PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

PROBLEMS IN METHYLENE BLUE TESTING SINCE 10/4

ISARD COUNTY PRISON 5 BURNESVILLE MDN 22017 USA
TEL 1 800 705 7446 FAX 614 85 7002 TLR 5110000000

National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Service

Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

**Soil Moisture Estimation using Ground Scatterometer Data :
Evaluation of the Potential of ERS-1, JERS-1 and RADARSAT**

by

Terry J. Pultz, B.A.

**A Thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of**

Master of Arts

**Department of Geography
Carleton University
Ottawa, Ontario
December, 1991**

**© Copyright
1991, Terry J.Pultz**

National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Service Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

The author has granted an irrevocable non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of his/her thesis by any means and in any form or format, making this thesis available to interested persons.

The author retains ownership of the copyright in his/her thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without his/her permission.

L'auteur a accordé une licence irrévocable et non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de sa thèse de quelque manière et sous quelque forme que ce soit pour mettre des exemplaires de cette thèse à la disposition des personnes intéressées.

L'auteur conserve la propriété du droit d'auteur qui protège sa thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

ISBN 0-315-75930-5

Canada

Carleton University
Ottawa, Canada K1S 5B6

Carleton University
Library
111 Somerset Street West
Ottawa, Ontario K1S 5B6
Canada

The undersigned recommend to the Faculty of Graduate Studies
and Research acceptance of the thesis

Soil Moisture Estimation using Ground Scatterometer Data :
Evaluation of the Potential of ERS-1, JERS-1 and RADARSAT

Submitted by Terry J. Pultz, B.A.

in partial fulfilment of the requirements for
the degree of Master of Arts

Thesis Supervisor

Chair, Department of Geography

Carleton University
December, 1991

Abstract

Water stored in the form of soil moisture strongly influences the success of our agricultural crops and the distribution of precipitation between storm runoff and storage. The development of microwave sensors and the research on their application to soil moisture monitoring has proceeded rapidly in the past few years. The two primary reasons for this are the all weather capability of microwave sensors and that the unique dielectric properties of water cause it to be a dominant parameter influencing microwave interactions with the surface of the earth.

In this study, data acquired by the Canada Centre for Remote Sensing ground-based scatterometer were used to evaluate how radar backscatter varied as a function of frequency, polarization and incidence angle, soil moisture and plant moisture for fallow, wheat and canola targets. Specifically, the radar data were collected at 1.5 GHz (L-Band), horizontal polarization, 5.3 GHz (C-Band) vertical polarization and C-Band horizontal polarization at incidence angles of 20°, 40° and 60°.

Linear correlation coefficients were computed between the radar backscattering coefficient and soil moisture. Similarly, the correlation coefficients were calculated between the radar parameters and plant moisture for the wheat and canola targets and between each set of radar parameters and soil moisture and plant moisture for all targets combined.

In general, the linear models indicated that radar correlation to soil moisture decreases and correlation with plant moisture increases with increasing incidence angle and as frequency was increased from L-Band to C-band.

The results suggest that data acquired from ERS-1 or RADARSAT at 20° will have stronger correlations with soil moisture than JERS-1 or RADARSAT data acquired at larger incidence angles. It is also evident that no single observation from any of these satellites will accurately estimate soil moisture without a priori information regarding canopy conditions and/or surface roughness.

Acknowledgements

I would like to thank Professors Mike Fox and Tom Wilkinson of the Geography Department for their constructive comments on a draft of this thesis. Dr. Ron Brown (CCRS) is also thanked for providing the data used in this study. Thanks are extended to Dr. Brian Brisco (Intera Information Technologies Ltd.) for informal discussions and regular inquiries as to the completion date of this work.

I would also like to thank my wife Nancy for her patience during the course of my graduate studies. Finally, I would like to thank my parents, Ken and Leona, for encouraging me to read and for conveying the benefits of education.

Table of Contents

	Page
Abstract	iii
Acknowledgements	v
Table of Contents	vi
List of Figures	viii
List of Tables	x
List of Appendices	xi
Chapter 1 - Introduction	
1.1 The Research Context	1
1.2 Research Objectives	13
1.3 Research Methods	14
1.4 Thesis Organization	16
Chapter 2 - Radar Remote Sensing	
2.1 Principles of Radar Remote Sensing	17
2.2 Radar Backscatter	19
2.3 Soil Moisture Retrieval	29

Chapter 3 - Data Collection and Methodology

	Page
3.1 Data Acquisition	35
3.2 Temporal Observations	39
3.3 Statistical Procedures	42

Chapter 4 - Analysis and Discussion

4.1 Analysis	50
4.1.1 Fallow	51
4.1.2 Wheat	55
4.1.3 Canola	60
4.1.4 Combined Data	64
4.2 Discussion of Individual Target Results	68
4.3 Discussion of Combined Results	73
4.4 Discussion in Relation to Proposed Satellite Platforms	75

Chapter 5 - Conclusions and Future Research

5.1 Conclusions	78
5.2 Future Research	80

References	82
-------------------	-----------

Appendix A	95
-------------------	-----------

Appendix B	96
-------------------	-----------

List of Figures

	Page
1 Fallow Temporal Moisture Observations	40
2 Wheat Temporal Moisture Observations	40
3 Canola Temporal Moisture Observations	41
4 Fallow C-HH Temporal Radar Observations	43
5 Fallow C-VV Temporal Radar Observations	43
6 Fallow L-HH Temporal Radar Observations	44
7 Wheat C-HH Temporal Radar Observations	45
8 Wheat C-VV Temporal Radar Observations	45
9 Wheat L-HH Temporal Radar Observations	46
10 Canola C-HH Temporal Radar Observations	47
11 Canola C-VV Temporal Radar Observations	47
12 Canola L-HH Temporal Radar Observations	48
13 Fallow C-HH Correlation Coefficients	52
14 Fallow C-HH Moisture Sensitivity	52
15 Fallow C-VV Correlation Coefficients	53
16 Fallow C-VV Moisture Sensitivity	53
17 Fallow L-HH Correlation Coefficients	54
18 Fallow L-HH Moisture Sensitivity	54
19 Wheat C-HH Correlation Coefficients	56
20 Wheat C-HH Moisture Sensitivity	56

List of Figures (continued)

	Page
21 Wheat C-VV Correlation Coefficients	57
22 Wheat C-VV Moisture Sensitivity	57
23 Wheat L-HH Correlation Coefficients	58
24 Wheat L-HH Moisture Sensitivity	58
25 Canola C-HH Correlation Coefficients	61
26 Canola C-HH Moisture Sensitivity	61
27 Canola C-VV Correlation Coefficients	62
28 Canola C-VV Moisture Sensitivity	62
29 Canola L-HH Correlation Coefficients	63
30 Canola L-HH Moisture Sensitivity	63
31 Combined C-HH Correlation Coefficients	65
32 Combined C-HH Moisture Sensitivity	65
33 Combined C-VV Correlation Coefficients	66
34 Combined C-VV Moisture Sensitivity	66
35 Combined L-HH Correlation Coefficients	67
36 Combined L-HH Moisture Sensitivity	67
37 Radar Correlations to Soil and Plant Moisture for JERS-1, RADARSAT and ERS-1	76

List of Tables

	Page
1.0 Radar Band Designations	18

List of Appendices

	Page
A University of Saskatchewan Kernan Crop Research Farm Site Map	95
B CCRS Ground-Based Scatterometer	96

Chapter One

Introduction

1.1 The Research Context

Soil Moisture

Of the fresh water on Earth, about one part in five is in liquid form. Of the liquid portion of this fresh water that is unfrozen and available, ground water occupies nearly 99%, 1% is in the form of water stored in lakes, 0.2% is in the form of soil moisture, 0.1% is in rivers, 0.1% is atmospheric water and 0.005% exists in plants. In terms of equivalent depth, about 1 meter falls in the form of precipitation and is evaporated from the Earth each year (Dooge, 1973).

However insignificant the amount of water stored in the form of soil moisture may seem, when compared to the total amount of water on the global scale, it is this thin layer that strongly influences the success of our agricultural crops and the distribution of precipitation between storm runoff and storage. Soil moisture is highly variable both spatially and temporally, as the result of inhomogeneity of soil properties, topography, land cover and the variability of precipitation and evapotranspiration (Engman, 1990). As a result, soil moisture is typically measured at points (sites) and averages of these point measurements are used to characterize the soil moisture of an area. Therefore, conventional in situ measurements of soil

moisture are costly and provide information at only a few selected areas. In many cases, particularly watershed scale monitoring or modelling, soil moisture is inferred from more easily obtainable hydrologic data (frequently spatially and temporally integrated) such as rainfall, runoff and temperature.

Remote sensing provides a unique tool for soil moisture monitoring because discrimination of soil moisture patterns can be estimated (in both space and time) and can provide a time series of soil moisture changes. However, the signal received at a remote sensing platform is usually the result of a mixture of land cover, topographic and atmospheric effects. Therefore, knowledge of electromagnetic energy interaction within the biosphere and atmosphere is required to separate these components.

In general, most remotely sensed measurements of moisture in the soil either directly respond to soil moisture in the upper few centimetres (1 - 10 cm) or use the response of plants as related to their ability to transpire, thereby indirectly providing an indication of the soil moisture status in the root zone (1 - 100 cm). Therefore, either direct observations of the soil by remote sensors or indirect estimates using plant condition could be useful in soil moisture observations (Schmugge et al., 1980, Tucker, 1980). The precise amount of vegetation limiting a direct approach or required to use an indirect approach, has not yet been determined. In any case, it is clear that some estimate of the amount and type of vegetation present is necessary for applying remote sensing observations of soil moisture both accurately and

precisely.

Remote Sensing of Soil Moisture

Nearly all portions of the electromagnetic spectrum have been shown to be sensitive to soil moisture (Schmugge et al., 1980). In general, the amount of solar radiation reflected from the soil decreases with increasing soil moisture. However, the use of reflected solar energy from soils does not appear at this time to be a very promising technique. This is due to the soil spectral response as a function of moisture content depending on several other variables such as the spectral reflectance of dry soil, surface roughness, geometry of illumination, organic matter, soil texture and the fact that the observations represent only a very thin surface layer (< 1 mm) (Bowers and Hanks, 1965; Allan, 1972; Blanchard et al., 1974; Stockhoff and Frost, 1974; Janza, 1975; Tucker, 1980).

An indirect approach in the use of reflected solar energy to estimate soil moisture is to observe the condition of vegetation which, as stated, may serve as an indicator of soil moisture status in the root zone. When plants are subjected to high levels of moisture stress their reflectance in the near infrared (0.7 - 1.2 μ m) tends to decrease, due to the wilting and deterioration of the plant leaf structure. If stress conditions exceed the plant's tolerance, the plant may die, thereby exposing more of the soil, a process which further lowers the reflectance in the near infrared. Therefore, crop status can be monitored and a general assessment of moisture

conditions can be made. Thompson and Wehlman (1980) discussed the use of Landsat for this purpose.

The use of thermal infrared observations is based on the measurement of the surface or vegetative canopy temperatures. Models have been developed that relate the thermal infrared measurements to soil moisture. Reported results using this method indicate that the basic attributes of remotely sensed observations (ability to survey a relatively large area with high repetition) can be used for obtaining indicators of soil moisture status, but they should be carefully interpreted to allow for differences in meteorological conditions, vegetation and soil types (Blanchard et al., 1974; Idso et al., 1975; Cihlar, 1976; Jackson et al., 1978; Cihlar, 1980; Jackson et al., 1981).

A gamma ray attenuation technique can provide reliable, real-time, areal soil moisture measurements for the upper soil layer if both the background and current uncollided terrestrial gamma count rates and background soil moisture data are available. However, due to radiation sources present in the atmosphere, it is necessary to fly at low altitudes to minimize the counts from extraneous sources. This makes the technique impractical for regions of significant relief. Also, the spatial resolution of the system is twice the aircraft altitude, and at least five seconds of data are required to obtain sufficient counts. With these types of limitations in mind, the gamma ray technique can provide useful areal averages of soil moisture (Carrol, 1981).

Microwave Techniques

Microwave techniques appear to be useful for measuring near surface soil moisture. The rationale for using microwave instruments to measure soil water content is due to the large contrast between the dielectric properties of liquid water and those of dry soil at microwave frequencies. The dielectric constant is a measure of the response of a material to an applied electric field, such as an electromagnetic wave. The large dielectric constant of water results from the fact that it is a polar molecule that is free to rotate along the direction of the applied electric field. The dielectric constant at microwave frequencies is approximately 80 compared to 3 to 5 for dry soils; as a result, the dielectric constant of wet soils can reach 20 or more (Schmugge, 1985).

The strong dependence of the dielectric properties of soils on their moisture content at microwave wavelengths affects the soil reflectivity and emissivity. These quantities can be remotely sensed with active (radar) and passive (radiometry) techniques. With current technology, radiometer observations from space are limited to spatial resolutions on the order of kilometres. Radar, using synthetic aperture technology (SAR), is capable of resolution on the order of meters (Engman, 1990).

Microwave techniques also have the capability of sensing through a moderate amount of vegetative cover, a feature which extends their utility. In particular, by

selecting the right combination of frequency, incidence angle and polarization, it may be possible to observe the backscattering from the canopy alone, or to look through a canopy and observe the condition of the underlying surface. Backscattering from a canopy is dominated by the geometry of leaves, stems and trunks, as well as the moisture content within the canopy. It has been shown (Eos Report, 1989) that higher frequencies at shallow incidence angles will be useful for measurements of biomass, geometry, and moisture of canopies. Lower frequencies at near nadir incidence angles will be used for measurements of the surface boundary layer state. Numerous experiments (Ulaby, 1974; Ulaby, 1975; Blanchard and Chang, 1983; Dobson and Ulaby, 1986; Jackson and O'Neill, 1987; Bruckler et al., 1988) have shown the response of these sensors to be strongly linearly correlated with soil moisture in a layer about 5 cm thick. However, there are several factors which contribute uncertainty to the extraction of soil moisture information from the microwave responses. In addition to vegetative cover, these include surface roughness and shape, soil variability and soil temperature.

Although no purpose-built hydrological satellite has yet been launched, many past and present satellites have yielded data or provided facilities of use in hydrology. Pre-eminent amongst these have been the meteorological satellites (both geostationary and polar-orbiting), the Heat Capacity Mapping Mission (HCMM) and the Landsat series (Barret and Herchy, 1989).

A major problem with the satellites listed above is the inability of the optical and infrared signals to penetrate clouds. Microwave sensors are not limited by this problem, so both passive (radiometers) and active sensors (radars) show a high potential for remote sensing applications. However, these sensors are still in a state of development. Active microwave sensors are able to illuminate a target beneath a cloud cover and to receive scattered signals at any time of day or night. For these reasons, research is being undertaken to understand microwave scattering from various types of targets, and to improve the technical capabilities of existing radar systems.

In the basic operation of a radar, the word radar, being an acronym for a radio detection and ranging system, an active microwave sensor sends out a pulse of microwave energy and then measures the return that is reflected back to it. The intensity of the reflected signal is described by the backscattering coefficient (σ^0) and can be angularly separated from different locations on the ground. Therefore, if the radar is mounted in an aircraft or a satellite, it is possible to produce backscatter images of the ground. Analogous to the optical reflectivity of terrain, the backscattering coefficient describes the scattering properties of the terrain in the direction of the illumination source.

Microwave return from terrain is governed by two sets of parameters: 1) the radar parameters: frequency, incidence angle (look angle), and polarization, and 2) the terrain parameters: complex dielectric properties and surface and subsurface

geometry. Increasing the dielectric constant of a target can cause a change in both the shape and the relative magnitude of the microwave reradiation pattern due to changes in the magnitudes and phases of the reflected signals from the differential facets in the illuminated cell (Ulaby, 1974). In addition, the backscatter of terrain is in part governed by the penetration properties of the terrain at the wavelength used. This thickness will be approximately the same for active and passive systems. However, as stated, in addition to the dependence on soil moisture content, backscatter is a function of the surface (or volume) roughness and the vegetation or snow cover (if not bare).

Radar offers sensitivity to the geometrical characteristics of the Earth's surface and its cover, and to water in all its forms - soil and vegetation moisture, ice, wetlands, oceans, and atmospheric water vapour. As such, microwave remote sensors provide perspectives of the Earth's surface which are of unique value in scientific studies of geomorphology, oceanic waves and topography, atmospheric water vapour and temperatures, vegetation classification and stress, ice types and dynamics, and hydrological characteristics.

Space Based Radar Platforms

Proposals for spaceborne Earth observation SARs were made in the early 1960s, but the first such radar to fly in space was Seasat, launched in June 1978. It operated at a single wavelength (L-Band, 1.275 GHz, 23 cm) with a horizontally

polarized transmitted and received signal (HH polarization), and a fixed viewing angle (incidence angle) of 20° (from nadir). Unfortunately, system failure 99 days after launch severely limited the data produced by the satellite (Lillesand and Kiefer, 1979). The next spaceborne SAR to be launched was the Shuttle Imaging Radar (SIR-A) launched on November 12, 1981 on the space shuttle Columbia. Like Seasat, it carried an L-Band HH polarized radar, with an angle of incidence fixed at 47° . SIR-B was launched on the space shuttle in October, 1984 and was again an L-Band HH polarized SAR, but could mechanically tilt the antenna to achieve variable incidence angles (Carver, 1985).

The next decade will be a very active transition period between the early stage of experimentation with spaceborne microwave sensors and routine application of data from these sensors for geoscientific research. Synthetic aperture radars are at the centre of current developments in remote sensing technology. Most countries involved in spaceborne remote sensing are building or planning satellite SARs.

In July 1991, the European Space Agency (ESA) launched its ERS-1 into a sun-synchronous, near-polar orbit at an altitude of 780 km. The ERS-1 payload includes a C-Band (5.3 GHz) SAR with vertical polarization. The fixed viewing geometry over an 99 km wide image swath results in incidence angles around 23° . The spatial resolution is specified as 30 m. The ERS-1 SAR features two different modes of data collection : a standard image mode and a 'sampled' wave mode. The latter will be used to derive ocean wave direction and wave length from 5 km by 5

km small SAR scenes sampled every 200 to 300 km within the 99 km wide image swath. The SAR operating time is limited by power constraints to a maximum of 10 minutes per orbit. The radar return signals will be processed digitally onboard and transmitted to a series of four receiving stations.

ERS-1 data for parts of Canada are received at the Gatineau Receiving Station near Ottawa. Canadian participation in the ERS-1 experiment will yield valuable experience prior to the launch of the Canadian radar remote sensing satellite, RADARSAT. The ERS-1 mission objectives are both scientific and application oriented in nature. They are to : increase the scientific understanding of coastal zones, global ocean processes and polar ice regions, and to develop and exploit coastal, ocean and ice applications. The satellite is designed for a lifetime of two to three years (Werle, 1988).

Japan is planning to launch its radar satellite, JERS-1 in 1992. The satellite will be in a sun-synchronous, 580 km high orbit. The payload of JERS-1 will be an L-Band SAR with horizontal polarization and a fixed incidence angle of 35°. The image swath will be 75 km with a spatial resolution of 18 m. Like ESA's ERS-1 the Japanese JERS-1 is an experimental satellite. The data will be used for exploration of non-renewable land resources and monitoring of land use, agriculture, forestry, fisheries, disaster monitoring, and surveillance of coastal zones (Ishiwada and Nemoto, 1986).

The United States National Aeronautical and Space Administration (NASA) and the Jet Propulsion Laboratory (JPL) are planning to launch two Space Shuttle missions to conduct the SIR-C experiment in both 1992 and 1993. The SAR will be ferried into a 57° inclined orbit approximately 225 km high. This third Shuttle imaging radar experiment is based on a multifrequency C- and L-Band SAR with a multipolarization capability and a German built X-Band SAR (9.6 GHz) with vertical polarization. The SIR-C allows steering of the antenna beam for data acquisition at incidence angles between 15° and 55°. The swath width will range from 15 km to 90 km depending on the number of simultaneously used frequencies and polarizations. The resolution of SIR-C will be 30 m in low resolution mode and 15 m in high resolution mode. The SIR-C mission represents an important step. It will provide the first opportunity for simultaneously acquired multi-frequency, multi-polarization SAR imagery from space (Werle, 1988).

RADARSAT is a Canadian led cooperative program to launch and operate a satellite with a SAR as its principal sensor. RADARSAT is scheduled for launch in 1994 for a five year mission in a 792 km high, sun-synchronous polar orbit (Shaw, 1989). This time frame positions RADARSAT at the end of the lifetime of ERS-1, JERS-1 and SIR-C. As a result, valuable experience will be accumulated regarding SAR data handling and applications from these previous satellites. The objective of the RADARSAT program is to generate data for both operational applications and for scientific research related to ice, oceans, renewable and non-renewable resources both in Canada and on a global scale.

The RADARSAT SAR will be operating at C-Band with horizontal polarization. The sensor will have the capability to shape and steer the radar beam over a 500 km wide swath which may be extended to include a 300 km wide experimental swath in far range. The incidence angle geometry may vary accordingly between 20° and 49° for the 500 km wide swath, and between 49° and 59° for the experimental swath. This will provide daily coverage of the Canadian Arctic, coverage of the entire Canadian territory within three days and global coverage within 16 days. In addition, the SAR swath can be altered in spatial resolution between 10 and 55 m to the specification of a particular application requirement. The operation of the SAR will be limited to a maximum of 28 minutes per orbit because of power constraints. However, considering the wide accessibility swath, the potential maximum SAR coverage per orbit will be 5.5 million square kilometres (Werle, 1988).

The availability of microwave data in the 1990s from several satellite programs will provide "core" data sets around which an effective Earth observation program may be built. These microwave perspectives of the Earth are also synergistic with those obtained in other portions of the spectrum and will be further exploited in future satellite systems.

Significant progress has been made in the application of microwave remote sensing for measuring soil moisture. However, before soil moisture can be routinely determined with microwave instruments there are several issues which need to

addressed. These include a need to understand more clearly the effects of surface roughness and the vegetation canopy in response to variations in microwave frequency, incidence angle and polarization.

1.2 Research Objectives

Presently, radar research in Canada is conducted using a combination of data from the Canada Centre for Remote Sensing's (CCRS) ground-based scatterometer facility, which is operated at the University of Saskatchewan, and from the CCRS airborne SAR and scatterometers (Brown, 1989).

The purpose of this study is to examine the dependency of the radar backscattering coefficient (σ^0) on soil moisture under various crop types and sensor parameters. More specifically, data acquired by the CCRS ground-based scatterometer will be used to provide answers to the following questions;

- 1) How does radar backscatter (σ^0) vary with frequency (f), polarization, incidence angle (θ), soil moisture (Ms), and plant moisture (Mp) for wheat, canola, and fallow targets?
- 2) How does σ^0 vary with Ms and Mp for all crops combined and can a single linear relationship be used to estimate Ms from σ^0 ?

and finally to,

- 3) evaluate the results of the first two objectives in regards to potential soil moisture applications of ERS-1, RADARSAT and JERS-1.

This study is limited to evaluating the radar frequency and polarization parameters being proposed for ERS-1, RADARSAT, and JERS-1 at incidence angles of 20°, 40° and 60° in relation to data acquired at the University of Saskatchewan Kernan Crop Research Farm with, or in support of, the CCRS ground-based microwave scatterometer, over the 1988 growing season.

1.3 Research Methods

Remote sensing measurements are typically used either to determine what a target is, or to determine the value of some parameter associated with a known target. These two objectives have led to the development of different empirical study approaches. The two most common approaches are the separability and the correlation type studies. Although the two approaches are not unrelated, many previous studies seem to follow one approach only (Sheppard, 1987).

In order to determine the identity of a target, it is necessary to employ a sensor system which can differentiate between the target types which could be expected to be present. By using statistical separability measures, one can determine

the sensor system best suited to a particular application. It is reasonable to assume that the sensor system which best separates various types of targets will provide the least error in subsequent target classification. Examples of measures of statistical separability include; differences in class means relative to standard deviation (Mentha, 1984), divergence measures (Goodenough et al., 1978), and Jeffries-Matusita distance (Waker, 1971).

In other instances, the aim has been to experiment with different types of remote sensing systems in order to identify those which provide a high correlation between system measurements and the values of the target parameter of interest. This can be an effective way to determine the best sensor system to use for a specific measurement; however, results can be confused by the presence of uncontrolled variables and must be carefully interpreted using ancillary information. This approach has been used by a number of researchers to study the relationship between radar backscatter and soil moisture (Ulaby, 1974, LeToan and Pausader, 1981, Dobson and Ulaby, 1986).

This study will use the correlation approach to determine the strength of the relationship between radar backscatter and soil moisture using system parameters similar to ERS-1, RADARSAT, and JERS-1. The linear regression model was the statistical technique selected for this analysis. The selection was based on past research that has shown that for a given soil condition (roughness or texture), radar backscatter is linearly dependent upon soil moisture content in the upper 2 to 5 cm

of soil and to have correlation coefficients typically on the order of 0.9 (Dobson and Ulaby, 1986; Engman, 1990).

The linear correlation coefficient will be computed between radar backscatter (σ^0) C-HH, C-VV and L-HH and soil and plant moisture for incidence angles of 20, 40, and 60 degrees on wheat, canola, and fallow fields. Similarly, the linear correlation coefficient will be calculated between each set of radar parameters and soil and plant moisture for all crops combined to determine if a single algorithm would be suitable for the estimation of soil moisture. The results will be evaluated based on the strength of the relationship, the sensitivity of σ^0 to changes in soil and plant moisture and existing literature. Lastly, based on the results of the first two objectives, the utility of ERS-1, RADARSAT, and JERS-1 data for soil moisture estimation will be assessed.

1.4 Thesis Organization

Chapter One has introduced remote sensing techniques for the estimation of soil moisture and has outlined the purpose of the thesis and the research approach adopted. Chapter Two will discuss in detail radar remote sensing and the nature of radar backscatter from terrain. The experimental design, including a description of the radar, ground observations and statistical approach will be presented in Chapter Three. Statistical analysis and results will be detailed in Chapter Four. Finally, conclusions and directions for future research will be discussed.

Chapter Two

Radar Remote Sensing

2.1 Principles of Radar Remote Sensing

Microwave Spectrum

The microwave spectrum which has been used for remote sensing extends from about 500 MHz to 100 GHz. Table 1.0 lists some of the common frequencies and their letter codes. At frequencies above 20 GHz, microwave signals passing through the Earth's atmosphere are significantly attenuated due to absorption by water and oxygen molecules. The exact shape of the attenuation profile depends on the distribution of atmospheric water vapour. The attenuation peak near 22 GHz is the pressure broadened absorption line due to atmospheric water vapour and that near 60 GHz is a broadened complex O₂ absorption line (Carver et al., 1985).

The frequency range between 1 and 20 GHz has been used primarily for radar remote sensing of the Earth's land and ocean surface, due in part to the low attenuation of the atmosphere and in part to naturally enhanced sensitivities in this frequency range to such surface features as soil moisture and ocean capillary waves (Carver et al., 1985). Frequencies above 20 GHz have been used primarily for spaceborne sensing of atmospheric water vapour, oxygen, and temperature.

Band Designation	Wavelength (λ) (cm)	Frequency (GHz)
K	1.1 - 1.67	26.5 - 18
X	2.4 - 3.75	12.5 - 8
C	3.75 - 7.5	8 - 4
S	7.5 - 15	4 - 2
L	15 - 30	2 - 1

Table 1.0 Radar Band Designations (Lillesand and Kiefer, 1979)

Radar Types

Radars used in remote sensing fall into three categories - imaging radars, scatterometers, and altimeters. Although these radars measure different features of a target, their basic operation is the same. For most remote sensing applications, the imaging radar, usually a Side-Looking Airborne Radar (SLAR) or a SAR is used to produce an image of the target. On the other hand, the scatterometer and the altimeter are nonimaging radars, and are used to measure specific properties. The altimeter is primarily used for accurate measurements of range to the earth's surface, usually the ocean surface, from a satellite. If the altimeter is calibrated in amplitude, it could be used as a scatterometer, which measures the absolute backscattered signal intensity from a target. For remote sensing purposes, the scatterometer can

be used as an operational tool for measuring wind speeds at sea, and is widely used in studying the characteristics of the radar return for radar design and analysis purposes (Ulaby et al., 1982).

2.2 Radar Backscatter

Backscattering Principles

The radar cross section of a point target such as an aircraft, building, truck, etc., is a measure of its effective area in scattering an incident wave in some given direction, and has units of square meters. The radar cross section is an angularly dependent function whose shape can be thought of as the antenna pattern of a point target for a given illumination angle. When the scattering angle is equal to the illumination angle, the signal is said to be backscattered (Carver et al., 1985).

Radar remote sensing deals principally with area-extensive targets such as terrain or sea surfaces instead of individual point targets. The intensity of the backscattered signals from area-extensive targets is measured in terms of the radar backscattering coefficient (σ^0), which is defined to be the radar cross section of the distributed target per unit area. The backscattering coefficient (σ^0) is a dimensionless quantity which actually has the units of square meters per square meters.

The range of measurable backscatter intensity levels in a radar scene is enormous compared to other remote sensing devices. The human eye, for instance, can only discern approximately 40 different grey levels. Photographic film, or computer compatible tapes for Landsat data are capable of recording a larger, but still limited number of intensity levels, i.e. 256 different intensities of grey tone. A radar system is capable of differentiating backscatter intensities on the order of ten thousand to a hundred thousand levels (Ulaby et al., 1982). Because of the wide range involved, the intensity of a radar scene is generally considered in units of decibels (dB), defined as

$$\text{dB} = 10 \log (I_1 / I_2)$$

where I_1 and I_2 are maximum and minimum intensity (power) levels. The dynamic range of radar backscatter values within a scene may vary from very weak and low intensity, for example a calm water surface, to very strong returns and high intensity, such as from corner reflections.

Microwave backscatter from terrain is governed by two sets of parameters: 1) radar parameters: frequency, look angle, and polarization, and 2) terrain parameters: complex dielectric properties and surface and subsurface geometry. When a microwave is incident upon the surface of the terrain, part of its power is scattered back into the air medium by the surface, and the remainder is transmitted across the boundary into the terrain. The component backscattered by the surface

is referred to as the surface scattering contribution. If the terrain is spatially inhomogeneous, volume scattering can take place, and the component backscattered across the boundary toward the radar is referred to as the volume scattering contribution (Ulaby, 1982).

Surface scattering is due to the dielectric discontinuity at the interface between two media such as air and soil. An incident wave is scattered by a surface in many directions. The rougher a surface is, the broader the scattering pattern will be. Surface roughness is usually characterized by two parameters: 1) standard deviation of surface height (or root mean square (rms) height); and 2) surface correlation length (periodicity of the surface), both measured in wavelength units. Therefore, a surface may be made to appear rough by the radar by increasing the rms height, decreasing the correlation length, or operating at a shorter wavelength (Ulaby, 1982).

Microwave Penetration Depth

To model the scattering behaviour of a terrain class such as snow or soil, one must determine the vertical extent (in the medium) of the region responsible for the majority of the backscattered energy. This is referred to as the penetration depth, which is defined as the depth below the surface at which the magnitude of the power of the transmitted wave is equal to $1/e$ of the power of the transmitted wave at a point beneath the surface (Ulaby, 1982).

In the microwave region, the two most important parameters governing the penetration depth are wavelength and the dielectric constant, which has a strong dependence on water content. The dielectric properties of a material are characterized by its dielectric constant (ϵ) which is split into two fractions described by the real (dielectric permittivity, ϵ') and imaginary (loss factor, ϵ'') parts. The real (ϵ') determines the propagation characteristics of the wave, i.e., its velocity and thus its wavelength in the material. The imaginary (ϵ'') determines the energy losses or absorption as the wave travels through the material. Thus;

$$\epsilon = \epsilon' + j \epsilon''$$

where $j = (\sqrt{-1})$. The square root of ϵ determines the index of refraction for the material (Schmugge, 1985).

Therefore, the penetration depth is determined by the absorption and scattering losses in the medium, but in most cases the loss due to absorption dominates. With very few exceptions, the microwave dielectric permittivity (ϵ') of dry material falls in the range between 1.2 and 6, and the loss factor (ϵ'') is seldom larger than 0.1. This means that the penetration depth in dry materials is at least a few wavelengths long. Increasing the liquid water content of a medium results in an exponential-like decrease of the penetration depth (Ulaby, 1982).

Volume scattering is caused by the spatial inhomogeneity in a volume at a scale comparable to that of the wavelength of the incident wave. Examples of volume scattering include ice crystals in snow and plants in a vegetation canopy (Ulaby, 1982). The relevance of which is outlined below.

In general, the following trends are observed as the radar frequency is increased from 1 to 35 GHz:

- 1) The penetration depth in a material medium decreases with increasing frequency.
- 2) The scale of surface roughness increases with increasing frequency, leading to a weaker dependence of backscatter on the angle of incidence.
- 3) Inclusions in a volume (such as leaves in a canopy) increase in size relative to wavelength. This leads to the greater importance of diffuse (or multiple) scattering within the volume with increasing frequency, because the scattering pattern of an individual scatterer becomes more directional as the relative size of the scatterer increases.

Backscatter from Bare Soil

Depending on the wavelength, soils with similar moisture contents but with different surface roughness characteristics can display a range of backscatter values.

Smooth surfaces behave as specular reflectors and therefore only have strong backscatter when the incidence angle is near zero. Rough surfaces, on the other hand, behave as isotropic scatterers and thus there is minimal angular variation. The variations of backscatter with soil moisture, surface roughness, incidence angle, and observation frequency have been studied extensively in ground-based experiments at the University of Kansas, using a truck-mounted active microwave system operating from 1 to 18 GHz. The results indicate that the effects of surface roughness can best be reduced by using a system operating at 4 - 5 GHz (C-Band), at incidence angles of 7° - 17° from nadir, with horizontal transmit and horizontal receive polarization (HH) (Ulaby et. al., 1978).

Agricultural crops are generally planted in parallel rows in either a rectangular format or in concentric rings (as is the case of some centre pivot irrigation systems). Soil tillage is also conducted by parallel operations using farm implements which typically produce nonrandom and periodic ridge/furrow boundary conditions that modulate the small scale and isotropic roughness components. The periodic components of surface roughness are of particular interest in the soil moisture estimation problem because they have been observed to exert a considerable angular effect on radar backscattering (Dobson and Ulaby, 1986). Radar view angles orthogonal to row directions typically yield higher levels of backscattering than view angles parallel to row direction. Observations of agricultural fields with truck-mounted and airborne scatterometers, and on Seasat imagery suggest that radar is most sensitive to azimuthal viewing geometry for angles within

15° of orthogonal to the row direction. In addition, this sensitivity decreases in an exponential fashion as the view angle becomes parallel to the row direction. However, this response is unique to the combination of effects from the frequency, incidence angle, row spacing and row height (Blanchard et al., 1981).

In addition to surface roughness, the effects of soil texture on the microwave response to moisture have been observed. Schmugge (1980) observed a difference in sensitivity in a study of the effects of texture on passive microwave response to soil moisture. To incorporate soil texture in the microwave response to soil moisture, the latter parameter was expressed in terms of percent of field capacity. Although Schmugge (1980) reported that the dependence of backscatter on soil texture can be removed by expressing moisture content in percent of field capacity, additional experiments that cover a wide range of soil textures are needed.

The relationship between radar response and soil moisture content for the soil surface component depends on the dielectric contrast across the air/soil interface. However, one must also consider the depth of a soil profile that should be used to determine the dielectric properties of the soil (penetration depth). In most studies on microwave measurements on bare soils, experimental relationships between soil moisture content and radar backscatter were conducted using mean volumetric water content measured from the soil surface to a depth of 5 or 10 cm. In fact, the shape of the water content profile in this surface layer varies widely under natural conditions. If there is wide variation over an interval of one wavelength, correct

evaluation of the reflection coefficient necessitates accurate knowledge of the moisture profile at depth intervals on the order of $0.1 \lambda_m$, where λ_m is the wavelength in the soil medium (Ulaby and Batlivala, 1976).

In general, dry conditions generally result in large soil penetration depths, and as a result, taking into account a shallow soil profile in determining the soil dielectric properties may introduce significant errors. Wet soil conditions generally result in very shallow microwave penetration depths, and thus, taking into account a large soil profile is probably unsatisfactory, particularly if a large water gradient exists (Bruckler et al., 1988).

Radar Backscatter From Vegetated Soil

Remotely sensing soil moisture beneath a vegetation canopy has been the subject of keen interest and experimental attention for a number of years (Dobson and Ulaby, 1986). The early work, based on ground scatterometer measurements, sought to identify those sensor combinations of frequency and angle of incidence least sensitive to the presence of agricultural canopies. These studies concluded that the optimum parameters for moisture sensing should be frequencies of less than 6 GHz and angles of incidence of less than 20° , in order to minimize both direct backscattering by the vegetation and the effective attenuation loss related to the two-way transmission through the canopy (Ulaby, 1975).

Ulaby et al. (1979), in their discussion of the effects of vegetation attenuation on radar response to soil moisture proposed the following model;

$$\sigma^0 = \sigma_{\text{v}}^0 + \sigma_{\text{s}}^0 e^{-2}$$

in which the observed backscatter is assumed to consist of two components: backscatter by the vegetation (σ_{v}^0) and backscatter from the underlying soil surface (σ_{s}^0) (or volume). The latter is attenuated by the vegetation according to e^{-2} . The attenuation is in general a function of the vegetation parameters (plant height, density, water content, and shape) and the radar parameters. Although experiments have been conducted to measure the attenuation properties of vegetation canopies, the results can be only used on a qualitative basis due to the poor precision associated with the measurements (Ulaby et al., 1979).

Subsequent investigations have proposed that radar backscatter from a vegetated soil surface actually consists of three components, these being the soil surface component, the vegetation component as previously described, and a surface/vegetation interaction component (Dobson and Ulaby, 1986). This interaction term is thought to become significant for sensor configurations for which the transmission loss is small and when there is significant scattering from either the vegetation volume or the soil surface (Dobson and Ulaby, 1986).

For example, we can think of the target consisting of a scattering volume (vegetation) bounded on the top side by the canopy/air interface and on the bottom side by the soil/air interface. When energy from the radar enters the volume, both single and multiple scattering (depending on vegetation density) takes place. If the vegetation density is relatively low, a portion of the incident wave will reach the soil/air interface. When this interface is dry, the efficiency with which the energy is directed back to the radar is low. Therefore, in dry soil conditions very little energy that reaches the air/soil interface is actually backscattered. However, under wet soil conditions the target consists of a scattering volume bounded on one side by the canopy/air interface and the other side by a reflective wet soil/air interface. Therefore, energy that reaches the wet soil/air interface is backscattered toward the radar receiver. As a result, this interaction enhances the radar's sensitivity to changes in soil moisture.

Analysis of scatterometer data have generally ignored the contribution of the interaction term and have sought to define the remaining model coefficients based upon multifrequency and multiangle curve-fitting solutions for single target observations, or have sought to define crop averages for the vegetation term and loss over a growing season. In general, the studies conducted to date show that:

- 1) both the canopy loss and the vegetation volume scattering coefficient are linked to the canopy's biophysical properties, and especially, but not exclusively, to canopy type, canopy structure, and the water volume fraction within the canopy;

- 2) the canopy loss and the volume scattering coefficient increase with frequency;
- 3) the vegetation term tends to dominate the net return as either frequency or incidence angle increase; and
- 4) the interaction term functions to enhance radar sensitivity to the moisture contained in the soil beneath a vegetation canopy (Dobson and Ulaby, 1986).

2.3 Soil Moisture Retrieval

Backscatter Prediction/Regression Models

The main objectives of the scatterometer studies previously described are to model the radar backscatter for the prediction of σ^0 for a given set of geometrical and dielectric parameters and the development of schemes for the solution of the inverse scattering problem e.g., the estimation of target parameters from measured values of σ^0 (Attema, 1978).

Several prediction models have been proposed in the literature, ranging from very crude to very refined theoretical approaches. In order to satisfy the objective of estimating target parameters from σ^0 , which is the most important from an applications point of view, most of the effort has been devoted to the development of prediction models that only involve a few predominant target properties. These

models will hopefully facilitate the solution of the inverse scattering problem with respect to these predominant target properties.

Prediction models for σ^0 can be divided into two major categories, these being theoretical and empirical models. Empirical models are not necessarily based on any physical hypothesis for the scattering mechanism involved. They are given in the form of a functional relationship for σ^0 as a function of frequency, polarization, incidence angle and target parameters. The proposed functions usually need to be determined by regression analysis of radar signature data (Attema, 1978).

In view of the application to remote sensing it is preferable to limit the number of these parameters. A very simple and attractive model for soil moisture estimation from bare fields was developed at the University of Kansas using their truck-mounted scatterometer system. For a given soil condition (roughness or texture), radar backscattering was found to be linearly dependent upon the volumetric soil moisture (M_{sv}) in the upper 2 to 5 cm of soil and to have correlation coefficients typically in the order of 0.9 (Ulaby, 1975).

$$\sigma^0(\text{dB}) = A + B M_{sv}$$

For a given sensor combination of frequency, polarization, and angle of incidence, the empirically derived regression coefficients A and B were found to be dependent upon soil surface roughness and soil texture, wherein A is primarily

controlled by surface roughness and B is primarily controlled by soil texture. For the prairie mollisols examined in the Kansas studies, polarization had no statistically discernible effect on the sensitivity term B. Both combinations of like polarizations (HH and VV) yielded equivalent A, whereas cross-polarization (HV) produced substantially lower values of A. In addition, the sensitivity term B was observed to be dependent upon both frequency and angle of incidence, gently decreasing with either increasing frequency or angle of incidence (Dobson and Ulaby, 1986).

Subsequent studies by independent groups using ground-based scatterometers in the United States, France and Japan have verified many of these results (Bruckler et al., 1988, Le Toan and Pausader, 1981). However, the results obtained by Hirosawa et al. (1978), based on 9 GHz observations of Kanto loam represent an exception; they found that the cross-polarized sensitivity to near surface soil moisture was four times that of the like polarized backscattering. This result was attributed to the effects of multiple surface scattering. However, a similar effect has not been observed for very rough mollisols (Dobson and Ulaby, 1986).

Unfortunately, the prediction of σ^0 in general is far more complex and requires multiple linear regression equations involving many parameters. Still, these rather simple linear regression models can be useful for radar backscatter interpretation purposes. However, some care should be taken in the general application of these models, since they have been derived at a limited number of sites for a limited number of observations, and the statistical significance of the

model parameters is not always clear, nor is the physical basis of the functional relationships (Attema, 1978).

In order to provide a theoretical basis for empirical models and to gain insight into the scattering process involved in the radar response of the target, it would be desirable to have adequate theoretical models available. However, the development of such models is hampered by difficulties in defining the target mathematically. Therefore the real targets are usually approximated by another physical structure for which the electromagnetic scattering problem can be solved. Examples of such models include Peake's (1959) and Fung and Ulaby's (1977). However, both models neglect the effect of the soil and are therefore limited to very dense vegetation.

In another approach, taken by Attema and Ulaby (1978), vegetation is represented by a cloud of scatterers, randomly distributed throughout the vegetation layer covering the soil. The soil reflection is assumed to be proportional to the soil moisture and the particle density is chosen to be proportional to the volumetric water content of the vegetation layer. A further input parameter is plant height. The model also involves three parameters that were determined empirically using non-linear regression analysis of measured signature data. The model facilitates the evaluation of the relative importance of the soil reflection to the total backscattered power. This model has been successfully applied to measurements made in the 8 to 18 GHz frequency range including HH and VV polarizations and crop types of

alfalfa, corn, milo and wheat.

The studies described thus far have shown that by using a certain combination of frequency, polarization and incidence angle, one can minimize the effects of surface roughness and vegetation for certain classes of vegetation on radar backscatter. A more robust approach would make use of multiple angles, frequencies, and polarizations to predict the backscatter contributions of the vegetation, soil and interactive terms (Eos Report, 1989). However, the value of a remote sensing system is not restricted to producing a single, one-time soil moisture map, but is also in providing the temporal information that can be derived from a frequent series of these observations (Jackson and O'Neill, 1987, Brisco et al., 1983).

Backscatter Prediction/Change Detection

A second approach to soil moisture involves the use of change detection. This approach does not require "multi" radar parameter data except in the time domain. It assumes that target variables, other than soil moisture, exhibit negligible change over short time increments (for a given resolution element) and fixed viewing geometry. Therefore, changes in backscatter can be attributed to changes in soil moisture. The foregoing assumption is generally true, except during tillage operations, periods of rapid foliage development, and harvest of crops (Eos Report, 1989).

Microwave techniques can be used to estimate soil moisture for soil depths of 5 - 10 cm. However, this depth is too shallow since the root zone for many plants is a 1- 2 m zone. Jackson (1980) proposed a method for estimating profile soil moisture from surface measurements. He assumed that, at some time during the day, the hydraulic potential would be near enough to equilibrium so that the water content profile could be calculated from a knowledge of the water characteristic and the surface moisture content. Using a simulation model to calculate the profiles for several soil textures he produced error bounds for various surface layer thicknesses, time of day, and conditions of rainfall and evaporation. He found that if the water content of the surface 10 cm is known, the average water content in the 0.1 - 1 m layer could be estimated with a standard error of 0.04 cm^3 . These optimum results were obtained using the surface water contents measured before dawn when the moisture profile most closely approximated the hydraulic equilibrium assumption.

This chapter has discussed principles of radar remote sensing and the nature of radar backscatter from bare and vegetated soil. Finally prediction models for the estimation of soil moisture from radar data were introduced. This study will adopt the linear regression model to determine the correlation between radar backscatter and target moisture. This selection is based on past research that has shown that for a given soil condition, radar backscatter is linearly dependent upon soil moisture in the upper 2 to 5 cm of soil and to have correlation coefficients typically on the order of 0.9.

Chapter Three

Data Collection and Methodology

3.1 Data Acquisition

Test Site

Scatterometer and target description data were collected on test plots, devoted to the Ground Microwave Operations (GMO) project, situated at the University of Saskatchewan Kernan Crop Research Farm a few kilometres east of Saskatoon (Appendex A). The soils for all of the plots are from the Sutherland Association (specifically, the dominant soil being from the Orthic Dark Brown Sutherland series). The period of May to September of 1987 marked the first full growing season for data collection, with data collection continuing during the 1988 and 1989 growing seasons. Data collected during the 1988 season were made available by CCRS for this analysis.

There is a meteorology station operated by the Saskatchewan Research Council (SRC) located approximately six kilometres to the west of the Kernan Farm. Drought conditions occurred in the Canadian prairies in 1988. During the 1988 radar data collection season (June to August), 148.9 mm of precipitation were recorded for the study site.

Microwave Data

The CCRS ground-based scatterometer was acquired in 1985 as an updated version of the scatterometer used extensively at the Remote Sensing Laboratory of the University of Kansas (Appendix B). The system comprises three microwave scatterometers operating in L (1.5 GHz), C (5.17 GHz) and Ku (12.8 GHz) frequency bands, each collecting data in four polarizations (HH, HV, VH, VV). Along with a television camera these are mounted on a hinged-arm hydraulic boom supported on the flat bed of a 5 ton truck. The radars are attached to a positioner, whose inclination angle can be set either manually or by computer; as a result, the incidence angle of the radar beams on a target field can be set for any desired sequence of values from 0° to 80°. The radar operating mode, the positioner angle and the data lines from the three radars are controlled by the combination of a personal computer and a data acquisition unit.

The system is externally calibrated by observing corner reflectors, which have a known radar cross section, and thus provides absolute measurements of radar backscattering coefficients. By moving the truck during data acquisition a large number of independent samples are collected and then averaged to reduce the signal scintillation inherent in active microwave measurements. The field data are initially written directly on to floppy diskettes and subsequently sorted and transferred to VAX compatible digital tapes for storage and analysis (Brisco et al., 1988, Sofko et al., 1989).

As the scope of this study is limited to addressing the radar parameters being proposed for ERS-1, RADARSAT and JERS-1, only a portion of the data set will be analyzed. This will include the C-HH, C-VV and L-HH at incidence angles of 20, 40 and 60 degrees, looking parallel to the row direction, on wheat, canola and fallow field plots. In order to increase the number of observations for statistical analysis, two wheat plots (plot identification numbers 1 and 12) were combined for a total of 38 collection dates. Three canola plots (plots 2, 5, 23) were combined to comprise 16 data collection dates. Data on 11 collection dates were obtained on a single fallow plot (plot 4).

Ground Truthing

While the radar measurements were being collected, independent non-radar measurements or 'ground truthing' was also being performed on the crops (Oliver et al., 1989). 'Ground truthing' provides directly sampled information about the characteristics of the radar target through either destructive or non-destructive sampling. Basically the ground truthing procedures were derived from a review article by Cihlar et al. (1987) and an Agriculture Canada manual by King and Mack (1984). As with the radar observations the ground truth measurements are the average of a number of independent samples collected over the target area. Photographs of the target were also taken at the time of the radar data collection. In addition, agricultural data which are constant or need to be recorded once throughout the growing season were collected, including : seeding dates, seeding

rates, fertilizer rates, spraying dates and chemicals, and yield.

As the research objective of this thesis is to examine the dependency of radar backscatter on soil moisture, only soil and plant moisture data will be used in this analysis. The rationale for the choice of these data being that soil moisture may be estimated using radar data by either direct observation of the soil or by indirect observation of plant moisture, which would provide an indication of soil moisture status.

To determine the plant moisture content a sample of five to ten plants were placed in a plastic bag, weighed and then dried in an oven at 80° C for two days. After the drying period, the bags were closed to prevent moisture absorption from the air and weighed again. Only a few samples were weighed at a time to reduce further the possibility that dried samples would absorb moisture before they could be weighed. The moisture content was then calculated using

$$\text{percent plant moisture content} = \frac{(\text{wet weight} - \text{dry weight})}{\text{dry weight}} \times 100.$$

In order to determine soil moisture, eight samples of the top 5 cm of soil were collected per plot. The soil samples were all placed into a plastic bag and tied to prevent moisture loss. Wet soil samples were placed in pre-weighed tins, weighed, and placed in an oven for two days at 110° C. Once the drying period was completed,

the lids for the drying tins were replaced to prevent the dried samples from absorbing moisture from the air, and re-weighed to obtain dry mass data. The difference between the wet and dry weights was then used to calculate the gravimetric moisture content, which is defined as the weight of water in the soil divided by the dry weight of the soil.

$$\text{percent soil moisture content} = \frac{(\text{wet weight} - \text{dry weight})}{\text{dry weight}} \times 100$$

3.2 Temporal Observations

Soil and Plant Moisture

Temporal soil moisture data for the fallow plot are shown in Figure 1. The fallow plot soil moisture varied between 8.4% and 23.43% having a mean and standard deviation of 15.47% +/- 4.65%.

Soil and plant moisture data for a typical wheat field (Plot 1) over the course of the growing season are presented in Figure 2. For the total combined wheat sample the surface soil moisture varied between 6.84% and 32.18% with a mean and standard deviation of 15.38% +/- 6.56%. The wheat reached a height of 0.42 m during the experiment with plant moisture decreasing as the plant matured. Wheat

Figure 1 Fallow Temporal Moisture Observations

Figure 2 Wheat Temporal Moisture Observations

Figure 3 Canola Temporal Moisture Observations

plant moisture changed from a maximum of 76.5% during the early part of the season to a minimum of 8.83% obtained at the end of the season.

Soil and plant moisture data for a canola field (Plot 5) during the experiment are presented in Figure 3. Soil moisture on the combined canola plots varied between 8.56% and 26.91% with a mean and standard deviation of $13.92\% \pm 5.87\%$. The canola grew to a height of 0.5 m and, as with the wheat observations, plant moisture decreased as the plant matured. The data show a significant decrease in canola plant moisture in the final ripening stage (senescent stage) preceding harvest.

Radar

Figures 4 to 12 present the temporal C-HH, C-VV and L-HH radar data collected at incidence angles of 20°, 40° and 60° for fallow, wheat and canola plots respectively. While overall trends are noticeable, it is evident that detailed visual comparison of the variations in the scattering coefficient and the variations in target parameters is a difficult task. Therefore statistical techniques are required to evaluate the relationships.

3.3 Statistical Procedures

The linear regression model was the statistical technique selected for this analysis. The selection was based on past research that has shown that for a given soil condition (roughness or texture), radar backscatter is linearly dependent upon soil moisture content in the upper 2 to 5 cm of soil and to have correlation coefficients typically in the order of 0.9 (Dobson and Ulaby, 1986, Engman, 1990).

The linear model relating radar parameters to a targetparameter can be written as

$$y = a + bx$$

where y is a measurement of the radar parameter (σ^0 , expressed in dB), and x is a

Figure 4 Fallow Temporal C-HH Radar Backscatter

Figure 5 Fallow Temporal C-VV Radar Backscatter

Figure 6 Fallow Temporal L-HH Radar Backscatter

measurement of the target parameter (% moisture). The constant b describes the sensitivity (or linear rate of change) between the radar measurement (σ^0 (dB)) and the target parameter (% moisture), the constant a is the scaling factor or intercept of the y parameter.

In most applications, sensitivity (b) is of more interest than scaling (a) as it represents the slope of the regression line, namely, the change (increase or decrease) in the variable to be predicted, in this case σ^0 (dB), which corresponds to an increase in one unit of x , namely % moisture. On the other hand, a represents the y intercept, namely, the value of y which corresponds to $x = 0$ (Freud, 1967).

Figure 7 Wheat Temporal C-HH Radar Backscatter

Figure 8 Wheat Temporal C-VV Radar Backscatter

Figure 9 Wheat Temporal L-HH Radar Backscatter

In a general model, the radar measurements are treated as dependent variables because their values depend on the target parameters. The most accurate linear model is obtained through the least squares criterion to estimate b . The estimate of b is selected such that the sum of the square error (y predicted and y observed) in the model is a minimum. The use of the linear regression model requires that the conditional distributions of the residuals (y predicted - y observed for every value of x) be normally distributed.

The most widely used measure of the strength of a linear relationship between two variables is the correlation coefficient (R) (Freund, 1967). It indicates the goodness of the fit of a line fitted by the method of least squares and this, in

Figure 10 Canola Temporal C-HH Radar Backscatter

Figure 11 Canola Temporal C-VV Radar Backscatter

Figure 12 Canola Temporal L-HH Radar Backscatter

turn, tells us whether or not it is reasonable to say that there exists a linear relationship (correlation) between x and y . If R is close to 0, the fit is poor, and the relationship is very weak or nonexistent. If R is close to +1 or -1, the fit is good and this is indicative of a strong linear relationship between x and y .

The significance of a proposed model can be checked by a variety of methods. Two common significance tests are the F- and t-tests. The F-test can be used to test the hypothesis that all the coefficients in the model are zero except for the intercept. When F is calculated, the value is compared to a tabulated value, which indicates the minimum value of F required for the equation to be significant. The t-test tests the hypothesis that the regression coefficient is zero. As with the F-test, the value

of t is compared with a corresponding value in a table.

Chapter Four

Analysis and Discussion

4.1 Analysis

The linear correlation coefficient (R) was computed between σ^0 C-HH, C-VV and L-HH (which will be referred to as R_{C-HH} , R_{C-VV} , and R_{L-HH} respectively) and soil moisture for incidence angles of 20, 40, and 60 degrees on fallow, wheat and canola fields. Similarly, the correlation coefficient between the above radar parameters and plant moisture was calculated for the wheat and canola targets. In addition, the linear correlation coefficient was calculated between each set of radar parameters and soil, and plant moisture for all targets combined to determine if a single model could be developed for the estimation of soil moisture.

The residuals for the wheat and combined targets regressions were tested for normality using a Chi Square test. There were insufficient observations to test the distributions for the fallow or canola targets. The Chi Square analysis indicated that approximately 70% of the regressions computed met the requirement of a normal distribution of residuals. In addition, Spearman's rank correlation coefficients were calculated using the data for each of the described linear regressions. The rank correlation approach has the advantage of not requiring normal residual distributions. However, the rank correlation entails some loss of information,

including scaling and sensitivity. As the correlation coefficients computed using linear regression or rank correlation did not differ significantly, the analysis continued using the linear regression model.

A t-test was used to test the significance of the relationship between σ^0 and the target parameter under investigation. In all cases the results were significant at a level of .005, or greater.

4.1.1 Fallow

Correlation coefficients between radar backscatter and soil moisture for the fallow target data (11 observations) shown in figures 13, 15 and 17 show a similar general pattern. Both the C-HH and C-VV data on the fallow targets displayed similar correlations with soil moisture of approximately 0.47 at an incidence angle of 20°. At an incidence angle of 40°, the C-HH correlation remained relatively constant. The C-VV correlation at 40° increased slightly to 0.57. At an incidence angle of 60° both R_{C-HH} and R_{C-VV} displayed a marked decrease.

The L-HH data acquired at incidence angles of 20° and 40° had slightly higher correlations with soil moisture than the C-Band data. The R_{L-HH} also displayed a similar trend as the C-VV data having an increase in R_{L-HH} from 0.58 at 20° to 0.74 at 40°. As with the C-Band data, R_{L-HH} decreased at 60°.

Figure 13 Fallow C-HH Correlation Coefficients

Figure 14 Fallow C-HH Moisture Sensitivity

Figure 15 Fallow C-VV Correlation Coefficients

Figure 16 Fallow C-VV Moisture Sensitivity

Figure 17 Fallow L-HH Correlation Coefficients

Figure 18 Fallow L-HH Moisture Sensitivity

The sensitivity (slope of the linear regression model, b) of the radar data to changes in soil moisture ($\sigma^0(\text{dB})/\%\text{moisture}$) are shown in figures 14, 16 and 18. These figures illustrate the increase in radar backscatter, measured in dB, for a 1% increase in target moisture. At 20° , the C-HH, C-VV and L-HH data all had similar sensitivities. Both the L-HH and C-HH data displayed a decrease in sensitivity as the incidence angle was increased from 20° to 60° . However, the C-HH sensitivity did not decrease as rapidly as the L-HH having slightly greater sensitivities at 40° and 60° . The C-VV data had a slight increase in sensitivity at 40° and decreased to a rate similar to the C-HH observations at 60° .

4.1.2 Wheat

Correlation coefficients between radar backscatter and soil and plant moisture for the wheat target (38 observations) are shown in figures 19, 21 and 23. The C-HH and C-VV backscatter correlations displayed similar trends in regards to both soil and plant moisture. Each C-Band polarization had correlations with soil moisture of approximately 0.36 at 20° , increased at 40° to 0.45 and had a more pronounced decrease at 60° to approximately 0.22. Plant moisture correlations for both polarizations were greater than soil moisture correlations at 20° and 60° but at 40° , the correlations were approximately the same.

Figure 19 Wheat C-HH Correlation Coefficients

Figure 20 Wheat C-HH Moisture Sensitivity

Figure 21 Wheat C-VV Correlation Coefficients

Figure 22 Wheat C-VV Moisture Sensitivity

Figure 23 Wheat L-HH Correlation Coefficients

Figure 24 Wheat L-HH Moisture Sensitivity

As the frequency is decreased to L-Band, the microwave penetration in a material increases. As a result, the L-HH data had greater penetration through the wheat canopy and displayed higher correlations with soil moisture than the C-Band data at an incidence angle of 20° ($R_{L-HH} = 0.77$). At 20° and 40° R_{L-HH} for plant moisture was close to zero. At 40°, R_{L-HH} for soil moisture was similar to that for the C-Band data and at 60° R_{L-HH} was similar to the C-Band data for both the soil and plant moisture.

The sensitivities of the radar data to the wheat target soil and plant moisture are shown in figures 20, 22 and 24. Again, both C-Band polarizations followed similar trends of decreasing sensitivity to soil and plant moisture with increasing angle of incidence. The L-Band data shows a large decrease in sensitivity to soil moisture as the angle of incidence is increased from 20° to 40° and a smaller decrease from 40° to 60°. Plant moisture sensitivity was close to zero over the 20° to 60° incidence angle range for the L-Band observations.

In general, at incidence angles of 20° and 40°, the correlation coefficients between σ^0 and soil moisture were slightly less than those obtained on the fallow plots. The exception were the L-HH observations which had a higher correlation with soil moisture at 20° for wheat targets than for fallow targets. At 60°, all of the radars displayed a slightly higher correlation with soil moisture for wheat targets than for fallow targets. However, there was also a decrease in the radar sensitivity to changes in soil moisture from the fallow target observations. This decrease in

sensitivity was greater at C-Band than at L-Band.

4.1.3 Canola

Correlation coefficients between radar backscatter and soil and plant moisture (16 observations) are shown in figures 25, 27 and 29. As with the wheat observations, the C-HH and C-VV data display similar trends. However, for canola there seems to be very little angular dependency. Correlations were in the range of 0.7 to 0.8 for plant moisture and in the range of 0.1 to 0.2 for soil moisture over the range of incidence angles studied. This could be the effect of the more random canopy structure which has a larger number of inclusions in the canola canopy than the wheat canopy. This results in an increase in diffuse (multiple) scattering in the canopy volume and as such a decrease in the penetration through the canopy and subsequent scattering from the soil surface. Therefore, correlations are stronger with plant moisture than with soil moisture.

In addition to increased penetration at L-Band, the relative importance of the inclusions in the canopy also decrease. As a result, a stronger correlation between the L-HH observations and soil moisture than the C-Band data was observed at 20°. However, at 40° the strength of the relationship decreased to a level similar to the C-Band observations. At 60°, R_{L-HH} increased to a level greater than the C-Band results. The plant moisture R_{L-HH} was lower than the C-Band data at 20° and similar to the C-Band data at 40° and 60°.

Figure 25 Canola C-HH Correlation Coefficients

Figure 26 Canola C-HH Moisture Sensitivity

Figure 27 Canola C-VV Correlation Coefficients

Figure 28 Canola C-VV Moisture Sensitivity

Figure 29 Canola L-HH Correlation Coefficients

Figure 30 Canola L-HH Moisture Sensitivity

The sensitivities of the radar data to the canola plant and soil moisture are shown in figures 26, 28 and 30. Again both C-Band polarizations followed similar trends. Unlike the wheat observations, radar sensitivity to changes in soil and plant moisture increased with the incidence angle. The L-HH data also showed the same trend.

Overall, the correlations between σ^0 and plant moisture were greater for the canola target than for the wheat target. As well, the correlations with soil moisture were less for the canola target than for the wheat target. The one exception to this was the L-Band observations which had a slightly stronger relationship with soil moisture for canola targets than for wheat targets at an incidence angle of 60°.

4.1.4 Combined Data

Correlation coefficients between radar backscatter and soil and plant moisture for the combined fallow, wheat and canola data are shown in figures 31, 33 and 35. Unfortunately, the results of the combined model may be biased toward the wheat target because of the larger number of wheat observations (38 observations) as compared to the fallow (11 observations) and the canola (16 observations).

As previously observed, the two C-Band polarizations followed similar trends. Correlations with soil and plant moisture were similar at 20°. As the incidence angle was increased there was an increase in plant moisture correlations and a decrease

Figure 31 Combined C-HH Correlation Coefficients

Figure 32 Combined C-HH Moisture Sensitivity

Figure 33 Combined C-VV Correlation Coefficients

Figure 34 Combined C-VV Moisture Sensitivity

Figure 35 Combined L-HH Correlation Coefficients

Figure 36 Combined L-HH Moisture Sensitivity

in soil moisture correlations. At an incidence angle of 20° the L-Band data had a greater correlation with soil moisture than the C-Band at 20° and had a small negative correlation with plant moisture. The L-Band correlations with soil moisture decreased at 40° to being less than that obtained with the C-Band. At 60°, R_{L-HH} with soil moisture remained relatively unchanged and was similar to the C-Band results. The L-Band correlations with plant moisture increased at 40° and remained relatively constant at 60°. Overall, plant moisture correlations at L-Band were lower than those obtained at C-Band.

The sensitivity of the radar data to changes in soil moisture and plant moisture for the combined data set are shown in figures 32, 34 and 36. The C-Band data displayed a slight increase in sensitivity to changes in plant moisture and a slight decrease to changes in soil moisture as the incidence angle is increased from 20° to 60°. The L-Band had a marked decrease in sensitivity to soil moisture between 20° and 40° and remained relatively constant at 60°. Sensitivity at L-Band to plant moisture showed a modest increase as the incidence angle increased from 20° to 60°.

4.2 Discussion of Individual Target Results

The effect of soil moisture on the radar backscatter can be deduced from the correlation coefficients of the linear regression model, which also indicate the

sensitivity of the radar signal to the soil moisture conditions. The models show that the L-Band radar tends to have a higher correlation with soil moisture than the C-Band data analyzed at steep incidence angles (20°) for the fallow, wheat and canola targets. This was to be expected in the vegetated soil case due to the L-Band's longer wavelength and corresponding ability to penetrate the vegetation canopy more easily. Analysis of SIR-B L-Band data acquired at an incidence angle of 21° has indicated that vegetation cover does not play a significant role at low incidence angles due to the penetration depth of this combination of frequency and incidence angle. However, Wang et al. (1976) also state that the effect of vegetation would become significant at large incidence angles. Indeed, the data in this study show that for incidence angles of 40° and 60° , the L-Band correlations with soil moisture were similar to the C-Band observations.

The results also showed a slight increase in correlation with soil moisture at 60° over 40° on the wheat targets for all of the radars studied. A similar effect was observed in the L-Band canola observations. As the incidence angle is increased, the influence of the soil surface on the scattering process should decrease, while the importance of the plant increases. An explanation for this apparent anomaly is that at these high incidence angles the radars are responding to another target parameter which was not a factor at 20° or 40° . One possible parameter is canopy roughness which is the result of the orientation of the plants relative to the incidence angle of the microwaves. As discussed in Chapter Two, roughness effects are minimized at lower incidence angles.

As stated, the L-Band also produced stronger correlations with soil moisture than the C-Band on the fallow target at 20° and 40°. This may be related to the penetration properties of the frequency/incidence angle combination and the 0-5 cm soil moisture sampling depth that was used in this experiment. As referred to in Chapter Two, the relationship between radar response and soil moisture content depends upon the dielectric constant across the air/soil interface and the penetration depth of the microwave signal. However, experimental determination of the penetration depth is almost unrealistic in situ.

Le Toan and Pausader (1981) used a model to calculate the penetration depth from a wide range of soil permittivity profiles. They found that at 4.5 GHz (C-Band), the penetration depth varies between 0 cm (wet soil profile) to 3 cm (dry soil profile). Newton et al. (1982), in their investigation found that at 1.4 GHz (L-Band) the penetration depth was in the 2 to 5 cm range. Therefore, given the 1988 drought conditions and corresponding low soil moisture status, the 0-5 cm sampling depth may have been better suited to the penetration characteristics of the L-Band radar. Correct evaluation of the radar backscatter to the soil moisture would require knowledge of the soil moisture profile over the 0-5 cm profile.

The models also show that the L-Band radar tends to have greater sensitivity to soil moisture than the C-Band data at 20° and slightly lower sensitivity at 40° and 60°. On the fallow and wheat targets the sensitivities of the radars (C-HH, C-VV and L-HH) to soil moisture were highest at steep incidence angles and decreased

with increasing angles of incidence. Dobson and Ulaby (1986) also found that the sensitivity term decreases with either increasing frequency or angle of incidence.

The canola observations show an increase in soil moisture sensitivity with increasing angle of incidence for all of the frequencies studied. Again, a possible explanation for this is that the microwaves are responding to some target parameter unique to the structure of the canola plant. A second explanation is that the assumed linear relationship for the regression is incorrect for the canola target. Future analysis could consider non-linear functional relationships for some targets.

Jackson et al. (1981, 1983) analysis of aircraft scatterometer data acquired over a group of four pasture grass watersheds found that the L-band (1.6 GHz) had approximately the same statistical correlations with soil moisture as the C-Band (4.75 GHz). In addition, the L-Band radar had twice the sensitivity. These results seem to contradict the optimum set of radar parameters for monitoring soil moisture proposed by Ulaby et al (1978)(4.25 GHz, an incidence angle between 7° and 17°, and an HH or VV polarization). However, this selection of C-Band for soil moisture estimation was also due to its lesser sensitivity to surface roughness. Therefore, L-Band radar may be more effective than C-Band as a soil moisture sensor for repetitive observations of the same or similar surface conditions (Schmugge, 1983).

The models show that the C-Band radar had higher correlations to plant moisture content than L-Band observations. This is a reflection of the increased

volume scattering in the crop canopy as a result of the higher frequency microwave observation. The L-Band results on the wheat and canola targets show that as the incidence angle increases the correlations and sensitivity to plant moisture increase. In fact, the L-Band data have correlation coefficients of near zero with wheat plant moisture at incidence angles of 20° and 40°. The C-Band observations displayed a slight increase in correlation with wheat plant moisture as the incidence angle was increased from 40° to 60° but remained relatively constant for the canola targets over the 20° to 60° range. These results agree with observations by LeToan et al. (1984), Allen and Ulaby (1984) and Ulaby and Wilson (1985) who found that the structure in a vegetation canopy affects the radar response.

Le Toan et al. (1984) studied the attenuation loss factor as a function of plant orientation angle for a wheat crop in its heading stage. The results suggest that the orientation of the plants affects the strength of the scattered signal. Since wheat plants have a predominately vertical orientation, it was not surprising that the received VV signal was attenuated more than the received HH signal. In another study, Ulaby and Wilson (1985) also observed that a wheat canopy in its heading stage attenuated the vertically transmitted signal more than the horizontal signal. However, no such effect was observed in this data set.

In the above studies, it was noted that the radar observations taken through the growing season are significantly influenced by canopy moisture content. Although the radar backscatter does tend to increase with an increase in plant moisture

content, the direct effect of the plant moisture on radar backscatter is difficult to determine because the measurement is complicated by the complex geometry of the vegetation and the additional contributions from the underlying soil.

4.3 Discussion of Combined Results

From the previous discussion, it is evident that to estimate soil moisture accurately and precisely from C-Band radar over the range of incidence angles studied, some estimate of the nature of the vegetation is required. The results show that C-Band correlations with plant moisture were generally higher than those with soil moisture. As the incidence angle is increased, the correlation with plant moisture increases and the correlation with soil moisture decreases.

The C-Band correlations with soil moisture were less than those reported by Ulaby et al.,(1979). In their study of fallow, corn, milo, soybean and wheat targets they found that the correlation of C-HH (4.25 GHz) radar at an incidence angle of 10° to soil moisture (0-5 cm) for the combined targets to be $R=0.86$. Given the strong correlation, they concluded that there was a possibility of monitoring soil moisture with a single radar in bare and vegetated fields. This study resulted in a correlation of the C-HH (5.3 GHz) radar at an incidence angle of 20° to soil moisture (0-5 cm) for the combined targets (fallow, wheat and canola) resulted in a correlation of $R=0.36$. This relationship suggests that additional data would be required to estimate soil moisture from a single C-Band radar operating at 5.3 GHz,

HH polarization and an incidence angle of 20°. It should be noted however that these observations were collected during drought conditions and therefore may only be interpreted in relation to soil and plant conditions during that time.

At incidence angles of 40° and 60° the L-Band results also show stronger correlations with plant moisture than with soil moisture. However at 20° the L-Band radar backscatter has a strong correlation with soil moisture and close to zero correlation with plant moisture. Wang et al. (1987) concluded that at L-Band and an incidence angle of 20°, the effect of surface roughness was more important for backscatter measurements than that of vegetation. Therefore, for L-HH (1.5 GHz) radar at 20°, the following model can be proposed :

$$\sigma_{L-HH\ 20^\circ}^0 = 0.199829 (\%M_s) - 11.8172$$

with a correlation coefficient of $R=0.65$. Chang et al. (1980) in their study of L-Band data between incidence angles between 15° and 25° found that surface roughness appeared to mask differences in radar backscatter which were thought to be due to soil moisture variation. They therefore concluded that surface roughness needs to be determined before soil moisture can be estimated using microwave remote sensing techniques.

4.4 Discussion in Relation to Proposed Satellite Platforms

Figure 37 shows the radar backscatter correlations with soil and plant moisture for the combined targets and radar parameters similar to JERS-1 (L-HH, $\theta = 40^\circ$), ERS-1 (C-VV, $\theta = 20^\circ$) and RADARSAT (C-HH, $\theta = 20^\circ$, 40° and 60°) from this study. As stated in the introduction, the actual incidence angle for JERS-1 is 35° , ERS-1 is 23° and RADARSAT with the ability to tilt the antenna will be able to achieve incidence angles over the range of 20° to 59° . It is evident from Figure 37 that the highest correlations with soil moisture are obtained using either ERS-1 or RADARSAT data parameters acquired at 20° . The horizontal polarization of RADARSAT also seems to have a slightly higher correlation with plant moisture than the vertical polarization of ERS-1. A greater variety of crops and soil moisture conditions would be required to verify this. This study is limited to a rather small number of observations on fallow, wheat and canola targets, on one soil type, over the course of one growing season during which drought conditions prevailed.

As discussed in the previous section, the correlation with soil moisture decreases and the correlation with plant moisture increases as the incidence angle is increased over the range of incidence angles proposed for RADARSAT. The JERS-1 parameters indicate lower correlations with soil moisture and plant moisture than ERS-1 or RADARSAT at any incidence angle.

Figure 37 Radar Correlations to Plant and Soil Moisture for JERS-1, RADARSAT and ERS-1

These data suggest that no single observation from JERS-1, ERS-1 or RADARSAT will accurately estimate soil moisture without either a priori information regarding canopy conditions and scene roughness (target type). However, the multitemporal change detection approach, as discussed in Chapter Two, could provide an approach for updating near-surface soil moisture conditions. This assumes that target variables, other than soil moisture, exhibit negligible change over short time increments and fixed viewing geometry. Such an approach would be most effective when the revisit period of the satellite is less than that over which significant changes would occur in surface roughness (primarily related to seasonal tillage operations) and/or vegetation cover (in the order of two to four weeks except at harvest)(Dobson and Ulaby, 1986).

As spaceborne single and multi-channel SARs become a reality, it may be possible to select a certain combination of frequency, polarization and incidence angle to minimize the effects of surface roughness and vegetation. However, the results of this study indicate that accurate estimates of soil moisture will require class (target) specific algorithms. Therefore, there will be a need to classify imagery for land cover classes and then apply class specific algorithms.

Chapter Five

Conclusions and Future Research

5.1 Conclusions

In this study, data acquired by the CCRS ground-based scatterometer were used to evaluate how radar backscatter varied as a function of frequency, polarization and incidence angle versus soil and plant moisture for fallow, wheat and canola targets. Specifically, the radar data were collected at 1.5 GHz (L-Band), horizontal polarization, 5.3 GHz (C-Band) vertical polarization and C-Band horizontal polarization at incidence angles of 20°, 40° and 60°. The soil and plant moisture data for all of the targets were then combined to determine if a single linear relationship could be developed between radar backscatter and soil moisture. Finally, these results were evaluated in regards to the potential of ERS-1, JERS-1 and RADARSAT for soil moisture estimation.

The linear correlation coefficient was computed between the radar backscattering coefficient for each of the radars at each incidence angle versus soil moisture for the fallow, wheat and canola targets. The correlation coefficient was also calculated between the radar parameters and plant moisture for the wheat and canola targets. In addition, the linear correlation coefficient was computed between each set of radar parameters and soil moisture and plant moisture for all targets

combined. The results were evaluated based on the strength of the correlation coefficient, the sensitivity of the radar backscatter to changes in soil moisture and existing literature.

In general, the linear models indicated that radar correlation to soil moisture decreases and correlation with plant moisture increases with increasing incidence angle. In addition, as the frequency was increased from L-Band to C-band the correlation with soil moisture decreased and the correlation with plant moisture increased. Therefore, the L-HH data acquired at 20° had a greater correlation and sensitivity to soil moisture than either C-Band Polarizations for all targets. The strength and sensitivity of the relationship was also found to vary as a function of the target. The C-Band data had stronger correlations with plant moisture than L-Band, with the strongest correlations occurring at 60°. Again, the strength and sensitivity of the relationship was a function of the target.

The L-Band observations at 20° were the only data which exhibited minimal correlation with plant moisture. A linear regression model was proposed which had an R value of 0.65. It was suggested that the effects of surface roughness would have to be determined before soil moisture could be estimated using single date microwave observations.

The results suggest that data acquired from ERS-1 or RADARSAT at 20° will have stronger correlations with soil moisture than JERS-1 or RADARSAT data

acquired at larger incidence angles. It is also evident that no single observation from any of these satellites will accurately estimate soil moisture without a priori information regarding canopy conditions and surface roughness. An alternative may be to use a multitemporal change detection approach which could update soil moisture conditions over short time increments when other target variables would be constant.

5.2 Future Research

A number of questions regarding microwave target interactions need to be answered before soil moisture can be routinely determined with microwave instruments. In order to develop algorithms to estimate soil moisture directly from radar observations other target characteristics related to vegetation and surface roughness will have to be parameterized. Vegetation variables include the geometry of the individual plant as well as the canopy as a whole, water content and stage of growth. These parameters will also have to be understood in relation to microwave frequency, polarization and incidence angle.

In addition to the microwave/target interactions which need to be further explored, the application areas must also be prepared to exploit remotely sensed estimates of soil moisture. Neither hydrologists or agriculturalists have routinely used soil moisture in many operational decisions. Therefore, there is a need to modify or develop existing hydrologic and crop yield models so that spatial and temporal soil

moisture data can be used as input (Engman, 1990).

References

Attema, E.P.W., 1978. "The Interaction of Vegetated and Bare Fields with 3 cm Wavelength Electromagnetic Radiation; Modelling and Experiment". Earth Observation from Space and Management of Planetary Resources, Toulouse, France, March 6-11.

Attema, E.P.W., F.T.Ulaby, 1978. "Vegetation Modelled as a Water Cloud". Radio Science Vol.13, No.2, pp. 357-364.

Allen, C.T., F.T.Ulaby, 1984. "Modelling the Polarization Dependence of the Attenuation in Vegetation Canopies". IEEE International Geoscience and Remote Sensing Symposium, Strasbourg, France, 27-30 August, pp. 119-124.

Allen, W.D., 1972. "Remote Sensing of Fallow Soil Moisture Using Visible and Infrared Sensors". Ph.D. Dissertation, University of Tennessee.

Barret, E.C., Herchy, 1989. "Opportunities for Satellite Remote Sensing in Hydrology and Water Management". Geocarto International, Vol 2, pp. 11-18.

Batlivala, P.P., F.T.Ulaby, 1977. "Estimation of Soil Moisture with Radar Remote Sensing". Proc.11th Int. Symp. of Remote Sensing of Environ.,v.II,pp. 1557-1566.

Blanchard, M.B., R.Greely, R.Goettelman, 1974. "Use of Visible, Near Infrared and Thermal Remote Sensing to Study Soil Moisture". Proceedings 9th International Symposium on Remote Sensing of Environment. Environmental Research Institute of Michigan, Ann Arbor.

Blandchard, B.J., A.T.C.Chang, 1983. "Estimation of Soil Moisture from Seasat SAR Data". Water Resources Bulletin, Vol. 19, No.5, pp. 803-810.

Brisco, B., F.T.Ulaby, M.C.Dobson, 1983. "Spaceborne SAR Data for Land-Cover Classification and Change Detection". Digest of the 1983 International Geoscience and Remote Sensing Symposium, Vol. 1, San Francisco, June, pp.739-745.

Brisco, B., R.J.Brown, G.J.Sofko, 1988. "The CCRS Ground-Based Microwave Facility". Proceeding of IGARSS'88, Edinburgh, Scotland, Sept. 13-16, pp.575-576.

Bruckler, L., H.Witono, P.Stengel, 1988. "Near Surface Soil Moisture Estimation from Microwave Measurements". Remote Sensing of Environment, 26:101-121.

Bowers,S.S., R.J.Hanks, 1965. "Reflection of Radiant Energy From Soils". Soil Sci.100,pp. 130-138

Brown, R.J., 1989. "Land Applications of RADARSAT". Proceedings of IGARSS'89, Vancouver, Canada, July 10-14, pp. 208-210.

2

of/de

2

PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

Carroll, V.T.R., 1981. "Airborne Soil Moisture Measurement using Gamma Ray Radiation". Soil Science, vol.132, no.5, pp.358-366

Carver, K.R., C.Elachi, F.T.Ulaby, 1985. "Microwave Remote Sensing from Space". Proceedings of the IEEE, Vol.73, No. 6, pp.970-996.

Cihlar, J., F.T.Ulaby, 1974. "Dielectric Properties of Soils as a Function of Moisture Content". RSL Technical Report 177-47, University of Kansas, Centre for Research Inc.

Cihlar, J., 1976. "Soil Moisture Determination by Thermal Infrared Remote Sensing". Proceedings of the Workshop on Remote Sensing of Soil Moisture and Groundwater. 8 - 10 November, Toronto, Ont.

Cihlar, J., 1980. "Soil Water and Plant Canopy Effects on Remotely Measured Surface Temperatures". International Journal of Remote Sensing, v.1, pp. 167-173.

Cihlar, J., M.C.Dobson, T.Schmugge, P.Hoogebloom, A.R.P.Janse, F.Baret, G.Guyot, Th. Le Toan, P.Pampaloni, 1987. "Procedures for the Description of Agricultural Crops and Soils in Spectral and Microwave Remote Sensing Studies". International Journal of Remote Sensing, Vol.8, No.3, pp. 427-439.

de Loor, G.P., 1983. "The Dielectric Properties of Wet Materials". IEEE Transactions on Geoscience and Remote Sensing, Vol.GE-21, pp.769-775.

Dobson, M.C, F.T.Ulaby, 1981. "Microwave Backscatter dependence on Surface Roughness, Soil Moisture, and Soil Texture : Part III - Soil Tension". IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-19, pp. 51-61.

Dobson, M.C., F.T.Ulaby, 1986. "Active Microwave Soil Moisture Research". IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-24, No.1, pp.23-36.

Dobson, M.C., F.T.Ulaby, 1986. "Preliminary Evaluation of the SIR-B Response to Soil Moisture, Surface Roughness, and Crop Canopy Cover". IEEE Trans. on Geos. and Remote Sensing, Vol. GE-24, No.4, pp. 517-526.

Dooge, J.C.I., 1973. "The Nature and Components of the Hydrologic Cycle". Man's Influence on the Hydrologic Cycle, Irrigation and Drainage Paper 17, F.A.O., Rome, pp. 1-18.

Eos Synthetic Aperture Radar Instrument Panel Report, 1989. National Aeronautics and Space Administration.

Engman, E.T., 1990. "Progress in Microwave Remote sensing of Soil Moisture". Canadian Journal of Remote Sensing, Vol. 16, No.3, pp. 6 -14.

Estes, J.E., M.R.Mel, J.O.Hooper, 1977. "Measuring Soil Moisture with an Airborne Imaging Passive Microwave Radiometer". Photogram. Eng. and Remote Sens., Vol.43, No.10, pp 1273-1281.

Fung, A.K., F.T.Ulaby, 1977. "A Scatter Model for Leafy Vegetation". IEEE Transactions on Geoscience Electronics, October.

Goodenough, D.G., P.M.Narrendra, K.O'Neil, 1978. "Feature Subset Selection in Remote Sensing". Canadian Journal of Remote Sensing, Vol.4, pp. 143-148.

Hallikainen, M.T, F.T.Ulaby, M.C.Dobson, M.A.El-Rayes, L.K.Wu, 1985. "Microwave Dielectric Behaviour of Wet Soil-Part 1:Empirical Models and Experimental Observations". IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-23, No.1, pp.25-33.

Hirosawa, H., S.Komiyama, Y.Matsuoka, 1978. " Cross Polarized Radar Backscatter From Moist Soil". Remote Sensing of Environment, Vol.7, pp. 211-217.

Idso, S.B., R.D.Jackson, R.J.Reginato, 1975. "Estimating Evaporation: A technique adaptable to Remote Sensing". Science 189:991-992

Idso, S.B., T.J.Schmugge, R.D.Jackson, R.J.Reginato, 1975. "The Utility of Surface Temperature Measurements for the Remote Sensing of Soil Water Status". *Journal of Geophysical Research*, vol.80, pp. 3044-3049.

Ishiwada, Y., Y.Nemoto, 1986. "Present Status of the Japanese ERS-1 Project". *Proc. 2nd Spaceborne Imaging Radar Symposium*, JPL Publication 82-26, Jet Propulsion Laboratory, Pasadena, Calif., pp.79-83.

Jackson, R.D., J.Cihlar, J.E.Estes, J.L.Ralke, E.T.Kanemasu, J.Mallard, J.C.Price, and C.Wiengand, 1978. "Soil Moisture Estimation Using Reflected Solar and Emitted Thermal Radiation;Ch.4 of Soil Moisture Workshop". *NASA Conference Publication* 2073,219 p.

Jackson, R.D., S.B.Idso, R.J.Reginato, P.J.Pinter, 1981. "Canopy Temperatures as a Crop Water Stress Indicator". *Water Resources Research*, vol.17, pp. 1133-1138

Jackson, T.J, P.O'Neill, 1986. "Microwave Dielectric Model for Aggregated Soils". *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-24, No.6, pp.920-929.

Jackson, T.J., P.O'Neill, 1987. "Temporal Observations of Surface Soil Moisture Using a Passive Microwave Sensor". *Remote Sensing of Environment*, 21:281-296.

King, G.J., A.R.Mack, 1984. "A Manual for Recording Significant Agricultural Ground Information in Remote Sensing Programs". Agriculture Canada, Ottawa.

Le Toan, Th., M.Pausader, 1981. "Active Microwave Signatures of Soil And Vegetation - Cover Surfaces, Results of Measurement Programmes". Signatures Spectrales D'Objects en Teledetection, Avignon, Sept 8 -11, pp. 303-313.

Le Toan, Th., A.Lopes, M.Heut, 1984. "On the Relationship Between Radar Backscattering Coefficient and Vegetation Canopy Characteristics". IEEE International Geoscience and Remote Sensing Symposium, pp. 155-160.

Lillesand, T.M., R.W.Kiefer, 1979. "Remote Sensing and Image Interpretation". John Wiley and Sons.

Mentha, N.C., 1984. " Separability of Agricultural Crops with Airborne Multiparameter Radars". IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-22, No.6, pp.540-546.

Moore, R.K., 1976. "Active Microwave Systems: Chapter from Remote Sensing of Environment". Addison-Wesley Pub.Co.,Reading,Mass.

Morton, C.M., 1987. "Backscatter Behaviour of Agricultural Crops in the Microwave Region". Master's Thesis, Department of Physics, University of Saskatchewan, 158 p.

NASA, 1980. "Plan of Research For Integrated Soil Moisture Studies". Recommendations of the Soil Moisture Working Group, Scientific and Technical Office.

Newton, R.W., 1976. "Microwave Remote Sensing and its Application to Soil Moisture Detection". Tech. Rep.RSC-81, Remote Sensing Centre, Texas A&M University, College Station, Texas.

Newton, R.W., Q.R.Black, S.Makanvand, A.J. Blanchard, 1982. "Soil Moisture Information and Thermal Microwave Emission". IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-20, pp. 275-281.

Oliver, E.A., M.J.McKibben, G.J.Sofko, J.A.Koehler, A.G.Waker, 1989. "Agricultural Sampling Procedures and Data Summary for Ground Microwave Operations 1988". Technical Report GMO-TR-004-89, University of Saskatchewan.

Peake, W.H., 1959. "Theory of Radar Return From Terrain". IEEE National Convention Record 7, part 1, p.27.

Salomonson, V.V., R.J.Gurney, T.J. Schmugge, 1985. "The Use of Soil Moisture Data in Large Scale Models of the Hydrologic Cycle". Proceedings of the 36 th International Astronautical Federation Congress, Stockholm, Sweden, Oct 7-12.

Schanda, E., 1987. "On the Contribution of Volume Scattering to the Microwave Backscattered Signal from Wet Snow and Wet Soil". International Journal of Remote Sensing, Vol. 8, No. 10, pp 1489-1500.

Schmugge, T.J., P. Gloerson, T. Wilheit, F.Geiger, 1974. "Remote Sensing of Soil Moisture with Microwave Radiometers". Journal of Geophysical Research, 79, pp.317-323.

Schmugge, T.J., J.Meneeley, A.Rango, R.Neff, 1977. "Satellite Microwave Observations of Soil Moisture Variations". Water Res. Bul., Am. Water Res. Assoc.,v.13,no.2, pp. 265-281.

Schmugge, T.J., 1980. "Effect of Soil Texture on the Microwave Emission From Soils". IEEE Trans. on Geoscience and Remote Sensing, GE-18, pp. 353-361.

Schmugge, T.J., 1980. "Microwave Approaches in Hydrology". Photogrammetric Engineering and Remote Sensing, Vol.46, No.4, pp. 495-507.

Schnugge, T.J., 1983. "Remote Sensing of Soil Moisture: Recent Advances". IEEE Transactions on GEoscience and Remote Sensing, Vol GE-21, No. 3, pp. 336-335.

Schnugge, T.J., 1985. "Remote Sensing of Soil Moisture. Ch. 5, Hydrological Forecasting". John Wiley and Sons Ltd., pp 101-124.

Shaw, E., E.J. Langham. 1989. "RADARSAT: Canada's Microwave Satellite". Proceedings IGARSS'89 12th Canadian Remote Sensing Symposium, Vancouver, Canada, Vol. 2, pp 197-199.

Sheppard, P., 1987. "Crop Separability Using a 3-Band Microwave Scatterometer". Master's Thesis, Department of Physics, University of Saskatchewan, May, 79 p.

Sofko, G.J., A.G.Wacker, J.A.Koehler, M.J.McKibbin, R.J.Brown, B.Brisco, 1989. "Ground Microwave Operations". Canadian Journal of Remote Sensing, Vol.15, No.1, pp.2-12.

Stockhoff, E.H., R.T.Frost, 1974. "Remote Detection of Soil Moisture". Proceedings of 9th Symposium of Remote Sensing of Environment, Ann Arbor, pp. 707-720.

Thompson, D.R., O.A.Wehrmann, 1980. "Using Landsat Digital Data to Detect Moisture Stress in Corn-Soybean Growing Region". Photogrammetric Eng. and Remote Sensing, Vol.46, No. 8, pp.1087-1093.

Tucker, C.J., 1980. "Remote Sensing of Leaf Water Content in the Near Infrared". Remote Sensing of Environment, Vol.10, No.1, pp.23-32.

Ulaby, F.T., 1974. "Radar Measurements of Soil Moisture Content". IEEE Transactions on Antennas and Propagation, Vol.AP-22, No.2, pp.257-265.

Ulaby, F.T. 1975. "Radar Response to Vegetation". IEEE Transactions on Antennas and Propagation, Vol. AP-23, pp 36-45.

Ulaby, F.T., T.F.Bush, 1976. "Monitoring Wheat Growth with Radar". Photogrammetric Engineering and Remote Sensing, Vol.42, No.4, pp.557-568.

Ulaby, F.T., P.P.Batlivala, M.C.Dobson, 1978. "Microwave Backscatter Dependence on Surface Roughness, Soil Moisture, and Soil Texture, Part 1-Bare Soil". IEEE Transactions on Geoscience Electronics, GS-16, pp.286-295.

Ulaby, F.T., G.A.Bradley, M.C.Dobson, 1979. "Microwave Backscatter Dependence on Surface Roughness, Soil Moisture, and Soil Texture: Part 2- Vegetation-Covered Soil". IEEE Transactions on Geoscience and Remote Sensing, GE-17, No.2, pp. 33-40.

Ulaby, F.T., P.P.Batlivala, M.C.Dobson, 1979. "Microwave Backscatter Dependence on Surface Roughness, Soil Moisture, and Soil Texture". IEEE Trans. Geosci. Electron., GE-17, pp. 33-40.

Ulaby, F.T., 1982. "Radar Signatures of Terrain: Useful Monitors of Renewable Resources". Proceedings of the IEEE, Vol.70, No.12, pp.1410-1428.

Ulaby, F.T., R.K. Moore, A.K. Fung, 1982. "Microwave Remote Sensing Active and Passive". Vol II, Chap 11, Addison-Wesley Publishing Company.

Ulaby, F.T., R.P.Jedlicka, 1984. "Microwave Dielectric Properties of Plant Materials". IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-22, pp.406-414.

Ulaby, F.T., E.A.Wilson, 1985. "Microwave Attenuation Properties of Vegetation Canopies". IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-23, No. 5.

Ulaby, F.T., R.K. Moore, A.K. Fung, 1986. "Microwave Remote Sensing Active and Passive". Vol III, Chap 21, Addison-Wesley Publishing Company.

Wacker, A.G., 1971. "The Minimum Distance Approach to Classification". LARS Information note 100771, Purdue University, West Lafayette, Ind..

Wang, J.R., T.J.Schmugge, 1980. "An Empirical Model for The Complex Dielectric Permittivity of Soils as a Function of Water Content". IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-18, No.4, pp.288-295.

Werle, D., 1988. "Radar Remote Sensing: A Training Manual". Dendron Resource Surveys Ltd., Canada Centre for Remote Sensing, Ottawa, Canada.

Appendix A

University of Saskatchewan Kernan Crop Research Farm Site Map
(Oliver et al., 1989)

Appendix B

CCRS Ground-Based Scatterometer

END

22/1 2/92

FIN