CANADA CENTRE FOR REMOTE SENSING
Surveys, Mapping and
Remote Sensing Sector

Energy Mines and
Resources Canada

Énergie, Mines et
Ressources Canada

Canada

THE ENERGY OF OUR RESOURCES

THE POWER OF OUR IDEAS

RADAR REMOTE SENSING FOR APPLICATION IN FORESTRY

A Literature Review
for Investigators and Potential Users of SAR Data in Canada

Commissioned by:

CANADA CENTRE FOR REMOTE SENSING
Technology Transfer Program / Applications Division
Ottawa, Ontario, Canada

Author:

DIRK WERLE
AERDE Environmental Research
Halifax, Nova Scotia, Canada

Ottawa, December, 1989

Published by:

Canada Centre for Remote Sensing
Energy, Mines & Resources Canada
1547 Merivale Road, 4th floor
Ottawa, Ontario, Canada
K1A 0Y7

Tel. 613 952-0500
Fax. 613 952-7353

Produced by:

AERDE Environmental Research
43 Parkhill Road
Halifax, Nova Scotia, Canada
B3P 1R4

Tel. 902 477-2266
Fax. 902 477-4477

Coordinated by:

Thomas T. Alfoldi
Canada Centre for Remote Sensing
1547 Merivale Road, 4th floor
Ottawa, Ontario, Canada
K1A 0Y7

Tel. 613 952-2803
Fax. 613 952-7353

Aussi disponible en francais.

ACKNOWLEDGEMENTS

The present document was prepared by AERDE Environmental Research, a remote sensing service bureau located in Halifax, Nova Scotia. The work was performed under DSS Contract No. 2341-8-8037/01-GS to the Applications Division / Technology Transfer Program of the Canada Centre for Remote Sensing in Ottawa, Ontario, as part of the Canadian Government's Radar Data Development Program (RDDP). Mr. Thomas T. Alfoldi, CCRS, acted as the Project Authority for the contract and also supervised the production of this document. Dr. Francis J. Ahern, CCRS, and Mr. John A. Drieman, RADARSAT Project Office/Intera Technologies Ltd., provided technical commentary and helpful suggestions as part of their critical review of this work. Portions of the work presented here to a wider circle of readers have originally been carried out in 1988 by AERDE Environmental Research on contract to the Canada Centre for Remote Sensing as part of a technical review for the Forestry Section of the Applications Division. The assistance of the CCRS Remote Sensing On-line Retrieval System (RESORS) staff in conducting literature searches and in providing selected papers reviewed in this work is also acknowledged.

ABSTRACT

Information provided in this document allows potential users of synthetic aperture radar (SAR) imagery as well as investigators participating in the Canadian Radar Data Development Program (RDDP) to obtain an overview of achievements, limitations and future potential of radar remote sensing for application in forestry, as portrayed in the published literature.

Investigations concerned with radar remote sensing and its potential for application in forestry are reviewed. The main focus of these studies was the determination of microwave backscatter characteristics of forestry targets using different radar parameters, such as frequency, polarizations and incidence angle. Examples of selected targets include the following: coniferous and deciduous tree species, stands of different structure, age, tree height, clearcuts, or forestry environments in general as they change with the seasons.

More than 75 studies based on airborne imaging radar, spaceborne radar as well as scatterometer data have been considered. Previous reviews which summarize information available in western Europe and North America are briefly introduced. Then, recent investigations covering the time period from the early 1980's onward are portrayed and discussed. The main results are summarized in a set of conclusions, followed by list of selected references and a list of Canadian institutions and organizations currently involved in radar remote sensing R&D for application in forestry.

TABLE OF CONTENTS

LIST OF TABLES

1.0 INTRODUCTION

In this introduction the scope and objectives as well as the organization of this document are presented. Further, some recent developments in the application of synthetic aperture radar (SAR) to forestry are outlined and the existing problem areas are introduced.

Preparation for ERS-1, J-ERS-1 and RADARSAT

Forestry related studies are currently carried out in preparation for several spaceborne radar missions, namely the European ERS-1, the Japanese ERS-1 and the Canadian RADARSAT. These satellites have been approved and scheduled for launch in 1991, 1992, and 1994, respectively. Their imaging radar instruments will provide a wealth of data for earth resources mapping and environmental monitoring in a variety of application areas, including forestry.

Scope and Objective

The Technology Transfer and Applications Development Sections of the Canada Centre for Remote Sensing have commissioned this document in order to assist potential users of SAR data as well as investigators participating in the Canadian Radar Data Development Program (RDDP). The main objective is to critically review and summarize the results of imaging radar and scatterometer studies relating specifically to applications in forestry. Therefore, the information provided in this document should allow researchers and potential users in Canada to obtain an overview of achievements, limitations and future potential of radar remote sensing for application in forestry, as portrayed in the published literature.

SAR Applications in Forestry, R&D

A growing number of research and development studies conducted in Canada, the United States and western Europe over the past two decades have examined the potential of microwave remote sensing for application in forestry. One of the often cited arguments for imaging radar is its usefulness in frequently fog or cloud covered forest regions where data acquisition for inventory purposes by means of optical remote sensing instruments has become either an unreliable or an expensive undertaking. In Canada, the image analysis effort was directed at practical application areas, for example cutover mapping at regular intervals by means of imaging radars, as these are of immediate interest to forest resource management.

R&D Results

As the study of radar imagery of forested terrain evolved in the 1970's and early 1980's, two things became obvious. First, the interaction of microwave energy and forestry targets can be a complicated one and our understanding of it is generally poor. Secondly, in examining microwave data from vegetation canopies, many studies found evidence that the radar data contained valuable biophysical information, for instance stand structure or plant water content.

Microwave-Target Interaction, Penetration

The energy emitted transmitted active microwave remote sensing instruments can penetrate deeply into vegetation canopies depending on radar wavelength, polarization and incidence angle. This results in various target - wave interaction mechanisms which may not only involve the multitude of targets within the canopy layer itself, but also the ground surface underneath. In addition to its 'all-weather' capability, 'active' sensors such as radars thus allows further characterization of vegetation canopies at the centimetre and decimeter scale which is outside the realm of 'passive' optical sensors.

Development of Algorithms, Backscattering Behaviour of Trees

A number of mathematical models have been developed for separating vegetation cover types and estimating biophysical properties. However, much of this research concentrated on cultural vegetation, such as uniformly planted agricultural crops. Only relatively few experiments have been conducted in the past to document the radar backscattering behaviour of natural forest environments. At present, sophisticated algorithms are under development for such inhomogeneous media as tree canopies; some preliminary results of these modelling efforts is also reviewed in this document.

Biophysical Properties, Modelling Efforts

The measurement of the biophysical properties of natural vegetation by means of imaging radars and the modelling of propagation and backscatter of microwave energy through tree canopies represents a difficult undertaking. In Canada, such radar backscatter modelling efforts are undertaken by the CCRS. They are at an early stage and not as advanced as similar studies in the United States where initial results are already available. According to F.T. ULABY and co-workers, four factors need to be considered in modelling the radar backscatter of trees, including:

- the complexity of the tree geometry; for instance, the trunks, branches, twigs and foliage of trees tend to be more randomly distributed, both spatially and in height, than a uniformly planted wheat field, resulting in distinctly different image textural properties;
- the abundance of tree constituents, i.e. trunks, branches, twigs, foliage, whose dimensions are comparable to the radar wavelengths;
- the lack of information regarding the relative importance of tree constituents, for example leaves vs. branches, in so far as attenuation of the microwave signal is concerned; and
- the lack of a consistent set of defined biophysical parameters which allow for a quantitative characterization of tree canopies in terms of their microwave absorption and backscattering properties.

Limitations for Operational Use and Application Potential

This recent assessment of the situation shows that the application of digital radar image processing and analysis techniques and the use of scatterometer measurements have so far provided only a small quantitative basis for analyzing radar imagery of forested environments. Therefore, the practical use of radar in forestry is regarded by many as being far from operational. Yet, from the first reconnaissance studies over tropical forest terrain to the exciting results of recent airborne and spaceborne SAR missions, imaging radar technology has still maintained, if not expanded, its potential for future application in forestry.

Objective of the Literature Review

In order to exploit this potential for operational or scientific use, information regarding previous research and development studies is a prerequisite. This literature review of radar remote sensing studies for forestry applications summarizes knowledge regarding the usefulness of different radar wavelengths and polarizations, radar viewing angles, and radar imagery in combination with other remote sensing data.

General Information on Radar Remote Sensing

A treatment of radar fundamentals can be found in a number of publications, including the Manual of Remote Sensing (see chapters by MOORE (1983); ELACHI (1983); FUNG & ULABY (1983); and BECKMAN (1983). WEHNER (1987), HOVANESSIAN (1984) and MENSA (1982) have described the principles of high resolution radars, system design and analysis as well as high resolution imaging. A three-volume set on microwave remote sensing has been prepared by ULABY, MOORE & FUNG (1981-1986). Spaceborne radar remote sensing applications and techniques have been described by ELACHI (1988). TREVETT (1986) prepared a general introduction to imaging radars for resource surveys. A handbook of radar scattering characteristics for different terrain and vegetation types has been provided by ULABY & DOBSON (1989). LEBERL (1990) provided a useful introduction to radargrammetric image processing.

Organization of the Document

The methodology adopted for this review is described first. This is followed by the main body of the text which consists of a literature analysis. The analysis concentrated first and foremost on active microwave imagers. Then a variety of investigations involving scatterometer instruments are considered. More than 75 publications are reviewed. The main results are summarized in tabular form and discussed at the end of each section. A set of conclusions and an outlook on planned investigations is presented, followed by a list of selected references.

2.0 METHODOLOGY

The review on microwave backscatter studies of forestry targets is based on the analysis of articles available in the published literature, research reports and other reference material. The literature review process was divided into different stages: search, collection and selection of relevant material; selection of analysis criteria; analysis of results; and summary of the results.

Search and Review 1980-89 RESORS

The literature search concentrated on investigations which used either imaging radars or scatterometers to study the backscatter characteristics of forestry targets. The collection of relevant literature relied on material available at the CCRS Library and CCRS RESORS facilities in Ottawa. Both computer assisted and manuel searches were conducted. Previous reviews on microwave backscatter studies of forestry targets were identified first. These offer a summary of qualitative and, to some extent, quantitative radar and forestry related work prior to the mid 1980's. Some reviews contain a detailed bibliography referring to studies conducted in the 1970's and early 1980's.

Categories, Instrumentation

The present review focuses on recent developments and, therefore, does not include in detail the literature prior to the 1980's. More than 75 studies were selected for review. These studies are grouped into the following categories: previous reviews; studies using single-frequency and multi-frequency airborne imaging radars; studies using spaceborne SARs; and studies using single-frequency and multi-frequency scatterometer measurements.

Categories, Forest Parameters

The selection of analysis criteria is guided by the question of how the tree characteristics, such as type and density, the condition of foliage, the geometry of trunks and branches, and the stand characteristics, such as diameter distribution, height distribution and density, affect the microwave backscatter as a function of radar wavelength, polarization and incidence angle.

3.0 LITERATURE ANALYSIS

A literature analysis of microwave backscatter characteristics of forestry targets is provided with regard to the following categories: Previous assessments and reviews; airborne imaging radar studies; spaceborne imaging radar studies; and scatterometer studies. An overview of these investigations is given in tabular form in the following sections. Each section is concluded by a brief discussion of the results.

3.1 Previous Assessments and Reviews of Microwave Backscatter Characteristics of Forestry Targets

Over the past 15 years various attempts have been made to assess and review studies concerned with radar and forestry applications. A summary of these investigations is presented in Table 1. The studies are presented in chronological order so as to document the development of radar and forestry related research.

Early 1970's: Regional Surveys at Reconnaissance Level

In the early 1970's SAVIGEAR et al. (1973) reviewed the few SLAR studies available at the time in order to assess the potential of SLAR for forestry applications and recommend areas of research and development for a European experimental radar program. Potential forestry applications of SLAR were identified as reconnaissance and general mapping of northern coniferous forest and tropical forest areas, broad classification of vegetation and site types, and limited use in some aspects of conservation and protection. Experimental areas for forestry applications were identified as regional reconnaissance and broad stratification of tropical forests, and detailed survey and stratification of managed forests in Europe.

Late 1970's and Early 1980's: R&D Experiments with SLAR & SAR

More than a decade later, HUNTING TECHNICAL SERVICES Ltd. et al. (1984) prepared a report for the European Space Agency (ESA) examining the usefulness of radar surveys and numerous experimental airborne radar missions prior to 1984 for land use. The forestry related aspects of this report were later presented by CHURCHILL, HORNE & KESSLER (1985). Among the various assessments and reviews available in the published literature the review provided in these two publications represents a comprehensive analysis of qualitative and some quantitative airborne imaging radar investigations in forestry up to the early 1980's. One of the above authors updated this assessment by reviewing recent applications of imaging radar for classifying forest vegetation in Germany (KESSLER 1987).

Results of Airborne SAR Campaigns

The reviews by HUNTING et al. (1984) and CHURCHILL et al. (1985) cover the results of Canadian SURSAT Project, the European SAR-580 campaign and, to some extent, reconnaissance surveys of tropical forest regions with regard to the delineation of woodland from non-woodland; forest boundary delineation; species classification; age classification; crop state and yield; crop geometry effects; canopy penetration; and topographic effects. An attempt was made to define optimum radar system parameters for the analysis of woodland with regard to wavelength; polarization; resolution; incidence angle and look direction; and multi-temporal radar imagery. Much of the imagery available in the studies concerned were optically processed, and the analysis procedures employed were qualitative and descriptive.

Modelling Work and Empirical Data Collection

KRUL (1985) noted that the development of models for the radar scattering of forests suffered from a lack of suitable measurement data. Both HUNTING and KRUL noted that the knowledge with regard to other vegetation types, e.g. agricultural crops, cannot be extrapolated for use in forestry. KRUL suggests semi-empirical interaction modelling, i.e. models based on simplified descriptions of the forest vegetation phenomena determined by means of multi-band and multi-polarization scatterometry.

Scatterometer and SAR Studies of Forestry Targets

ULABY, FUNG & MOORE (1986) prepared a brief review of the few scatterometer and imaging radar experiments that have been conducted prior to 1984 to document quantitatively the microwave interaction with tree canopies. More specifically, the attenuation of tree foliage and the backscattering of tree canopies were addressed. On both accounts the review concluded that the few scatterometer studies available could not provide a good understanding of how the attenuation and backscattering properties of tree canopies relate to their biophysical properties, e.g. leaf area index, tree type, size, age, height, density.

TABLE 1: Overview of previous assessments and reviews of SAR applications in forestry.

AUTHOR(S)	YEAR	RADAR SYSTEM	SUBJECT OF INVESTIGATION
NASA NASA/JPL	1987 1986	Planned spaceborne SAR missions (SIR-C, EOS)	Examination of potential science applications for planned multi-parameter spaceborne SAR regarding vegetation studies
Bullock	1987	Digital airborne SAR (STAR-1/2)	Commercial viability of digital SAR products for current market applications, e.g. tropical forest depletion mapping
Simonett, Sun, Strahler & Wang	1987	Imaging radars and scatterometers	Discussion of radar forest models, their construction and implementation, outling potentials, problems and approaches
Werle	1987	Airborne SLAR/SAR systems spaceborne SAR systems	Review of investigations regarding commercial & scientific applications of imaging radar to tropical forestry
Ulaby, Moore & Fung	1986	Airborne imaging radars and scatterometers	Examination of backscattering properties of tree canopies; attenuation and backscatter of tree foliage, based on selected quantitative studies in Europe and the US prior to 1984
Krul	1985	Scatterometers	Review of modeling and experimental aspects of microwave remote sensing/vegetation, based mainly on quantitative studies of the ROVE Team prior to 1983
Kessler	1987	Airborne and spaceborne imaging radars	Examination of imaging radar data for classifying forest vegetation, based on qualitative and quantitative studies in western Europe prior to 1986
Churchill, Horne & Kessler	1985	Airborne and spaceborne imaging radars	Review of woodland applications of imaging radars; ability to make boundary delineation, age and species classification; determination of optimum SAR parameters; mainly based on qualitative and quantitative studies of the European SAR-580 campaign and the SURSAT Project prior to 1984
Hunting Technical Services Ltd. et al.	1984	Airborne imaging radars and scatterometers	Review of forestry applications for imaging radars; radar system parameters, ground parameters; mainly based on qualitative and quantitative studies of SURSAT Project, the European SAR 580 campain, SAR/SLAR surveys of tropical forests and scattering models prior to 1983
Savigear et al.	1973	Side-looking airborne radars (SLARs)	Examination of potential forestry applications for single-frequency SLAR's based on surveys in North America and tropical countries prior to 1972; recommendations for experimental European R&D program

Preparations in the United States, Radar Forest Models

NASA (1987), NASA/JPL (1986) and SIMONETT et al. (1987) provided an assessment of the potentials, problems and approaches of multi-parameter SAR and scatterometer data for forestry science aspects and applications. The first two studies were prepared as an introduction to the objectives of the Shuttle Imaging Radar-C (SIR-C) missions and the Earth Observation System (EOS) in the 1990's. NASA and JPL put forward a set of proposals for forestry related science and applications orientated work, including the determination of stand volume; productivity or phytomass (LAI); seasonal variations; stress; tree species geometry; clear-cut areas; foliage characteristics; and stand structure by means of SAR. The very concise review by SIMONETT et al. (1987) combines evidence from scatterometer studies and the results from previous spaceborne and airborne SAR investigations in detail. The use of statistical descriptions of forest stands is advocated in order to model biophysical properties of forest structure by means of microwave remote sensing.

Plans for Forest Ecosystem Studies, ERS-1

In concert with the SIR-C and EOS SAR missions, SIEBER et al. (1986) and proposed the use of multi-temporal spaceborne SAR data for global ecosystem studies. The data will be provided by the European ERS-1 satellite during the early 1990's in order to quantify the different growth stages, seasonal and environmental conditions of woodlands. The radar signatures will then be correlated with forest ecosystem characteristics.

TABLE 2: General achievements of forestry related radar studies during the 1970's and 1980's according to studies as listed in Table 1.

TIMEFRAME	INSTRUMENTS	ANALYSIS	ACHIEVEMENTS
Early 1970's:	Commercial airborne radar (SLAR and SAR) systems	Visual interpretation of optically processed film	Regional forest surveys at reconnaissance scale level; e.g. tropical forests
Late 1970's:	Multi-channel experimental airborne imaging radars	Visual interpretation of optically processed film	Determination of radar system parameters for examining forest resources
	Experimental spaceborne SAR (SEASAT mission 1978)	Visual and digital image analysis of optically and digitally processed data	Evaluation of 25 m resolution, L-HH, small small incidence angle SAR data for various forestry applications
Early 1980's:	Multi-channel experimental airborne imaging radars	Visual and digital image analysis of digitally and optically processed data	Evaluation of high-resolution and multi-parameter digital SAR data from various test sites for forestry applications
	Ground-based scatterometers	Quantitative analysis of backscattering properties	Development of general backscattering and attenuation models for forest vegetation
	Experimental spaceborne SAR (SIR-A mission, Nov. 1981)	Visual interpretation of optically processed data	Evaluation of 30 m resolution L-HH, moderate incidence angle data for forestry applications
Mid 1980's:	Experimental spaceborne SAR (SIR-B mission, Oct. 1984)	Digital and visual image analysis of digitally and optically processed data	Evaluation of 17-50 m resolution, L-HH, multiple-incidence angle SAR data for forestry applications
Mid 1980's to present:	Multi-frequency, multi-pol. airborne and ground-based scatterometers	Quantitative analysis of backscattering properties	Development of backscattering models of various tree species or tree components
	Digital single-frequency commercial SAR systems	Digital data recording and processing, digital image analysis	Suitability for forest depletion mapping, e.g. deforestation in the tropics
	Digital multi-channel experimental airborne SARs	Digital data recording, processing and analysis	Simulation of spaceborne SAR imagery

Commercial SAR Applications

In assessing the viability of commercial airborne SAR operations, BULLOCK (1987) identified forest depletion mapping and monitoring of tropical forests as a promising future market application. The advantages of a digital, lightweight SAR with a real-time processor are discussed and operating costs are compared with those anticipated for spaceborne SARs. So far, only few commercial forestry projects have been conducted during the 1980's.

Application Potential of SAR in Tropical Forestry

A review of airborne and spaceborne radar projects with a focus on tropical forestry has been prepared by WERLE (1987). During the 1970's, airborne imaging radars operating at X-band have been used occasionally for regional resource surveys of tropical woodlands using visual image analysis procedures. During the 1980's, experimental spaceborne SARs have been used to detect dynamic land use phenomena, for example tropical forest depletion and seasonal flooding. Many investigations employed visual interpretation techniques, and only in a few cases was digital image analysis applied to the limited amount of L-band SAR data available.

3.1.1 Summary

The studies cited above provide an overview of the development of microwave research in forestry since the early 1970's to the present in terms of the scope of the investigations; the microwave instrumentation used in experimental research and development studies; and the techniques used in the analysis of the data provided. Much of this information is summarized in Table 2.

Instrumentation

In the 1970's, single-frequency and later on experimental multi-frequency and multi-polarization airborne radars, e.g. CCRS SAR 580, were used to provide optically processed imagery of forest vegetation. Measurements of ground based scatterometer systems were an exception. In the 1980's, digital SAR data recording and processing facilities became available, e.g. CCRS C/X SAR and STAR-1/2 SAR, along with SAR imagery from experimental spaceborne SAR systems, e.g. SEASAT, SIR-A, SIR-B. Image quality improved. During the same time, scatterometer measurements of trees or tree components were conducted more intensely in order to determine their microwave backscattering properties. Most of these studies are conducted in order to test the feasibility of microwave remote sensing of vegetation from planned spaceborne SAR systems, for example E-ERS-1, J-ERS-1 and RADARSAT.

Commercial Viability

Despite better image quality and lower operating costs compared to previous forest surveys in the 1970's, the commercial use of digital SAR systems, i.e. STAR-1/2, for forestry applications in the 1980's has been restricted to very few experiments or pilot projects. This indicates that a break-through of SAR technology as a commercially viable surveillance tool for forestry applications has yet to be achieved.

Approaches to Radar Image Analysis

The provision of digital SAR data brought about a change in image analysis techniques from qualitative interpretation of optically processed film to digital image analysis. In general, investigators use two different approaches to radar remote sensing of forest vegetation. The first group uses imaging radar data in much the same way as imagery in other portions of the electro-magnetic spectrum and considers digital manipulation procedures appropriate for radar image analysis. The second group uses an approach that is geared toward theinvestigations of the interaction of microwave energy and forestry targets by means of scatterometry.

Broadening of Scope of SAR/Forestry R&D

The development of multi-parameter radar instruments and data analysis techniques broadened the scope of forestry related investigations. These range from the potential use of airborne imaging radars for regional forest surveys, as perceived in the 1970's, to the monitoring of entire forest ecosystems by means of spaceborne SAR instruments, as envisaged on an experimental basis for the 1990's.

Data Collection

The collection and analysis of experimental radar data during the 1980's had three main goals: application development of SAR data; development of backscattering models of forest vegetation; and verification of these models, mainly through scatterometer experiments, and airborne SAR experiments geared toward the implementation of several planned spaceborne SAR missions during the 1990's. The specific objectives and the results of previous forestry related investigations are examined in the following sections.

3.2 Airborne Imaging Radar Studies

An overview of airborne imaging radar studies in forestry is given in tabular form. Investigations using single-frequency radars operating at X-, C- or L-band, are listed in Table 3, 4 and 5, respectively. Investigations using a multi-frequency radar data set are listed in Table 6. Note that none of the radar systems were calibrated. Only those investigations which have been conducted over the past ten years have been considered for the purpose of this study. The investigations were generally scientific experiments using digital as well as visual image analysis procedures. Invariably, the scope of these research and development studies was to determine the usefulness of imaging radar for specific forestry applications. The following is a detailed review and a discussion of investigations concerned with forest clearcut and regeneration assessment, forest biomass and canopy structure assessment and new development, including a brief overview of the radar instrumentation employed in these investigations.

3.2.1 Instrumentation

X-Band Systems

Studies using X-band data have relied on a variety of radars including the APQ-102 SAR, the Dutch NRS SLAR, as well as the Canadian STAR-1 SAR and CCRS SAR 580 systems. Analysis concentrated mainly on like-polarized (HH) data and to a lesser extent on cross-polarized data.

C-Band SAR Systems Canada

A growing number of C-band SAR data sets is under investigation in Canada. The majority of these studies are being performed as part of the Radar Data Development Program using digitally processed SAR data. A description of the new CCRS Airborne C/X SAR system has been provided by LIVINGSTONE et al. (1987). Forestry test sites have been chosen in a variety of regions, including the Boreal Forest Region, the Coastal Forest Region, the Great Lakes-St. Lawrence Forest Region and the Acadian Forest Region.

L-Band Systems NASA/JPL

Analysis work based on single-frequency multi-polarized L-band data was almost exclusively based on data provided by the NASA/JPL SAR instruments which most recently have also provided multi-polarization data in polarimeter mode.

Multi-channel CCRS SAR 580 Studies

Dual-frequency radar imagery for forestry related studies were almost exclusively provided by the CCRS SAR-580 following the Canadian SURSAT campaign and other Canadian SAR missions and the European SAR-580 campaigns.

Polarimetric SAR Systems and Principles

A new development in the measurement of multi-polarization radar signatures of objects was introduced in the mid 1980s by the Jet Propulsion Laboratory (ZEBKER et al. 1986). In radar polarimetry, the received wave of a multi-polarization SAR is decomposed into two orthogonally polarized components. These feed independently into two identical and coherent receiver channels whereby the reception is accompanied by transmission polarization diversity. Polarimetric synthesis allows for the measurement of an object's complete scattering matrix representing a more complete description of its polarimetric scattering properties, for example improved vegetation discrimination capabilities, than the like- and cross-polarized signatures alone (GUILI 1986; EVANS et al. 1988).

3.2.2 Discrimination of Forest Cover Types

Discrimination of Forest Cover Types using X-HH and X-HV

A qualitative analysis of dual-polarized X-band SAR data by KNOWTLON & Hoffer (1981) has shown that coniferous and deciduous forests are more easily identified on X-HH than on X-HV imagery. Shadow effects and forest boundary effects helped to delineate clear-cut areas, particularly on X-HV imagery. Both polarizations were regarded as equally valuable in identifying various forest cover types.

Textural Information

A quantitative analysis of the same data set was also conducted by KNOWLTON & HOFFER (1983). It was noted that the information content, with regard to forest cover type identification, improved using a textural classifier which classified groups of pixels as opposed to a pixel-by-pixel classifier.

Multi-temporal X-HH SLAR Analysis

In a multi-temporal analysis HOEKMAN (1985) classified managed forest stands of different species composition using geometrically and radiometrically corrected, digitally recorded X-HH SLAR data. The multi-temporal approach yielded overall classification error fractions of 10% to 28%. The backscattering properties of different trees were examined in order to establish some basic empirical relations between forest/tree structure and the radar parameters. Relationships were noted between tree age and radar backscatter for several tree species, between crown structure, leaf mass and radar backscatter for some poplar species, and between leaf orientation and radar backscatter. Recent forest clear-cuts and regeneration sites were also identified. The differences in the radar return signals were found to be relatively small. Further improvements in classification accuracy were achieved by using a textural classifier.

Textural Classifier

Using the same data set, HOEKMAN (1985b) reported that canopy roughness measures could be correlated with various spatial tree structures using X-HH data and textural classifier.

X-HH SAR Analysis, Winter Conditions

LOWRY, van ECK & DAMS (1986) examined high-resolution, digitally enhanced X-HH SAR data for use in forest management. Using a tone and texture analysis of imagery at a scale of 1:20,000 the following vegetation types of the Boreal Foothills Ecoregion of Alberta were differentiated under a snow cover of 20 to 40 cm: black spruce, lodgepole pine, deciduous wood, mixed wood, subalpine forest, and alpine herbs and shrubs. Under these conditions, deciduous stands provided very high radar return. Forest disturbance areas were also identified, e.g. a minimum of two age classes of clearcuts. Commission error between some vegetation and land cover classes could partly be corrected using stereo-viewing.

TABLE 3: Overview of recent single frequency airborne imaging radar studies in forestry using X-band data. (Note: Studies marked "*" were performed in a Canadian context.)

AUTHOR(S)	RADAR	BAND/POL	DATE(S)	TEST AREA	INVESTIGATION
Knowlton & Hoffer (1981, 1983)	APQ-102	X-HH/HV	7.1980 USA	S. Carolina,	Visual/digital image analysis for forest cover mapping and for forest classification
Hoekman (1985)	NRL SLAR	X-HH 3.1983	7./9.82	The Netherlands	Analysis of backscatter for various tree species in managed forests
* Lowry et al. (1986)	STAR-1	X-HH	12.1985 Canada	Alberta Foothills	Analysis of digital data for forest base maps and change detection
* Rochon et al. (1986)	CCRS SAR-580	X-HH	7.1978 Canada	Sooke Lake, B.C.	Separability of several forest cover classes using digitized imagery

TABLE 4: Overview of recent single frequency airborne imaging radar studies in forestry using C-band data. (Note: Studies marked "*" were performed in a Canadian context.)

AUTHOR(S)	RADAR	BAND/POL	DATE(S)	TEST AREA	INVESTIGATION
* Leckie	CCRS SAR-580 (1984)	C-VV/VH	8.1981	Petawawa, Ontario Canada	Forest classification, cutover and and regeneration mapping (visual)
* Leckie (in prep.)	CCRS SAR-580	C-VV/VH	8.1981	Petawawa, Ontario Canada	Synergism of SAR/visible/IR for forest discrimination (digital)
* Ahern & Drieman (1988)	CCRS C/X SAR	C-HH	10.1987	Whitecourt, Alta. Canada	Manual assessment of clearcut mapping accuracy
* Drieman et al. (1989a)	CCRS C/X SAR	C-VV/VH	6.1988	Whitecourt, Alta. Canada	Backscatter analysis of forest parameters/landforms/drainage
* Kneppeck & Ahern (1989)	CCRS C/X SAR	C-VV/VH	6.1988	Whitecourt, Alta. Canada	Stratification of regenreating burned forest area using SAR and TM (visual)
* Drieman et al. (1989b)	CCRS C/X SAR	C-HH	8./10.87 2./ 5.88	Petawawa, Ont. Canada	Analysis of multi-temporal SAR data for forest typing
* Edwards et al. (1988)	CCRS C/X SAR	C-HH	3.1987 Canada	Gaspe PI, Quebec	Digital texture analysis of forest regeneration sites
* Moulton & Peddle (1989)	CCRS C/X SAR	C-VV	9.1988	Central Newfound- land, Canada	Digital texture measurements of forest disturbance areas using SAR and TM
* Snow & McCourt (1989)	CCRS C/X SAR	C-HH/HV C-VV	8.1987	Truro, Nova Scotia Canada	Visual and digital image analysis of forest management activities

TABLE 5: Overview of recent single frequency airborne imaging radar studies in forestry using L-band data.

AUTHOR(S)	RADAR	BAND/POL.	DATE	TEST AREA	INVESTIGATION
Riom & LeToan (1980)	NASA/JPL CV-990 SAR	L-HH/HV	6.1977	SW France	Digital L-band SAR for analysis of tree height/age/species composition
Ford & Wickland (1985)	NASA/JPL CV-990 SAR	L-HH/HV L-VV/VH	3.1984	S. Carolina, USA	Examination of digital SAR data for discriminating for. cover variables
Wu (1987)	NASA/JPL CV-990 SAR	L-VV/VH	9.1983	Alabama, USA	Application of digital SAR for pine plantation biomass estimation
Wu & Sader (1987)	NASA/JPL CV-990 SAR	L-HH/HV L-VV/VH	9.1984	Gulf Coast, USA	Surface feature delineation and forest vegetation characterization (digital)
Sader (1987)	NASA/JPL CV-990 SAR	L-HH/HV L-VV/VH	9.1984	Gulf Coast, USA	Forest biomass, structure and species relationships (digital)
Muller & Hoffer (1985)	NASA/JPL CV-990 SAR	L-HH/HV L-VV/VH	9.1984	Florida, USA	Discrimination of different forest cover types (digital)
Hoffer et al. (1987)	NASA/JPL CV-990 SAR	L-HH/HV L-VV/VH	9.1984	Florida, USA	Characterization of forest stands with multi-polarization data (digital)
Evans et al. (1988)	NASA/JPL Polarim. SAR	L-HH/HV L-VV/VH	8.1985	Moosehead Lake, Maine, USA	Determination of vegetated areas based on different scattering mechanism
Cimino et al. (1989)	NASA/JPL Polarim. SAR	L-HH/HV L-VV/VH	3.1988	Bonanza Creek, Alaska, USA	Multi-temporal SAR observation of freeze-thaw moisture conditions

TABLE 6: Overview of dual-frequency airborne imaging radar studies in forestry using X-band, C-band and/or L-band systems. (Note: Studies marked "*" were performed in a Canadian context.)

AUTHOR(S)	RADAR	BAND/POL.	DATE(S)	TEST AREA	INVESTIGATION
* Shuchman, Inkster, Lowry & Wride (1978)	ERIM/CCRS SAR-580	X-HH/HV L-HH/HV	10.1977	Michigan, USA	Discrimination of tree species composition using visual/digital interpretation methods
* Wedler, Pala & Jano (1978)	CCRS SAR-580	X-HH/HV L-HH/HV	8.1978	NW Ontario, Canada	Assessment of clearcut/regeneration areas using visual/digital methods
* Inkster, Lowry Thompson (1980)	CCRS SAR-580	X-HH/HV L-HH/HV	7.1978	Sooke Lake, B.C. Canada	Testing various resolutions for forestry studies (visual/digital)
* Lee (1981)	CCRS SAR-580	X-HH/HV L-HH/HV	7.1978	Sooke Lake, B.C. Canada	Visual identification of forest cover conditions and infrastructure
* Werle, Lee & Brown (1986)	CCRS SAR-580	X-HH L-HH	7.1978	Sooke Lake, B.C. Canada	Discrimination of forest clearcut and regeneration sites (visual)
Sieber & Noack (1986)	CCRS SAR-580	X-HH/VV L-HH/VV	7.1984	Freiburg, W. Germany	Identification of deciduous and coniferous stands (visual/digital)
Churchill & Keech (1983)	CCRS SAR-580	X-HH/HV C-HH/HV	7.1981	Thetford, U.K.	Identification of tree species, height age and disease (visual/digital)
Kessler,Reichert & Loesche (1983)	CCRS SAR-580	X-HH C-HH	7.1981	Freiburg, W. Germany	Identification of deciduous tree species (visual/digital)

Broad Species Discrimination, C-VV/VH

DRIEMAN et al. (1989a) interpreted visually a set of digitally processed Narrow Swath C-VV and C-HV SAR imagery of a boreal forest area in central Alberta. Their work is part of an ongoing experiment to understand the relationships between microwave backscatter and forest stand parameters. C-VV data were more effective in discriminating between a variety of forest types, e.g. hardwoods, and biomass and age estimation of softwoods than C-HV, which was consistently better suited for identifying seismic lines, roads and other forest disturbances. Highest radar backscatter was recorded in both polarizations for hardwoods; spruce species as well as immature soft- and mixedwoods produced moderate backscatter; low backscatter values characterized pine, bogs and regenerating softwoods.

Detection of Forest Management Activities C-VV, C-HH, C-HV

SNOW & McCOURT (1989) visually and digitally analyzed like- and cross-polarized C-band data of a forestry test site near Truro, Nova Scotia. Narrow mode C-VV was found to be most suitable for visually detecting forest management activities. Forest cover type discrimination was not successful using standard visual and digital image analysis methods. The detection of recent cutover sites was successful.

Broad Vegetation Associations

Using multi-polarized L-band SAR data FORD & WICKLAND (1985) related polarization signatures to biophysical properties of a wide range of vegetation associations. Swamp forest showed high digital number (DN) values in all polarizations. Open pine forest gave relatively high response at L-HH; dense pine forests provided dominating cross-polarized response. Clearcuts were characterized by low DN values. In decreasing order, the most useful correlative forest data were identified as stand basal area, age, site condition, and forest management type. The multi-polarization imagery were also used to discriminate between variations in tree density, but differences between evergreen and deciduous stands were not detected.

Discrimination of Forest Cover Types, Incidence Angles

MULLER & HOFFER (1985) found that like-polarized L-HH or L-VV SAR data were best for discriminating between pine and swamp forest as well as between deciduous and non-deciduous forests. HV and VH provided greater contrast between forested and non-forested areas than like-polarized data. It was noted that large variations in incidence angles caused significant differences in image tone which was severely affecting the analysis of airborne SAR data sets.

Discrimination of Forest Cover Types, Polarization

Further analysis by HOFFER, LOZANO-GARCIA & GILLESPIE (1987) showed that a considerable amount of additional information can be obtained by using multi-polarization SAR data. Like polarized data were better suited to discriminate between natural pine stands and pine plantations that cross-polarized data. In some cases, distinct changes were observed at L-HV/VH when comparing pine stands of different age; little or no difference was evident at L-HH/VV.

Tree Species Composition, X- and L-Band

SHUCHMAN, INKSTER, LOWRY & WRIDE (1978) examined optically processed X- and L-band data using visual and digital interpretation techniques for distinguishing tree species under high incidence angle illumination conditions. Most broad-leaf tree classes were identified based on tone and texture differences. L-HH was most valuable in discriminating between spruce and pine species; X-HH was most valuable in separating coniferous and deciduous stands. The effects of radar imaging geometry and seasonal variation on the ability to discriminate tree species was not examined.

Deciduous vs. Coniferous Stands X- and L-Band

SIEBER & NOACK (1986) compared digitally processed X- and L-band data of coniferous, deciduous forest stands and clearings. Highest radar backscattering values were obtained at L-band for coniferous forests. Difficulties were encountered differentiating between deciduous forests and clearings as well as forested and agricultural areas at X-band. Neither L-band or X-band data provided textural differences over deciduous forests. L-band data analysis showed a higher success rate in identifying tree type, whereas X-band data was more successful in providing information on height and density of forest stands.

Tree Species, Age, Height, Disease, X- and C-Band

CHURCHILL & KEECH (1983) used X-HH/HV and C-HH/HV imagery in order to identify tree species, age classes, tree disease and canopy penetration. The statistical analysis showed that some tree species and broad categories of tree age, areas of diseased woodland as well as boundaries between forested and non-forested areas could be identified. Pine canopy penetration of up to 6 m was observed at X-band and C-band. X-band was particularly useful in identifying height differences of various stands. C-band was found more useful in identifying older coniferous regrowth.

Deciduous Tree Species, X- and C-Band

KESSLER, REICHERT & LOSCHE (1983) examined optically processed C-HH and X-HH imagery of a young Douglas fir stand, a young oak stand and a mixed stand of young and old deciduous trees. The conifers appeared in relatively dark tone at X-HH and separation from the other classes was possible. Tonal differences were not noticed at C-HH. The mixed stand was identified at X-HH because of its rough image texture which was not as clearly detectable at C-HH.

3.2.3 Forest Clearcut and Regeneration Assessment

Clearcut and Regeneration Sites, X-HH

ROCHON et al. (1986) used digitized data of optically processed SAR-580 imagery of the Sooke Lake Watershed Reserve Forest in order to determine the separability between several clearcut and regeneration stages. The statistical analysis showed that X-HH data could not successfully separate 1, 5, 10 and 15 year old cutover and regeneration sites. Maximum likelihood classifications of the SAR data also yielded low percentage of correctly classified pixels, whereas Landsat TM and MSS data provided much improved results. It was concluded that low quality SAR data are of limited use for application in cutover and forest regeneration mapping.

Forest Clearcut and Conifer Regrowth, C-VV/VH

LECKIE (1984) examined optically processed, dual polarized SAR-580 C-band data in order to identify and delineate clearcuts and assess conifer regrowth. Cross polarized imagery allowed better clearcut identification than like-polarized imagery. However, ground vegetation in clearcuts was often confused with regeneration sites, wetlands, and pastures because of similar backscatter intensities. A combination of SAR and VIR data was suggested for improving classification results of various forest types which could not be separated consistently using C-band imagery.

Clearcut Mapping Accuracy and Error Sources, C-HH

AHERN & DRIEMAN (1988) examined clearcut mapping accuracy in a boreal forest area of central Alberta. They based their assessment on manual interpretation techniques and digitally processed Narrow Swath C-band SAR (C-HH) data of 95 clearcuts and a comparison with boundaries derived from aerial photography. The areal extent of the 5 to 120 ha large cut blocks was underestimated by 11% on average using SAR; the average boundary placement error was 30 m. The results indicate that, at present, 6 m resolution airborne SAR data cannot fulfil operational forest inventory accuracy requirements set by most provinces. Several sources of error were identified relating to difficulties in edge detection of cut blocks and to subtle geometric distortions resident in the SAR data. Proposed error reductions were deemed possible through analysis of multi-date and multi-look direction data and through improved geometric integrity of SAR data.

Forest Regeneration in Burned Areas, C-VV/VH

The same data set was used by KNEPPECK & AHERN (1989) to analyze a 16-year old regenerating burn area as part of a larger multi-sensor experiment. Visual image analysis of radar image tone concentrated on the possibility of differentiating between forest regeneration, dead standing timber, clearcuts and mature timber. Difficulties were generally encountered in identifying different levels of regrowth because deciduous brush, slope aspect and dead standing timber resulted in confusing radar backscatter; like-polarized data were found to be more helpful than cross-polarized data. Cross-polarized data were more useful in detecting dead standing timber, brush and clearcuts.

Textural Analysis, Clearcut and Regeneration Areas, C-HH

EDWARDS et al. (1988) presented preliminary results of a digital, Narrow Swath C-band SAR (C-HH) image analysis involving texture measurements of different stages and types of forest regrowth in a test area on the Gaspe Peninsula, Quebec. Using a co-occurrence or spatial grey level dependence matrix analysis technique, they were able to discriminate five texture/ contrast classes which were previously completely confused using image tone/grey level analysis alone. These classes include water, clearcuts without regrowth, clearcuts with dense competing vegetation, clearcuts with young saplings and mature stands. Sampling windows of 9x9 pixels were found to be most useful.

Textural Analysis of Disturbed Areas, C-VV & TM

MOULTON & PEDDLE (1989) also concentrated their analysis of Narrow Swath C-band SAR data (C-VV) of forest conditions and cutting practices in Newfoundland on the use of textural classifiers. They found that TM spectral and SAR tone and texture data of forest disturbance areas share common variance. SAR texture measures were preferred over tonal analysis. TM data were preferred by a per-pixel classifier.

Forest Clearcut and Regeneration, X- and L-Band

WEDLER, PALA & JANO (1980) specifically addressed the potential of optically processed X- and L-band imagery in identifying clearcut and conifer regeneration sites. Results from both visual and digital image analysis showed that L-band is more suitable for determining successful or unsuccessful regeneration and the existence of hardwood within coniferous stands, even at resolutions coarser than 11 m. X-band was not suitable for distinguishing different regeneration sites. However, X-band was found to be particularly useful in delineating cutover boundaries in forested areas.

Spatial Resolution, X- and L-Band

INKSTER, LOWRY & THOMPSON (1980) studied SAR imagery with various simulated resolutions between 2 and 20 m for landuse and forestry applications in order to determine minimum acceptable resolution, data rates and cost factors. Rapidly decreasing interpretation success occurred with degraded resolution cells of 10 to 20 m. This was largely attributed to the loss of textural information. Clearcut area identification was difficult at resolutions coarser than 6 m. High resolution systems were recommended with regard to forest resource surveys.

Forest Clearcut and Regeneration, X- and L-Band

The same optically processed data set was examined visually by LEE (1981) and later by WERLE, LEE & BROWN (1986) using the high resolution L-HH and X-HH data to assess different forest regeneration classes and areas of forest disturbance. At L-band, clearcut and forest regeneration areas generally appeared in darker image tone than at X-band. At L-band, the high amount of speckle resulted in a homogeneous, rough image texture. In contrast, texture information at X-band is more diverse and allows for differentiation of various ground cover types and some forest regeneration stages.

3.2.4 Forest Biomass and Canopy Structure Assessment

Tree Height, Age L-HH, L-HV

RIOM & LETOAN (1980) examined dual polarized L-band data taken over a managed pine forest site. A microdensitometric analysis of the optically processed imagery revealed a statistically significant relationship between tree height, age groups, and radar return intensities at both L-HH and L-HV. Using both polarizations interpretation results were in part better than Landsat MSS analysis results (see also LETOAN, SHAHIN & RIOM 1980).

Biomass, Tree Height and Age Estimation

WU (1987) examined L-VV and L-VH SAR data acquired at incidence angles around 50 degrees and used a linear regression technique for estimating pine plantation biomass, tree height and age. The data were highly related to biomass and to a lesser degree to age; very little relation was found with regard to tree height.

Broad Vegetation Characterization

WU & SADER (1987) examined the usefulness of multi-polarization L-band SAR data for delineating surface features and forest vegetation characteristics. Cross-polarized data provided better overall definition of surface features, i.e. clearcuts, marsh vegetation, pine, hardwoods, test stands, buildings. A median value filtering technique was applied which resulted in an increase of class separability. Polarization and polarization ratio data were also used for examining forest parameters such as tree height, basal area and total forest biomass. L-VH data provided the best overall correlation coefficients, particularly for basal area and biomass estimates. For tree height estimates, L-HH was also found suitable; the combined use of HH and VH data significantly improved tree height estimates.

Biomass, Canopy Structure, Species Composition

SADER (1987) studied the effect of forest biomass, canopy structure, and species composition with multi-polarization L-band SAR data. Best results were achieved for classifying pine plantations. A strong relationship was observed between HV polarization and nearly all stand structure variables, e.g. green weight biomass. Using a HV/VV ratio only, highly significant correlation coefficients were obtained for canopy roughness. Differences in biomass and canopy structure, including branching patterns and vertical canopy stratification were identified as important sources of volume scatter affecting multi-polarization L-band data.

3.2.5 New Developments

Multi-seasonal Analysis, Forest Typing, C-HH

DRIEMAN et al. (1989b) examined visually a multi-temporal set of four Narrow Swath C-band SAR images (C-HH) of a test site near Petawawa, Ontario, for forest typing purposes. Data acquired during February, May and August were assembled digitally to form an across-track intensity corrected and contrast-stretched colour composite image using blue, green and red colour guns, respectively. This resulted in a clear differentiation between recently cleared and standing vegetation as well as major forest types and wetland classes, including red and white pine, spruce, jack pine, hardwoods, mixedwoods, open bog, and thickly vegetated marsh. This result was not possible using individual single-date images alone and demonstrated that the use of the multi-seasonal data sets has much greater potential for forest management.

Multi-temporal Analysis, Moisture Conditions, L-Band

CIMINO et al. (1989) reported on preliminary analysis results of a 5-day multi-frequency, multi-temporal, multi-polarization airborne SAR mission over a northern boreal forest site in Alaska in March, 1988. Environmental conditions during the mission ranged from warm (1 to 9 degrees Celsius) to well below freezing (-8 to -15 degrees Celsius) thus affecting moisture content of the snow and the tree vegetation.

L-band SAR data analysis indicated clearly that the radar return is sensitive to these changes from liquid to frozen state. A 0.4 to 5.8 dB increase in radar cross-section was recorded under warm conditions relative to cold conditions. The increase depended on polarization and forest cover type. These results illustrate the opportunity afforded by SAR to monitor temporal changes in forest ecosystems.

Determination of Different Backscatter Mechanisms

Using polarimetric SAR data of a managed forest site EVANS et al. (1988) demonstrated that backscatter minima and maxima of clearcut and forested areas occurred at different polarizations indicating that several scattering mechanisms are present. By identifying those coefficients of variation (ratio of minimum received power to the maximum received power of the polarimeter), which provided low coefficients for cleared areas and high coefficients for forested areas, they were able to maximize the contrast between these two categories. The difference in scattering mechanisms was most likely related to the structural differences between these two areas.

Polarization Signatures of Forested Areas, Clearcuts, Wetlands

DURDEN et al. (1989) used the same data set to verify modelling of the radar polarization signatures forested areas, clear cuts and wetlands. The high accuracy of their model indicated that the inclusion of leaves and twigs is not necessary when modelling the polarization signature at L-band for the site under study.

Synergism of SAR and Visible/IR Imagery

LECKIE (in prep.) found that the synergistic use of multi-polarization X- and C-band SAR and visible/infrared airborne MSS data improved forest mapping capabilities. Radar was better at discriminating softwood species. Red and white pine were characterized by low radar backscatter; jack pine and white spruce were characterized by high radar backscatter. The use of mid- and near-infrared band data was important for discriminating softwoods from hardwoods. The best five bands and combinations thereof regarding the discrimination of general forest stand types were a near IR band, a green band, a mid-IR band, X-VV and C-HH. Classification accuracy utilizing these five bands was 67%.

3.2.6 Summary

Data Acquisition X-Band, C-Band, L-Band

A variety of radars were used for the acquisition of X-band data including optically processed APQ-102 SAR and SAR-580 (prior to 1981) imagery and digitally recorded NLR SLAR, SAR-580 and STAR-1 data. Digitally and optically recorded L-band data were collected by the NASA/JPL CV-990 SAR and the SAR-580 systems. C-band data were collected by the CCRS SAR-580 in both digital and optical format, and by the new CCRS C/X SAR system in fully digital format. Multi-frequency SAR data analysis for forestry purposes has concentrated on SAR-580 data in the past. Analyses of multi-frequency imagery from the CCRS C/X SAR systems are not available yet; investigations concentrated mainly on the analysis of C-band and Narrow Mode data sets. Little use has been made of Nadir Mode and Wide Swath Mode data. Multi-polarized, digital C-, L- and P-band imagery have been collected over a limited number of forestry sites by the NASA/JPL DC-8 SAR. Few data sets have been analyzed to-date; they represent a most comprehensive source of information both in terms of frequency and polarization.

Acquisition Dates, Multi-temporal/ seasonal data

The data acquisition dates indicate that most studies were conducted during the summer months, i.e under leaf-on conditions. The potential of multi-temporal/seasonal data has not been sufficiently explored and there is only scarce evidence. Two multi-temporal data sets have been analyzed to-date. Another data set included forested environments under winter conditions. However, multi-temporal/seasonal SAR composite imagery acquired under leaf-on and leaf-off conditions, under moist, dry or frozen conditions, or under snow and no-snow cover conditions seem to hold considerable promise for forestry related SAR investigations.

Test Areas

Most test areas are located in moderate latitudes of western Europe and North America. Some areas are located in higher latitudes. The areas are very diverse in terms of their geography, climate and terrain, and the composition of their forest vegetation, species composition, stand density, tree height, and age. It is difficult to compare the results of investigations, even when the scope of was similar, e.g. tree species identification within homogeneous forest plantations vs. natural forest growth.

Analysis Methods

A variety of image analysis approaches were chosen by the investigators. Procedures ranged from visual interpretation, densitometric analysis of image film, colour additive viewing techniques, to digital image analyses of both digitized optical SAR film products to digitally processed data. Some Canadian investigations using CCRS C/X SAR data frequently used what could be termed a 'hybrid' approach; first, the quality of the digital SAR image products was improved digitally through radiometric and geometric correction procedures as well as image enhancement techniques, and then a rigorous image analysis was performed visually based on these enhanced image products. Digital image enhancements significantly improved analysis results.

TABLE 7: Interpretation results of different forestry related SAR studies using single-frequency and dual-frequency imaging radar systems, as noted by investigators listed in Table 3, 4, 5 and 6.

INTERPRETATION ELEMENT	X-Band				C-Band				L-Band				
	HH	HV	VV	VH	HH	HV	VV	VH	HH	HV	VV	VH	
Forest - non-forest boundary	p	p			+		p	+		p		p	
Coniferous vs. deciduous forest	+	p					p	-	p	-	p	-	
Conifereous forest identification	p						p	p	+	+			
Deciduous forest identification	p						+	p	p	p			
Clearcut identification	p	+			+		p	+	p	p	p	p	
Regeneration identification	p				p	p	+	p	p				
Stand structure	p						p		+	+			
Biomass estimate	p											+	+
Tree height estimate	p								p	p	-	-	
Age estimate									p		p	p	
Moisture conditions									p	+	+		

INTERPRETATION KEY:

+ = identification generally possible
p = identification possible under certain conditions
- = identification very vague or impossible

Texture Analysis

A number of image analysis procedures relied exclusively on digital methods. The extraction of textural information proved to be valuable because analysis based on grey tone intensity alone did not provide reliable results. A loss of information was noted when reducing resolution, or when relying exclusively on pixel-by-pixel classifier.

Interpretation Success

An overview with regard to the general interpretation success of single-frequency and dual-frequency imaging radar studies in forestry is given in Table 7. Table 7 details the interpretation elements of the various SAR investigations, for example deciduous forest, clearcuts or tree height, and the radar system parameters, i.e. frequency/band and polarization, against which the interpretation elements have been evaluated by the investigators. Three broad categories of interpretation success have been chosen for the purpose of this study: (1) 'generally possible'; (2) 'possible under certain conditions'; and (3) 'very vague or impossible'. It should be noted that, with one exception, specific accuracy assessments of airborne SAR data for practical application in forestry have not yet been performed. Also, caution should be exercised when generalizing or extrapolating the results of the above mentioned studies, because any indication of interpretation success may be based on only one investigation which can be very time specific, site specific or dependent on image quality (see Tables 3-6 and Section 3.2.2 for detail). Nonetheless, Table 7 provides not only an indication of the overall achievements but also of existing knowledge gaps.

Radar Parameters

Most airborne SAR information is available on multi-polarization L-band data and C-band data. Notable knowledge gaps exist with regard to X-VV and X-VH. There is also a lack of information on biomass, tree height and age estimates regarding C-band data. Recent deployments of the new CCRS C/X SAR and the NASA/JPL DC-8 SAR over forestry test sites have resulted in the acquisition of new data sets. These are presently under investigation by researchers in the United States, Canada and western Europe. Preliminary results are available for the analysis of C-band and L-band data. The influence of the radar incidence angle on the backscatter and attenuation of forestry targets has not been studied in detail using airborne SAR data. In Canada, C-band SAR image analysis concentrated on Narrow Mode data (incidence angles of 45 to 76 degrees). The analysis of Nadir Mode data which affords the study of radar backscatter of forestry targets over a wider range of incidence angles, i.e. 0 to 76 degrees, is underway at the Petawawa National Forestry Institute (Drieman, pers. comm. 1989). The influence of radar look-direction has also received little attention.

Main Results

The delineation of forest - non forest boundary is possible at all three frequencies, although L-band data was reported as being the single most useful among the three. The differentiation of deciduous and coniferous forest cover was more successful at X-band than at L-band. Evidence from C-band SAR data analysis is scarce, but multi-temporal C-band SAR imagery provided promising results. Attempts to identify individuals stands of coniferous species met with good success at L-band and multi-temporal C-band. It was rated possible under certain conditions using single date X- and C-band data. Few results have been obtained with regard to the identification of individual stands of deciduous tree species, although these have been identified at all three frequencies under certain conditions.

Clearcut and Regeneration Assessment

The identification of forest clearcut and regeneration sites has met with mixed success. Clearcuts have generally been identified in various polarizations at X-, C- and L-band; the use of high-frequency, cross-polarized data appears to be more suitable than like-polarized data. The potential of identifying regeneration sites at X-HH was rated as very vague.