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Summary

This report summarizes scope, research and results of a multi-departmental project on the evaluation and application development of the Compact Polarimetric (CP) configuration in the context of the Canada's RADARSAT Constellation Mission (RCM). This Natural Resources Canada (NRCan) led $3M, four year project began in 2011-12 with contributions from the Canadian Space Agency's Data Utilization and Applications Program (DUAP) and from the participating government departments and agencies.

Beginning in 2011, a team of more than 20 scientists and researchers conducted a host of studies under the DUAP in a variety of Earth observation application areas that could potentially benefit from the implementation of the Compact Polarimetry mode as part of the RCM. At NRCan’s Canada Centre for Mapping and Earth Observation (CCMEO), Canada Centre for Remote Sensing (CCRS) scientists concentrated their efforts on Compact Polarimetry simulator development, surface modeling, calibration-related issues, change detection and InSAR, lake ice and river ice studies, wetland classification, and 3D radargrammetry. Other government departments and agencies involved in the Project included Defence Research and Development Canada, Agriculture and Agri-Foods Canada, Environment Canada’s Canadian Ice Service, NRCan’s Canadian Forestry Service, Parks Canada Agency, and the Royal Military College. Within the context of their respective mandates, these scientists focused on the detection of ships and icebergs, the classification of crops, grasslands and forest, the classification of sea ice, and the detection of land cover changes.

The Compact Polarimetry configuration is a recent addition to the RADARSAT Constellation Mission. The CP configuration on RCM refers to a right circular polarization emitted by the antenna and coherently received horizontal and vertical polarizations. This configuration tends to contain more polarimetric information than linear dual-polarization or multi-polarization configurations of the SAR, thus providing better characterization of ground surfaces, vegetation cover, ocean surfaces and sea ice. From an operational mapping and monitoring point-of-view, a most appealing feature of the compact polarimetric configuration is the feasibility to collect this feature-rich data over a wide swath width, up to 500 km, where the fully polarimetric mode offering similar information, will be limited to 20 km on RCM.

Central to the CP project was the provision of simulated RCM CP products to the research team. The newly developed simulator provided other government departments access to a series of new parameters that can be derived from Compact Polarimetry for various application domains. Importantly, it provided the opportunity to evaluate CP mode configurations versus traditional HH/HV or VV/VH configurations and advanced their preparation of the standard coverage acquisition plan prior to the launch of the RCM.

Using simulated CP data, the following significant findings were produced within the four year project. Quantitative bare soil moisture can be estimated from CP data with the same level of

accuracy obtained with fully polarimetric data. Crop classification with CP data performs significantly better than linear dual polarization configuration on single dates (20% improvement in classification) and with a multi-temporal approach (5 to 10% increase). Compared to dual-linear configurations, CP data improves sea ice typing (multi-year, first year) and open water discrimination. As with sea ice, access to circular Right-Left (RL) polarization (maximized backscattered intensity for surface scattering media) will help in mitigating the expected higher RCM noise floor which could severely impact the effectiveness of oil slick detection and characterization, as well as ocean wind speed estimation. Wetland water extent, grassland classification and forest clear cuts and fire scars can be easily assessed from CP SAR data at a similar level of reliability as fully polarimetric configurations. Finally, CP-InSAR studies of horticultural sites did show promise, despite the fact that RADARSAT-2's current 24 day repeat cycle did not allow for a robust assessment of RCM CP-InSAR in an operational context. Finally, since the transmitted radar signal won't be perfectly circular, mitigation approaches will have to be developed pre and post-launch in order to use all of the potential of the CP configuration. It should be noted that while this study assessed CP performance within the context of a wide range of government applications, not all relevant applications were assessed and thus, further evaluations should be considered. Table 5.1 summarizes project findings regarding CP performance.

In conclusion, the results obtained from this wide range of user oriented studies suggest that compact polarimetry should be strongly considered by end-users as their default polarimetric configuration over the duration of the RADARSAT Constellation Mission for maritime and land extended area monitoring. By concurrently satisfying a large amount of users, the regular use of CP configuration could significantly reduce the volume of RCM acquisition conflicts.

Sommaire

Ce rapport résume la portée, la recherche et les résultats d'un projet multi-ministériel sur l'évaluation et le développement d'applications utilisant la configuration Polarimétrie Compacte (PC) dans le cadre de la Mission Constellation RADARSAT du Canada (MCR). Ce projet d’une valeur de 3M $ comprend la contribution du Programme d'utilisation des données et des applications (PUDA) de l'Agence spatiale canadienne, ainsi que celle des ministères et organismes gouvernementaux participants.

En 2011, une équipe de plus de 20 scientifiques et chercheurs a mené une série d'études sur une variété d'applications d'observation de la Terre importantes pour les activités opérationnelles du gouvernement canadien qui pourraient bénéficier de l’utilisation d’un mode Polarimétrie Compacte dans le cadre de la MCR. Au Centre canadien de cartographie et d’observation de la Terre (CCCOT) de Ressources naturelles Canada (RNCan), un groupe de scientifiques a concentré leurs efforts sur le développement du simulateur PC, sur la modélisation de la surface, les problèmes de calibration liés, la détection des changements, l’interférométrie polarimétrique, la glace de lac et de la glace de la rivière, la classification des zones humides, et radargrammétrie 3D. Les autres ministères et organismes gouvernementaux impliqués dans le projet inclus Recherche et développement pour la défense Canada, Agriculture et Agroalimentaire Canada, Service canadien des glaces d'Environnement Canada, Service canadien des forêts de RNCan, l’Agence parcs Canada, et le Collège militaire royal. Ils ont engagé leurs scientifiques à prendre part à la recherche axée sur les applications, en se concentrant sur la détection des navires et des icebergs, la classification des cultures, les prairies et les forêts, la classification de la glace de mer, et la détection des changements de la couverture terrestre.

Sous la MCR, la configuration PC consiste à une émission par l’antenne radar à synthèse d’ouverture (RSO) d’une polarisation circulaire droite et à la réception du signal rétrodiffusé aux polarisations horizontale et verticale et ce de façon cohérente. Cette configuration a l’avantage de renfermer plus d’information que les configurations habituelles émission-réception linéaire-linéaire, offrant ainsi une meilleure caractérisation de l'interaction du signal incident avec la surface terrestre, la couverture végétale, la surface des océans et des glaces de mer. D'un point de vue opérationnel en cartographie et en surveillance à grande échelle, la caractéristique la plus attrayante de la configuration PC est la possibilité de recueillir des données sur une large fauchée, jusqu’à 500 kilomètres. Ce qui n’est pas possible pour une configuration complétement polarimétrique (20 km pour MCR).

La base du projet Polarimétrie Compacte était de fournir aux chercheurs l'accès à des produits simulés MCR PC. Les objectifs du simulateur développé étaient double: (i) développer et fournir aux autres ministères une série de nouveaux paramètres qui peuvent être tirés de la Polarimétrie Compacte pour divers domaines d'application; et (ii) offrir la possibilité d'estimer et de comparer le potentiel d'utilisation de la PC par rapport aux polarisations traditionnelles dual-linéaires HH-HV ou VV-VH et ainsi permettre une préparation optimisée du plan d’acquisitions standard pour les applications canadiennes.

À l'aide des produits MCR PC simulés, les diverses analyses appliquées ont permis de mettre en lumière des faits importants. L'estimation quantitative de l'humidité du sol à partir de données PC pourrait être fait au même niveau de précision qu'avec les données entièrement polarimétriques. La classification des cultures avec les données PC performe mieux qu'avec la configuration à double polarisation linéaire sous l'approche à date unique (augmentation de 20%) ou qu'avec une approche multi-temporelle (augmentation de 5 à 10%). Par rapport aux configurations double-linéaires, les données PC améliorent la classification des types de glace de mer (multi-année, première année) et la discrimination avec les zones d'eau libre. De la même façon que pour la glace de mer, l'accès à la polarisation droite-gauche (RL) circulaire (maximise l'intensité rétrodiffusée pour un média de diffusion de type ''surface'') contribuera à atténuer l'impact du bruit système de l'antenne MCR qui pourrait sérieusement affecter l'efficacité de la détection des nappes d'hydrocarbure et leur caractérisation, ainsi que l'estimation de la vitesse du vent de surface en milieu océanique. L'étendue des zones humides, la classification des prairies ainsi que les zones de coupes forestières et les cicatrices résultantes d'incendie peuvent être facilement évalués à partir des données RSO PC et ce à un niveau de fiabilité similaire à celle de la configuration entièrement polarimétrique. Enfin, les études PC interférométriques (PC-InSAR) de sites horticoles se sont révélées prometteuses, malgré la limitation qu'implique le cycle InSAR de 24 jours dans le cas de RADARSAT-2 par rapport à celui de quatre jours pour MCR (avec 3 satellites). Néanmoins, une série d'applications de caractérisation bio/géo-physiques et de suivit ont été mis en évidence. Des approches de calibration et d'atténuation de l'impact de la non-circularité du signal transmis par l'antenne MCR devront être développées durant les phases de pré et post-lancement afin de bénéficier de tout le potentiel de la configuration PC. Il est à noter que bien que cette étude ait évalué la performance de la configuration PC sur un vaste éventail d'applications essentielles pour le gouvernement, il réside d'autres applications pertinentes qui devraient être considérées pour évaluation dans un avenir proche. Le Tableau 5.1 résume les résultats du projet concernant la performance de la configuration polarimétrique compacte.

En conclusion, les résultats obtenus, à partir d'un large éventail d'études axées sur les utilisateurs canadiens départementaux fédéraux, suggèrent que la polarimétrie compacte devrait être adoptée en tant que configuration polarimétrique par défaut durant la mission de la Constellation RADARSAT pour la surveillance de zones étendues requise par les applications maritimes et terrestres. En satisfaisant un grand nombre d'usagers, cette configuration a l'avantage de réduire considérablement les conflits lors du processus de planification des acquisitions.

Acknowledgments

This study was made possible with the financial support of the Government of Canada through the Canadian Space Agency's Data Utilization and Applications Program (DUAP) and through contributions by the participating government departments and agencies. Special thanks to Keith Raney for his instrumental support in the early steps of this journey. Editorial services for this report were provided by Dirk Werle of ÆRDE Environmental Research.

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1. Introduction

1.1 Purpose of the Report and Project Background

This report summarizes the scope, research and results of the multi-departmental project on the evaluation and application development of the Compact Polarimetric (CP) configuration in the context of the Canada's RADARSAT Constellation Mission (RCM). The project was initiated during Fiscal Year 2011/12 and completed at the end of FY 2014/15, with a total funding envelope of $3.13M provided in part by the Canadian Space Agency's (CSA) Data Utilization and Applications Program (DUAP) and by the participating government departments and agencies. Many of these project results have been recently published and presented in various fora. This report serves as a complete synthesis of the project's results (NRCan, 2012, 2013, and 2014).

The concept and design of a compact polarimetry mode was initially not considered in the RCM Phase A and Phase B requirement studies carried out by CSA, but gained prominence in 2008, when CP had proven effective and valuable in planetary remote sensing missions. Revised hybrid polarimetric spaceborne SAR architectures were proposed by Sourys et al. (2005) and Raney (2006) including experience with lunar crater analysis (Raney et al., 2012). Preliminary evaluations of technical feasibility and user-based recommendations to the RCM User and Science Team regarding the potential utility of a Compact Polarimetry Mode in a variety of important RCM applications [Charbonneau et al. 2010] led to its inclusion in the RCM mission requirements, design and build.

Following this important step in 2010, preliminary technical studies, applications research, and operational development were expanded to ensure that the participating government departments fully understood the potential of the newly added RCM Compact Polarimetry mode prior to launch. With support from CSA's RCM Data Utilization and Applications Program, NRCan's Canada Centre for Remote Sensing (CCRS) (later represented by CCMEO) led an interdepartmental project to develop a pre-launch evaluation of the potential of RCM's new CP mode, specifically within the context of the requirements of the participating departments.

1.2 Project Participants and Scope of Their Work

Beginning in 2011, under the project leadership of Dr. François Charbonneau, a team of more than 20 scientists and researchers from CCMEO, other government departments and external partners conducted a host of studies under the DUAP in a variety of Earth observation application areas that could benefit from the implementation of the Compact Polarimetry mode as part of the RCM (**Table 1-1**). Some of their efforts were supported by research carried out by scientific consultants.

Table 1.1 DUAP Compact Polarimetry Project Participating Departments, scope of work, and scientists and researchers engaged in the project.

Participating Departments, Scope of work	Scientists and Researchers
Natural Resources Canada/ CCMEO (Lead) **CP simulator development, surface modeling, change detection, CP-InSAR** **Calibration** **Wetland classification** **Lake and river ice** **3D Radargrammetry**	F. Charbonneau (Project Manager) - F. Charbonneau - R. Touzi - B. Brisco - J. van der Sanden - T. Toutin
Other Government Departments **CSA: DUAP management** **AAFC: Crop Classification** **DRDC: Ship and Iceberg detection** **EC/CIS: Sea ice classification and oil slick** **NRCCan/CFS: Forestry** **Parks Canada: Wetlands and change detection** **Royal Military College: Grasslands**	 - D. De Lisle - J. Shang and H. McNairn - C. Liu and P. Vachon - M. Arkett - H. Chen and D. Goodenough - J. Poitevin - J. Buckley
External Partners/ Consultants **2KR-LLC** **Torsten Geldsetzer, Consultant** **University of Calgary** **AEL Consultants** **Ducks Unlimited Canada** **CRIM**	 - K. Raney - T. Geldsetzer - M. Collins, M. Denbina and G. Atteia - S. Cloude - B. Tedford - S. Foucher

At CCMEO, a group of scientist concentrated their efforts on several key areas of Compact Polarimetry research as well as the development of select applications, as follows:

- RCM Compact Polarimetry simulator development,
- Surface modeling,
- CP calibration,
- Change detection and InSAR,
- Lake ice and river ice,
- Oil spill detection,
- Wetland classification, and
- 3D radargrammetry.

Other government departments and agencies involved in the Project included Defence Research and Development Canada (DRDC), Agriculture and Agri-Foods Canada (AAFC), Environment Canada's Canadian Ice Service (CIS), NRCan's Canadian Forestry Service (CFS), Parks Canada Agency (PCA), and the Royal Military College (RMC). They had tasked their own scientists to take part in the applications-oriented research, respectively as follows:

- Detection of ships and icebergs,
- Classification of crops,

- Classification of sea ice,
- Forestry,
- Land cover change detection
- Grasslands.

The results of these research and development efforts are discussed in Sections 3 and 4 of this report, following a brief overview of compact polarimetry and the RADARSAT Constellation Mission in Section 2. The work accomplished over the duration of the DUAP Compact Polarimetry project has also been summarized separately in three annual reports covering the Fiscal Years 2011/12, FY 2012/13 and FY 2013/14 (NRCan 2012, NRCan 2013, and NRCan 2014). Each of these reports contains an Annex of internal service and contract reports by the participating organizations and institutions.

2. RCM, compact polarimetry and the DUAP project

2.1 RADARSAT Constellation Mission

In 2018, the Canadian RADARSAT Constellation Mission (RCM), consisting of three identical satellites, will be launched into low Earth orbit, as a follow-on to the successfully completed RADARSAT-1 and the still ongoing RADARSAT-2 Earth observation satellite missions. The RCM payload of synthetic aperture radar (SAR) instruments continues the legacy of the two previously deployed SAR sensors, featuring common and enhanced imaging technology and significantly increasing data acquisition and utilization opportunities (http://www.asc-csa.gc.ca/eng/satellites/radarsat/default.asp). The mission is geared toward three core user areas:

- Maritime surveillance (ice, wind, oil pollution and ship monitoring);
- Disaster management (mitigation, warning, response and recovery); and
- Ecosystem monitoring (forestry, agriculture, wetlands and coastal change monitoring).

Having access to three satellites, equally separated over a 12 day orbital repeat cycle, and to a ground coverage swath width up to 500 km, will allow rapid revisit of target areas around the globe, assuring daily SAR coverage at Medium Resolution 50 m mode (**Figure 2-1B**) of Canada's land mass and adjacent ocean regions. Coherent change detection (CCD) and interferometric SAR (InSAR) related applications will be significantly improved by the equivalent four day orbital repeat cycle. The RCM radars are designed to operate at C-band in 10 different SAR imaging modes (**Figure 2-1A)** and **Table 2-1**), with single polarization, linear dual polarization, compact polarimetry, and, albeit experimentally, quad-polarization configurations.

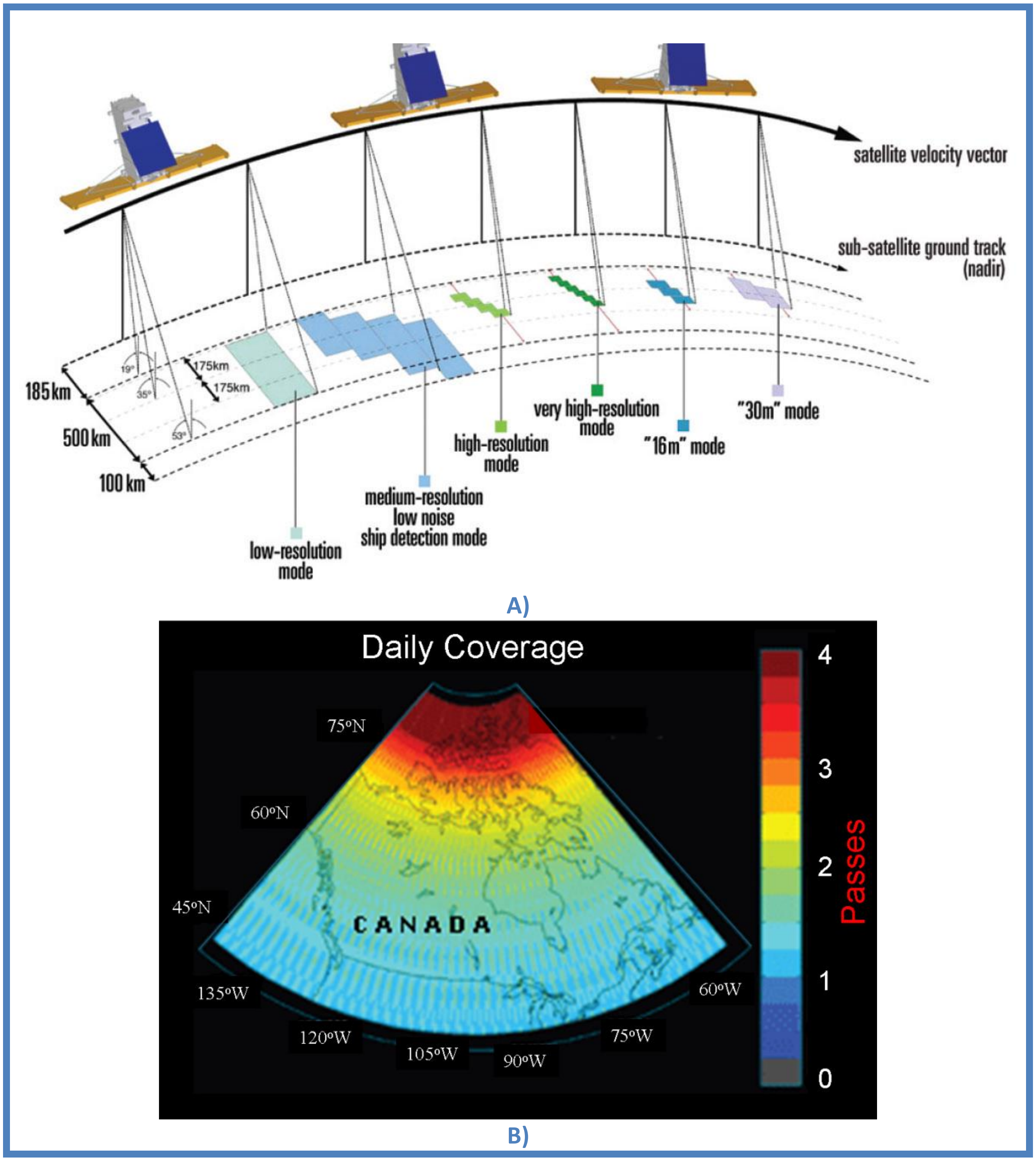


Figure 2.1 A) Schematic diagrams of RADARSAT Constellation Mission SAR imaging configurations and **B)** Frequency of daily coverage of Canada at Medium 50 m mode.

Table 2-1 List of RCM modes

Mode	Resolution [m] (Ground Range)	Looks Rng x Az	ScanSar Burst [nbr]	Swath Width (accessible) [km]	Nominal NESZ [dB]
Low Resolution	100	8 x 1	12	500 (500)	-22
Low Noise	100	4 x 2	10	350 (500)	-25
Med. Resolution 50m	50	4 x 1	8	350 (500)	-22
Med. Resolution 30m	30	2 x 2	4	125 (350)	-24
Med. Resolution 16m	16	1 x 4	-	30 (350)	-25
High Resolution 5m	5	1 x 1	-	30 (500)	-19
Very High 3m	3@35^{o}	1 x 1	-	20 (500)	-17
Spotlight	1x3@35^{o}	1 x 1	-	14 (350)	-17
Ship Detection	variable	5 x 1	10	350 (350)	variable
Quad-Polarization	9	1 x 1	-	20 (250)	-24

2.2 Compact Polarimetry

The Compact Polarimetry configuration is a recent addition to the RADARSAT Constellation Mission. As preliminary studies summarized by Charbonneau et al. (2010) have shown, this configuration tends to contain more polarimetric information than linear dual-polarization or multi-polarization configurations of the SAR, thus providing better characterization of the wave interaction with ground surfaces, vegetation cover, ocean surfaces and sea ice. From an operational mapping and monitoring point-of-view, a most appealing feature of the compact polarimetric configuration is the feasibility to collect these data over wide swath widths (hundreds of km), whereas fully polarimetric SAR operations are limited to a relatively narrow swath of only a few tens of kilometres in width (20 km for RCM). New generations of SAR antenna based on digital beam forming will allow wide swath (≈250 km) fully polarimetric acquisitions, but the current RCM system is not designed to support that technology.

With compact polarimetry, or coherent dual-polarimetric SAR, only one polarization is transmitted, and two orthogonal polarizations are received. Coherent dual-polarimetric radars require that the relative phase between the two receive polarizations be retained (Raney, 2006b), in distinct contrast to conventional “dual-polarized” SARs in which the relative phase is not available. Furthermore, CP differs from linear dual-polarized system by the fact that the antenna is set to transmit circularly polarized wave and receive the backscattered wave under linear Horizontal and Vertical polarimetric configurations (CTLR: Circular Transmit – Linear Receive configuration). In contrast, dual-linear systems transmit linear Horizontal or Vertical polarized wave and receive both orientations. A generic diagram of the hybrid-polarity architecture is shown in Figure 2-2. The major motivation for compact polarimetry is to strive for quantitative backscatter classifications with as high accuracies as those from a fully polarized system while avoiding the disadvantages associated with a quadrature-polarimetric ("quad-pol") SAR (i.e. narrow swath). The fundamental data product from a compact polarimetric radar is a complex target vector of the backscattered field, which in turn may be transformed into the Stokes vector or a 2x2 covariance matrix. Either form captures in its entirety the information contained in the observed electromagnetic (EM) field.

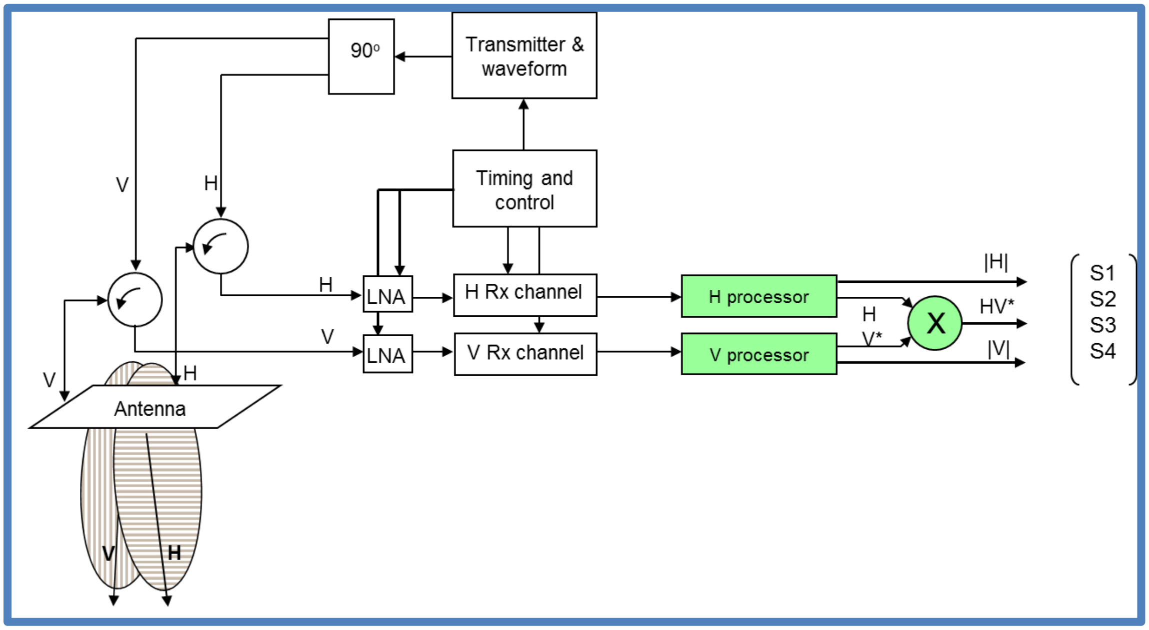


Figure 2-2 Generic architecture of a hybrid-polarity radar. (Raney 2009)

Characteristics of the backscattered field depend on the transmitted polarization. In contrast, the values of the Stokes parameters of the backscattered field are independent of the polarization basis of the receiver unit. Hence, there are only two high-level considerations for the architecture of a compact polarimetric radar: (i) the choice of the transmitted polarization, which is driven by the intended application of the radar; and (ii) optimization of the radar itself, which is driven by technical system trade-offs. A circular polarization configuration on transmission has been selected for RCM instead of pi/4 in order to not favor a specific target's geometrical axis against others. Since compact polarimetric SAR data contain less information than a fully polarimetric (FP) system provides, targets cannot be fully characterized as well as with FP data. However, in many applications, as is demonstrated in this study, the results provided from a CP radar are equivalent to those from an FP radar, to first order. Importantly, the results from a CP radar should constantly perform better than those from a singly polarized SAR (e.g. RADARSAT-1), and most of the time better than those from a conventional dual-polarized radar (e.g. RADARSAT-2) (Charbonneau et al. 2010). Figure 2-3 illustrates combinations of SAR polarization diversity.

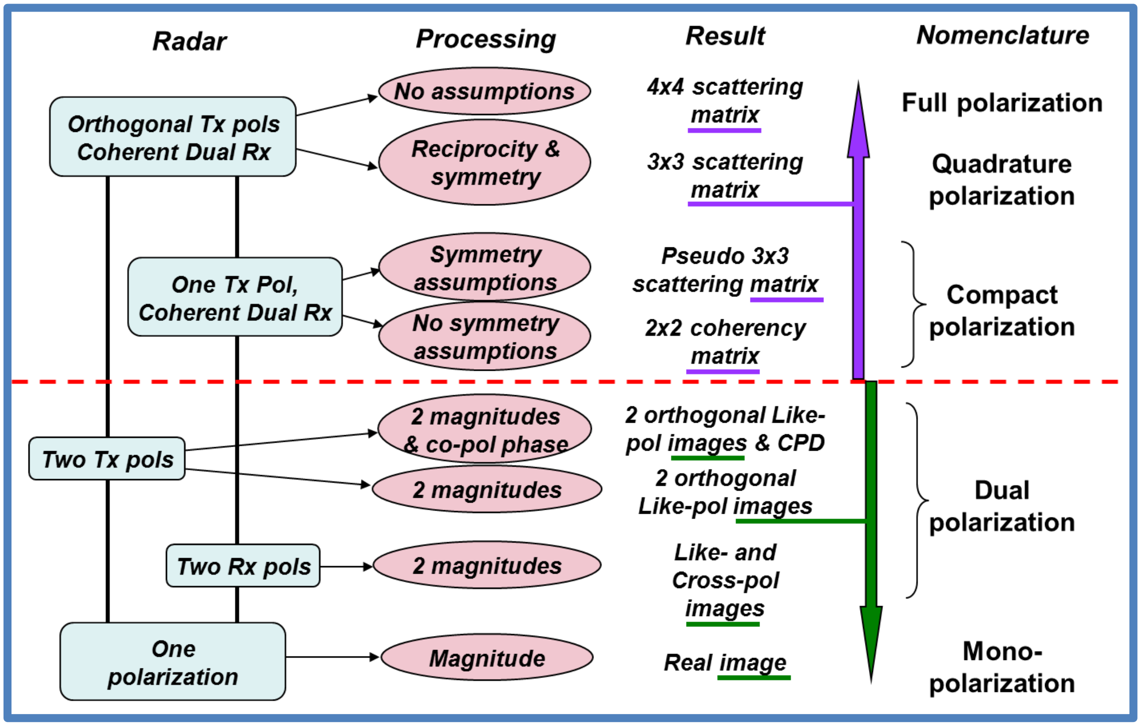


Figure 2-3 Family of polarization diversity and polarimetric imaging radars (Raney 2009 and Charbonneau et al. 2010)

2.3 Goals, Objectives, and Outcomes of the DUAP Project

One of RCM's greatest challenges will be to construct an optimal standard coverage acquisition plan that will fulfill Government user requirements/needs while minimizing imaging conflicts. The main goal of the DUAP Compact Polarimetry project was to evaluate the potential of the compact polarimetric configuration to concurrently meet the needs of a variety of user applications and thus reduce potential imaging conflicts. In support of this evaluation, the project had four main project objectives:

i. Provide access to simulated RCM CP products to support pre-launch evaluations by scientists, researchers, and software system developers in the public sector, academia, and the private sector. Simulated CP products were to be complemented by stringent data calibration, validation and modeling exercises;
ii. Develop and provide other government departments access to a series of new parameters that can be derived from Compact Polarimetry for various application domains;
iii. Estimate the potential use of Compact Polarimetry mode configurations over departmental applications versus traditional HH/HV, VV/VH or HH/VV modes; and
iv. Develop algorithms/methodologies optimizing departmental applications.

Since many of the Federal Departments (FD) had no or little prior experience with Compact Polarimetry data, the DUAP project largely focused on the evaluation of these new parameters under FD-specific theme areas, or applications. The evaluation concentrates on numerical modeling processes, on classification procedures, and on quantification of analysis results. The evaluation highlights the most promising applications and assists operational users of Earth observation satellite data in their pre-launch consideration and post-launch adoption of Compact Polarimetry data. Successful cases could be geared toward operational implementation. Finally, it is expected that following results will better orient and stimulate other users to consider the potential of CP configuration for their specific applications.

3. Simulation and calibration

3.1 Compact Polarimetry Simulator Development

Since EO SAR CP data were not available at the beginning of the project, the development of a Compact Polarimetry Simulator (Charbonneau 2016) and its utilization by the scientists and researchers involved in CP application and evaluation studies represented a fundamental and essential component of the DUAP RCM CP project. The development was led and managed by François Charbonneau at CCRS/NRCan. The CP Simulator software has also been distributed, under license, as a standalone executable (i.e. no third party software required) to user organizations outside the Government of Canada, including Canadian research institutions, universities, and private sector companies.

RCM system specifications were used to design and develop the simulator. Using RADARSAT-2 fully polarimetric data, the tool simulates the ten RCM beam modes at their planned spatial resolutions, ranging from Spotlight 1m resolution to ScanSAR 100m, and their expected noise equivalent sigma zero (NESZ) ranging from -25 dB to -17 dB (see **table 2-1**). Users are also able to define their own desired NESZ. Since fully polarimetric data contain all the backscattering information, it is possible to exactly generate CP data by the product of the transmitting Right circular Stokes vector with the Kennaugh backscattering matrix. From the resulting received Stokes vector, it is possible to estimate the Right-Horizontal (RH) and Right-Vertical (RV) polarization intensities (RCM received configuration), and also to simulate the full spectrum of receiving polarization, as for example Right-Right (RR) and Right-Left (RL) or to simplify the information under derived CP parameters (Charbonneau et al. 2010, Cloude et al. 2012, Raney et al. 2012). Overall, a set of 22 CP and five Standard parameters are derived, as listed in **Table 3-1**. The naming conventions of these parameters in the table are used throughout the report. It is worth noting that the four linear intensities HH, HV, VH and VV are not CP derived products and those data won't be available to users if CP configuration is selected. Those data were simulated to RCM specifications in order to ease comparison studies of CP against dual-linear products. Three optional speckle filters adapted to CP data are available to users (Foucher and Landry, 2014).

Table 3-1. Type and description of Compact Polarimetry parameters and four standard polarization intensities generated by the CP Simulator.

Short form, symbol (alternate short form)	Description
RH	σ^o Right circular transmit, Horizontal receive
RV	σ^o Right circular transmit, Vertical receive
RR	σ^o Right circular transmit, Right circular receive
RL	σ^o Right circular transmit, Left circular receive
ϕ_{RHRV*}	Coherent phase between RH and RV
Sv	Received Stokes vector
m	Degree of polarization
μ_C	Circular polarization ratio
δ	Relative phase between RH and RV
χ	Circularity angle
μ_E	Ellipticity
μ	Conformity
SE	Shannon Entropy
α_s	Cloude alpha angle
ρ	Correlation coefficient between RH and RV
m-chi (m-χ)	Power decomposition based on circularity
m-delta (m-δ)	Power decomposition based on relative phase
HH	σ^o Horizontal transmit, Horizontal receive
HV	σ^o Horizontal transmit, Vertical receive
VH	σ^o Vertical transmit, Horizontal receive
VV	σ^o Vertical transmit, Vertical receive

The RCM CP products can be simulated to conform to user preferences of the planned RCM beam modes in such a way that, as an example, ScanSAR 50 m and 100 m data are used for sea ice monitoring and medium resolution 30 m or 50m data are used for crop monitoring. The products, which may include intensity and derived products, are analyzed in conjunction with in situ data collected during field surveys. The bio/geo-physical parameters contained in these simulations databases are specific to application themes. Statistical analyses and quantitative modeling can then be performed for bio/geo-physical parameters estimation, thematic classification and change detection.

Main parameters of interest used in the studies which have shown great operational potential are

1. Circular polarization RL and RR, which in general can be respectively related to surface scattering mechanism and depolarizing properties (volumetric media like vegetation).

2. m-chi, which decomposes the CP information into three intensity parameters referring to general scattering mechanisms: surface (odd bounce), double bounce (even bounce) and volumetric (depolarizing). This decomposition shows similar performance with the Freeman-Durden or Yamaguchi decompositions used with fully polarimetric data. For general classification of natural media such as wetland, sea ice, and agriculture, this simple approach appears effective.
3. Stokes vector, which is composed of four elements where the first on S_0 refers to the total backscattering power received, while the other elements are related to polarization difference and relative polarimetric phase. Users like to use the Stokes vector in unsupervised classification. It is important to note the Stokes vector is the input for m-chi decomposition, so users need to pay attention to the cross-correlation of inputs while performing classification.
4. Shannon Entropy, which is a two parameter decomposition where the first one refers to the total power received (slightly different than S_0) while the second one is linked to the polarization diversity (similar to m, the degree of polarization) of the interacting media. Shannon Entropy has been revealed to be of interest for monitoring areas with spatial or temporal biomass diversity.

3.2 Calibration Issues

The early concepts of Compact or Hybrid Polarimetry adapting the dual circular polarization RR-RL to a linear H-V antenna were introduced in the 1960s by Long (1967) and P.E. Green (1968). Modern adaptations of Compact Polarimetry to satellite SAR architecture, and attendant calibration issues, as more recently proposed by Souyris (2005) and Raney (2007), have been implemented, albeit uncalibrated, in the Indian RISAT SAR mission (2012) and the Japanese ALOS SAR mission (2013). For CP to fulfill its considerable promise as a mode of choice on the Canadian RADARSAT Constellation Mission for operational monitoring of large areas, CP calibration is an essential element in order to ascertain reliable and accurate information extraction for a host of potential applications.

A White Paper on calibration of hybrid-polarimetric orbital SAR prepared by Raney (2012) emphasized that reliable data interpretation requires the observed phases and amplitudes of the output data sequences to be relatively calibrated. Imperfections in radar-related phase and amplitude balance must be measured and subsequently calibrated (characterized and then compensated) so that the resulting phase and amplitude data reflect polarimetric properties of the scene rather than the distortions of the radar. Polarimetric radars transmitting circular polarization while receiving mutually coherent orthogonal linear polarizations (CTLR or CP) offer both new challenges and new opportunities for relative polarimetric calibration. Within practical constraints, the receive portion of the system—antenna through the processors—can be calibrated to be essentially perfect, to first and second order. In contrast, imperfections in the transmitted EM field cannot be fully corrected. The transmitted field, nominally circularly polarized, should be constrained by design and pre-launch testing to satisfy strict circularity specifications. Various applications impose polarimetric measurement requirements that have their own tolerances to imperfect circularity of the transmitted EM field. Axial ratio (circularity) requirements on the transmitted field should be constrained with respect to such application-specific tolerances. The paper concluded that a CTLR polarimetric SAR can be relatively calibrated. Ground-based references are advisable. It is recommended that any orbital CTLR radar should include a hybrid quad-pol mode, even if only to generate end-to-end data to help calibration of the dual-polarization modes.

The CP calibration effort is led by Dr. Ridha Touzi, in cooperation with S. Nedelcu, B. Montpetit and Francois Charbonneau at CCMEO/Natural Resources Canada, and S. Côté at the Canadian Space Agency. The requirements and plans for CP calibration have been summarized by Touzi and Charbonneau (2013, 2014). The main objective is the assessment of the impact of non-circularity of transmitted polarization on the radiometry and phase of Compact SAR measurements and determination of the calibration requirements of the C-band L-band Compact SAR for the RCM and ALOS-2 missions.

The results to-date suggest that variations in the orientation and helicity – and hence non circularity – of the transmitted polarization can affect significantly the radiometry of RH and RV with a radiometric error that varies with incidence angle. The error was found to reach up to 3 dB for major key applications, such as ice, urban and forest characterization and monitoring (Charbonneau, 2010). An illustration is provided in **Figure 3-1** for the radiometric error in sea ice classification. The non-circularity error also affects significantly the capabilities of the Compact for polarization synthesis as well as the degree of polarization, with an error that can reach up to 5 dB in urban areas. Moreover, the quantitative study conducted with C- and L-band simulated Compact data was used to set up the calibration requirements on the CP radiometric and phase measurements, so as to ensure extraction of meaningful polarimetric SAR information. It was determined that RH and RV should be calibrated with a radiometric error of less than 0.5 dB and phase difference lower than 10 degrees for accurate synthesis of sigma nought (σ^o) at other receiving polarization, such as RR and RL, that are of very important for key applications such as forest mapping and ship detection.

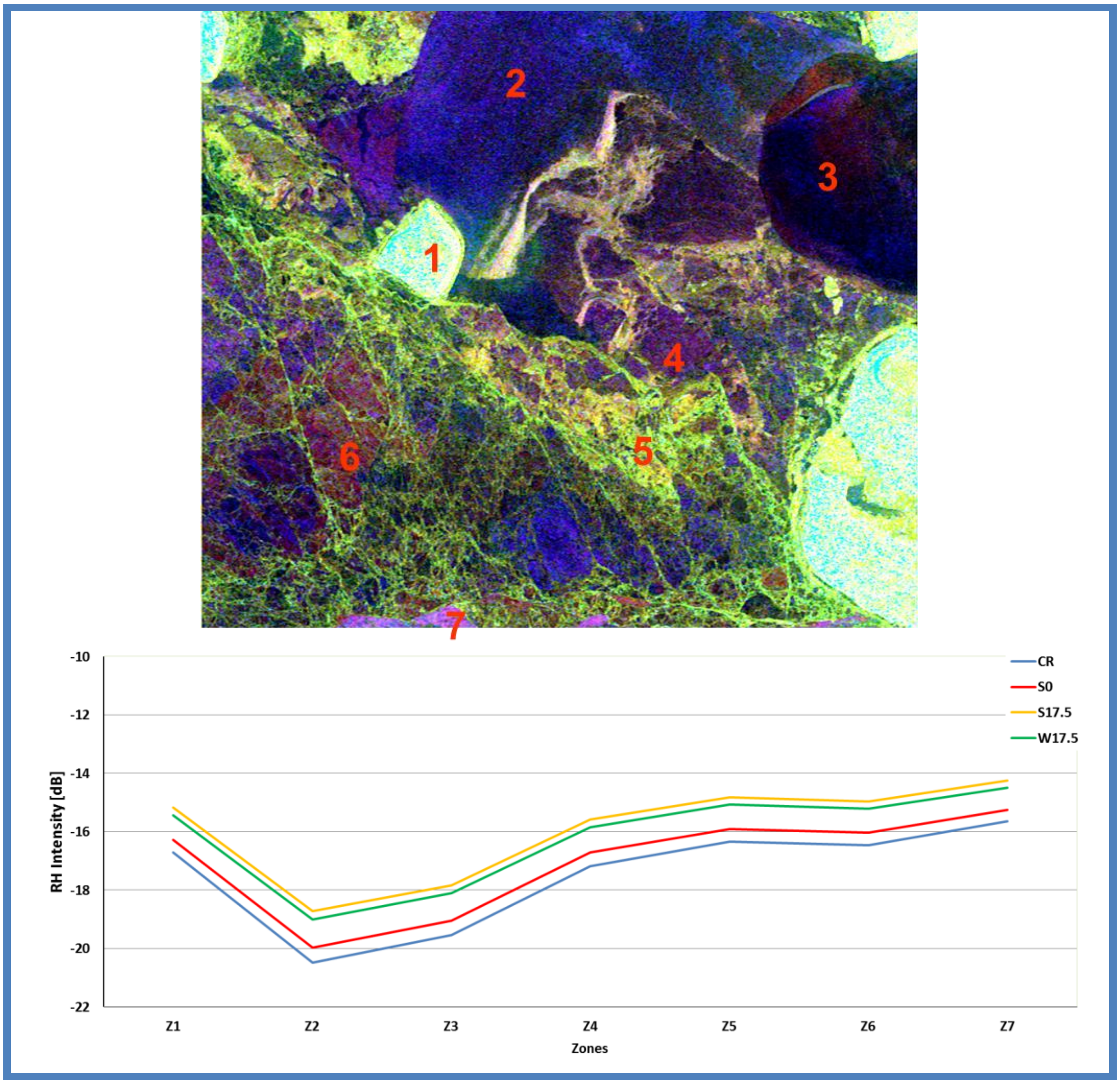
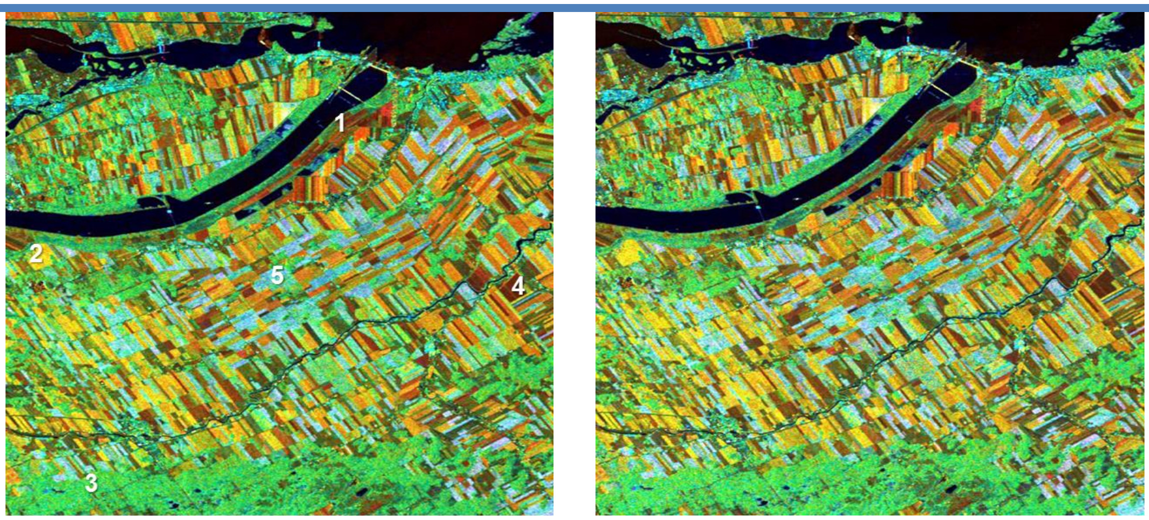


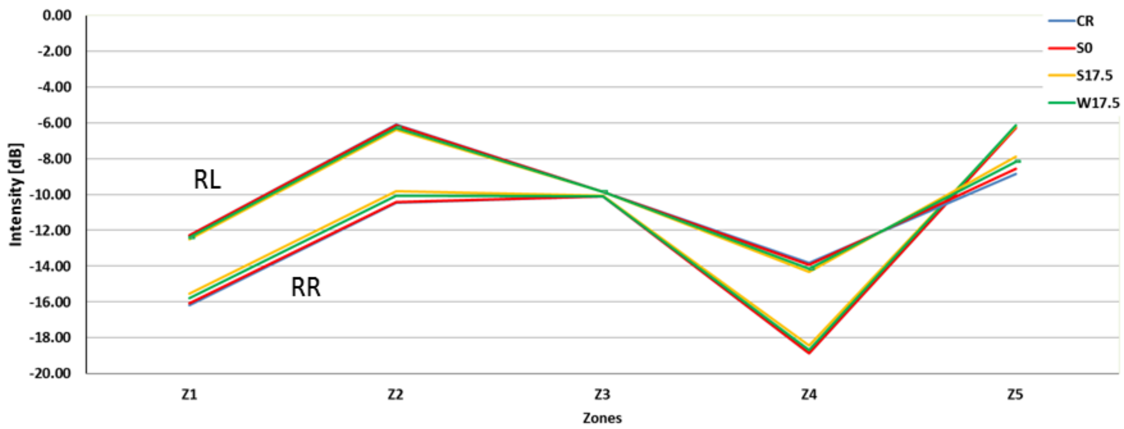
Figure 3-1 RH backscattering coefficients over different sea ice types. Blue curve (CR) corresponds to a perfect circular transmission while the Red curve refers to what should be expected in term of statistically optimal performance at the beam center (θ = 35^o). Yellow and green curves show 3dB error that the

system might have at near and far edge of the swath (θ = 17° and 59°) in terms of statistical and worst-case scenarios. (Charbonneau 2010)

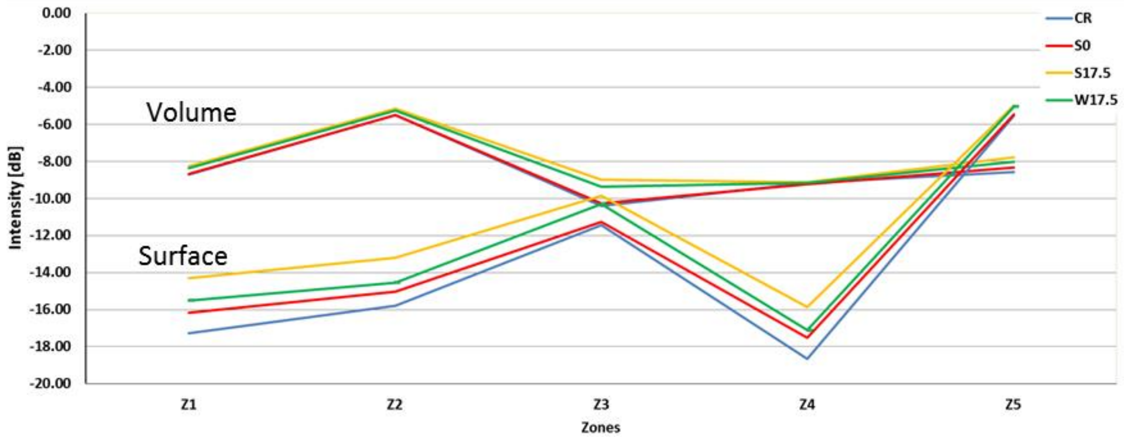
Since the fully polarimetric information is not available with CP, it won't possible to calibrate the system to a pure right circular polarization at transmission. The incoming interaction radar wave won't be "seen" as circular and it is not possible to correct for that. The non-circularity problem seems to be a stopper for the operational use of CP. Nevertheless, there are mitigating strategies that can be developed. As for examples in **figure 3.2**, by using the circular polarization at reception, the radiometric offset is almost null while with the use of m-chi decomposition parameters, we observe that the bias is reduced and mainly present for lower scattering intensity component. Based on the mission definition user requirements, it worth noting that RCM should have a temporal radiometric stability inside 1dB. This implies that, despite transmission non-circularity, temporal analyses will be consistent for classification and monitoring. Also as shown in **figure 3.2**, the intensity offset is fairly constant for the various media types (zones), which imply that relative comparison between media classes won't be affected as much as we expected for a similar incident angle viewing geometry. Furthermore, considering that classification methodologies over a large swath often have to account for the scattering mechanism dependency with the incident angle, including the known circularity dependency into the classification process should be trivial. The main domain where the non-circularity will have an impact, if not carefully taken into account, would be for applications using absolute backscattering coefficients with theoretical models (e.g. ocean wind and soil moisture models). On the other hand, there are still mitigating approaches that can be applied simply by using the fully polarimetric form of those models (NRCan 2014) and feed them with the non-circularity parameter pattern that will be provided by the calibration team. Lastly, the non-circularity issue will have limited impact on CP-InSAR applications.



A) **B)**



C)



D)

Figure 3-2 m-chi Color composite (red: even bounce; green: depolarized; blue: odd bounce) of an agricultural scene **A)** Perfect circularity; **B)** Worst case circularity scenario. **C)** RL and RR backscattering coefficients for five different zones identified on **A)** at four different levels of circularity performance; **D)** Same as **C)** but for the surface and volume parameters of m-chi decomposition.

Several calibration activities have been performed and some are still in development:

1) Under the supervision of Ridha Touzi, B. Montpetit updated the RADARSAT-2 global antenna pattern modeling and antenna pattern synthesis workstation (APSW) (Touzi 2005) to the RCM antenna specifications. The tool allows generating the antenna pattern in the presence of T/R module failures, as well as the optimum T/R excitation law to be applied for minimizing the T/R failure impact. It also generates the excitation law to apply to the T/R elements in order to generate the optimum antenna gain pattern.

2) R. Touzi is working on a new calibration approach specific to CP configuration

3) MDA will provide lab measurement of the RCM antenna from which the polarization circularity will be assessed along the antenna transmitting pattern. This will permit better

understanding of the effect of the non-circularity of subarrays on the global antenna. R. Touzi's work will concentrate on the development of a mitigation model handling the RCM antenna parameters, antenna gain and antenna cross-talk.

4) S. Cloude and the CFS have proposed a new approach to the calibration of polarimetric quad-pol data and validation of compact-pol data. The technique involves solution of a matrix Sylvester equation in the Pauli basis and, unlike most other approaches, does not require assumptions of zero correlations in clutter, nor does it require deployment of expensive and complicated active calibrators. The key development is to make full use of information from deployed trihedral corner reflectors to remove receiver distortion before using reciprocity and uncalibrated dihedrals to perform efficient full calibration in the Pauli matrix basis.

5) With the help of the new RCM simulator tool to be released in December 2016, users will be able to simulate various levels of non-circularity. It is strongly recommended that users use this new feature to assess the impact of the non-circularity on their application in their pre-launch preparation and think about mitigation strategies.

4. Results of applications related R&D projects

4.1 Surface Modeling

Surface scattering of incident radar wave is probably the most common type of scattering mechanism used in several useful applications for Provincial and Federal Departments. It is the dominant mechanism for surface soil moisture, ocean wind speed, oil spill detection, and sea ice characterization. Having a good surface model for Compact Polarimetric data is essential when quantitative parameter estimation is required by users (e.g. soil moisture and wind speed estimations). Consequently the study is in twofold, one theoretical approach based on Integral Equation Model (IEM) for soil moisture estimation (this section) and a semi-empirical approach based on the CMOD model for ocean wind retrieval (section 4.8).

The research effort concerning surface modeling in the context of soil moisture estimation was led by Francois Charbonneau at CCMEO/NRCan in cooperation with Heather McNairn at Agriculture and Agri-Foods Canada. Aspects of their surface modelling work were published as a conference paper and as a workshop presentation (Charbonneau et al. 2013a, 2013b, 2014).

The surface modeling work concentrated on three different study areas in southern and northern Canada. In-situ moisture and roughness measurements in agricultural settings were provided by AAFC for the Casselman study area in Ontario. In addition, the SMAPVEX12 field campaign database (McNairn et al. 2015) for the Carman agricultural and forested area in Manitoba were used. As for the northern site, the Melville Island, Nunavut, study represents mostly bare surface arctic environments. Data were provided by Queen University.

At C-band, whatever the polarization used, the backscattering coefficient is always a function of the soil dielectric constant (ε_r) and the surface roughness parameters (σ_{RMS} and *l* respectively the root mean squared height and horizontal correlation length). The dependency level is function of the local incident angle. The main parameters of interest are the dielectric constant, which is directly related to moisture. These parameters are direct inputs in the IEM, which is the model used by AAFC under co-pol configurations (HH and/or VV). In the same manner from the IEM polarimetric version, it is possible to simulate the backscattering behavior for CP configuration. **Figure 4-1** shows trends of backscattering coefficient as a function of roughness, dielectric constant, and incident angle for the compact polarimetric intensities RH, RV and RL. The RR polarization is not shown since its average intensity for "relatively smooth" bare soil is too close to the RCM noise floor which would introduce inaccuracy in the soil moisture inversion scheme.

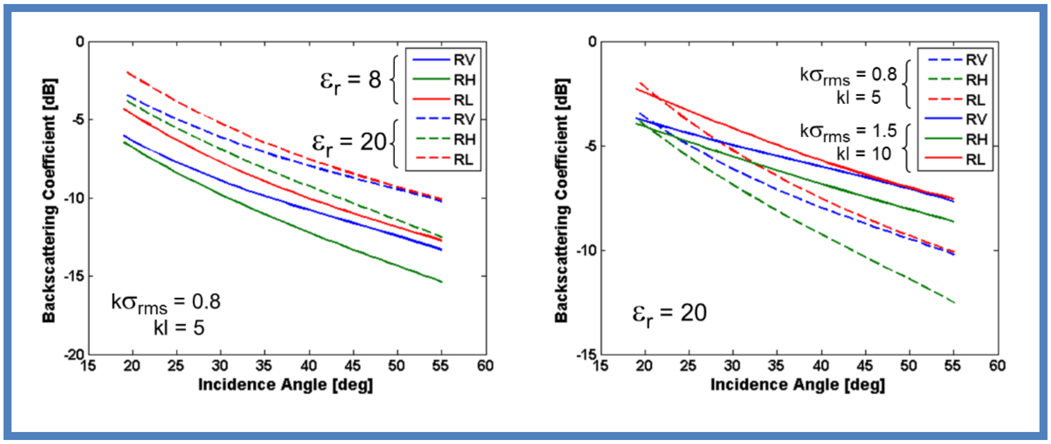


Figure 4-1 Backscattering coefficient RV, RH and RL function of the incident angle: **Left** at two dielectric constants; **Right** at two roughness conditions. ε_r, σ_{rms}, l, and k are respectively the surface dielectric constant, rms height and horizontal correlation length and the radar wavenumber.

Inversion of the surface model with a single acquisition doesn't provide satisfactory results at C-band, even under fully polarimetric configuration. Separating the dielectric contribution from the roughness is an inherent problem, still unsolved for several decades. Optimal methodologies require the use of a multi-temporal and/or a multi-incident angle approaches. **Figure 4-2 A) and B)** show in-situ volumetric soil moisture (Mv) graphics against estimated Mv, using the multi-incident angle approach, obtained from RADARSAT-2 FQ5 and FQ19 data acquisitions on October 12 and 15, 2009, for HH and RL respectively. The two examples show that HH overestimates Mv, while the RL results are well distributed along the 1:1 line. Considering the three days period between acquisitions, the surface moisture and roughness distribution additionally to the difficulty to measure/characterize adequately the surface roughness, the RL results are very encouraging in the context of operational monitoring. Similarly, soil moisture maps can be generated from HH and RL polarizations (**Figure 4-2 C) and D)**) and compared. Obviously, MvHH is overestimated and it is related to the presence of vegetation as detected from the m-chi decomposition (not shown here). The vegetation impact/bias on the soil moisture estimation has been reduced simply by using the RL polarization instead of HH or VV, without any use of a correction algorithm for vegetation.

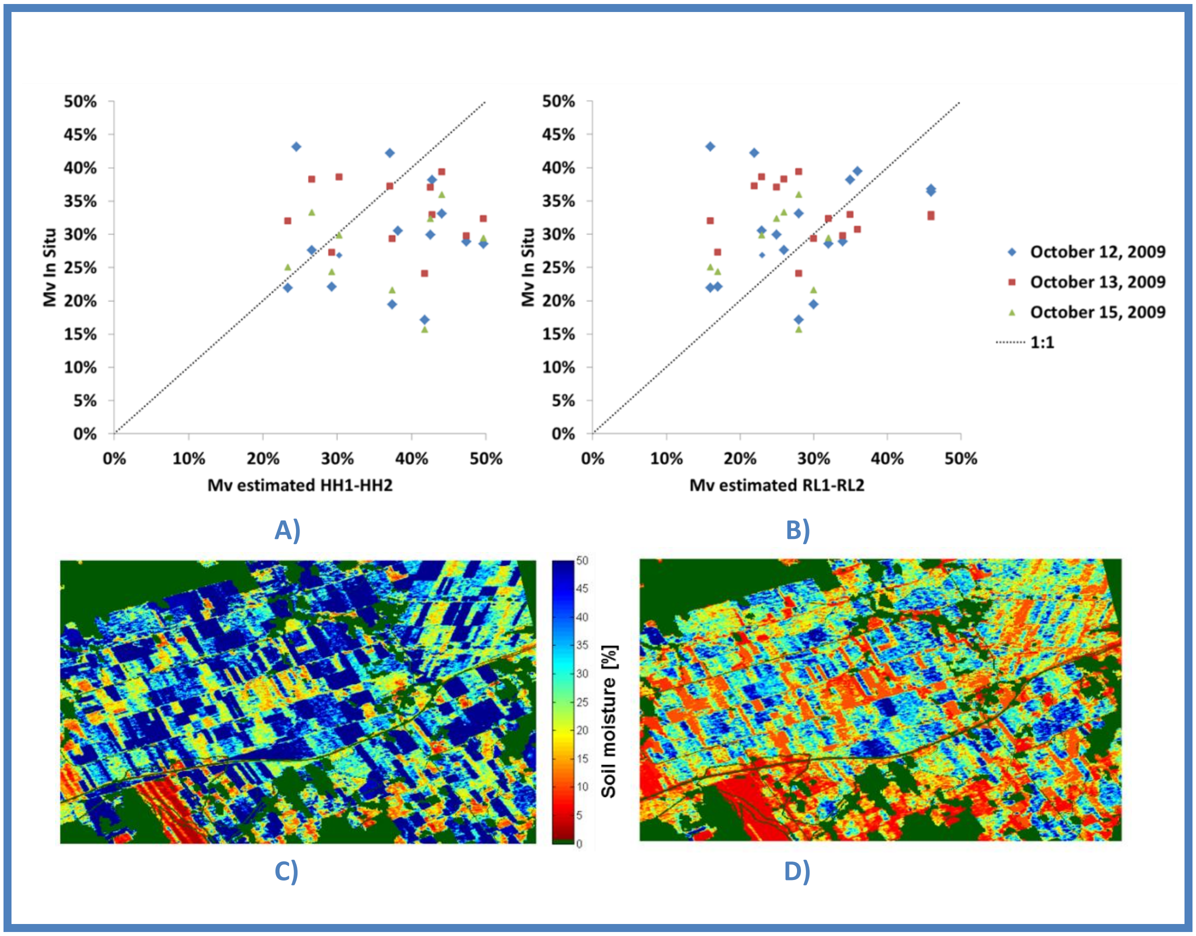


Figure 4-2. Soil moisture estimations, Casselman site, Ontario, based on multi-angle approach obtained with RADARSAT-2 FQ5-FQ19 data. InSitu soil moisture against estimated for HH and RL polarizations (A) and (B) respectively and Resulting soil moisture maps estimated from HH (C) and RL (D).

AAFC are encouraged by these results and will pursue further the research and validation of CP for operational soil moisture monitoring. RCM HH/VV mode has an advantage over CP since users know its performance, but will be limited to half swath (system limitation) compared to CP. Vegetation is and will always be a problem at C-band for soil moisture estimation. CP can help in detecting the presence of vegetation, and roughly estimate its amount, which information can be used in an attenuation model like “water cloud” in order to isolate the surface scattering contribution. This cannot be done under HH/VV configuration, but possible to some degrees at HH/HV or VV/VH.

4.2 Change Detection and CP-InSAR

The utility of Compact Polarimetry for environmental change detection as well as interferometric SAR (InSAR) applications was explored from a methodology point-of-view and from an application validation perspective. Francois Charbonneau from NRCan led the CP and change detection studies in cooperation with Jean Poitevin from Parks Canada Agency and with Grace Frank at AAFC-Summerland. Their work concentrated on two study areas located in the Elk Island National Park area of Alberta and the fruit growing region of Kelowna, British Columbia.

CHANGE DETECTION

A presentation on Earth observation application using RADARSAT-2 and planned RCM imagery was prepared by Poitevin et al. (2014) for Parks Canada personnel. Parks Canada's main objective was to investigate and evaluate the capability of CP for ecological integrity monitoring and reporting needs relevant to National Parks. Parks Canada has also an interest in other activities of the DUAO CP project as it related to soil moisture, wetlands, grasslands, forestry, as well as lake ice & river ice. Characterization and monitoring change of ecosystem components within protected area is a key activity for Elk Island National Park in Alberta.

Preliminary trials involving change detection by way of pre-classified simulated CP imagery were inconclusive. The K-mean classification method provided unreliable results for the type of land use change encountered in the Okanagan Valley. Henceforth, the study adapted a technique using the Wishart distribution. The size of the polygons delineating the land use in that study area is relatively small compared to the spatial resolution of the RADARSAT-2 and planned RCM data, which necessitates the use of advanced filters to enhance the performance of the classifiers. While the change detection products based on scattering mechanisms provide useful results, the multiplicity of products associated with the decomposition methods appeared to be difficult to handle and interpret for a non-initiated user. Consequently, the research activities took advantage of a more advanced methodology based on the Bhattacharyya distance, as described by Conradsen et al. (2003). This method is very effective for fully polarimetric data and can be adapted with ease for CP data as well. The Bhattacharyya distance is widely used in Wishart classifiers to estimate the belonging of a sample to a class from its covariance matrix behavior. This technique has the advantage of taking into account the intensity and polarimetric states of a sample. The basic change detection approach is to estimate the Bhattacharyya distance between co-located groups of samples of two scenes acquired at different times.

Figure 4-3 shows the change detection results based on the CP Bhattacharyya distance, derived from multi-temporal series of SAR data acquired over the Kelowna areas from 2008 to 2014. Major changes in the horticulture field have been detected and classified by year of occurrence.

This type of change detection map is useful for watershed managers who can better plan their field visits for their database update by focusing only on changed fields.

While detecting changes can be also done with linear dual-polarization, albeit at lesser degrees, classifying those changes to sub-categories requires Compact or Fully Polarimetric data. A general classification scheme (**Figure 4-4 A**) based on CP m-chi decomposition is proposed. Detected change class is function of the change in the dominant scattering mechanism between first and second scenes. It is recognized that a change can occur without a change of scattering mechanism, e.g. soil moisture variation. The example over the Elk Island National Park (**Figure 4-4 B to D**) shows the evolution of detected changes from spring to summer (surface scattering to volumetric in the agriculture areas), from summer to fall (volumetric to surface) and the lake ice formation between the two November acquisitions.

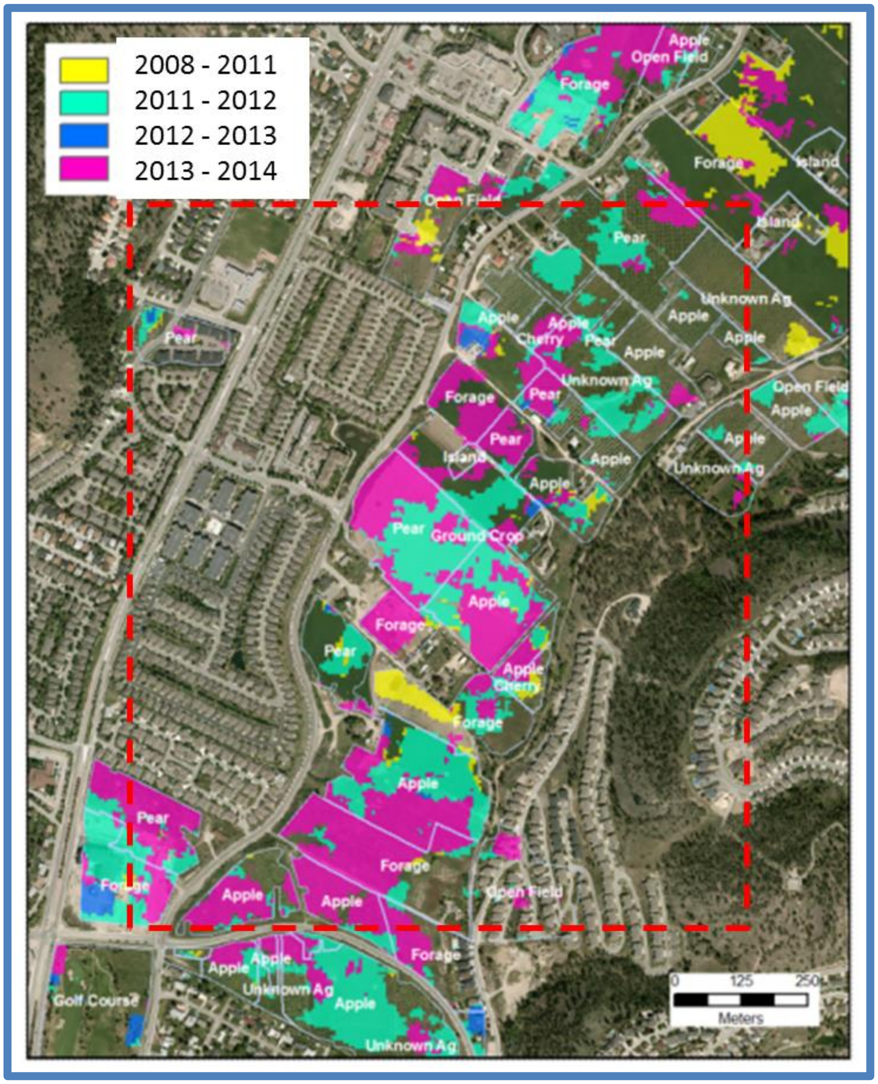


Figure 4-3 Sequential change detection over horticultural fields from 2008 to 2014, Kelowna, BC.

Overall, the results to-date suggests that CP will allow the efficient detection of changes and the optimization of methodologies to highlight seasonal, one-time or permanent changes. The detection performance will be as good as with dual-polarized linear configurations. It appears that detecting a change is fairly simple, but linking that change to relevant information for users remains a challenging task. This is where a CP configuration distinguishes from a dual-linear configuration. From the CP information diversity, general classification of the changes can evolve to specific Land Use and Land Cover (LULC) classes of change but it requires good knowledge of the statistical distribution of each class which is not obvious in presence of diversified LULC but possible when undesired LULC classes can be masked out.

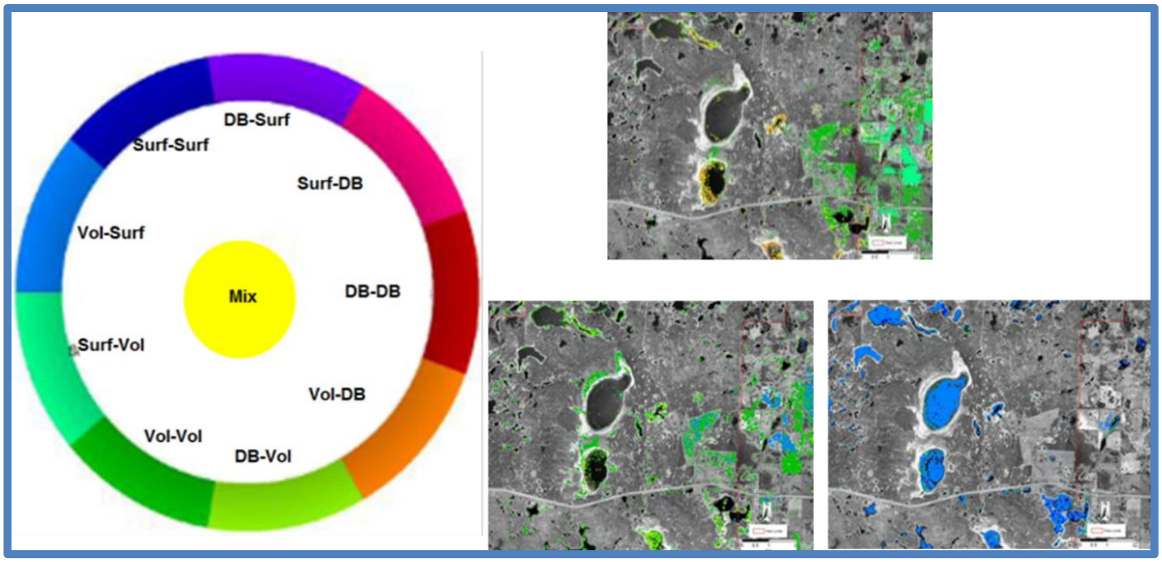


Figure 4-4 A) Change detection legend; Classified change in between acquisitions **B)** Spring to summer; **C)** Summer to fall; and **D**) early and end of November. Elk Island National Park, Ab.

CP-InSAR

The potential of CP InSAR is more difficult to assess because of the relatively long 24 days repeat pass cycle of RADARSAT-2. With its four day repeat pass, RCM CP-InSAR should have some potential for vegetated media despite the fact that its C-band frequency doesn't sufficiently penetrate through the biomass. CP-InSAR refers to the use of the polarization diversity of the backscattered signal combined with the multi pass interferometric phase in between those polarizations. CP-InSAR is based on the same methodology as Pol-InSAR, the only difference being the reduction of the polarimetric information with CP data e.g. going from a 3x3 covariance matrix to a 2x2 covariance matrix. The analysis of CP/Pol-InSAR was examined to assess its ability to improve upon the:

1. Number of InSAR coherent targets;
2. Structural characterization of vegetation.

Improvement of the InSAR coherence is very important in interferometric applications like surface displacement because the quality of the interferometric phase (related to spatial displacement) is directly a function of the coherence. Essentially, the higher the coherence, the better defined the relative phase and consequently, a more accurate surface displacement will be estimated. **Figure 4-5 A)** shows the coherence map over Vancouver obtained with RH polarization compared with the optimal one generated by using all the polarimetric information contained in a CP product (**Figure 4-5 B**). From these maps and the probability density function distribution graphic (**Figure 4-5 C**), it can be clearly seen that the coherence amplitude is significantly improved. For the optimum configuration, most of the distribution is above the 0.3 coherence threshold commonly used for phase quality assurance, while the maximum of the distribution is below that threshold for RH and RV polarizations (similar distributions would be estimated from HH and VV single or dual polarization configuration). This has a direct impact on the standard deviation of the InSAR phase which has a narrower distribution when using all the CP information. Furthermore, by increasing the number of coherent samples in a scene, less smoothing of the InSAR phase is required, leading to more accurate phase unwrapping which consequently results in a better characterized local surface deformation. Coherence optimization with dual-polarization HH-HV or VV-VH will be possible on RCM to a lower extent since the covariance terms HHHV* and VVVH* are close to zero for natural targets.

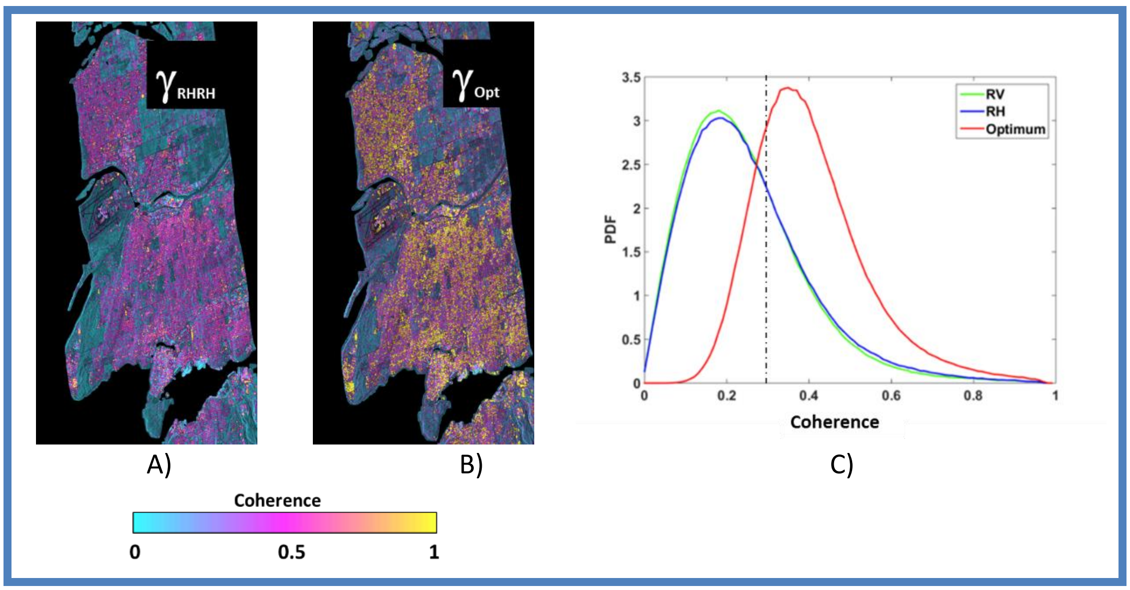


Figure 4-5 Coherence maps over Vancouver area. **A)** RH polarization; **B)** Optimal polarization and **C)** PDF of the coherence by polarization.

Several Pol-InSAR examples of biomass and forest height estimation have been published during the last decade. Similar results are obtained from simulated CP data. However, it is important to note that those experiments were done at longer wavelengths than C-Band and/or from airborne acquisitions with minimal temporal distance (minutes to hours). These factors are important for minimizing the volumetric and temporal decorrelation. The RCM four-day repeat pass should help reduce the temporal decorrelation for low biomass area but this factor will still be of concern at C-band, as seen with hourly airborne acquisition experiments. Furthermore, the tight orbit (max. InSAR perpendicular baseline of 200 m) will limit the height accuracy of the vegetation. Nevertheless, interferometric analysis with CP data acquired in Kelowna, BC, indicated that interferometric pairs contained information that may be exploited to characterize structural horticultural features. At C-band and as shown on **Figure 4-6**, we are moderately limited by the density of the vegetation cover for an optimal use of CP-InSAR. With too low biomass (**Figure 4-6a** new planting apple trees), the incident wave barely interacts with the trees/vegetation structure to generate a non-negligible InSAR phase difference, while too high biomass (**Figure 4-6c** old apple trees) strongly depolarizes radar and reduces InSAR coherence to a level too low to exploit. **Figure 4-6b**, a coherence polar plot of a cherry orchard, is an example of a useful Pol/CP-InSAR signature. The extended InSAR phase distribution and its extremes depend on the height and density of vegetation while the positions and level of consistency is a function of the structure of the radar interaction elements. The information gained from InSAR may be used to enhance the classification performance while at the same time improving change detection.

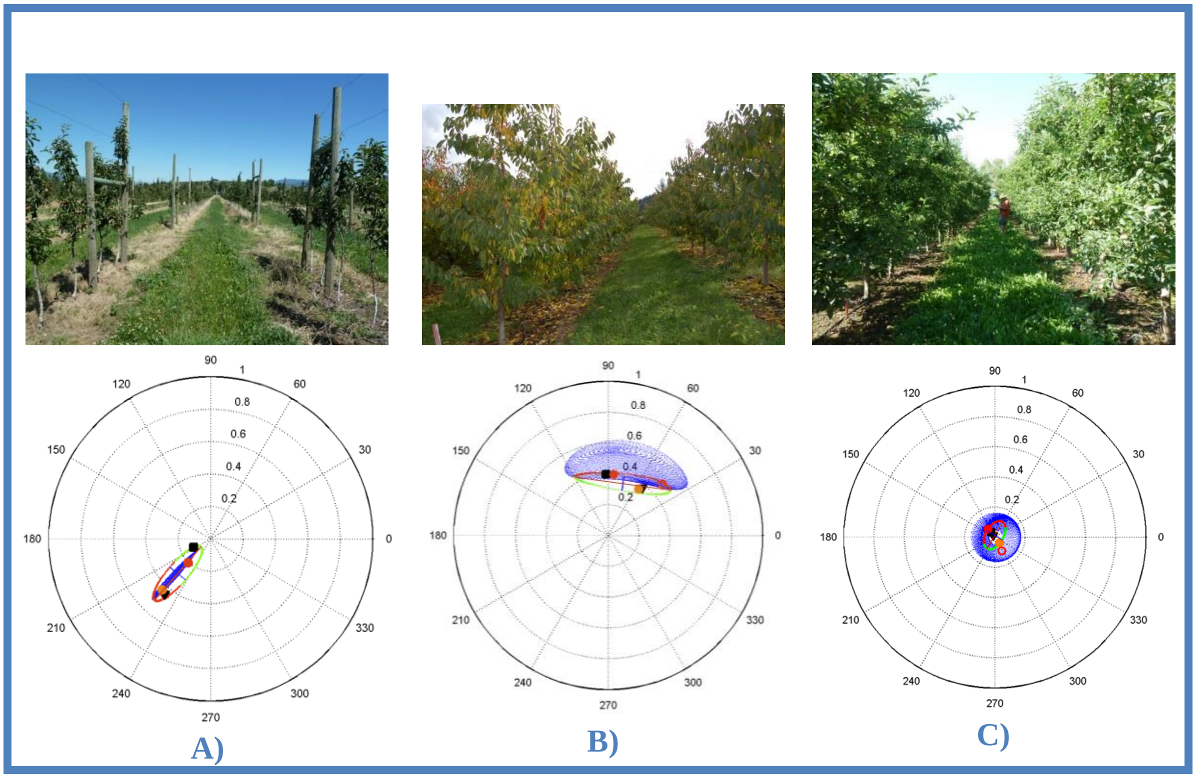


Figure 4-6 Photos and CP-InSAR coherence polar plots (coherence amplitude 0 to 1 and phases) of three horticulture plantations. **A)** High density apple; **B)** cherry and **C)** old style mature apple. Each blue dot refers to coherence values of all received polarimetric combination for a master and slave acquisition pairs. Red and green lines form the elliptical region of possible values when the coherence is estimated from same received polarization for the master and the slave acquisitions.

4.3 Agriculture and Crop Classification

Crop classification potential within Canadian agricultural settings using Compact Polarimetry was studied by a team of Agriculture and Agri-Foods Canada led by Jiali Shang, AAFC (Shang et al. 2014). The potential of rice crop monitoring within an agricultural setting in China was explored jointly by researchers from CCRS at NRCan, led by Brian Brisco, in cooperation with Kun Li and Shao Yun of the Institute of Remote Sensing Applications of the Chinese Academy of Sciences (Yang et al. 2014).

Agricultural Crop Classification in Canada

The objective of the study was to evaluate the capability of compact polarimetry for crop inventory mapping and crop growth condition monitoring by comparing the classification results of dual-polarization SAR data and simulated CP parameters for several study areas in Canada. The Casselman and Stratford areas in Ontario are characterized by a crop mix of corn, soybean, cereals and pasture-forage, with relatively small field sizes of 20 ha on average. The Brunkild area in southern Manitoba is more complex and consisted of cereals, corn, soybean, canola, potato, sunflower, and hay-pasture, with relatively large, quarter section (65 ha) field sizes. Both regions support non-irrigated dry land farming with one crop grown during the relatively short May to September growing season.

The study relied on reprocessed RADARSAT-2 data collected between 2008 and 2010, and on 20 new RADARSAT-2 FQ5, FQ9, FQ19 SAR data collected between 2011 and 2013, using the CP simulation tool developed at CCRS, with added CP decomposition parameters, noise floor and spatial resolution. The multi-temporal RADARSAT-2 quad-pol data were supported by crop survey data, crop phenology information, and leaf area index measurements. RADARSAT-2 data analysis generally relied on a supervised classification approach and a AAFC-developed Random Forest (RF) classifier to perform the crop classification, the latter using a large number of individually trained decision trees and a majority vote to finalize the classification process. Classifications were first performed on single-date pairs of RADARSAT-2 quad- and dual-pol SAR data and the simulated CP data. Classification comparisons were also performed using multi-temporal data pairs. In addition to general crop classification, the capability of CP parameters in tracking crop growth and phenological development was also explored. **Table 4-1** summarizes crop classifications for 2008, 2010 and 2011, using CR parameters and RADARSAT-2 reference data for a variety of crops prevalent in the Ontario study site.

The Casselman and Brunkild area classification results based on simulated CP data reached the benchmark of 85 per cent overall accuracy, while for classification of corn crops, results exceeded 93 per cent -- suggesting that CP is sufficient for operational crop mapping. There were small variations when comparing simulated CP with fully-polarimetric RADARSAT-2 data. Crop classification with CP data performs much better than linear dual polarization configuration on single dates (20% improvement in accuracy) and with a multi-temporal approach (5 to 10% improvement in accuracy). The results indicated that the best CP derived overall accuracy is equivalent or better than the accuracy achieved using the original fully polarimetric fine-quad data. At the individual crop level, the original fine-quad data showed higher accuracy for wheat; CP showed higher accuracy for soybean. This finding is significant in the sense that CP not only performed better than dual polarization; in many cases, CP outperformed fully polarimetric data when used with the operational classifier. It is worthwhile to note that, in theory, fully polarimetic data should provide more information than CP if fully exploited. However, it is clear that the RCM CP mode offers clear value over currently used dual-polarization modes within the current operational workflow of crop inventory mapping and that CP can be used for operational crop monitoring.

In terms of crop biophysical parameter analysis of corn, the correlations generated using CP parameters and the ground measured LAI revealed that many CP parameters correlated significantly with LAI. Among all the parameters, the degree of polarization, VV intensity, RH-RV correlation, and Shannon Entropy Polarimetry gave the best correlations. The results for soybean showed a reduced level of correlation. Overall the results derived from CP and the original quad-pol data suggests that CP is a useful mode for tracking crop phenological changes, and slightly better than linear cross-polarizations (HV or VH). Yet, in order to better understand the relationship between CP parameters and crop growth, additional studies are needed using data collected over other geographic regions with varying crop types cropping systems.

Table 4-1 Classification accuracies [%] and kappa coefficients derived from RADARSAT-2 fully polarimetric data (RS2) and simulated CP data. Casselman study area, Ontario.

In Situ Year	Data Type	Crop Classes Pasture	Soybean	Corn	Wheat	Overall	Kappa
2008	**CP**	95.9	88.3	99.7	90.7	93.6	0.91
	RS2	94.1	85.0	99.8	91.1	91.8	0.88
2010	**CP**	72.4	94.3	99.3	93.9	90.9	0.87
	RS2	78.2	87.9	96.8	94.0	89.6	0.85
2011	**CP**	74.0	84.2	94.4	82.6	86.5	0.79
	RS2	75.0	82.1	93.3	85.3	85.6	0.78

Rice Crop Monitoring in China

During 2012, a RADARSAT-2 data set consisting of nine multi-temporal FQ9 and FQ20 mode polarimetric SAR images was acquired over the Jinhu study area in Jiangsu Province, China, and Compact Polarimetry data were simulated. The simulated data was transmitted as right-circular polarization (R) and received as horizontal (H) and vertical (V) polarizations, with a resolution of 30 m and a noise floor of -25 dB. Eleven CP parameters were extracted in each of the nine RADARSAT data acquisitions.

The study area is part of a major rice-production region where the subtropical monsoon climate results in ample light, heat and precipitation to support one rice crop per year. There are two types of rice fields in the test site (**Figure 4-7**), transplanted hybrid rice fields and direct-sown japonica rice fields. Apart from agricultural land, other land cover types consist of forest, bare land, urban, crab pond and water. Field data were collected concurrently with the SAR data acquisition for 29 hybrid rice sample parcels and 12 for japonica rice. Information recorded during field work included rice growth stages, rice height, leaf area index (LAI), fresh and dry weight and global positioning system (GPS) locations. The study focused on hybrid and japonica rice discrimination and rice phenology monitoring.

After analyzing the backscatter behavior of rice in CP mode during the whole rice growth season, it was found that the tillering stage in mid-July was the optimal phase for rice identification. The signatures of bare land, crab ponds, and water were very different from rice, often by an amount larger than 5 dB. Thus, rice was easily distinguished from other land cover types, including urban areas. A simple threshold method to selected scenes and polarizations configurations yielding an accuracy of 96% when compared to field data. Classification errors were introduced by the confusion between rice and grass in rice field ridges due to their similar geometric structure and radar response.

The study of CP SAR data concerning the hybrid and japonica rice areas revealed that the difference between the two types is most significant at the seedling stage. The configurations of both rice fields were totally different owing to the differences in planting patterns; the hybrid rice was transplanted into the fields in regular lines and row spacing of about 15 cm and 30 cm respectively, whereas the japonica rice was sown randomly. The planting density of the latter was higher. The underlying surface of hybrid rice fields was water, while the underlying surface of the japonica rice fields was a rough soil. As the plants grew, the geometrical structures and features of plants in both rice fields become more similar, especially after the canopy leaves and stems were fully developed.

The study concluded that Compact Polarimetry has very promising application potential for rice monitoring. Hybrid and japonica rice varieties can be discriminated with the accuracy of 94 per cent and 86 per cent, respectively; they can be discriminated before the heading stage, with accuracies of 84 per cent and 77 per cent. No more than four Compact Polarimetry parameters are required to retrieve rice phenology successfully for accuracies to exceed 85 per cent level.

Overall, RH/RV/RR/RL, m-chi decomposition components and conformity coefficient (μ) are sensitive to rice phenology.

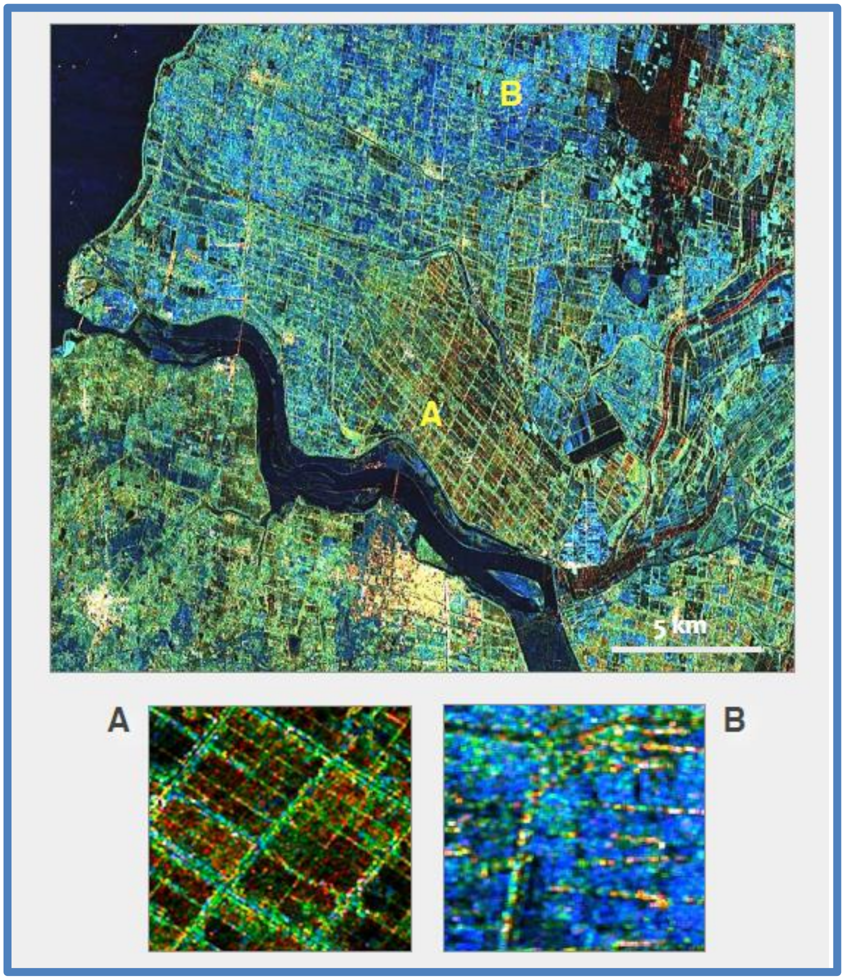


Figure 4-7 Simulated CP m-chi decomposition of a RADARSAT scene acquired over the Jinhu area in Jiangsu Province, China. Zone A and B correspond respectively to hybrid and Japonica rice crop.

4.4 Grasslands

Information on grassland extent and change is scarce. Grasslands are important for domestic and wildlife grazing, for wildlife habitat, in maintaining faunal and floral biodiversity, and in influencing global carbon and water fluxes. In the Canadian Prairies, grasslands are under threat due to expansion of agricultural production, urban development, and oil and gas exploration. In Alberta, a spatial inventory of native grasslands is near completion. However, future updates are not sustainable based on digital aerial photographs and manual interpretation. Synthetic aperture radar offers a potential "weather-independent" alternative, as demonstrated by researchers from the Royal Military College and Agriculture and Agri-Foods Canada (Smith and Buckley 2011).

Under the Compact Polarimetry project, a research team led by Joseph Buckley (RMC) and Anne Smith (AAFC) investigated the ability to discriminate native grassland from surrounding vegetation using simulated compact and dual polarimetry data derived from quad-pol RADARSAT-2 imagery. Their main goal was to determine the potential for updating grassland inventories using imagery acquired by the planned RADARSAT Constellation Mission. The study focused on Newell County, Alberta, located on the western edge of the dry mixed grass prairie. This area exhibits a mix of native grassland, seeded grassland, dryland and irrigated annual and perennial crops. Ground reference information on different land cover types was collected between 2009 and 2011, including native grasslands, cultivated crops of various kinds, and improved pasture.

A multi-year series of 36 high-resolution RADARSAT-2 quad-pol images were collected during ascending orbits over the study area between 2009 and 2011 at steep and moderate incidence angles, FQ3 and FQ16, respectively. Processing streams for the RADARSAT-2 imagery differed between the regular quad-pol and the simulated RCM compact and dual-pol modes. The Cloude-Pottier, Freeman-Durden, van Zyl Yamaguchi 4-component decomposition was computed using PolsarPro. For the RCM simulation, data were initially processed through the RCM simulator developed by NRCan. Simulation was done in the RCM Medium Resolution 30 m mode with a nominal noise floor of -24 dB. Both the Raney m-χ, and the dual-polarization VV/VH modes were retained for further processing (Buckley et al., 2015).

Classifications were initially conducted using all land cover types, but in the accuracy assessment only two land cover groups were of interest, native grassland and “other” (combined fallow, crops and improved pasture). These results were compared with classifications where the “other” classes were amalgamated before classification. No significant difference in the final accuracy was noticed, and processing times were much less using only two classes. Hence, all further classifications were done using only the two classes.

Figure 4-8 shows a typical example of processed and classified images of native grassland and cropping areas. The left column shows the quad-pol image, decomposition and classification chain; the centre top and bottom shows the dual-pol image and classification, respectively; and the right column shows the compact polarimetry case. The decomposed imagery (centre left and right) reveal various backscattering effect (red=double bounce, green=volume scattering, blue=surface bounce). Classification of the dual-pol imagery is based just on the magnitudes of the two channels VV and VH. The three grassland vs. non-grassland classifications are almost indistinguishable.

The study concluded that classification using either compact polarimetry or dual-polarization imagery was successful for most of the growing season. The classification was inaccurate only in the early part of the season. Quad-pol imagery contains more information than CP imagery, which, in turn, contains more information than dual-polarization imagery. There appears to be sufficient information even in dual-polarization imagery to allow the monitoring of native grassland extent. Imagery collected over the prairie regions of western Canada is likely to be useful for much more than this simple task. As shown it the previous section, separation of crops, fallow, range and improved pasture will likely be improved with the additional information contained in compact pol imagery.

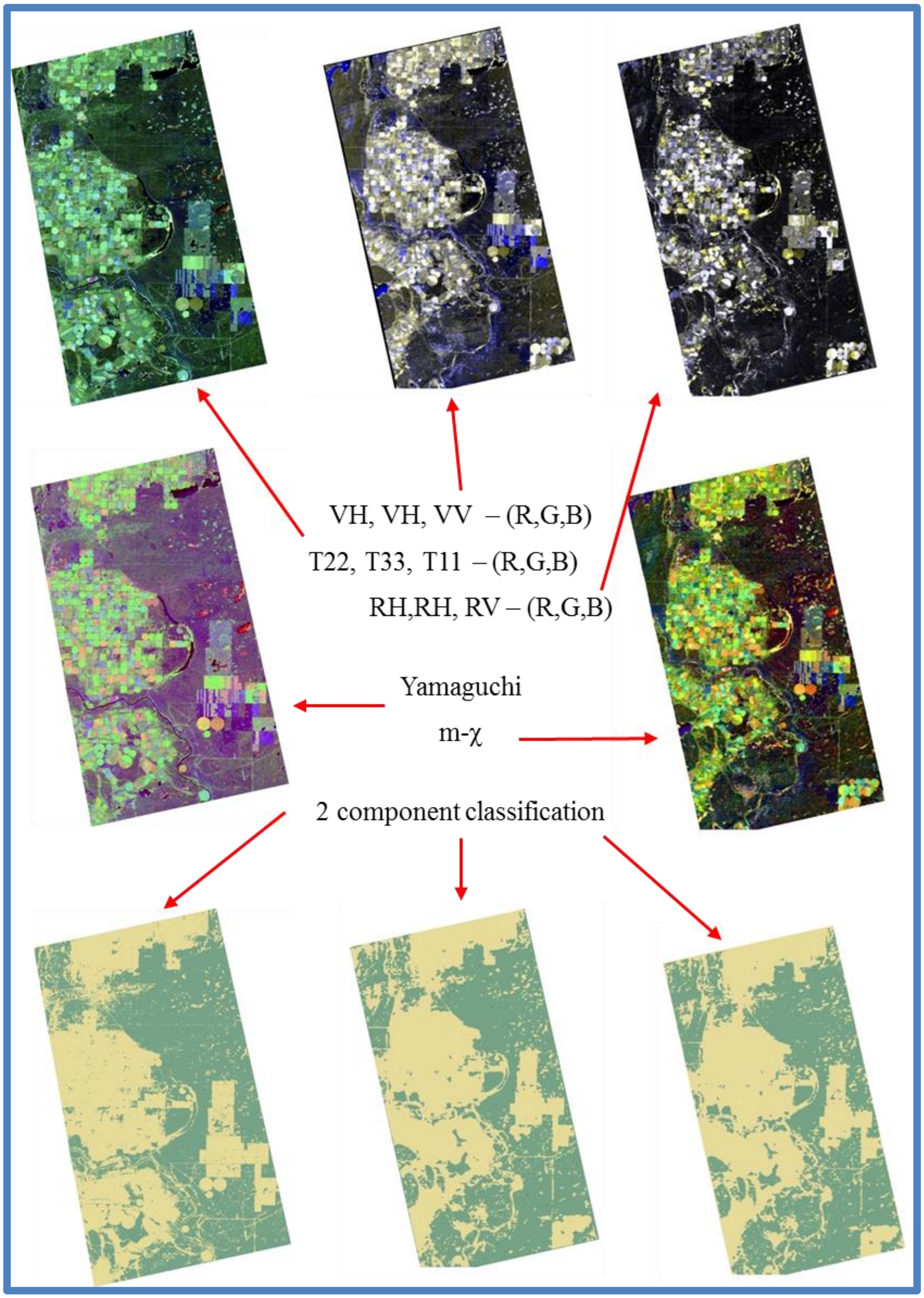


Figure 4-8 SAR image and processing examples of grasslands and cropping area, Newell County, Alberta. **Top:** Polarization color composites; **Centre:** Polarimetric Yamaguchi and CP m-chi decomposition color composites; **Bottom:** Classification resulting maps.

4.5 Wetlands

Early research with the Compact Polarimetry simulations from test sites in Manitoba have demonstrated the classification capability of the CP mode for wetlands (Brisco et al. 2013). Based on the encouraging results, emphasis has been on wetland monitoring applications with the CP data. Over the duration of the RCM Compact Polarimetry project, a team of researchers led by Brian Brisco of Natural Resources Canada, in cooperation with Ducks Unlimited Canada researchers Bill Thetford and Andrew Platt and Parks Canada researchers Prabir Roy and Jean Poitevin, have concentrated their efforts on two main study areas in southern Manitoba and the Georgian Bay Islands national Park area. Their evaluation of the simulated CP data sets for this application focused on the m-chi decomposition in comparison with the Freeman-Durden decomposition and the Shannon entropy (Brisco et al. 2013, Pratt 2014). Additional work has been performed on mapping and monitoring the change in the flooded vegetation, the open surface water, the saturated soil zone and the upland boundary (Dabboor et al. 2015), which are all of particular interest to wetland biologists.

Oak Lake and Whitewater Lake, Manitoba

The Oak Lake and Whitewater Lake study areas are located within the Prairie mixed-grass biome in an agricultural region of Southwestern Manitoba. Wetlands in this region are composed of a variety of hydrophytic species. During 2010, five fully polarimetric RADARSAT-2 Fine Quad images at 26 degrees incidence angle were acquired for the Oak Lake area and four images at 36 degrees incidence angle for the Whitewater Lake area. Late-July imagery was further analyzed as it was acquired near peak vegetative growth conditions when class separability is the best. In addition, field data were collected during late summer for 200 sample locations of 10x10 meter dimension at Oak Lake and for 70 locations at Whitewater Lake. For Oak Lake, the land-cover classes included cattail, sedge, rushes, phragmites, bulrush, water, and upland. For Whitewater Lake, the land-cover classes included whitetop, cattail, pondweed, rushes, sedge, water, and three classes of farmland (Tedford 2012).

The overall classification accuracy assessments for both wetland sites, first done with linear polarized (HH, HV, VH and VV) and CP (RR, RL and RH) backscattering coefficient, showed that CP data combination outperformed linear polarizations with classification accuracies of 86% and 94% for Oak Lake and Whitewater Lake sites respectively, while the best linear polarization combination resulted in 85% and 82% (**Figure 4-9**). However, when the polarimetric phase is taken into account, fully polarimetric decomposition parameters (like Freeman-Durden approach) out-performed CP decomposed parameters (Stokes vector or m-chi). The classification of the Oak Lake site is clearly improved by the fully polarimetric information, jumping from 85% to 97%, while the classification is not significantly improved by CP decomposed parameters. On the other hand, for Whitewater Lake, the use of the polarimetric phase results in a classification accuracy of 96% and 97% for CP and fully polarimetric data respectively.

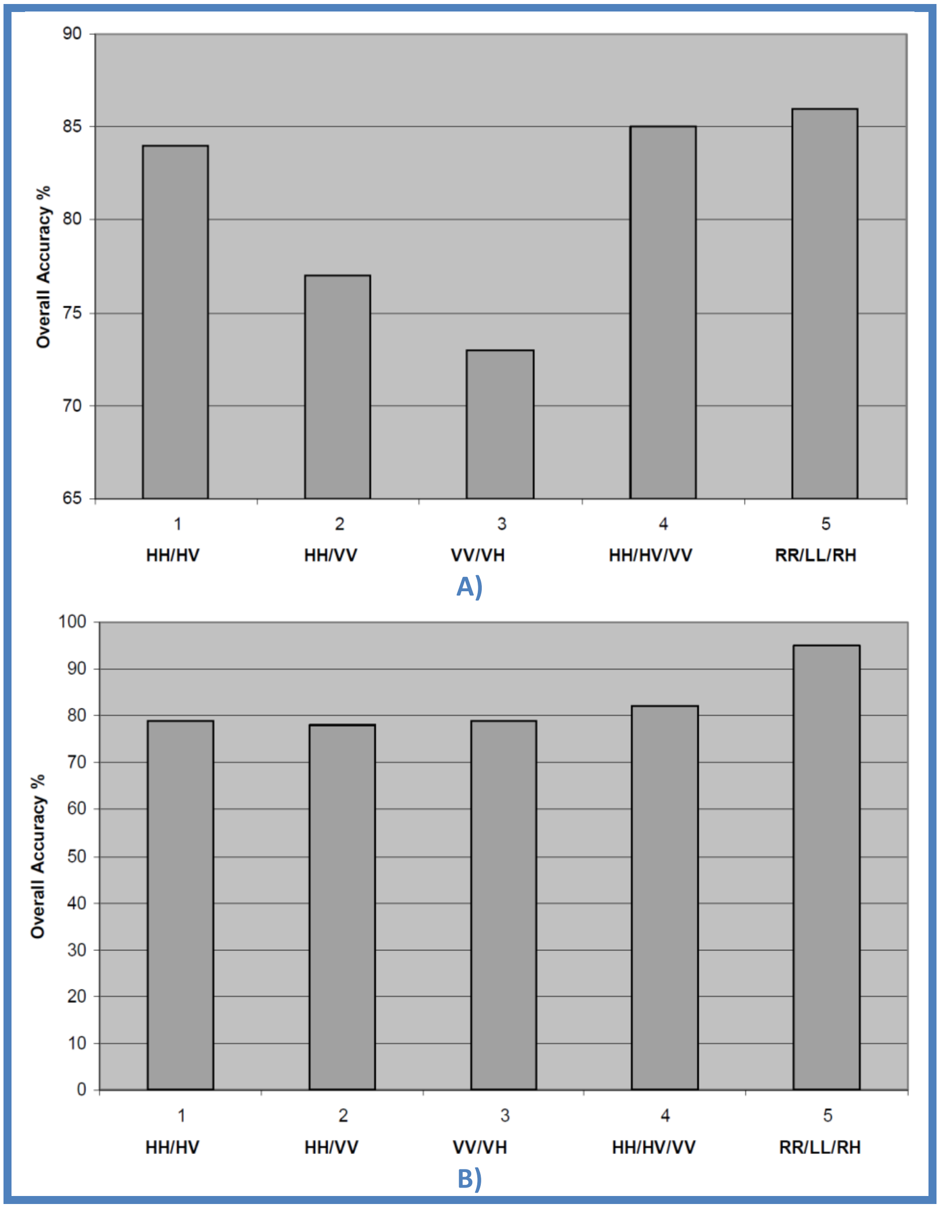


Figure 4-9 Comparison of overall wetland classification accuracy for the various polarization combinations of polarimetric data and simulated CP data. **A)** Oak Lake test site; **B)** Whitewater Lake test site

Other analysis of visual qualitative evaluation results have demonstrated that both the Freeman-Durden and the m-chi decompositions allow monitoring the changes in the surface water, flooded vegetation, and upland proportions of the land cover over time (**Figure 4-10 A to D**). The open water shows up as surface scattering, the flooded vegetation has a predominant

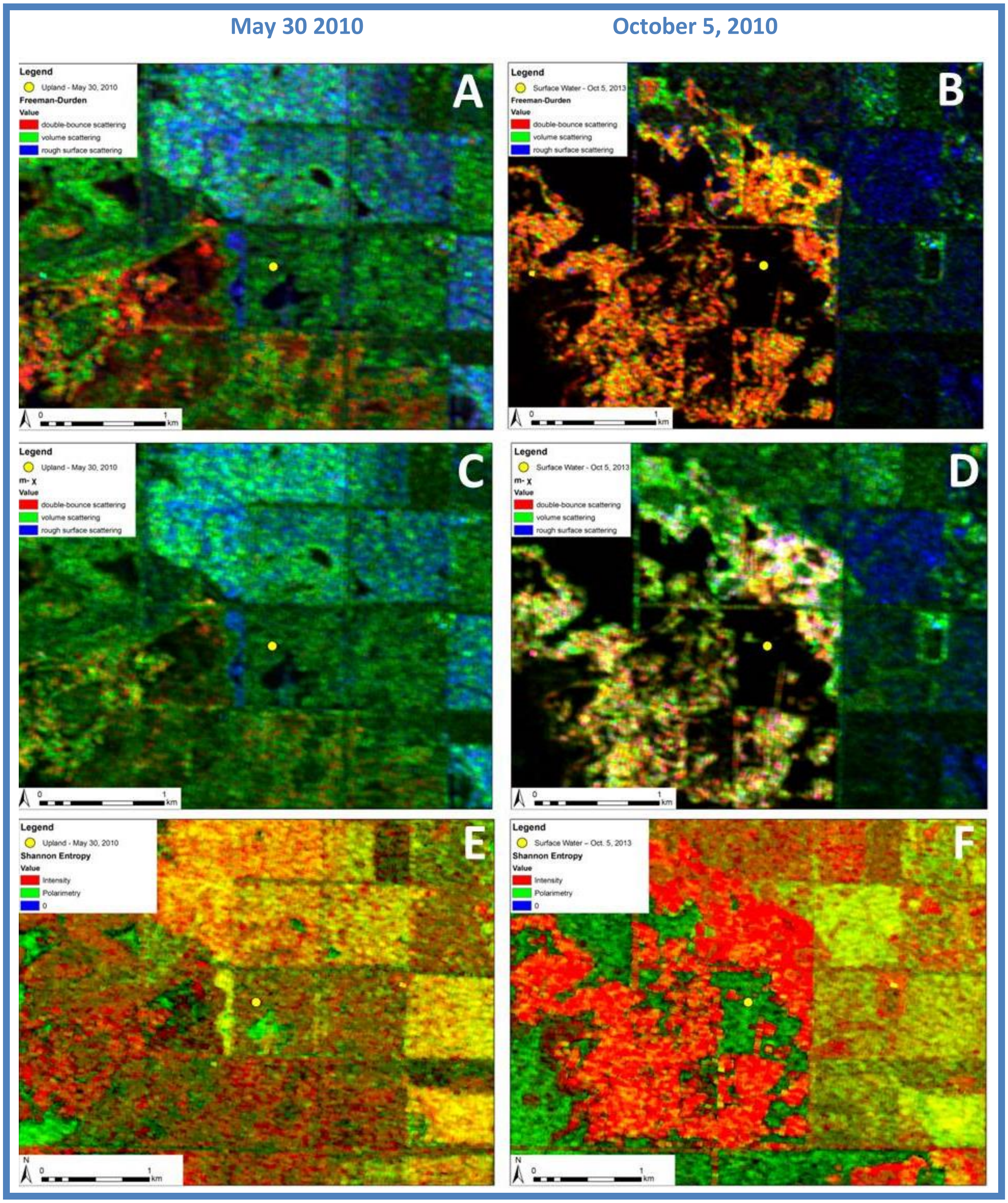


Figure 4-10 Examples of land cover qualitative change from "upland" on May 30, 2010 and October 5, 2010 to "surface water" for the Whitewater Lake study area in Manitoba. **A) and B)** refer to Freeman-Durden approach; **C) and D)** to m-chi; and **E) and F)** to Shannon entropy approach.

double bounce and the upland land cover is mostly volume scattering. Using this approach one can monitor the seasonal evolution of the wetland land cover and annual difference due to climate warming or anthropomorphic effect. The Shannon entropy total power and polarimetric scattering entropy components appear to be useful to identify the upland wetland boundary by discriminating between saturated soil regions, standing water and unsaturated soil (**Figure 4-10 E & F**). This is useful for delineating the wetland extent which varies both within a year and between years in this environment.

Overall, the Compact Polarimetry data provided accurate wetland classifications. The m-chi decomposition results were found to be similar to Freeman-Durden decomposition and can monitor the extent and temporal development of marsh (flooded vegetation). The Shannon entropy shows potential for monitoring the change from flooded/saturated soils to upland environments.

Georgian Bay Islands National Park, Ontario

On-going ecological monitoring in Georgian Bay Islands National Park of Canada indicated that non-native phragmites is invading aggressively in new locations along coastal shorelines, posing a threat to ecosystem balance. A change in wetland vegetation composition and structure by invasive plants, including phragmites, can greatly affect the species that live within these wetlands and ultimately can affect food sources and nesting grounds. Parks Canada Agency's conservation mandate calls for the protection of wetland native species by preventing or controlling invasive species.

Preliminary results involving multi-temporal RADARSAT-2 and simulated data sets demonstrated the possibility of detecting the marsh wetland class from the water and upland land cover using both the Freeman-Durden decomposition from the fully polarimetric data and the m-chi decomposition from the Compact Polarimetry data. Early in the spring, and before the presence of flooded vegetation in the marshes, the decompositions could not detect the marsh class, but as the summer progressed the marsh class became well differentiated due to the predominant double bounce scattering mechanism (**Figure 4-11**).

Phragmites patches are very dense mono-specific stands that do not deteriorate as much over the winter months as other marsh wetland classes, such as cattail and bulrush. Hence some winter imagery was acquired to determine if the phragmites patches could be identified at that time of year. Preliminary results were discouraging as the wetland classes and the phragmites patches could not be differentiated. The relatively small patch size implies that high resolution data is needed for this application. Overall, the results indicated that Compact Polarimetry data can separate wetlands from uplands but not phragmites from marsh. Mapping phragmites invasion requires very high spatial resolution data; polarization diversity is important, but to a lesser extent.

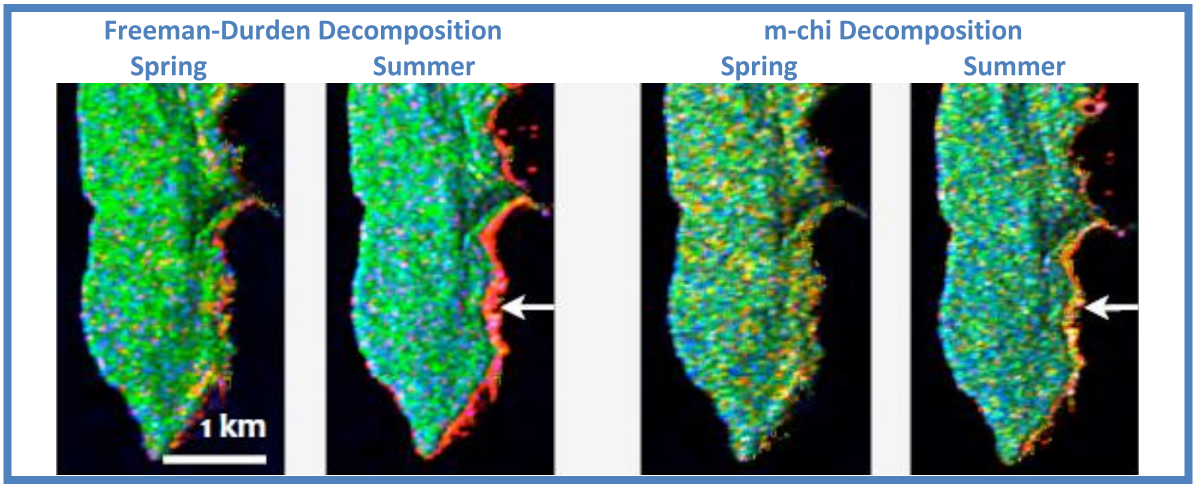


Figure 4-11 Seasonal detection and delineation possibility of phragmite patches along the shore, Georgian Bay Islands National Park. **Left:** Fully polarimetric Freeman-Durden representation; and **Right:** Compact polarimetric m-chi color composite.

4.6 Forestry

As part of Natural Resources Canada, the Canadian Forest Service (CFS) is a major national and international stakeholder for the Canadian forest sector. The CFS provides science and policy expertise and advice on national forest sector issues. Within the RCM Compact Polarimetry project, the CFS, in cooperation with the University of Victoria in British Columbia, undertook a number of studies. The research team was led by Hao Chen and David Goodenough with Shane Cloude providing support as a consultant to the team. Over a four-year period the scientists pursued a number of study objectives, as follows:

- Software readiness for batch processing fully polarimetric and simulated CP data.
- Apply CP methodology to a selection of simulated RCM data for CFS sites.
- Focus on potential forest applications of RCM compact polarimetry mode: landcover classification, fire scar detection, tree-height estimation, and change monitoring.
- Assess the impact of compact polarimetry on classification accuracy.
- Optimize model-based decomposition theories and identification of useful reversed model parameters for biomass estimates and fire scar identification.
- Conduct a time series analysis of simulated compact-pol data with different environmental conditions.
- Implement the heuristic rule-based classification based on compact decomposition theories.

The results of their work were summarized in three annual reports (NRCan 2012, 2013, 2014) and contractor reports (Cloude, 2012a, 2012b), presented at workshop (Cloude et al. 2013), and published as peer-reviewed articles (Cloude et al. 2012) and conference papers (Chen et al. 2014).

A total of 45 multi-temporal RADARSAT-2 SAR images were acquired in Fine quad-pol mode for analysis and RCM CP simulation purposes, covering three CFS study sites located in the Hilton and Keg River areas of Alberta, and in the Petawawa area of Ontario. A fourth area near Sooke Lake on Vancouver Island in British Columbia is being used as a LiDAR and calibration site. For some sites SAR data validation was supported by Airborne Imaging Spectrometer three-dimensional land cover data and mapping information and high-resolution LIDAR data to generate a high spatial resolution Digital Terrain Model (DTM), a Bare Earth Model (DEM), a Canopy Height Model (CHM), and canopy structural statistics. The Petawawa study site is supported by extensive ground truth time series data on forest types and properties in the form of GIS polygons.

The Hinton study site is located some 285 kilometres west of Edmonton and 85 km east of the town of Jasper in Alberta. The area covers approximately 2600 square kilometres, with elevations ranging from 1000 to 1700 meters above sea level. The forest stands are dominated by lodgepole pine and white spruce. The ages of the mature dominant species vary between 80 and 110 years and stand heights range from 11 to 21+ meters. Covering approximately 300 square kilometres, the Petawawa Research Forest and the Canadian Forces Base Petawawa are located approximately 200 kilometres northwest of Ottawa. The PFC maintains more than 2000 experimental plots and sites, making it an excellent test site. CFB Petawawa covers a variety of forest types, harvest operations, wetlands and open fields. The Petawawa site is part of the Great Lakes St. Lawrence forest region, containing both boreal and temperate forest species. Common species are white pine, red pine, jack pine, white spruce, black spruce, poplar and red oak. The Keg River study site is located in northern Alberta, covering an area of approximate 900 square kilometres, with site elevations ranging from 400 to 800 meters above sea level. This region is dominated by coniferous forests and is known for its history of wild forest fires. The latest fire in this region occurred in 2002, burning approximately 4830 hectares of forest. In addition to these three study sites, the Greater Victoria Watershed District near Sooke Lake, BC, was used as a proposed calibration/validation site for Japanese ALOS-2 SAR and future Canadian RCM SAR data.

The methodological approach of the CFS studies took into consideration the fact that a compact-polarimetry system configuration only measures a projection of the complex scattering matrix of quad-pol data, with limitations that affect the quality of classification products for forest studies. Also CP is a maximum entropy choice for vegetation, meaning that as volume scattering increases, the degree of polarization decreases, essentially representing a low coherence processing environment. In order to reduce these limitations, a time series filtering approach is employed in addition to spatial filtering. A rule-based compact decomposition and classification scheme was applied to the three main study sites. Furthermore, simulated CP data were fused with a forest height estimate based on a POLInSAR analysis of Tandem-X single pass interferometric data. This fusion demonstrated an ability to successfully classify several important land-use types and map a very important forest parameter, forest tree height.

The rule-based CP classification results for the Petawawa site revealed good discrimination of open water, despite the fact that over the time series these water bodies experience variable roughness and freeze conditions. Built-up areas, wetlands, and sparsely vegetated areas were also detected. Areas of vegetation, including extensive forest cover, and low biomass vegetation areas were well delineated in the classification.

The results for the Hinton site showed a generally good agreement between reference imagery and the rule-based classification. Forested and non-forested areas were discriminated well. Topography seemed to introduce some classification errors. One striking feature is the progress of forest clearance and fresh clearcut scar caused by active mining activities. Despite its change over time, the average Stokes vector from simulated CP data contained information on its current state of land use for mapping the evolution of the clearance process.

The Keg River study site has been used by the CFS for fire scar studies. By applying the data processing and classification procedures, we obtained the rule-based classification image in **Figure 4-12**. A fire scar class was further identified by combining three CP decomposition thresholds. The fire scars from the simulated CP radar were compared with the Alberta historical wild fire GIS polygons (red). Even though there are some false alarms outside the fire scar region, the fire scars were clearly identified in the radar image and have very good agreement with the GIS fire polygons. Additional analyses showed that CP was capable of maintaining important polarimetric information and detecting fire scars less than 10 years old (Chen et al. 2014).

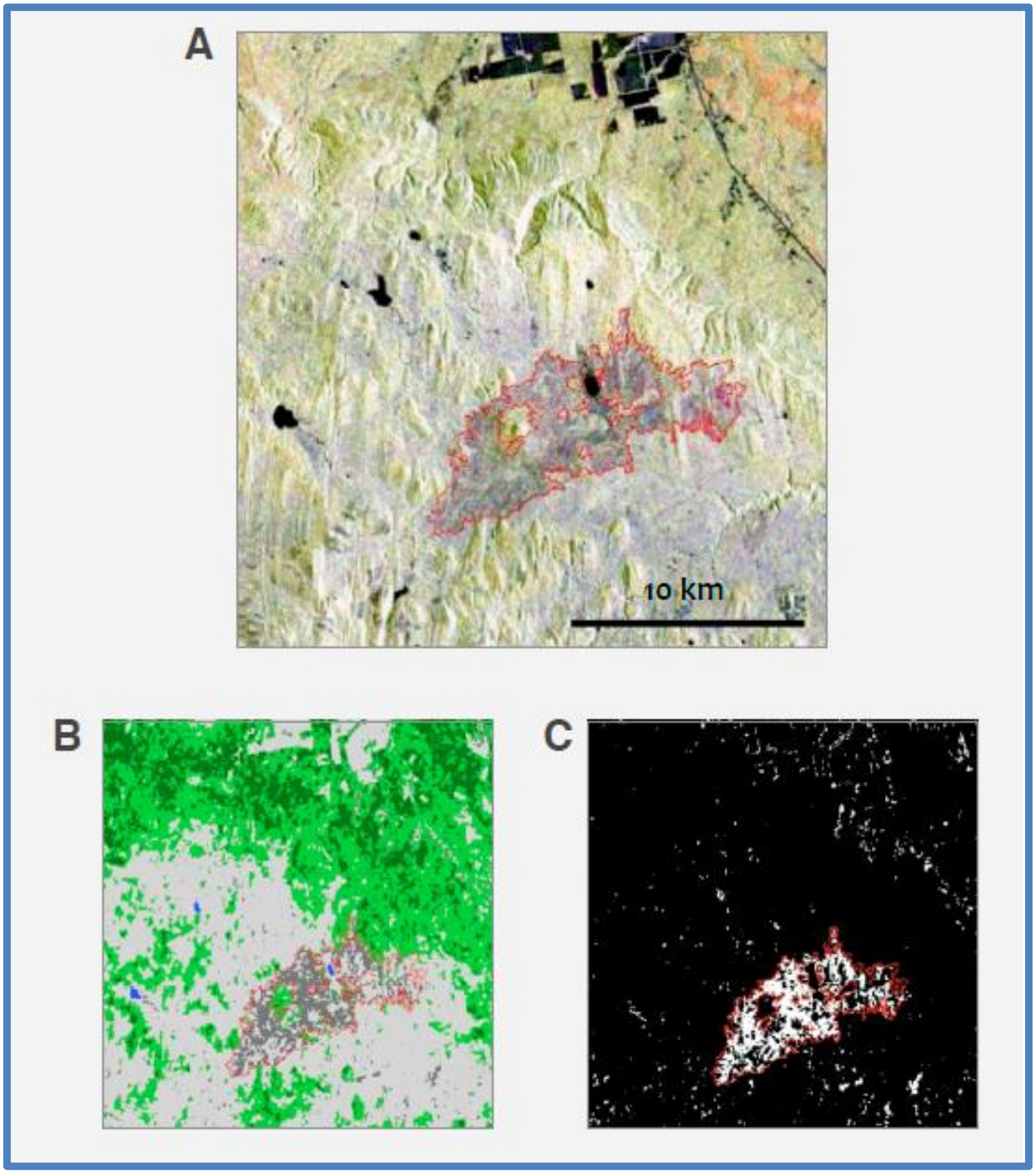


Figure 4-12 Historical forest fire scare detection, Keg River study area, Compact Polarimetry classification. A) CP Pauli representation; B) Rule-based classification results and C) Fire scar extraction.

TanDEM-X SAR data in dual-copol bistatic mode were also collected over the Hinton study site, and the use of polarization diversity in radar interferometry for forest tree heights was instigated. Tree height results from radar interferometry were well correlated with LIDAR measurements. The radar height product was generated using an optimization algorithm on the polarimetric channels, but more importantly the algorithm can also be used with single-pol TanDEM-X data, opening the possibility for wide area height and biomass mapping from the TanDEM-X archive and future RCM C-band interferometry. This is especially important for CFS. In order to further improve the forest cover classification, the RADARSAT-2 time series data were combined with TanDEM-X forest height estimates. The TanDEM-X dual-copol data over Hinton was used to generate a three-level biomass classification based on canopy heights. The

CP classification was then merged with the X-band height data to generate a new multi-class product capable of dealing with a wide range of land-use types, including forest biomass based on height variations.

Overall, Compact polarimetric data outperform the dual-linear configuration and reach similar performance than fully polarimetric configuration considering the limitation of C-Band for forestry applications. At CFS, the initial plan is to use CP as default configuration for the standard coverage acquisition plan.

4.7 Lake Ice and River Ice

Freshwater ice on lakes and rivers represents an important component of the environment in northern countries like Canada and affects hydrological, climatic, biological, cultural and economic systems. Accordingly, information on lake/river ice phenology and lake/river ice cover characteristics supports a large number of science, engineering and management activities. Phenological information of interest includes the timing of the processes of freeze-up and breakup. Information needs regarding ice cover characteristics typically relate to coverage, type, thickness, and/or condition. Radar remote sensing satellites make outstanding tools for collecting up-to-date information on ice-covered lakes and rivers thanks to their capability to routinely and systematically image extended remote areas independent of weather and daylight conditions. Moreover, radar systems are capable of capturing information about the physical structure of frozen ice cover and offer good sensitivity to presence of open water, new ice, and breaking ice. Compared to non-polarimetric SAR systems, polarimetric SAR systems typically offer more potential for the characterization of features observed thanks to an increased sensitivity to physical structure. In the context of freshwater ice, this strength of radar polarimetry is most advantageous when the images are acquired under mid-winter conditions, that is, when the ice is frozen solid and therefore allows radar waves to penetrate and interact with features that define its internal structure.

The objective of the study was to assess and develop the utility of C-band compact polarimetry (CP) data from Canada's forthcoming RADARSAT Constellation Mission (RCM) in support of lake/river ice monitoring and mapping (ice freeze-up / breakup surface conditions). To this end, comparisons of the relevant information content of simulated RCM CP data against RADARSAT-2 polarimetric data have been performed. The research team led by Joost van der Sanden (CCRS) included Thorsten Geldsetzer, Alice Deschamps (CCRS) and Jean Poitevin at Parks Canada. Their studies were summarized in annual RCM-CP project reports (NRCan 2012 to 2014), contract reports (Geldsetzer 2014), and peer-reviewed scientific papers: The results of a study that aimed to assess and develop the utility of RCM-type CP data for the purpose of lake ice breakup monitoring have been reported in detail in van der Sanden and Geldsetzer (2015) and build on Geldsetzer et al. (2010); The work relating to lake ice freeze-up builds on research reported in Geldsetzer and van der Sanden (2013).

Lake Ice

Research and development work relating to application of RCM CP data to lake ice breakup and freeze-up monitoring focused on the Old Crow Flats. Located in northern Yukon, Canada (68°N, 140°W) the area is characterized by a high density of freshwater lakes the majority of which is ≤ 100 ha in size and < 2 m deep. Vuntut National Park, established in 1995, comprises the northern portion of Old Crow Flats (Parks Canada, 2015).

Lake Ice Breakup

The breaking ice and open water information content of RADARSAT-2 polarimetric data and simulated RCM CP data was compared. Despite relative losses in terms of polarization diversity and radiometric sensitivity, RCM CP data were concluded to make a good source of information in support lake ice breakup monitoring. For that reason, a CP-based approach, named CP_LakeIceBC, to classify breaking ice and open water for the purpose of lake ice breakup monitoring was developed. CP_LakeIceBC is driven by incidence angle information, uses five CP backscatter variables (RH, RR, RV/RH, RR/RL, and conformity), and is compatible with high and medium resolution RCM CP products. Application of CP_LakeIceBC to representative simulated products yielded classification accuracies ranging from 73.2% to 99.1% and 60.8% to 99.5% for breaking ice and open water, respectively. **Figure 4-13** illustrates the application of CP_LakeIceBC for the purpose of monitoring lake ice breakup in the Old Crow Flats study area during the spring of 2011.

Lake Ice Freeze-up

In the same manner as for the lake ice break-up activity, analysis of available data to assess correlation between variables and, for each variable, new ice / open water separability, incidence angle effects, and environmental/temporal effects provided a basis for the design of a CP-based approach for lake ice freeze-up classification/monitoring named CP_LakeIceFC. RADARSAT-2 Fine Quad-Polarization images acquired in 2009 to 2012 were used as the basis for simulation. Although this classifier does not produce the highest accuracy possible for each image, it does provide consistently good results for conditions throughout the freeze-up season, for various noise floors, and a wide range of incidence angles. Application to a series of representative products of type RCM ScanSAR medium resolution 30 and 50m yielded classification accuracies ranging from 75.6% to 99.3% and 94.2% to 98.9% for new ice and open water, respectively. Low quality backscatter, resulting from low wind speeds and marked by conformity values ≤ 0.1, and poor new ice/open water backscatter contrast at incidence angles ≥ 50° obstruct reliable classification. As such, image pixels that experience these conditions are labelled as ‘Unknown’. The number of unclassifiable pixels increases with a decrease in radiometric sensitivity which is marked by larger NESZ values.

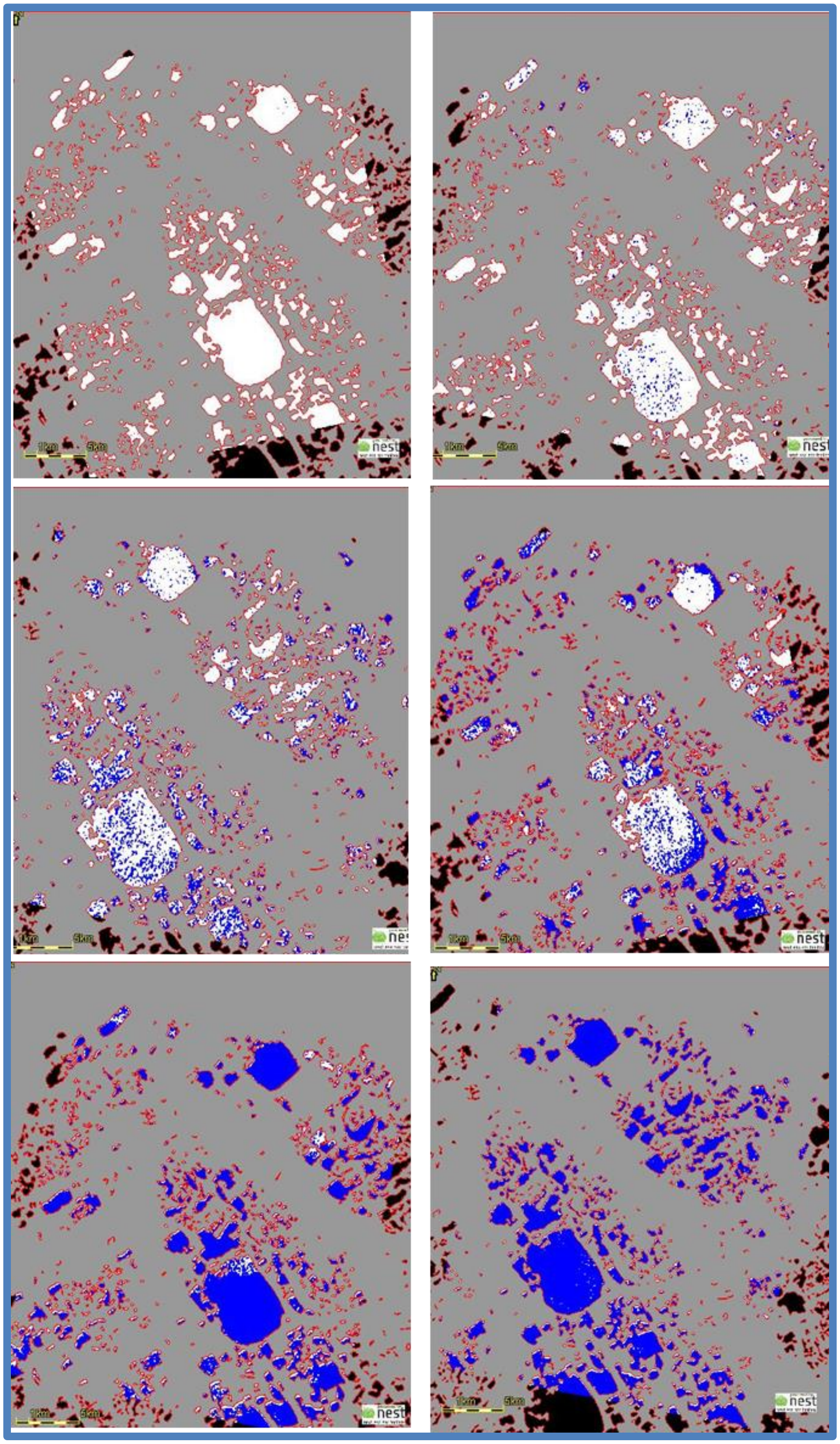


Figure 4-13 Lake ice breakup in the Old Crow Flats during the spring of 2011 (May 14, 22, 29 and June 7, 15, 22). Classification of ice (white) and water (blue) achieved using CP_LakeIceBC.

River Ice

To date, research and development relating to application of RCM CP data to river ice mapping and monitoring has been limited to a preliminary assessment of the utility of these data in support of river ice freeze-up monitoring. The Athabasca River near Fort McMurray (66°43' N, 111°25' W) was selected as the primary study area. To facilitate analysis of RADARSAT-2 images acquired, time-lapse cameras were installed at five locations and set to photograph the river every 15 minutes during freeze-up and breakup. Eight RADARSAT-2 Standard Quad-Polarization (SQ) images acquired in November 2013, with incidence angles ranging from 23° to 41°, were used as the basis for simulation.

As a basis for supervised classification assessment, identified classes represent open water as well as the following river ice types: consolidated, juxtaposed, pancakes, frazil rafts/pans, and skim ice. The level of statistical separation between each pair of classes was assessed, as a function of variable, product type, and incidence angle range, by means of the Kolmogorov-Smirnov (KS) distance (Massey, 1951). KS distances estimated from 12 CP derived variables over a range of incidence angles were analyzed for different NESZ values. Results demonstrate that, for all NESZ and in each incidence angle range, many variables offer good separability between open water and river ice types. Differentiation between river ice types, in particular between frazil rafts/pans and pancake ice, juxtaposed ice and frazil rafts/pans, and juxtaposed ice and consolidated ice is more challenging. The CP variables that best support the classification of these river ice types are RR intensity, Shannon Entropy (SE_i) component, and m-chi volume component. The utility of SE_i and m-chi volume is largely limited to the 30°-40° incidence angle range. In terms of polarimetric variables, the potential of RR is matched by HV. Furthermore, relative to HV, RR offers the advantage that it is a stronger signal and therefore less affected by lower radiometric resolutions. Differentiation between frazil rafts/pans and pancake ice can be expected to be challenging in most instances because these ice types are quite similar and non-homogeneous, i.e. are a mixture of water and frazil ice. The only features that set pancake ice apart from frazil rafts/pans are its round shape and rough edges. Regardless of RCM beam mode and incidence angle range, the following CP variables support differentiation between a minimum of 7 out of 10 class pairs: RH, RV, RR, Shannon Entropy Intensity component, m-chi odd bounce and m-chi volume. It follows that RCM CP data products can be expected to offer good utility in support of river ice freeze-up monitoring. As was the case with lake ice freeze-up monitoring, reliable classification of image pixels with low conformity will not be feasible.

Future work will include analysis of data sets acquired during the 2014 freeze-up of the Athabasca River at Fort McMurray. The limited incidence angle variability comprised in the 2013 data set discussed here hampers the derivation of models that captured the effect of the incidence angle on the signal associated with the compact polarimetric and polarimetric variables studied. Access to data for river reaches with different hydrological/ice regimes would strengthen the applicability of a resulting CP-based river ice freeze-up monitoring approach further.

The study has resulted in prototype CP-based approaches for the monitoring of both lake ice breakup and freeze-up. Research and development in terms of the application of RCM CP data products in support of river ice freeze-up monitoring is ongoing. Studies towards the application of CP-data products in support of river ice breakup monitoring and the mapping of freshwater ice cover characteristics (e.g. composition, integrity, groundedness) are pending. Current results support the expectation that CP configuration will provide relevant information for the purpose of mapping freshwater ice cover characteristics. Its operational potential is anticipated to hinge on the radiometric resolution which is also the case for the other RCM polarimetric configurations. The increases spatial and temporal coverage made possible by RCM will increase both operational coverage and monitoring precision.

4.8 Sea Ice Classification

Preliminary studies of Compact Polarimetry and sea ice classification have shown promise for discriminating various sea ice types and open water (Dabboor and Geldsetzer 2014, Geldsetzer 2014, Geldsetzer et al., 2015). The Canadian Ice Service (CIS) of Environment Canada will be a significant user of SAR data provided by the RADARSAT Constellation Mission (RCM). As part of the coordinated Standard Coverage Working Group, it would be beneficial for CIS to be able to ingest and utilize CP data in its operations. Therefore, the CIS engaged in the CP project with a goal to conduct a full assessment of CP parameters. Matt Arkett led the team of CIS' scientists and researchers involved in the sea ice component of the Compact Polarimetry project. Torsten Geldsetzer provided substantial consulting support. Their assessment included both quantitative as well as visual analyses. Overall, the results of the Canadian Ice Service study indicated that the potential of CP imagery is high for both enhanced visual interpretation and robust automated classification.

4.8.1 Quantitative Assessment

This study included three main objectives: (i) assessment of CP signatures for all sea ice types as they occur throughout the annual cycle; (ii) analysis of incidence angle effects of CP parameters, as they may occur across the relatively large RCM swath width; and (iii) differentiating open water areas from areas covered by sea ice, which also requires an analysis of wind retrieval capabilities. The latter aspect is of interest not only to CIS but also to other scions of Environment Canada and other government departments.

The CIS study was conducted over a three year period and included the following steps:

- Image processing and derivation of 26 CP parameters simulated from polarimetric RADARSAT-2 SAR data;
- Open water analysis, sea ice analysis, and incidence angle analysis of samples from RADARSAT-2 quad-pol scenes;
- Statistical distance testing;
- Identification of CP parameters for each ice season;
- Classification tests and evaluation of CP parameters for automated classification; and
- Assessment and recommendations for future work.

The Compact Polarimetry simulations for CIS emulated data that will be available from RCM. The analysis of 26 CP parameters was supplemented by five standard parameters, such as linear HH or HV polarizations, to facilitate comparison with other RCM polarization configurations. Sea ice and open water samples were obtained from approximately 200 RADARSAT-2 quad-pol scenes; the samples covered the incidence angle range of 19 to 40 degrees. CIS will likely make use of three wide-swath RCM ScanSAR modes, including Low Noise, Low Resolution and Medium Resolution 50 meter. Figure 4-14 gives sea ice classification examples obtained from these beam modes under CP configuration. Therefore, the study also assessed the effect of the different noise levels and resolutions associated with these RCM modes.

For sea ice, the incidence angle dependence of all 26 CP parameters and five standard parameters was determined for the winter, spring, summer and fall seasons. Regression models were calculated for 11 ice types or ice conditions for each of the 31 parameters in total, for each season, and for each RCM mode. The work amounted to the collection of almost 1000 samples of data relevant to sea ice classification, enabling the comparison of ice types – and their separability – and open water for a given parameter by way of visual interpretation and automated classification. In order to collate information on useful parameters sets for each sea ice season, statistical distance testing was carried out, allowing for the identification of opportunities and challenges that CP imagery from RCM might pose for Canadian Ice Centre operations.

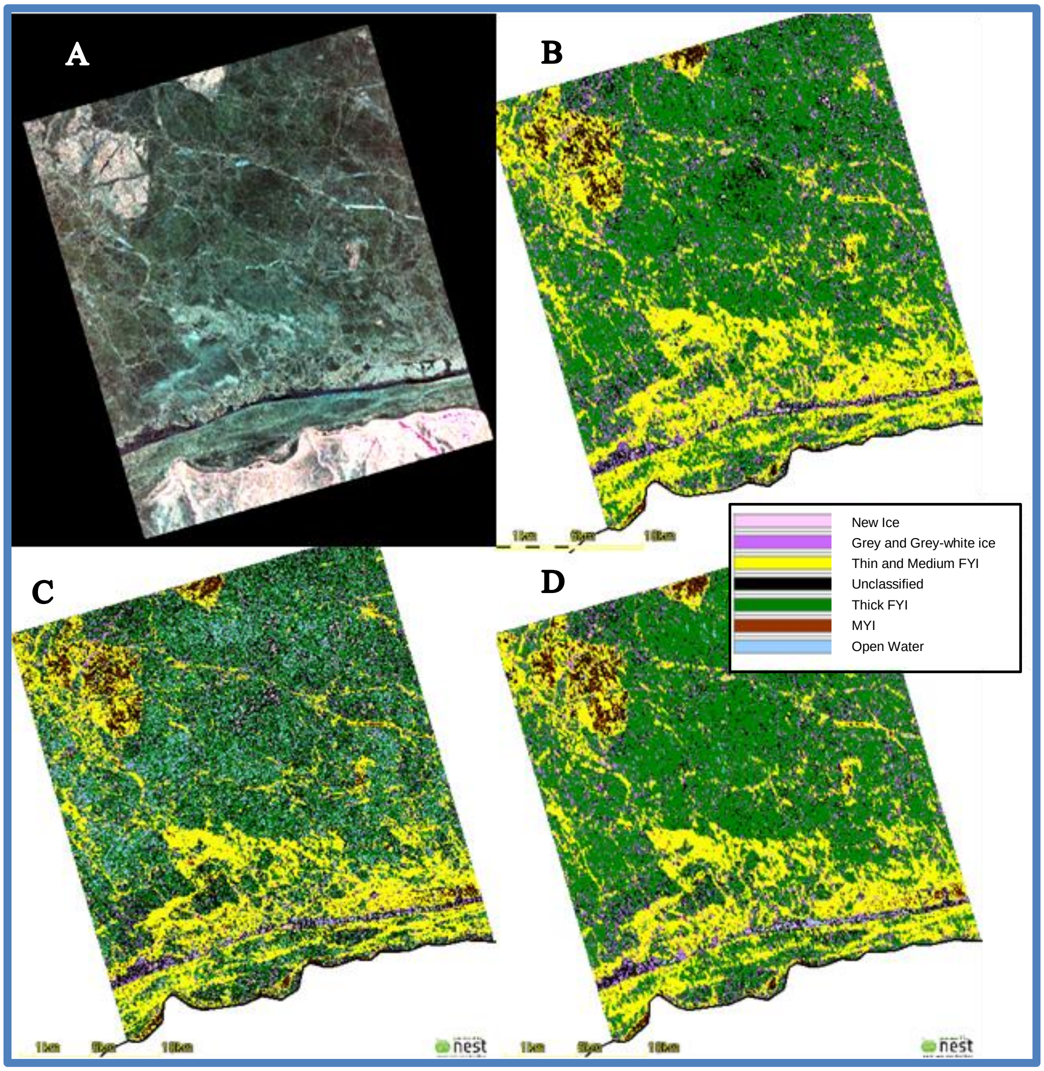


Figure 4-14 RADARSAT-2 FQ14 SAR imagery of sea ice south of Resolute, NU, dated April 21, 2010, in simulated CP mode. A) m-chi representation; B) Low Noise mode classification; C) Medium 50m classification; and D) Low resolution classification.

The results of the quantitative assessment indicate that the potential of CP imagery is high for automated classification of sea ice and for open water areas. In term of modeling CP coefficients and conventional backscattering coefficients (HH, HV, and VV) against incident angles for each sea ice type, second order regressions revealed that over the nine ice classes the coefficient of determination (R^2) raised by 0.03 to 0.29 for five of them with CP parameters compared to linear dual polarization data. Estimated R^2 for Melting MYI and Thin & Medium FYI types were identical with both polarization configurations, while slightly less, by 0.05 and 0.02, with CP over New Ice and Melting Thick respectively. In all cases, model standard errors were significantly lower with CP data. Based on the statistical Kolmogorov-Smirnov (KS) separability coefficients (Massey, 1951), the classification potential is greatest during the winter ice season, followed by fall freeze-up. The spring and summer ice seasons remain challenging, although several CP parameters do improve the potential for ice type and open water discrimination. The application of specific parameters within a wide swath image changed with incidence angle. This necessitated the use of complementary CP parameters, as some were found promising at small incidence angles and other at larger incidence angles. The differences between the three RCM modes that CIS will likely use are relatively small; none of the three modes appear to pose significant barriers to operational use.

In order to mitigate dynamical range of σ^o over open water, the incidence angle and wind speed dependency of 28 CP parameters were determined, with wind speeds ranging from zero to 24 meters per second. The SAR data were validated by reference data from eight meteorological buoys located off the west and east coast of Canada. The analysis for 28 of the 31 parameters was based on 98 RADARSAT-2 scenes. Results provided regression models for each CP parameter as a function of wind speed, incidence angle, and a combination of both; 26 parameters showed significant dependence on both incidence angle and wind speed, whereas two parameters were dependent on wind speed only. The regression models provided a means for wind retrieval and a set of values for comparison with sea ice surfaces adjacent to open water. Quantitative wind retrieval CP models are summarized in a section below.

Based on the ice type statistical modeling and KS distance results, it appears that CP configuration significantly improves the characterization of a sea ice scene compared to a dual polarization configuration. Future development of a robust classifier using CP parameters is recommended, although numerous factors must be considered for successful implementation. Additional sampling of selected ice types and conditions is recommended to improve confidence in the models, and to expand the application potential to more ice types. Any further development should be accompanied by a validation exercise. This should comprise carefully validated quad-polarized images encompassing the variety of ice types per season, and should be available throughout the incidence angle range. The validated images could be prepared after careful consideration by ice analysts in cooperation with university fieldwork programs.

4.8.2 Visual Assessment

In addition to the numerical analysis, Canadian Ice Service analysts also conducted a visual assessment of RCM Compact Polarimetry modes for CIS operational implementation (Drouin et al. 2015). The objective was to find out if CP imagery can increase interpretive potential over the dual-polarization (HH/HV) synthetic aperture radar (SAR) data stream currently used within the CIS Forecast Operations analysis environment. As a demonstration, T. Geldsetzer with the help of CIS analysts developed a CP Sea Ice (CPSI) decomposition product comprised of RGB composite image products that generally differentiate various ice types and open water areas in most cases.

A total of 12 Fine Quad (FQ) images were chosen for visual analysis. The data was acquired in the Canadian Arctic during the spring and summer seasons, with one image acquired during the fall freeze-up period. Six of these FQ images were fully analyzed while the remaining six case studies involved an analysis of the Low Noise dual-pol mode versus the CPSI product. Full analysis involved the comparison of the Low Noise, Low Resolution, and Medium Resolution 50 m (MR50) in dual-polarization mode, to determine a preferred beam mode. The "preferred" dual-pol image was then evaluated against the CPSI decomposition product. An example is shown in **Figure 4-15**.

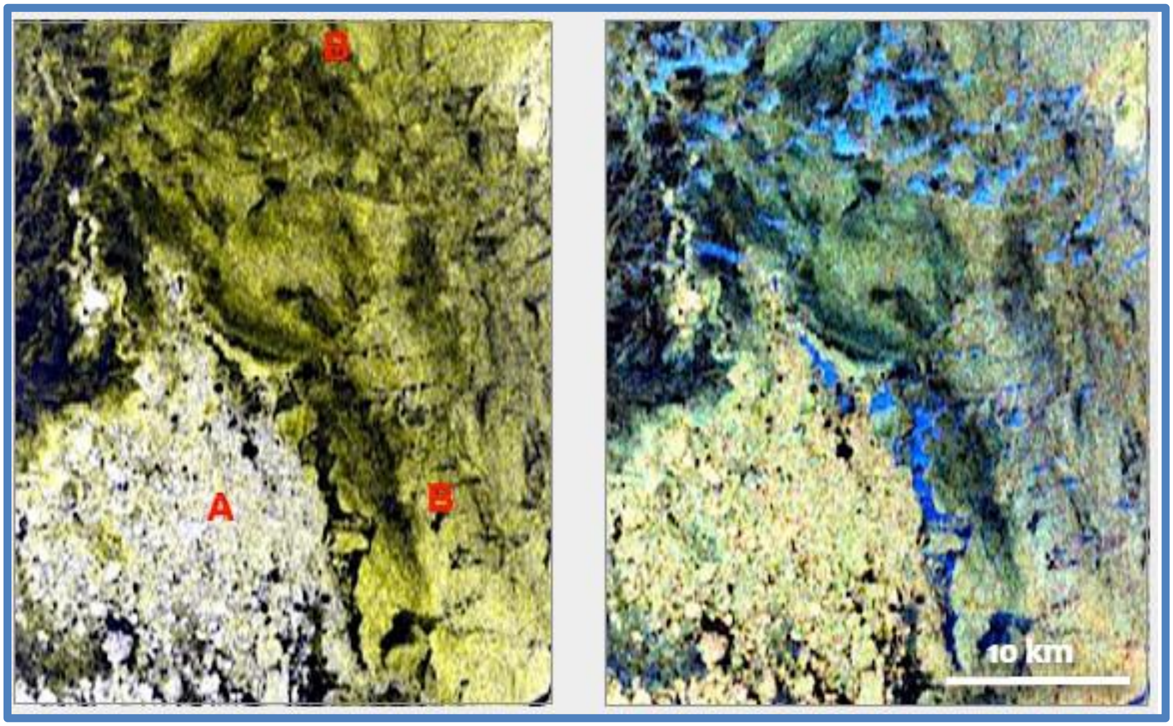


Figure 4-15. Comparison of sample Low Noise linear dual-pol **(Left)** and Low Noise CPSI decomposition **(Right)** products of sea ice conditions in the Labrador Sea.

The visual analysis of the 12 samples was conducted at a high level and did not constitute an in-depth analysis. The case studies only represent a subset of ice types, ice seasons and viewing geometries, pointing to the need to expand the scope of the qualitative study. Nonetheless, the results of preliminary assessment were encouraging:

- Low Noise and MR50 image products would be the preferred RCM ScanSAR modes at the CIS;
- Low Noise mode is preferable when detecting smooth newer ice types, wet ice and snow, and open water; the higher noise floor of the Low Resolution and MR50 beam modes hinder analysis in low backscatter ice types and open water.
- MR50 has the advantage of higher spatial resolution, improving ice floe delineation and edge discrimination; this mode is preferred in the winter season, over older and rougher ice types with high signal to noise ratios.
- The CPSI decomposition product provides more visual ice information than its dual-pol equivalent in a variety of ice conditions.

CIS will be conducting a more comprehensive qualitative assessment as part of their larger preparations for the upcoming RCM.

4.8.3 Wind Speed Dependencies

As mentioned in the previous section, Geldsetzer et al. (2015) provided a preliminary statistical assessment of wind speed dependencies in the context of the CIS ice classification study. As a function of wind speed, all 28 CP parameters show significant dependence at the 0.95 level. This result applies for both Low Noise and Low Resolution modes, with RV/RH, delta, 2nd Stokes vector element and VV/HH being the least dependent. The wind speed dependency of CP parameters dominated by surface scattering is weaker than for incidence angle. CP parameters dominated by depolarizing effects are more strongly dependent on wind speed than on incidence angle; RR exhibits sufficient power to maintain observations above the noise equivalent sigma zero (NESZ) of the Low Noise mode and it exhibits a linear increase. The greater power of RR over HV enables its use for wind speed retrieval with higher NESZ. For RCM Low Noise mode, RR can provide wind speed information for wind speeds > ~ 6 m/s, instead of > ~13 m/s with HV. CP parameters that are sensitive to depolarization effects are less dependent on wind speed than on incidence angle. Variance increases at low wind speeds. CP parameters that are sensitive to polarization differences in resonant Bragg scattering exhibit no dependence on wind speed.

Those observations can be easily reproduced by the adaptation of the C-band Geophysical Model Function, CMOD5.N (Hersbach, 2010) as done in Geldsetzer et al. 2015. Over 100 in situ samples (buoys) with a range of surface wind speed from 0 to 24 m/s measured at various orientations were used to validate the model. Current operational wind speed assessments are mainly done from VV and VH (HV) polarizations, where VV model is robust up to 12m/s and where VH is independent of wind orientation and more efficient for higher wind speed condition. **Figure 4-16 A) and B)** show the measured σ° for RL and VV polarization against CMOD5.N values generated from in situ wind speed and direction. **Figure 4-16 C) and D)** express the measured σ° for RR and HV against the in situ measured wind speed data. It is clear that the RL polarization obtained from CP data can perform as well as VV in term of modeling the ocean surface in function of wind speed and direction. Whereas RR is slightly less accurate than HV, but its coefficient of determination with in situ is 89 and it has the advantage of having a higher backscattering coefficient which distances the model to the system noise.

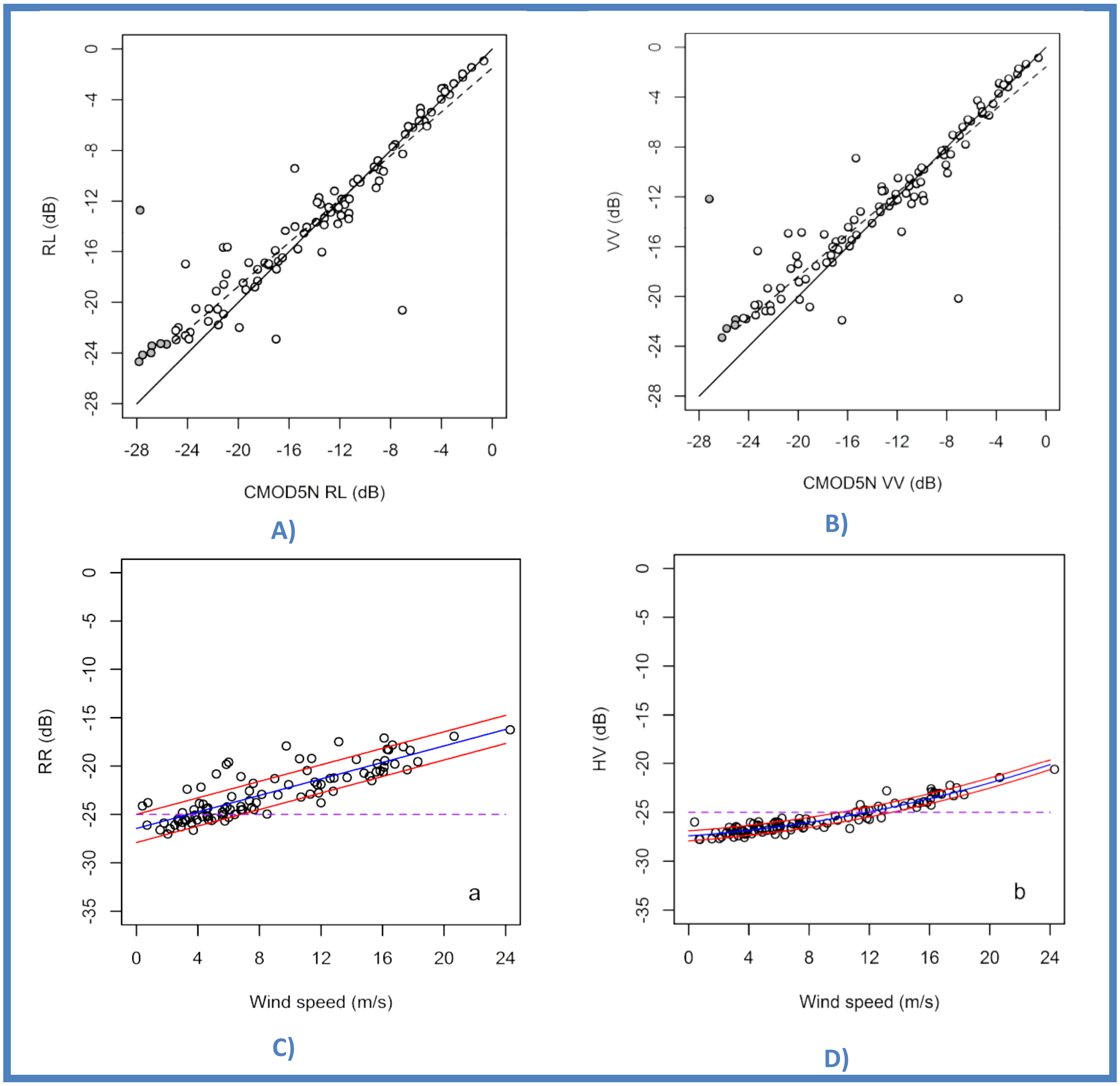


Figure 4-16. A) and B) RL and VV estimated from SAR scenes against CMOD5N simulated intensity from buoys measurements. **C) and D)** are respectively RR and HV (both at all incidence angles and all wind directions) over open water versus wind speed. The blue line is the model fit, the red lines are ± the standard error, and the purple dashed line is the nominal NESZ of RCM Low Noise mode.

From this simple adaption of the operational model, it is apparent that CP could be used as default configuration for wind speed assessment. RR would be instrumental for high wind estimation and mitigating the wind direction dependency. Naturally further validation is needed and analysis should be conducted in the context of Environment Canada's current operational National SAR Winds service.

4.9 Detection of Ships and Icebergs

The use of synthetic aperture radar for ship and iceberg detection has been increasing following the greater availability and coverage of SAR data, particularly polarimetric data. Greater amounts of polarimetric information can increase detection performance, preventing false alarms and missed detections. However, quad-polarization SAR systems with limited swath coverage are less attractive for ship and iceberg detection. Dual-linear HH-HV Ship Detection detected product is the initial configuration requested by DRDC for ship detection application during the RCM mission definition. On the other hand, Compact polarimetry is a compromise that would allow keeping valuable polarimetric information while being an available configuration on all RCM beam modes.

Up to now, ad hoc research has been performed on the topic by scientists at Defence Research and Development Canada (DRDC) in Ottawa, led by Chen Liu. Their main interest is in studying the potential of the Single Look Complex (SLC) product from the RCM simulator for the ship detection mode. In the initial RCM Ship Detection mode design, only the detected product was available. Without the relative phase information between polarizations, the added value of CP is lost. Therefore, the CP detected product format does not improve ship detection capabilities; worse, it has less performance than HH/HV. A common approach to assess the detection performances is to display them in the form of a receiver operating characteristic (ROC) curve. The ROC is a standard measure for detection performance and to show the probability of false alarm versus the probability of missed detection. The closer the estimation is to the origin of the graphic (low false alarm and low missed-detection probabilities), the better is the detection performance. Initial results show that CP performs better than dual-linear configuration (**Figure 4-17**). By using both RH and RV polarization channel, the ROC curve is lower than the HV or HH-HV curves. Individual polarizations (RH, RV, HH and VV) perform in a similar manner.

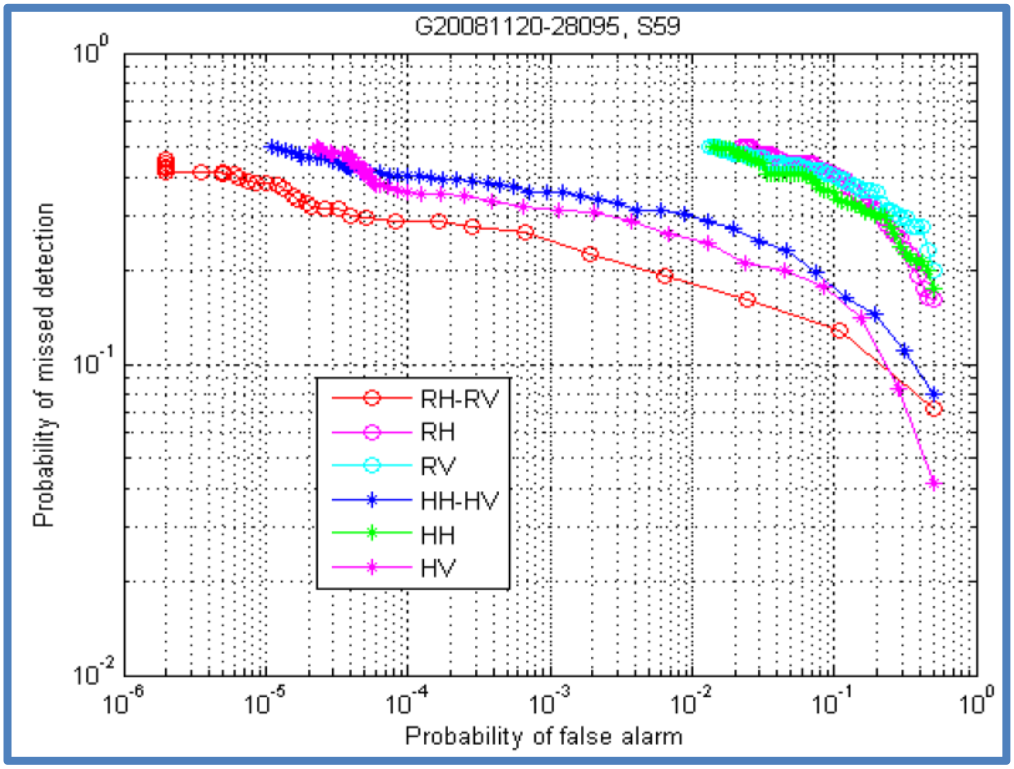


Figure 4-17 Example of ship detections ROC curves for dual-linear and compact polarimetric configurations.

With some financial and scientific support from this RCM Compact Polarimetry project, a research team composed of Michael Collins, Michael Denbina and Ghada Atteia of the University of Calgary in Alberta concentrated their work on the reconstruction (approximation) of quad-pol SAR data from Compact Polarimetry data for ocean target detection (Ship and Iceberg). Their study results are accessible through RCM-CP annual reports (NRCan 2011 and 2012) and in Denbina et al. (2015), Attaia and Collins (2015), Atteia and Collins (2013). As for DRDC, their results are expressed under the ROC form.

With the help of the CCRS RCM-CP simulation tool, they focused their detection performance analyses by simulating three RCM beam modes at various polarimetric configurations: Ship Detection, Low Resolution (100 m), and Medium Resolution (50 m). Their results of the ship and iceberg detection experiments show that the likelihood ratio test performance of the detection algorithm is clearly enhanced by using their constant-N method compared to two other reconstruction methods. The performance of their approximation constant-N method is less impacted by the variation of the local incident angle. For the ship detection case, the performance improves slightly as the angle gets larger and for the iceberg case (Figure 4-18), the performance improves significantly. Naturally, CP detection performance is weaker than with fully polarimetric data, but not significantly (except at steep incident angles). The study confirmed that the compact polarimetric SAR detectors outperform the conventional linear dual-pol detectors at the three RCM modes for medium to high incidence angles. At steep angles, the performance of the CP configurations was suboptimal. Detection performance improved as incidence angle and spatial resolution increased.

Based on their first results and in order to benefit from the polarimetric phase (for CP and dual linear configuration), DRDC has recommended to CSA to add the SLC product format to the Ship detection mode. Recently that suggestion has been implemented in the RCM design. By having access to the polarimetric phase, detection performance would be further enhanced than the results showed here. It is recommended the further study focus on circular polarizations (RR and RL), the degree of polarization (m) and on other polarimetric target decomposition approaches rather than trying to reconstruct the fully polarimetric information from CP data in order to keep performance stability over different sea state conditions. Nevertheless due to the large amount of data acquired under the Ship detection mode, the downlink of the data from the Satellite to the receiving station will have to be compressed to a Block Adaptive Quantization (BAQ) of 1 or 2 bit/sample, which is too low data quantization for having accurate polarimetric phase. What would be the impact of 2-BAQ on phase accuracy? Until that information is provided by MDA, it will be unknown. Under current mission specifications, if DRDC wants to use CP for ship detection and if the low BAQ impacts the polarimetric phase quality too significantly, they would have to move their acquisition plan to Medium Resolution 50 m mode.

Finally, these results are important to the maritime SAR user community since the ship detection application requirement of daily coverage of the Canadian coastal waters often conflicts with the coverage requirements of other operational marine applications like ocean winds, oil spill and sea ice monitoring. Using a common Compact polarimetric configuration could ease the standard acquisition planning rather than being limited to dual-linear polarized configurations where ship detection users prefer HH-HV and other users prefer VV-VH.

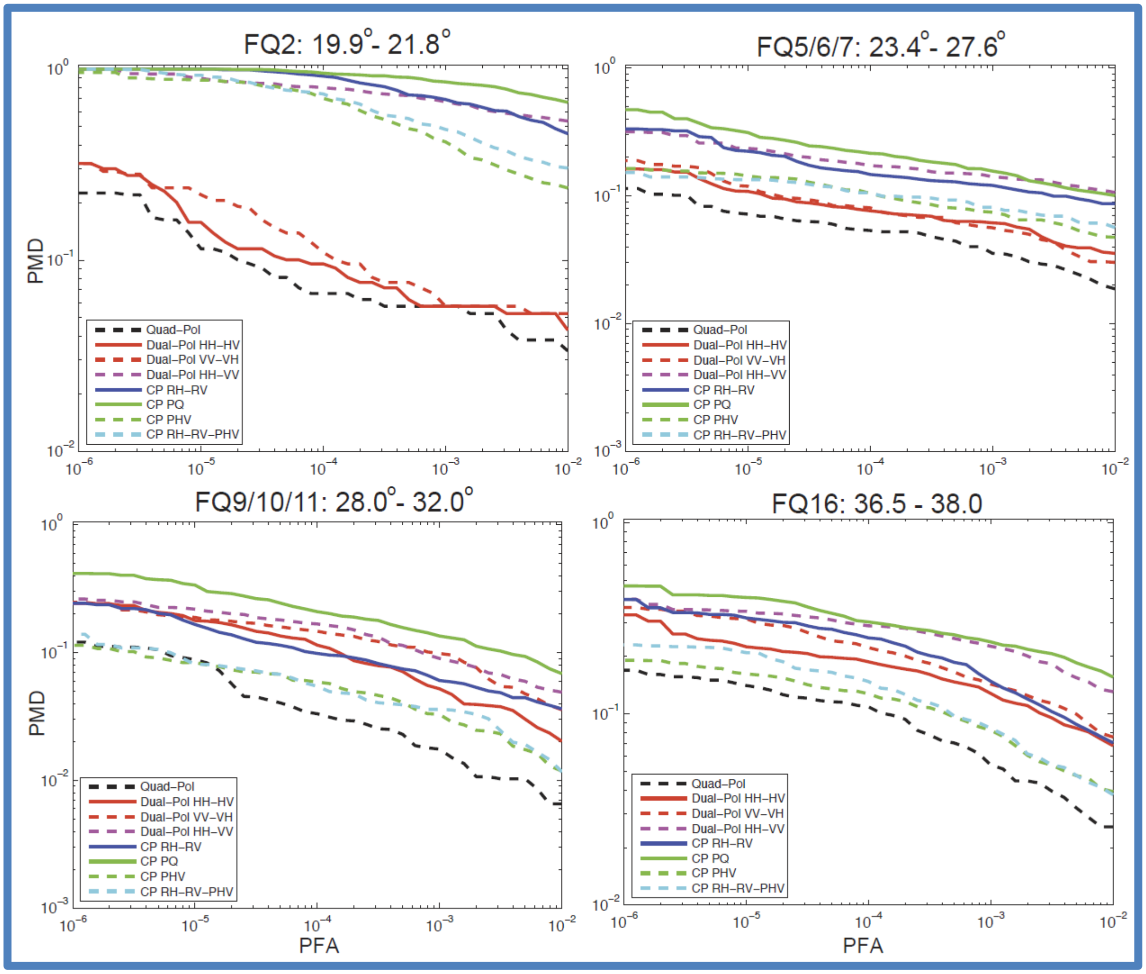


Figure 4-18 Iceberg detection ROC curves estimated for fully polarimetric (Quad-Pol), Dual-polarization and CP reconstructed configurations at four difference ranges of incident angle.

4.10 Detection and Characterization of Oil Slicks

Hydrocarbon spills on water due to on route cargo reservoir clean up or by accident (oil platform failure) is a major environmental issue in Canadian coastal waters. Integrated Satellite Tracking of Pollution program (ISTOP) of Environment Canada relies on frequent SAR acquisitions to fulfill its operational mandate. At NRCan, SAR hydrocarbon reservoir prospecting through oil seep detection is a current research interest for CCRS and Geological Survey of Canada (GSC). This activity was led by F. Charbonneau with the support of S. Eddine-Zidane and V. Decker, all from CCRS/NRCan.

Oil slicks can be easily detected in a SAR scene due to its higher viscosity than salt water, which dampens the wind driven capillary waves. Since the backscattering coefficient is function of the surface roughness (capillary waves), a dampened surface reduces the backscattering coefficient resulting in a dark distributed target in a SAR scene. Unfortunately, there are several other sources of dark patches or linear dark features that could occur in a maritime SAR scene: wind streaks, wind shadow, currents, biogenic oil from plants, and others. Since ERS-1, these look-alikes remain the main challenge for fully automatic detection of oil spills. It is possible to reduce the number of false alarms by applying some geometrical analyses, by looking for a bright target (ship or platform) in the neighborhood, and by using a GIS database (topographic map for wind shadow, blooming algae seasonal maps, and bathymetry). Those techniques were outside the scope of this study since they are not related to the polarization of the incoming radar wave. As for the overall CP project, the main objectives are to determine if CP outperforms the operational linear dual pol configuration (VV/VH) and which CP parameter(s) should be used to optimize the detection of oil slicks.

Operational SAR modes for routine ocean monitoring often rely on ScanSAR which is only available as mono-polarized or linear dual-polarized configurations. With their narrow swaths, fully polarimetric beam modes are used mainly over known natural oil seep areas, experimental studies or following a maritime disaster (oil platform or ship). Acquiring polarimetric data over an illegal oil spill cannot be planned for. Furthermore, having cases under different wind speed conditions and with in situ information about the slick is not trivial. For this study, compact polarization data have been simulated and analyzed for different sites: 1) In 2012, EC has acquired a series of RADARSAT-2 Fine Quad polarized data over the Coal Oil Point seep field, near Santa Barbara, California which is the most natural seep area in the world; 2) Salberg et al. 2014 have set up two experiments in 2011 and 2102, where crude oil and vegetable oil were spilled coincidently with RADARSAT-2 acquisitions; and 3) Other ad-hoc scenes of Canadian Arctic offshore basins for potential natural oil seeps were analyzed. Nearby buoy-based wind speed and direction were also included in the analysis. A total of 33 scenes were simulated to RCM CP and dual-linear polarizations with NESZ set to -32 dB (average RADARSAT-2 value) and -22 dB (RCM Medium 50m mode) for which the 26 parameters described in **table 3-1** were estimated for dark ocean patches and their “clean water” surroundings.

Some published studies (Haiyan et al. 2015, Junjun et al. 2015 and Salberg et al. 2014) claimed that fully polarimetric and compact polarimetric acquisitions allow the discrimination of biological oil slicks from new and emulsified hydrocarbon slicks by using decomposition techniques. Nevertheless, those findings need to be carefully considered in the context of RCM where the NESZ is at least 10 dB higher than RADARSAT-2’s fully polarimetric configuration. A higher NESZ level is fatal for characterization of low backscattering features like oil slicks. It affects the polarimetric diversity and the relative contrast between slick and water. First, the loss of polarimetric diversity can be shown by the use of the CP intensity signature function on the received configuration, as shown on **Figure 4-19**. The clean water surface expresses a typical surface signature with constant increase in intensity from right to left circular polarization and with a low pedestal height, while the oil slick signature is fairly independent of the received polarization and has a pedestal height close to 1 (i.e. no polarimetric information).

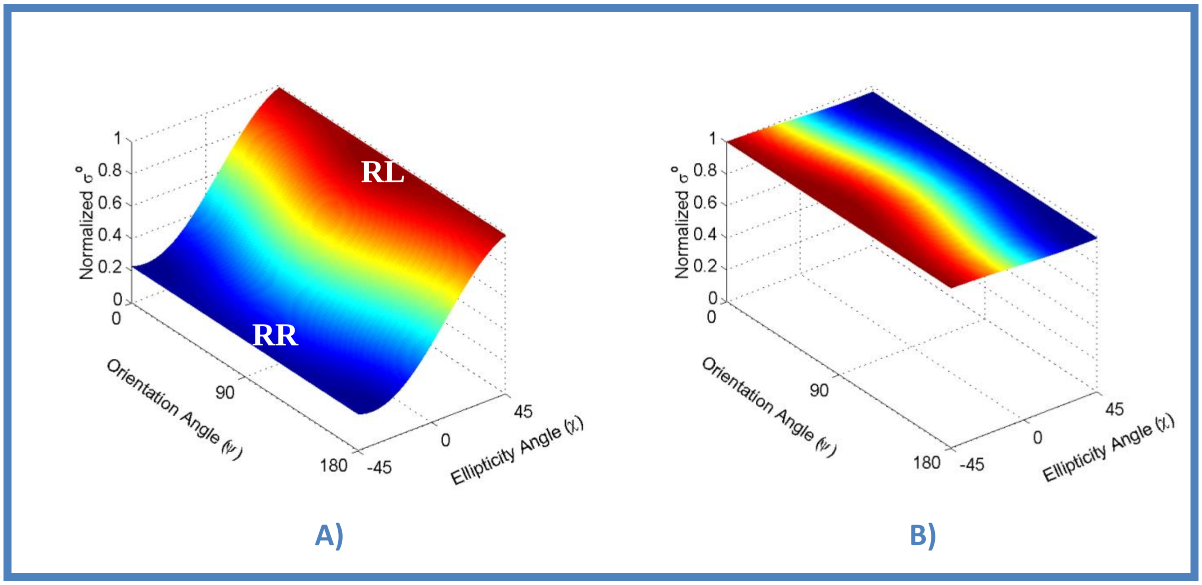


Figure 4-19 Compact polarimetric signatures showing the normalized backscattered intensity function of the receiving polarization for **A)** ocean surface and; **B)** oil slick.

Secondly, **Figure 4-20 A)** shows the intensity contrast between clean water and 28 oil slicks as a function of the local incident angle for the polarizations VV, RV and RL, estimated with a system NESZ of -22 and -32 dB. The relative contrast is significantly reduced since lower oil slick backscattering coefficients are raised by a higher system noise, which can be observed in **Figure 4-20 B).** Intensities over oil slicks were stable around -23dB for 22 of 28 cases, which means that in only 25% of the cases the local wind speed was strong enough to generate sufficient capillary wave amplitudes over the slicks in order to induce backscattering coefficients above NESZ, and so for all polarizations (CP or non-CP). The incident angle dependency of the contrast of **Figure 4-20 A)** for NESZ = -22 dB is purely due to the one over clean water, which is well defined by ocean wind speed models (like CMOD) as used by Environment Canada. Naturally contrasts are driven by wind speed and surface viscosity, but with RCM, since most of the time the energy returned from the detected slick will be too low, it won't be possible to characterize its viscosity of thickness in an operational manner. Nevertheless the good news is that the RCM CP polarization RL performs as well as the VV polarization, so the CP configuration can be used without a problem. It is important to note that the NESZ value refers to the worst value along the slant range of a scene (usually near or far range). That explains why backscattering coefficients were lower than the -22 dB NESZ value taken. The RCM simulator mimics the NESZ pattern and NESZ is often 3 dB lower in the middle of the swath.

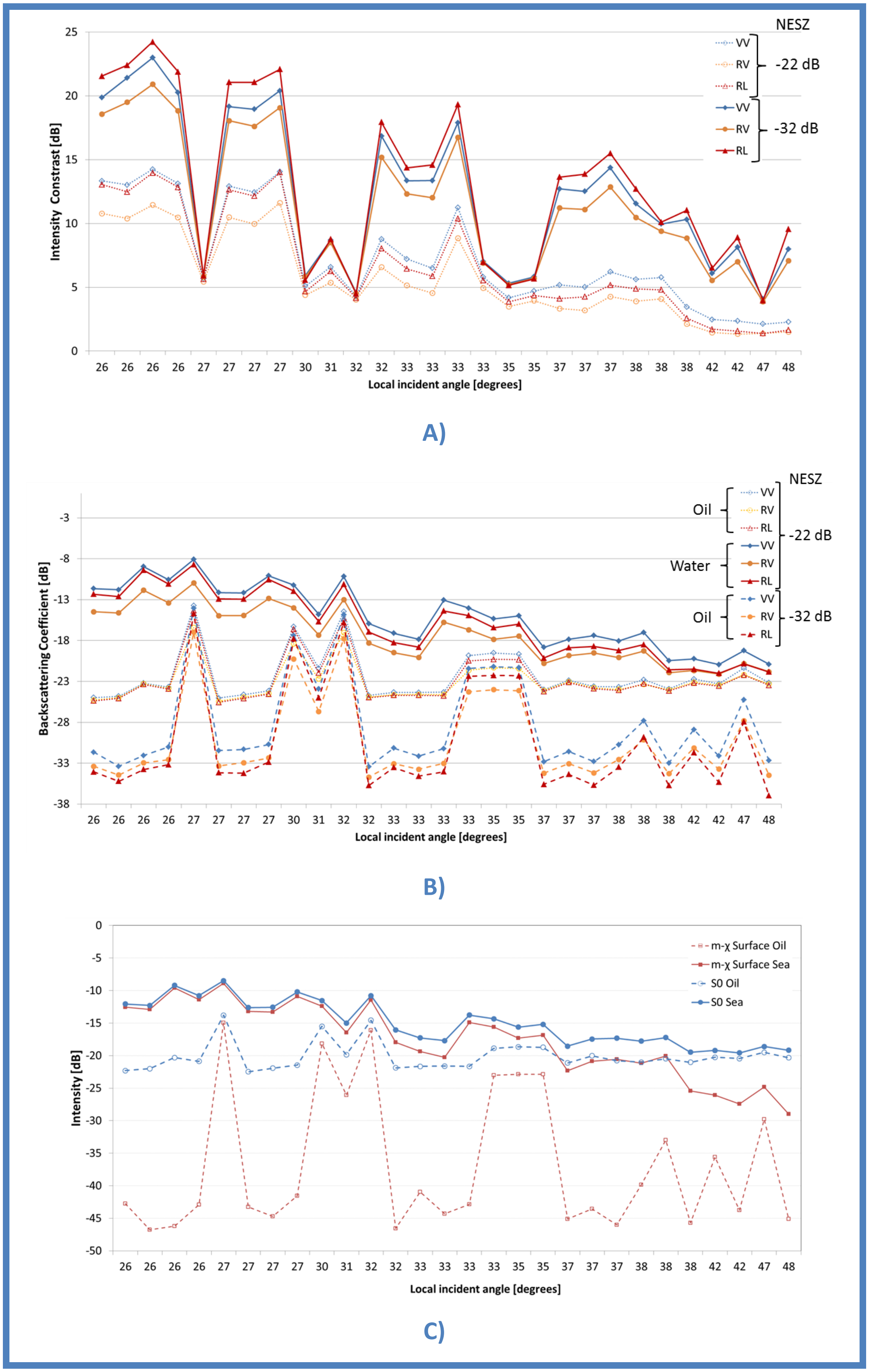


Figure 4-20 Statistical estimates over oil slick and surroundings clean water for VV, RV and RL polarizations **A)** Relative intensity contrast between both surface types for simulated RCM data with NESZ

of -22 and -32 dB; **B)** Backscattering coefficients and; **C)** 1st Stokes vector element (S_o) and m-chi surface component.

Another measure of surface discrimination could be the use of m-chi decomposition. Since the surface component of the m-chi decomposition approach is based on the total backscattered energy (1st Stokes vector element S_o) and the degree of polarization (m), which are sensitive to surface roughness and noise, the contrast between water and hydrocarbon is enhanced (**Figure 4-20 C**). This contrast is artificially raised by the fact that m is close to zero; nevertheless, the m-chi surface helps detection at higher incident angles. Shannon entropy components which are similar to S_o and m show similar detection performance.

The study concludes that compact polarimetry and simply using RL polarization will be just as successful as the VV polarization on RCM for the detection of hydrocarbons on water. The CP contribution to oil slick detection can potentially solve the polarization beam mode conflict between ship detection (HH-HV) and oil spill (VV) applications, as polarimetric diversity can provide parameters that enhance ocean surface features with some limitations for low intensity features due to the lower RCM NESZ. For visual interpretation of an oceanic scene, the RL polarization does improve the contrast of features such as atmospheric fronts, ocean currents and gravity waves. The color composite of m-chi components allows preservation of the water-slick contrast and also raises the water-point target (oil platform, ship, iceberg) contrast, which is important when the monitoring task cannot be fully automatized and requires visual interpretation. However, further research is required to optimize the detection while minimizing false positives. At present, the operationalization and automatization without analyst intervention does not seem feasible with CP, or even with fully polarimetric SAR data.

4.11 3D Radargrammetry

Three-dimensional (3D) radargrammetric processing is a prerequisite for integrating the different compact polarimetric modes data with other cartographic and remote sensing data in order to develop thematic and topographic map products. The RCM compact high-resolution mode could demonstrate some advantages over single polarization mode for the generation of digital terrain models. The radargrammetry component of this DUAP RCM Compact Polarimetry project was to evaluate the guidelines and best practice for the use of RCM data, based on the analysis and CP simulations of three RADARSAT-2 FQ mode SAR data. The investigation was carried out by Thierry Toutin (CCRS/NRCan).

The work resulted in a project report and two scientific papers (Toutin et al. 2013 a and b) that compare two methods for the ortho-rectification of fully polarimetric and compact polarimetry SAR data. In the first one, designated as an ideal scientific "image space" pathway, polarimetric processing preceded geometric processing, and in the second one, designated as a user oriented "ground space" pathway it took place after geometric processing (**Figure 4-21**). The “image space" approach is the best practice way to preserve all the polarimetric information while the "ground space" approach is often privileged by users coming from GIS or optical sensor domains. The RADARSAT-2 FQ mode data (FQ5, FQ11 and FQ18) over hilly terrain and Very High Resolution (VHR) beam mode RCM-CP products simulated from those FQ data were processed using a LiDAR derived digital surface model. The quantitative evaluation between the two ortho-rectification methods as a function of different geometric and radiometric parameters revealed the impact on the final product quality. The compact entropy (H) computed from the T2 compact covariance matrix was used to evaluate quantitatively the difference in the compact polarimetric information between the ortho-rectification methods. H is the most efficient and suitable basis-invariant parameter for this kind of analysis, as shown in a previous study with fully polarimetric data (Toutin et al. 2013a).

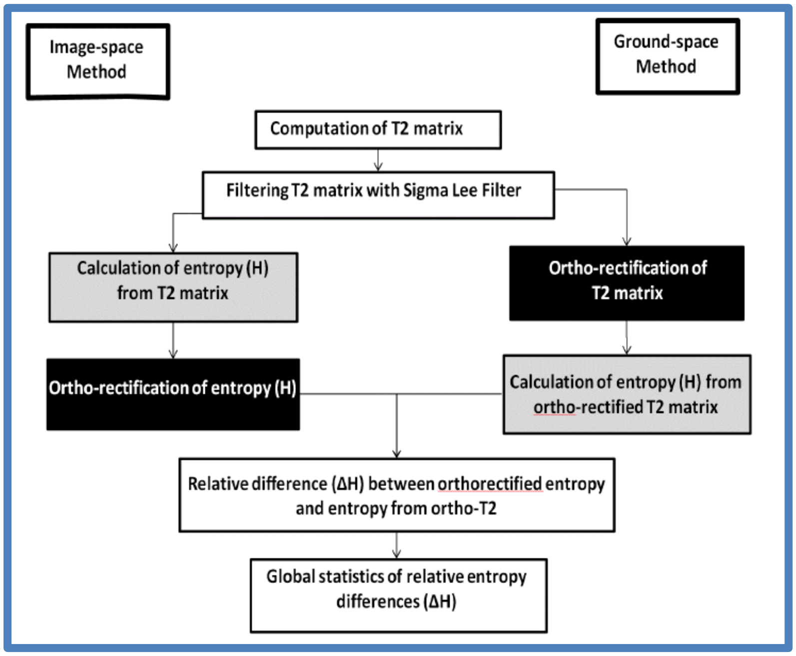


Figure 4-21 Processing steps of polarimetric data with Image-space and Ground-space methods.

From the two methods, the relative compact entropy difference ΔH (ortho_H − H_ortho) was estimated for every pixel of each VHR simulated data, where H_ortho is the "image_space" error-free method and ortho_H is the "ground_space" method. The error statistics over the full images were first computed to describe the difference over the whole image. The results were then summarized under histogram chart of pixels count showing a relative ΔH > 10%, for each VHR image using different simulation scenarios (Figure 4-19). The first statistical results (first scenario: default RCM simulation parameters, black boxes) show 10-20% relative entropy differences ΔH, which are relatively large (mainly VHR5) when compared to H sensitivity range (not-significant variation of around 0.1). On the other hand, the same trend is found for the look angle as with RADARSAT-2 data: the steeper is the look angle from VHR18 to VHR5, the worse are the error results and, consequently the less similar are the two entropies (image-space and ground-space methods). Those results are discouraging when compared to the results obtained with RADARSAT-2 fine quad data (Toutin et al., 2013a), which were relatively small (3.6% for FQ18 to 8.2% for FQ5). Even for the best result (VHR18), almost 10% of the pixels have a relative ΔH close to the 10% error range, demonstrating that the ground-space method cannot safely be applied for the ortho-rectification of simulated RCM data with the VHR specifications.

To forecast the applicability of the ground-space method to other simulated or future RCM data, and to better understand the previously described behaviour, supplemental scenarios and simulation tests were carried out to track the errors during the RCM data simulation. Whatever the quality of the simulation process, the simulated RCM data are not exactly a fully accurate representation of the future RCM data, mainly for VHR data. Three main parameters (compact mode, oversampling and NESZ) are the key parameters in the simulation of RCM data. In order to know which parameter was the main source in the previous error budget, each parameter was thus independently applied in the simulation:

1. The simulation generated only polarimetric images (compact mode) with the same resolution and noise floor than R-2 fine quad images;
2. The simulation generated only VHR images (3-m resolution) with full polarimetry and the same noise floor as R-2 fine quad images; and
3. The simulation generated only noisier images (-17dB) with full polarimetry and the same resolution as R-2 fine quad images.

Due to the complex simulation process and the computation of the polarimetric parameter, it should be noted that these separate errors do not have a strictly cumulative quantitative effect in the total error budget. However, they are still representative of the role of each parameter. The results are displayed in **Figure 4-22:** white, diagonal-bars and dot boxes for the three simulation scenarios 1, 2 and 3, respectively. Whatever the look angles, it is obvious that (i) the compact mode (white boxes) did not contribute to the previous error budget, because it only generated negligible relative ΔH (less than 0.3%); and (ii) the oversampling (diagonal-bar boxes) and mainly the noise floor (dot boxes) generating very large entropy differences have the largest impact in the previous error budget when using all three parameters in the simulation. While the large oversampling is not present in other simulated or future RCM data, the NESZ of -17dB will certainly be a limitation to ortho-rectifying RCM VHR data with the ground-space method. However, other simulated RCM beam modes or future RCM real data with a better NESZ could be good candidates for the ground-space method. Until this verification, the image-space method should thus be preferred with RCM Compact polarimetric products.

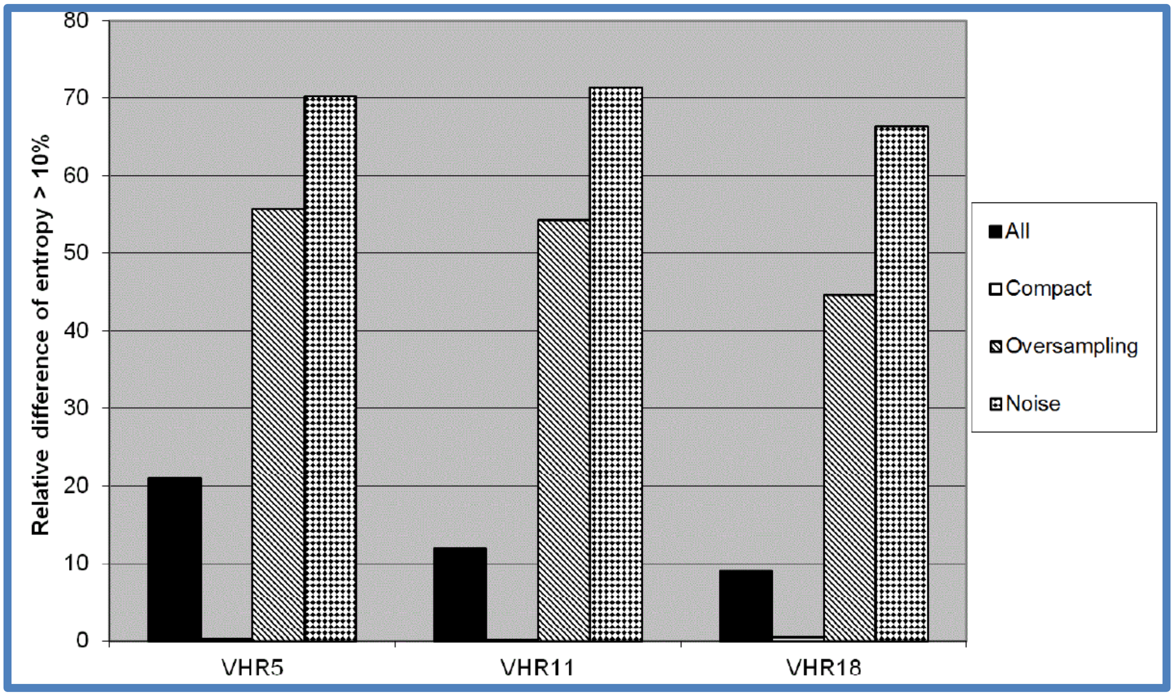


Figure 4-22 Relative entropy difference ΔH over 10% for each VHR image with all parameters (black), the compact mode only (white), the oversampling (diagonal bars) and the noise only (dots) used.

5. Summary and conclusion

In preparation of the Canadian RADARSAT Constellation Mission (RCM), the Canadian Space Agency's Data Utilization and Applications Program (DUAP) supported a multi-year, cooperative research and development effort focused on the evaluation of compact polarimetry (CP) by Government of Canada Earth observation data users. Taken together, the analyses considered the uses and requirements of Natural Resources Canada, Agriculture Canada, Environment Canada, National Defense, Royal Military College and Parks Canada Agency. Researchers and scientists focused their work on a variety of operational applications and related CP considerations, chief amongst them being their ability to exploit CP information content over wide operational swaths while preserving polarimetric information diversity. Of special interest to the Canadian Space Agency was a pre-launch understanding of the potential of CP mode to meet the requirements of multiple government users in order to reduce the level of ordering conflicts.

The DUAP project compared results obtained with standard methods from mono-, dual-linear and fully-polarized data acquired over various natural and man-made targets using CP data simulated from RADARSAT-2 fully polarimetric acquisitions. The project also conducted these analyses over a wide range of RCM beam modes specifications. Inspired from the list of applications shown in van der Sanden (2004), **Table 5-1** contains a summary of the Compact Polarimetry evaluations to-date by federal government departments as a result of this DUAP project. This table highlights meaningful CP parameters and briefly comments on assessed applications. It also identifies applications which have not yet been evaluated.

The following key findings are noted:

- The non-perfect circularity of the transmitted wave will impact EO application performance. Strategic use of the data should mitigate this issue and its impact on many operational applications.
- Of the 26 CP derived parameters analyzed, RH, RV, RR, RL, Stokes vectors, m-chi and Shannon Entropy were recurrent best performers for most applications.
- Quantitative soil moisture estimation from CP data could be done at the same level of accuracy as with fully polarimetric data or dual HH-VV data, but with an improved spatial coverage. The other advantage of CP over dual HH-VV is the access to some information about above ground biomass which helps in the attenuation model definition.
- Crop classification with CP data performs much better than linear dual polarization configuration on single dates (20% improvement in accuracy) and with a multi-temporal approach (5 to 10% improvement in accuracy). Furthermore, CP has the potential to develop LAI models as a function of crop type.
- Compared to dual-linear configurations, CP data improves sea ice typing (multi-year, first year) and open water discrimination.

- The access to RL polarization (maximized backscattered intensity for surface scattering media) will help in mitigating any issues with the higher RCM noise floor which could significantly impact the effectiveness of detection of young, smooth ice, oil slick detection / characterization, and ocean wind speed estimation.
- Wetland water extent, grassland classification and forest clear cuts and fire scars can be easily assessed from CP SAR data at a similar level of reliability as fully polarimetric configurations.
- CP-InSAR studies of horticultural sites have shown promise despite the fact that repeat cycle limitations made it difficult to fully assess its potential. Some potential bio/geo-physical features were highlighted.

In conclusion, this study has shown that, given its ability to provide additional polarimetric information, RCM CP mode is expected to perform as well as, if not better than, current single and dual polarization modes used today with RADARSAT-2 by operational government users. In fact, some users should consider it as their primary mode. This is a significant finding as government users begin their pre-launch operational preparations for the RCM. With some confidence in performance, they can now consider investments in terms of further operationalizing the use of this mode. As well, the results of this study will further inform federal users and the CSA in their development of standard coverages for the Government of Canada. It is now understood that CP mode has clear potential as a multi-use mode that could serve many users and as a result, reduce planning conflicts and maximize the use of RCM resources. It is recommended that as soon as the RCM is operational, the CSA and related federal users validate and expand on the results of this study with a post-launch evaluation of the CP mode.

Table 5.1 Evaluation summary of CP performance relative to linear dual-polarization configuration for a list of applications. Meaningful CP parameters are identified per application.

Applications	CP vs Dual-linear	CP Parameters of value	Comments / Limitation
Agriculture			
Crop type	B	SE, m-χ	Assist with typing under single acquisition condition
Crop condition/phenology	NA		
Crop Yield	NA	m-χ vol	Limited by signal saturation at C-Band
Cartography			
DEM InSAR, DEM Stereoscopy, DEM Polarimetry, Feature Extraction	NA		Could help with feature extraction
Change detection			
Detection	E	S_v, m-χ	
Characterization	B	S_v, m-χ	Assist with classifying change type
InSAR	B	S_v	Assist with maximizing InSAR coherence
Forestry			
Forest Type	NA		
Clearcuts	E	m-χ	
Fire-scars	E	m-χ	
Biomass	B	S_v, m-χ	CP-InSAR might improve estimation
Geology			
Terrain Mapping, Structure, Lithology	NA		
Hydrology			
Soil moisture	E B	RL, RH, m-χ	Considering the reduced swath width (1/2) under HH-VV configuration, CP configuration would be preferable. HH-VV models are more impacted by above ground vegetation.
Snow	NA		
Wetlands	B	SE, m-χ	
Flood	B	SE, m-χ	Indirectly assessed under the wetland activity
Ocean			
Winds	E W	RL, RR	Slightly weaker performance since empirical CMOD type models need to be recalibrated. Not an issue.
Ships	E B	RR, S_v, μ	Under Ship Detection: BAQ (1 or 2) will limit optimal performance
Oil slick detection	E	RL, μ	RCM NESZ will limit performance at low wind speed condition (valid for all polarization configurations)
Oil slick characterization	E	RL, μ	RCM NESZ will limit performance
Waves	NA		Based on ad hoc observation, wave patterns can be highlighted with CP parameters
Currents	NA		
Coastal zones	NA		Not assessed, but a separated ongoing study led by EC shows positive results about coastal land classification. CP should also help in coastal line determination.
Sea and Land Ice			
Sea Ice Edge and Ice Concentration	B	CPSI, various	Various = Optimal CP parameters for ice typing are function of local incident angle
Sea Ice Type	B	CPSI, various	Various = Optimal CP parameters for ice typing are function of local incident angle
Sea Ice Topography & Structure	NA		
Icebergs	E B	RR, S_v, μ	Under Ship Detection: BAQ (1 or 2) will limit optimal performance
Lake Ice and River Ice Freeze-up/ Break-up	B	RR,RL, SE_i, m-χ, μ	RCM NESZ will limit performance
Polar Glaciology	NA		

Keys: **'W'** Worst, **'E'** Equal, **'B'** Better, **'NA'** Not Assessed

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