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CROP DISCRIMINATION AND MONITORING
WITH MULTI-FREQUENCY AND MULTI-POLARIZED SAR DATA:
A DRYLAND FARMING EXAMPLE

by

Christine A. Hutton

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
October 12, 1990

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WITH MULTI-FREQUENCY AND MULTI-POLARIZED SAR DATA:

A DRYLAND FARMING EXAMPLE

submitted by Christine A.Hutton, B.E.S.
in partial fulfilment of the requirements for
the degree of Master of Arts

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ABSTRACT

The objective of this paper is to introduce a variation on the standard classification techniques used in the analysis of agricultural land use with Synthetic Aperture Radar (SAR). Following an overview of background leading to SAR research and the basic SAR fundamentals, several issues were considered. A Maximum Likelihood Pixel Classifier, a filter of the Pixel Classifier results and a Field Classifier were the techniques used. The methodologies used were designed to investigate the effects of frequency and polarization on: 1) the capability to discriminate crop type with C-, X- and L-band SAR, 2) the classification accuracies possible with single band SAR and numerous combinations of frequency and polarization and 3) the effects of crop row orientation on the potential to classify the crop type. The SAR data used were acquired over a dryland farming region near the city of Swift Current Saskatchewan in 1984. Alternating strips of wheat and summerfallow comprise the major ground cover types. The results showed that only C-VH data were an adequate single band data source and that greater accuracies were found as the number of band and polarization combinations was increased.

ACKNOWLEDGEMENTS

I would like to thank the Canada Centre for Remote Sensing for allowing me access not only to the data used in this study but also for the time made available on their computer analysis systems. Without their cooperation this effort could not have been undertaken. Also I would like to thank my advisors Professors M. Fox and P. Johnson for their comments and suggestions regarding this work.

CHAPTER 1

INTRODUCTION

The ability to monitor agricultural resources nationally and globally is an economic concern for Canada. As one of the world's major wheat producers, Canada needs an accurate and timely method to monitor the amount and condition of all grain crops. The ability to predict yields and monitor areas under production will allow appropriate pricing policies to be developed. Nationally this would also allow planners to set up irrigation policies, anticipate difficulties in soil conditions, organize trade policies, monitor insurance claims and set farm subsidies.

The dynamic nature of crop growth and development requires a timely, accurate and reliable monitoring tool. The spatial requirements for monitoring crops can be fulfilled by utilizing Visible and Infrared (VIR) satellites. However, these sensors are not adequate for monitoring the dynamics of crop growth. Synthetic Aperture Radar (SAR) sensors (see Appendix E, Glossary of Terms), unrestricted by atmospheric conditions that plague the VIR sensors, and recording unique ground information that VIR sensors cannot capture, have

become a new source of information.

The potential to use remotely sensed data to monitor crops was realized in the 1950's with aerial photography (Goodman, 1959). Information concerning crop type, areal extent and condition, and the ability to predict yield were identified as necessary components of a resource monitoring program. The dynamics of crop growth and development require timely information, which cannot consistently be provided by aerial photography.

Using spaceborne platforms, early work began in the 1970's with numerous investigations conducted after the launch of the first of the Landsat series of satellites (Cihlar et al., 1984). The feasibility of estimating crop area was investigated (NASA, 1979) as well as crop condition monitoring (Mack et al., 1977; and Schubert and Mack, 1978).

Although the potential for using VIR sensors was demonstrated, many of these studies also highlighted the limitations of these satellites. The infrequent revisit period and cloud cover reduced the effectiveness of these tools for monitoring crop growth.

In the search to overcome such limitations, efforts focused on the evaluation of the information content of the NOAA AVHRR

(National Oceanic and Atmospheric Administration) (Advanced Very High Resolution Radiometer) sensor. AVHRR data are available on a daily basis covering a very large region on each image. Although general growing conditions can be monitored, this sensor still suffers from the inability to penetrate cloud cover.

Limitations of the VIR satellites led to investigations and early interest in microwave remote sensing. Sensors operating in the microwave portion of the electromagnetic spectrum can penetrate cloud and operate under most atmospheric conditions. Active microwave sensors or radars, which generate and transmit their own energy, respond to and receive different surface information than that derived from VIR sensors. Microwaves are particularly sensitive to moisture content, structure and roughness of the target, characteristics allowing distinctive information regarding the surface of the earth.

The first involvement by Canadian scientists with microwave sensors was through the SURSAT (Canadian Surveillance Satellite) program. This program was established by the Canadian government in 1977 and included participation in the NASA (National Aeronautical and Space Administration) SEASAT program. As a second part of the SURSAT program a SAR with X- and L-Band capability was acquired from the Environmental

Research Institute of Michigan. Later a C-band capability was added and all were operated from an airborne platform. In the late 1970's many investigations were undertaken to assess the effectiveness of this sensor as a resource tool. For agricultural investigations data were collected beginning in 1978 at three sites in Western Canada. This author worked with some of these data but the results were never published due to the advent of better multi-temporal data sets acquired in 1983 and 1984. Data collection continued through to the demise of the sensor in 1984 when the C-band antenna was damaged in transit to Europe. Most published works discuss the efforts conducted on the 1983 and 1984 data sets (Cihlar and Hirose, 1984; Poirier et al., 1988).

The results of this program proved to be encouraging and ultimately led to the initiation of a program that will launch a Canadian SAR satellite in the mid 1990's (RADARSAT). As part of the RADARSAT program and later the Radar Data Development Program (RDDP), work continued on development of the techniques, procedures and expertise to use SAR data effectively as a tool to monitor agricultural crops in Canada.

The overall objectives of the RDDP agricultural group were and are to further the understanding of microwave interaction with a vegetation canopy. Present investigations include efforts to identify the effect sensor characteristics such as band,

polarization, look direction and incidence angle have on the expected response from surface targets. Target characteristics such as crop type, growth stage, condition, roughness and soil and plant moisture, are being investigated to develop a better understanding of microwave responses.

Experimental investigations continue with airborne, spaceborne and ground-based microwave sensors in anticipation of the launch of a number of SAR satellites in the 1990's (Brown, 1987).

Canada's RADARSAT satellite, scheduled for launch in 1994 (Shaw and Langham, 1989) will carry a C-band, horizontally-polarized SAR. RADARSAT is a joint program between the Canadian federal government, a number of the provincial governments, private industry and NASA, the satellite will orbit the earth at an altitude of 800 km. Shaw and Langham (1989) discuss the capabilities of RADARSAT. This satellite will provide data in near-real time on a three day subcycle in four operating modes. These operating modes will provide SAR data with a combination of resolutions and swath widths.

The European Space Agency will launch a C-band, vertically-polarized satellite SAR in late 1991 or early 1992. In addition to the SAR a number of other microwave sensors will be carried. Canada is participating in the experimental phase

of this work, conducting an agricultural and forestry experiment.

The American Shuttle program includes a SAR mission with a payload consisting of C-, X- and L-band Synthetic Aperture Radars (SARs). Although this mission will be short lived (approximately 10 days) in comparison with the satellites, the opportunity to study the multi-frequency effects on crop monitoring from a spaceborne platform will be invaluable.

1.1 Fundamentals of Imaging Radar (see Appendix E - Glossary)

Radar remote sensing operates in the microwave portion of the electromagnetic spectrum. The microwave region extends from 0.3 GHz to 300 GHz in frequency or 1m to 1mm in wavelengths. The three wavelengths of the data in the present study were C-band at 5.3cm; X-band at 2.3cm and L-band at 23cm.

Radar is an acronym for RADio Detection And Ranging. "Radar was developed as a means to use radio waves to detect the presence of objects and determine their range (position)" (Lillesand and Kiefer, 1979, p 489).

Active microwave sensors or radars transmit microwave energy

towards a target (i.e. surface). A portion of the energy, depending on the characteristics of the target, is scattered back to the antenna. The measurement of the intensity, time delay and the phase history of these returned signals are the basis for SAR operation.

Most SAR systems are side-looking. The geometric configurations of SAR and SLAR (Side-looking airborne radar) are the same. The microwave signal is transmitted from an antenna and fans out with distance from the source (beam). (Figure 1.1) The beam is wide in a vertical direction and narrow in the horizontal. As the aircraft moves forward, the imaging plane is produced by recording the intensity and

Figure 1.1 (adapted from Lillesand and Kiefer, p. 483)

distance of the returned signals as they pass through the area "illuminated" by the radar (Figure 1.1). The ability to discern targets or objects on the ground is determined not only by the nature of the target, but also by parameters such as resolution, incidence angle, polarization and frequency.

Resolution is defined in terms of both azimuth (flight direction of the aircraft) and range (the direction perpendicular to flight). Resolution in the range direction is governed by the length or duration of the radiated pulse. Targets are resolved if the distance between them (in slant range) is greater than half the pulse length (Figure 1.2). To increase the resolution the length of the pulse is shortened.

The azimuth resolution is determined by the beam width "B" of the antenna (Figure 1.3). The beam fans out with increasing distance from the aircraft and the azimuth resolution is degraded. To increase the azimuth resolution, the physical length of the antenna must increase as with Real Aperture Radar (RAR), the altitude of the sensor must be reduced or a longer antenna must be synthesized (SAR). Synthetic Aperture Radars or SARs synthesize a greater antenna length through use of the Doppler frequency shift information. As a target passes through successive "beams" the intensity and frequency shift of the target are recorded and retained.

Dependence of range resolution on pulse length.

Figure 1.2 (adapted from Lillesand and Kiefer, p.496)

Figure 1.3 (adapted from Lillesand and Kiefer, p.498)

The effective length of the antenna becomes the distance over which this Doppler information is recorded (Figure 1.4).

Images are created by an amplitude/video signal which represents the return echoes from the surface along a single beam width. As the aircraft advances the image is filled in along the azimuth plane as successive microwave pulses are transmitted and their backscatter recorded.

Image data are recorded onboard the aircraft in slant range presentation due to the geometry of the SAR system (Figure 1.5). The returned signals or backscatter from the surface targets are recorded at the time delay distance that they are returned to the antenna. Since the time to travel to and return from the target is shorter from targets physically closer to the aircraft, the signals from these targets are recorded first. This type of recording produces a compression of the target's representative location, producing the effect known as slant range presentation. More detailed descriptions of these radar fundamentals can be found in Lillesand and Kiefer, 1979; American Society of Photogrammetry, 1983; and Siegel and Gillespie, 1980.

Figure 1.4 (adapted from Barrett and Curtis, 1983, p62)

Figure 1.5 (adapted from Lillesand and Kiefer, p 497)

1.2 Target Sensor Interactions

The interaction of the microwave or radar energy with the ground or surface is controlled by a complex series of interrelated system and target parameters and characteristics. The relationship between the received power to these characteristics or radar parameters can be described by the radar equation (American Society of Photogrammetry (ASP), 1983 p115).

The scattering coefficient, σ^0 , which describes the amount of energy representative of a target is a function of both sensor characteristics (polarization, incidence angle, look direction, wavelength), and surface properties (geometric, dielectric, and conductive) of the target.

The two primary factors influencing the transmission characteristics of the signal and those under investigation here are frequency and polarization. Maxwell's equation (Elachi, 1987) describes the behaviour of electromagnetic waves, but for our purposes it is sufficient to note the length or frequency of the wave will vary and alter the interaction with the surface target. Short wavelengths (e.g. X-Band) tend to interact with and provide information about the canopy, while the longer wavelengths (e.g. L-Band) will penetrate the canopy and provide information about the soil.

Polarization describes the electric vector of propagation associated with the electromagnetic field. Horizontal (H) polarization describes the vector when perpendicular to the plane of incidence while Vertical (V) polarization is in the plane of incidence (Elachi, 1987). With present SAR operating systems the capability exists to acquire data with like polarizations (HH or VV) or cross polarizations (HV or VH) describing the orientation of the transmitted and received signals.

In general the three ground factors radar responds to are geometric, dielectric and conductive. Geometric factors of crop type include structure, height, growth stage and roughness. Dielectric properties include soil or plant moisture. Conductive factors include density, height and condition of the target. These factors are not the only ones controlling the backscatter responses from the targets in the present work, nor do they reflect the exhaustive list of possibilities.

A radar image is composed of a series of grey tones representing the relative backscatter from the targets. The grey tones over a homogeneous area on a radar image are proportional to the average return power strength and, hence, to σ^0 .

Radar returns from a target depend upon both the strength of the transmitted energy and the reflecting or scattering capability of the target. Most radar targets scatter with various strengths along different axes. The strength of the return signal is dependent on the amount of scattering, reflecting and attenuation which occurs before reception at the antenna. Each target on an image is characterized by a unique set of measurable properties represented by the backscatter in the radar image.

The interactions and parameters affecting the radar cross-section from the surface are far too complex a topic to be fully discussed here. More detailed discussion can be found in Lillesand and Kiefer, 1979; American Society of Photogrammetry, 1983 and Siegel and Gillespie, 1986

1.3 Objectives

Consistent with the Canadian radar program and the advent of a number of planned SAR sensors, the general objectives of the present work are to investigate the multi-frequency and multi-polarized effects on radar backscatter from agricultural targets. To further the understanding of the interaction between microwaves and crops the present study investigated

the effects of frequency and polarization on:

1) the capability to discriminate crop type. C-, X- and L-Band, HH polarized data and C-band VV, HH and VH polarized data were assessed;

2) the classification accuracies possible with single band SAR and numerous combinations of frequency and polarization.

3) the effects of crop row orientation on the potential to classify the crop type.

This study analyzes the effects of frequency and polarization using data acquired over a site in western Canada near the town of Swift Current, Saskatchewan. This site has been used as a representative dryland farming region by the Agricultural group at CCRS since 1978. Most of the experimental sites used by this group have (until recently) been in western Canada because large field sizes allow easier analysis. As the technologies improve and expertise increases, investigations are expanding into regions where the fields are smaller and more representative of the majority of agricultural regions of the world. A great deal of unanalyzed data existed from the Swift Current site and was made available to the author by CCRS for the present work.

Many of the radar basics will be discussed in more detail in Chapter 2 as they relate to the specific sensor characteristics or to the site used in the present analysis.

CHAPTER 2

DATA

The data used in the present study were collected with the CCRS CV-580 SAR sensor. This sensor was initially designed in 1978 to operate in both X- and L-bands (Rawson et al., 1975). The C-band capability was added in 1982. X-, C- and L-band are the most commonly used frequencies for radar remote sensing. X-band radar operates with wavelengths between 2.4 and 3.75 cm; while C-band operates at 3.75 to 7.5 cm. In general, these shorter wavelengths tend to be more sensitive to surface roughness and volume scattering. The longer L-band wavelengths between 15 and 30cm penetrate the crop to a greater degree and provide information on the soil surface.

The polarizations available with this sensor were horizontal (H) or vertical (V). Like and cross polarization combinations (VV, HH, HV and VH) could be acquired simultaneously. The structure of ground targets can significantly alter the amount of energy received at the antenna, based on the polarization of transmitted and/or received signal. The ability to collect data in numerous polarity combinations increases the potential of identifying a target under investigation. Data acquisition

of three bands and four polarizations was almost simultaneous, eliminating many of the ground-target changes which occur over relatively short periods of time and which can alter backscatter responses not related to sensor characteristics.

The data were processed to amplitude images due to recording restrictions. The data were processed at one look to reduce post processing averaging, resulting in a nominal resolution of 3 meters. This allows for the data to be retained in the full range of values collected. This processing is conducted by the production facility at Canada Centre for Remote Sensing (CCRS) at the user's request and is described more fully in Davis and Princz, (1981). In addition to the standard processing described, the user requested averaging to reduce quantity and output. The resulting data were at 16-bits with a pixel spacing of 5.6 m. The 16 bit digital data are preferred by some investigators since the full dynamic range of the original data collected is retained (0 to 65535 grey levels). Although at the present time few image analysis systems have the capability to conduct analysis of data at 16 bits, they do offer the capability to compress the data to 8 bits (0 to 255 grey levels) based on preference and applications needs.

2.1 Site Description

The site used for this study is located in south-western Saskatchewan just north of the city of Swift Current (Figure 2.1). Centred at approximately 50 degrees 11 minutes north, 107 degrees 30 minutes west, the site lies within the major prairie wheat growing region. This region is extremely dry with an annual mean rainfall of 380 mm. As a dryland farming region it is often plagued by drought and high winds. Some fields of rye, oats and forage crops are grown in addition to the wheat.

Dryland farming is a technique used in western Canada and many other regions where rainfall is poor and water supplies do not allow for irrigation. In order to retain the small quantities of available soil moisture, alternating fields of crop with bare soil is common (Saskatchewan Agriculture, 1984). Every second or third plot of land is left in fallow to allow the moisture and minerals to be retained for the next growing season. The alternation of fields with crop and fallow is particularly common at the Swift Current site, and it creates distinctive radar signatures. The crops grown in dryland farming areas are commonly grains, with wheat dominating. The limited quantities of rye and barley planted at the site were too small to provide a statistically significant sample.

Figure 2.1 Location of the Swift Current test area in South-Western Saskatchewan.

SCALE (INSET) 1cm = 2km

2.2 Data Set

During the growing seasons of 1983 and 1984 a substantial amount of data was collected by the CCRS CV-580 sensor in Western Canada. Unfortunately only a limited set of digitally recorded data was available. Consistent with the objectives of this study to compare X-, C- and L-band data and, due to the poor quality of much of the acquired data, the final data set chosen was collected between June 19 and 21, 1984. Early season data collection consisted of recently emergent wheat approximately 10 to 30 cm in height. The SAR data available was C-HH, X-HH, L-HH, C-VH and C-VV.

Ancillary ground truth data consisting of a number of measured variables including crop type were recorded. These data were collected by the author between the 18th and 23rd of June, 1984.

2.3 Previous Research

Previous research has investigated backscatter responses from various important crop related parameters: crop type (Cihlar and Hirose, 1984; Rosenthal and Blanchard, 1984), leaf area index (Brakke et al, 1981) and plant moisture content (Allen and Ulaby, 1984). Other factors, including row orientation effects, growth stage and condition also significantly modify

the backscatter coefficient. The present study is a description of a methodology derived to investigate specific SAR backscatter responses. Only those published works closely related to this study are discussed below.

A wide variety of works have been published which discuss the frequency and polarization effects on radar backscatter. Ulaby et al., (1985) noted that three linear polarizations (HH, VV and HV) used in combination were clearly superior to any single polarization for purposes of crop classification. Row orientation has also been investigated (Hutton and Brown, 1986 & 1989). The published works lead to a general understanding of expected responses from various crop types and are used as background to the present study. Examples of some of this literature is documented in Appendix F. The main thrust of this work is an analysis of the effectiveness of two classification techniques applied to early season radar data. The two techniques used were the Maximum Likelihood Classifier and the Field Classification Method. These classification methodologies are very common and are discussed in both general texts and technical literature. The combination of early season radar and row orientation effects has not been investigated in detail. Two closely related works which were found, although data acquisition circumstances vary from the present work, are described below - Brown et al., 1990 and Brisco et al., 1989.

Brown et al., (1990) examined the correlations between X-, C- and L-band SAR at an agricultural site near Melfort, Saskatchewan. The Melfort Site is approximately 200 miles north of Swift Current site. At Melfort rainfall is sufficient to allow the growth of a wide variety of crops not possible at the Swift Current site. The results of the study by Brown et al. (1990) indicated that the existing differences between C- and X-band frequencies could be explained by the micro-roughness responses to which each of the frequencies are sensitive. L-band responses varied from either C- or X-band (5.3cm and 2.3cm, respectively), and were concluded to be a function of the increased penetration of the crop canopy by the longer L-band wavelength. Backscatter responses at L-band are dominated by the soil or soil surface. Brown et al. concluded the shorter wavelengths of X- and C-band indicated a greater influence by volume and canopy scattering.

The data set used in the Brown et al. (1990) study were collected in July and August. A comparison between their results with those found in the present study is only valid in a general context as the data used in Browns study were collected much earlier in the growing season and over a substantially different agricultural region.

Brisco et al. (1989) investigated the responses from both SAR

and VIR data acquired at a site near North Battleford, Saskatchewan. The SAR data were collected on May 10th and June 12th of 1987. The Landsat TM data were collected on the 24th on May, 1987. They investigated the capability of the two different data types, used separately and in combination to discriminate certain crops. The methodology used in their investigations is similar to those used in the present analysis. Their conclusions indicated single date SAR could only discriminate adequately between a limited variety of crops (canola, peas and lentils). They hypothesized better results could be expected using a combination of multi-date SAR and TM.

The author suggests there is still a need for early season crop discrimination for better crop monitoring, and an adequate method still remains to be found.

Building on the research and findings of investigations to date, of which only a small number have been mentioned, the present work seeks to examine the potential of multi-frequency and multi-polarized SAR response to crop type discrimination and the effects of crop row orientation on this discrimination.

Chapter 3 outlines the steps used in the preprocessing, processing and analysis of the present data set.

CHAPTER 3

METHODOLOGY

A variety of methods and procedures are available for preprocessing, processing and analyzing SAR data for crop discrimination purposes. Preprocessing software is intended to allow system-induced influences (e.g. antenna pattern and speckle) to be removed or reduced. Processing uses software to enhance and highlight the tonal differences between targets on the ground. The analytical steps are partly based on the methodology established by the agricultural section at CCRS. A variation on the standard classification methods was developed and tested here to compare frequency, polarization and row orientation effects on discriminating wheat and fallow at the Swift Current site.

In order to fulfil the objectives of this work, (e.g. to assess multi-frequency and multi-polarization SAR data to discriminate between agricultural targets) two classification methods, as well as a classification filter, are used to conduct the analysis.

The data in the present study were acquired by the CCRS CV-

580 sensor. Although this system is no longer state-of-the-art radar, a wealth of data was acquired and much of it has not been fully utilized. After the new X and C SAR sensor was introduced at CCRS, little work was continued using the older data. Although the data from this sensor contain useful information, the new sensor produces data of superior quality. Data from the new sensor were not available when this experiment was initiated. To remain in the forefront of technology CCRS is now using the new X and C SAR data exclusively.

All the digital processing of the data was carried out on a Dipix Aries III, VAX-based image analysis system. A combination of Dipix tasks (Dipix Systems, 1987) and RADARSAT in-house software (RADARSAT, 1988) were used to undertake the manipulation of these data.

The first step entailed reading the data from tape, locating where the majority of the information resided and compressing it into a format that could be used on the image analysis system (Data format 3.1.1).

The data were both geometrically corrected to improve the ability to register these images to each other and radiometrically corrected to remove antenna pattern effects (3.2.2) introduced by the operating system. Filtering (3.2.3)

was carried out to remove the speckle introduced during data acquisition. These steps are commonly referred to as preprocessing.

Processing of the data includes resampling the data to 12.5m pixels to reduce the computer file size. Each image is then registered to a master image to facilitate the classification stages used in the analysis (3.2.4).

The classifications (3.3) used to identify the ground cover type encompass the main body of the analysis. The SAR combinations of frequency and polarization used were designed to allow a comparison of the frequency, polarization and row orientational effects on the ability to discriminate ground cover type. The final procedures identify and discuss the differences between the two classification methods used, the Maximum Likelihood Pixel Classifier and the Field Classification method.

3.1 DATA FORMAT

The data were recorded on a High Density Digital Tape (HDDT) onboard the aircraft. The ground facility produces data according to user specifications and a Computer Compatible

Tape (CCT) was created (see section 2.1). The production facility at CCRS produced the data, in 16 bits, or a dynamic range from 0 to 65535 (digital numbers). These tapes were produced in a standard LGSOWG (Landsat Ground Station Operating Working Group) format.

Histograms of the data are produced with software available on the DIPIX image analysis system which shows the grey levels or dynamic range (at 16 bits) of the data. The data for each flight line, will occupy a slightly different dynamic range (due to variations in backscatter caused by differing bands or polarizations). The onboard setup of SAR system parameters (e.g. band, polarization, gain, etc.) as well as the range of ground targets being imaged will create these variations in the dynamic range represented on each pass. The data are seldom represented in the full dynamic range and the user can determine the range which has been used.

The data were compressed from 16 to 8 bits using software written at the RADARSAT project office. The resulting data occupied the dynamic range of 0 - 255 and could now be displayed and analyzed on the image analysis system.

Due to the nature of CCRS's digital recording capabilities only a portion of each flight line was contained on one tape. Two or three tapes were needed to produce an image covering

the Swift Current site. The images were then mosaicked together to produce one complete image, which became the input to all subsequent processing discussed.

3.2 PREPROCESSING

SAR data acquired in a digital format, regardless of the source, require a certain amount of preprocessing before they can be analyzed. The stability of the aircraft, coupled with variations in the terrain, often results in a radiometric distortion known as antenna pattern. The antenna pattern causes variations in the grey levels across the swath which are not representative of the responses from the ground targets. In addition, the data must be geometrically corrected from slant range to ground range presentation. The source of the data or sensor involved, coupled with the nature of the application, will determine the level of preprocessing necessary.

3.2.1 Slant to Ground Range Correction

Features recorded by the CV-580 SAR system are presented in slant range (see section 1.3 and Figure 1.5). To correct for

this distortion and allow registration between images, a slant to ground range correction is carried out using software resident on the image analysis system..

3.2.2 Radiometric Correction

An empirical technique described by Guindon et al, (1984) was used to balance each scene radiometrically for variations due to antenna pattern. These distortions occur in the range dimension since the antenna transmits more power from its centre than the edges, resulting in variations in return intensities. Although radiometric variations are possible in azimuth, none of the data used in the present study was affected in this manner, so no corrections were necessary. To remove range distortion and estimate the correction factor to be applied across the image, a mean grey level profile was calculated representing the pixel intensities across the image (in range). Some operator control can be exerted by allowing a choice of the ground targets over which the profile is calculated. A correction factor was applied by means of a low-order polynomial (3rd) to produce a scene with constant brightness. Unfortunately the X-Band data exhibited such severe antenna pattern effects even after the corrections, that antenna patterns were still visible. This is expected

to have a significant effect on the usefulness of the X-band data.

3.2.3 Filtering

Speckle in a radar image (the salt and pepper appearance) significantly reduces the information content of the SAR image. Speckle is introduced into radar imagery due to the coherent nature of the radar. McCandless (1985) describes this effect as:

"The coherent interference between targets contained within a resolution cell is the basis for much of the scintillation of coherent radar imagery, an effect often referred to as "speckle". In general, there are many individual radar scatterers contained within a resolution element, and their amplitudes and phases add vectorially to establish a single resultant complex number which may take on a wide range of values, depending on the exact phase of each of the scatterers within the resolution cell."

To reduce this "salt and pepper" appearance in the imagery, filters are routinely applied. In the present study a 3x3 mean filter was passed over the imagery. A study by Hutton and Brown (1989) indicated 3x3 or 5x5, mean or median filters were the most appropriate for speckle reduction in agricultural scenes. The 3x3 mean filter used here resulted

in a reduction of speckle without loss of the field boundary edges.

3.3 PROCESSING

3.3.1 Resampling and Registration

The preprocessing stages were conducted with image files at a 5.6 m pixel spacing. The pixel size was reduced from 5.6m to 12.5m to decrease the time needed to process the data. The processing times were reduced from a number of hours to 30-40 minutes.

For the generation of training area statistics and subsequent classification of the imagery, each image must be registered to every other image. Ground control points were collected using easily recognizable features (e.g. road intersections) to allow the geometric alteration of one image with reference to another. A "master" image chosen by the user, usually the image on which a number of ground control points were most easily located, becomes the standard to which all other images are registered. A reference grid is set up and pixel residual error estimates were calculated by the computer. To produce a good registration or have the boundaries of fields on each

image lined up, the degree of accuracy in registration must be high. Should a poor registration be used, pixels which are not representative of the backscatter from the "crop" may be included in the subsequent analysis and produce inaccurate results. Once the error estimate has been accepted a transform was calculated by the computer to undertake the registration and applied to each image. A nearest neighbour resampling algorithm was used to conduct the resampling. A visual check of the accuracy of the registration was carried out after the processing was complete.

3.4 CLASSIFICATIONS

The previous stages of computer manipulation are termed "preprocessing and processing" and prepared the data for analysis and classification. A number of steps are involved in the classification stage and the particular data combinations used were chosen to fulfil the objectives to assess the multi-frequency, multi-polarization effects of SAR on crop discrimination.

3.4.1 Training Area Generation

Training areas were the basis on which all processing, signature generation and classification were determined. Training areas were chosen based on "a priori knowledge", obtained from "ground truth" information collected at the time of the SAR overflights. The training areas were "drawn" using the bit pad capability of the image analysis system, over selected areas on the SAR image representing the crops to be classified. The computer used this information to create "signatures" (e.g. mean and standard deviation values) from each training area. The signatures were the input used by the classification algorithm to classify the crop type.

Effects due to differences in ploughing or seeding directions termed "row orientation" are pronounced in dryland farming areas such as the study site of Swift Current (Hutton and Brown, 1987). These effects can increase or decrease the backscatter received from a crop based on factors not directly related to crop type and severely complicate efforts to classify the data. Figure 3.1 is an aerial 35mm shot of the ground at Swift Current. The patterns causing the row orientations can be seen in the grain fields.

FIGURE 3.1 Aerial Photography showing row orientation patterns
in grain fields

To assess the effect of row orientation on crop classification in the present study three ground cover types were determined, including 1) fallow fields, 2) the portion of each wheat field with rows oriented 90° to the radar look direction, termed "bows" and 3) the portion of each wheat field with rows oriented 0° to the radar look direction, termed "wheat". The rows oriented orthogonal to the radar look direction (90°) were expected to have a greater backscatter on some of the SAR bands. (Figure 3.2) Thus training areas were derived for all three "ground cover types", resulting in the two ground cover case represented by fallow and all the wheat (bows and wheat)

Figure 3.2 Training Area Locations Within the Wheat Fields

while the three ground cover case distinguished between fallow, wheat and bows.

After all the training areas had been drawn they were combined into either "training" or "test" files. Approximately one third of the available training areas in each ground cover class were used to generate the signatures, or provide the information necessary for the computer to conduct a supervised Maximum Likelihood Classification (MLC). The remaining training areas, approximately two thirds of those available were used to check the accuracy of the subsequent classifications and are referred to as test areas. About one hundred training areas were used in the present study representing all the fields in which ground truth information was available.

3.4.2 Statistics and Signature Generation

Once the training areas have been grouped into the training and test areas, the mean, standard deviation, correlation, and co-variance matrices were calculated for each ground cover type. This information was used by the computer to calculate spectral signatures for each ground cover type as represented on each SAR image or combination of images.

The signature files were input to the MLC program based on the combinations of SAR imagery for which classifications were desired. The data combinations used in the present work are identified in Table 3.1. The training areas were divided into either the two ground cover or three ground cover cases.

TABLE 3.1

COMBINATIONS OF SAR DATA USED FOR CLASSIFICATION

Single Band	Combinations
C-HH	C-HH/VH
C-VH	C-HH/VV
C-VV	C-VV/VH
L-HH	C, X & L-HH
X-HH	ALL 5 PASSES

3.3.3 Maximum Likelihood Classification (MLC)

Classification of an object by definition is "the decision regarding the category to which the object belongs" (Frost and Yuirovsky, 1985). Each target on an image (each cover type to be differentiated) is characterized by a set of measurable properties represented by the backscatter and will be categorized accordingly.

Maximum Likelihood Classification and the Maximum Likelihood Decision rule are described in detail in Lillesand and Kiefer, 1979. In summary the assignment of each field to the proper "class" is based on a maximum likelihood criterion. This standard classification technique is based on the probability that a target belongs to a certain class. In the present agricultural context the probability that a field belongs to a certain crop type is based on grey level alone. Maximum likelihood classification assumes an a priori knowledge of the targets in the scene, obtained through field work as in this study. This "a priori" knowledge guides the subsequent selection of training areas.

3.4.4 Accuracy Assessment

The accuracy assessment of the classification results and

capability to discriminate between the various cover types using radar data, was based on the accuracies derived from the test areas.

The output from the Maximum Likelihood Classification is a theme map where the colour of each pixel indicates the class to which it was assigned (for examples see Appendix C). The group of training areas used to test the classification were also generated in the form of a theme map.

The accuracy of the classification was determined by comparing the computer classified pixel theme map and the known pixel theme map (e.g. predicted vs observed) by creating matrices showing the percentage of pixels correctly classified.

3.4.5 Post Classification Filtering

A post classification filter was employed to remove "anomalous" or "outlying" pixels from the classified map (Dipix, 1987). The filter was used with the intention of increasing the overall accuracies attained. Although acceptable classifications depend on a particular application and sensor, for the purposes of this work acceptable accuracies are those greater than 70%. The poorer classifications (those under 50%) will have their accuracy reduced.

3.4.6 Field Classifier

The MLC is a pixel classifier and it assesses the likelihood of each pixel belonging to a defined class (i.e. in this case crop type). In this study the number of fields accurately classified was to be determined. In an attempt to improve the capability of discriminating field crop types a threshold field classifier was developed for use at CCRS (RADARSAT, 1988). The pixel results from the MLC were input to this software and an accuracy threshold was defined by the operator. Assuming a threshold of 70% has been chosen, then if 70% of the pixels in the field area were classified as one ground cover type by the MLC, it was assumed that the entire field consists of that crop. This method was an extreme form of classification filtering but allows for a better assessment of the classification results. The ground cover type was either correctly or incorrectly classified. The method was used in the present study as a comparison with the more accepted MLC classification technique.

The results from each of these methods and for each of the band and polarization combinations will be discussed in more detail in the following chapters.

CHAPTER 4

ANALYSIS AND RESULTS

A short overview of the structure of the results is necessary due to the complex nature and variety of the terminology needed to adequately discuss the results found in this work. Documentation of the analysis and results can be found in this chapter while the implications of these results will be discussed in detail in Chapter 5.

Table 4.1 summarizes the results, indicates the data used and the Appendix in which these data can be found. Since each image, graph or figure will be referred to numerous times during the following discussion they have been included as appendices for reference and comparison, rather than being integrated with the text.

A description of the difference between the two and three crop class cases was discussed in Chapter 3.

Appendix C contains some representative examples of the theme files which are one form of output from the Maximum Likelihood Classifications. These them. files were used as input to software which generates the numerical accuracies discussed

TABLE 4.1
ORGANIZATION OF ANALYSIS AND RESULTS

DISCUSSION	DATA	APPENDIX
General Tonal Properties	C-HH, C-VH, C-VV L-HH and X-HH	A
Maximum Likelihood Two ground cover case	Fallow-Unfiltered Fallow-Filtered Wheat-Unfiltered Wheat-Filtered	B
Maximum Likelihood Three ground cover case	Fallow-Unfiltered Fallow-Filtered Wheat-Unfiltered Wheat-Filtered Bows-Unfiltered Bows-Filtered	B
Field Classification - Two ground cover case	50% threshold-Unfiltered 70% threshold-Unfiltered 85% threshold-Unfiltered	D
Field Classification - Three ground cover case	50% threshold-Unfiltered 70% threshold-Unfiltered 85% threshold-Unfiltered	D

in this chapter. A subset of those available were reproduced in Appendix C for reference.

4.1 General Tonal Properties

First, the general tonal properties of each image will be discussed. Visual analysis was first undertaken to assess the tonal quality of each image and to estimate whether the classification algorithms would be successful. The images discussed in this sub-section are reproduced in Appendix A. The prints created on the Dipix Image Analysis system represent the data used in all subsequent classification procedures.

4.1.1 C-HH SAR Data

Figure 4.1 shows the C-HH SAR data used in the present study. It can be seen that the tones of many of the wheat fields are both lighter and darker than the fallow fields. The alternating strips of wheat and fallow are clearly distinguished due to distinct field boundaries rather than the tonal properties from the fields themselves. Parts of the wheat fields are evident due to the "bows" (seen more clearly at near range or the bottom of the image). The high backscatter from the bows relative to the other fields is

caused by row orientational effects in the near range where there are steeper incidence angles. This type of backscatter response makes computer classifications difficult since the probability of distinguishing either crop is poor. In addition to the row orientation effects, two other target characteristics may be exerting their influence. The differences in appearance between wheat fields could be a response to differing emergence stages or crop height. Some of these fields may contain enough "crop" to be creating a signature from the canopy, while in others, short crop may be penetrated and signatures would be derived from the soil directly or volume scattering responses from a combination of soil and crop. Another characteristic worth considering is variations due to surface roughness in the fallow fields. Regardless of the causal factors influencing the crop signatures, little discrimination is expected from these data as a single band source.

4.1.2 C-VH SAR Data

The C-VH SAR image is shown in Figure 4.2 (Appendix A). The tonal contrast seen between fields is quite clear on this image. Fallow is represented by dark tones, alternating with the lighter tones of wheat. Variations in tone within the fallow fields are also visible. This is attributed to

roughness or the amount of trash (wheat stubble from the previous year) left in the field. The ground photographs taken at the time of the radar overflight support this assumption.

The lighter tone of wheat appears (due to frequency, polarization combination) to be in response to volume scattering from the canopy. Volume scattering is a term used to describe multiple scattering facets, in this case from the wheat heads, stems and leaves.

Very faint row orientation effects can be discerned in the wheat fields near the bottom or near range portion of the image. In this case these areas are slightly darker than the rest of the wheat. For the purposes of discrimination of fallow and wheat this image was one of the better single data sources.

4.1.3 C-VV SAR Data

Although a radiometric correction (see Section 3.2.2) was applied to this data set (Figure 4.3 Appendix A) effects from the antenna pattern were not entirely removed. In the lower portion of this image alternating strips (light and dark) are visible in the range direction.

The tonal contrasts between wheat and fallow are poor due to this banding effect. The row orientation effects are also quite apparent. The poor radiometric balance characterizing this image made it a poor candidate for a single source of classification.

4.1.4 L-HH SAR Data

The L-HH example (Figure 4.4 Appendix A) appeared to be the only image other than the C-VH which had a significant tonal contrast between wheat and fallow. Wheat was represented by the darker tones and the bows or row orientation effects were quite clear. It was interesting to note that the row orientation effects exhibited on the L-band example were evident across the entire range of the image, indicating no dependence on incidence angle.

Theoretically, the tonal responses representative of wheat and fallow on the L-HH image can be explained due to the frequency. The L-band SAR, having significantly longer wavelengths than either C- or X-bands, penetrates further into the target (crop or soil) and responses at L-band are due to an entirely different set of causal or target factors.

The dark representation of the wheat suggests that penetration

of the canopy cover and responses are due to surface soil features which were quite smooth. The fallow which is of a substantially lighter tone than wheat may be responding to soil moisture at subsurface levels. No ground data were collected to support this; thus it remains hypothetical.

4.1.5 X-HH SAR Data

Figure 4.5 (Appendix A) shows the X-HH SAR data. This image was of very poor quality and in the near range the image is nearly black. The sensor configuration of the CV-580 was always plagued by this problem and so good quality X-band data in this case were unavailable. The data were used in the present analysis to fulfil the requirements stated in the objectives. It was not unexpected that results were poor. The tonal contrasts in the better part of the image were good.

Unfortunately to allow spatial consistency with the other images, this poorer section could not be removed.

4.2 Maximum Likelihood Classification

The MLC software outputs a theme file or map as output (Section 3.3). Examples of a number of these theme files can be found in Appendix C. They are included as reference only

and are not directly used in the analysis. These classified theme files and the test files are compared using software on the image analysis system. Results are provided in percentage of pixels correctly classified. These percentages are documented here in Appendix B in both tabular and graphical form.

The eleven SAR combinations used in these classifications were: C-HH: C-VH: C-VV: L-HH: X-HH: C-HH/VH: C-HH/VV: C-VV/VH: C,X & L-HH: C-HH/VV/VH and the entire data set. The entire data set combination contains all of the five SAR passes available, C-HH, C-VV, C-VH, X-HH and L-HH. These combinations were used to help determine the best single SAR image, or combination of SAR images for crop discrimination. The results are structured for easy reference as was outlined in Table 4.1. Accuracies of less than 70% indicate poor crop discrimination capabilities. Due to the accuracies available with the VIR sensors, sometimes in excess of 95% accuracy, SAR results under 70% appear quite poor.

The assessment of frequency, polarization and row orientation effects will be inferred through the discussion of the accuracies associated with the classifications.

To reiterate, the classifications were undertaken on two major subgroups of ground cover type. The separability of wheat and

fallow was investigated using the two ground cover type. The three ground cover type was used to analyze the row orientation effects.

For the three ground cover type, designed to allow insight into the row orientation effects, the method of analysis is more complex. The three "crops" that will be used are fallow, wheat and bows. The bows are represented by higher backscatter and encompass approximately one third of the wheat in the field. Previous studies indicate that backscatter responses from row crops will vary with frequency, polarization and incidence angle (Hutton and Brown, 1984). The classification results representing the three ground cover types are found in Appendix B.

The single band SAR data provided the poorest results as was expected. As more SAR bands were included in the analysis it was anticipated that the results would be improved. Using this premise the simplest cases and combinations are presented first. As the more complex combinations and ground cover cases are considered a comparison with initial results will be attempted.

4.2.1 MLC Results for the Two Ground Cover Case

4.2.1.1 Fallow Unfiltered (Figure 4.6)

Fallow could be classified with accuracies which ranged from 62.7% to 91.1%. The lowest accuracy (62.7%) was associated with the X-HH SAR single classification, a result that was not unexpected in view of the poor tonal contrasts on this image.

The C-HH and C-HH/VV combinations were the only other data sets with accuracies below 79%. Classification accuracies for the entire group of combinations ranged from 79% for the C-VV example to 91.1 % for the entire data set combination.

In general, these results indicate that fallow can be accurately classified when two ground cover types are considered. The most significant single band SAR classifications were associated with the L-HH and C-VH data sets. When the combined sets were used the results from the entire data set were superior.

4.2.1.2 Fallow Filtered (Figure 4.7)

When maximum likelihood classifications are filtered, this author's experience (Hutton and Brown, 1984) has indicated

that good classifications prior to filtering usually have increased accuracies after filtering. The mid-range classifications (50-60%) accuracies remain static and the poorest are reduced. The results from the present study, when fallow was filtered, deviated from this expectation for a number of combinations.

Filtering had very little effect on the mid-range classification accuracies as anticipated. The magnitude of differences were between 0.8 and 3.9%. Of the original "good" classifications accuracies all increased with the exception of the C-HH/VV and C-VV/VH cases. The span of increases ranged from 3.7 to 10.4% with an mean increase of 7.7%. For the C-HH/VV example the accuracies were reduced from 71.2% before filtering to 39.3% after filtering. In the C-VV/VH combination the accuracies were reduced from 84.6% to 47.7% respectively.

4.2.1.3 Wheat Unfiltered (Figure 4.8)

Classification accuracies for unfiltered wheat were significantly poorer than those for unfiltered fallow. Four of the class combinations resulted in accuracies well below 50%. The poorest data set used was the C-HH with 11% accuracy followed by C-VV/HH at 26%, C-VV at 32.7% and C,X & L-HH at

47%. Two classifications had mid-range accuracies, the L-HH at 52.0% and X-HH at 59.7%.

The influences of frequency and polarization effects on SAR classification can be noted as the C-VH data were included in the classifications. The best classification accuracies ranged from 77.3% to 80.9% for C-VH/VV; C-HH/VV/VH; C-HH/VH; C-VH and the entire data set. The C-VH was the common element in the better results. Thus the conclusion can be made that the C-VH pass and any classification which included C-VH had reasonably good results. Five unfiltered combinations exhibited acceptable to good results when assessed for the discrimination of wheat.

4.2.1.4 Wheat Filtered (Figure 4.9)

Filtering of this wheat class significantly increased the disparity between the best and worst cases for classification accuracies. Four combinations are still very good, C-HH/VH, C-HH/VV/V, C-VH and the entire data set with accuracies of 89%, 90.5%, 91.5% and 88.9%, respectively.

Of the rest of the classification combinations used a few were found to have accuracies in the mid-ranges, 50-60%, although most were quite low. The poorest of these was reduced to

accuracies of 3.6 and 9.9% for C-HH and C-HH/VV combinations. Accuracies of less than 70% indicate poor crop discrimination capabilities.

It is worthwhile to note that the C-VH single SAR classification and those with which it was combined, were again among the best accuracies found.

4.2.2 MLC Results for the Three Ground Cover Case

4.2.2.1 Fallow Unfiltered (Figure 4.10)

In comparing the fallow unfiltered results from the two ground cover case with those found here the results associated with the three ground cover case were significantly poorer overall. In an attempt to increase the discrimination of wheat by separating it into two row orientations, the results for fallow were significantly reduced.

Specifically, there were four combinations with accuracies below 42% whereas previously (two crop class case) the lowest accuracy was 62.7%.

The poorest classifications found were for C-HH with 23.9%,

X-HH with 37.2%; C-VV with 41%; and C-HH/VV, with 41.4%. The rest of the classification combinations showed accuracies of at least 70% for the L-HH case and up to 91.2%, for the entire data set combination.

4.2.2.2 Fallow Filtered (Figure 4.11)

Those SAR combinations which were identified as having good accuracies for the unfiltered case, also remain the best filtered classifications although the absolute values were somewhat different. The good classifications had increased accuracies of 7.6% on average and the poor results were either reduced or remained constant.

4.2.2.3 Wheat Unfiltered (Figure 4.12)

As described earlier, "wheat" in the three ground cover case, was the portion of each wheat field with row orientations parallel to the look direction of the radar beam. This portion of the wheat field was (in most band/polarization combinations) darker than the "bows" segment. In an attempt to use this phenomenon as a method to increase classification

accuracies of row crops, each row orientation was trained on separately and assumed to be a different ground cover type.

Subdividing ground cover types on the basis of row orientation relative to the look direction of the radar and treating each subgroup increased the overall classification accuracy. Only one extremely poor classification was found to exist using the wheat unfiltered case, that of X-HH which had an accuracy of 20%.

One intermediate accuracy of 55.8% was found to be associated with the C-VH example. All the other examples or combinations had accuracies in excess of 75% (for C-VV) and increased to 91.7% for the entire data set. Nine combinations displayed accuracies in excess of 75% and five of those were over 85%.

4.2.2.4 Wheat Filtered (Figure 4.13)

With the exception of the X-HH SAR data, filtering increased the classification accuracies by an average of 6.3%. The classification accuracies, with the exception of the X-HH (at 14.8%) and the C-VH case (60.1%), all had accuracies in excess of 86.8% and six exceeded 90%.

The accuracies associated with the C-HH/VV/VH example were 97% and from the entire data set 99.9%, the highest accuracies found so far.

4.2.2.5 Bows Unfiltered (Figure 4.14)

The previous discussion of the wheat ground cover case outlined the improvement in the results which can be expected when the two row orientations for wheat are considered separately. Following is a discussion of the results for the portion of wheat labelled "bows" or wheat with row orientations orthogonal to the look direction of the radar.

Although there was little difference between the best and worst classifications for the "bows", they exhibited the poorest overall results of any ground cover class assessed.

None of the classification combinations showed results in the 90% range and only three were in the 80% range. The majority of the results indicated the best classification accuracies that could be expected were between 70%-80%.

The best classification accuracy was associated with the L-HH data set and had an accuracy of 86.6%. The author's previous

experience (Hutton, 1984) has shown that L-band parallel polarized data, regardless of date of acquisition, quite often provided greater contrast between the two row orientations of wheat than the other bands and polarizations under study.

4.2.2.6 Bows Filtered (Figure 4.15)

As was found with the classification of fallow (two ground cover case) the post filtering of the bows data set reduced the overall accuracies. In addition, the accuracies after filtering were reduced in every combination used. The accuracies were reduced by an average of 19.6% and a maximum of 46.6%. The unfiltered and filtered results are too poor to be useful as a method for crop discrimination.

4.3 Field Classification Results - Two Ground Cover Case

The field classification technique (described in Section 3.6) is considered by many investigators to be superior to the pixel method as a means of SAR classification analysis, as suggested by Megier et al., 1984.. It can be argued that if a certain number of pixels (or threshold) has been correctly classified the proportion of these pixels is not important, only the conclusion that the field was correctly classified.

Natural variations are expected within any crop or field. Homogeneity may be unrealistic to expect particularly considering the numerous, often subtle, factors affecting SAR signatures. In addition, noise and speckle, inherent in SAR imagery by the very nature of its collection mechanisms, will invariably cause misclassification of some pixels.

The results from the field classification method can be found in Appendix D and represent the unfiltered information only. Only unfiltered data were assessed since the objective was to compare the methodologies derived here, not undertake the entire analysis a second time. The varying results which have been associated with the classification filtering previously discussed lend additional support to the choice of the unfiltered data to conduct this portion of this exercise. The thresholds assessed include 50%, 70% and 85% levels or correctly classified pixels, for the two and three ground cover cases. All classification combinations have been included. These arbitrarily chosen levels were intended to represent poor, acceptable and good cases.

4.3.1 Fallow and Wheat 50% Threshold

Table 4.3 indicates the results associated with fallow for a threshold of 50%. As can be noted the general accuracies

associated with the field classification method using a 50% threshold are superior to the pixel classifier. Accuracies of 100% were found for C-VH, C-HH/VH, C-VH/VV, C-HH/VH/VV and the entire data set. The only poor field classifications resulted when the X-HH data were used and an accuracy of 55% was discovered, actually lower than the pixel classifier (62.7%). The rest of the accuracies associated with the field classifier were increased over their pixel classifier counterparts.

For wheat the field classifier method (Table 4.4) yielded much poorer accuracies than those associated with the pixel method. The best classification accuracy was 77% for C-VH; all the others were less than 65%. It was interesting to note that the accuracy for the entire data set (all five SAR passes) for the pixel classification was 80.9% while this was reduced by the field classifier to 53%.

4.3.2 Fallow and Wheat 70% Threshold

The field classifier results for fallow (Table 4.5) were 70% for the 70% threshold. They were quite good with the three exceptions of C-VV, X-HH and C-HH/VV. The remaining field classifiers had accuracies in excess of 70% and six cases were over 85%.

For the 70% threshold of the wheat class (Table 4.6) the results were extremely poor. In all cases the field classifier was poorer than 58%. Many, including C-VV, L-HH, C-HH/VV, C, X & L-HH, were below 20% accuracy.

4.3.3 Fallow and Wheat for 85% Threshold

As might be expected as the threshold is increased, the accuracies associated with each SAR combination was decreased. The results seen with the 50% and 70% threshold levels (exception of Fallow at 50% threshold) were all quite poor and at the 85% threshold are of limited, if any use in the present SAR analysis.

For fallow (Table 4.5) only three combinations C-VH/VV, C-HH/VV/VH and the entire data set had accuracies of 75%, the rest of the combinations were very poor, bottoming out at 40% for the X-HH example.

The results for wheat (Table 4.8) were extremely poor indicating wheat could not be classified with a confidence level of 85%. The best accuracy was 45% for the L-HH example and reached as low as 7% for the C-VV and 5% for the C-VH/VV combination.

In general when the two crop class case is considered the results from the pixel classifier method using unfiltered data were far superior overall and post MLC filtering was a much more effective method of removing anomalous pixels than was the field classifier method even at a threshold of 50%.

A variety of studies have used a field classifier. Among these, Megier et al. (1984) compared a field and pixel classification method using SPOT and SAR data concluding that the field method permitted improved classification results. Ulaby et al. (1982) also found increased accuracies associated with the field method. No significant variation was found between these two works and the present, nor was a viable explanation for the poor results shown here identified.

4.3. Field Classification Results - Three Ground Cover Case

Although a number of the accuracies associated with these three crop classes using the field classification technique were increased to 100%, (various thresholds) in general the results showed sporadic increases and decreases. This method (field classification) appears to provide results that are not statistically or logically explainable.

The three crop class results can be found in Appendix D

(Tables 4.6 to 4.8) but will not be discussed here since the results are so poor.

The field classification method provided extremely poor overall results on its own and in comparison with the pixel classification method was proved to be inadequate with the data used here.

CHAPTER 5

CONCLUSIONS

The ability to monitor crops has been identified as a major concern to Canada (Brown et al, 1986). Having the ability to predict or forecast the yields both nationally and internationally would be economically beneficial to Canada. Remote sensing techniques have a great potential for assisting with agricultural resource management. Due to limitations with the VIR sensors and since a number of SAR satellites will be operational in the 1990s, recent research emphasis in Canada has been aimed toward developing procedures and techniques to use these data accurately and efficiently when they become available. Presently data from a number of airborne SAR sensors are being used to simulate data from future satellite sensors.

The first step toward operational crop monitoring and condition assessment is crop discrimination. The response or backscatter from targets illuminated by microwave energy is unique. In addition, the need to determine crop type characteristics, both target and sensor parameters, exerting an influence over the signal response from SAR, still remain to be defined and understood sufficiently. Much of the

present work in the Canadian remote sensing community emphasizes this need.

The purpose of this study has been to build on the work being carried out at the Canada Centre for Remote Sensing. This work has been designed using SAR to test a methodology for determining crop type early in the growing season, while taking into account row orientation effects. The pixel classification methodology or Maximum Likelihood Classification (MLC) was used as the major method of data analysis. Post classification filtering as well as field classification techniques were assessed for their potential as alternative methods. Crop row orientation is known to have an adverse effect on the homogeneity of SAR signatures from various crops. In an attempt to remove or reduce these effects a second stage of analysis was incorporated into the methodology. First the potential for discrimination was carried out assuming only two ground cover types existed (fallow and wheat). To evaluate the influence of row orientation the entire procedure was repeated using three ground cover types, fallow, wheat and bows.

The conclusions have been structured in the same format as the analysis section to allow easy reference. Each method will be discussed individually, based on band and polarization combinations. General conclusions related to the entire

effort and recommendations for improvement and future work follow.

5.1 General Tonal Properties

The first discussion in the analysis and results section concerns the general tonal properties of the images used in this study. This discussion is designed to provide a general impression of the expected performance of the data, for classification, based on the visual analysis of the images. The data used were C-HH, C-VV, C-VH, L-HH, and X-HH. Later in the study these data were combined to assess the significance and accuracy possible with more than one band or polarization.

The C-HH SAR data show minimal contrast between the two ground cover types, often exhibiting opposing tonal contrast between fallow and wheat. Row orientation effects were evident in the wheat fields and are a result of the orthogonal orientation of the rows to the radar look direction. Brown et al. (1984) suggested confusion between these two crop types to be related to the roughness of the soil in the fallow fields. The size of the clods of earth and possibly trash remaining in the field could increase the returns expected from fallow. A

preference for C-VV SAR over C-HH was noted by Teillet et al. (1984). The increased coupling of the vertical polarized waves and the wheat was represented by higher backscatter. Reversing this theory lower backscatter values would be expected with the C-HH data. The interaction of these two opposing characteristics could help explain the confusion found between the crop types on the C-HH data. The tonal contrast on individual SAR passes (with the exception of the C-VH data) was insufficient to provide the information necessary to conduct an acceptable classification.

The C-VH SAR provided a much greater contrast between the two ground cover types. Very faint row orientation effects were exhibited although not strongly enough to confuse the classifications. Rosenthal and Blanchard, (1984) noted C-band cross polarized (HV) data was more sensitive to crop differences than was the HH data. This was based on the sensitivity of the like polarized data to row orientation effects. This band and polarization proved to be one of the better combinations as both a single data source and in combination with the others, due to the distinctive contrast between wheat and fallow. As the only cross-polarized data set C-VH indicates the importance of polarization.

Although a preference was noted with the C-VV data earlier, many of the poorer results were associated with this frequency

and polarization. Residual effects due to antenna pattern which could not be removed adequately were prominent. These radiometric effects produced tonal properties not related to the targets and reduced the expected performance of this data.

The L-HH data exhibited very good contrast between the ground cover types. Also in evidence were row orientation effects. They appear to be independent of incidence angle as their even contrast across the entire range of the imagery indicates. Since all the data were collected early in the growing season and theory states a greater penetration of L-band wavelengths into the crop and soil, L-band was not a good choice for crop discrimination during this period of plant phenology. The responses seen are more likely due to surface roughness variations and row orientation effects than the crop type. Cihlar and Hirose (1984) also found the row orientation to be strong on the L-HH images used in their investigations at the Swift Current site. Since investigators at other sites (Melfort, Brown et al., 1984) have found no evidence of row orientation effects we must assume other factors in addition to row orientation also exert an influence. The growth stage, height and condition of the crop are suggested as secondary concerns or causal factors. Through extrapolation the L-band data did allow separation between the two ground cover types assessed, although uncertainty in the nature of the response resulted.

The X-HH SAR data were adversely affected by antenna pattern. The results from the X-HH SAR as a single data source and in combination with the others resulted in poor ground cover discrimination. In hindsight, these data should not have been used, but they were necessary to fulfil the objectives. It is unfortunate that better X-Band data were not available. X-HH data has been noted (Brown et al., 1984) to provide good crop type discrimination. X-band data due to its short wavelengths responded to the roughness or structure variations in the canopy itself (Brown et al., 1990). The poor results obtained from X-band do not warrant it's exclusion in future efforts. Although the CV-580 sensor produced some poor quality X-band data, not all was as poor as the pass used in the experiment. The new C and X-band SAR and privately owned X-band sensors provide excellent data and studies using these alternate sources have proven more useful.

Single date, single band and single polarization SAR data were not expected to produce good classification accuracies. The combination of data was undertaken to determine the most compatible grouping of SAR band and polarization combinations.

5.2 Maximum Likelihood Classification

The maximum likelihood classification technique proved to be the best method for agricultural ground cover determination used here. The fallow was classified with increasingly high accuracies with the two ground cover case, as the data were combined. It appeared that the greater the number of bands and polarizations used, the more accurate the results. This suggests that each band and polarization possesses unique crop discrimination information highlighted in combination. However, when the three ground cover case was used or the two row orientations of wheat were considered, results from fallow were reduced. The tonal contrasts between fallow and wheat, which appeared separable visually, were shown to be insufficient when the digital data were assessed. When the higher responses from the "bows" were removed from the wheat signature, the contrast and possible discrimination between wheat with rows parallel to the look direction of the radar and fallow were reduced. The basis for MLC is the likelihood that one ground cover type exists uniquely over another. The signatures from the fallow and wheat with rows parallel to the radar look direction were confused, and the algorithm determined wheat to be more likely than fallow. Even with the limitations discussed, fallow was most consistently discriminated overall and in most cases provided the greatest accuracies seen.

In contrast the wheat, and with less consistency the bows, showed higher classification accuracies when the three ground cover case was used.

In general, the poorest classification accuracies were associated with single band and polarization cases. The X-HH, C-HH and C-VV being among the poorer. Using combinations of the data, C-HH/VV was found among the poorest combined classifications, although some dependence on ground cover type or the number of ground cover types used was exhibited.

5.3 Filtering of the Classification Results

Experience has indicated the filtering of the MLC will increased the overall accuracies associated with the better combinations, and reduced those from the poor. The nature of pixel classification is to assess individual pixels for their inclusion in a crop class. With SAR imagery the value of each pixel may be composed not only of a response from the ground target but also include system influences such as speckle or remnant antenna pattern effects. Filtering is an acceptable method for the removal of anomalies from the classifications. This technique was designed to improve the better classifications. The results from the poorer classifications,

as well as an inability to discriminate between the crops are of little use to the investigator. The poorer classifications were often well below the suggested 70% level prior to filtering. Thus the filtered results proved no more useful than the originals.

5.4 Field Classification Methodology

The principle behind field classification remains sound. When a certain acceptable number (or percentage) of pixels within a field are classified as members of one ground cover type, the entire field is concluded to be that cover type. After much consideration the reason for the failure of this method was postulated. An assumption was made that a 70% classification accuracy for ten fields indicates that approximately 70% of the pixels in each field have been identified correctly. Assume that three of ten fields assessed had 95% of their pixels correctly classified and seven had 65% correctly classified. This would result in a 74% classification accuracy with the pixel method. However, with the field methodology, only 3 of 10 fields reached a threshold of 70% or greater, resulting in a 30% accuracy. The varied results from these two methods indicates the lack of homogeneity between and within the ground cover classes. This variation in signatures could be associated with the SAR's response to minute differences in crop phenology early in the

season.

The choice of method and associated implications of that choice, could be debated indefinitely. For the purposes of the present study and using the classification accuracies derived, the field classification method was shown to be extremely poor.

5.5 Summary

In summary the conclusions of this work are:

1. Single band/polarization SAR data provided inconsistent classification results.
2. The C-VH SAR data was the best single data source used. When combined with some of the others, it produced even more reliable classification accuracies.
3. The X-HH SAR did not provide a satisfactory level of crop discrimination. The poor quality of this band and polarization were due to antenna pattern effects and does not adequately represent its potential. The new CCRS SAR sensor collected superior quality X-Band data over sites in 1989 and

1990 (Personal experience and communication with CCRS scientists).

4. The best classifications were obtained when the entire set of bands and polarizations were used in combination. The next most significant results were found with the C-band combination of the VV/VH/HH polarizations.
5. SAR can produce crop discrimination results similar to those found with the VIR sensors, if used in a multi-band or multi-polarization context.
6. The field classification method proved to be entirely unsuitable for crop discrimination within the realms of the present effort.
7. Filtering of the Maximum Likelihood Classifications resulted in an overall improvement of the better accuracies. However, when the results were poor this method tended to reduce the accuracies.
8. The period in the crop phenological cycle during which these data were collected (emerging vegetation) was too early to assume SAR responses were entirely or predominantly from the wheat

canopy. Mid-season data may have provided better results for some of the band and polarization combinations since the crop would be more advanced and provide a greater scattering surface. In addition, the influence of crop row structure might be reduced.

9. Due to the early acquisition date of the SAR data penetration of the crop canopy may be occurring, and the responses could be influenced more by soil roughness or moisture, especially at L-Band.
10. Combining the SAR data improved overall classification accuracies as each band and polarization possesses unique crop discrimination information highlighted in combination.
11. The use of wheat as two separate ground cover classes to reduce row orientation effects displayed mixed results. As a general tool or method it obviously displayed better results on those images where significant row orientation effects had been noted (L-HH and C-VH). Unfortunately, when the results from wheat were improved using this method, in most cases the fallow results were reduced.

12. Fallow was most accurately discriminated from other ground cover types when the two ground cover case was assessed. Overall, the results from the two wheat segments or row orientations were better when the three ground cover case was used, indicating the significance of row orientation. For the best results a combination of the two methods introduced here should be considered.

Airborne SAR sensors are now available in which the quality of the data collected is superior to that used in this study. A better quality data set may have provided significantly improved results. Due to the unique nature of SAR and the often variable interaction between microwaves and crops, a standard method of analysis is difficult to identify. Data quality and availability in addition to the ground cover types imaged will lend insight in the determination of a methodology.

5.6 Recommendations for Future Work

The methods used in this study were useful although some of the results were inconsistent. Improved results might have been obtained had the growth stage of the crop been more

advanced. Considering the conclusions, future work towards the improvement of these methods is suggested below. These procedures are a logical continuation of the work conducted within the context of this thesis.

1. Assess the methods used in this thesis under mid-season or multi-temporal conditions.
2. Acquire a better quality data set and repeat the methodology outlined here (e.g. C- and X-band SAR from the new CCRS sensor).
3. Reassess the field classification methodology at a different site or under different conditions.

When scientific research is undertaken the investigator always hopes the results will be irrefutable. In reality extrapolations and interpretation are usually necessary. The findings lend some insight into the validity of the methodologies used and further the understanding of SAR band and polarization dependencies with respect to crop discrimination. Areas of future work have also been indicated by the analysis. Scientific research is often a series of building blocks allowing us to improve on previous works and outline areas of credible future research.

APPENDIX A

Contained within this appendix are photographic reproductions of the data used in this work.

FAR RANGE

**LOOK
DIRECTION** ↑

NEAR RANGE

FIGURE 4.1 C-HH SAR DATA

FAR RANGE

NEAR RANGE

LOOK
DIRECTION ↑

FIGURE 4.2 C-VH SAR DATA

FAR RANGE

NEAR RANGE

LOOK
DIRECTION ↑

FIGURE 4.3 C-VV SAR DATA

FAR RANGE

LOOK
DIRECTION ↑

NEAR RANGE

FIGURE 4.4 L-HH SAR DATA

FAR RANGE

NEAR RANGE

LOOK
DIRECTION ↑

FIGURE 4.5 X-HH SAR DATA

APPENDIX B

This appendix contains the results from the Maximum Likelihood Classifications in both tabular and graphical forms.

Table 4.2 indicates the classification accuracies associated with each band and polarization combination used in this exercise. Clearly identified are the two and three ground cover cases as well as the unfiltered and filtered methods.

2

of/de

2

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Table 4.2 CLASSIFICATION ACCURACIES - PERCENT OF 100

Two Ground Cover Class	Sar Combinations										Entire Data Set
	C-HH	C-VH	C-VV	L-HH	X-HH	C-HH C-VH	C-HH C-VV	C-VV C-VH	C-HH X-HH L-HH	C-HH C-VV C-VH	
Fallow Un-filtered	70.9	80.7	79.0	81.0	62.7	85.4	71.2	84.6	85.	86.6	91.1
Fallow Filtered	74	88.5	82.7	86.2	61.9	95.8	39.3	47.7	93	96.2	99.7
Wheat Un-filtered	11.6	82	32.7	52	59.7	80.3	26	77.3	47	80	80.9
Wheat Filtered	3.6	91.5	31.4	54	61.6	89	9.9	43	51.5	90.5	88.9
Three Ground Cover Class											
Fallow Un-filtered	23.9	72.0	41	70	37.2	81.5	41.4	80.5	78.4	83.9	91.2
Fallow Filtered	18.7	80.5	41.8	75.6	37.1	95.5	43.5	91.1	87.2	97.7	99.8
Wheat Un-filtered	87.6	55.8	75.6	89	20.2	87.6	80.8	77.6	86.2	84.2	91.7
Wheat Filtered	95.1	60.1	87.2	95.6	14.8	97.5	89.2	93.6	86.8	97.0	99.9
Bows Un-filtered	41.5	50.3	79.1	86.6	58.6	34.6	74	74.3	85	71.6	82.7
Bows Filtered	20.8	48.8	69.9	86	56.9	20	69.9	70.3	38.4	63.8	79.9

FALLOW CLASSIFICATION ACCURACIES
UNFILTERED - TWO GROUND COVER CASE

BAND/POLARIZATION COMBINATIONS-

FIGURE 4.6

FALLOW CLASSIFICATION ACCURACIES
 FILTERED - TWO GROUND COVER CASE

FIGURE 4.7

WHEAT CLASSIFICATION ACCURACIES
UNFILTERED - TWO GROUND COVER CASE

FIGURE 4.8

WHEAT CLASSIFICATION ACCURACIES
FILTERED - TWO GROUND COVER CASE

FIGURE 4.9

FALLOW CLASSIFICATION ACCURACIES
UNFILTERED - THREE GROUND COVER CASE

FIGURE 4.10

FALLOW CLASSIFICATION ACCURACIES
 FILTERED - THREE GROUND COVER CASE

FIGURE 4.11

WHEAT CLASSIFICATION ACCURACIES
UNFILTERED - THREE GROUND COVER CASE

FIGURE 4.12

WHEAT CLASSIFICATION ACCURACIES
 FILTERED - THREE GROUND COVER CLASS

FIGURE 4.13

**BOWS CLASSIFICATION ACCURACIES
UNFILTERED - THREE GROUND COVER CASE**

FIGURE 4.14

**BOWS CLASSIFICATION ACCURACIES
FILTERED - THREE GROUND COVER CASE**

BAND/POLARIZATION COMBINATIONS

FIGURE 4.15

APPENDIX C

Photographic reproductions of the computer screen are displayed in this appendix and indicate the theme results from the Maximum Likelihood classifications for both the unfiltered and filtered cases. Used only as a reference, a subset of the original themes available were chosen for reproduction. Included are the two ground cover case for C-VH and the entire data set and the corresponding three ground cover cases for the same bands. The colours on these photographs indicate the following;

Two ground cover case

red = fallow

green = wheat

Three ground cover case

red = fallow

blue = wheat

green = bows

FIGURE C-1

MLC THEME FILES FOR THE TWO GROUND COVER CASE

C-VH

UNFILTERED

FILTERED

FIGURE C-2
MCL THEME FILES FOR THE TWO GROUND COVER CASE
ENTIRE DATA SET

UNFILTERED

FILTERED

FIGURE C-3

MLC THEME FILES FOR THE THREE GROUND COVER CASE

C-VH

UNFILTERED

FILTERED

FIGURE C-4
MLC THEME FILES FOR THE THREE GROUND COVER CASE
ENTIRE DATA SET

UNFILTERED

FILTERED

APPENDIX D

FIELD CLASSIFICATION RESULTS

TABLE 4.3
FIELD CLASSIFICATION DATA
50 THRESHOLD TWO CROP CASE

BAND/POLARIZATION	CROP	THRESHOLD	ACCURACY
C-HH	FAL	50	85
C-VH	FAL	50	100
1C-VV	FAL	50	90
L-HH	FAL	50	95
X-HH	FAL	50	55
C-HH/VH	FAL	50	100
C-HH/VV	FAL	50	75
C-VH/VV	FAL	50	100
C, X & L-HH	FAL	50	95
C-HH/VV/VH	FAL	50	100
ALL COMB	FAL	50	100
C-HH	WHT	50	23
C-VH	WHT	50	77
C-VV	WHT	50	32
L-HH	WHT	50	37
X-HH	WHT	50	63
C-HH/VH	WHT	50	56
C-HH/VV	WHT	50	32
C-VH/VV	WHT	50	60
C, X & L-HH	WHT	50	36
C-HH/VV/VH	WHT	50	65
ALL COMB	WHT	50	53

TABLE 4.4**FIELD CLASSIFICATION DATA****70 THRESHOLD TWO CROP CASE**

BAND/POLARIZATION	CROP	THRESHOLD	ACCURACY
C-HH	FAL	70	70
C-VH	FAL	70	75
C-VV	FAL	70	65
L-HH	FAL	70	85
X-HH	FAL	70	40
C-HH/VH	FAL	70	90
C-HH/VV	FAL	70	60
C-VH/VV	FAL	70	85
C, X & L-HH	FAL	70	90
C-HH/VV/VH	FAL	70	90
ALL COMB	FAL	70	95
BAND/POLARIZATION	CROP	THRESHOLD	ACCURACY
C-HH	WHT	70	06
C-VH	WHT	70	58
C-VV	WHT	70	18
L-HH	WHT	70	16
X-HH	WHT	70	58
C-HH/VH	WHT	70	40
C-HH/VV	WHT	70	19
C-VH/VV	WHT	70	47
C, X & L-HH	WHT	70	18
C-HH/VV/VH	WHT	70	47
ALL COMB	WHT	70	44

TABLE 4.5
FIELD CLASSIFICATION DATA
85 THRESHOLD TWO CROP CASE

BAND/POLARIZATION	CROP	THRESHOLD	ACCURACY
C-HH	FAL	85	50
C-VH	FAL	85	60
C-VV	FAL	85	65
L-HH	FAL	85	60
X-HH	FAL	85	40
C-HH/VH	FAL	85	65
C-HH/VV	FAL	85	50
C-VH/VV	FAL	85	75
C, X & L-HH	FAL	85	65
C-HH/VV/VH	FAL	85	75
ALL COMB	FAL	85	75

BAND/POLARIZATION	CROP	THRESHOLD	ACCURACY
C-HH	WHT	85	0
C-VH	WHT	85	15
C-VV	WHT	85	07
L-HH	WHT	85	45
X-HH	WHT	85	27
C-HH/VH	WHT	85	08
C-HH/VV	WHT	85	29
C-VH/VV	WHT	85	05
C, X & L-HH	WHT	85	34
C-HH/VV/VH	WHT	85	20
ALL COMB	WHT	85	34

TABLE 4.6
FIELD CLASSIFICATION DATA
70 THRESHOLD THREE CROP CASE

BAND/POLARIZATION	CROP	THRESHOLD	ACCURACY
C-HH	FAL	70	10
C-VH	FAL	70	60
C-VV	FAL	70	30
L-HH	FAL	70	65
X-HH	FAL	70	30
C-HH/VH	FAL	70	80
C-HH/VV	FAL	70	20
C-VH/VV	FAL	70	75
C, X & L-HH	FAL	70	65
C-HH/VV/VH	FAL	70	85
ALL COMB	FAL	70	100
C-HH	WHT	70	87
C-VH	WHT	70	22
C-VV	WHT	70	100
L-HH	WHT	70	87
X-HH	WHT	70	45
C-HH/VH	WHT	70	87
C-HH/VV	WHT	70	83
C-VH/VV	WHT	70	74
C, X & L-HH	WHT	70	87
C-HH/VV/VH	WHT	70	83
ALL COMB	WHT	70	96
C-HH	BOWS	70	26
C-VH	BOWS	70	10
C-VV	BOWS	70	56
L-HH	BOWS	70	72
X-HH	BOWS	70	59
C-HH/VH	BOWS	70	23
C-HH/VV	BOWS	70	51
C-VH/VV	BOWS	70	54
C, X & L-HH	BOWS	70	69
C-HH/VV/VH	BOWS	70	54
ALL COMB	BOWS	70	66

WHT=WHEAT ROWS PARALELL TO RADAR LOOK DIRECTION

BOWS= WHEAT ROWS ORTHOGONAL TO RADAR LOOK DIRECTION

TABLE 4.7
FIELD CLASSIFICATION DATA
50 THRESHOLD THREE CROP CASE

BAND/POLARIZATION	CROP	THRESHOLD	ACCURACY
C-HH	FAL	50	20
C-VH	FAL	50	80
C-VV	FAL	50	40
L-HH	FAL	50	75
X-HH	FAL	50	50
C-HH/VH	FAL	50	95
C-HH/VV	FAL	50	45
C-VH/VV	FAL	50	91
C, X & L-HH	FAL	50	100
C-HH/VV/VH	FAL	50	96
ALL COMB	FAL	50	100
C-HH	WHT	50	100
C-VH	WHT	50	48
C-VV	WHT	50	91
L-HH	WHT	50	100
X-HH	WHT	50	
C-HH/VH	WHT	50	91
C-HH/VV	WHT	50	91
C-VH/VV	WHT	50	72
C, X & L-HH	WHT	50	82
C-HH/VV-VH	WHT	50	72
ALL COMB	WHT	50	82
C-HH	BOWS	50	33
C-VH	BOWS	50	49
C-VV	BOWS	50	77
L-HH	BOWS	50	87
X-HH	BOWS	50	91
C-HH/VH	BOWS	50	31
C-HH/VV	BOWS	50	69
C-VH/VV	BOWS	50	72
C, X & L-HH	BOWS	50	90
C-HH/VV/VH	BOWS	50	100
ALL COMB	BOWS	50	100

WHT=WHEAT ROWS PARALELL TO RADAR LOOK DIRECTION

BOWS= WHEAT ROWS ORTHOGONAL TO RADAR LOOK DIRECTION

TABLE 4.8
FIELD CLASSIFICATION DATA
85 THRESHOLD THREE CROP CASE

BAND/POLARIZATION	CROP	THRESHOLD	ACCURACY
C-HH	FAL	85	100
C-VH	FAL	85	50
C-VV	FAL	85	20
L-HH	FAL	85	60
X-HH	FAL	85	15
C-HH/VH	FAL	85	50
C-HH/VV	FAL	85	10
C-VH/VV	FAL	85	65
C, X & L-HH	FAL	85	40
C-HH/VV/VH	FAL	85	60
ALL COMB	FAL	85	85
C-HH	WHT	85	26
C-VH	WHT	85	17
C-VV	WHT	85	35
L-HH	WHT	85	70
X-HH	WHT	85	70
C-HH/VH	WHT	85	74
C-HH/VV	WHT	85	60
C-VH/VV	WHT	85	20
C, X & L-HH	WHT	85	57
C-HH/VV/VH	WHT	85	57
ALL COMB	WHT	85	83
C-HH	BOWS	85	0
C-VH	BOWS	85	0
C-VV	BOWS	85	51
L-HH	BOWS	85	54
X-HH	BOWS	85	41
C-HH/VH	BOWS	85	18
C-HH/VV	BOWS	85	44
C-VH/VV	BOWS	85	41
C, X & L-HH	BOWS	85	59
C-HH/VV/VH	BOWS	85	33
ALL COMB	BOWS	85	51

WHT=WHEAT ROWS PARALELL TO RADAR LOOK DIRECTION

BOWS= WHEAT ROWS ORTHOGONAL TO RADAR LOOK DIRECTION

APPENDIX E

GLOSSARY

GLOSSARY

The terms described are found in the present work and relate to their definitions as they are used in remote sensing. Many of these are taken directly or partially from the Manual of Remote Sensing, 1983, American Society of Photogrammetry, Vol 1, pp 1183-1198.

Accuracy	The success in estimating the true value. The closeness of an estimate of a characteristic to the true value of the characteristic of the population.
Active Microwave	Ordinarily referred to as a radar.
Active System	A remote sensing system that transmits its own electromagnetic energy at an object(s) and then records the energy reflected or refracted back to the sensor.
Algorithm	(1) A fixed step-by-step procedure to accomplish a given result: usually a simplified procedure for solving a complex problem: also a full statement of a finite number of steps (2) A computer-oriented procedure for resolving a problem.
Altitude	Height above a datum: the datum is usually mean sea level.
Ancillary data	In remote sensing, secondary data pertaining to the area or classes of interest, in this case information concerning crop type, growth stage, condition, height, etc.
Angle of depression	In SLAR or SAR usage, the angle between the horizontal plane passing through the antenna and the line connecting the antenna and the target.
Angle of incidence	(1) The angle between the direction of incoming EMR and the normal to the intercepting surface; (2) In SLAR or SAR systems this is the angle between the vertical and a line connecting antenna and target.

Attenuation	In physics, any process in which the flux density (or power, amplitude, intensity, illuminance) of a "parallel beam" of energy decreases with increasing distance from the energy source.
Azimuth	The geographical orientation of a line given as an angle measured clockwise from north.
Backscatter	The scattering of radiant energy into the hemisphere of space bounded by a plane normal to the direction of the incident radiation and lying of the same side as the incident ray; the opposite of forward scatter. Also called backscattering.
Band	(1) A selection of wavelengths. (2) Frequency band. (3) A range of radar.
Beam	A focused pulse of energy.
Bit	An abbreviation of binary digit.
Byte	A group of eight bits of digital data.
Classification	The process of assigning individual pixels of an image to categories, generally of the basis (in SAR) of backscattered strength or gray tones.
Coherent	(1) Of EMR, being in phase, so that waves at various points in a space act in unison, as in a laser producing coherent light. (2) Having a fixed relation between frequency and phase of input and output signal.
Contrast stretching	Improving the contrast of images by digital processing. The original range of digital values is expanded to utilize the full contrast range of the recording film or display device.
Decision rule (or classification rule)	The criterion used to establish discriminant functions for classification (eg. maximum likelihood rule or nearest neighbour rule)
Doppler effect	A change in the observed frequency of EM or other waves caused by relative motion

between the source and the observer.

Dynamic range The ratio of maximum measurable signal to minimum detectable signal.

Filtering In analysis, the removal of certain spectral or spatial frequencies to highlight features in the remaining image. In SAR the means by which the speckle is reduced in the image.

Frequency Number of oscillations per unit time or number of wavelengths that pass a point per unit time. The frequency bands used by radar were first designated by letters for military secrecy. Those designations are:

Frequency	GHz range	Wavelength range (cm)
P-band	.225-.39	140-76.9
L-band	.39-1.55	76.9-19.3
S-band	1.55-5.20	19.3-5.77
X-band	5.0-10.90	5.77-2.75
K-band	10.90-36.0	2.75-.834
C-band	3.9-6.2	5.3-7.5

Gain (1) A general term used to denote an increase in signal power in transmission from one point to another. Gain is usually expressed in decibels. (2) An increase or amplification.

GCP Ground control point. A geographical feature of known location that is recognizable on images and can be used to determine geometrical corrections.

Gray Scale A sequence of gray tones ranging from black to white.

Ground range The distance from the ground track (nadir) to a given object.

Ground truth	(jargon) Term coined for data and information obtained on surface or subsurface feature to aid in the interpretation of remotely sensed data. Ground data and ground information are preferred terms.
Histogram	The graphical display of a set of data which shows the frequency of occurrence (along the vertical axis) of individual measurements or values (along the horizontal axis); a frequency distribution.
Image	(1) The counterpart of an object produced by the reflection or refraction of light when focused by a lens or mirror. (2) The recorded representation (commonly as a photo-image) of an object produced by optical, electro-optical, optical mechanical, or electronic means. It is generally used when the EMR emitted or reflected from a scene is not directly recorded on film.
Image processing	Encompasses all the various operations that can be applied to photographic or image data.
LGSOWG	Landsat Ground Stations Operating Working Group, pronounced LOGSWOG is a family of tape formats standardized in 1980 by the Landsat Technical Working Group. It describes the information and layout of the data on the tape.
Look direction	Direction in which pulses of microwave energy are transmitted by a SLAR or SAR system. Look direction is normal to the azimuth direction.
Maximum Likelihood rule	A statistical decision criterion to assist in the classification of overlapping signatures; pixels are assigned to the class of highest probability.
Microwave	A very short EM wave; any wave between 1 meter and 1 millimetre in wavelength or 300 GHz to 0.3 GHz in frequency. The

portion of the electromagnetic spectrum in the millimetre and centimetre wavelengths, bounded on the short wavelength side by the far infrared (at 1mm) and on the long wavelength side by very high-frequency radio waves. Passive systems operating at these wavelengths sometimes are called microwave systems. Active systems are called radar, although the literal definition of radar requires a distance-measuring capability not always included in active systems. The exact limits of the microwave region are not defined.

Mosaic	An assemblage of overlapping aerial or space photographs or images whose edges have been matched to form a continuous pictorial representation of a portion of the Earth's surface.
Nadir	That point on the ground vertically beneath the perspective center of the camera lens or in case of the airborne radar directly below the aircraft.
Near range	Refers to the portion of a SAR image closest to the aircraft flight path.
Noise	Random or regular interfering effects in data which degrade its information-bearing quality.
Passive system	A sensing system that detects or measures radiation emitted by the target. Compare to active system.
Polarization	The direction of vibration of the electrical field vector of electromagnetic radiation. In SAR systems polarization is either horizontal or vertical.
Pulse	(1) A variation of a quantity whose value is normally constant; this variation is characterized by a rise and a decay, and has a finite duration. (2) A short burst of EMR transmitted by the radar.
Radar	Acronym for RADio Detection and Ranging. A method, system or technique including

	equipment components, for using beamed, reflected, and timed EMR to detect, locate, and (or) track objects, to measure altitude and to acquire a terrain image. In remote sensing of the Earth's or a planetary surface, it is used for measuring and, often, mapping the scattering properties of the surface.
Radar beam	The vertical fan-shaped beam of EM energy produced by the radar transmitter.
Radar, SAR	A radar in which a synthetically long apparent or effective aperture is constructed by integrating multiple returns from the same ground cell, taking advantage of the Doppler effect to produce a phase history film or tape that may be optically or digitally processed to reproduce an image.
Range direction	For radar images this is the direction in which energy is transmitted from the antenna and is normal to the azimuth direction. Also called look direction.
Real-aperture radar (RAR)	SLAR system in which azimuth resolution is determined by the physical length of the antenna and by the wavelength. The radar returns are recorded directly to produce image. Also called brute-force radar.
Resolution	The ability of an entire remote sensor system, including lens, antennae, display, exposure, processing, and other factors, to render a sharper defined image. It may be expressed as line pairs per millimetre or meter, or in many other ways. In radar, resolution usually applies to the effective beam-width and range measurement with, often defined as the half-power points.
Roughness	For radar images this term describes the average vertical relief of small-scale irregularities of the terrain surface.

APPENDIX F

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