would suggest that the changes in the NRCS of the uncontaminated ice in the latter half of the experiment were closely related to the ice temperature.

4.2.6.2 NRCS observations for the contaminated case

The NRCS measured in the VV polarization for the oil-contaminated ice grown during the second phase of the experiment also demonstrates a decrease prior to injection of the oil,

as the ice grew from open water. However, this decrease appeared to be approximately 7 dB, which is slightly lower than the decrease observed for the NRCS of uncontaminated ice. This discrepancy may be a result of the differences in ice formation observed between the phases of the experiment. Immediately after the oil was introduced into the water column beneath the ice, the measured NRCS dropped rapidly before stabilizing approximately 4 hours later. The rapid decrease in NRCS may have been the result of the rapid upward oil migration through the ice that was observed. The oil may have migrated up through cracks in the ice, or potentially through the brine channels displacing the brine downwards. Both of these potential oil migration paths would have caused a decrease in the effective permittivity of the ice, thus reducing the magnitude of the electromagnetic reflection and subsequently the NRCS. Unfortunately, some of the NRCS data measured from February 10 to 12 was lost due to software issues with the scatterometer's data collection unit.

From February 12 to 13 there was substantial oil pooling on the surface of the ice, and the NRCS continued to decrease, which was likely due to a decrease in surface roughness caused by the oil on the surface. Following this period, a rapid increase in the NRCS was observed. This increase was likely the result of the snowfall event on February 13 which left a layer of snow on top of the ice. Following this increase, the measured NRCS in the VV polarization rapidly decreased and began to gradually increase until the early hours of February 14. On February 14 there was a period of snowfall and blowing snow for approximately 12 hours, during which the NRCS rapidly increased and subsequently decreased. After this period, the NRCS increased until the evening of February 15, after which it decreased until the afternoon of February 17. Due to a power-outage, no data was measured from the evening of February 17 to the morning of February 18. A significant spike in the NRCS was observed in the afternoon of February 18, during which ambient temperature was unseasonably high (see Fig. 4.5a) and caused the oil-wetted snow layer on the surface of the ice to begin melting. An additional spike was observed in the NRCS in the afternoon of February 19, which again corresponded to a snowfall event. Temperatures began to return to seasonal values during February 20 and 21, and the NRCS tended to decrease until February 26 when the ambient air temperatures again became unseasonably high. As such, there was a spike in the NRCS in the afternoon of February 26. An additional spike in the the NRCS was measured on the afternoon of February 27, which corresponds to warm air and ice temperatures. Subsequently, temperatures returned to seasonal levels, and the NRCS decreased until the end of the experiment.

4.3 Complex Permittivity

In an attempt to relate the measured temperature, bulk salinity, and oil volume profiles of the artificial sea ice to microwave measurements, *e.g.*, the measured normalized radar cross-section, the (relative) complex permittivity profile of the ice was modelled using the measured physical parameters in the presence and absence of oil spills. Several models based on the predominant models used for uncontaminated sea ice were explored. In addition to the modelling based on physical measurements, the permittivity profile of the ice was modelled based on the results of the performed quantitative analysis of the *x*-ray microtomography scans, again using several models based on those often applied to uncontaminated sea ice. The modelled complex permittivity profiles were used to simulate the NRCS of the ice, and the simulated NRCS was compared to its measured counterpart in an effort to evaluate the accuracy of the models used. As well, the performance of each model was evaluated for different sea ice temperatures and excitation frequencies and compared to the model for the permittivity of oil-contaminated sea ice presented in [14]. The following sections discuss the permittivity modelling, NRCS simulation, and evaluation of the models.

4.3.1 Permittivity Modelling Using Physical Measurements

The complex permittivity profile for each uncontaminated sample was calculated from the measured temperature and bulk salinity profiles using the two-phase Polder-van Santen/de Loor mixture model for spherical inclusions [22–24]. It is important to note that this model treats uncontaminated sea ice as a mixture of pure ice with brine inclusions, and neglects air trapped within the ice. The permittivity of both the pure ice and brine, as well as the brine volume fraction needed for the model were determined using the empirical relations presented in [24–28]. Since the empirical relation for brine volume fraction does not necessarily hold for oil-contaminated sea ice, the brine volume fraction for the oil-contaminated sea ice [29], assuming that the brine was the only constituent component of the ice that contributed to the salinity of the mixture. Oil volume measurements for each sample were made following the procedure described in [17]. In order to account for the volume of oil in the contaminated samples, the three-phase Polder-van Santen/de Loor mixture model for spherical inclusions was adopted from [24, 30] and applied to the oil-contaminated data. This three-phase mixture model given by

$$\varepsilon_{mix} = \varepsilon_{ice} + 3v_{brine}\varepsilon_{mix}\frac{\varepsilon_{brine} - \varepsilon_{ice}}{\varepsilon_{brine} + 2\varepsilon_{mix}} + 3v_{oil}\varepsilon_{mix}\frac{\varepsilon_{oil} - \varepsilon_{ice}}{\varepsilon_{oil} + 2\varepsilon_{mix}}$$
(4.1)

approximates the effective permittivity of oil-contaminated sea ice by considering pure ice as the host medium with brine and crude oil as separate inclusions. Here ε denotes the complex permittivity and v denotes volume fraction. As with its two-phase counterpart, the three-phase Polder-van Santen/de Loor mixture model assumes that inclusions contain either brine or oil exclusively, and air content is neglected.

In addition to the three-phase Polder-van Santen/de Loor model, the two-phase Tinga-

Voss-Blossey mixture model for spherical inclusions [24, 31] was adapted to account for oil and brine inclusions within the ice. While a three-phase Tinga-Voss-Blossey mixture model exists, it is more suitable for materials with multiple confocal ellipsoidal structures than fluids which poorly mix, and was not expected to reflect the true geometry of the inclusions. This quasi two-phase model, given by

$$\varepsilon_{mix} = \varepsilon_{sea\,ice} + \frac{3v_{oil}\varepsilon_{sea\,ice}(\varepsilon_{oil} - \varepsilon_{sea\,ice})}{2\varepsilon_{sea\,ice} + \varepsilon_{oil} - v_{oil}(\varepsilon_{oil} - \varepsilon_{sea\,ice})}$$
(4.2)

approximates the effective permittivity of oil-contaminated sea ice by considering sea ice as the host medium and the crude oil as the inclusions. In the evaluation of this model, the effective permittivity of the sea ice was calculated using the standard two-phase Tinga-Voss-Blossey model for pure ice with brine inclusions. As with the three-phase Polder-van Santen/de Loor mixture model, the quasi two-phase Tinga-Voss-Blossey model assumes that inclusions contain either brine or oil exclusively, and neglects air within the ice.

Due to the vast complexity of modelling the complex permittivity of an oil-contaminated snow layer such as that observed during the experiment, an appropriate model for oilcontaminated snow is not presented in this work. Oil-contaminated snow can potentially be a mixture of ice grains and crude oil, as well as brine and/or pure water, and further research is required to develop a model for such a mixture.

The complex permittivity profiles of both the uncontaminated and oil-contaminated ice were computed for a frequency of 5.5 GHz, as the NRCS measurements of the ice were performed at that frequency. The permittivity of the crude oil used in this experiment was measured using the cavity perturbation method [32, 33] and found to be 2.2332 - j0.0373 at approximately 4.5 GHz, which is consistent with the trend in the results presented in [34]. (A time dependency of $e^{j\omega t}$ is implicitly assumed, where $j^2 = -1$, and ω denotes the angular frequency.) Unfortunately, due to the size of the cavity used for the measurement, it was not possible to measure the permittivity of the crude oil at a higher frequency as there was interference from higher order resonant modes. In lieu of higher frequency data for crude oil, as well as data for sub-zero temperatures, this permittivity was used in the computation of the complex permittivity profiles of the oil contaminated ice samples.

The complex permittivity profiles for the uncontaminated ice grown, computed using the two-phase Polder-van Santen/de Loor mixture model, are shown in Fig. 4.10, where $\varepsilon_r = \varepsilon'_r - j\varepsilon''_r$. Similarly, the complex permittivity profiles for the oil-contaminated ice computed using the three-phase Polder-van Santen/de Loor and the quasi two-phase Tinga-Voss-Blossey mixture models are shown in Figs. 4.11 and 4.12 respectively. The majority of the results of modelling the dielectric profile of the uncontaminated ice are in agreement with typical values for sea ice, such as those presented in [24, 35–37], however the modelled permittivity for the bottom 3 cm of the core from 8:30 pm January 16 is larger than expected. This is likely due to the measured temperature for this section of the ice being considerably close to the melting point of sea ice, which corresponds to higher values of both the real and imaginary parts of the permittivity of brine, as well as a higher brine volume fraction. In examining the results of these models, it is evident that the magnitudes of the real and imaginary parts of the complex permittivity are higher for the uncontaminated ice than for the oil-contaminated ice. This difference is to be expected, as the oil-contaminated ice was less saline and thus had less brine included within it. In addition, the oil encapsulated within the ice would contribute to an overall decrease in the magnitude of both terms of the complex permittivity, as it has the lowest permittivity of the constituent components of the ice. It is also evident from the model results that the magnitudes of the real and imaginary parts of the complex permittivity of the oil-contaminated ice are lower when computed using the quasi two-phase Tinga-Voss-Blossey mixture model than with the three-phase Polder-van Santen model. However, this difference stems purely from the differences in the model formulations. In examining the permittivity of the top layers of both the uncontaminated and oil-contaminated sea ice, which are important from a microwave remote sensing point of view, the average real and imaginary parts of the permittivity for the oil-contaminated case are lower than that of the uncontaminated case. Specifically, the average permittivity for the top 2.5 cm of the uncontaminated ice, determined using the two-phase Polder-van Santen/de Loor mixture model, was 4.75 - j0.37, and the average permittivities for the top 2.5 cm of the oil-contaminated ice as determined through the three-phase Polder-van Santen/de Loor and quasi two-phase Tinga-Voss-Blossey mixture models were 4.08 - i0.13 and 3.97 - i0.08respectively. This difference in the permittivity of the top layer of the sea ice between the uncontaminated and oil-contaminated cases has the potential to be of use in a detection scheme. Since the permittivity of the top layer of the oil-contaminated ice resulting from both models generally had lower values of both the real and imaginary parts than the top layer of uncontaminated sea ice, the penetration depth into the oil-contaminated sea ice can be expected to be greater than for its uncontaminated counterpart. As the majority of the oil was contained within the top 5 cm of the ice, and this portion of the ice had the lowest real and imaginary parts of the permittivity, the measured NRCS of the oil-contaminated sea ice would have had a larger scattering contribution from deeper portions of the ice, as compared to the uncontaminated case. However, since the real and imaginary parts of the permittivity of the oil-contaminated ice tend to increase with depth, the attenuation of the penetrating wave would also increase with depth, thus it is unlikely that there was significant scattering contribution from the interface at the bottom of the sea ice.

4.3.2 Permittivity Modelling Using x-ray Microtomography

The complex permittivity modelling of the oil-contaminated ice from the volume fractions determined through quantitative analysis of the x-ray microtomography scans (see Table 4.1) differed from the modelling performed purely from the physical measurements in that it ac-



Fig. 4.10: The magnitudes of the (a) real and (b) imaginary parts of the permittivity of the uncontaminated sea ice grown from January 15 to 21, 2016 calculated using the two-phase Polder-van Santen/de Loor mixture model for spherical inclusions at a frequency of 5.5 GHz.



Fig. 4.11: The magnitudes of the (a) real and (b) imaginary parts of the permittivity of the oilcontaminated sea ice grown from February 8 to March 1, 2016 calculated using the threephase Polder-van Santen/de Loor mixture model for spherical inclusions at a frequency of 5.5 GHz. Note that the horizontal axes are not to scale, and any unlabeled tick has the same time-stamp as the closest labelled tick to its left.



Fig. 4.12: The magnitudes of the (a) real and (b) imaginary parts of the permittivity of the oilcontaminated sea ice grown from February 8 to March 1, 2016 calculated using the quasi two-phase Tinga-Voss-Blossey mixture model for spherical inclusions at a frequency of 5.5 GHz. Note that the horizontal axes are not to scale, and any unlabeled tick has the same time-stamp as the closest labelled tick its left.

counted for the air trapped within the ice as well as the geometry of the inclusions observed in the *x*-ray images of the samples. Two mixture models were explored for determining the effective permittivity of the oil-contaminated ice using the *x*-ray data: a quasi two-phase Polder-van Santen/de Loor model, and a variation on the previously discussed quasi twophase Tinga-Voss-Blossey model. As before, the applied models assumed that inclusions were spherical in shape. Since it was observed that a large portion of the oil included within the ice was surrounding the air pockets in the ice, and the brine and oil inclusions were distinctly separate (see Figs. 4.8 and 4.9), the air and oil inclusions were modelled in both cases as an air pocket surrounded by a concentric shell of oil, all within a background medium of pure ice. As such, the initial step for applying both models was to determine the effective permittivity of the mixture of air, ice, and oil by utilizing the three-phase Tinga-Voss-Blossey mixture model [31] assuming spherical inclusions using air as the innermost medium and pure ice as the background. The three-phase Tinga-Voss-Blossey mixture model employed here is given by

$$\varepsilon_{air, ice, oil} = \varepsilon_{ice} + 3\varepsilon_{ice} \frac{\kappa}{\psi}$$
(4.3)

where

$$\kappa = v_{oil}(\varepsilon_{oil} - \varepsilon_{ice})(2\varepsilon_{oil} + \varepsilon_{air}) - v_{air}(\varepsilon_{oil} - \varepsilon_{air})(2\varepsilon_{oil} + \varepsilon_{ice})$$

and

$$\psi = (2\varepsilon_{ice} + \varepsilon_{oil})(2\varepsilon_{oil} + \varepsilon_{air}) - 2\frac{v_{air}}{v_{oil}}(\varepsilon_{oil} - \varepsilon_{ice})(\varepsilon_{oil} - \varepsilon_{air}) - v_{oil}(\varepsilon_{oil} - \varepsilon_{ice})(2\varepsilon_{oil} + \varepsilon_{air}) + v_{air}(\varepsilon_{oil} - \varepsilon_{air})(2\varepsilon_{oil} + \varepsilon_{ice}).$$

This effective permittivity was then treated as that of the background medium, and the contribution of the brine within the ice to the permittivity was determined by applying either the two-phase Polder-van Santen/de Loor mixture model for spherical inclusions or the twophase Tinga-Voss-Blossey mixture model for spherical inclusions. The two-phase Poldervan Santen/de Loor mixture model for spherical inclusions is given by

$$\varepsilon_{mix} = \varepsilon_{air, ice, oil} + 3v_i \varepsilon^* \frac{\varepsilon_{brine} - \varepsilon_{air, ice, oil}}{\varepsilon_{brine} + 2\varepsilon^*}$$
(4.4)

in which the value of ε^* is determined based on the brine volume fraction as

$$\varepsilon^* = \begin{cases} \varepsilon_{air, ice, oil}, & v_{brine} \le 0.1 \\ \varepsilon_{mix}, & v_{brine} > 0.1 \end{cases}$$

Similarly, the two-phase Tinga-Voss-Blossey mixture model for spherical inclusions is given by

$$\varepsilon_{mix} = \varepsilon_{air, ice, oil} + \frac{3v_{brine}\varepsilon_{air, ice, oil}(\varepsilon_{brine} - \varepsilon_{air, ice, oil})}{2\varepsilon_{air, ice, oil} + \varepsilon_{brine} - v_{brine}(\varepsilon_{brine} - \varepsilon_{air, ice, oil})}.$$
(4.5)



Fig. 4.13: The modelled permittivity of an oil-contaminated ice sample using volume fraction data obtained through *x*-ray microtomography, utilizing the quasi two-phase Polder-van Santen/de Loor mixture model (PvS/dL) and the quasi two-phase Tinga-Voss-Blossey mixture model (TVB), both at a frequency of 5.5 GHz. The sample was taken at 3:30 pm on March 1, 2016.

In the evaluation of these models, the measured temperature profiles of the ice were used to determine the appropriate permittivities for pure ice and brine to utilize in the calculations, as was described in Section 4.3.1. The complex permittivity profiles for the oil-contaminated ice generated from applying the quasi two-phase Polder-van Santen/de Loor and quasi two-phase Tinga-Voss-Blossey mixture models to the volume fraction data obtained through analysis of the *x*-ray microtomography scans of the ice are shown in Fig. 4.13. Due to the limited amount of samples analyzed through *x*-ray microtomography, these permittivity profiles represent a single ice core sample taken at 3:30 pm March 1, rather than a time series. There is minimal difference between the results of both models, however the magnitudes of the real and imaginary parts of the permittivity modelled using the data from *x*-ray microtomography of the contaminated ice are lower than that of the permittivity modelled from the physical measurements. This difference is to be expected, due to the observed differences in the volume fractions of brine and oil determined through *x*-ray microtomography and physical measurements, as well as the incorporation of air into the models.
Tab. 4.2: Comparison of Calibrated Measured and Simulated NRCS for Oil-Contaminated Sea Ice generated using the Three-Phase Polder-van Santen/de Loor (3-PvS/dL) and Quasi Two-Phase Tinga-Voss-Blossey (2-TVB) Mixture Models Assuming Spherical Inclusions

Calibrated Measured	3-PvS/dL	2-TVB
-20.7774 dB	-17.6893 dB	-18.9606 dB

4.3.3 Normalized Radar Cross-Section Simulation

In an effort to compare the accuracy of the mixture models for the permittivity of oilcontaminated sea ice presented herein, an NRCS simulation-based approach was utilized. Within this framework, the modelled permittivity profiles of the oil-contaminated ice were to be input to the forward model utilized in [38], and originally proposed in [39], to generate simulated NRCS values for the associated permittivity profiles produced by the mixture models. In addition, similar to [17], the surface roughness parameters used in the NRCS simulation were obtained through lidar scans of the uncontaminated sea ice, due to the absence of lidar data for the oil-contaminated case. These simulated NRCS values were then to be compared with the calibrated measured NRCS corresponding to the time at which the ice core was taken in order to determine which mixture model produced a simulated NRCS that was the closest to the calibrated measured value. Unfortunately, due to the presence of an oil-contaminated snow layer on top of the ice when the majority of sea ice samples were taken, and the lack of a reliable permittivity model for oil-contaminated snow, this comparison could only be performed on the oil-contaminated sea ice sample taken February 12, 2016. The simulated NRCS values generated from the permittivity profiles modelled for the sample using the three-phase Polder-van Santen/de Loor and quasi two-phase Tinga-Voss-Blossey mixture models are shown in Table 4.2.

It is clear that for this sample, the simulated NRCS produced from the permittivity profile calculated using the quasi two-phase Tinga-Voss-Blossey mixture model is closer to the measured NRCS than the value obtained from using the profile generated using the threephase Polder-van Santen/de Loor mixture model. However, no meaningful conclusions can be drawn from this result, as only one oil-contaminated ice core could be evaluated in this manner. While it remains inconclusive as to which, if any, of the permittivity mixture models presented herein is more accurate in modelling the complex permittivity profile of oilcontaminated sea ice, this framework for comparing the accuracy of permittivity models may prove useful for future studies of oil-contaminated sea ice.

4.3.4 Evaluation of Permittivity Models

In order to compare the performance of the permittivity models for oil-contaminated sea ice presented herein with the model presented in [14], each model was evaluated at several temperatures and frequencies for different oil volume fractions. For consistency across the models, simulations were performed using a bulk salinity of 6 psu, and an air volume fraction of 1.5% (for the models that account for included air). The results of these simulations are shown in Fig. 4.14. As can be seen from these plots, the real part of the permittivity, ε' , tends to decrease as the oil volume fraction increases regardless of temperature or frequency, which is to be expected. At the same time, ε'' tends to decrease with increasing oil volume fraction if initially higher than the ε'' of oil, or increase with volume fraction if initially lower than the ε'' of oil. In addition, the three-phase Polder-van Santen/de Loor and quasi twophase Tinga-Voss-Blossey mixture models applied, as well as the quasi two-phase Poldervan Santen/de Loor and quasi two-phase Tinga-Voss-Blossey mixture models which account for air included within the ice, appear to be more sensitive to changes in temperature than the linear mixture model presented in [14]. This difference is primarily due to the treatment of sea ice within the models. That is to say, the linear mixture model utilized in [14] employs the dielectric model of sea ice presented by [40], in which the only temperature dependence

is in the brine volume fraction, whereas the models presented herein treat the constituent components of sea ice (i.e. pure ice and brine) separately. The empirical formulas for the permittivities of pure ice and brine are both functions of temperature [24–27] (although the permittivity of pure ice has a very weak temperature dependence), thus the temperature of the oil-contaminated sea ice plays a larger role in the evaluation of the complex permittivity in the models presented in this paper. In addition to the temperature sensitivity, the models that employ the Polder-van Santen/de Loor formulation also appear to have a higher sensitivity to frequency than the linear mixture model. The models that employ the Tinga-Voss-Blossey formulation do not appear to have significant difference in frequency sensitivity in the real part of the permittivity compared to the linear mixture model, however there is a larger difference between the values of ε'' calculated at 1 and 10 GHz using these models than there is for the linear mixture model. Additionally, the sensitivity of the mixture models to changes in the oil volume fraction appears to be dependent on temperature. Although there are evident differences in the responses of the permittivity mixture models to changes in temperature, frequency, and oil volume fraction, it is unclear if one model is superior to the rest. Further work will be needed to evaluate the accuracy of the dielectric mixture models as applied to oil-contaminated sea ice.

4.4 Conclusion

Observations and experimental measurements from an oil-in-sea ice mesocosm experiment conducted at the University of Manitoba Sea-ice Environmental Research Facility from January to March 2016 were presented. The temperature and bulk salinity profiles, as well as the measured NRCS of the contaminated sea ice appeared to be impacted by the presence of crude oil as it migrated upward from the water column to the surface of the ice and into the snow layer that formed on the ice surface. In addition, models for the complex



Fig. 4.14: Comparison of the performance of the permittivity mixture models for oil-contaminated sea ice. Top: Complex permittivity of oil-contaminated sea ice at 1 GHz evaluated at temperatures of -20, -10, and -1.8 °C. Bottom: Complex permittivity of oil-contaminated sea ice at a temperature of -1.8 °C evaluated at frequencies of 1, 4, and 10 GHz. Mixture models as listed in the plot legends: (a) three-phase Polder-van Santen/de Loor, (b) quasi two-phase Tinga-Voss-Blossey, (c) quasi two-phase Polder-van Santen/de Loor with air inclusions, (d) quasi two-phase Tinga-Voss-Blossey with air inclusions, (e) the linear mixture model presented in [14]. All models were evaluated assuming a bulk salinity of 6 psu, an oil permittivity of 2.2332 - j0.0373 (which is assumed to be constant across the entire frequency range), and an air volume fraction of 1.5% when applicable.

permittivity profile of oil-contaminated sea ice were explored using physical measurements and compared using simulated NRCS data. As well, the use of *x*-ray microtomography in modelling the complex permittivity profile of crude oil-contaminated sea ice was explored. The performance of the permittivity models presented herein when subjected to changes in temperature, frequency, and oil volume fraction was evaluated and compared to that of an existing theoretical model. It was shown that the permittivity models presented herein are more sensitive to changes in ice temperature, and in some cases, more sensitive to changes in frequency and oil volume fraction than the existing linear model. Further research is required to determine which of the permittivity models most accurately represents the true permittivity of oil-contaminated sea ice.

Acknowledgment

The authors would like to thank Dave Babb, Dave Binne, Greg Bridges, Monika Pućko and Fei Wang for their contributions. In addition, the authors would like to thank Tundra Oil & Gas Ltd. for donating the crude oil used for this research. This work was funded in part by the Canada Research Chair (CRC) and the Canada Excellence Research Chair (CERC) programs and the Natural Sciences and Engineering Research Council (NSERC), and is a contribution to the ArcticNet Networks of Centres of Excellence and the Arctic Science Partnership (ASP).

References

- D. A. Rothrock, Y. Yu, and G. A. Maykut, "Thinning of Arctic sea-ice cover," *Geophysical Research Lett.*, vol. 26, no. 23, pp. 3469–3472, Dec. 1999.
- Y. Yu, G. A. Maykut, and D. A. Rothrock, "Changes in the thickness distribution of Arctic sea ice between 1958–1970 and 1993–1997," *J. Geophysical Research: Oceans*, vol. 109, no. C8, 2004.
- [3] J. C. Comiso, C. L. Parkinson, R. Gertsen, and L. Stock, "Accelerated decline in the Arctic sea ice cover," *Geophysical Research Lett.*, vol. 35, no. 1, Jan. 2008.
- [4] J. C. Comiso, "Large decadal decline of the Arctic multiyear ice cover," J. Climate, vol. 25, pp. 1176–1193, Jul. 2011.
- [5] Oceans North Canada, "The integrated Arctic corridors framework: Planning for responsible shipping in Canada's Arctic waters," *PEW Charitable Trust Rep.*, 2016.
- [6] Ø. Harsem, A. Eide, and K. Heen, "Factors influencing future oil and gas prospects in the Arctic," *Energy Policy*, vol. 39, no. 12, pp. 8037–8045, 2011.
- [7] M. Fingas and C. E. Brown, "Detection of oil in ice and snow," J. Marine Sci. and Eng., no. 1, pp. 10–20, 2013.

- [8] M. Fingas and C. Brown, "Review of oil spill remote sensing," *Marine Pollution Bulletin*, vol. 83, Apr. 2014.
- [9] C-Core, "Oil spill detection and mapping in low visibility and ice: Surface remote sensing," C-Core Rep. R-12-081-1001, ver. 5.1, 2013.
- [10] D. Dickins and J. H. Andersen, "Remote sensing technology review and screening," Oil in Ice - JIP Rep. No. 22, SINTEF Materials and Chemistry, Marine Environment Technology, 2009.
- [11] C. E. Brown and M. F. Fingas, "Review of the development of laser fluorosensors for oil spill applications," *Marine Pollution Bulletin*, vol. 47, no. 9, pp. 477–484, 2003.
- [12] J. P. Wilkinson, T. Boyd, B. Hagen, T. Maksym, S. Pegau, C. Roman, H. Singh, and L. Zabilansky, "Detection and quantification of oil under sea ice: The view from below," *Cold Regions Sci. and Technology*, vol. 109, pp. 9–17, 2015.
- [13] J. H. Bradford, E. L. Babcock, H.-P. Marshall, and D. F. Dickins, "Targeted reflectionwaveform inversion of experimental ground-penetrating radar data for quantification of oil spills under sea ice," *Geophysics*, vol. 81, no. 1, pp. WA59–WA70, 2015.
- [14] C. Brekke, B. Holt, C. Jones, and S. Skrunes, "Discrimination of oil spills from newly formed sea ice by synthetic aperture radar," *Remote Sensing of Environment*, vol. 145, Feb. 2014.
- [15] NORCOR Engineering & Research Limited, "The interaction of crude oil with Arctic sea ice," *Beaufort Sea Project Tech. Rep. No.* 27, Dec. 1975.
- [16] D. Dickins, "Behaviour of oil spills in ice and implications for Arctic spill response," in *Proc. Arctic Technology Conf.*, Houston, TX, Feb. 2011.

- [17] N. Firoozy, T. Neusitzer, D. Desmond, T. Tiede, M. Lemes, J. Landy, P. Mojabi, S. Rysgaard, G. Stern, and D. G. Barber, "An electromagnetic detection case study on crude oil injection in a young sea ice environment," *IEEE Trans. Geosci. Remote Sens.*, vol. 55, no. 8, 2017.
- [18] M. F. Fingas and B. P. Hollebone, "Review of behaviour of oil in freezing environments," *Marine Pollution Bulletin*, vol. 47, 2003.
- [19] P. J. Brandvik and L.-G. Faksness, "Weathering processes in Arctic oil spills: Mesoscale experiments with different ice conditions," *Cold Regions Sci. and Tehcnology*, vol. 55, Jun. 2009.
- [20] Environment Canada. Historical climate data. [Online]. Available: http://climate. weather.gc.ca/historical_data
- [21] T. Geldsetzer, J. B. Mead, J. J. Yackel, R. K. Scharien, and S. E. L. Howell, "Surfacebased polarimetric C-band scatterometer for field measurements of sea ice," *IEEE Trans. Geosci. Remote Sens.*, vol. 45, no. 11, pp. 3405–3416, Nov. 2007.
- [22] D. Polder and J. H. van Santen, "The effective permeability of mixtures of solids," *Physica*, vol. 12, no. 5, pp. 257–271, 1946.
- [23] G. P. de Loor, "Dielectric properties of heterogeneous mixtures containing water," J. *Microwave Power*, vol. 3, no. 2, pp. 67–73, 1968.
- [24] F. T. Ulaby and D. G. Long, *Microwave Radar and Radiometric Remote Sensing*. Ann Arbor, MI: University of Michigan Press, 2014, ch. 4.
- [25] C. Mätzler and U. Wegmüller, "Dielectric properties of fresh-water ice at microwave frequencies," J. Physics D: Appl. Physics, vol. 20, no. 12, pp. 1623–1630, 1987.

- [26] G. Hufford, "A model for the complex permittivity of ice at frequencies below 1 THz," *Int. J. Infrared and Millilmeter Waves*, vol. 12, no. 7, pp. 677–682, 1991.
- [27] A. Stogryn, "Equations for calculating the dielectric constant of saline water," *IEEE Trans. Microw. Theory Tech.*, vol. 19, no. 8, Aug. 1971.
- [28] G. Frankenstein and R. Garner, "Equations for determining the brine volume of sea ice from -0.5 to -22.9 °C," J. Glaciology, vol. 6, no. 48, 1967.
- [29] G. F. N. Cox and W. F. Weeks, "Equations for determining the gas and brine volumes in sea ice samples," J. Glaciology, vol. 29, no. 102, 1983.
- [30] M. Hallikainen, F. T. Ulaby, and M. Abdelrazik, "Dielectric properties of snow in the 3- to 37-GHz range," *IEEE Trans. Antennas Propag.*, vol. 34, no. 11, pp. 1329–1340, 1986.
- [31] W. R. Tinga, W. A. G. Voss, and D. F. Blossey, "Generalized approach to multiphase dielectric mixture theory," *J. Applied Physics*, vol. 44, no. 9, pp. 3897–3902, 1973.
- [32] M. S. Venkatesh and G. S. V. Raghavan, "An overview of dielectric properties measuring techniques," *Canadian Biosystems Eng.*, vol. 47, no. 7, pp. 15–30, 2005.
- [33] L. F. Chen, C. K. Ong, C. P. Neo, V. V. Varadan, and V. K. Varadan, *Microwave electronics: Measurement and materials characterization*. New York, NY: Wiley, 2004, ch. 6.
- [34] T. Friisø, Y. Schildberg, O. Rambeau, T. Tjomsland, H. Førdedal, and J. Sjøblom,
 "Complex permittivity of crude oils and solutions of heavy crude oil fractions," J. Dispersion Sci. and Technology, vol. 19, no. 1, pp. 93–126, 1998.
- [35] P. Hoekstra and P. Cappillino, "Dielectric properties of sea and sodium chloride ice

at UHF and microwave frequencies," J. Geophysical Research, vol. 76, no. 20, pp. 4922–4931, Jul. 1971.

- [36] M. R. Vant, R. O. Ramseier, and V. Makios, "The complex-dielectric constant of sea ice at frequencies in the range 0.1-40 GHz," *J. Applied Phys.*, vol. 49, no. 3, pp. 1264– 1280, Mar. 1978.
- [37] S. A. Arcone, A. J. Gow, and S. McGrew, "Microwave dielectric, structural, and salinity properties of simulated sea ice," *IEEE Trans. Geosci. Remote Sens.*, vol. GE-24, no. 6, pp. 832–839, Nov. 1986.
- [38] N. Firoozy, P. Mojabi, and D. G. Barber, "Nonlinear inversion of microwave scattering data for snow-covered sea-ice dielectric profile reconstruction," *IEEE Geosci. Remote Sens. Lett.*, vol. 12, no. 1, pp. 209–213, Jan. 2015.
- [39] P. Imperatore, A. Iodice, and D. Riccio, "Electromagnetic wave scattering from layered structures with an arbitrary number of rough interfaces," *IEEE Trans. Geosci. Remote Sens.*, vol. 47, no. 4, pp. 1056–1072, Apr. 2009.
- [40] M. Hallikainen and D. P. Winebrenner, "The physical basis for sea ice remote sensing," in *Microwave remote sensing of sea ice*, F. D. Carsey, Ed. Washington, DC: American Geophysical Union, 1992, ch. 3, pp. 29–46.

Normalized Radar Cross-Section Simulation Studies

As noted in Chapter 4, the difference in the permittivity of the top layer of oil-contaminated sea ice compared to uncontaminated sea ice has the potential to be employed for the purpose of detecting oil-contaminated sea ice using microwave remote sensing technologies. Thus, simulation studies of the normalized radar cross-section of both uncontaminated and oil-contaminated young sea ice were conducted in an effort to determine the extent to which the NRCS of young sea ice would be expected to change when contaminated with crude oil. As such, this chapter presents the details of the NRCS simulations for both the monostatic and bistatic measurement configurations, as well as general comments and observations based on the simulation results.

5.1 Monostatic NRCS Simulation

For the purposes of normalized radar cross-section simulation for monostatic measurement configurations, the improved integral equation model, or I²EM, for backscattering from a single scale random surface [1, 2] was utilized. Note that in this context, a single scale random surface has a roughness that varies with a single spatial frequency, whereas a multiscale random surface would be characterized by different roughnesses varying at different spatial frequencies. This model computes the NRCS in the VV, HH, and HV polarizations for a single-scale rough interface between air and a half-space of arbitrary permittivity given the roughness parameters of the surface, the frequency of operation, the angle of incidence, and the permittivity of the half-space. Since the permittivity of sea ice varies with depth, for simulation purposes it was assumed that both uncontaminated and oil-contaminated sea ice could be represented as a half-space with a permittivity equal to that of the top 2.5 cm of the ice. As sea ice is a lossy material due to the presence of brine, it is assumed that the penetration depth at C-band frequencies would be sufficiently small that the halfspace assumption would be reasonable.¹ The simulations were performed for an operating frequency of 5.5 GHz to match the frequency at which the NRCS measurements in Chapter 4 were taken. The roughness parameters of the air/sea ice interface used were obtained through lidar measurements of the uncontaminated sea ice grown during the oil-in-sea ice mesocosm experiment in the winter of 2016, and are shown in Tab. 5.1 [3]. It was assumed that the roughness corresponded to a Gaussian correlation function. The I²EM model was applied to the permittivities for uncontaminated and oil-contaminated sea ice shown in Tab. 5.2, which correspond to the average values of the top 2.5 cm of the uncontaminated sea ice modelled

¹ Although the presence of crude oil within the top portion of the sea ice would tend to increase the penetration depth of the interrogating wave (from approximately 5 cm at to roughly 20 cm at 5.5 GHz), since the real and imaginary parts of the permittivity of the contaminated ice tend to increase with depth the attenuation of the incident wave would also increase with depth. Thus the scattering contributions from the lower portions of the oil-contaminated sea ice would be much smaller than that of the top portion of the ice, and may be neglected for simulation purposes.

Tab. 5.1: Roughness parameters used for NRCS simulation assuming a Gaussian correlation function.

RMS Height (cm)	Correlation Length (cm)
0.390	0.965

Tab. 5.2: Assumed permittivities for the half-space for NRCS simulation modelled using the twophase Polder-van Santen/de Loor (2 PvS/dL) mixture model for uncontaminated sea ice, and the three-phase Polder-van Santen/de Loor (3 PvS/dL) and quasi two-phase Tinga-Voss-Blossey (q2 TVB) mixture models for oil-contaminated sea ice.

Uncontaminated Sea Ice	Oil-Contaminated Sea Ice	
2 PvS/dL	3 PvS/dL	q2 TVB
4.75 - j0.37	4.08 - j0.13	3.97 - j0.08

using the two-phase Polder-van Santen/de Loor mixture model, and the top 2.5 cm of the oilcontaminated sea ice modelled using the three-phase Polder-van Santen/de Loor and quasi two-phase Tinga-Voss-Blossey mixture models as per Chapter 4.

The monostatic NRCS for each half-space was simulated for incidence angles between 1° and 70° inclusive, with respect to the nadir, and the results are shown in Fig. 5.1. It is clear from these plots that the simulated monostatic NRCS of the oil-contaminated young sea ice is less than that of the uncontaminated young sea ice in every polarization. As well, the simulated monostatic NRCS produced from both dielectric mixture models for oil-contaminated sea ice are quite close in each polarization, with the NRCS produced from the oil-contaminated sea ice permittivity modelled using the quasi two-phase Tinga-Voss-Blossey mixture model being slightly lower in each case.

The largest differences between the simulation results for the uncontaminated and oilcontaminated sea ice are observed in the VV and HV polarizations, which would suggest that these polarizations would be more sensitive to oil-contamination in sea ice. However, since the NRCS in the HV polarization is much smaller in value than the NRCS in both the VV and HH polarizations, the signal to noise ratio for the HV polarization can be expected to



Fig. 5.1: Simulated monostatic NRCS of both uncontaminated and oil-contaminated sea ice in the (a) VV, (b) HH, and (c) HV polarizations.

be lower. As a result, the HV polarization would likely be less sensitive to oil-contamination of the ice than the VV polarization in practice. For the VV polarization, the difference between the NRCS of the uncontaminated sea ice and that of the contaminated ice is at a minimum at the lowest incidence angle, and increases as incidence angle increases. Although this difference may not be immediately clear in Fig. 5.1, it is evident in the plots of the differences between the simulated monostatic NRCS of uncontaminated and oil-contaminated sea ice shown in Fig. 5.2. In particular, this difference increases from 0.84 dB to 1.17 dB

108

with respect to the contaminated ice modelled using the three-phase Polder-van Santen/de Loor model, and from 1.00 dB to 1.39 dB with respect to the contaminated ice modelled using the quasi two-phase Tinga-Voss-Blossey model. Conversely, for the HH polarization the difference between the NRCS of uncontaminated and contaminated sea ice decreases with increasing incidence angle. For the HH polarization, this difference decreases from 0.84 dB to 0.47 dB with respect to the contaminated ice modelled using the three-phase Polder-van Santen/de Loor model, and from 1.00 dB to 0.56 dB with respect to the contaminated ice modelled using the quasi two-phase Tinga-Voss-Blossey model. The difference between the NRCS of uncontaminated and oil-contaminated sea ice in the HV polarization remains largely constant across the range of incidence angles considered herein, with only a slight decrease as the incidence angle increases. In the HV polarization, the difference in the NRCS decreases from 1.57 dB to 1.49 dB with respect to the contaminated ice modelled using the three-phase Polder-van Santen/de Loor model, and from 1.87 dB to 1.78 dB with respect to the contaminated ice modelled using the quasi two-phase Tinga-Voss-Blossey model. Since the difference between the simulated NRCS of uncontaminated sea ice and the simulated NRCS of oil-contaminated sea ice is less than 2 dB for all polarizations and incidence angles, it remains to be seen if this difference is sufficiently large enough to distinguish oil-contaminated sea ice from its uncontaminated counterpart in practice.

5.2 Bistatic NRCS Simulation

In order to simulate the NRCS for the bistatic measurement configuration, the I²EM model for bistatic scattering from a single scale random surface [1, 2] was used. Similarly to its monostatic counterpart, this bistatic model computes the NRCS in the VV and HH polarizations for a single scale rough interface between air and a half-space of arbitrary permittivity. However, this model does not compute the NRCS for the HV polarization, thus the cross-



Fig. 5.2: Differences between the simulated monostatic NRCS of uncontaminated and oilcontaminated sea ice in the (a) VV, (b) HH, and (c) HV polarizations.

polarized bistatic NRCS is not considered here. This bistatic model requires the same input parameters needed for the monostatic model, as well as the elevation and azimuth angles of the observation point. As before, the roughness parameters in Tab. 5.1 were used for all bistatic simulations assuming a Gaussian correlation function, and the simulation frequency was 5.5 GHz. The bistatic model was applied to three half-spaces with permittivities corresponding to those in Tab. 5.2 for incidence angles ranging from 1° to 70° and observation elevation angles with the same range. For each bistatic simulation, the azimuth angle of the observation point was taken to be 0° such that there would be 180° between the transmitter and receiver in the azimuth plane. The results of the bistatic NRCS simulation using the I²EM model for bistatic scattering from a single scale random surface are shown in Fig. 5.3.

It is evident from Fig. 5.3 that there is minimal difference in the simulated bistatic NRCS in the HH polarization between uncontaminated and oil-contaminated sea ice. From the plots of the simulated bistatic NRCS in the VV polarization, it is evident that the most significant differences are at the Brewster angles where the NRCS drops significantly. These discrepancies are easier to visualize in the plots of the differences between the simulated bistatic NRCS of uncontaminated sea ice and both models of oil-contaminated sea ice, calculated as $\sigma_{uncontaminated}^0 - \sigma_{contaminated}^0$, shown in Fig. 5.4. From these plots it is evident that there is a clear shift in the Brewster angles of the bistatic NRCS for oil-contaminated sea ice towards lower incidence angles, and the shift becomes more prominent as the elevation angle of the observation point increases. Since the surface roughness is constant across each simulation, this difference must be due to the lower permittivity of the oil-contaminated ice. Such a shift in the incidence angle at which the bistatic NRCS in the VV polarization is at its minimum is consistent with the decrease the Brewster angle for a perfectly smooth interface would experience as a result from a decreasing the permittivity in the lower half-space. From the results of the bistatic NRCS simulation, this shift appears to be greatest at large observation elevation angles, at which point the Brewster angle is roughly 4° lower for oil-contaminated sea ice. Conversely, for an observation point at normal incidence, there is virtually no shift in the Brewster angle between uncontaminated and oil-contaminated sea ice.



Fig. 5.3: Simulated bistatic NRCS for the (a) VV and (b) HH polarizations of uncontaminated sea ice, the (c) VV and (d) HH polarizations of oil-contaminated sea ice modelled using the three-phase Polder-van Santen/de Loor mixture model, and the (e) VV and (f) HH polarizations of oil-contaminated sea ice modelled using the quasi two-phase Tinga-Voss-Blossey mixture model.



Fig. 5.4: The difference between the simulated bistatic NRCS of uncontaminated sea ice and oilcontaminated sea ice modelled using (a) the three-phase Polder-van Santen/de Loor and (b) the quasi two-phase Tinga-Voss-Blossey mixture models in the VV polarization.

5.3 Comments and Observations

As was noted in Section 5.1, the differences between the simulated NRCS of uncontaminated and oil-contaminated sea ice with the same roughness parameters was less than 2 dB for all polarizations and incidence angles. Since a 2 dB difference is relatively small, in practice it may require detection systems to have tremendously low noise levels for differentiation between uncontaminated and contaminated sea ice to be made. However, the surface roughness may not necessarily be identical between uncontaminated and oil-contaminated sea ice in practice. In particular, oil may migrate to the surface of young sea ice as observed in Chapter 4, which could potentially decrease the surface roughness of the ice and further decrease the associated monostatic NRCS. Thus, the simulations presented herein may be considered to be somewhat of a simplified scenario for detection of oil-contaminated sea ice through monostatic NRCS measurement.

Similarly, the maximum shift in the Brewster angle of approximately 4° observed in

the simulated bistatic NRCS of oil-contaminated sea ice is relatively small. In practice, using such a shift in the Brewster angle to differentiate between uncontaminated and oilcontaminated sea ice may be limited by the mechanical accuracy to which the desired incident and observation angles can be achieved. In addition, since the NRCS at the Brewster angle is at its minimum, noise within the measurement system can potentially hinder the accuracy with which the Brewster angles can be measured. As with the monostatic NRCS simulation, the bistatic NRCS simulation presented herein does not account for potential changes in the surface roughness of the sea ice that may arise from upward oil migration to the ice surface, and as such may not fully reflect the differences between the bistatic NRCS of uncontaminated and oil-contaminated sea ice that may be seen in practice. Oil which has migrated to the surface of the sea ice may exaggerate the differences between the measured bistatic NRCS for the uncontaminated and oil-contaminated cases, thus reducing the difficulty of differentiating between the two from field measurements. It is important to note that the discussion presented in this chapter is based on a rough half space model which does not fully represent the actual system. Finally, it should be noted that the complex permittivities utilized in this chapter are based on the models presented in Chapter 4, and the level of accuracy of these models needs to be investigated further.

References

- F. T. Ulaby and D. G. Long, *Microwave Radar and Radiometric Remote Sensing*. Ann Arbor, MI: University of Michigan Press, 2014, ch. 10.
- [2] A. K. Fung, W. Y. Liu, K. S. Chen, and M. K. Tsay, "An improved IEM model for bistatic scattering from rough surfaces," *J. Electromagnetic Waves and Applications*, vol. 16, no. 5, pp. 689–702, 2002.
- [3] N. Firoozy, T. Neusitzer, D. Desmond, T. Tiede, M. Lemes, J. Landy, P. Mojabi, S. Rysgaard, G. Stern, and D. G. Barber, "An electromagnetic detection case study on crude oil injection in a young sea ice environment," *IEEE Trans. Geosci. Remote Sens.*, vol. 55, no. 8, 2017.

Conclusions and Future Work

This thesis has contributed to the study of Arctic sea ice from an electromagnetic remote sensing point of view by examining how the presence of crude oil beneath, within, and on top of young sea ice would affect the electromagnetic properties of the ice. In particular, the research presented herein has addressed aspects of modelling the dielectric profile of the oil-contaminated sea ice, as well as the differences in the normalized radar cross-sections of oil-contaminated and uncontaminated sea ice. Within this thesis, the preliminary experimentation conducted in the University of Manitoba Centre for Earth Observation Science cold laboratory was described. As such, the details of the experiment, including the measured geophysical parameters of both the uncontaminated and contaminated ice grown, were presented. In addition, the measurement of the permittivity of the corn oil used in the preliminary experimentation and the crude oil used in the outdoor mesocosm experiment was discussed, and the results of modelling the dielectric profiles of the ice samples were presented. Following this, the oil-in-sea ice mesocosm experiment conducted at the University of Manitoba Sea-ice Environmental Research Facility during the winter of 2016 was

discussed. This discussion included experimental observations, the measured geophysical and electromagnetic properties of the uncontaminated and oil-contaminated sea ice grown, examination of the ice microstructure through *x*-ray microtomography, and models for approximating the permittivity profile of the oil-contaminated sea ice. Finally, the details of a simulation study of the normalized radar cross-section of oil-contaminated sea ice was presented. This included the simulation of both the monostatic and bistatic normalized radar cross-section of uncontaminated and oil-contaminated sea ice across multiple polarizations for a wide range of incidence and observation angles.

It is evident from the results presented herein that the presence of corn and crude oils beneath, within, and on the surface of young sea ice appears to decrease the bulk salinity of the ice. In addition, the presence of crude oil appeared to impact the temperature profile of the sea ice and contribute to the exaggerated diurnal variations in ice temperature observed. These differences, in combination with the inclusion of the oil within the ice, appear to contribute to decreasing both the real and imaginary parts of the permittivity profile of the sea ice, regardless of the mixture model used. The presence of crude oil was observed to contribute to an immediate decrease in the measured NRCS of the contaminated sea ice, and simulation results indicate that the monostatic NRCS of oil-contaminated sea ice should be lower than that of uncontaminated sea ice regardless of polarization or incidence angle. These observed differences between the NRCS of uncontaminated and oil-contaminated sea ice, as well as the exaggerated diurnal variation in the temperature profile of the oil-contaminated sea ice, suggest that the differentiation between uncontaminated and oil-contaminated young sea ice using microwave remote sensing technologies may be possible.

As the mesocosm experiment was limited by the size of the pool used to grow the ice, future oil-in-sea ice mesocosm experiments that will be conducted at the Churchill Marine Observatory facility, which is currently under construction, will be significantly less restricted and may provide further insight into the dielectric profile and NRCS of oil-contaminated sea ice. Since the pool will be much larger, it will be possible to measure the NRCS of oil-contaminated sea ice at a range of incidence angles with a larger sweep in the azimuth direction without having the footprint of the main beam of the scatterometer overlap with the edges of the pool. In addition, the larger available ice surface will allow for the collection of physical samples of the ice more regularly without interfering with NRCS measurement, which will facilitate modelling the evolution of the permittivity profile of the ice with better temporal resolution. It may also be of interest to measure the NRCS of the oil-contaminated ice in future experiments across a range of multiple frequencies to increase the amount of information available for use with inversion schemes.

There are several potential paths which can be pursued to extend the research presented in this thesis. The first of these would include further investigation into which, if any, of the models for the permittivity of oil-contaminated sea ice proposed herein most accurately reflects the true permittivity. This may be done through more thorough examination of the contaminated ice through *x*-ray microtomography, or by simulating the normalized radar cross-section of the contaminated ice from modelled permittivity profiles and comparing the results with measurements as proposed in Chapter 4. Another potential extension of this research would be the pursuit of an accurate model for the effective relative permittivity of oil-contaminated snow. Such an endeavour would extend the research community's ability to model the normalized radar cross-section of oil-contaminated sea ice from the bare ice case to also include ice with an oil-contaminated snow layer. A third avenue to pursue in extension of this research would be the development of a robust algorithm to differentiate between uncontaminated and oil-contaminated sea ice based on the measured normalized radar cross-section. Such an algorithm could be applied to a variety of active microwave remote sensing technologies, including airborne and satellite-based SAR, and would allow for remote detection of Arctic crude oil spills should such catastrophic events take place. Finally, existing electromagnetic inversion methods which are used to recover the geophysical and dielectric properties of sea ice could potentially be extended to allow for reliable quantification of the oil entrapped within contaminated sea ice. APPENDIX

A

Brine Permittivity Formulas

This appendix presents the emirical formulae which can be used to determine the values utilized in the calculation permittivity of brine as per (2.23) and (2.24). Further details of the formulae shown here may be found in chapter 4 of [1] and in [2].

The dc permittivity, relaxation time constant, and conductivity of brine are all functions of the temperature and the normality of the brine. The normality of the brine is itself a function of the bulk salinity of the brine, and may be calculated as

$$N_b = S_b (1.707 \times 10^{-2} + 1.205 \times 10^{-5} S_b + 4.058 \times 10^{-9} S - b^2).$$
 (A.1)

The dc permittivity of brine is given by

$$\varepsilon_{b0}(T, N_b) = \varepsilon_{b0}(T, 0)a_1(N_b) \tag{A.2}$$

where the factors $\varepsilon_{b0}(T,0)$ and $a_1(N_b)$ are given by

$$\varepsilon_{b0}(T,0) = 88.045 - 0.4147T + 6.295 \times 10^{-4}T^2 + 1.075 \times 10^{-5}T^3$$
 (A.3)

and

$$a_1(N_b) = 1.0 - 0.255N_b + 5.15 \times 10^{-2}N_b^2 - 6.89 \times 10^{-3}N_b^3$$
(A.4)

respectively. Similarly, the relaxation time constant of brine is given by

$$\tau_b(T, N_b) = \tau_b(T, 0)b_1(T, N_b)$$
 (A.5)

where the constituent factors can be caluclated using

$$\tau_b(T,0) = \frac{1}{2\pi} (1.1109 \times 10^{-10} - 3.824 \times 10^{-12} T + 6.938 \times 10^{-14} T^2 - 5.096 \times 10^{-16} T^3)$$
(A.6)

and

$$b_1(T, N_b) = 1.0 + 0.146 \times 10^{-2} T N_b - 4.89 \times 10^{-2} N_b - 2.97 \times 10^{-2} N_b^2 + 5.64 \times 10^{-3} N_b^3.$$
 (A.7)

Finally, the conductivity of the brine is given by

$$\sigma_b(T, N_b) = \sigma_b(25 \,^\circ \text{C}, N_b)c_1(\Delta, N_b) \tag{A.8}$$

where the factors $\sigma_b(25\ {}^\circ\mathrm{C},N_b)$ and $c_1(\Delta,N_b)$ are determined by

$$\sigma_b(25\,^{\circ}\mathrm{C},N_b) = N_b(10.39 - 2.378N_b + 0.683N_b^2 - 0.135N_b^3 + 1.01 \times 10^{-2}N_b^4) \quad (A.9)$$

and

$$c_1(\Delta, N_b) = 1.0 - 1.96 \times 10^{-2} \Delta + 8.08 \times 10^{-5} \Delta^2 - N_b [3.02 \times 10^{-5} + 3.92 \times 10^{-5} \Delta + N_b (1.72 \times 10^{-5} - 6.58 \times 10^{-6} \Delta)].$$
(A.10)

Note that in the above equation $\Delta = 25 - T$. These equations are valid for bulk salinities between 0 and 157 psu.

References

- [1] F. T. Ulaby and D. G. Long, *Microwave Radar and Radiometric Remote Sensing*. Ann Arbor, MI: University of Michigan Press, 2014.
- [2] A. Stogryn, "Equations for calculating the dielectric constant of saline water," *IEEE Trans. Microw. Theory Tech.*, vol. 19, no. 8, pp. 733–736, Aug. 1971.

B

Additional Contributions to the Literature

In addition to the manuscript that comprises Chapter 4, several refereed journal and conference papers were published throughout the course of the research presented herein. These contributions to the literature are listed below.

N. Firoozy, **T. Neusitzer**, D. Desmond, T. Tiede, M. Lemes, J. Landy, P. Mojabi, S. Rysgaard, G. Stern and D.G. Barber, "An electromagnetic case study of crude oil injection in a young sea ice environment," *IEEE Trans. Geosci. Remote Sens.*, vol. 55, no. 8, pp. 4465–4475, Aug. 2017.

T. Neusitzer, N. Firoozy, T. Tiede, D. Desmond, P. Mojabi, D. Barber, M. Lemes and G. Stern, "Investigating the complex permittivity profile of oil-contaminated sea ice," in *Proceedings of the ArcticNet Annual Scientific Meeting*, Winnipeg, MB, Dec. 2016.

D. Desmond, **T. Neusitzer**, M. Lemes, J. Xidos, N. Firoozy, G. Stern, D. Barber and P. Mojabi, "Examining the weathering processes and interactions of corn oil in sea ice," in *Proceedings of the ArcticNet Annual Scientific Meeting*, Winnipeg, MB, Dec. 2016.

Pu. Mojabi, N. Firoozy, N. Bayat, T. Brown, C. Narendra, Pe. Mojabi, C. Niu, T. Tiede, **T. Neusitzer**, X. Li, I. Jeffrey, J. LoVetri and D. Barber, "Electromagnetic inversion for biomedical imaging, antenna characterization, and sea ice remote sensing applications," in *Proceedings of the URSI Asia-Pacifc Radio Science Conference*, Seoul, South Korea, Aug. 2016. (Invited)

N. Firoozy, P. Mojabi, T. Tiede, **T. Neusitzer** and D.G. Barber, "Normalized radar crosssection analysis of oil-contaminated young sea ice," in *Proceedings of the IEEE International Symposium on Antennas and Propagation/USNC-URSI National Radio Science Meeting*, Fajardo, PR, June 2016.

T. Tiede, N. Firoozy, **T. Neusitzer**, P. Mojabi and D. Barber, "Complex permittivity profile reconstruction of sea ice using a transmission line model," in *Proceedings of the IEEE International Symposium on Antennas and Propagation/USNC-URSI National Radio Science Meeting*, Fajardo, PR, June 2016.