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Spaceborne Ocean Intelligence Network

SOIN Final Activity Report 2007-13

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Canada

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This document is the SOIN Final Activity Report, 2007 to 2013, delivered to the Canadian Space Agency's Government Related Initiatives Program.

Abstract

The Spaceborne Ocean Intelligence Network (SOIN) was a six-year research and operational development project that addressed barriers to developing and implementing oceanographic applications derived from Earth-observation sensors such as RADARSAT-2 and MODIS, capabilities that were provided by the Polar Epsilon Project, combined with existing AVHRR and MERIS sensor data. The project was divided into two phases. The 2007/08 to 2009/10 three-year Phase I focused on developing state-of-the-art sea-surface temperature and diver-visibility products, operational tools, supporting infrastructure and an ability to detect thermal fronts, eddies and water mass boundaries with RADARSAT-2 synthetic aperture radar (SAR) imagery. The 2010/11 to 2012/13 three-year Phase II focused on operationalization and implementation of SOIN capabilities. The SOIN project began in June 2007 with funding provided by the Canadian Space Agency through its Government Related Initiatives Program. This report provides the SOIN Final Activity Report of project activities and accomplishments from 2007 to 2013.

Résumé

Le réseau spatial de renseignements océanographiques (RSRO) a été un projet de recherche et développement opérationnel d'une durée de six ans qui a porté sur l'étude des obstacles à l'élaboration et à la mise en œuvre d'applications océanographiques dérivées des capteurs d'observation de la Terre, comme RADARSAT 2 et MODIS, capacités qui étaient fournies dans le cadre du projet Polar Epsilon et combinées aux données des capteurs AVHRR et MERIS. Le projet s'est déroulé en deux phases. La phase I, qui s'est étalée sur trois ans, soit de 2007 2008 à 2009 2010, a porté sur le développement de produits de pointe appelés à fournir des données sur la visibilité des plongeurs et la température de la surface de la mer, des outils opérationnels, une infrastructure de soutien et une capacité de détection des fronts thermiques, des tourbillons et des limites des masses d'eau au moyen de l'imagerie de radar à synthèse d'ouverture (SAR) de RADARSAT 2. La phase II, qui s'est également étalée sur trois ans, soit de 2010 2011 à 2012 2013, a porté sur l'opérationnalisation et la mise en œuvre des capacités du RSRO. Le projet a débuté en juin 2007 grâce à un financement de l'Agence spatiale canadienne (ASC) par l'entremise de son programme d'Initiatives gouvernementales en observation de la Terre (IGOT). Le présent rapport constitue le rapport final sur les activités et les réalisations du projet RSRO pour la période allant de 2007 à 2013.

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Executive summary

Spaceborne Ocean Intelligence Network: SOIN Final Activity Report 2007-13

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Introduction: The SOIN project began in June 2007 with funding provided by the Canadian Space Agency through its Government Related Initiatives Program. Led by MetOc Halifax, SOIN was a six-year research and operational development project that addressed barriers to developing and implementing operational oceanographic applications derived from Earth-observation sensors. The project positioned both the east and west coast MetOc centres to take full advantage of the Near Real Time Ship Detection (NRTSD) and Environmental Sensing (ES) capabilities that were implemented for the Canadian Forces (CF) by the Polar Epsilon Project.

SOIN was divided into two phases. Phase I was completed in March 2010 and focused on developing state-of-the-art sea-surface temperature (SST) and diver-visibility products, operational tools, supporting infrastructure and the ability to detect thermal fronts, eddies and water mass boundaries with RADARSAT-2 synthetic aperture radar (SAR) imagery. Phase II was completed in March 2013 and focused on implementing and operationalizing SOIN outputs. Throughout its six-year life the SOIN team grew to encompass representation from numerous Federal Government Departments, Canadian Academia and private industry. This report provides the final project overview and summarizes project activities and accomplishments from project launch in 2007 to project completion in March 2013.

Results: SOIN was composed of nine work packages:

- WP 1 – Project Management and Scientific/Technical Support Services. The SOIN Project Management Team consisted of the Senior Staff Officer of MetOc Halifax as Project Manager throughout the project, with support from Defence R&D Canada – Ottawa (DRDC Ottawa) as Scientific Authority and Maritime Way Scientific Ltd. (during the last two years of the project) as Operations Manager. The Project Management Team addressed all aspects of managing the project including the coordination of all scientific research, the management of GRIP funding, the application of project management methodology and processes, and the writing of all correspondence, minutes, fiscal-year end and final reports.

- WP 2 – Automated Processing System. MetOc Halifax is operating a Canadian version of the US Navy's Automated Processing System (C-APS), and is processing MODIS, AVHRR, and MERIS data. RADARSAT-2 data ordering and de-confliction procedures (with the Canadian Ice Service (CIS), DRDC Ottawa and the Royal Military College of Canada (RMC)) are well established, MetOc Halifax's Ocean Work Station (OWS) was upgraded to ingest Shapefiles of RADARSAT-2-derived thermal features. Furthermore, the Department of Fisheries and Oceans' (DFO) Institut Maurice-Lamontagne (IML) developed and delivered frontal climatologies for inclusion into C-APS.

- WP 3 – SAR processor, Image Analyst Pro (IA Pro) and Commercial Satellite Imagery Acquisition Planning System (CSIAPS). DRDC Ottawa successfully installed and throughout the project continued to upgrade the IA Pro and CSIAPS software tools, two cutting-edge software packages instrumental to the acquisition, archiving and evaluation of space-based imagery. DRDC Ottawa also implemented and upgraded within IA Pro the SAR Ocean Feature Detection Tool (SOFDT), which generates numerous SAR-derived products including Shapefiles of RADARSAT-2-derived features and new SAR-derived output products. A capability for interactive vector feature validation was also implemented to assist with the gathering of feature attributes for statistical analysis.

- WP 4 – Ocean features from SAR. DFO's Bedford Institute of Oceanography (BIO) investigated the physical characteristics of the marine atmospheric boundary layer (MABL) to determine methodologies for their identification, and their research yielded some interesting and important results. Of particular note, they demonstrated that the fine-resolution measurements of near-surface wind speed and direction over the Gulf Stream region from RADARSAT-2 imagery can be used to reveal the existence of small-scale surface features in the curl and divergence fields of the wind stress. Moreover, as suggested by corresponding AVHRR and MODIS images, evident in the wind stress curl and divergence fields are sea surface temperature front features. By combining the wind stress curl and divergence fields, they were able to provide a predictor for sea surface thermal temperature gradients. The Gulf Stream thermal signature is particularly evident. The importance of this methodology is that SAR can penetrate clouds. A limitation on the method is the use of ancillary data such as QuikSCAT wind directions (no longer available), or other data, to infer SAR-derived wind speeds, or wind stress vectors. BIO also developed the methodology to infer wind stress from the dual-polarization RADARSAT-2 data used in SOIN for high wind-speed cases.

- WP 5 – SOIN compatible Ocean Workstation. MetOc Halifax uses the Ocean Workstation (OWS) to produce their operational Ocean Feature Analysis (OFA) product. A contract was completed that enabled IA Pro-derived SAR ocean features to be ingested into the OWS. SOIN-related computer hardware and software was installed at MetOc Esquimalt, and staff training was conducted on those systems and RADARSAT-2 ordering to integrate the west coast fully into the SOIN project.

- WP 6 – West Coast Ocean features. DFO's Institute of Ocean Sciences (IOS) was incorporated into the project in 2010 to exploit their expertise in chlorophyll and frontal analysis as it applies to SAR imagery of the west coast. IOS worked closely with ASL Environmental and MetOc Esquimalt when ordering imagery and comparing SAR, thermal IR, and ocean colour imagery results. The IOS and ASL analysis demonstrated that RADARSAT's ability on the West Coast to detect ocean frontal features was not as effective as it was on the East Coast, this most likely due to the absence of a dramatic feature such as the Northern Wall of the Gulf Stream (NWGS).

- WP 7 – SAR Ocean Imaging model. RMC undertook the implementation of a SAR ocean imaging model, and conducted research on inverting the SAR image to determine the underlying ocean surface. The Radar Imaging Model (RIM) from the Nansen Environmental and Remote Sensing Centre (NERSC) has been implemented at RMC. The M4S model has been installed and run for a number cases involving current shear. Results from these models are promising. While neither model is ready for integration into the SOIN system, the RIM model source code is available, so the model physics can be

validated and updated as necessary. In a longer term sense, this model will help explain many of the features visible in SAR imagery.

- WP 8 – Statistical analysis of SAR data. Dalhousie University case studies demonstrated that the automated detection and classification of SST front signatures in RADARSAT-2 images of the Gulf Stream region, in conjunction with manual analysis, has the potential of contributing to the accurate assessment of the location of major water-mass boundaries (the GSNW, the shelf-slope front, and warm-core rings) under conditions that preclude the use of satellite SST images due to cloud cover. The model has been integrated into IA Pro. Dalhousie also developed a training module with a standardized series of steps to follow when analyzing an R2 image for Gulf Stream features. The intent is for participants to gain a basic proficiency in signature recognition and an understanding of how to apply the standardized approach to image analysis.

- WP 9 – Acoustical Environmental application. DRDC Atlantic determined the impact of SAR-identified ocean features on Anti-Submarine Warfare (ASW), in particular the effects of ambient noise calculated from SAR-derived winds and thermal fronts. The work done under WP 9 of the SOIN project was successful, and showed the potential of using RADARSAT and other satellite data to characterize the underwater acoustic environment. The acquisition of Rapid Environmental Assessment (REA) data is a valuable tool in the development of a Recognized Environmental Picture, and the work done in the SOIN project shows that satellite-derived environmental data can provide accurate and timely information about the acoustic environment.

Significance: The SOIN project successfully completed Phase I and Phase II and all project objectives were met. As a result, SOIN delivered a cutting-edge operational capability to the Royal Canadian Navy.

Sommaire

Spaceborne Ocean Intelligence Network: SOIN Final Activity Report 2007-13

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Introduction : Le projet RSRO a débuté en juin 2007 grâce à un financement de l'Agence spatiale canadienne par l'entremise du programme d'Initiatives gouvernementales en observation de la Terre. Dirigé par le Centre météorologique et océanographique (METOC) de Halifax, le projet RSRO a été un projet de recherche et de développement opérationnel d'une durée de six ans qui a porté sur l'étude des obstacles à l'élaboration et à la mise en œuvre d'applications océanographiques dérivées des capteurs d'observation de la Terre. Le projet a permis de positionner les METOC de la côte Est et de la côte Ouest de façon à ce qu'ils puissent tirer pleinement profit des capacités de détection de navires en temps quasi réel (NRTSD) et de détection environnementale qui ont été mises en œuvre pour les Forces canadiennes (FC) dans le cadre du projet Polar Epsilon.

Le projet RSRO s'est déroulé en deux phases. La phase I s'est terminée en mars 2010 et elle a porté sur le développement de produits de pointe appelés à fournir des données sur la visibilité des plongeurs et la température de la surface de la mer, des outils opérationnels, une infrastructure de soutien et une capacité de détection des fronts thermiques, des tourbillons et des limites des masses d'eau au moyen de l'imagerie de radar à synthèse d'ouverture (SAR) de RADARSAT 2. La phase II a pris fin en mars 2013 et elle a porté sur l'opérationnalisation et la mise en œuvre des capacités du RSRO. Durant ces six années de travail, l'équipe du RSRO s'est élargie pour inclure des représentants des ministères fédéraux, des universitaires canadiens et des gens du secteur privé. Le présent rapport fournit un aperçu du projet final et il résume les activités et les réalisations du projet RSRO à partir de son lancement, en 2007, jusqu'à son achèvement en mars 2013.

Résultats : Le RSRO comportait neuf blocs de travail :

- BT 1 – Gestion de projet et soutien technique/scientifique. Le gestionnaire de projet désigné (l'officier supérieur d'état major du METOC de Halifax) a été à la tête de l'équipe de gestion du RSRO pour toute la durée du projet. Il pouvait compter sur l'aide du responsable scientifique (Recherche et développement pour la défense Canada – Ottawa [RDDC Ottawa]) et, pour les deux dernières années du projet, du directeur des opérations (Maritime Way Scientific Ltd.). L'équipe de gestion de projet a abordé tous les aspects de la gestion du projet, notamment la coordination des recherches scientifiques, la gestion du financement dans le cadre de l'IGOT, l'application des méthodes et processus de gestion de projet et la rédaction de toute la documentation, des procès verbaux, des rapports annuels et des rapports finaux.

- BT 2 – Système de traitement automatisé. Le METOC de Halifax exploite une version canadienne du système de traitement automatisé de la marine américaine (C APS) et traite les données des capteurs MODIS, AVHRR et MERIS. À cette fin, des procédures de commandes de données RADARSAT 2 et d'évitement des conflits (avec le Service canadien des glaces [SCG], RDDC Ottawa et le Collège militaire royal du Canada [CMRC]) ont été établies. Le poste de travail océanique du METOC de Halifax a été mis à niveau pour permettre la réception des fichiers de formes des caractéristiques thermiques dérivées de RADARSAT 2. De plus, l'Institut Maurice Lamontagne (IML) du ministère des Pêches et Océans (MPO) a mené et terminé les travaux de climatologie des fronts afin qu'ils soient intégrés au C APS.

- BT 3 – Processeur SAR, outil Image Analyst Pro (IA Pro) et système de planification d'acquisition d'imagerie par satellite commercial (CSIAPS). RDDC Ottawa a installé avec succès et a continué à améliorer les outils logiciels IA Pro et CSIAPS, deux progiciels d'avant garde utiles à l'acquisition, à l'archivage et à l'évaluation de l'imagerie spatiale. RDDC Ottawa a également installé et mis à niveau, à l'intérieur de l'outil IA Pro, l'outil de détection des éléments océaniques SAR (SOFDT), qui génère de nombreux produits dérivés SAR, y compris des fichiers de formes de caractéristiques dérivés de RADARSAT 2 et de nouveaux produits dérivés de SAR. Une capacité de validation interactive de caractéristiques vectorielles a été mise en œuvre pour aider à la collecte d'attributs de caractéristiques en vue d'analyses statistiques.

- BT 4 – Caractéristiques océaniques déterminées à partir de données SAR. L'Institut océanographique de Bedford (IOB) du MPO a étudié les caractéristiques physiques de la couche limite atmosphérique marine (MABL) pour établir des méthodes d'identification, et ses recherches ont donné des résultats intéressants et importants. Notons, en particulier, qu'il a démontré que les mesures de fine résolution prises près de la surface en ce qui concerne la vitesse et la direction du vent dans la région du Gulf Stream à partir de l'imagerie RADARSAT 2 peuvent servir à révéler l'existence de caractéristiques de surface à petite échelle dans le champ de rotation et le champ de divergence de la pression du vent. En outre, comme le laissaient entendre les images correspondantes de l'AVHRR et de MODIS, les caractéristiques du front de température à la surface de la mer sont évidentes dans le champ de rotation et le champ de divergence de la pression du vent. En combinant les champs de divergence et de rotation de la pression du vent, il a été possible de fournir un prédicteur des gradients thermiques à la surface de la mer. La signature thermique du Gulf Stream est particulièrement évidente. L'intérêt de cette méthode, c'est que le SAR peut pénétrer dans les nuages. La méthode présente cependant une limite quant à l'utilisation de données accessoires, comme les directions du vent QuikSCAT (elles ne sont plus disponibles), ou d'autres données pour déduire les vitesses du vent dérivées du SAR ou les vecteurs de tension du vent. L'IOB a travaillé à la mise au point d'une méthode qui permet de déduire la tension du vent à partir des données RADARSAT 2 à double polarisation qui servent dans le cadre du RSRO dans le cas du vent à grande vitesse.

- BT 5 – Poste de travail océanique compatible RSRO. Le METOC de Halifax se sert des postes de travail océaniques pour produire ses analyses opérationnelles des caractéristiques océaniques (OFA). Des travaux ont été effectués à contrat en vue de l'intégration, aux postes de travail océanique, des caractéristiques océaniques SAR dérivées de l'outil IA Pro. Le matériel informatique du RSRO, assorti d'un logiciel, a été installé au METOC d'Esquimalt, et le personnel a reçu la formation requise à l'égard de ces systèmes et de la

commande RADARSAT 2, ce qui a permis d'intégrer entièrement la région de l'Ouest au projet RSRO.

- BT 6 – Caractéristiques océaniques de la côte Ouest. On a fait appel à l'Institut des sciences de la mer (ISM) du MPO en 2010 pour tirer profit de son expertise dans les domaines de l'étude de la chlorophylle et de l'analyse frontale appliquées à l'imagerie SAR sur la côte Ouest. L'ISM a travaillé en étroite collaboration avec ASL Environmental et le METOC d'Esquimalt pour commander des images et comparer les résultats en ce qui concerne les images SAR, les images IR thermiques et les images de la couleur de l'océan. Les analyses de l'ISM et d'ASL Environmental ont démontré que la capacité RADARSAT de détecter les fronts océaniques sur la côte Ouest était moins efficace que sur la côte Est, probablement en raison de l'absence d'une caractéristique marine aussi importante que la bordure nord du Gulf Stream.

- BT 7 – Modèle d'imagerie SAR de l'océan. Le CMR a entrepris la création et la mise en œuvre d'un modèle d'imagerie SAR de l'océan, et il a mené des recherches sur l'inversion d'une image SAR pour déterminer la surface sous-jacente de l'océan. Le modèle d'imagerie radar (MIR) du Nansen Environmental and Remote Sensing Centre (NERSC) a été déployé au CMR. Le modèle M4S a été installé et utilisé dans de nombreux cas concernant le cisaillement de courant. Les résultats obtenus avec ces modèles sont prometteurs. Même si aucun modèle n'est prêt à être intégré au projet RSRO, le code source du MIR est disponible, si bien que la physique du modèle peut être validée et mise à jour, selon les besoins. À long terme, ce modèle expliquera bon nombre de caractéristiques visibles à l'aide d'imagerie SAR.

- BT 8 – Analyse statistique des données SAR. Les études de cas de la Dalhousie University ont démontré que la détection automatisée et la classification des signatures thermiques des fronts océaniques à l'aide d'images RADARSAT 2 de la région du Gulf Stream, conjointement à l'analyse manuelle, pourraient réellement contribuer à localiser précisément les limites des importantes masses d'eau (la bordure nord du Gulf Stream, le front plateau talus et les anneaux centraux chauds) lorsque les conditions font en sorte qu'il est impossible de recourir aux images satellites de la température de la surface de la mer en raison de la couverture nuageuse. Le modèle a été intégré à l'outil IA Pro. La Dalhousie University a également élaboré un module de formation comprenant une série d'étapes à suivre pour analyser les images des caractéristiques du Gulf Stream fournies par RADARSAT 2. L'idée est de permettre aux participants d'acquérir les compétences de base pour reconnaître les marques d'action et de comprendre comment recourir à l'approche normalisée en matière d'analyse d'images.

- BT 9 – Application environnementale acoustique. RDDC Atlantique a déterminé l'incidence des caractéristiques océaniques identifiées par SAR sur la guerre anti sous-marine (GASM), en particulier les effets du bruit ambiant calculé à partir des fronts thermiques et du vent dérivés de données SAR. Le travail accompli dans le BT 9 du projet RSRO a été utile et a démontré le potentiel offert par les données produites par RADARSAT et d'autres satellites pour caractériser le milieu acoustique sous marin. L'acquisition de données sur l'évaluation environnementale rapide (REA) est un outil utile pour connaître la situation générale de l'environnement, et le travail accompli dans le cadre du projet RSRO montre que les données environnementales obtenues au moyen de satellites fournissent de l'information exacte et à jour sur l'environnement acoustique.

Perspectives : Les phases I et II du projet RSRO ont été menées à bien et tous les objectifs ont été atteints. Entre autres résultats, le projet RSRO a fourni une capacité opérationnelle de pointe à la Marine royale canadienne.

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1   Introduction

The Spaceborne Ocean Intelligence Network (SOIN) project began in June 2007 with funding provided by the Canadian Space Agency through its Government Related Initiatives Program. Led by MetOc Halifax, SOIN was a six-year research and operational development project that addressed the three fundamental barriers of (i) a lack of required infrastructure; (ii) insufficient auxiliary data provided in required time frames, spatial scales and file formats; and (iii) insufficient knowledge of how to interpret synthetic aperture radar (SAR) imagery for operational ocean feature applications [1] to developing and implementing operational oceanographic applications derived from Earth-observation sensors [31], [32]. The SOIN Mission Statement was:

> *To produce next-generation and new environmental products by fusing thermal-IR, multi-spectral and SAR imagery, in operationally-relevant time frames, so as to garner a greater appreciation and understanding of the environmental situation and its impact on operational effectiveness [32].*

The project positioned MetOc Halifax to take full advantage of Polar Epsilon's Near Real Time Ship Detection (NRTSD) and Environmental Sensing (ES) capabilities that were implemented for the Canadian Forces (CF) through the Polar Epsilon (PE) Project.

Details concerning SOIN objectives, work packages, milestones, deliverables and due dates were identified in the Phases I and II project proposals [32],[35], and in prior annual reports [33], [34], [35], [36], [37].

SOIN was divided into two phases. Phase I was completed in March 2010 and focused on developing state-of-the-art sea-surface temperature and diver-visibility products, operational tools, supporting infrastructure and an ability to detect thermal fronts, eddies and water mass boundaries with RADARSAT-2 synthetic aperture radar (SAR) imagery. Phase II was completed in March 2013 and focused on the implementation and operationalization of SOIN products. The SOIN project is depicted in Figure 1:

- RSAT-2: RADARSAT-2 imagery which will be pulled from the PE ftp server that will be located at Aldergrove, BC (starting in 2011) or from the National Earth Observation Data Framework (NEODF) server at the Canada Center for Remote Sensing (CCRS);

- NWP: Numerical Weather Prediction model outputs will be used as a guide to assist in the detection of ocean features;

- MODIS: Ocean Colour imagery that will be read directly from the PE ES capability;

- AVHRR: Sea surface temperature (SST) imagery from MetOc Halifax's existing L-band dish;

- MERIS: Colour imagery obtained via ftp from the CCRS (MERIS is now defunct);

- IA Pro/SOFDT: The DRDC Ottawa-developed Image Analyst Pro/SAR Ocean Feature Detection Tool will automatically extract and classify Ocean Features in SAR ocean imagery.

- C-APS: The Canadian Automated Processing System will produce SST, True Colour, and Diver Visibility products for the SOIN Area of Interest (AOI).
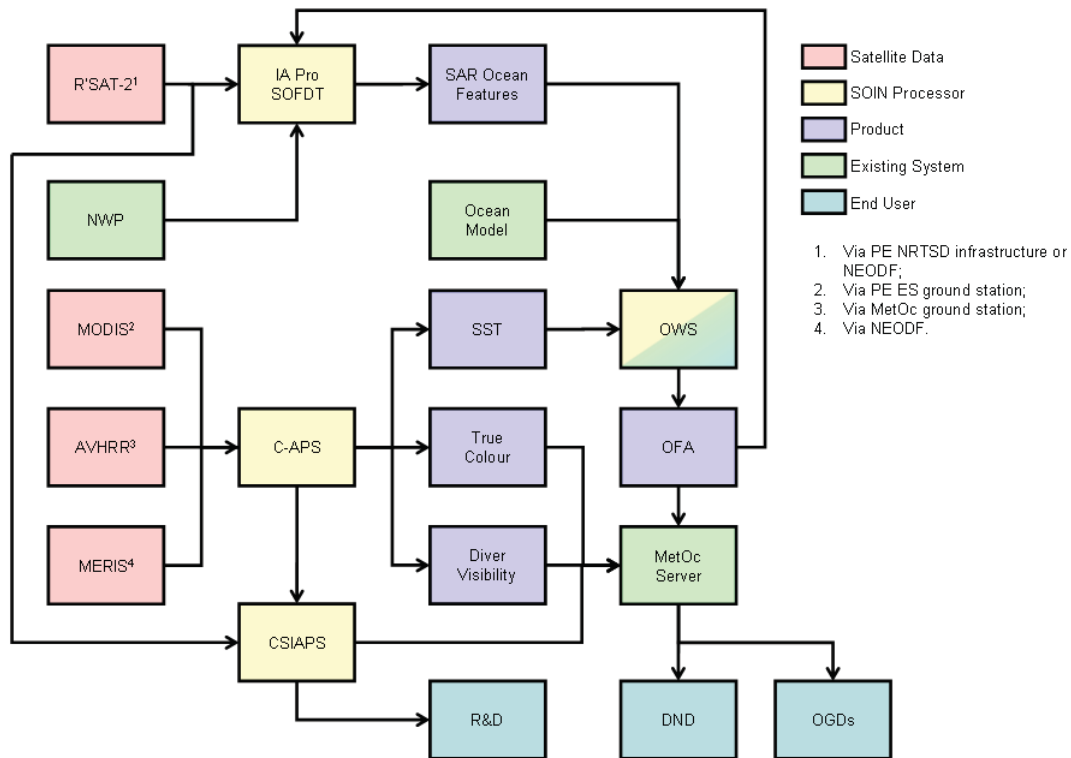
Figure 1 - SOIN Schematic Representation.

- CSIAPS: The DRDC Ottawa-developed Commercial Satellite Imagery Acquisition Planning System archives all SOIN imagery and C-APS products. The CSIAPS archive was intended to feed R&D activities as well provide an imagery search tool for MetOc clients. In later developments CSIAPS was replaced by a data storage capability. CSIAPS remains a DRDC Ottawa research ;

- OWS: The Ocean Workstation that uses Ocean Feature and SST products to produce the Ocean Feature Analysis (OFA); and

- MetOc Server: The MetOc Halifax server that will host SOIN and OFA products for DND users and Other Government Departments (OGDs).

The SOIN work packages were as follows:

- WP 1 – Project management, delivery and communications;

- WP 2 – Automated Processing System;

- WP 3 – SAR processor, IA Pro and CSIAPS;

- WP 4 – Ocean features from SAR;
- WP 5 – SOIN compatible Ocean Workstation;
- WP 6 – West coast features
- WP 7 – SAR ocean image model
- WP 8 – Statistical analysis of SAR data
- WP 9 – Acoustic Environment Application

This report provides a complete project overview of SOIN project activities on a work package basis as well as accomplishments during the projects six-year duration.

2   Work Packages

2.1   WP 1 Project Management, Delivery and Communications

2.1.1   Work Tasks

The purpose of WP 1 was to manage all aspects of the SOIN project including meetings, deliverables, all written correspondence and reports, and communications. WP 1 was comprised of the following tasks (please note that the Work Task numbers have been revised from the original proposal so as to conform to the current numbering system):

From SOIN Phase I [32] the Work Tasks were:

- WP 1.1 – Organizing and chairing meetings;

- WP 1.2 – Deliverables management;

- WP 1.3 – Port management and Financial plans into Microsoft Project;

- WP 1.4 – Written reports and communications; and

- WP 1.5 – Systems management:

- WP 1.5.1 – Operational APS with required thermal data products;

- WP 1.5.2 – SAR METOC automatic processor Version 1.0 (V1.0);

- WP 1.5.3 – 1st interim version of METOC-Pro V1.0;

- WP 1.5.4 – 2nd interim version of METOC-Pro V1.0;

- WP 1.5.5 – MetOc's MODIS X-band ground station integrated with APS;

- WP 1.5.6 – Field-trial version of METOC-Pro V1.0; and

- WP 1.5.7 – METOC-Pro V1.0 delivered.

From the SOIN Phase II proposal [35], in addition to the Work Tasks listed above, WP 1.5 was further modified to include the following sub-tasks:

- WP 1.5 – Systems (continued):

- WP 1.5.8 – Upgraded Dalhousie University logistic regression model;

- WP 1.5.9 – Project monitoring of RMC and IOS WPs to include:

- WP 1.5.10 – EO tools implemented in IA Pro;

- WP 1.5.11 – Report on implementation of RMC SAR Imaging Model.

2.1.2   WP 1 Overview

SOIN delivered on all aspects of the project as per the SOIN proposal.

2.1.3　Composition of the Project Management Team

The Project Management (PM) Team consisted of a Project Manager (LCdr Wayne Renaud 2007-2009, LCdr Darryl Williams 2009-2012, Major Norm Scantland 2012-2013), a Scientific Advisor (Dr. Paris Vachon 2007-2013), and an Operations Manager (Dr. Brian Whitehouse 2007-2008, LCdr Wayne Renaud 2007-2009, LCdr Darryl Williams 2009-2010, Mr. Wayne Renaud 2010-2013). As can be seen, there was continuity in the Project Management Team throughout the life of the project. In fact, LCdr Darryl Williams acted as assistant-Project Manager to LCdr Wayne Renaud during 2007-2009. The consistency in management meant that the initial vision was never lost, and the project was able to progress and grow with this vision in mind. This solid foundation enabled project team members to understand the management and leadership of the PM Team.

The PM Team members also fully recognized their roles within the team. All decisions affecting the project were discussed and agreed to as a team, and the team monitored progress very carefully. The PM Team had an excellent working relationship, and this was communicated to the entire team during meetings.

The PM Team was in frequent contact throughout the project. While the entire project team met twice yearly to review progress and plan for the next cycle, the PM Team effectively met monthly, either in person or via teleconference.

The PM Team was also composed of senior personnel who had managed large projects before and therefore knew how best to approach most issues and problems.

2.1.4　Scope management

Scope was reviewed at every bi-yearly meeting, and the PM Team monitored scope very carefully.

Decisions to include new aspects to the project, such as WP 7 and WP 8 were discussed in detail prior to being taken on, and the ramifications of such decisions were carefully analyzed. WP 6 was adopted on recommendation from the CSA as it was felt that there were some IOS activities that were potentially beneficial to SOIN. IOS delivered unique insights on West Coast oceanographic dynamics and clearly showed that SOIN was not as applicable to their coast as the dramatic temperature gradients association with the Gulf Stream are not present.

Overall the project scope was carefully managed and the project remained within scope throughout.

2.1.5　Time management

Clear deliverables with established timelines ensured that all project members knew what was expected of them, and careful monitoring of all deliverables by the Operations Manager ensured prompt delivery.

The PM Team also reviewed deliverables and timelines at each semi-annual meeting to ensure problems were identified early and addressed in an effective manner.

The entire project team was kept apprised of exactly what phase the project was in, what was expected for the next cycle, what the objectives were and what would be considered as measures of success. As a whole, the SOIN project team was focused on delivering a fully-functional operational capability to the Canadian navy.

2.1.6 Cost management

The PM Team successfully managed the budget, with most FYs ending with only a slight surplus with the exception of FY 09/10, which ended with a larger-than-expected surplus, this due to un-forecasted resource changes.

The Project Manager in particular stayed on-top of project team and prompted them to take payment when they were delinquent.

2.1.7 Human Resources Management

The SOIN project team as a whole was a very convivial group that was easy to manage and eager to deliver operationally useful results. Excellent Project Management ensured that all project team members clearly understood their roles and management's expectations, and the agreed-upon vision of delivering a fully-functional operational capability remained the clear objective throughout the project. Issues, concerns and problems were addressed immediately so as to reduce overall risk and their effects on the project. Finally, unexpected change was embraced as an opportunity to explore new avenues and scientific possibilities.

2.1.8 Communications Management

Communications was an intrinsic part of the SOIN project from the beginning.

Full team meetings were held on a semi-annual basis, usually in the Nov-Dec and April-May timeframes, to capitalize on approaching fiscal years and summer/fall activities.

Papers and submitted articles:

- Thomson, R.E., and Hourston, R.A.S. (2011). A matter of timing: The role of the ocean in the initiation of spawning migration by Late-run Fraser River sockeye salmon (*Oncorhynchus nerka*). *Fisheries Oceanography*, 20(1), 47-65.

- Borstad, G., Crawford, W., Hipfner, M., Thomson, R., and Hyatt, K. (2011). Environmental control of the breeding success of rhinoceros auklets at Triangle Island, British Columbia. *Marine Ecology Progress Series*, 424, 285-302.

- Jones, C.T., Sikora, T., Vachon, P.W., and Wolfe, J. (2012). Towards automated identification of sea-surface temperature front signatures in RADARSAT-2 images. *Journal of Atmospheric and Oceanic Technology*, 29(1), 89-102.

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- Thomson, R.E., Beamish, R.J., Beacham, T.D., Trudel, M., Whitfield, P.H., and Hourston, R.A.S. (2012). Anomalous ocean conditions may explain extreme variability in Fraser River sockeye salmon production, *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystems Science,* 4, 415-437.

- Borstad, G.A., Brown, L.N., Thomson, R.E., Willis, P., and Crawford, B. (2012). Spatial and temporal variability of satellite-derived chlorophyll and SST off the British Columbia coast, *Fisheries Applications of Remotely-Sensed Ocean (FARO) Workshop on: Applications of Ocean-Colour Radiometry for the Study of Marine Ecosystems, including Fisheries*, Nanaimo, BC, 20-22 March 2012.

- Ersahin, K., Thomson, R.E., Brown, L.N., and Borstad, G.A. (2012). Surface ocean feature detection on the West Coast of Canada: Radar versus colour, *Fisheries Applications of Remotely-Sensed Ocean (FARO) Workshop on: Applications of Ocean-Colour Radiometry for the Study of Marine Ecosystems, including Fisheries*, Nanaimo, BC, 20-22 March 2012.

- Loos, E., Borstad, G.A., Brown, L.N., and Thomson, R.E. (2012). Satellite oceanography of the North East Pacific off British Columbia. *33rd Canadian Symposium on Remote Sensing*, Ottawa, Ontario, June 11-14, 2012.

- Jones, C.T., Sikora, T.D., Vachon, P.W., and Wolfe, J. (2013). Automated discrimination of certain brightness fronts in RADARSAT-2 images of the ocean surface. *Journal of Atmospheric and Oceanic Technology*. In press.

- Jones, C.T., Sikora, T.D., Vachon, P.W., and Buckley, J.R. (2013). Ocean feature analysis using semi-automated detection of sea-surface temperature front signatures in RADARSAT-2 images. *Bulletin of the American Meteorological Society*. In press.

Conferences:

- Project members attended two Earth Observation Marine Security Coordination Committee (EOMSCC) meetings, in Montreal (June 2008) and in Ottawa (March 2009).

- SOIN members attended the International Geoscience and Remote Sensing Symposium (IGARSS) in Boston (July 2008) and the CSA RADARSAT-2 Workshop in St Hubert (September 2008).

- Chris Jones gave an oral presentation on the logistic regression model for fronts and eddies at the 3rd RADARSAT-2 Workshop held at the CSA (September 2010).

- Chris Jones gave an oral presentation on RADARSAT-2 brightness fronts at the SeaSAR conference in Tromsø Norway (June 2012).

- Darryl Williams and Paris Vachon presented a SOIN overview poster highlighting the logistic regression work at the Maritime Rapid Environmental Assessment (MREA) Conference in Lerici, Italy (October 2010).

- Chris Jones gave a presentation on the semi-automated classification of RADARSAT-2 imagery of ocean fronts at the 8th CSA ASAR Workshop at the CSA (June 2011).

- Joe Buckley attended the SeaSAR meeting in Tromsø (June 2012) and the IGARSS meeting in Munich (July 2012), where he presented a poster on the relationship between MODIS and

Argo sea surface temperatures, and the PolinSAR meeting in Frascati (January 2013), where he met with members of the NERSC SAR ocean modeling group.

Attended working groups:

- Darryl Williams attended the SAR Applications Working Group (SARAWG) meeting in May 2011, and has participated in the Enhanced Marine Order Coordination (EMOC) process for sorting out RADARSAT 2 ordering conflicts.

2.1.9 Risk Management

The PM Team assessed all risks to project success at every meeting and was therefore able to minimize risk throughout the life of the project. For the most part, risks took the form of accepting new participants into the project and assigning funding to these new entities without fully knowing the contribution each would make (e.g., Chris Jones from Dalhousie, Dr. Joe Buckley from RMC and the IOS and ASL teams). Risk was managed through frequent meetings, clear and concise direction, and unabashed demands as to deliverables.

2.1.10 WP 1 Final Observations and Recommendations

Overall, from a Project Management perspective, SOIN was a grand success as it delivered the promised operational capability on time, within scope and within budget. SOIN was recognized by many Federal and Academic institutions, as well as some private industry organizations, as a very well-managed project that delivered what was promised. As a result of this recognized success, the CSA asked SOIN to bring ASL and IOS onboard, and other outside organizations (both private and public) approached SOIN asking to participate. Throughout the life of the project SOIN can boast of not a single point of failure. By all measures SOIN was a great success.

2.2 WP 2 Automated Processing System

2.2.1 Work tasks

The purpose of WP 2 was to acquire, install, upgrade and integrate the U.S. Navy's Automated Processing System (APS) into MetOc Halifax operations, thereby creating the Canadian-APS (C-APS), in preparation for exploitation of the Polar Epsilon ES capability. C-APS automatically ingests spaceborne thermal infrared (IR) and multispectral data and produces thermal and water-visibility products required for purposes pertaining to maritime defence and homeland security. WP 2 was comprised of the following tasks:

From SOIN Phase I [32] the Work Tasks were:

- WP 2.1 – Hire MetOc Halifax programmer;
- WP 2.2 – Purchase and install C-APS hardware;
- WP 2.3 – Staff training on C-APS;

- WP 2.4 – Install C-APS at MetOc Halifax;

- WP 2.5 – Connect MetOc Halifax L-band dish (for AVHRR data reception) to C-APS;

- WP 2.6 – Assess standard C-APS SST product suite to meet client needs – modify as required;

- WP 2.7 – Import MERIS and MODIS offline data and assess resulting C-APS products;

- WP 2.8 – Connect MetOc Halifax X-band dish (for MODIS data reception) to C-APS; and

- WP 2.9 – Conduct frontal climatology analysis for east coast waters.

From the SOIN Phase II proposal [35] the Work Tasks are (please note that the Phase II Work Task numbers have been revised from the original proposal so as to continue from the Phase I Work Task numbering system):

- WP 2.10 – Work Package management;

- WP 2.11 – Calculate climatology of frontal occurrence probability for the East coast using high spatial resolution imagery;

- WP 2.12 – Test the frontal filtering scheme system prior to delivering it to MetOc;

- WP 2.13 – Implement the frontal filtering scheme into C-APS; and

- WP 2.14 – Further evaluate IML climatological could masking filter implemented in C-APS.

The following new WP was added for FY 2011/12:

- WP 2.15 – Calculate climatology of frontal occurrence probability for the West coast using high spatial resolution imagery.

2.2.2 WP 2 Overview

Brendan DeTracey was seconded from Fisheries and Oceans Canada and commenced work as SOIN's MetOc programmer on 1 October 2007. His addition to the team, and his participation throughout the life of the project, were invaluable. LCdr Darryl Williams (MetOc Halifax) and Brendan DeTracey visited NRL Stennis 2-3 October 2007 where they received an introduction to the APS software, training, and established contacts at NRL. By November 2007 APS was successfully installed and running on a substitute MetOc Halifax computer system, and by end-FY 2007/08 AVHRR was connected to APS and latest-pixel composite and mean composite thermal products were being produced daily.

Sea surface temperatures (SST) are used for a variety of purposes by the Department of National Defence. One of these applications is the detection of strong SST gradients that are an indication of subsurface physical features. The generation of SST gradients is particularly sensitive to noise that can produce biased identification of features. It is thus crucial that as much noise as possible be removed from the imagery. Many factors can influence the quality of SST maps, such as the adequate detection of cloud and ice on the images, the quality of the image navigation to precisely geo-locate features and the precision of the algorithm allowing the transformation of brightness temperatures into physical temperatures.

Considering its expertise in the field of remote sensing, and as part of the SOIN project, the Remote Sensing Laboratory of DFO's Institut Maurice-Lamontagne (IML) was contracted to help DND with the development of their operational system. This final report summarizes the results from the six years of the project.

2.2.2.1   Results

The first year of the project was devoted to putting together the required SST image database as a series of daily SST images of eastern Canada [15]. All the necessary software to process the SST images was put in place and tested on a set of images of eastern Canada. This included scripts to access the individual SST images, extract the area of interest, detect the fronts using the Windows Image Manager (WIM) software, and calculate the frontal probability.

During this first year, IML conducted an analysis of the quality of the SST maps generated by the APS system owned by DND. The work focused on the identification of problems with the various compositing techniques used to generate time-averaged images. Four main problems were identified:

- The cloud detection of the APS system was generating false clouds in areas of strong spatial SST gradients;

- The latest pixel composite method generated strong artefacts in the mean images producing a patchwork appearance;

- There was a loss of cold SST on nighttime images;

- There was a problem with inappropriate cloud detection leading to false cold SST.

These problems with the quality of SST images generated by the APS system [13] translated into false frontal features being identified. This was a major problem that needed to be addressed in order for DND to generate high quality frontal feature maps for its operational activities.

The study indicated that efforts should be made towards the development of a better cloud masking capacity in the APS system. In particular, it was recommend that DND integrate an additional step in its processor in the form of a climatological filter that will generate better SST products.

The second year of the project saw the realization of the frontal probability analysis using 25-years of data covering the area 30-65N, 80-35W. The analysis was done using the Single-Image Edge Detection algorithm [5] using the variable window approach (VW-SIED) [7] as implemented in the commercial WIM software. Before being processed to detect SST fronts, images undergo a series of preprocessing steps that include a projection to a linear space and the creation of a dilated land mask. After processing, results are post-processed using Matlab™ to calculate the climatologies. Three climatologies were calculated: monthly, seasonal and annual.

During this second year, pursuant to the results from the first year, IML was contracted to evaluate the possibility of including a new form of image filter that would decrease the amount of noise in SST images that result in false frontal feature detection. Using real images, noise was simulated in various ways and its effect analyzed on the detection of fronts.

The analysis showed that:

- Spatial convolution filters are found to be a robust, easy-to-implement tool for removal of noise in the tested AVHRR images;

- A major limitation is that a too-selective filter threshold will remove a large number of non-noisy pixels (false positives), while a too high threshold may be too permissive;

- Insufficient removal of noise particularly happens when the intensity of noise pixels are close to the mean intensity of the SST in the image;

- Excessive filtering (removal of non-noise pixels) happens especially when the SST values in the image have a high standard deviation. This implies that false positives are more probable at zones where strong thermal gradients are present.

Pursuant to these results, IML went on to develop potential solutions for these problems [14]. The approach was based on the possibility of using a priori knowledge of frontal features locations as a filtering step in the elimination of noise in the SST images and the generation of better frontal maps. The proposed solution is to adapt the spatial convolution filter tested in the first part of the analysis. A constraint has been added to the spatial noise removal filter to render the filter threshold less selective at zones of high temperature gradients. The constraint makes the filter threshold increase by one-fifth of the gradient parameter. Applying the noise removal process with this constraint, we showed that the good pixels located on the fronts were not removed by the constrained filter. Meanwhile, the front-adapted nature of the filter allowed complete removal of the true noise in the image.

Based on the performed tests, a number of site-specific, qualitative and/or quantitative findings are worth mentioning:

- Front climatology-based filters are found to be useful in reducing the number of false positives caused by spatial filtering;

- Noise filtering processes are particularly delicate for curvilinear fronts and spiral ridges. Often regular frontal pixels can be mistaken as noise in such zones. Front climatology proxies based on larger kernel sizes seem to slightly better represent the frontal structures in such zones;

- The density of false positive noise pixels is rather high in the Gulf Stream. They are more probable on the warmer side of the front;

- If the aim is not to lose any non-noise pixels, the unconstraint filter threshold to be applied must be site-specific. For summer months, in the Arctic or inside the Gulf of St. Lawrence, a filter threshold of ~2°C can be large enough to prevent false positives, while in the Gulf Stream zone it should be at least ~4°C. With the front-constraint, the filter threshold can be optimized to ~2°C + std for the Gulf Stream zone, and to ~1.5° C + std for most other regions, where std is the standard deviation;

- Use of standard deviation-based front climatology with large kernel filtering provides good recovery of false positives, and does not cause significant loss of efficiency in removing true positives. Gradient-based front climatology provides even better recovery of false positives, but leads to a detectable decrease in noise removal efficiency.

The two criteria of efficiency that we considered in the performed tests were:

- How many pixels classified as "noise" (false positives) can be saved by applying a filter constraint? (this is tested by considering original pixels in the images);

- Can the spatial filter still remove real noise efficiently when the filter constraint is applied? (this is tested by adding and then removing artificial noise in the images);

- The optimal parameters were determined as:

  - Filter threshold: 3 or 4°C

  - Filter kernel size: 7x7 or 5x5

  - Front climatology proxy method: std

  - Front climatology kernel size: 7x7

  - Climatology moderated filter threshold: 2° + std

During the third and fourth years, work from the previous two years indicated that a frontal climatology could be used to filter abnormal SST pixels (noise) in satellite imagery. It thus appeared important that the DND operational systems included information on SST frontal occurrence. IML was thus contracted to prepare the frontal SST climatology of eastern Canadian waters. The images covered the period 1985-2010 at the full resolution of the AVHRR sensor (1 km). These images consist of daily means having been processed to eliminate as much as possible artifacts caused by clouds or ice. Ice cover is filtered using daily passive microwave images with a very strict criterion of no ice present in a given pixel. Each acquired pass was also filtered using a 7 days (±3 days) temporal window to make sure that the SST is relatively stable with time. Finally, the processing included using a 25-year climatology to eliminate abnormal SST values.

Figure 2 shows the climatology (probability of occurrence) for the full 25-year period. Results show the location of major oceanographic features (Labrador current, Grand Banks, Gulf Stream) together with more regional features (Scotian Shelf, Gulf of Maine) also being observed. Monthly and seasonal climatologies were also calculated and delivered to METOC as HDF files [16]. Figure 3 shows the same results for west coast waters.

As DND expanded the SOIN project to also include the Pacific region during the last year of the project, and considering the success of the generation of the frontal probability climatology, DND asked IML to generate a similar climatology for the region comprised between 30°-67°N and 180°-115°W. This work was completed in December 2012.
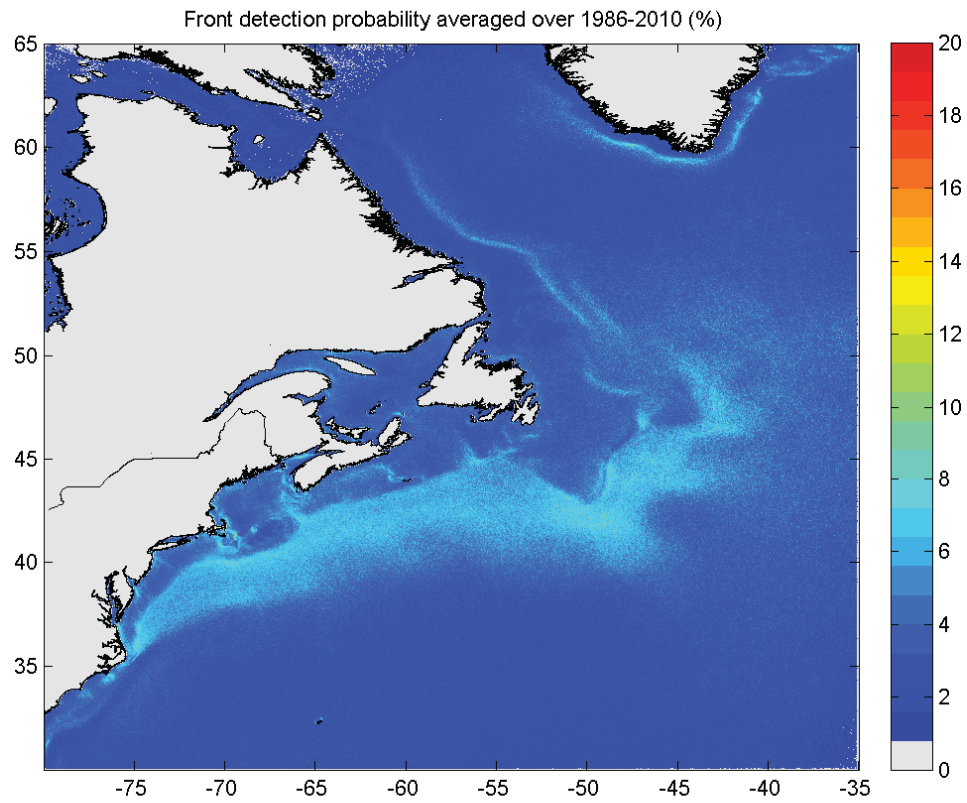
Figure 2 – 25-year (1986-2010) climatology of frontal occurrence probability over the eastern Canadian waters. Colors indicate % values.
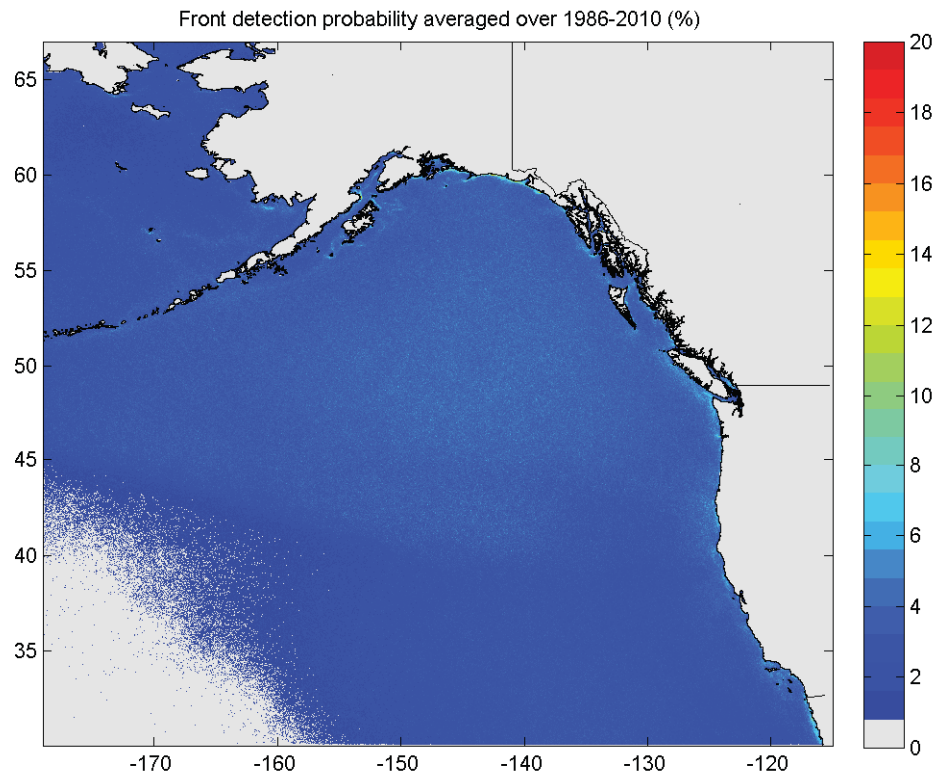
Figure 3 - 25 years (1986-2010) climatology of frontal occurrence probability over the western Canadian waters. Colors indicate % values.

2.2.3   WP 2 Final Observations and Recommendations

The synergy built during the SOIN project between IML and DND lead to significant accomplishments that helped develop the DND operational system to generate and process satellite images into good quality, higher level products. The products can now be fed into the MetOc centre's operational activities to support the mandates of the DND.

2.3   WP 3 SAR processor, IA Pro and CSIAPS

2.3.1   Work tasks

The purpose of WP 3 was to develop, build, and install a MetOc SAR processor, and to modify Image Analyst Pro (IA Pro) and the Commercial Satellite Imagery Acquisition Planning System (CSIAPS) to produce MetOc-specific versions of these tools, which were developed by DRDC Ottawa. IA Pro is a test bed and demonstration tool that assists in the visual interpretation of remote sensing imagery. Among other things, it provides capabilities to overlay multiple imagery sources and to locate and visualize target information. CSIAPS includes an imagery archive

component. The overall expected result of this work package was to have a MetOc-specific SAR processor / IA Pro and CSIAPS system integrated into MetOc Halifax operations by the end of SOIN Phase 1. WP 3 was comprised of the following tasks:

From SOIN Phase I [32] the Work Tasks were:

- WP 3.1 – Develop approach;

- WP 3.2 – Hire contractors and assign DRDC Ottawa staff;

- WP 3.3 – Recommend hardware for purchase by MetOc Halifax;

- WP 3.4 – Develop SAR automatic processor V1.0 & install at MetOc Halifax;

- WP 3.5 – Upgrade/modify and install IA Pro and CSIAPS data archive at MetOc Halifax;

- WP 3.6 – Produce shapefiles of bathymetric contours at depths of 30, 50, 100, 200, 500, 1000, 2000 metres;

- WP 3.7 – Interim status reviews for SAR-related work (WP 3 & 4);

- WP 3.8 – Develop specifications for the MetOc Halifax version of IA Pro;

- WP 3.9 – Evaluate RADARSAT-2 data within MetOc SAR processor; and

- WP 3.10 – Develop interim and final versions of MetOc-specific version of IA Pro.

From the SOIN Phase II proposal [35] the Work Tasks are (please note that the Phase II Work Task numbers have been revised from the original proposal so as to continue from the Phase I Work Task numbering system):

- WP 3.11 – Work Package management;

- WP 3.12 – Upgrade/modify and provide support for IA Pro and CSIAPS data archive at MetOc Halifax and MetOc Esquimalt;

- WP 3.13 – Improvements to SOFDT; and

- WP 3.14 – Improvements and upgrades to implementation of Dalhousie University statistical logistic regression model.

All work packages have been completed as of October 2012. The latest version of IA Pro was provided in October 2012.

2.3.2   WP 3 Overview

2.3.2.1   Synthetic Aperture Radar Ocean Feature Detection Tool (SOFDT)

One of the key DRDC Ottawa contributions to the SOIN project was the development of SOFDT. SOFDT is designed to provide the capability to auto-detect, geo-locate and classify specific ocean features such as thermal fronts, eddies, and water mass boundaries observed by SAR. Furthermore, the classification algorithm itself was researched and developed as part of the SOIN project [9], [10]. SOFDT is capable of processing RADARSAT-1/2 & ENVISAT ASAR image products. SOFDT generates geo-referenced MetOc products as a suite of *geotiff* and *Shapefiles*

that may be ingested and analyzed by IA Pro. The output MetOc products include radiometrically-balanced SAR images, a landmask, ocean feature detection products (including ocean feature masks and edge detection of SAR ocean features), a radar backscatter image, and SAR-derived wind field products. SOFDT is a near-real time processor capable of end-to-end processing in under two minutes with minimal operator involvement. SOFDT can be executed in either an *Operational Mode* or an *R&D Mode*. The Operational Mode is specifically designed for MetOc operations in order to minimize operator inputs, to maximize end-to-end processing speed, and to provide the necessary geo-referenced outputs. The R&D Mode is designed to allow the user to modify all input parameters and produce a full suite of geo-referenced outputs.
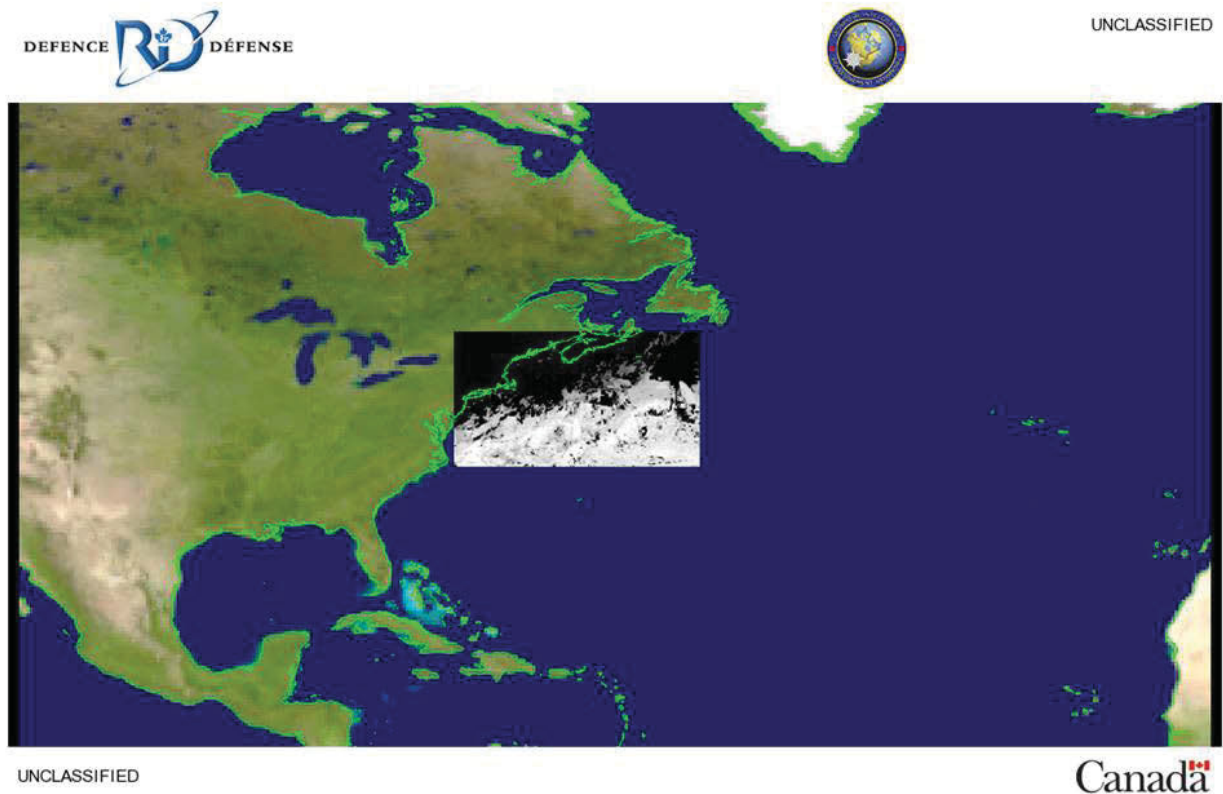
Figure 4 - Inset image is an AVHRR Sea Surface Temperature composite image acquired on September 15, 2008 that illustrates the MetOc Halifax AOI.

DEFENCE R&D DÉFENSE
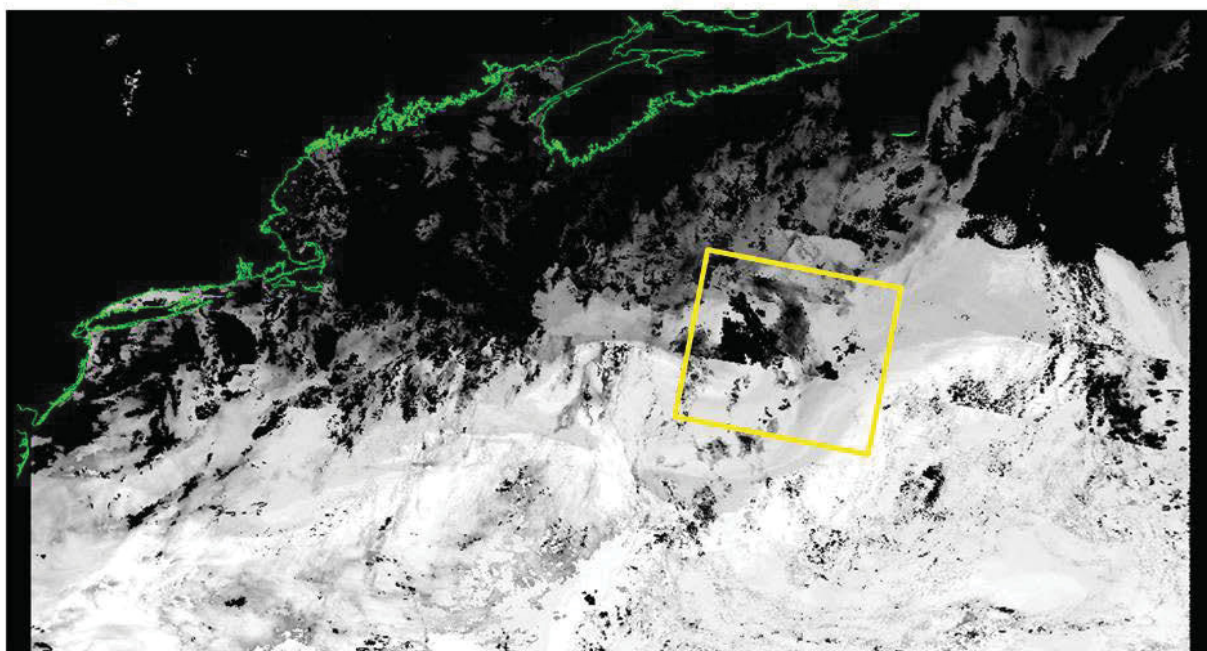
Figure 5 - Illustrates the full extent of the AVHRR Sea Surface Temperature composite image acquired on September 15, 2008. The yellow box shows the extent of the RADARSAT-2 image shown in Figure 6.
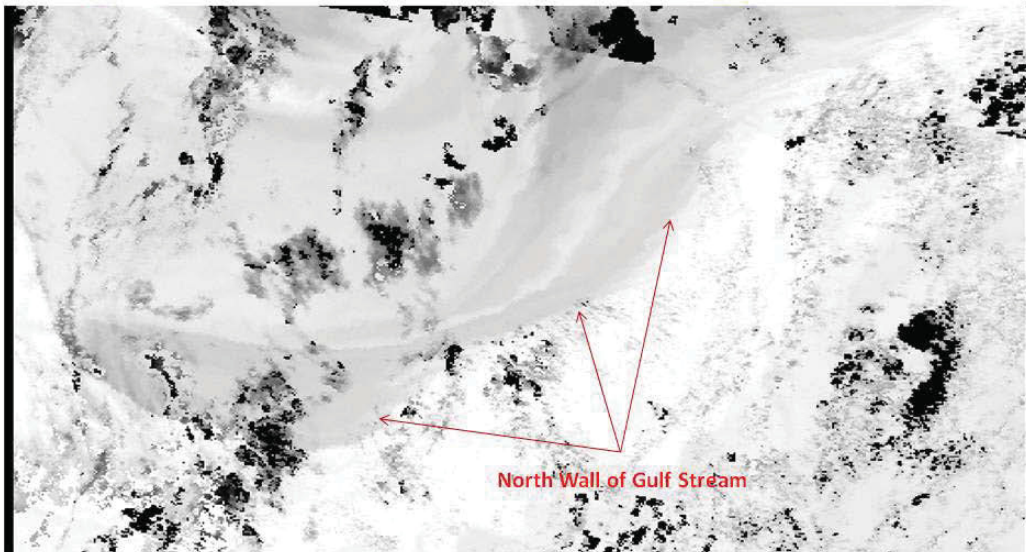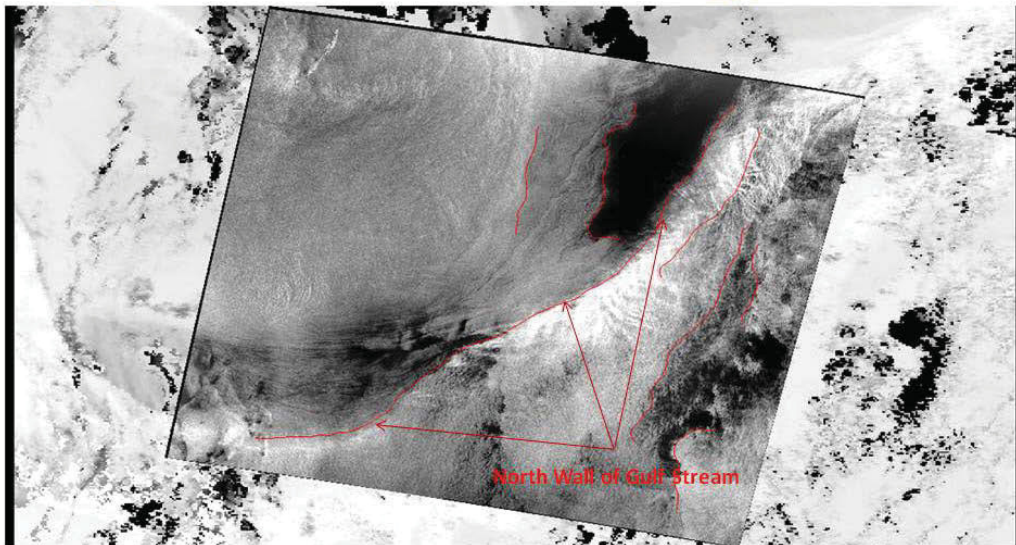
Figure 6 - Top image is a zoom of the AVHRR SST image and the bottom image has the RADARSAT-2 SCNB image overlaid onto the SST image with the SOFDT-detected and classified features (red=Sea Surface Temperature fronts). The long detected feature extending from the bottom-left to the top-right of the image is the north wall of the Gulf Stream. Both images were acquired on September 15, 2008. RADARSAT-2 Products © MacDonald, Dettwiler and Associates Ltd. (2008) – All Rights Reserved.
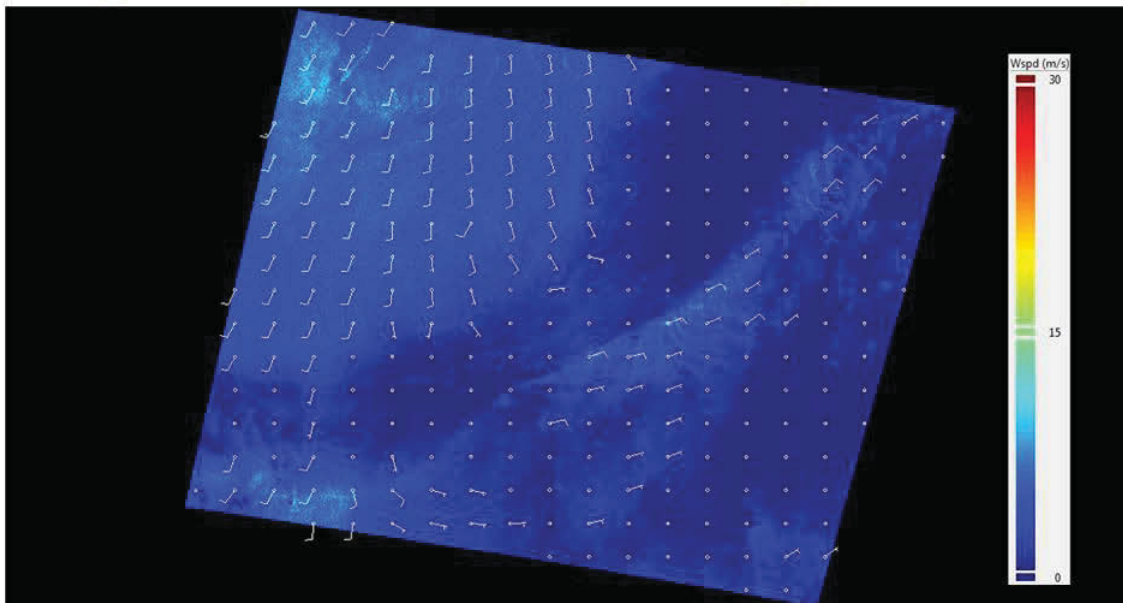
Figure 7 - The above image is the SAR-derived wind field product generated by SOFDT for the September 15, 2008 RADARSAT-2 acquisition.

2.3.2.2   Image Analyst Professional (IA Pro)

Another key component provided by DRDC Ottawa to the SOIN project is IA Pro. IA Pro has evolved extensively since the beginning of the SOIN project and has been improved to support SOIN and many other projects/requirements. A description of all IA Pro updates since the beginning of the SOIN project is beyond the scope of this document; however, the relevant SOIN-related IA Pro developments include the *Import Bathymetry Contours* tool, *Sea Surface Temperature (SST)* tool and *SOFDT*. All SOIN functional capabilities were integrated into the general IA Pro development stream. As such, IA Pro improvements made for the SOIN project are also available to other users (and vice-versa). The current, state-of-the-art, IA Pro V2.3, was provided to MetOc Halifax in October 2012 in both Linux and Windows built versions.
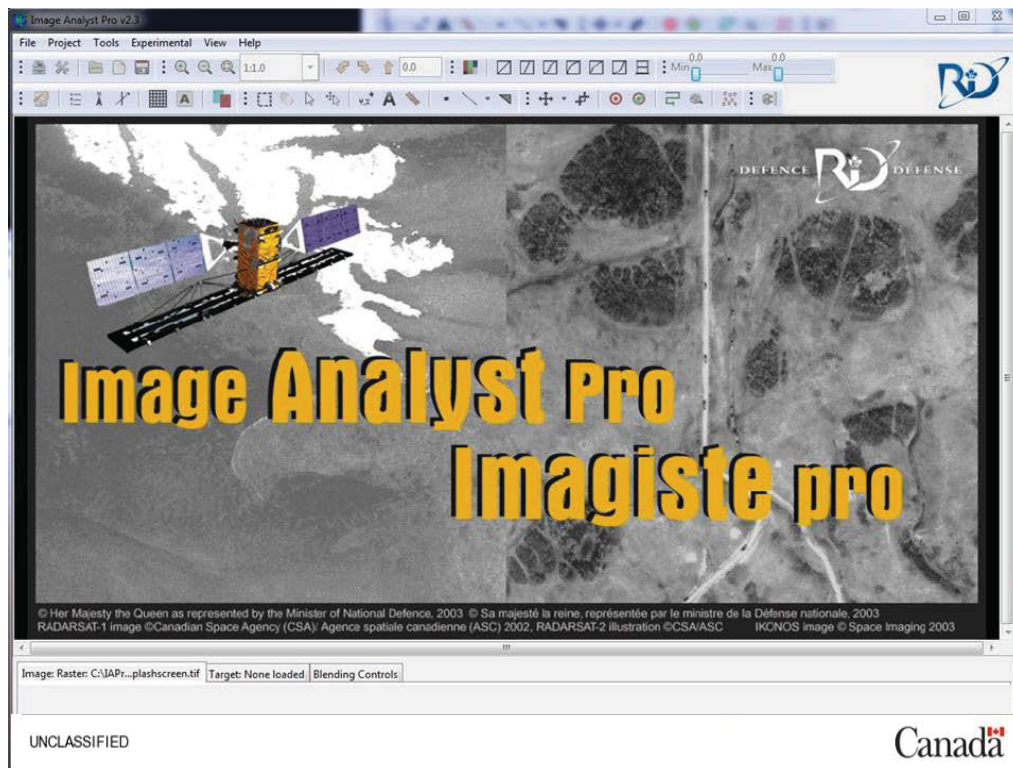
Figure 8 - Illustrates the main IA Pro GUI-interface.
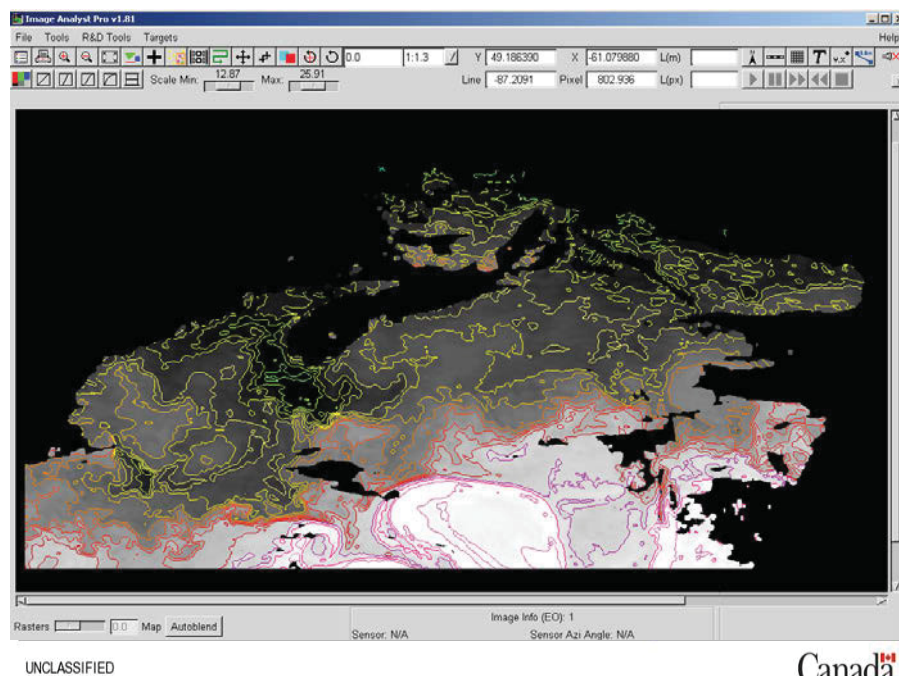
Figure 9 - SST median image and contouring results from a 7x7 median filter.
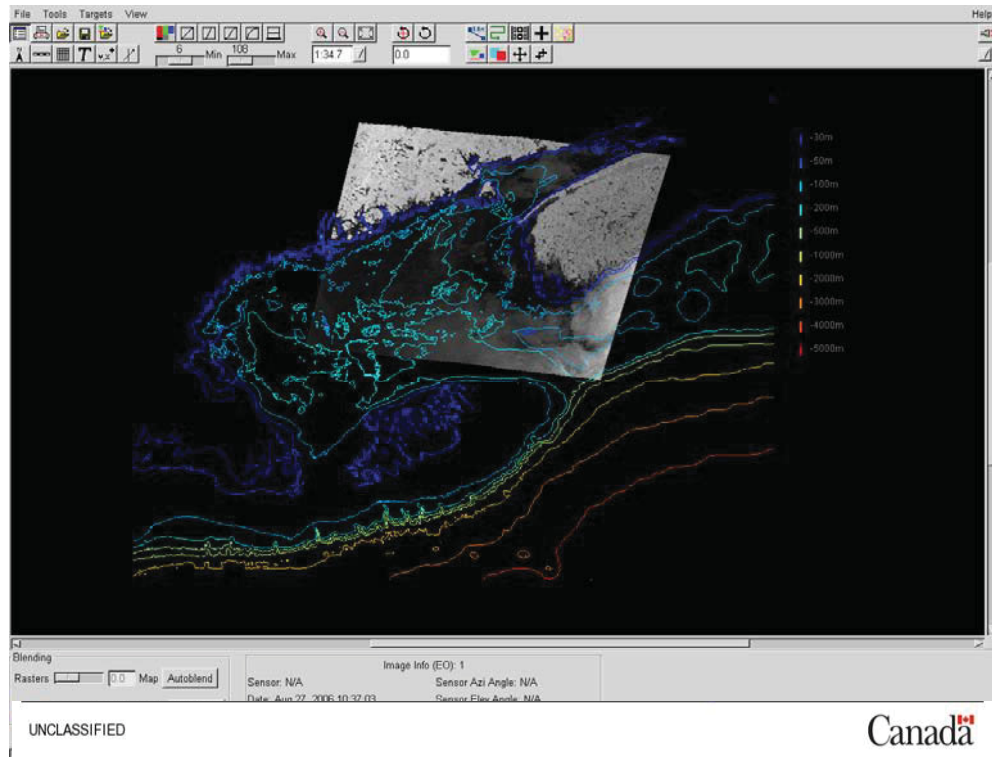
*Figure 10 – Visual output after loading bathymetry contours. RADARSAT-2 Products ©
MacDonald, Dettwiler and Associates Ltd. (2008) – All Rights Reserved.*

2.3.2.3   The Commercial Satellite Imagery Acquisition Planning System (CSIAPS)

CSIAPS continues to be upgraded and used extensively at DRDC Ottawa and other locations. To date, MetOc Halifax has not incorporated or made use of CSIAPS for SOIN.

2.3.3   WP 3 Final Observations and Recommendations

With the completion of SOIN, on operational capability to use RADARSAT-2 imagery to augment MetOc Halifax's Ocean Features Analysis (OFA) product is available. This permits use of RADARSAT-2 imagery to augment the traditionally-used Sea Surface Temperature during commonly occurring overcast and foggy conditions off the East coast of Canada.

In the future, it would be prudent to upgrade the SOIN infrastructure in preparation for the RADARSAT Constellation Mission (RCM). Of note, RCM will also offer operational Doppler anomaly products, which can be interpreted in terms of radial ocean current velocity. It is recommended that SOIN should routinely use the RCM Doppler anomaly product to generate an improved OFA products.

2.4   WP 4 Ocean features from SAR

2.4.1   Work tasks

The focus of WP 4 was to develop the means to routinely detect the north wall of the Gulf Stream plus associated eddies and fronts, using spaceborne SAR. WP 4 was comprised of the following tasks:

From SOIN Phase I [32] the Work Tasks were:

- WP 4.1 – Develop approach and work plan;

- WP 4.2 – Identify and secure auxiliary data sources;

- WP 4.3 – Order RADARSAT data;

- WP 4.4 – R&D on SST front indicators in SAR that are associated with marine atmospheric boundary layer (MABL) phenomena;

- WP 4.5 – Integrate auxiliary surface current data;

- WP 4.6 – Conduct field trial.

From the SOIN Phase II proposal [35] the Work Tasks are (please note that the Phase II Work Task numbers have been revised from the original proposal so as to continue from the Phase I Work Task numbering system):

- WP 4.7 – Work Package management;

- WP 4.8 – Develop MABL approach & work plan to positively identify meteorological and oceanographic features;

- WP 4.9 – Investigate the use of CODAR surface currents in discerning between meteorological and oceanographic features; and

- WP 4.10 – Integrate auxiliary surface current, SST and meteorological data.

2.4.2   WP 4 Overview

The WP 4 team used the polarimetric properties of RADARSAT-2 SAR, co-located with in-situ data, to develop new algorithms for the retrieval of marine winds, waves, detection of crude oil spills on the ocean surface, sea surface temperature fronts and the detection of other features such as man-made objects. Many of these results were not possible with RADARSAT-1 data, and those that were certainly were not achievable to the same extent as they can be with RADARSAT-2.

The CODAR portion of the project was abandoned after a thorough analysis by BIO and the Project Management Team. It was decided the resources available were insufficient in addressing their use in discerning between meteorological and oceanographic features. As well, the Canadian Coast Guard was no longer able to support the network of CODARs installed in south

west Nova Scotia, and there were some concerns about how CODAR would be funded after the project.

2.4.2.1 Retrievals of Sea Surface Temperature Fronts from SAR Imagery

References [12] and [38] presented a new methodology to identify SST fronts of the Gulf Stream, using linear relationships between SST gradients, and the curl and divergence of wind stress fields, derived from km-scale resolution SAR data. The new approach used a composite metric determined from the wind stress divergence and curl fields from individual SAR images. Multi-stage spatial filtering, Wiener and Gaussian low-pass filters, and a statistically-based high pass spatial filter were applied to the derived wind stress curl and divergence fields. The results showed significant improvement by restricting SAR imagery to cases where the wind speed was less than 12 m/s, thus removing strong wind shear fronts. The method was demonstrated with SAR images of the Gulf Stream and has the potential to be applied in near-real time operations. The advantages of SAR over optical sensors are its independence of cloud or night, and its high accuracy. For demonstration purposes, the retrieval methodology was applied to 45 SAR images in the Gulf Stream region. Since it was difficult to find collocated, cloud-free, single-pass SST images from MODIS and AVHRR data, some cases used a 3-day or 7-day averaged SST data to validate the location of the detected SST front features. Figure 11 shows the detection results for four of these cases, with detected thermal fronts from SAR (black), overlaid on SST features. Because of the shift of the Gulf Stream, there is some inaccuracy in the averaged, blended SST images. Results indicate that although this method cannot detect *all* the thermal fronts, for these four cases, more than 95% of the SAR-detected fronts in each case are thermal fronts. It is clear that there is not a total correspondence between the blended SST front features and the SAR-derived thermal fronts. This may be due to strong, distorting small scale (~1 km) features in the SAR images, noise, or competing ocean processes. Some SST fronts cannot be retrieved because of SAR limitations, e.g., high winds or rain.

2.4.2.2 Cross-Polarized SAR: New Potential Measurement Technique for Hurricanes

In references [41] and [42], the empirical C-band Cross-Polarization Ocean backscatter (C-2PO) model for wind retrievals was developed and applied, which included hurricane-force winds, from RADARSAT-2 SAR data. The C-2PO model relates normalized radar cross section in cross-polarization mode to the wind speed at 10-m height. C-2PO is remarkable because it is independent of SAR radar incidence angles or wind directions but is extremely linear with respect to wind speeds, especially for high winds. To test the accuracy of C-2PO, winds with resolution ~1 km were retrieved from a dual-polarization SAR image of Hurricane Earl acquired on September 2, 2010; the C-2PO model results with compared with those of CMOD5.N, the newest available C-band geophysical model function, and validated with the "truth", namely collocated airborne Stepped Frequency Microwave Radiometer (SFMR) measurements and National Data Buoy Center (NDBC) data. Results suggest that for winds up to 38 m/s, C-2PO has a bias of -0.89 m/s and a root mean square error (RMSE) of 3.23 m/s, compared to CMOD5.N, with bias of -4.14 m/s and RMSE of 6.24 m/s. Another remarkable thing about C-2PO is that it does not seem to saturate under high winds and reproduces the hurricane eye structure rather well, which was not the case for RADARSAT-1 SAR ([24], [25]), thereby providing a promising new technique for hurricane observations from space. Figure 12 presents some of the comparison results.
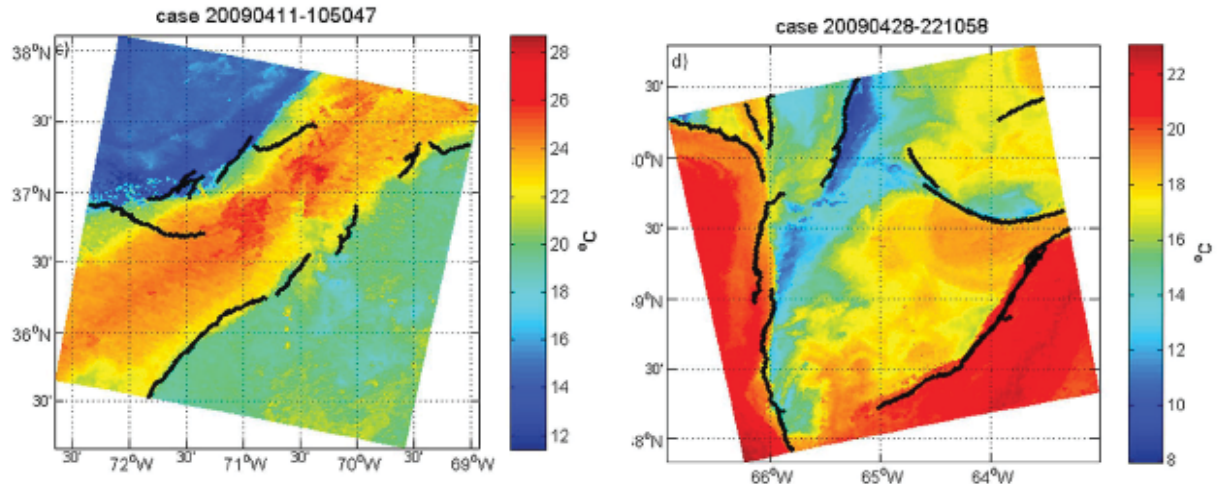
Figure 11 - Detection of SST thermal fronts from variation in wind stress divergence and curl from SAR (black), overlapped on blended SST data (background image): (left panel) 10:50:47 UTC on 11 Apr. 2009 with 3 days averaged SST data, and (right panel) 22:10:58 UTC on 28 Apr. 2009 with blended SST data 4 hours later.
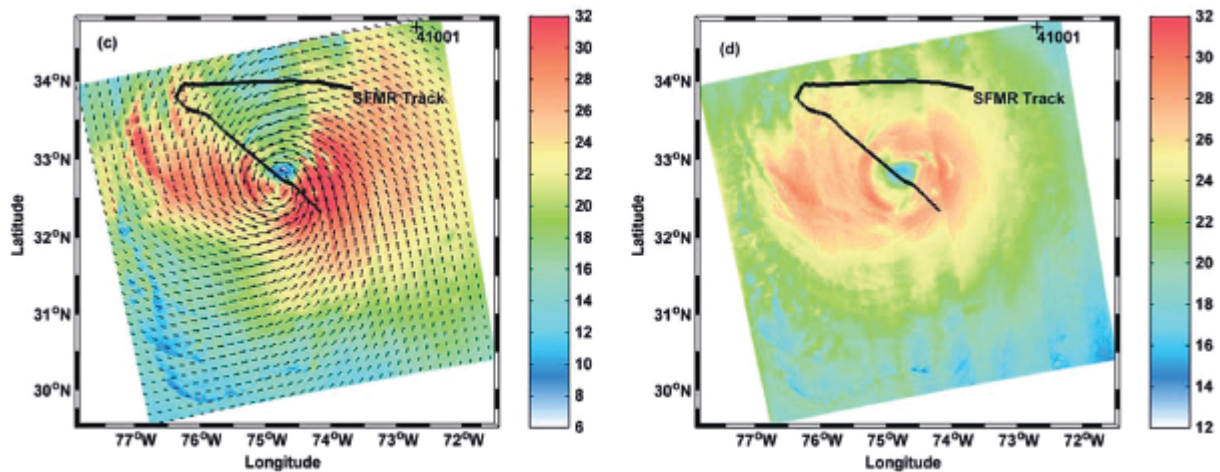
Figure 12 - RADARSAT-2 dual-polarization SAR image acquired over Hurricane Earl at 22:59 UTC on September 2, 2010. SAR-retrieved wind speeds from (left panel) the CMOD5.N model and σ_{VV}^{0}, with external wind directions from NOAA HRD H*Wind are overlaid, and (right panel) from the C-2PO model and σ_{VH}^{0}. Colorbar shows wind speeds (U_{10}) in m/s. Note saturated areas in CMOD5.N.

2.4.2.3   Target detection on the ocean with compact polarimetric SAR

In terms of ocean surface features, it is always important to recognise other features, such as manmade objects. In reference [17], the WP 4 Team explored the potential for automatic ocean surveillance using compact linear polarization (CL-pol) SAR, which will be available on RCM (RADARSAT Constellation Mission) with large area coverage. In this study, the target was a

wind farm in the North Sea. The relative phase, as derived from CL-pol SAR, was used to detect the wind turbines, apart from their wakes, based on fine mode quad-polarization RADARSAT-2 SAR images. The relative phase of CL-pol measurements improved the contrast between the wind turbines and their wakes, because it had opposite signs for these two entities. Moreover, there was almost no variation in the relative phase with respect to wind speed or incidence angle. The results were verified by high sea state cases, up to 8.7m significant wave height and 24.3 m/s wind speed, and also 641 quad-pol RS-2 SAR images collocated with 52 NDBC buoys at different incidence angles and sea states. Thus, the relative phase of CL-pol SAR gives new light to operational auto-detection of man-made targets, under high sea state conditions, over large areas. Figure 13 is a photograph of the wind farm, and Figure 14 shows the detected targets in analyzed SAR imagery.

Figure 13 - North Sea wind farm Alpha Ventus (http://www.alpha-ventus.de), showing platform FINO 1.
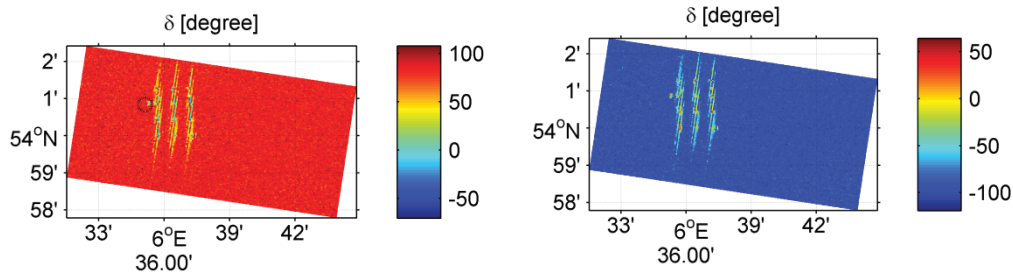
Figure 14 - For SAR image at 05:40 UTC on 8 April 2011: left and right panels give the SAR-derived relative phase δ of RCTLR and LCTLR results. The platform FINO 1 is indicated by the circle.

2.4.2.4 Ocean vector winds retrieval from fully polarimetric SAR

Retrieval of wind information from SAR has always been difficult because wind direction is not easily provided by the SAR image and usually is derived from separate sources which are not often reliable at the fine-resolution of SAR-derived winds ~ 1 km. Reference [43] determined vector winds from SAR, both wind speed and direction, using fully polarimetric SAR measurements based upon the co-polarized geophysical model function, CMOD5.N and the previously reported cross-polarized ocean backscatter model, C-2PO. Analysis of fine quad-polarization mode single-look complex SAR data and collocated *in-situ* moored buoy

observations showed that the polarimetric correlation coefficient between co- and cross-polarization channels had an odd symmetry with respect to the wind direction. This characteristic was different from the feature that normalized radar cross sections for quad-polarization have given their symmetry regarding the wind direction – a key observation. The C-2PO model was used first to directly retrieve wind speeds without any external wind direction and radar incidence angle inputs. Subsequently, the retrieved wind speeds, along with incidence angles and CMOD5.N were employed to invert the wind direction, still with ambiguities. The odd symmetry property was then applied to remove the wind direction ambiguities. Thus, the polarimetric SAR measurements were used to get complementary directional information for the ocean surface winds. This method has the potential to improve wind vector retrievals from space. As an example, Figure 15 presents SAR- retrieved vector winds, in comparison with buoy-measured winds.
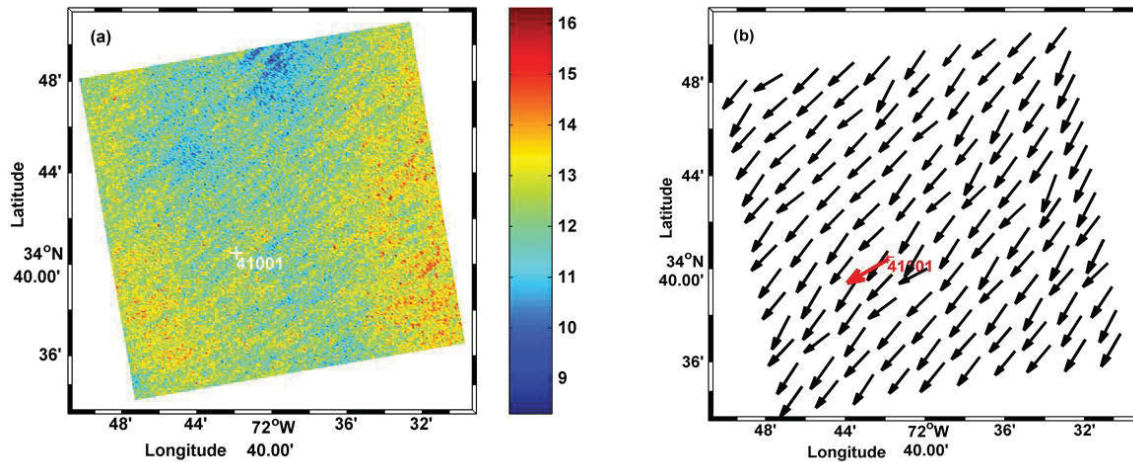
Figure 15 - SAR-retrieved wind speeds from C-2PO model and VH-polarized SAR image (left panel) without external wind direction and radar incidence angle inputs, and (right panel) SAR-retrieved wind directions without ambiguities: from polarimetric correlation coefficient between VV and VH channels, C-2PO-retrieved wind speeds, CMOD5.N and VV-polarized SAR image, and radar incidence angle.

2.4.2.5   Oil spill monitoring

Besides manmade objects, surfactants, including crude oil are sometimes present on the ocean surface. Before it can be ascertained that SST thermal fronts are being observed, the SAR signature of crude oil must be determined. Numerous images of areas where known oil seeps are supposed to occur in the Arctic were collected and archived, and then analyzed to determine the presence of oil slicks. Next, algorithms were tested on oil seeps in the Gulf of Mexico [41]. Polarimetric SAR decomposition parameters were used, with an average alpha angle $(\overline{\alpha})$ and entropy (H) for oil-slick contaminated sea surfaces and slick-free conditions using a RADARSAT-2 quad-polarization SAR image. This method showed potential for operational determination of oil slicks in Arctic waters. Examples are shown in Figure 16.
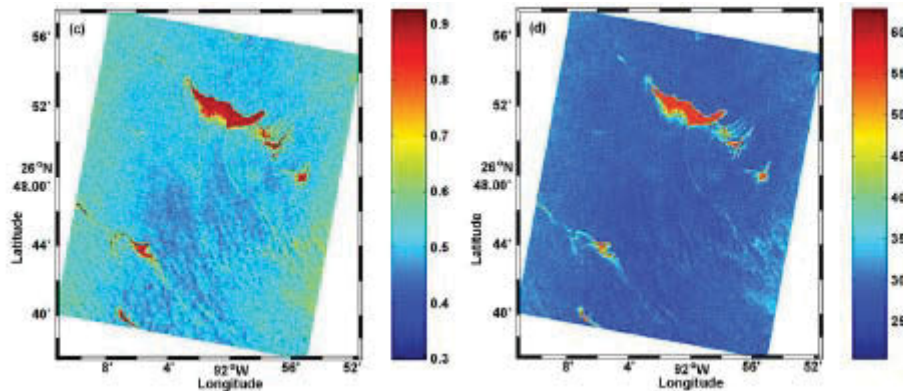
Figure 16 - C-band SAR image of sea oil slicks in the Gulf of Mexico from RADARSAT-2 quad-polarization data acquired on May 8, 2010, showing: Left: entropy H; and Right: average alpha angle, $\overline{\alpha}$.

2.4.3 WP 4 Final Observations and Recommendations

2.4.3.1 Mechanisms for thermal fronts, frontal jets, ocean currents

It is widely accepted that given an unstable marine atmospheric boundary layer, the wind speed is enhanced on the warm side of the thermal front and thus results in bright bands in remotely sensed SAR (synthetic aperture radar) images. However, sometimes dark bands can be detected on the warm side of the thermal front in some anomalous SAR cases, which might seem confusing. These are comparatively weak backscattering areas. An example is shown in Figure 17.

It is therefore suggested that this weak backscattering in SAR images might be induced by nonlinear Ekman current divergence occurring in the frontal jet region, which can modulate the short-wave roughness. The WP 4 Team is investigating cases where relatively high winds are parallel to the front (hereafter termed "down-front"), and the nonlinear effects of Ekman transport induce different transport rates on either sides of the Gulf Stream frontal jet. Consequently, the resulting strong surface current gradient can cause a decrease in the sea surface roughness owing to the interactions of the current and short capillary waves. A primitive ocean model is being used along with scatterometer wind observations to look for the maximum current divergence, to see if it corresponds to sharp decreases in backscatter intensity in SAR images, over the warm frontal region, and to investigate the mechanism.
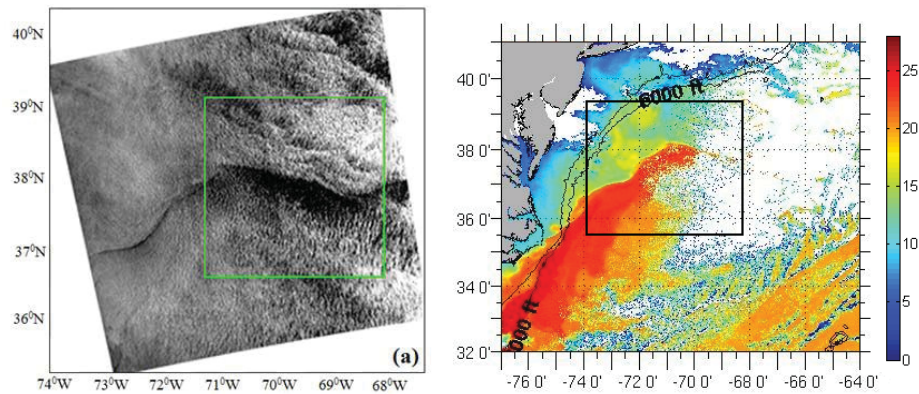
Figure 17 - (a) RADARSAT-2 SAR image at 22:28 UTC on 30 January 2012 of the Gulf Stream region, and (b) associated sea surface temperature from NOAA-16 at 00:11 UTC on 31 January 2012.

2.5   WP 5 SOIN compatible Ocean Workstation

2.5.1   Work tasks

MetOc Halifax uses the Ocean Workstation (OWS) to produce their operational Sea Surface Temperature (SST) and Ocean Feature Analysis (OFA) product. The OFA is one of MetOc Halifax's primary oceanographic products. It is produced twice weekly (Tuesday and Friday) and provides the ocean conditions (SST and watermass boundaries) within the Maritime Forces Atlantic (MARLANT) Area of Responsibility (AOR). The OFA is used primarily to determine impacts on acoustic propagation for anti-submarine warfare.

The purpose of WP 5 was to integrate MetOc Halifax's existing OWS with SOIN-related data outputs. Work in FY 09/10 had planned to include further development of the OWS to integrate ocean features detected in SAR imagery by IA Pro. WP 5 was comprised of the following tasks:

From SOIN Phase I [32] the Work Tasks were:

- WP 5.1 – Integrate MetOc Halifax auxiliary data from C-APS into the OWS;
- WP 5.2 – Integrate C-APS and SAR processor; and
- WP 5.3 – Staff training.

From the SOIN Phase II proposal [35] the Work Tasks are (please note that the Phase II Work Task numbers have been revised from the original proposal so as to continue from the Phase I Work Task numbering system):

- WP 5.4 – Work Package management;
- WP 5.5 – Automatically ingest RADARSAT-2 fronts and eddies into OFA;
- WP 5.6 – Upgrade OWS software, deliver and install at MetOc Esquimalt;

- WP 5.7 – Conduct staff Training on ingesting RADARSAT-2 features; and

- WP 5.8 – Define best way to represent non-thermal fronts in OFA.

2.5.2 WP 5 Overview

JASCO Research Ltd. enabled the existing ocean workstation at MetOc Halifax able to ingest APS SST output in Shapefile format, a capability that was created in IA Pro by DRDC Ottawa. MetOc Halifax ocean personnel now use this capability in the bi-weekly production of the Ocean Features Analysis chart, which has enhanced their productivity and reduced MetOc Halifax reliance on third party data sources. The work also involved conducting a comprehensive analysis of the existing OWS system and software application.

In 2007-8 SOIN-related equipment was installed at MetOc Esquimalt by MetOc Halifax personnel during a week-long visit to their offices. IA Pro and C-APS were installed, configured, and tested, and MetOc Esquimalt staff was trained in their use and operation. MetOc Esquimalt personnel were also authorized as RADARSAT-2 users. Training was conducted using the Radarsat planning software and the NEODF website for submitting and downloading RADARSAT-2 orders. A west coast SOIN region for ordering RADARSAT-2 data was identified, and was taken into consideration for order de-confliction by the EMOC group. MetOc Esquimalt cooperated closely with IOS and ASL Environmental in ordering RADARSAT-2 imagery for use in the SOIN project.

With respect to WP 5.7 (Training) the intent was to develop basic IA Pro training packages for MetOc Sonar Operators using existing project resources as no funding was allocated to this task. Chris Jones of Dalhousie University volunteered to address the requirement, and to that end he created training packages for training Sonar Operator staff at MetOc Halifax, an example of which can be found in Annex D. The training packages consist of:

- Participants receiving instruction in the standard operational procedure for the production of R2 images with classified Canny edges using IA Pro, and in the incorporation of R2 SST front signatures into the OFA (Richard Wood); and

- Participants receiving instruction on the manual recognition of classes of signatures including those of Gulf Stream features and various atmospheric processes. This will include case studies to demonstrate a standardized sequence of steps for the analysis of an R2 image with classified Canny edges yielding an R2 image with Gulf Steam features marked. (Chris Jones, half-day plus follow-up).

The half-day training course includes the following modules:

- Basics of ocean SAR, including a description of how SST front signatures are produced in an R2, image and the different types of R2 images available (beam modes);

- Common Gulf Stream features, including conceptual diagrams showing the features (meanders and their components, warm-core rings), and a comparison of R2 and SST imagery of real examples;

- Common atmospheric signatures, such as atmospheric gravity waves, small- and large-scale cell convection, squall lines, and atmospheric fronts; and

- Image Analysis.

In the fourth training module a standardized series of steps to follow when analyzing an R2 image for Gulf Stream features will be introduced and used to analyze a series of case studies. By this means, participants will gain a basic proficiency in signature recognition and will understand how to apply the standardized approach to image analysis. Follow-ups will take place on designated days after the training, during which Chris Jones will observe the data flow from R2 image to OFA to assess the participant's proficiency in identifying Gulf Stream features in the R2 images.

The standardized image analysis will include a written form to keep as a record of the analysis results. This will be used to retrospectively assess the analyst's proficiency, and also will provide a means of compiling data for future studies. The information to be retained will be carefully considered, and will be re-assessed during the follow-ups to ensure that everything that may be useful in a future study is properly documented and archived.

2.5.3   WP 5 Final Observations and Recommendations

The main goal was to implement WP 5.7 and WP 5.8, which was somewhat dependent on results from WP 8. As the automatic detection algorithm improves and evolves within IA Pro, that will give MetOc Halifax a good indication as to the level of operator intervention required to discriminate fronts, and the level of training required will become clearer.

2.6   WP 6 West Coast Ocean Features

2.6.1   Work Tasks

WP 6 was built upon previous GRIP-funded research led by Richard Thomson of the IOS and Gary Borstad of ASL Environmental Sciences, Inc. where they investigated the use of EO imagery for fisheries and seabird applications on the west coast of Canada. In 2009-10, the group began to examine the detection of ocean frontal features in RADARSAT imagery, and in 2010-11 they joined the SOIN project to continue their research as part of a Canada-wide initiative. The stated goals of WP 6 included the:

- Completion and application of the EO-based biophysical analysis tools begun under previous GRIP projects; and

- Use of IA Pro, along with the "Belkin" and other algorithms, to begin the detection and analyses of ocean fronts and associated chlorophyll signatures off the west coast.

The RADARSAT detection algorithms contributed to a more general initiative for linking physical oceanographic features, such as fronts, to biological productivity in British Columbia coastal regions. The new satellite work involved comparisons of thermal and ocean colour fronts against wind conditions on the British Columbia coast in order to determine likely constraints for users of radar products to map ocean fronts in the region. Numerical modeling of the ocean circulation and water property structure developed for the west coast under separate research programs was compared to fronts defined by satellite imagery and in situ oceanic data in order to develop a preliminary understanding of the physics of frontal formation off coastal BC. Results

allowed for the linkage of observed frontal features to coastal dynamics and biological processes, and provided enhanced tools for frontal detection using colour, thermal, and modeling specific to the BC coast. Through cooperation with DND, DRDC, and the Canadian Ice Service (CIS), frontal mapping RADARSAT algorithms for operational use were improved and maps of oceanographic fronts for BC coastal waters were produced using radar to supplement thermal and visible EO-based products. SOIN funding also enabled the conduct of studies that related frontal features to fish productivity statistics and known seabird aggregations for the northeast Pacific. Measurable outcomes included interim and final reports, draft versions of primary scientific manuscripts, algorithms for mapping fronts in SST, colour and radar imagery, maps of seasonal fronts off BC and links to possible oceanic processes, and comparison of frontal variability to fishery and seabird populations for the northeast Pacific.

The first Work Task addressed aspects of previous work that were relevant to the current front detection project, including determination of the background climatology (canonical annual cycle) and possible long term trends in west coast properties as observed in EO imagery. The remaining Work Tasks involved new work related to front detection in west coast RADARSAT imagery.

From the SOIN Phase II proposal [35] the Work Tasks were:

- WP 6.1 – Report on West Coast oceanography as observed from EO imagery;

- WP 6.2 – Modify IDL code for Belkin O'Reilly algorithm. Install and test IAPro v2.0.1;

- WP 6.3 – Assemble and process RADARSAT, chlorophyll and SST imagery for analysis; and

- WP 6.4 – Compare fronts in SST, chlorophyll and radar imagery. Determine radar detectability with wind speed and front gradient magnitude.

2.6.2   WP 6 Overview

The goals of WP 6 were (1) to develop and apply RADARSAT-based ocean feature detection algorithms for west coast waters, and (2) to contribute to a more general initiative to link physical oceanographic features, such as fronts, to biological productivity in British Columbia coastal regions. The work compared thermal and ocean colour fronts detected on the British Columbia coast with corresponding radar-derived fronts for given wind conditions in order to determine constraints on the use of radar products to map ocean fronts in the region. Frontal features were important components of BC coastal dynamics and biological processes. Although the features were well mapped by optical and thermal imagery, the region was and is notoriously cloudy, thereby limiting the usefulness of the imagery. Satellite radar offered the possibility of all-weather imaging. SOIN funding also enabled IOS to conduct studies that related frontal features to fish productivity statistics and to known seabird aggregations for the northeast Pacific. In addition, spatially averaged chlorophyll time series developed during SOIN were used to link interannual variations in the timing of the spring transition off the BC coast – the transition from down-welling favourable to upwelling favourable ocean conditions – to corresponding changes in phytoplankton, zooplankton, and juvenile fish production.

2.6.2.1 Front detection

2.6.2.1.1 Datasets and Tools

IOS/ASL matched satellite datasets of SST (from AVHRR or MODIS) and chlorophyll (MODIS or MERIS) acquired from NOAA and NASA, with RADARSAT-1 and 2 and ENVISAT ASAR imagery obtained from CCRS. Large numbers of SAR images were screened in order to find low wind scenes that matched cloud-free SST and colour imagery in separate archives. Comparisons were limited by infrequent matchups of SAR, SST and chlorophyll imagery, by the limited coverage of the study area, by cloud cover blocking optical and thermal imaging, and by the presence of non-ocean features in the SAR imagery.

The Belkin O'Reilly algorithm for front detection [3], the Canny edge detector in PCI Geomatica and the IA Pro front detector were tested. Frontal features from MERIS chlorophyll and SST image data were calculated using the Canny edge detector in PCI Geomatica, and then they were directly compared to results from IA Pro SST, chlorophyll and SAR imagery. Six-hourly NARR (North American Regional Reanalysis) wind data were used as input to the SAR processing using SOFDT in IA Pro.

IOS/ASL found that SOFDT was a convenient tool for the analysis of SAR imagery and it greatly improved during SOIN. They noted that de-trending of SAR imagery sometimes removed real onshore/offshore trends. This removal appeared to depend on the location of the scene coverage relative to the coastline. Because the de-trending was broad in scale whereas fronts were highly localized, the impact of de-trending was primarily on visualization and not on front detection. The wind direction was a critical parameter for detection and classification of fronts in SOFDT. If wind direction was erroneous, then both front detection and front classification were affected. IOS/ASL found that NARR winds were more reliable than Blended SeaWinds. They also found that the calculated winds often did not reflect the smaller wind features seen in the imagery near the coast [18] and that radar derived winds were less accurate within 100 km of the coast.

2.6.2.2 West coast ocean fronts observed by SAR

IOS/ASL found some recognizable fronts and other ocean features in SAR imagery off British Columbia but only when winds as reported by SOFDT were below 5m/s – in fact, mostly between 1 and 3 m/s. However, there were many false positives at these low wind speeds since no Bragg waves were formed under calm conditions and the signal was reflected away from the radar. Such low wind speeds (< 3m/s) were rare on the west coast in winter, but increased to about 30% probability in certain areas of the BC coast in late summer and fall [4]. Their findings suggested a lower wind threshold than observed elsewhere. A 2004 summary of many similar studies [8] reported that currents and fronts were detected by SAR imagery at wind speeds of 3 to 10 m/s.

Although IOS/ASL had not verified the SOFDT wind speeds *vs* buoy data, they hypothesize that the relatively low wind threshold was because the fronts on the BC coast were generally weaker than those elsewhere. RADARSAT could see certain strong fronts like the north wall of the Gulf Stream and those around Georges Bank up to wind speeds of 8-14 m/s [32]. At the semi-permanent north wall of the Gulf Stream, SST gradients can be as much as 2°C/km and the wind speed is accelerated over these strong fronts making them more visible to radar via increased

ocean roughness [12],[27] [28]. By contrast, coastal SST fronts off the BC coast are much weaker and more dynamic. The Vancouver Island Coastal Current and Shelf Break Current, which dominate the surface flow structure off Vancouver Island, are highly variable and frequently breakdown as the winds strengthen and weaken on a daily to weekly basis. The flow structure is also often disrupted by remotely forced coastally trapped waves originating to the south [6], [39]. Because the near surface thermal contrast in the northeast Pacific are weak, the winds are not constrained to be along-front as they are at strong fronts like those that form the Gulf Stream wall. Ocean frontal thermal gradients off British Columbia are usually at or below 0.5 °C/km and are sometimes detectable under low wind conditions, but they found examples of stronger fronts that were not detectable in SAR imagery even though winds were low. Similarly, most of the coastal fronts off Maine and Nova Scotia are less than about 0.5 °C/km and were not seen by RADARSAT [32]. West coast water masses were sometimes defined as well by chlorophyll as by SST, which was not surprising given that the biology and physics are tightly linked (Figure 18).
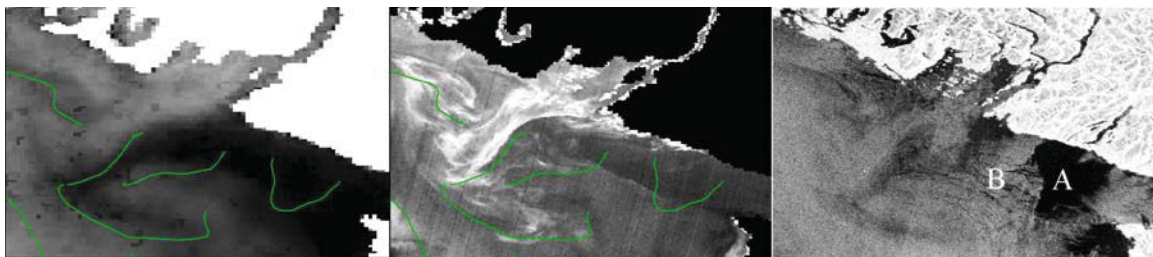
Figure 18 - Comparison of SST, Chlorophyll and ASAR imagery (with the position of the SAR fronts longer than 20 km marked on the SST and Chl images) for September 4, 2011.

IOS/ASL often saw slicks in low wind SAR images, and the pattern of low SAR returns in the vicinity of high chlorophyll patches suggested that they were sometimes due to slicks resulting from organic release associated with biological production. Their pattern often suggested the direction of water movement (see B in Figure 18), but they did not usually appear to delimit the water mass; i.e., slicks did not directly detect the *front* between the high and lower chlorophyll water types. Figure 18 provides an example from September 4, 2011 where some, but not all of the SST and chlorophyll frontal features, were visible in the coincident ASAR scene. SAR features like "A" in Figure 18 do not have matching SST or chlorophyll manifestations and must be related to very low wind speeds. There are also SST and chlorophyll fronts that do not appear in the ASAR scene.

2.6.2.3 Physical and biological processes off British Columbia and Links to frontal features

Several fisheries studies based on GRIP and SOIN derived satellite datasets have now been published and several others are in preparation. One paper [30] used EO products developed under SOIN to establish links between variable ocean conditions and the timing of returning fish stocks, suggesting that the earlier than normal river entry of Late-run Fraser River sockeye salmon that began in the mid-1990s is linked to changes to weaker than normal surface currents in the Gulf of Alaska and to lower than normal surface salinities along the coasts of British Columbia and Alaska. A second paper **Error! Reference source not found.** used chlorophyll time series generated during SOIN for the Strait of Georgia and Queen Charlotte Sound to help

show that the record low returns of sockeye salmon to the Fraser River in 2009 (the reason for the ongoing Cohen Commission) may have been due to poor early marine survival of juvenile sockeye salmon in 2007. The poor survival was likely due to low food levels (low chlorophyll) arising from unfavourable wind and runoff conditions in the Strait of Georgia and the Queen Charlotte Sound-Hecate Strait region in the spring of 2007.

A third paper conducted as part of the SOIN program [4] relates seabird biology to the oceanography of the central BC coast, using satellite data time series of sea surface temperature, chlorophyll, and winds. Colonial seabirds are excellent indicators of ocean conditions. Results show that rhinoceros auklets at the Triangle Island colony breed more successfully when the spring transition in regional winds and the resulting spring phytoplankton bloom occur early in April. These factors appear to control the annual recruitment (and amount in the diet of the auklet chicks) of Pacific sandlance *Ammodytes hexapterus.* Marine survival of economically and culturally important sockeye salmon from nearby Smith Inlet was also strongly correlated with auklet success, sandlance in the chicks' diets, and regional chlorophyll in April and imply bottom-up physical control of this ecosystem. By comparing at-sea bird observations with coincident EO imagery [30], we have also showed that these and other seabirds congregate at ocean fronts with more and larger congregations at stronger chlorophyll gradients.

SOIN funded EO chlorophyll data products were also used to show that spawning by herring in the Strait of Georgia is closely linked to the annual plankton production cycle. As in the case of the seabirds, the match (or mismatch) between egg deposition and the initiation of the spring plankton bloom has a substantial impact on survival and production of young of the year (YOY) herring [21].

The ocean colour and thermal datasets derived as part of WP 6 of the SOIN program are currently being processed for possible publication in a peer-reviewed journal. Focus is on the background statistical properties (means, variance, and canonical annual cycles), interannual variability (including extreme years), and possible long-term climate-scale trends for the west coast of North America, in the region extending from the western Aleutian Islands to central Baja California.

SOIN-funded data products also have been distributed to fisheries biologists at the Pacific Biological Station (Nanaimo) studying the survival of west coast salmon smelts (Godbout, Irvine and Trudel pers. comm., 2012) and the survival of juvenile Fraser River sockeye salmon progressing northward through Queen Charlotte Sound (Irvine and Trudel pers. comm., 2012). EO imagery is being combined with other physical data available for the northeast Pacific to investigate the role of ocean conditions on the return migration of Early Stewart and Chilko Lake sockeye salmon [30].

2.6.3 WP 6 Final Observations and Recommendations

IOS/ASL observed that SAR imagery over the British Columbia coastal area was dominated by wind as has been reported previously. Ocean features, including fronts could be seen under conditions of low wind and did provide useful information to supplement thermal and optical imaging. Also, SAR produced high resolution wind fields of such phenomena as outflow winds that may have important implications for near surface oceanography. However, at IOS' and ASL's present state of understanding, SAR did not provide an operational tool to supplant

thermal and optical imagery for mapping of ocean fronts in the Canadian coastal waters of the NE Pacific.

2.7 WP 7 SAR ocean imaging model

2.7.1 Work Tasks

The goal of WP 7 was to implement an existing numerical SAR Ocean Imaging Model describing the interaction of SAR signals with the ocean surface and modify it to suit the needs of the SOIN project. The model was to assess the effects of ocean surface conditions (temperature, winds, currents, waves) on SAR imagery, and provided estimates of these parameters from SAR imagery. Due to lateness in the provision of funding, and difficulty in acquiring model code, the project was not completed as it had been envisioned. Nevertheless, significant progress toward the WP goal was made by the end of the project.

From the SOIN Phase II proposal [35] the Work Tasks were:

- WP 7.1 – Work Package management;

- WP 7.2 – Conduct a survey of existing SAR models;

- WP 7.3 – Acquire the agreed-to SAR model;

- WP 7.4 – Install, modify and validate the forward model;

- WP 7.5 – Develop and validate the inverse model; and

- WP 7.6 – Provide a way-ahead plan for integration of the SAR Ocean Imaging Model into SOIN operations.

WP 7.2, 7.3 and 7.4 have been substantially completed. There was insufficient time to start WP 7.5. Work with the models has been insufficiently comprehensive for a realistic approach to WP 7.6.

2.7.2 WP 7 Overview

The search for an existing SAR model has been completed. The literature review yielded several candidate models, with the two most suitable being M4S, written by R. Romeiser of the University of Miami, and RIM, written by V. Kudryavtsev and J. Johannessen of the Nansen Environmental Research Centre, Norway. Both models work in the forward (using environmental conditions to predict the SAR image) but not in the inverse (using the SAR image to predict environmental conditions). Both appeared to work in a range of frequencies and polarisations. The documentation for M4S was better, so we decided to pursue acquisition of it, with RIM as a strong second candidate. M4S was readily available in Windows executable form, but extended discussions with Dr. Romeiser did not lead to the release of source code to SOIN. The executable was acquired anyway, and was used for some tests.

In discussion with J. Johannessen and V. Kudryavtsev, it became apparent that there were different versions of the RIM code. Dr. Kudryavtsev maintained a personal research version of

the code in MATLAB at his home institution in St. Petersburg, and, from that code, a C++ version was being written at NERSC in Bergen, Norway. While agreement in principle was reached for transfer of the code to RMCC at the SeaSAR meeting in Tromsø, Norway in June 2012, code was not actually received in Canada until December. Since that time, a significant effort has been made to understand the model and run it in a series of canonical cases.

To verify backscatter intensities, code for the CMOD5 algorithm was downloaded from the KNMI website, compiled and run on RMCC computing facilities. This code relates C-band microwave VV backscatter to wind speed for a neutral atmosphere using incidence angle, wind direction and radar look direction as parameters, and is the internationally accepted standard for this relationship.

2.7.3   M4S Results

While negotiations for source code for RIM were underway, some tests were performed on the basic performance of a SAR ocean imaging model using the executable code from M4S.

In the first test, an idealised Gulf Stream North Wall current grid was established: a 256 square grid of 9X11m pixels split diagonally from southwest to northeast, with the current north of the diagonal zero, and south of the diagonal 1 m/s parallel to the current front. A uniform westerly wind of 10m/s was input into the model. The programme "M4Sw320" was run with these inputs to compute wave spectra at each current grid point. Once the surface roughness was established, the radar imaging model "M4Sr320" was run for a variety of RADARSAT-2 like scenarios. Figure 19 below shows the model output for three polarisations at a 20° incidence angle.
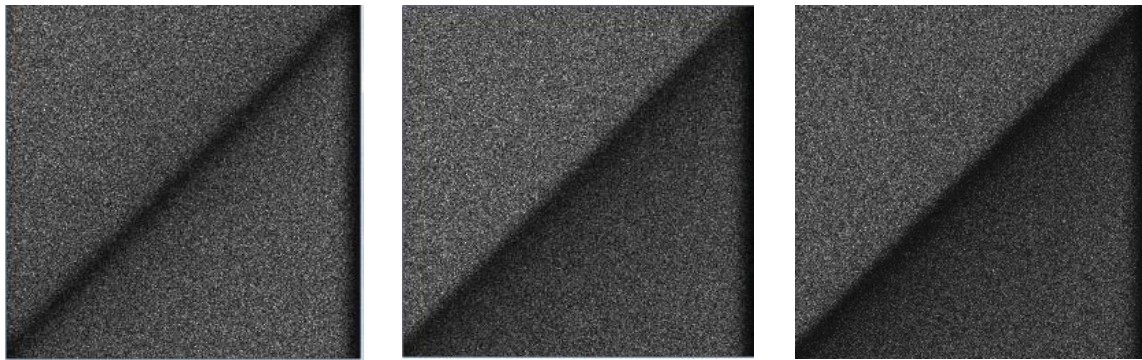
Figure 19- M4S model output for a simulated Gulf Stream North Wall, imaged at an incidence angle of 20°. The left image is HH polarisation, the middle HV and the right VV. All images are in dB (autoscaled).

A quantitative exploration of this model was performed using an image containing an east-west oriented front, with a 1 m/s current flowing eastward in the northern half of the image, and zero current in the southern half. A 20 m/s westerly wind was imposed on the system. Radar parameters appropriate for RADARSAT-2 fine mode were chosen.

Figure 20 shows the model output when the look direction of the radar was perpendicular to the front.
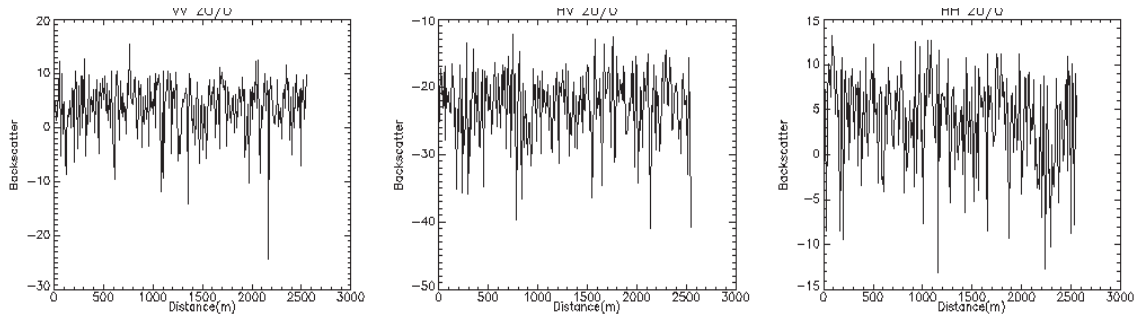
Figure 20 - South-North profile of radar backscatter (dB) across a current front for VV, HV and HH polarisations. This is 1-look imagery at 20° incidence angle.

In this one-look imagery, the front is totally obscured by speckle noise. However, when reprocessed in 81 look (9X9) the front is evident in all three polarisations (Figure 21).
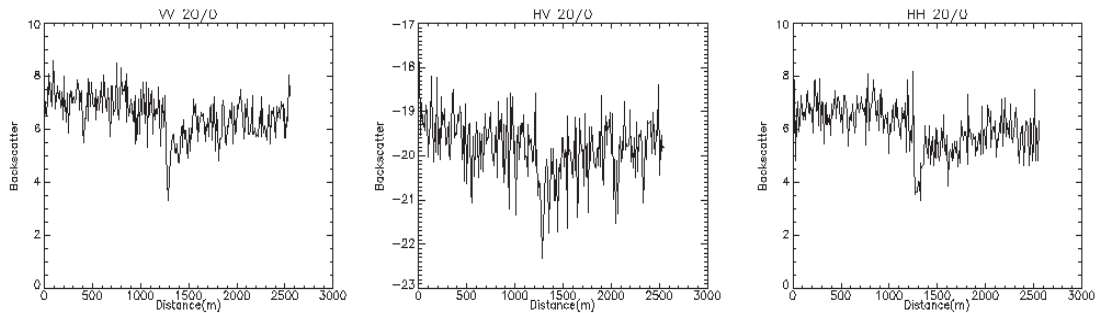
Figure 21 - South-North profile of radar backscatter (dB) across a current front for VV, HV and HH polarisations. This is 81-look imagery.

One model output is the SAR image before the addition of speckle, representing the "true" image. The same front imaged without speckle is shown in Figure 22.
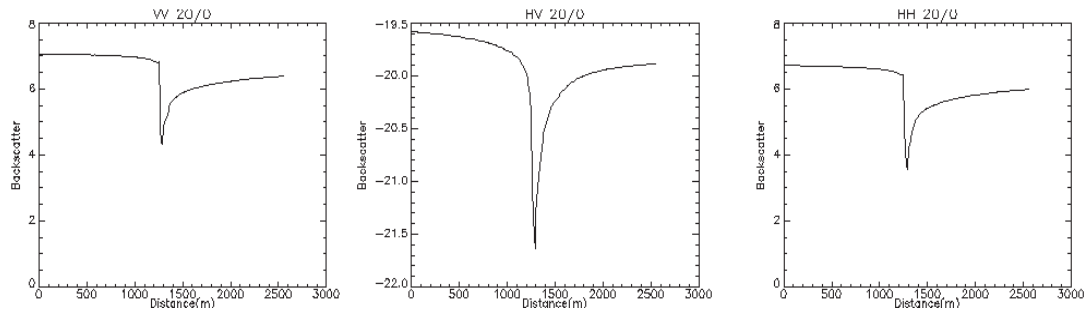
Figure 22 - South-North profile of radar backscatter (dB) across a current front for VV, HV and HH polarisations. This is "true", unspeckled imagery.

There is a significant difference in response with changing incidence angle, as shown in Figure 23.
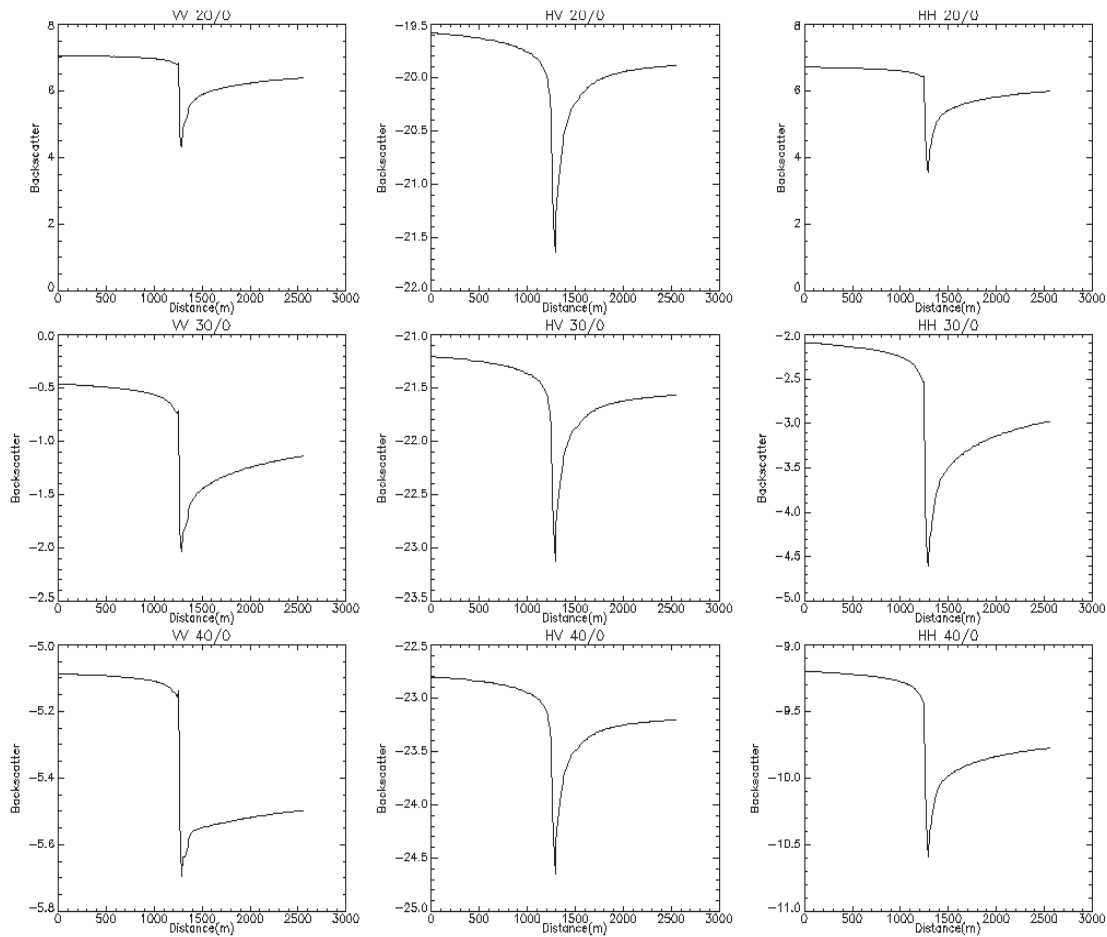
Figure 23 - South-North profile of radar backscatter (dB) across a current front for VV, HV and HH polarisations. The top row is at 20° incidence angle, the middle at 30° and the bottom at 40°.

As the incidence angle increased, the backscatter in all polarisations decreased, although HV was much less affected than the two like-polarisations. In all cases, the backscatter on the current side of the front is lower than on the non-current side. Tests showed that this effect is independent of wind direction.

The situation is quite different when the radar look direction is aligned with the front. Figure 24 shows that only at the steeper incidence angles is the front visible. In the co-pol images there is no difference in the backscatter on opposite sides of the front. At best, the backscatter minimum on the front is only 1dB below the backscatter on both sides. HH polarisation seems to be more sensitive to the presence of the front than VV, but HV is most sensitive, although at backscatter levels that may be below the noise floor of many beam modes.
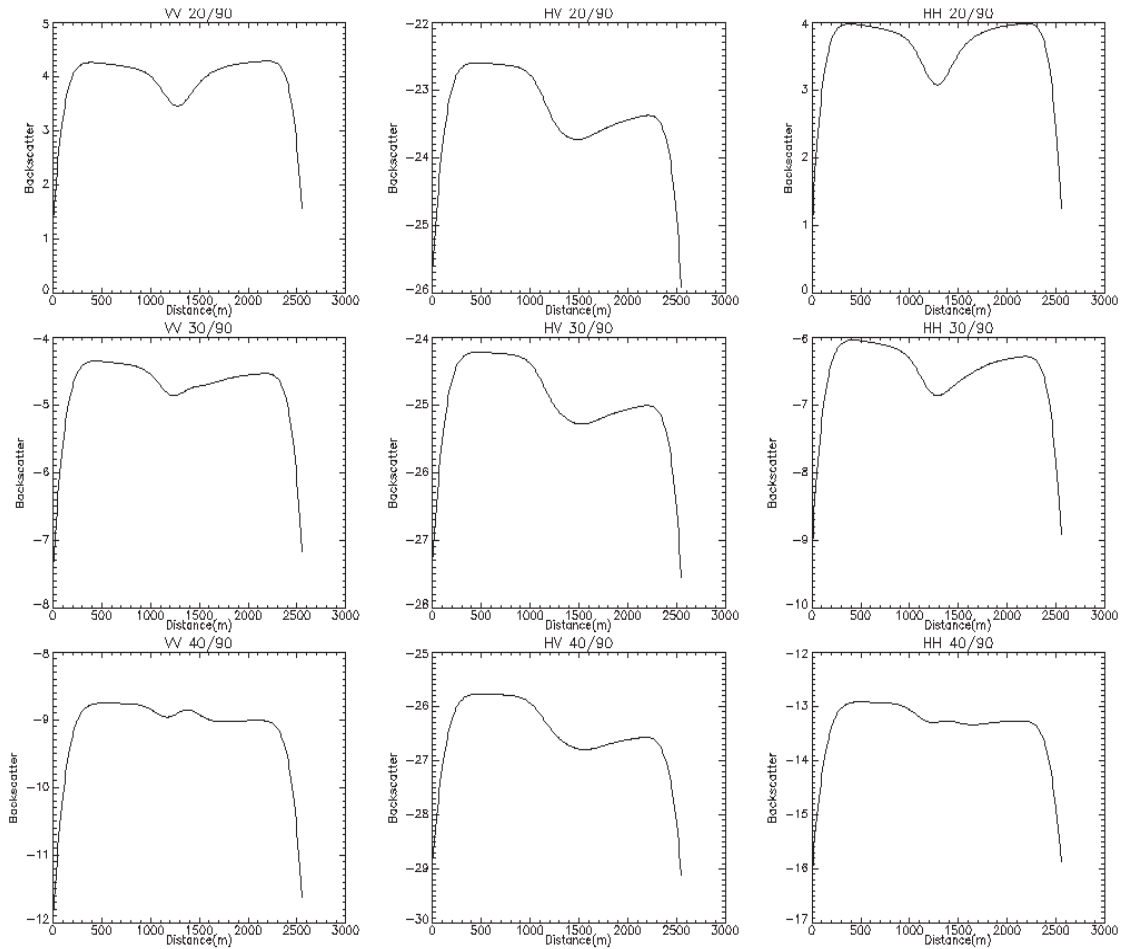
Figure 24 - South-North profile of radar backscatter (dB) across a current front for VV, HV and HH polarisations. Radar look direction is along the front. The top row is at 20° incidence angle, the middle at 30° and the bottom at 40°.

A further investigation into the behaviour of the SAR image as a function of the angle between the radar look direction and the direction of the current front is shown in Figure 25 for all three polarisations. The depth of the frontal trough is less than 1dB for all polarisations at angles less than about 50°, and for VV polarisation at angles less than 70°. At large angles HH pol is the most sensitive to the presence of the current front.

Current fronts look entirely different than wind shear fronts. With a constant current, and an east-west wind shear of 20m/s, the model gives the results shown in Figure 26. As might be expected, the backscatter on the calm side of the front is very low, and is much higher on the windy side. The VV response is strongest, and the HV response is very weak. Similar behaviour was seen for all incidence angles and for all angles between wind and radar look direction.

Exploration of this model is limited because the source code is unavailable, and hence the model physics cannot be examined, nor can it be modified.
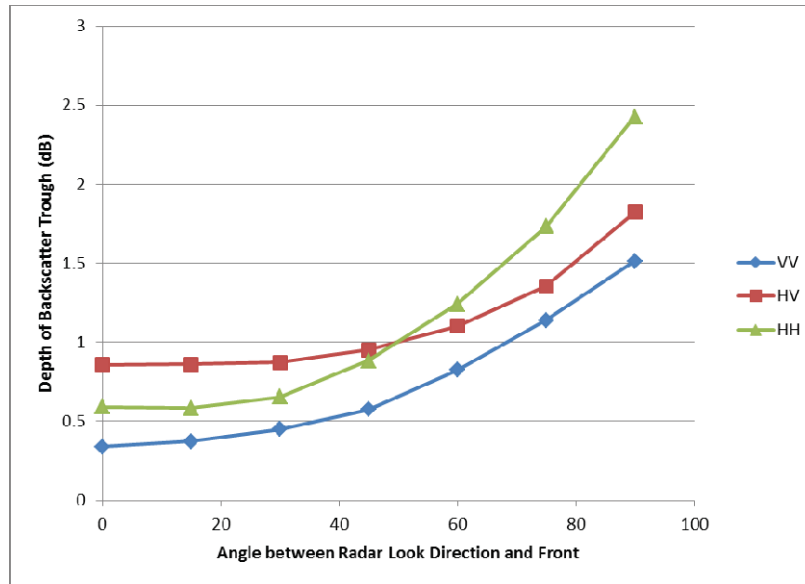
Figure 25 - Depth of the backscatter trough along a current front as a function of angle between the radar look direction and the front, and of the radar polarisation.
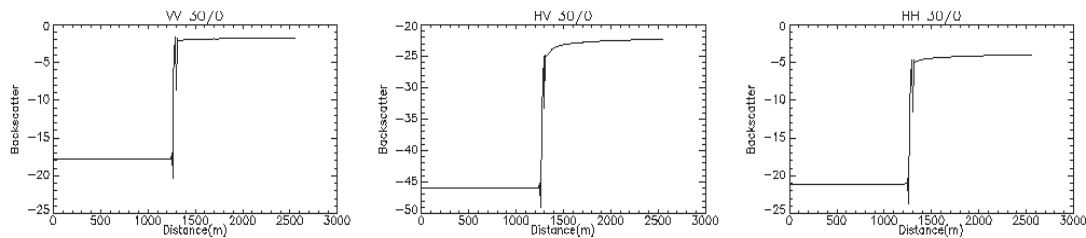
Figure 26 - Radar backscatter across a 20m/s wind shear at 30° incidence angle and 90° radar look direction.

2.7.4   RIM Results

The C++ code supplied by NERSC to RMCC is in an early stage of development. Unlike M4S, it works only in 1 dimension, and does not contain the Doppler code required to simulate SAR/current interaction. Nor does it model cross-polarized behaviour. It does however, have some features that extend our understanding of SAR modeling with a separation of the wind interaction into Bragg scattering and wave breaking partitions, and an atmospheric boundary layer stability model that allows investigation of air-sea temperature differences on radar backscatter.

Figure 27 shows a basic result for HH polarization at the wavelength of RADARSAT-2 at an incidence angle of 40° with a neutrally stable atmosphere. A look angle of 0° corresponds to a radar look direction directly downwind. σ_0^{br} is the Bragg scattering contribution to the backscatter, and σ_{wb} the wave breaking contribution. As expected, the Bragg contribution is largest both up and downwind, and weakest crosswind. Wave breaking is strongest looking upwind, and weakest downwind, giving a total response which is still weakest crosswind, but has a significant up/down wind asymmetry. With an increase in wind speed from 5 m/s to 20 m/s,

there is a greater increase in the wave breaking component than in the Bragg response, giving a greater up/down wind asymmetry.
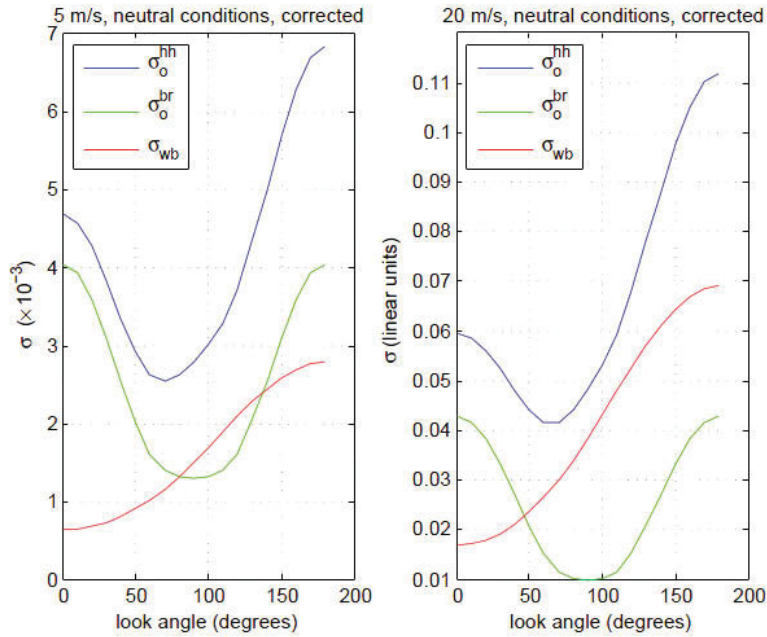
Figure 27 - Radar backscatter at 40° incidence angle as a function of look angle for wind speeds of 5 m/s (left) and 20 m/s (right).

This behaviour is expected, and is entirely consistent with the CMOD5 relationship between wind speed and microwave backscatter. Figure 28 shows the same information, but computed at an incidence angle of 20°.
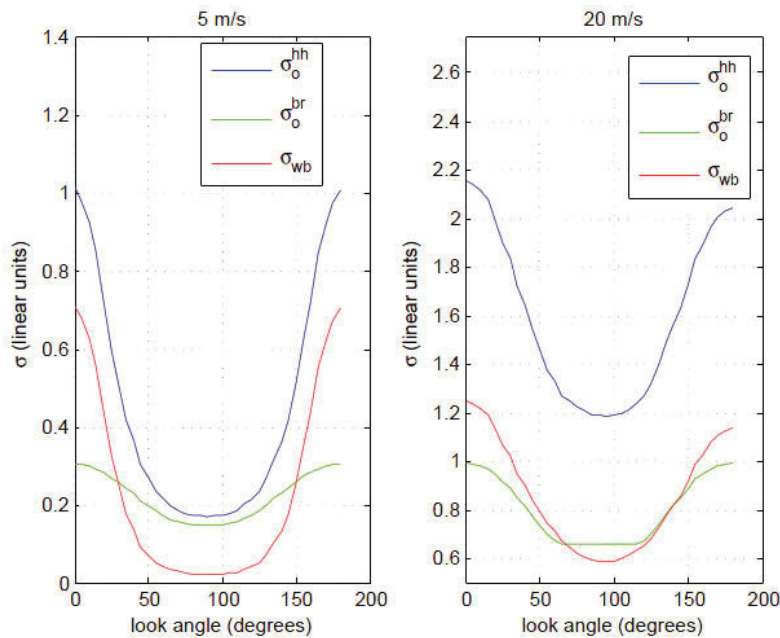
Figure 28 - Radar backscatter at 20° incidence angle as a function of look angle for wind speeds of 5 m/s (left) and 20 m/s (right).

The overall backscatter is higher than at 40° as expected, but now the wave breaking contribution is stronger both up and down wind than cross wind. We have not been able to confirm yet whether this is an observable phenomenon, or is a programming anomaly.

We have simulated the effect of imagery across a temperature front by hypothesizing a westerly wind blowing over cold water, then over a warm Gulf Stream. On the cold water side, $T_{air} = T_{water}$ = 7°C, but on the warm side, T_{air} =7°C, T_{water} =17°C. This latter case leads to atmospheric boundary layer instability and increased momentum transfer from wind to water, and hence to increased backscatter. At low wind speeds, the difference is about 1 dB, decreasing to essentially no difference at a wind speed of 20 m/s (see Figure 29).
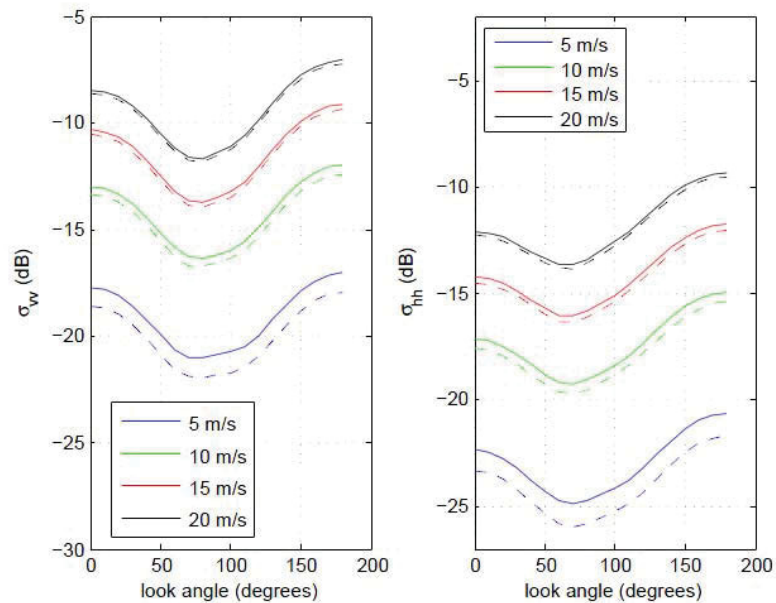
Figure 29- Radar backscatter in dB at 40° incidence angle for stable (dashed) and unstable (solid) boundary layer conditions. Both HH and VV polarizations are shown for various wind speeds.

An analysis of the unstable/stable difference, as shown in Figure 30, shows that the difference is strongest upwind at VV polarization.

These calculations are at a single point where the instability occurs. When the cold wind blows over a warm front, the instability will form quickly. Over some distance the atmospheric boundary layer will return to neutrality, and the effect of the temperature front will no longer be visible in the radar image. RIM does not currently have the capability of modeling this phenomenon.

A comparison of Figure 23 and Figure 29 shows a large calibration difference between M4S and RIM. Figure 23 (bottom left panel) shows the result of a 10 m/s wind blowing in the radar look direction at a 40° incidence angle, and indicates a VV backscatter of approximately -5.1 dB. The green curve in the left panel of Figure 29 shows a backscatter of about -13 dB under the same conditions. Direct computation of expected backscatter from CMOD5 yields -13 dB, implying that RIM is calibrated correctly, but M4S imagery is not.
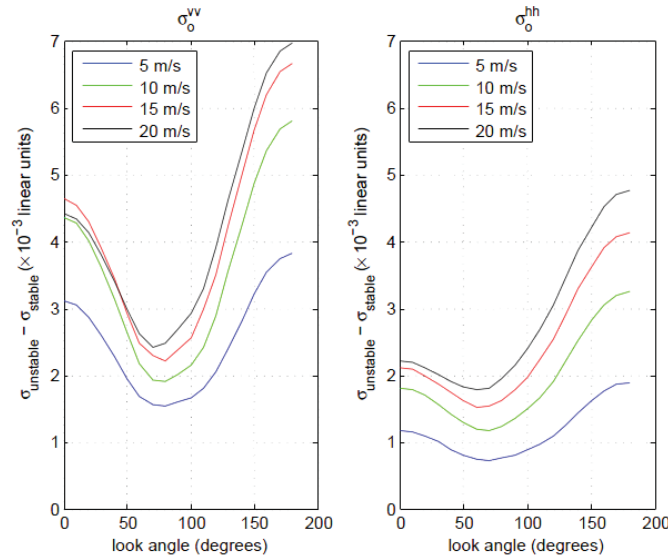
Figure 30 - Difference between unstable and stable radar backscatter at 40° incidence angle. Both HH and VV polarizations are shown for various wind speeds.

2.7.5 WP 7 Final Observations and Recommendations

The Radar Imaging Model (RIM) from the Nansen Environmental and Remote Sensing Centre (NERSC) has been implemented at RMC. The radar backscatter values it produces are consistent with those produced by CMOD5 at 40° incidence angle. Results at steeper angles are suspect due to uncertainties in the wave breaking algorithm. RIM shows evidence that temperature fronts will be imaged weakly at lower wind speeds. The M4S model has been installed and run for a number cases involving current shear. Although the absolute calibration of the model is suspect, there is a strong indication that current fronts will be weakly imaged as a darker band along the front. Anecdotal information from SAR imagery of the Gulf Stream corroborates this model result.

Results from these models are promising. Wind, current and temperature fronts cause features in the SAR image. The character of these features differs with the cause, i.e. a wind front does not look like a temperature front which does not look like a current shear. The effects appear to be enhanced when the wind is perpendicular to the current or temperature front.

Neither model is ready for integration into the SOIN system. M4S is not a candidate for integration because it does not contain boundary layer stability physics, and therefore cannot model temperature fronts, and because its source code is not available. RIM does not yet contain HV polarization, current field interaction, or even the ability to work in a two dimensional domain. However, it is a model in development, and will contain these features in the near future. Its source code is available, so the model physics can be validated and updated as necessary. In a longer term sense, this model will help explain many of the features visible in SAR imagery.

Considerable work is still required to validate RIM and compare its output to actual Radarsat-2 imagery. Development of this model should be monitored, and, as its functionality increases, should be reconsidered for inclusion in the operational output of SOIN.

2.8 WP 8 Statistical analysis of SAR data

2.8.1 Work tasks

The objective of WP 8 was to refine the probabilistic model used to identify features detected by IA Pro's Canny edge detector as signature of one of the following classes of phenomena: SST front and/or North Wall of the Gulf Stream, atmospheric front, eddy or ring. The specific tasks were as follows:

From SOIN Phase I [32] the Work Tasks were:

- WP 8.1 – Work Package management;

- WP 8.2 – Apply logistic regression model to SAR Gulf Stream rings, ocean eddies, smaller thermal fronts;

- WP 8.3 – Investigate application of logistic regression model to positive identification of chlorophyll in EO images;

- WP 8.4 – Continue to refine and adjust parameters as more data become available.

From the SOIN Phase II proposal [35] the Work Tasks are (please note that the Phase II Work Task numbers have been revised from the original proposal so as to continue from the Phase I Work Task numbering system):

- WP 8.5 – Make a comparison of the GSNW Search Region and the estimated location of the GSNW from OFA (Ocean Features Analysis) data supplied by MetOc Halifax;

- WP 8.6 – Collect a set of feature vectors from SAR/SST image pairs on an ongoing basis from which to develop a statistical model;

- WP 8.7 – Consult with DRDC Ottawa on ways to automate the identification of features that correspond to SST fronts using RADARSAT/SST image pairs;

- WP 8.8 – Investigate a variety of statistical models to identify the best approach to feature identification;

- WP 8.9 – Consult with DRDC to produce an objective classification algorithm for feature vectors that can be implemented in IA Pro;

- WP 8.10 – Working with the team on the West Coast, collect data from RADARSAT/Ocean Color pairs to build a classification algorithm based upon Ocean Color;

- WP 8.11 – Document the modified version of the speckle reduction algorithm and forward to DRDC Ottawa and to RMC;

- WP 8.12 – Train on how to recognize the signatures of various atmospheric and oceanographic processes in RADARSAT-2 imagery based on material provided by Todd Sikora;

- WP 8.13 – Determine the feasibility of collecting and analyzing all data (SAR, SST, Ocean Color and Winds) for all of the SOIN project RADARSAT-2 images by estimating the rate at which images can be processed;

- WP 8.14 – If feasible, begin collecting and tabulating the data in paragraph 2. Otherwise, advise SOIN management team on hiring and training a student to do this, either locally or via Todd Sikora;

- WP 8.15 – As this data is tabulated, begin tabulating concurrent weather information from EC GEM regional model data collected by MetOc Halifax;

- WP 8.16 – Investigate measures of texture in RADARSAT-2 imagery and ways to compare and classify textures;

- WP 8.17 – Complete a draft of a paper for peer review and journal submission to include documentation of work accomplished to date; and

- WP 8.18 – Recollect labeled feature vectors for a second try at the logistic regression classifier.

The following new WPs were added to FY 2011-12:

- WP 8.19 – Write code for manual interrogation of RADARSAT-2 SCNA VV images and nearest–in–time winds from QuikSCAT to collect data for use in training an automated ocean feature classification algorithm. Documentation for the code will be required to facilitate incorporation into IA Pro;

- WP 8.20 – Use the code to collect a large data set;

- WP 8.21 – Build and validate a classification model using the collected data;

- WP 8.22 – Write code for manual interrogation of RADARSAT-2 SCWA VV images and nearest–in–time GEM model winds;

- WP 8.23 – Use the data to validate the classification model;

- WP 8.24 – Prepare documentation of all results for publication;

- WP 8.25 – Collaborate with DRDC Ottawa to implement components of the classification algorithm in IA Pro.

2.8.2   WP 8 Overview

A SAR image reveals spatial variations in the small-scale roughness of the ocean surface forced by near-surface winds and modulated by longer waves, currents, and surfactants [40]. Often, there is unstable atmospheric surface layer stratification on the warm side of an SST front, corresponding to a positive buoyancy flux within the marine atmospheric boundary layer (MABL), manifested by convective processes that transport momentum from the upper MABL toward the surface. Moreover, the atmospheric temperature gradient often present across an SST

front can result in a corresponding pressure gradient in the atmosphere [26]. These processes enhance near-surface horizontal wind speed on the warm side of the front, with concomitant intensification of surface roughness compared to the cold side that sometimes generates a backscatter gradient (i.e., a brightness front) in a SAR image that is the signature of the SST front [2], [5], [8].

Our objective, as a component of the SOIN project, was to integrate RADARSAT-2 images into the OFA data stream to help identify the location of major water-mass boundaries such as the GSNW, the shelf-slope front, and warm-core rings. An algorithm that automatically detects brightness-fronts in RADARSAT-2 images and then identifies those that are most likely to be SST front signatures has met this objective. The purpose of this report is to provide an overview of the algorithm as it will be used in the operational setting at MetOc Halifax, with special emphasis on the statistical classifier that discriminates between SST front signatures and signatures of horizontal wind shear not associated with SST fronts.

2.8.2.1 Semi-automated Detection of Candidate SST Fronts in RADARSAT-2 Images

RADARSAT-2 images will be processed using the SAR Ocean Feature Detection Tool (SOFDT) in IA Pro [22], [23]. Using SOFDT, a land mask is applied to the image; a special filter removes targets of opportunity such as ship signatures; the image is block averaged to reduce pixel spacing from 25 meters (12,000 by 12,000 pixels) to 300 meters (1000 by 1000 pixels); and the image is radiometrically flattened to remove systematic variation in backscatter in the range direction. A Canny edge detector is then applied to the image to identify brightness fronts, some of which will be candidate SST front signatures. Only edges more than 50 km in length will be considered, both to reduce the number of edges to a manageable level for manual validation, and because identifiable SST front signatures in the region of the Gulf Stream have been observed to be typically of this length-scale or greater.

Once they have been automatically identified, the Canny edges (or targets) will be manually inspected for easily recognizable signatures including: alternating bands of high and low backscatter associated with atmospheric or oceanographic gravity waves; crater-like signatures of convective squalls; signatures of obvious atmospheric fronts (which can be validated using wind vectors and/or meteorological surface analysis); and bright/dark filaments commonly associated with current shear in the region of the GSNW. All such edges will be removed from the analysis. The remaining Canny edges – candidate SST front signatures – will be subjected to an automated statistical classification algorithm that uses the mean wind direction (μ_θ) with respect a Canny edge to discriminate between SST front signatures (designated SST) and those of horizontal wind shear not associated with SST fronts (a. k. a. pure atmospheric wind shear, designated WIN).

2.8.2.2 Semi-automated Classification of Candidate SST Fronts[1]

Figure 31 shows the estimated probability distributions of μ_θ for the two classes (WIN and SST) estimated from 495 test cases that included 302 examples of Canny edges that were labelled SST, and 193 that were labelled WIN. Labels were manually determined by comparing each Canny

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[1] The results reported in this and in the next two sections were taken from [10] and [11].

edge to MODIS daytime SST averaged over 8 days and 4 km obtained using the PO.DAAC Ocean ESIP Tool (http://poet.jpl.nasa.gov/): edges closely aligned with concurrent SST fronts were labeled SST, and those that were not were labeled WIN. Fig. 1 demonstrates that near-surface wind (the directions of which were determined from Level 3 QuikSCAT data; wind speeds were computed from SAR images using CMODifr2K) is typically directed along edges labeled WIN (solid curve), with a mode μ_θ at about 15°, whereas the wind is directed more in the cross-front direction for edges labeled SST (dashed curve).
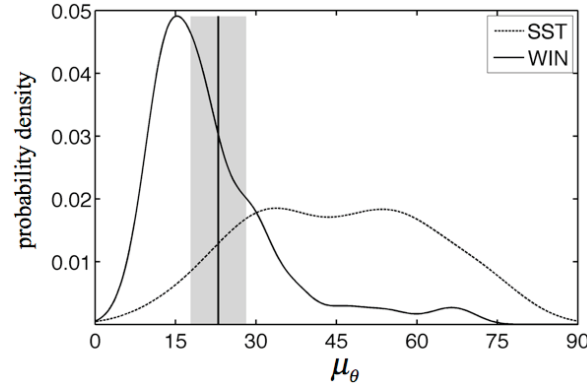
Figure 31 - The estimated probability distributions for signatures labeled WIN (solid curve) and SST (dashed curve) exhibit some separation: the vertical line at 23° indicates the statistically determined optimal decision bound: edges to the left are more likely

Because there are regions where the two distributions do not overlap, μ_θ can be used to discriminate between the two signature classes. The statistically determined optimal decision bound between the two classes occurs at $\mu_\theta = 23°$, indicated by the vertical line in Figure 31: classifying Canny edges as WIN when $\mu_\theta < 23°$ and as SST when $\mu_\theta \geq 23°$ results in a classification accuracy (the proportion of cases of agreement between label and class) of 80% for the 495 cases. But because the probability densities overlap heavily near the bound, classification error is high for features with μ_θ close to 23°. As a practical semi-automated operational approach, μ_θ will be partitioned into three regions by expanding the decision bound to cover an interval on which edges will be flagged to indicate that they could not be classified with a reasonable level of certainty (gray band in Figure 31). The automated decision rule will take on the following form:

$$
class = \begin{cases} \text{WIN if } \mu_\theta \leq 23° - R \\ \text{SST if } \mu_\theta \geq 23° + R \\ \text{Flagged otherwise} \end{cases}
$$

The radius (R) of the interval can be adjusted to enhance classification skill without producing an excessive number of flagged edges. For example, when the decision rule is applied to all 495 cases with R = 8.75°, the classification accuracy increases to almost 90% at the expense of only 30% of the edges flagged. In the operational setting, flagged edges will be classified manually by an analyst trained to make use of all available contextual information, including visual cues in the SAR image commonly associated with SST fronts, previous determinations of the location of the

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GSNW in the most recent OFA, MODIS and/or AVHRR SST, surface weather analyses, as well as the classes assigned to other edges on the same image. Note that, unlike the first manual intervention described above where Canny edges were manually inspected for easily recognizable signatures of processes not associated with SST fronts, the manual analysis of flagged edges at this stage has the purpose of finding SST front signatures, using contextual cues, that could not be identified using $\mu\theta$ alone.

2.8.2.3 Operational Constraints – Temporal Lag and Wind Speed

The classification of brightness fronts as described depends on local wind direction in the vicinity of a Canny edge. This suggests the possibility that the temporal lag between the acquisition of the RADARSAT-2 image and the near-surface wind data (to be supplied by the Global Environmental Multiscale (GEM) model in place of the now defunct QuikSCAT data stream) may be a critical factor in classification accuracy. It was found that temporal separations (between RADARSAT-2 images and their nearest-in-time level 3 QuikSCAT image) up to 88 minutes (the maximum value in the data set; the mean was 38 minutes with a standard deviation of 19 minutes) had no significant impact on accuracy. Although this implies that temporal separations not exceeding 90 minutes should be acceptable in the operational setting, this has not been validated using the GEM model data. Validation using Global Environmental Multiscale (GEM) winds should a component of any future efforts that might be undertaken.

Some evidence was found to suggest that classification accuracy breaks down under extremes in near-surface wind speed. In the small number of cases for which the wind speed was less than 1.4 m/s, all edges were labeled SST even when μ_θ was less than 23°. Also, there were a few cases of edges labeled WIN for which μ_θ was five to ten degrees greater than 23°, but these occurred only when the wind speed was in excess of 12 m/s. Consequently, edges for which the wind speed falls outside of the interval (1.4 m/s, 12 m/s) will be flagged for manual analysis using all available contextual information as described in the previous section. Validation of these bounds, which were determined using only a small number of test cases, should be a component of future studies.

2.8.2.4 Cold versus Warm Advection

The bimodal shape of the probability density function for SST shown in Figure 31 is a point of interest. It was suggested that this feature might be due to differences in atmospheric dynamics when winds are directed from the cold toward the warm side of an SST front (cold advection) as compared to the opposite case (warm advection). An analysis conducted to test this hypothesis revealed that the mean of μ_θ was 43° for warm advection and 47° for cold. The 95% confidence interval for the difference between the two means was (0.53°, 8.3°), indicating significance (p-value = 0.03 for a t-test comparing the means). It follows that differences between the two types of advection are partially responsible for bimodality. Other factors remain undiscovered however, as the probability distributions of μ_θ for the two types of advection are themselves bimodal, as shown in Figure 32. Nevertheless, we can say that SST front signatures with warm advection are more likely to be confused for signatures of pure atmospheric wind shear (compared to SST front signatures with cold advection) because the bulk of the probability density of μ_θ for such cases is closer to the decision bound at 23°.
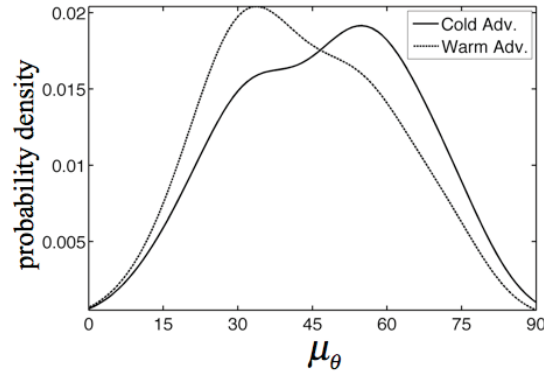
Figure 32 - The bimodality of the estimated probability distribution of μ_θ for SST front signatures is partly due to differences in the distributions of cold (solid) and warm (dashed) advection. The mean of μ_θ (47°) in the case of cold advection is slightly but significantly (p-value = 0.03 for a t-test comparing the means) greater than the mean (43°) in the case of warm advection. SST front signatures with warm advection are more likely to be confused for signatures of pure atmospheric wind shear (compared to SST front signatures with cold advection) because the bulk of the probability density of μ_θ for such cases is closer to the decision bound at 23°.

2.8.2.5   Case Study

The following case study serves to model the semi-automated detection of SST front signatures in RADARSAR-2 images in the operational setting. In Figure 33a, two contiguous RADARSAT-2 SCNA VV frames acquired on 7 March 2009 at approximately 2230 UTC are shown. The automatically detected Canny edges are color-coded according to their automatically assigned class: red for SST, blue for WIN, and yellow for flagged edges determined by the decision rule with R = 8.75°. White numbers indicate μ_θ for each edge computed from QuikSCAT wind directions acquired within less than 10 minutes of the acquisition time of the RADARSAT-2 images. The parallel black lines running through the bottom frame show the estimated location of the Gulf Stream taken from the OFA produced on the previous day, 6 March 2009. Composite MODIS SST acquired between 1300 and 1900 UTC on 7 March 2009 is shown in Figure 33b. Next to each edge is its assigned class (in black letters), each of which was determined by manual analysis of the color-coded Canny edges. The following points describe how this was done using only Figure 33a (i.e., it was assumed that the SST image in Figure 33b was not available to the analyst):

- Figure 33a is intended to provide validation of the classes assigned to each edge.

- The top-most edge was automatically classified as an SST front signature. Although this edge may be the signature of an SST boundary associated with cold upwelling in the shallow water off Cape Cod, it was discarded from the analysis because it is certainly not the signature of an SST front associated with a major water-mass boundary, being very close to the coast.
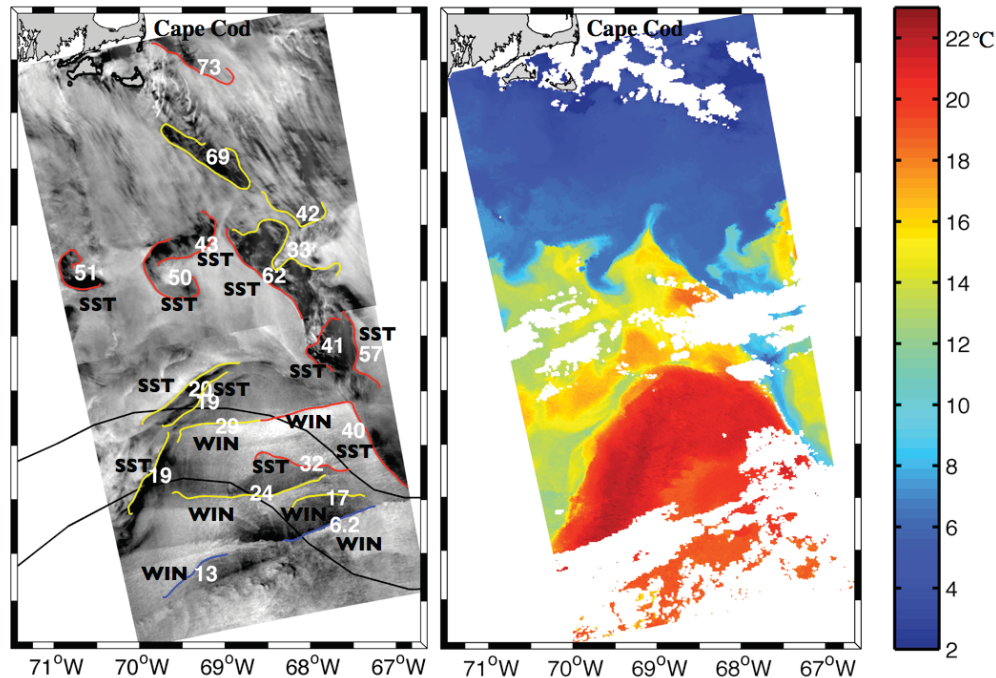
Figure 33 - (a) Two contiguous RADARSAT-2 SCNA VV frames acquired on 7 March 2009 at approximately 2230 UTC. The red and blue curves are Canny edges automatically classified as SST and WIN respectively; the yellow curves are edges that were flagged; the number in white nest to each edge indicates its mean μ_θ; the parallel black lines running through the bottom frame shows the estimated location of the Gulf Stream taken from the OFA for 6 March 2009. RADARSAT-2 Data and Products [©]MacDonald, Dettwiler and Associates Ltd. (2009) - all rights reserved. (b) The composite MODIS SST acquired between 1300 and 1900 UTC on the same day.

- The three yellow edges to the south of Cape Cod were also rejected because they correspond to a mean wind speed of less than 1.4 m/s and occur in a region on the shelf apparently dominated by atmospheric gravity wave signatures.

- The band of six red edges that extend from the southwest portion of the top frame into the northeast portion of the bottom frame marks a region of horizontal instability located at the boundary between cold shelf water and the warmer shelf-slope water-mass. All of these edges were correctly classified as SST front signatures by the automated classifier.Figure 33a, starting near the SST front with $\mu_\theta = 62°$ and extending to the front with $\mu_\theta = 40°$, is what appears to be a cold intrusion, a finger of cold shelf water that penetrated past the shelf-slope water mass into the Sargasso Sea to the south. The main indication of this feature is its dark appearance, but this assessment is supported by the location of the Gulf Stream indicated by the OFA from 6 March 2009 that indicates a possible meander in the lower frame: cold intrusions are frequently observed along the east side of Gulf Stream meanders. Although portions of the boundary of this feature were automatically identified by the Canny edge detector and classified by the statistical algorithm, its identity as a cold intrusion could only have been determined by manual inspection of the detected edges in the context of the entire image.

- On the east side of the lower frame is a well-defined brightness front that has been automatically classified SST ($\mu_\theta = 40°$). But this edge includes an atypical dogleg at the juncture of what are actually two signatures. In the context of the apparent cold-water intrusion described in (4), the portion of this edge with the roughly north-south orientation is most likely the signature of an SST front. The remaining portion appears to cut across the SST front, and so was manually labeled WIN.

- On the west side of the bottom frame are three yellow edges approximately aligned southwest to northeast (with $\mu_\theta = 19°$, $19°$, and $20°$). All three edges correspond to signatures of surfactant accumulation that are commonly observed in the lee of Gulf Stream meanders. These contextual cues, in combination with the OFA that indicates the existence of a Gulf Stream meander in the frame, and the SST front signature previously described that supports the supposition of a meander, resulted in these edges being manually classified SST.

- The two blue edges at the bottom of the figure were automatically classified WIN. It is reasonable to suspect that flagged edges roughly parallel to these are also signatures of pure atmospheric wind shear. For this reason, the three yellow edges in the middle of the bottom frame (with $\mu_\theta = 17°$, $24°$, and $29°$) were manually classified WIN. This is consistent with the portion of the red doglegged edge that was also manually classified WIN.

- The red edge in the middle of the bottom frame with $\mu_\theta = 32°$ was automatically classified as SST. It location and orientation is not inconsistent with the southern boundary of the supposed Gulf Stream meander in the bottom frame.

In summary: by using contextual information (not the least of which the automatically assigned classes) to manually assign classes (or reject) the Canny edges in Fig. 3a, the analyst has identified 12 SST front signatures that are easily validated using Fig. 3b. Furthermore, the six edges labeled WIN do not correspond to any SST feature in Fig 3b, but are consistent with cloud streaks in that image and with a weather analysis chart (not shown) that indicted a cold front in the region roughly aligned with the orientation of the WIN signatures. It is therefore not unreasonable to claim perfect classification accuracy by semi-automated analysis in this case (cf. the case study in Jones et al. [10], where classification accuracy was only 31%).

2.8.3   WP 8 Final Observations and Recommendations

As the case study demonstrates, automated detection and classification of SST front signatures in RADARSAT-2 images of the Gulf Stream region, in conjunction with manual analysis, has the potential of contributing to the accurate assessment of the location of major water-mass boundaries (the GSNW, the shelf-slope front, and warm-core rings) under conditions that preclude the use of satellite SST images due to cloud cover. However, several key questions remain:

- What is the best way to integrate SST fronts identified in RADARSAT-2 images into the OFA?

- How much information can we expect to gain by including RADARSAT-2 images in the production of the OFA?

- How might *a priori* information contained in surface weather analysis and OFA charts be integrated into the automated component of the analysis?

- Is further automation possible, perhaps by using more sophisticated statistical approaches (e.g., neural networks)?

2.9 WP 9 Acoustic Environment Application

2.9.1 Work Tasks

WP 9 determined the extent to which SAR-derived thermal features and winds can be used to characterize the acoustic conditions for naval sonar operations.

From the SOIN Phase II proposal [35] the Work Tasks were:

- WP 9.1 – Collect in situ meteorological, oceanographic, and acoustic data in the SOIN study area on a non-interfering basis during other DRDC R&D activities involving CFAV *Quest*;

- WP 9.2 – Predict underwater acoustic ambient noise levels using SAR-derived wind fields; and

- WP 9.3 – Predict underwater acoustic transmission loss through thermal fronts detected in SAR imagery.

2.9.2 WP 9 Overview

Meteorological, oceanographic, and acoustic data were collected during two DRDC Atlantic sea trials involving CFAV *Quest*. The first trial, designated Q316, took place in September and October of 2008, with the data for this work package acquired 15-17 Sep 2008, in the Northeast Channel and Brown's Bank area (42.30ºN, 65.50ºW). The second trial, designated Q325, took place in the Emerald Basin and Emerald Bank area (43.75ºN, 62.75ºW) in October and November of 2009. In both cases, an acoustic source was towed along a straight-line track 30-40 km in length, and moored acoustic receivers were used to monitor the received sound pressure level. Acoustic transmission loss (TL), the difference between [transmitted] source level and [received] sound pressure level, depends in a complicated way on ocean sound speed profiles and bottom composition. Variations in ocean properties (temperature, salinity) on which sound speed profiles depend can therefore strongly affect measured TL. During the TL experiments, sound speed profiles and conductivity-temperature-depth (CTD) profiles were acquired for use as inputs to models capable of predicting TL for comparison with measurements. The data acquired were analyzed during FY 10/11 in support of WP 9.2 and 9.3 as described in the following sections.

Underwater ambient noise levels were collected during the Q316 and Q325 sea trials. During Q316, three sets of ambient noise data were collected during periods that coincided with the acquisition of RADARSAT SAR imagery, on the 16th, 17th, and 18th of September. During Q325, ambient noise data were acquired coincidentally with RADARSAT SAR imagery on only one occasion (the 5th of November), although a second set of ambient noise data was collected on October 31st, 12 hours after a SAR image was collected. Wind speed data were also collected during both trials using ship-borne instruments and deployed sensors. Wind speeds were

computed from the SAR data by Halifax MetOc and used to model ambient noise levels, which were then compared to the measured ambient noise. This process and the results thereof are described in Canadian Acoustical Association proceedings [19] and a TTCP report [20]. These results are summarized here.

Figure 34 shows a comparison of wind speeds derived from the RADARSAT images versus wind speeds as measured on the instruments (all adjusted to a 10 m height using a logarithmic wind speed vs. height profile). The wind speed obtained from the GoMoos buoy was an hourly average. The wind speed measurements with the DRDC met buoy were made every 2 minutes, and the mean and standard deviation were computed over one hour of measurements (centred on the RADARSAT image acquisition time). The wind speed measurements acquired aboard the CFAV QUEST were made every minute, and again the mean and standard deviation were computed over one hour of measurements. In the cases where RADARSAT images were acquired in a location where CFAV QUEST was operating, CFAV QUEST was typically travelling at about 5 knots. Wind speed readings were taken from the NADAS feed from the port-side anemometer, adjusted to a true wind speed based on the ship speed and heading. The starboard anemometer was not functional. The mean and standard deviation of the wind speeds for the RADARSAT estimates were taken from the wind speeds in a 10-km radius around the location of each instrument.
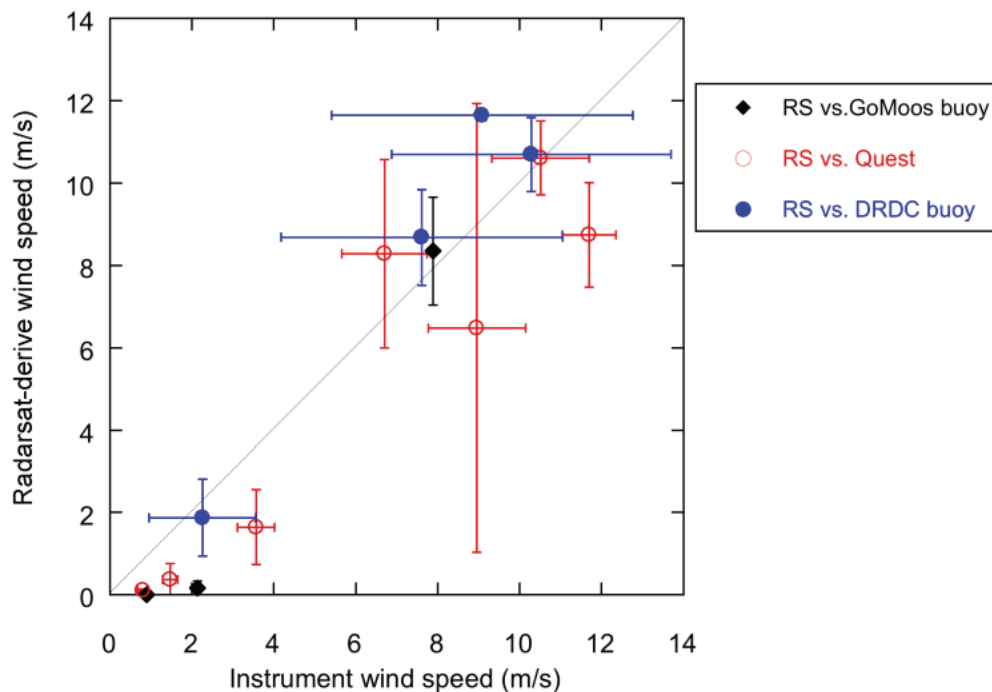
Figure 34 - Comparison of RADARSAT-derived wind speed to wind speed measured by GoMoos buoy, DRDC met buoy, and ship-borne (CFAV QUEST) instruments (reproduced from [20]).

The fairly good agreement ($R^2 = 0.87$) between RADARSAT wind speed estimates and instrumental measurements re-affirms previous results that RADARSAT can be used to provide a good wide-scale estimate of wind speeds.

The ambient noise measured with the acoustic sensors (Figure 35) was compared to ambient noise modeled using a modified Merklinger-Stockhausen model. A simple, ship-parameter model setting the peak noise level based on shipping at 60 Hz can be used for the shipping component of the ambient noise.
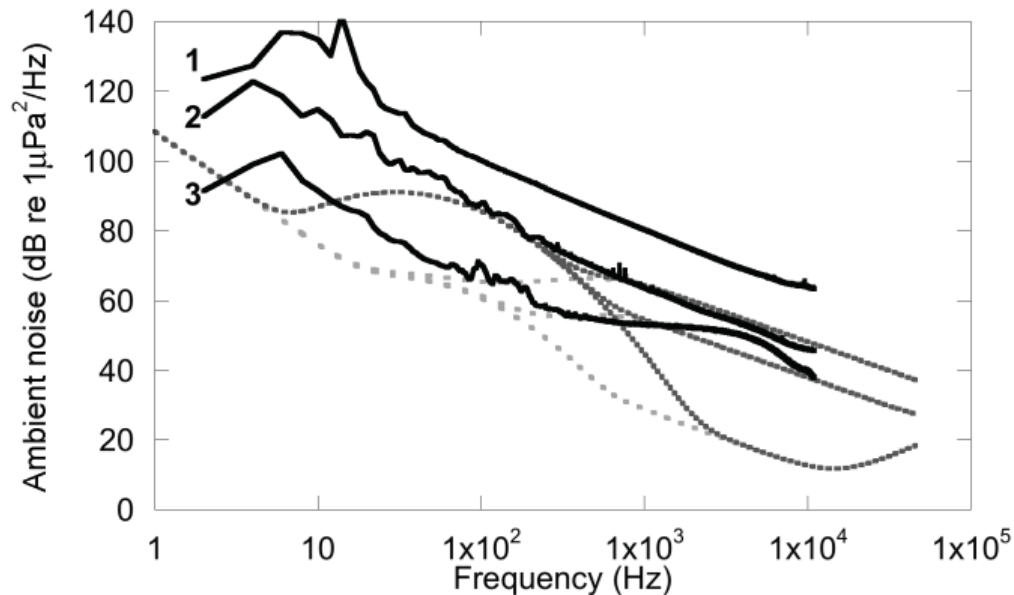
Figure 35 - Measured ambient noise (1) Sept. 16, 2008, 6.6 m/s wind speed; (2) Sept 17, 2008, 1.8 m/s wind speed; (3) Sept. 18, 2008, 0.1 m/s wind speed. Dashed lines show MS model results for given SAR-derived wind speeds, together with light and heavy shipping curves (light and heavy dashed lines) (reproduced from [19]).

Figure 36 shows a comparison of ambient noise power spectral level measured during Q316 on one recording unit, during the periods when SAR imagery was collected (RADARSAT-1 on September 16th, RADARSAT -2 on the 17th and 18th). There is an obvious dependence of the measured ambient noise on wind speed, demonstrating the potential for ambient noise estimates over a wide area to be derived from the SAR data. However, the measured ambient noise is considerably higher than that predicted by the Merklinger-Stockhausen model, particularly at the lowest wind speed (0.1 m/s). There is also wind speed dependence at all frequencies, including the frequency regime normally expected to depend on shipping noise.

Comparisons of measured ambient noise to modeled ambient noise power spectral level for Q325 are shown in Figure 36 and Figure 37. The model data shows the Merklinger-Stockhausen ambient noise predicted for the wind speed computed for the receiver location from the November 5th RADARSAT SAR image, using the mean wind speed of 1.6 m/s and the mean

wind speed plus and minus one standard deviation of 0.9 m/s. A moderate ship noise parameter of 70 dB was assumed for shipping noise.
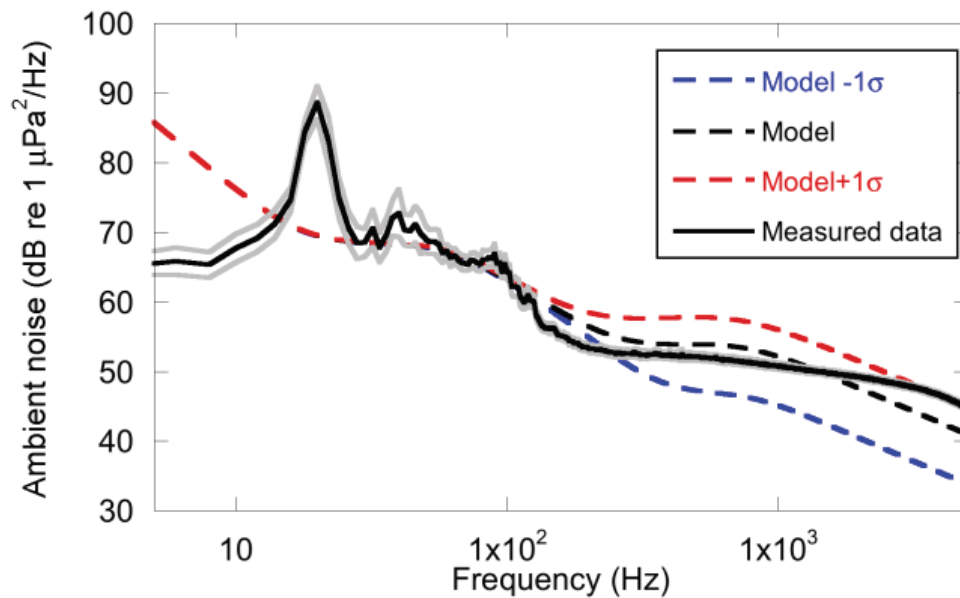
Figure 36 - Measured vs. modeled ambient noise power spectral level for November 5th, 2009. The black line shows the mean ambient noise level, with the gray lines showing ± 1 standard deviation (reproduced from [20]). The model is based on a mean wind speed of 1 .6 m/s and the mean wind speed plus and minus one standard deviation of 0.9 m/s.

There is reasonable agreement between the measured and modeled data above 30 Hz. The peak at 20 Hz in the measured data likely corresponds to fin and blue whale vocalizations that are not included in the model.

Figure 37 shows data for October 31st, 2009. In this case, the model data shows the ambient noise predicted for the wind speed computed for the receiver location. The noise prediction was made using the RADARSAT SAR image from twelve hours prior to the ambient noise data collection. The wind speeds measured at the DRDC met buoy location at the time of the ambient noise acquisition were within one standard deviation of those measured during the RADARSAT image acquisition, and so the model results should therefore be valid. The mean wind speed was 8.7 m/s, with a standard deviation of 1.2 m/s. As the CFAV QUEST was on station near the acoustic receiver, a higher ship noise parameter of 76 dB was assumed for shipping noise. In addition to the whale vocalizations that are once again observed near 20 Hz, there are also low frequency tonals from the ship evident in the ambient noise spectrum.
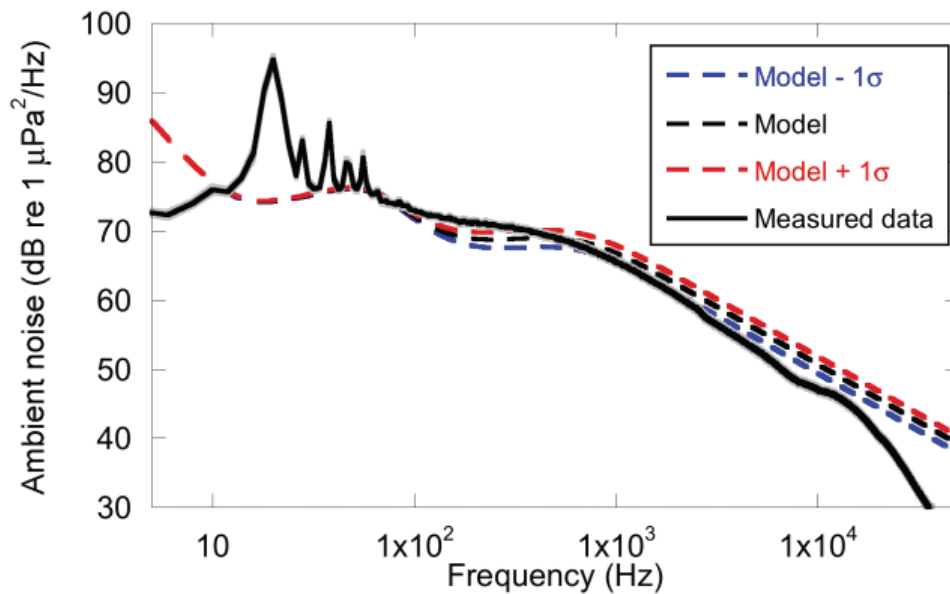
Figure 37 - Measured vs. modeled ambient noise power spectral level for October 31ˢᵗ, 2009. The black line shows the mean ambient noise level, with the gray lines showing ± 1 standard deviation (reproduced from [19], [20]). The model is based on a mean wind speed of 8.7 m/s and the mean wind speed plus and minus one standard deviation of 1.2 m/s.

In general, reasonable estimates of underwater ambient noise can be obtained using SAR imagery, although it seems that the accuracy of the ambient noise models may be location dependent.

This observation was supported by further work done under WP 9.1 and 9.2 on a June 2011 sea trial involving CFAV Quest. Again, co-located RADARSAT data was acquired from MetOc Halifax for analysis in conjunction with the acoustic data acquired during the trial. Ambient noise levels predicted using RADARSAT-derived wind speeds were in reasonably good agreement with those measured during the course of the trial.

The work undertaken in support of WP 9.3, predicting underwater acoustic transmission loss through thermal fronts detected in SAR imagery, did not directly test the applicability of SAR imagery to transmission loss measurements. This was primarily due to a lack of opportunity for long-range transmission loss experiments through detected ocean fronts that also corresponded to times when SAR imagery was available. However, during two sea trials (Q320 in January–February 2009 and Q343 in January 2012), temperature profiles were taken as part of WP 9.1 in support of WP 4.6 while transiting the north wall of the Gulf Stream. These measurements confirmed that SAR imagery could be used to detect ocean fronts that would affect acoustic propagation.

Some additional work was done looking at using satellite imagery to estimate SST variability and potentially variability of acoustic transmission loss during sea trials Q316 and Q325 (September

2008 and November 2009), as described in a previous SOIN report. This work was based on infrared imagery rather than SAR. Although it appeared that the increased variance in ocean properties observed in situ during Q316 was also manifested in satellite SST images from the same time period, statistical tests did not support the hypotheses that the SST variances differed significantly between experiments and remained the same throughout a given experiment. Clouds obscuring the Q325 measurements may have confounded the analysis, and there may have been a small effect from diurnal heating present in the satellite-derived SST data. Overall, no firm conclusions can be drawn from these particular datasets.

2.9.3   WP 9 Final Observations and Recommendations

The work done under WP 9 of the SOIN project was successful, and showed the potential of using RADARSAT and other satellite data to characterize the underwater acoustic environment. The acquisition of REA (Rapid Environmental Assessment) data is a valuable tool in the development of a Recognized Environmental Picture, and the work done in the SOIN project shows that satellite-derived environmental data can provide accurate and timely information about the acoustic environment.

The work done in the SOIN project could be carried forward in a number of ways. An extension of the work done under WP 4 could be made to investigate if SAR data could be used to drive ocean forecast models in place of other satellite data. Another area of investigation that was not touched on during SOIN Phase I and II was to what extent SAR data could be used in examining the acoustic environment in the Arctic, where the nature and extent of ice cover, and ambient noise caused by changes in sea ice, are important features. Given the difficulties in emplacing sensors in the Arctic, the ability to use remotely sensed data to provide information on how acoustic sensors would perform would be invaluable. Hopefully this work may be progressed in the future.

3   Summary

SOIN was a six-year research and operational development initiative that addressed barriers to implementing oceanographic applications of the Earth-observation sensors RADARSAT, AVHRR, MERIS and MODIS. Lead by MetOc Halifax, SOIN was launched in June 2007 with funding provided by CSA through GRIP. The project was divided into two phases with the first three-year phase focusing on developing state-of-the-art sea-surface temperature and diver-visibility products, operational tools, supporting infrastructure and the ability to detect thermal fronts, eddies and water mass boundaries with RADARSAT.   This report provides a summary of project activities and accomplishments during the ongoing Phase II of the project, in particular for FY 11/12.

DRDC Ottawa's SAR processor, IA Pro, CSIAPS and Canny edge detector proved operationally beneficial SOIN, providing excellent functionality when identifying ocean thermal features. Developments to MetOc Halifax's Ocean Work Station (OWS) enabled it to ingest C-APS outputs and display these as part of its SST and OFA outputs, a key operational requirement. The installation of SOIN infrastructure at MetOc Esquimalt expanded the project to a national level, and coincided with other west coast partners contributing to the effort. The introduction of IOS and ASL Environmental technology and continued R&D brought an analysis of Pacific Ocean features using biophysical analysis tools and chlorophyll signatures. The involvement of RMC and their undertaking to develop a SAR ocean imaging model brought a new and exciting possibility to the ocean feature analysis arsenal, and its continued development foreshadows an exciting capability that will contribute to efficient and effective SAR employment. DRDC Atlantic's WP to determine the extent to which SAR-derived thermal features and winds can be used to characterize the acoustic conditions for naval sonar operations brings a new operational application for SOIN-derived technology.

SOIN members participated in many CSA led groups and committees such as EMOC and SARAWG, and attended various workshops and conferences, as detailed in WP 1.5. SOIN participants have seized many opportunities to promote the success and results of the project so far.

SOIN successfully addressed the three fundamental barriers to the achievement of its operational objectives: (i) a lack of required infrastructure; (ii) insufficient auxiliary data provided in required time frames, spatial scales and file formats; and (iii) insufficient knowledge of how to interpret synthetic aperture radar (SAR) imagery for operational ocean feature applications.

In summary, the SOIN Project was a great success by all measures. It achieved its operational objectives, and did so while incorporating new capabilities and participants, and adhering to its established project timelines and budget. SOIN received much recognition and applause as it delivered new ground-breaking and operationally focused products that will one day be integrated into existing and planned defence and security operations. SOIN will be sustained through Canadian Forces MetOc operations, which are a component of Canada's maritime security operations, and through relevant components of cooperating departments. In conclusion, SOIN was not only a success attributable to its participants but to the CSA's GRIP – without that source of funding and the CSA's oversight, SOIN would never have been able to achieve its successes.

The SOIN team members are grateful to the CSA for the opportunity afforded them to advance their fields of science and create new and exciting operational capability.

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Annex A   GRIP Proposal summary tables

Id. WP 1.0

Title:	**Project management, delivery & communications**
Purpose:	project management, reporting and communications plus participation in certain technical teams

Work tasks:	1.1 meetings
	1.2 deliverables
	1.2.1 port management and financial plans into Microsoft Project
	1.2.2 written reports
	1.2.3 systems
	      (a) operational APS with required thermal data products
	      (b) SAR MetOc automatic processor Version 1.0
	      (c) 1st interim version of MetOc-Pro V1.0
	      (d) 2nd interim version of MetOc-Pro V1.0
	      (e) MetOc's MODIS X-band ground station integrated with APS
	      (f) field-trial version of MetOc-Pro V1.0
	      (g) MetOc-Pro V1.0 delivered

Expected results:	execute project as defined, on time and within budget; written reports; progress meetings & workshops; participate in technical development teams

Id. WP 2.0

Title:	**APS – Automated Processing System**
Purpose:	Obtain, install, upgrade and integrate APS system
Work tasks:	2.1 hire MetOc programmer 2.2 purchase & install APS hardware 2.3 staff training 2.4 install APS at MetOc Halifax 2.5 connect MetOc L-band (AVHRR) to APS 2.6 assess standard APS SST product suite to meet client needs – modify as required 2.7 import MERIS and MODIS offline data (ftp pull) and assess resulting APS products 2.8 connect MetOc X-band (MODIS) to APS
Expected results:	Canadian version of APS integrated into MetOc operations

Id. WP 3.0

Title:	**SAR processor & MetOc-Pro** (tentative name for proposal purpose)
Purpose:	Develop, build and install MetOc SAR processor; modify IA Pro to deliver a MetOc-specific version (MetOc-Pro)
Work tasks:	3.1 develop approach 3.2 hire contractors & assign staff 3.3 recommend hardware for purchase by MetOc Halifax 3.4 develop SAR automatic processor V1.0 & install at MetOc Halifax 3.5 upgrade/modify and install IA-Pro and CSIAPS data archive at MetOc Halifax 3.6 produce ESRI shape file of bathymetry contours at 30, 50, 100, 200, 500, 1000, 2,000 m 3.7 interim status reviews for SAR-related work (WP 3 & 4) 3.8 develop specifications for MetOc-Pro V1.0 (i.e. IA Pro for MetOc Halifax operations) 3.9 evaluate RADARSAT 2 data within SAR processor 3.10 develop interim and final versions of MetOc-Pro V1.0

Expected results:	MetOc SAR processor & MetOc-Pro installed and integrated into MetOc operations

Id. WP 4.0

Title:	**Ocean Features from SAR**
Purpose:	Develop the means to routinely detect the northern wall of the Gulf Stream plus associated eddies and fronts, using spaceborne SAR
Work tasks:	4.1 develop approach & workplan 4.2 identify & secure auxiliary data sources 4.3 order RADARSAT data 4.4 postdoctoral R&D on front indicators in SAR 4.5 integrate auxiliary surface current data 4.6 conduct field program – Gulf Stream, shelf slope, GOMOOS & SW Nova
Expected results:	Written report on how to detect mesoscale fronts and eddies with SAR for operational MetOc applications; algorithms developed during project

Id WP 5.0:

Title:	**SOIN-compatible Ocean Workstation**
Purpose:	To initiate development of SOIN-compatible MetOc ocean workstation (OWS).
Work tasks:	5.1 – Integrate MetOc Halifax auxiliary data; 5.2 – Integrate APS and SAR processor; 5.3 – Staff Training.
Expected results:	Version 1.0 of SOIN ocean workstation (integrates APS, SAR processor + auxiliary data sets).

Id WP 6.0:

Title:	**IOS**
Purpose:	West Coast Ocean Features
Work tasks:	6.1 Work Package management; 6.2 Detect, examine, and interpret oceanic frontal features off the BC coast using thermal, colour and radar imagery; 6.3 Link observed frontal features off British Columbia to coastal dynamic physical and biological processes; 6.4 Provide for implementation in IA Pro enhanced tools and frontal products.
Expected results:	Algorithms and research to assist with identification of fronts, eddies and thermal water mass boundaries on the west coast.

Id WP 7.0:

Title:	**SAR Ocean Imaging Model**
Purpose:	To develop a Canadian SAR imaging model for ocean features. The interaction of the sea surface with electromagnetic radiation of the frequencies, polarizations and incidence angles appropriate to spaceborne SAR sensors, in particular to RADARSAT-2 is then modeled, resulting in a predicted SAR image for the specific sea surface conditions.

Work tasks:	7.1 – Work Package Management:
	• hire personnel (Postdoctoral Fellow, MSc students);
	• develop working procedures and plan;
	• report on model status at bi-annual SOIN review meetings;
	7.2 – Conduct survey of existing SAR models:
	• assess merits of each model in the context of the requirements of the Canadian user community and for RADARSAT-2 sensor;
	• present findings to SOIN Team along with recommendation on which model to acquire;
	7.3 – Acquire agreed-to SAR model;
	7.4 – Install, modify and validate forward model:
	• rebuild model to run on RMC computing facilities;
	• modify model to run using inputs from MetOc IA Pro system and its successors for imaging parameters appropriate for RADARSAT-2 beam geometries;
	• validate model with field data and RADASRAT-2 imagery
	7.5 – Develop and validate inverse model:
	• investigate inversion feasibility and methodology;
	• recommend to SOIN Team on inversion feasibility:
	    o if feasible, code inverse model to run on RMC computing facilities using IA Pro inputs;
	    o if the inverse model is implemented, validate with field data and RADARSAT-2 imagery;
	7.6 – Integrate model into IA Pro and it successors:
	• explore feasibility and methodology for integration of the model into IA Pro;
	• recommend to SOIN Team on integration feasibility and techniques.

Expected results:	The predicted SAR image will be validated against images collected simultaneously from the SAR sensors. Many validations will be required under significantly different circumstances to gain confidence in the model. Once the model is validated, it will be inserted as an imaging tool into the SOIN operational suite.

Id WP 8.0:

Title:	**Statistical Analysis of SAR data**
Purpose:	To develop a statistical analysis capability to assist in the development of a methodology to study ocean fronts and eddies from SAR imagery.
Work tasks:	8.1 – Conduct a study of the North Wall of the Gulf Stream (NWGS) to capture its statistical properties; 8.2 – Develop an algorithm as an "add-on" package to IA Pro that allows the user to select an identified edge in RADARSAT imagery; 8.3 – Develop a "shape and location based" algorithm that can identify portions of the NWGS, along with warm-core ring, eddy, boundary or thermal/dynamic fronts; 8.4 – Test all algorithms on a set of SAR images to gauge their effectiveness.
Expected results:	Algorithms and models of locations of the Gulf Stream and eddies to assist in the detection of these features in SAR images.

Id WP 9.0:

Title:	**DRDC Atlantic**

Purpose:	Examine the extent to which SAR-derived thermal features and winds can be used to characterize the acoustic conditions for naval sonar operations.
Work tasks:	9.1 Work Package management; 9.2 Collect in situ meteorological, oceanographic, and acoustic data in the SOIN study area on a non-interfering basis during other DRDC R&D activities involving CFAV QUEST; 9.3 Predict underwater acoustic ambient noise levels using SAR-derived wind fields; 9.4 Predict underwater acoustic transmission loss through thermal fronts detected in SAR imagery.
Expected results:	Oceanographic conditions and ambient noise are two significant factors that govern the performance of naval sonar systems. This WP will assess the impact of SAR derived winds and fronts on naval sonar systems.

Annex B GRIP Quad Sheet

Canadian Space Agency / Agence spatiale canadienne

Government Related Initiatives Program – Project Overview

CSA ASC

Project Title: Spaceborne Ocean Intelligence Network (SOIN)
Status: Phase II, Year 1 of 3
Lead Depart.: Department of National Defence [MetOc Halifax]
Keywords: maritime security, meteorology, oceanography, search and rescue, RADARSAT, AVHRR, MODIS, MERIS

Concept:
- Meteorology & oceanography (METOC) operations are overwhelmed with environmental information of civilian origin that they cannot use because: (i) it is not provided in operationally-compatible time frames and formats; and (ii) there are insufficient means to automate the product generation process;
- SOIN will address these barriers to operational use by: (i) developing image analysis, image processing and auxiliary data integration tools that produce METOC products in required formats; and (ii) integrating these tools and resulting products into existing and planned operations of MetOc Halifax, the Canadian Ice Service and the Joint Rescue Coordination Centre Halifax.

Objectives:
- To advance Canada's ability to produce operational METOC products for maritime defence and civilian security-related operations;
- To research & develop operational means to monitor mesoscale coastal & oceanic fronts and eddies with spaceborne SAR;
- To provide MetOc Halifax with the operational tools & infrastructure required to achieve these goals and to distribute resulting products to other agencies.

Description and Technical Approach:
- MetOc Halifax has established two technical teams – one that focuses on products based on thermal IR and multispectral imagery, the other on SAR;
- In Phase II of the project, products produced by both teams will be integrated into the METOC ocean workstation.

Results To Date:
- Thermal IR / multispectral APS system installed at MetOc Halifax;
- APS compatible OWS at MetOc Halifax and MetOc Esquimalt;
- Statistical modelling progress;
- Coastal & ocean fronts / eddies from SAR R&D continuing

Budget:

GRIP:	$1,210,000 (29%)	
Lead Dept.:	$2,663,304 (63%)	
Partner(s):	$ 334,454 (8%)	
Total	$4,207,758	

Schedule:

Phase I Start:	FY 2007/08
Phase I End:	FY 2009/10
Phase II Start:	FY 2010/11
Phase II End:	FY 2012/13

Partners:
- DND [DRDC Ottawa, DRDC Atlantic];
- EC [Canadian Ice Service];
- DFO [Maurice Lamontagne Institute, Bedford Institute of Oceanography, Institute of Ocean Sciences]
- US Navy [Naval Research Laboratory - NASA Stennis Space Flight Center];
- Academic [Dalhousie University, Royal Military College].

Outputs for 2011-2012:
- Provision of an east coast frontal climatology
- Ongoing improvements to IA Pro, including statistical modeling;
- Commencement of SAR ocean image modeling at RMC
- Coastal & ocean fronts / eddies from SAR R&D continued;
- Extensive collection and dissemination of RADARSAT-2 data among project partners.

Canada

April 2011

Annex C   GRIP Schedule

As shown in Table 1, SOIN Phase II will be delivered as a series of WPs, with each WP having defined objectives, resources, deliverables and schedules. See the annual report for definitions of tasks and items identified in Table 1.

.WP	FY 10/11				FY 11/12				FY 12/13			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	■	■	■	■	■	■	■	■				
1.1												
1.2.1												
1.2.2												
1.2.3												
2.1		■	■	■	■	■	■	■	■	■	■	■
2.2					■	■	■	■				
2.3							■	■				
2.4							■	■	■	■		
2.5	■	■	■	■	■	■	■	■	■	■	■	■
3.1	■	■	■	■	■	■	■	■	■	■	■	■
3.2	■	■	■	■	■	■	■	■	■	■	■	■
3.3	■	■	■	■	■	■	■	■	■	■	■	■
3.4	■	■	■	■	■	■	■	■	■	■	■	■
4.1	■	■	■	■	■	■	■	■	■	■	■	■
4.2	■	■	■	■	■	■	■	■	■	■		
4.3	■	■	■	■	■	■	■	■	■	■		
4.4							■	■	■	■	■	■
5.1	■	■	■	■	■	■	■	■	■	■	■	■
5.2	■	■	■	■	■	■						
5.3	■	■	■	■	■	■	■	■				
5.4	■	■	■	■	■	■	■	■	■	■	■	
5.5					■	■	■	■	■	■	■	
6.1	■	■	■	■	■	■	■	■	■	■	■	■
6.2		■	■	■	■	■	■	■	■	■	■	■
6.3					■	■	■	■	■	■	■	■
6.4					■	■	■	■				
7.1	■	■	■	■	■	■	■	■	■	■	■	■
7.2	■	■	■	■								
7.3			■	■								
7.4					■	■	■	■				
7.5						■	■	■	■	■		
7.6								■	■	■		
8.1	■	■	■	■	■	■	■	■	■	■	■	■
8.2	■	■	■	■	■	■	■					
8.3			■	■	■	■	■	■	■	■	■	
8.4	■	■	■	■	■	■	■	■	■	■	■	
9.1									■	■	■	■
9.2	■	■	■	■	■	■	■	■				
9.3					■	■	■	■	■	■		
9.4					■	■	■	■	■	■	■	■

Annex D   Ocean Feature Recognition Training

In February 2013, Chris Jones delivered a one-day course in ocean SAR-feature recognition to sonar operators at MetOc Halifax. The course consisted of two sessions. The first session included a basic description of wind-generated surface roughness that produces backscatter from the ocean surface, the relationships between roughness and sea-surface temperature as mediated by the marine atmospheric boundary layer, and a depiction of the basic features of the Gulf Stream (see Figure 38 for examples of meanders, warm rings, etc.) that most often produce signatures in RADARSAT-2 (R2) images. A systematic approach to computer-assisted feature recognition was introduced in the second session. The approach was first demonstrated in detail, followed by a number of case studies with which the participants were encouraged to apply their newfound knowledge and develop their analytic skills.

In each case study, participants were first shown a large-scale image of the western Atlantic onto which a land mask, the GSNWSR, the 200-meter isobath, and the SAR image were rendered. Course participants were then asked to judge whether they might expect to see Gulf Stream (GS) signatures in the SAR image based on its location. Participants were next shown a SAR-derived wind speed image and a nearest-in-time surface analysis and they were trained to use these images to judge where in the SAR image wind speed was too high (>12 m/s) to expect recognizable Gulf Stream signatures, and to identify any features in the SAR image that corresponded to charted atmospheric fronts. R2 Images that were judged to potentially contain recognizable GS signatures were then shown with automatically detected and classified Canny edges marked on. Participants were then shown how to use the Canny edges identified as SST front, in combination with their knowledge of basic GS features, to recognize signatures such as GS meanders, warm core rings, cold intrusions, and the GSNW. A SAR image with GS features marked on was then shown and compared with the nearest-in-time satellite SST data for validation. The SST image served as a proxy for the latest OFA image, which, in the operational setting, will be used to provide additional contextual information and/or validation of a marked-up image. To provide more practice, the participants were provided with 20 additional case studies to analyze on their own time.

Two tasks remain that require some attention before R2 images can be fully incorporated in OFA production. First, sonar operators require training in the use of IA Pro to produce images similar to those used in the training described above. Second, an appropriate method of drawing R2 SST front signatures onto an OFA needs to be developed. These tasks were left in the capable hands of MetOc staff, and are currently underway. Chris Jones will be continually available for consultation on these matters.
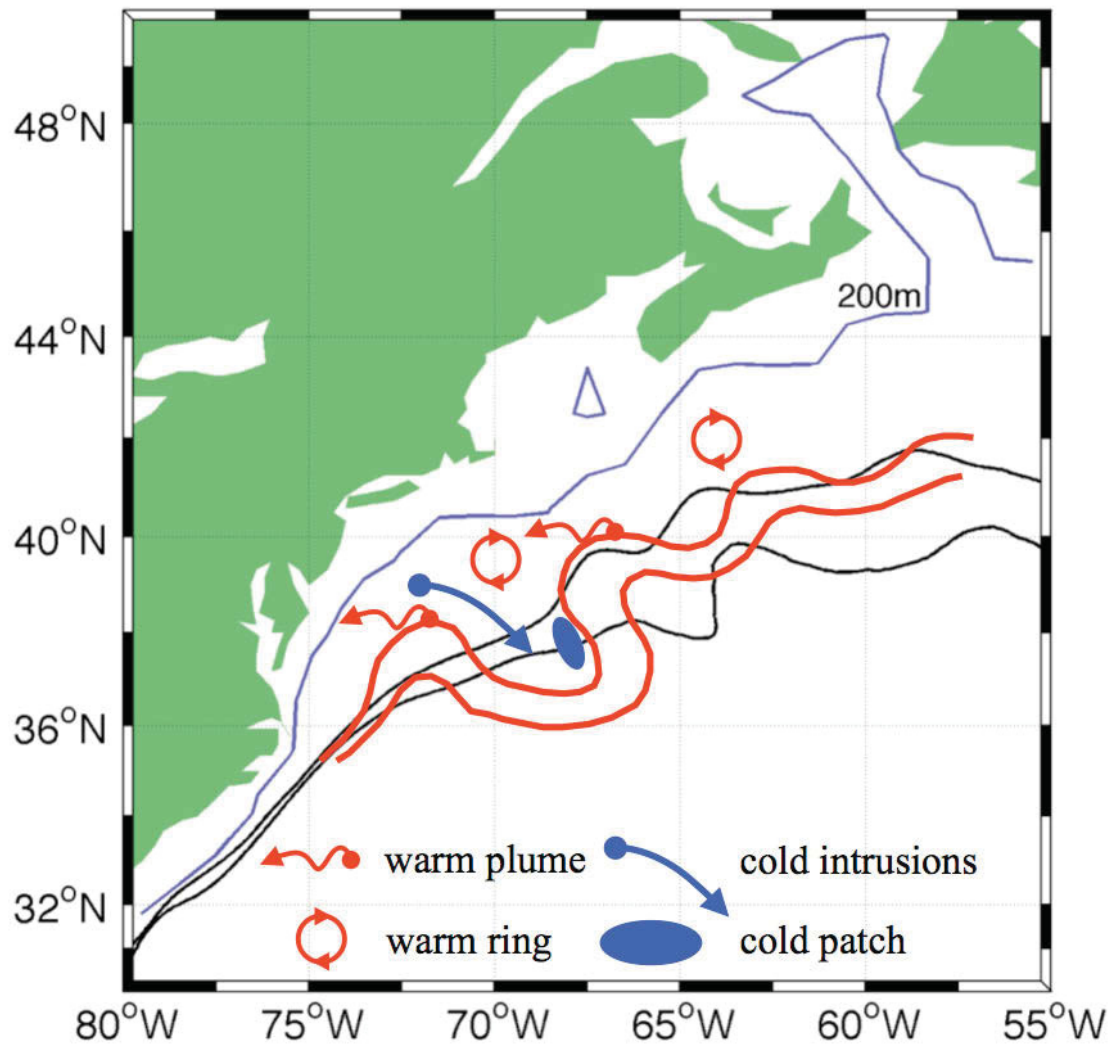
Figure 38 –Example training diagram depicting large-scale Gulf Stream features that are easily identifiable.

Figure 38 is a conceptual diagram presented in the first of two training sessions that depicts large-scale GS features that most commonly produce easily recognizable signature in R2 images. The envelope of black curves is the GSNWSR, and the thick red lines represent the path of the Gulf Stream – other symbols are labeled on the diagram. Several examples of warm plume, warm ring, cold intrusion, and cold patch signatures were included in the training material. The location of an image with respect to the land mask, the GSNWSR and the 200 m isobath provides important contextual information. For example, images that do not intersect a portion of the GSNWSR, or those that occur close to the coast or mainly on the continental shelf have a very low probability of exhibiting a GS feature. Culling such images helps to reduce the probability of incorrect assessment, and locating an image with respect to these features provides operators with a firm starting point for their analysis.

List of acronyms

2CMV	Two-Colour Multi-View
3CMV	Three-Colour Multi-View
AMSR-E	Advanced Microwave Scanning Radiometer - EOS
AOR	Area of Responsibility
APS	Automated Processing System (NRL Stennis software)
ASCII	American Standard Code for Information Interchange
ASW	Anti-Submarine Warfare
AVHRR	Advanced Very High Resolution Radiometer (sensor on NOAA's polar orbiting satellites)
BIO	Bedford Institute of Oceanography (DFO, Halifax, Nova Scotia)
C-APS	Canadian APS
CB	Composite Bragg
CCRS	Canada Centre for Remote Sensing (NRCan, Ottawa)
CF	Canadian Forces
CFAV	Canadian Forces Auxiliary Vessel
CIS	Canadian Ice Service (Environment Canada)
CMOD	C-band Model
CODAR	Coastal Ocean Dynamics Applications Radar (HF radar)
CSA	Canadian Space Agency (Industry Canada)
CSIAPS	Commercial Satellite Imagery Acquisition Planning System (DRDC Ottawa software)
CTD	Conductivity-Temperature-Depth
DFO	Department of Fisheries and Oceans
DND	Department of National Defence
DRDC	Defence Research & Development Canada (agency of DND)
ECR	External Client Report
EMOC	Enhanced Marine Order Coordination
EO	Electro-Optical
ES	Environmental Sensing (a Polar Epsilon capability)
ESA	European Space Agency
FY	Fiscal Year

GEM	Global Environmental Multiscale
GIS	Geographic Information System
GMF	Geophysical Model Function
GRIP	Government Related Initiatives Program (CSA)
HF	High Frequency
HH	Horizontal transmit, Horizontal receive polarization
HTML	Hypertext Markup Language
IA Pro	Image Analyst Pro (DRDC Ottawa software)
IML	Institut Maurice Lamontagne (DFO, Mont-Joli, Québec)
IOS	Institute of Ocean Sciences (DFO, Sidney, British Columbia)
IR	Infra-Red
JRCC	Joint Rescue Coordination Centre (DND and DFO) Halifax
LCMM	Life Cycle Materiel Manager
LPC	Latest Pixel Composite
MABL	Marine Atmospheric Boundary Layer
MARLANT	Maritime Forces Atlantic
MC	Mean Composite
MCC	Mesoscale Cellular Convection
MERIS	Medium Resolution Imaging Spectrometer (sensor on ESA's ENVISAT satellite)
MetOc	Meteorology and Oceanography
MODIS	Moderate Resolution Imaging Spectroradiometer (sensor on NASA's Terra and Aqua satellites)
MSOC	Maritime Security Operations Centre
NDBC	National Data Buoy Center
NEODF	National Earth Observation Data Framework
NERSC	Nansen Environmental and Remote Sensing Center
NOAA	National Oceanic and Atmospheric Administration (USA)
NRCS	Normalized Radar Cross Section
NRL	Naval Research Laboratory (USA)
NRTSD	Near Real Time Ship Detection (a Polar Epsilon capability)
NWGS	North Wall of the Gulf Stream
OFA	Ocean Feature Analysis

OGD	Other Government Department
OWS	Ocean Workstation
PE	Polar Epsilon
PM	Project Management
QuikSCAT	Refers to the SeaWinds Scatterometer aboard NASA's Quick Scatterometer satellite mission
R&D	Research and Development
REA	Rapid Environmental Assessment
RIM	Radar Imaging Model
RMC	Royal Military College of Canada
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
SCNB	ScanSAR Narrow B
SFMR	Stepped Frequency Microwave Radiometer
SOFDT	SAR Ocean Feature Detection Tool (an IA Pro tool)
SOIN	Spaceborne Ocean Intelligence Network
SST	Sea-Surface Temperature
UTC	Universal Time Coordinated
VV	Vertical transmit, Vertical receive polarization
VW-SIED	Variable Window - Single-Image Edge Detection
WIM	Windows Image Manager
WP	Work Package
YOY	Young of the Year

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The Spaceborne Ocean Intelligence Network (SOIN) was a six-year research and operational development project that addressed barriers to developing and implementing oceanographic applications derived from Earth-observation sensors such as RADARSAT-2 and MODIS, capabilities that were provided by the Polar Epsilon Project, combined with existing AVHRR and MERIS sensor data. The project was divided into two phases. The 2007/08 to 2009/10 three-year Phase I focused on developing state-of-the-art sea-surface temperature and diver-visibility products, operational tools, supporting infrastructure and an ability to detect thermal fronts, eddies and water mass boundaries with RADARSAT-2 synthetic aperture radar (SAR) imagery. The 2010/11 to 2012/13 three-year Phase II focused on operationalization and implementation of SOIN capabilities. The SOIN project began in June 2007 with funding provided by the Canadian Space Agency through its Government Related Initiatives Program. This report provides the SOIN Final Activity Report of project activities and accomplishments from 2007 to 2013.

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SOIN; RADARSAT; synthetic aperture radar; SAR; SST; ocean features; METOC

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