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Satellite Automatic Identification System (SAIS) Performance Modelling and Simulation

Final Findings Report

Garrett Parsons, James Youden, Bing Yue and Chris Fowler

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The initial version of this report was completed in November 2012. Following supplemental work, Version 2 of this report was completed in March 2013.

Defence R&D Canada – Ottawa

Canada

Contract Report
DRDC Ottawa CR 2013-096
December 2013

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The initial version of this report was completed in November 2012. Following supplemental work, Version 2 of this report was completed in March 2013.

Defence R&D Canada – Ottawa

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This document on Satellite Automatic Identification System (SAIS) Performance Modelling and Simulation is a deliverable of the Design of an Integrated AIS Sensor on a Radar Satellite (DIASRS) TDP.

Abstract

An Automatic Identification System (AIS) capability on the RADARSAT Constellation Mission (RCM) will enhance the Canada First Defence Strategy goals of conducting national and continental operations and defending Canada. Key to understanding this is the ability to model and simulate satellite AIS (SAIS) performance characteristics. This report provides an overview of a statistical simulation implemented by C-CORE to evaluate SAIS performance. Included is a discussion on the approach and methodology employed with results presented for the specific case of the proposed AIS payload on the RCM. The model is driven by a global ship density map (GSDM) derived from an AIS database developed over the course of this project. The database and derived products are generated from data provided by Defence Research and Development Canada – Ottawa (DRDC Ottawa) for this purpose including both SAIS data (from exactEarth (eE)) and terrestrial AIS data from the Maritime Safety and Security Information System (MSSIS). C-CORE has implemented a model based on previous analytical and stochastic model approaches reported in the literature. Model implementation relies on the AIS database and derived products, the satellite orbit and resulting field of view (FOV) for the AIS and synthetic aperture radar (SAR) sensors to generate probability of detection values for AIS and SAR on an area basis. Various options are available to select various imaging modes of the sensor and to vary the ability of the AIS sensor to handle message collisions. Additionally, the model incorporates the ability to utilize the two existing AIS channels (Channels 1 and 2) and the pending new AIS channels (Channels 3 and 4) dedicated to SAIS reception and not transmitted by vessels near shore (i.e., within the range of coastal base stations). A series of scenarios for RCM and RADARSAT-2 (RSAT2) with exactView-1 (EV1) have been run in various areas of interest (AOIs). Results show that the RCM configuration with co-located SAR and AIS sensors, utilizing four-channel AIS, will provide very good ship detection performance for most areas beyond base station coverage areas.

Résumé

La mise en œuvre d'un Système d'identification automatique (SIA) dans le cadre de la mission de la Constellation RADARSAT (MCR) contribuera à l'atteinte des objectifs de la Stratégie de défense Le Canada d'abord quant à la conduite d'opérations à l'échelle nationale et continentale et à la défense du Canada. La capacité à modeler et à simuler les caractéristiques de rendement du SIA par satellite est essentielle à la compréhension de cet énoncé. Le présent rapport donne un aperçu de la simulation statistique mise en œuvre par C-CORE pour évaluer le rendement du SIA par satellite. Vous trouverez ci joints un document de discussion sur l'approche et la méthodologie employées ainsi que les résultats présentés pour le cas spécifique de la charge utile du SIA proposée pour la MCR. Le modèle est dicté par la carte de la densité globale des navires produite à partir d'une base de données du SIA et conçue dans le cadre de ce projet. La base de données et les produits dérivés sont créés à partir de données fournies par Recherche et développement pour la défense Canada – Ottawa (RDDC Ottawa) à cet effet, y compris les données du SIA (provenant d'exactEarth [eE]) et les données terrestres du SIA provenant du Système d'information sur la sécurité et la sûreté maritimes (MSSIS). C-CORE a mis en œuvre un modèle fondé sur le modèle analytique et stochastique antérieur envisagé mentionné dans la littérature. La mise en œuvre du modèle repose sur la base de données du SIA et les produits dérivés, l'orbite des satellites et le champ de visée qui en résulte pour le SIA et les capteurs du radar à synthèse d'ouverture (SAR) afin de générer des valeurs de probabilité de détection pour le SIA et le SAR zone par zone. Diverses options sont offertes quant à la sélection des différents modes d'imagerie du capteur et à la variation de la capacité du capteur du SIA à traiter les collisions de messages. En outre, le modèle offre la possibilité d'utiliser les deux canaux du SIA existants (canaux 1 et 2) et les nouveaux canaux du SIA à venir (canaux 3 et 4) destinés à la réception du SIA et qui ne sont pas transmis par les navires situés près de la côte (p. ex., dans le rayon des stations de base côtières). Une série de scénarios relatifs à la MCR et aux satellites RADARSAT-2 (RSAT2) et exactView-1 (EV1) ont été réalisés dans divers centres d'intérêt (CI). Les résultats démontrent que la configuration de la MCR, dans laquelle on utilise des capteurs du SAR et du SIA copositionnés et quatre canaux du SIA, permettra d'obtenir un excellent rendement en matière de détection de navires pour la plupart des zones situées au-delà des zones de couverture des stations de base.

Executive summary

Satellite Automatic Identification System (SAIS) Performance Modelling and Simulation: Final Findings Report

Garrett Parsons; James Youden; Bing Yue; Chris Fowler; DRDC Ottawa CR 2013-096; Defence R&D Canada – Ottawa; December 2013.

Introduction: The Automatic Identification System (AIS) is an International Maritime Organization (IMO) mandated safety system designed as a line-of-sight (LOS) ship collision avoidance system based on low power, very high frequency (VHF) transponder broadcasts. Under the IMO's Safety of Life at Sea (SOLAS) convention, AIS transponders are required carriage for internationally voyaging ships with gross tonnage of 300 tons or more. It is estimated that there are over 100,000 ships worldwide with AIS transponders installed. While the prime purpose of the system is collision avoidance, broadcast information is very useful for surveillance and security purposes. Typical shore-based and vessel-mounted receivers are limited to LOS reception ranges on the order of 40 nautical miles. The advent of AIS receivers on satellites eliminates this range constraint providing global coverage.

This document provides the final findings report on the development of a Satellite Automatic Identification System (SAIS) statistical performance model. This model and simulation was used to assess the expected performance of an AIS receiver payload on the RADARSAT Constellation Mission (RCM). This work was conducted as a part of the Design of an Integrated AIS Sensor on a Radar Satellite Technology Demonstration Program (DIASRS TDP) project. The work described herein contributes to demonstrating the feasibility of implementation and the capability to enhance identification of ships in areas of interest (AOIs) to the Department of National Defence/Canadian Forces (DND/CF) in Canada and other regions worldwide.

The goals associated with this project included:

1. Development of a model that will incorporate statistical models from space-based AIS data sources and simulate the major factors affecting the quality of the AIS radio frequency link;

2. Identify issues and expected performance associated with the combination of space-based AIS and RADARSAT-2 (RSAT2) vessel detection data; and

3. Establish the expected performance for AIS on RCM.

The report provides an overview of the work carried out including development of an AIS database, the approach and methodology applied to statistical modelling and simulation, simulation results for RCM and RSAT2 scenarios and findings realized.

AIS Database: Defence Research and Development Canada (DRDC) Ottawa provided AIS data from both SAIS and terrestrial sources from which a database of information was derived. The data were primarily from exactEarth (eE) and their SAIS assets while the terrestrial AIS data was from the Maritime Safety and Security Information System (MSSIS). The database of AIS messages was parsed and filtered to generate required vessel information from which various

statistical distributions were derived. Critical among these was the development of a Global ship density map (GSDM) which forms the basis for the performance modelling and simulation. The GSDM provides the expected number of ships in each 1° by 1° grid cell for the entire globe. In addition to the GSDM, a number of relevant parameter distributions were also derived for use in the model. Derived information such as the GSDM and ship length distributions were compared against other available data sources where possible. It was found that the derived information compared well with other sources and was used for the purposes of this project.

Modelling and Simulation: C-CORE has implemented a model based on previous analytical and stochastic model approaches reported in the literature. Model implementation relies on the AIS database and derived products, particularly the GSDM to drive the simulation. The number of ships within the synthetic aperture radar (SAR) swath and AIS field of view (FOV) is based on the GSDM. Model development evolved to include three different implementations to simulate, basic, enhanced and decollider type AIS receiver implementations. The basic and enhanced receiver implementations use a simplified approach utilizing a tolerable number of collisions applied on a per message slot basis. The number of allowed collisions is a variable set by the user to simulate varying levels of receiver sophistication. The decollider implementation uses a statistics-based model as a basis for determining AIS receiver performance. A number of parameters are used in the model and are available to allow specific aspects of a receiver to be tuned to match actual receiver performance as simulated or represented by actual performance data as it becomes available.

Both the SAR swath location and the AIS FOV are based on the satellite position as determined by the propagation of satellite Two-Line Elements (TLEs) to the specific start time and duration of the acquisition. SAR swath size is determined from the incidence angle as determined from the SAR beam mode and beam number. The AIS FOV is calculated based on the view from the satellite to the geometrical horizon and is calculated at the centre point for each step along the satellite track. Within the AIS FOV, ships within the region that are visible for the entire specified duration of the AIS acquisitions are identified and used as the basis for calculating the AIS probability of detection.

Vessel detection probabilities using the SAR are calculated for ships located within the SAR swath using DRDC Ottawa Ship Detectability code.

The simulation calculates the probability of detection of ships within the SAR swath and AIS FOV. For the SAR swath, the various joint, marginal and conditional distributions are computed for the SAR and AIS detections. For the AIS, the probability of detection within the region which stays within the AIS FOV for at least five minutes is also computed and given in the output file.

In interpreting the detection capabilities, the number of ships in the AIS FOV for each step along the AIS satellite track is the most significant factor in determining the probability of detection. Within the SAR swath, $P(SAR)$, $P(AIS)$, $P(AIS|SAR)$, $P(AIS \cup SAR)$, and $P(AIS \cap SAR)$, in particular, all readily indicate the detection capabilities.

Results and Analysis: This project has seen the development of a performance modelling and simulation tool useful for evaluating various combinations of satellite-based AIS and SAR sensor arrangements. A significant database of AIS messages has been compiled, from which a number of characteristic statistical distributions of ship data has been derived. While these derived results are required to use the simulation tool, the database and derived products constitute a very useful data set in their own right.

Several model runs were executed to provide an assessment of AIS performance on RCM and for the combination of RSAT2 with a separate AIS satellite. Various scenarios were developed to provide a level of understanding of expected detection performance. Several model runs were executed to provide an assessment of AIS performance on RCM looking at both the two-channel and four-channel configurations planned. Various scenarios were developed to provide a level of understanding of expected detection performance. Results were generated and analyzed for ten specified AOIs of interest to DRDC. Model runs were also conducted in each AOI to evaluate the potential impact of the three satellite constellation arrangement for RCM.

Work has also been done to provide an assessment of the performance expected when temporally disparate AIS and SAR sensor data are used for target identification. A probability of association metric is developed and calculated for this purpose.

Based on the various performance metrics calculated through simulation and modelling, a methodology has been applied to provide an interpretation of these results in the context of "real-world" maritime surveillance needs.

Conclusions: The results of this work give a clear indication that using an AIS receiver with the ability to decollide messages, RCM will provide very good ship detection performance on AIS Channels 1 and 2 for the Canadian domestic AOIs and other low to moderate ship density (up to about 6,000 ships in the AIS FOV) AOIs modelled. For the Canadian domestic AOIs extending out to 1,200 nm on the east and west coasts, two-channel AIS will provide very good coverage with expected probability of detection (POD) on the order of 90%. For high ship density locations in other global AOIs, performance is shown to be significantly lower as the number of ships in the field of view increases. In the highest density areas with ship counts in excess of 30,000 within the FOV, the POD for two-channel AIS is effectively nil.

Conventional two-channel AIS systems using AIS Channels 1 and 2 are significantly influenced by the number of ships in the FOV. The transmission rates for vessels transmitting on these channels are quite high when under way resulting in extremely high message volume, particularly in high traffic areas. Based on the results obtained using the simulation tool, the use of an AIS receiver with AIS message decollision capability on RCM significantly improves AIS POD over the basic receiver designs currently deployed; however, simulation outputs indicate that the decollider receiver is still easily overwhelmed in high density areas. This can be somewhat mitigated by using the combined AIS detections from the three satellite constellation acquired within a short (approximately one hour) time period for a given AOI to improve AIS POD. Simulation results using the pending AIS Channels 3 and 4 indicate consistently high AIS PODs for all AOIs. As these channels will only be used beyond the range of coastal base stations and utilize lower transmission rates, performance is much better than the case with AIS Channels 1 and 2 alone. The advent of this capability offers extremely good vessel detection results for areas beyond coastal station coverage. As such, four-channel AIS on RCM will be a critical element in achieving very reliable ship detection performance in or around high density areas beyond terrestrial base station coverage. Complete operational coverage, especially in high traffic densities near shore, will require terrestrial AIS base station networks to augment SAIS coverage offshore.

Co-location of AIS and SAR sensors, as with RCM, is shown to offer much better target association probabilities than that of sensors located on separate satellites. As the temporal difference between the AIS and SAR acquisitions increases, probability of association declines quickly, especially for regions of higher ship density. Maintaining target tracks using this data becomes difficult as a result.

Overall, two-channel AIS co-located with the SAR on RCM offers very good ship detection performance under most circumstances for low to moderate ship density AOIs. With the advent of AIS Channels 3 and 4, the built-in four-channel AIS capability planned for RCM will provide improved ship detection performance in all AOIs, with the most profound impact in areas with very high ship density. When combined with terrestrial networks, four-channel SAIS will provide excellent ship detection performance in all AOIs.

Overall, the goals of this project have been achieved. The project has realized a statistics-based model and simulation tool that provides a means to evaluate detection probabilities for a range of AIS and SAR sensor combinations. An integral part of model development was the generation of an AIS database and related statistical distributions of ship information derived from it. The database in itself provides a valuable source of information for use beyond the modelling need of this project.

Through the course of this work, limitations and opportunities for future efforts have been identified. Consideration to pursuing these items to extend understanding of detection performance and model capability is recommended.

Sommaire

Satellite Automatic Identification System (SAIS) Performance Modelling and Simulation: Final Findings Report

Garrett Parsons; James Youden; Bing Yue; Chris Fowler ; DRDC Ottawa CR 2013-096 ; R & D pour la défense Canada – Ottawa; décembre 2013.

Introduction ou contexte : Introduction : Le Système d'identification automatique (SIA) est un système de sécurité exigé par l'Organisation maritime internationale (OMI) et conçu comme un système d'évitement des collisions entre navires en visibilité directe qui utilise les transmissions de transpondeurs de très haute fréquence (VHF) et de faible puissance. En vertu de la Convention internationale pour la sauvegarde de la vie humaine en mer de l'OMI, les navires qui sillonnent les eaux internationales et dont le tonnage brut est de 300 tonnes ou plus doivent être équipés de transpondeurs du SIA. On estime à plus de 100 000 le nombre de navires équipés de transpondeurs du SIA dans le monde. Alors que ce système vise essentiellement à éviter les collisions, la transmission d'informations est fort utile dans le cadre d'opérations de surveillance et de maintien de la sécurité. Habituellement, la portée de réception des récepteurs côtiers et des récepteurs présents à bord des navires se limite à celle en visibilité directe, soit 40 milles marins. L'arrivée de récepteurs du SIA par satellite élimine cette contrainte de portée et permet d'obtenir une couverture globale.

Le présent document contient le rapport de constatations final sur l'élaboration d'un modèle de rendement statistique pour le SIA. Ce modèle a été utilisé pour évaluer le rendement prévu d'un récepteur de données utiles du SIA dans le cadre de la MCR. Ces travaux ont été réalisés dans le cadre d'un projet de conception d'un capteur du SIA intégré à un satellite-radar du Programme de démonstration de technologies. Les travaux décrits aux présentes permettent de démontrer les possibilités quant à la mise en œuvre d'un système d'identification des navires et à l'amélioration de celui-ci dans des CI pour le ministère de la Défense nationale et les Forces canadiennes au Canada et dans d'autres régions du monde.

Voici les objectifs associés à ce projet :

1. Élaboration d'un modèle qui intégrera des modèles statistiques fondés sur des sources de données spatiales du SIA et qui simulera les principaux facteurs pouvant avoir des répercussions sur la qualité de la liaison par radiofréquence du SIA.

2. Détermination des enjeux relatifs à la combinaison d'un SIA fondé sur des données spatiales et de données de détection de navires du satellite RADARSAT-2 (RSAT2), ainsi que le rendement prévu.

3. Détermination du rendement prévu du SIA dans le cadre de la MCR.

Le rapport donne un aperçu des travaux réalisés, notamment la création d'une base de données du SIA, l'approche et la méthodologie utilisées lors de la mise en œuvre de la modélisation statistique et de la simulation, les résultats de la simulation obtenus dans le cadre de la MCR, les scénarios relatifs au RSAT2 et les conclusions tirées.

Base de données du SIA : RDDC Ottawa a fourni des données du SIA, provenant de sources spatiales et terrestres, à partir desquelles on a créé une base de données. Les données provenaient surtout d'exactEarth (eE) et des installations du SIA tandis que les données terrestres du SIA provenaient du MSSIS. La base de données des messages du SIA a été analysée et filtrée afin de générer l'information sur les navires requise à partir de laquelle les diverses distributions statistiques ont été effectuées. Parmi les activités les plus importantes, notons la production d'une carte de la densité globale des navires qui constitue la base de la modélisation du rendement et de la simulation. Cette carte indique le nombre de navires prévu dans chaque maille de 1° par 1° pour l'ensemble du globe. En plus de la carte de la densité globale des navires, un certain nombre de paramètres de distribution pertinents ont également été établis en vue de leur utilisation avec le modèle. On a comparé l'information dérivée comme la carte de la densité globale des navires et la répartition des longueurs de navires avec d'autres sources de données lorsque cela était possible. On a constaté que l'information dérivée se mesurait bien à d'autres sources et elle a été utilisée dans le cadre du présent projet.

Modélisation et simulation : C-CORE a mis en œuvre un modèle fondé sur le modèle analytique et stochastique antérieur envisagé mentionné dans la littérature. La mise en œuvre du modèle repose sur la base de données du SIA et les produits dérivés, plus particulièrement sur la carte de la densité globale des navires lors de la réalisation de la simulation. Le nombre de navires présents dans la fauchée du SAR et le champ de visée du SIA est établi selon les données de la carte de la densité globale des navires. L'élaboration du modèle a évolué de façon à y inclure trois types de mise en œuvre différents afin de simuler la mise en application d'un récepteur du SIA de base, d'un récepteur du SIA amélioré et d'un récepteur du SIA permettant de corriger les collisions. La mise en œuvre d'un récepteur de base et d'un récepteur amélioré fait appel à une approche simplifiée qui utilise un nombre de collisions tolérable mis en application selon un créneau de message. Le nombre de collisions permis est une variable établie par l'utilisateur visant à simuler différents niveaux de sophistication du récepteur. La mise en œuvre d'un récepteur permettant de corriger les collisions fait appel à un modèle fondé sur des statistiques qui sert de base à l'évaluation du rendement du récepteur du SIA. De nombreux paramètres sont utilisés dans le modèle et ceux-ci permettent de régler certains aspects d'un récepteur de façon à ce qu'il corresponde au rendement du récepteur réel simulé ou représenté par des données sur le rendement réelles au fur et à mesure qu'elles deviennent disponibles.

L'emplacement de la fauchée du SAR et le champ de vision du SIA sont établis selon la position du satellite qui est déterminée en fonction de la propagation des Two-Line Elements (TLE) du satellite au début de la transmission et de la durée de l'acquisition. La taille de la fauchée du SAR est déterminée selon l'angle d'incidence qui est établi en fonction du mode faisceau et du numéro du faisceau du SAR. Le champ de visée du SIA est calculé selon les images du satellite de l'horizon géométrique et selon un point principal de chaque étape le long de la trace du satellite. Dans le champ de vision du SIA, les navires présents dans la région qui sont visibles pendant tout le processus d'acquisition du SIA sont identifiés et servent de base au calcul de la probabilité de détection du SIA.

Les probabilités de détection de navires au moyen du SAR sont calculées pour les navires situés dans la fauchée du SAR à l'aide du code de détectabilité de RDDC Ottawa.

La simulation permet de calculer la probabilité de détection de navires dans la fauchée du SAR et le champ de vision du SIA. Pour ce qui est de la fauchée du SAR, le joint divers ainsi que les distributions marginale et conditionnelle sont évalués pour les détections du SAR et du SIA. Pour ce qui est du SIA, la probabilité de détection dans la région qui demeure dans le champ de vision du SIA pendant au moins cinq minutes est également évaluée puis indiquée dans le fichier de sortie.

Lors de l'interprétation des capacités de détection, le nombre de navires présents dans le champ de vision du SIA à chacune des étapes le long de la trace du satellite du SIA est l'élément le plus important dans le cadre de l'évaluation de la probabilité de détection. Dans la fauchée du SAR, les paramètres P(SAR), P(SIA), P(SIA|SAR), P(SIA∪SAR) et P(SIA∩SAR), en particulier, indiquent tous facilement les capacités de détection.

Résultats et analyse : Dans le cadre de ce projet, on a élaboré un outil de modélisation du rendement et de simulation utilisé dans le cadre de l'évaluation de diverses combinaisons de capteurs du SIA et du SAR satellitaires. Une riche base de données regroupant les messages du SIA a été établie à partir de laquelle un certain nombre de distributions statistiques caractéristiques relatives aux données sur les navires ont été tirées. Bien que ces résultats dérivés soient nécessaires à l'utilisation de l'outil de simulation, la base de données et les produits dérivés constituent un ensemble de données fort utile séparément.

Plusieurs simulations du modèle ont été exécutées afin d'évaluer le rendement du SIA dans le cadre de la MCR et de la combinaison du RSAT2 avec un satellite du SIA distinct. Divers scénarios ont été élaborés afin de fournir un niveau de compréhension du rendement de détection prévu. Plusieurs simulations du modèle ont été exécutées afin d'évaluer le rendement du SIA dans le cadre de la MCR au cours desquelles on a examiné les configurations à deux canaux et à quatre canaux prévues. Divers scénarios ont été élaborés afin de fournir un niveau de compréhension du rendement de détection prévu. On a généré puis analysé des résultats pour 10 CI particuliers présentant un intérêt pour RDDC. Des simulations du modèle ont également été exécutées dans chaque CI afin d'évaluer les répercussions possibles des trois combinaisons de constellation de satellites dans le cadre de la MCR.

Des travaux ont également été réalisés afin d'évaluer le rendement prévu lorsque des données des capteurs du SIA et du SAR provisoirement disparates sont utilisées pour l'identification de cibles. Une probabilité d'association de paramètres est élaborée et calculée à cet effet.

En se fondant sur les divers paramètres relatifs au rendement qui ont été calculés au cours de la simulation et de la modélisation, on a mis en application une méthodologie afin de fournir une interprétation de ces résultats dans le « vrai » contexte de la surveillance maritime.

Conclusions : Les résultats de ces travaux indiquent clairement que grâce à l'utilisation d'un récepteur du SIA pouvant corriger les collisions pour les messages, la MRC produira un très bon rendement quant à la détection des navires sur les canaux 1 et 2 du SIA pour les CI canadiens et d'autres CI de densité de navires faible à modérée modélisés (jusqu'à environ 6 000 navires dans le champ de visée du SIA). En ce qui concerne les CI canadiens se prolongeant jusqu'à 1 200 NM sur les côtes est et ouest, un SIA à deux canaux permettra d'assurer une très bonne couverture et offrira une probabilité de détection prévue de l'ordre de 90 p. 100. Quant aux emplacements à densité de navires élevée que l'on trouve dans d'autres CI à l'échelle mondiale, on constate que le rendement est beaucoup plus faible lorsque le nombre de navires dans le champ de visée augmente. Dans les emplacements où la densité est la plus élevée et où le nombre de navires est supérieur à 30 000 à l'intérieur du champ de visée, la probabilité de détection pour le SIA à deux canaux est en réalité nulle.

Les systèmes conventionnels du SIA à deux canaux utilisant les canaux 1 et 2 du SIA sont notablement influencés par le nombre de navires dans le champ de visée. Les taux de transmission pour les navires utilisant ces canaux sont plutôt élevés, ce qui occasionne un volume de messages extrêmement important, surtout là où la circulation est dense. D'après les résultats obtenus au moyen de l'outil de simulation, l'utilisation d'un récepteur du SIA pouvant corriger les collisions pour les messages du SIA dans le cadre de la MRC améliore notablement la probabilité de détection du SIA par rapport aux concepts de récepteurs de base actuellement mis en œuvre; toutefois, les résultats de simulation indiquent que la capacité du récepteur pouvant corriger les collisions devient rapidement insuffisante là où la circulation est dense. Ceci peut être quelque peu atténué par l'utilisation de capacités jumelées du SIA provenant de la constellation des trois satellites acquise dans un court laps de temps (environ une heure) pour un CI donné afin d'améliorer la probabilité de détection du SIA. Les résultats de simulation fondés sur les canaux 3 et 4 à venir du SIA montrent des probabilités de détection du SIA constamment élevées pour tous les CI. Étant donné que ces canaux seront utilisés uniquement par-delà le rayon des stations de base côtières et qu'ils nécessiteront des taux de transmission moins élevés, le rendement produit sera bien meilleur que le rendement produit au moyen des seuls canaux 1 et 2 du SIA. L'invention de cette capacité offre des résultats de détection des navires extrêmement bons pour ce qui est des zones situées au-delà de la zone de couverture des stations côtières. Ainsi, le SIA à quatre canaux utilisé dans le cadre de la MCR jouera un rôle essentiel dans l'obtention d'un rendement de détection des navires très fiable à l'intérieur des zones où la circulation est dense ou autour de ces zones, situées au-delà la zone de couverture des stations de base terrestres. Pour obtenir une couverture opérationnelle complète, particulièrement dans les zones situées près de la côte où la circulation est dense, il faudra mettre en place des réseaux pour les stations de base du SIA terrestres afin d'augmenter la couverture du SIA au large.

On présente le copositionnement des capteurs du SIA et du SAR, ainsi que dans le cadre de la MCR, afin d'obtenir de bien meilleures probabilités d'association de cibles que lorsque les capteurs sont positionnés sur des satellites distincts. Alors que l'écart temporel entre les acquisitions du SIA et du SAR augmente, la probabilité d'association diminue rapidement, particulièrement dans les régions où la densité de navires est plus élevée. C'est pourquoi il est plus difficile de maintenir la poursuite de cible à l'aide de ces données.

De manière générale, le copositionnement de deux canaux du SIA avec le SAR dans le cadre de la MCR permet d'obtenir un très bon rendement en matière de détection de navires dans la plupart des cas pour les CI de densité de navires faible à modérée. Avec l'avènement du SIA à trois et à quatre canaux, la capacité du SIA à quatre canaux intégrée prévue dans le cadre de la MCR améliorera le rendement en matière de détection de navires dans tous les CI et aura les répercussions les plus importantes sur les zones où la densité des navires est très élevée. Une fois combiné aux réseaux terrestres, le SIA à quatre canaux offrira un excellent rendement en matière de détection de navires dans l'ensemble des CI.

Globalement, les objectifs du présent projet ont été atteints. Dans le cadre de ce projet, on a élaboré un modèle fondé sur des statistiques et un outil de simulation qui permettent d'évaluer les probabilités de détection pour diverses combinaisons de capteurs du SIA et du SAR. Une partie intégrante de l'élaboration du modèle a été la création d'une base de données du SIA et des distributions statistiques de l'information sur les navires qui en découle. La base de données en elle-même constitue une source d'information précieuse qui peut être utilisée pour répondre à d'autres besoins que ceux liés à la modélisation dans le cadre du présent projet.

Dans le cadre de ces travaux, on a été en mesure de cerner les limites et d'établir les possibilités en vue des travaux futurs. On recommande d'envisager la poursuite de ces travaux afin d'en apprendre davantage sur le rendement en matière de détection et la capacité de modélisation.

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1 Introduction

The Radar Data Exploitation (RDE) Group of Defence Research and Development Canada – Ottawa (DRDC Ottawa) is investigating the feasibility of implementation and the capability to enhance identification of ships in the maritime approaches to Canada, including the Arctic. The Department of National Defence/Canadian Forces (DND/CF) is also concerned about other Maritime Areas of Interest (AOIs) worldwide. This report outlines the work done in this project on performance modelling and simulation of an Automatic Identification System (AIS) sensor payload for the Canadian Space Agency (CSA)-led RADARSAT Constellation Mission (RCM). This work was conducted as a part of the Design of an Integrated AIS Sensor on a Radar Satellite Technology Demonstration Program (DIASRS TDP).

In 2000, as a part of the Safety of Life At Sea (SOLAS) convention, the International Maritime Organization (IMO) added AIS to the shipboard navigational carriage requirement for a number of ship categories. These include ships of 300 tons (gross) or greater that travel internationally, cargo ships of 500 tons gross or greater, and all passenger ships. The requirement came into full force for these ships on December 31, 2004 and the system is known as "Class A" AIS. After this date, all ships in service in the said categories are mandated to operate their AIS equipment continuously, except where international agreements allow navigational data to be protected. In 2007, "Class B" was introduced for small craft, including pleasure vessels.

AIS was conceived mainly as a collision avoidance system and is based on regular very high frequency (VHF) transmission and reception of short binary messages containing information about the ship's identity, position, speed and course. The United Nations Conference on Trade and Development (UNCTAD) report, "Review of Maritime transport 2011," reports the worldwide commercial fleet of seagoing vessels in service as of January 2011 to be 103,392 [1]. In a presentation to IMO Nav 57, exactEarth (eE) reports a current worldwide deployment of AIS transponders on 65,000 vessels [2]. The AIS systems are based on Time Domain Multiple Access (TDMA). This means that short messages are sent during specific time slots. To avoid confusion when the signal traffic is high, schemes are adopted to ensure that signals are not transmitted simultaneously by different ships into the same time slot. For Class A, this is a self-organizing Time Domain Multiple Access method (SOTDMA). In this method, a transceiver actively searches for an appropriate empty slot before transmitting. The AIS device scans for an available slot in the AIS slot map, then reserves an available slot and transmits data into the reserved slot while notifying other AIS equipment of its intention to use this slot for the next transmission. For Class B, a transceiver first listens to a slot to determine if anyone is using it and, if free, proceeds to transmit. If no available space is found, the transmission is delayed until space is available. This then repeats for the next transmission. This is known as Carrier-Sense TDMA (CSTDMA).

Although the AIS capability was developed for line-of-sight (LOS) applications, there is worldwide interest in having a beyond line-of-sight (BLOS) capability based on AIS receivers on-board primarily, low earth orbiting satellites. The current shore-based AIS systems are limited by LOS distance (i.e., roughly 40 nautical miles). Space-based systems would eliminate this constraint and provide global coverage. However, satellite-based AIS (SAIS) systems also suffer from the collision of AIS messages when many ships are in the satellite's field of view (FOV). When AIS is operated as a terrestrial system, the SOTDMA protocols ensure that signals from different ships do not interfere with one another. However, the number of time slots is limited to

2,250 on each of two VHF channels and these slots are reassigned every 60 seconds. Therefore, in an area of very high shipping density, some signals may be dropped. The system is configured so that the weaker signals in the far range are omitted. This effectively reduces the size of a self-organized cell and has little effect on the collision avoidance aspect of the system. When signals are received by space-based platforms with large FOVs, the number of messages may easily exceed the number of message slots available. This issue of message collision is a significant issue for SAIS receivers and can result in a profound limit on SAIS ship detection performance.

1.1 AIS on RCM

RCM is the next generation mission of the RADARSAT (RSAT) Program with the objective of ensuring data continuity, improved operational use of Synthetic Aperture Radar (SAR) and improved system reliability. The three-satellite configuration will provide complete coverage of Canada's land and oceans offering an average daily revisit, as well as daily access to 95% of the world to Canadian and International users.

The baseline mission includes three satellites, but the constellation is designed to be scalable to six satellites. This allows the system to address future requirements as they arise with greater flexibility. For example, new functionality could be added to a fourth satellite and these functions could be made available to all constellation users. In this fashion, RCM is a paradigm shift from earlier RSAT missions. The capabilities of the system are distributed across several satellites, increasing revisit, and introducing a more robust, flexible system that can be maintained at lower cost and launched into orbit using smaller, less expensive launch vehicles. RCM will ensure C-band data continuity for RSAT users, as well as adding a new series of applications enabled through the constellation approach. The three satellite constellation is intended to be launched in time to ensure that there is no data gap at RADARSAT-2 (RSAT2) end of life. RCM will fly in a sun-synchronous orbit at a nominal altitude of 593 km.

RCM is being designed for three main uses:

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

For the maritime surveillance application, an important aspect of the system operation is the availability of an AIS payload for ship identification. Using AIS, ships exchange information on their identity, position, course etc. RCM will carry an AIS receiver to gather information on ships over the zone covered by the SAR payload.

The AIS capability on RCM is specified to be able to decode at least one AIS message from a ship that is underway and equipped with a Class A AIS transmitter using the default AIS channels (AIS Channels 1 and 2) with a minimum probability of 90% under the following conditions: an absence of in-band and adjacent VHF interference, the ship is within the horizon-to-horizon instantaneous field of view for a minimum of five minutes and in the presence of no more than 2,200 ships transmitting with class A AIS transmitters that are also within the same horizon-to-horizon FOV.

1.2 Project Goals

It is anticipated that an AIS capability on RCM will enhance the Canada First Defence Strategy goals of conducting national and continental operations and defending Canada. An AIS payload co-located with space-based radar is expected to enhance identification of vessels of interest in maritime approaches in a timely manner by significantly reducing the number of unidentified detected vessels in an operational AOI. The purpose of this study is to provide support for or contrary to this hypothesis.

The goals associated with this investigation include:

1. Development of a model that will incorporate statistical models from space-based AIS data sources and simulate the major factors affecting the quality of the AIS radio frequency link;

2. Identify issues and expected performance associated with the combination of space-based AIS and RSAT2 vessel detection data; and

3. Establish the expected performance for AIS on RCM.

The report is arranged in seven sections and provides a detailed discussion of the work conducted throughout the course of the project. A brief overview of the report layout is provided below.

1.3 Document Outline

Section 2 of this report presents the development of an AIS database generated from AIS data provided by DRDC Ottawa. The database was continually built and expanded over the course of the project. The database was used to derive a baseline global ship density map, as well as a number of relevant parameter distributions used in the performance model. Section 3 discusses development of the performance model including a background review, various modelling approaches and a discussion on potential interference sources. Section 4 details the implementation of the performance model and simulation in the MATLAB® programming environment. Section 5 provides a brief summary of the various scenarios simulated to provide model outputs. Scenarios are run for both RCM and RSAT2, and for RCM as a constellation. Section 6 outlines modelling results and associated analysis performed in this project. Section 7 provides conclusions drawn as a result of this work and provides a summary of efforts with some suggestions for future work using the model developed.

2 AIS Database

The AIS datasets provided by DRDC Ottawa and used in this project are listed in Table 1. A high-level processing chart of the steps used to process the data is shown in Figure 1. A description of each processing step is given in the following subsections.

Table 1: AIS Datasets.

AIS Dataset Name	Area of Coverage	Date Range	Days of Data
eENorth	Northern Hemisphere	08-Sep-2010 – 12-Jan-2011	126
eEGlobal	Global	13-Jan-2011 – 23-Mar-2011	70
eECanada	Area around Canada	27-Aug-2011 – 23-Oct-2011	58
eEFeed	Global	04-Apr-2011 – 13-Sep-2012	130
MSSIS	Global (coastal only)	01-Aug-2011 – 20-Oct-2011	42
	Global (coastal only)	19-Sep-2012 – 24-Sep-2012	6

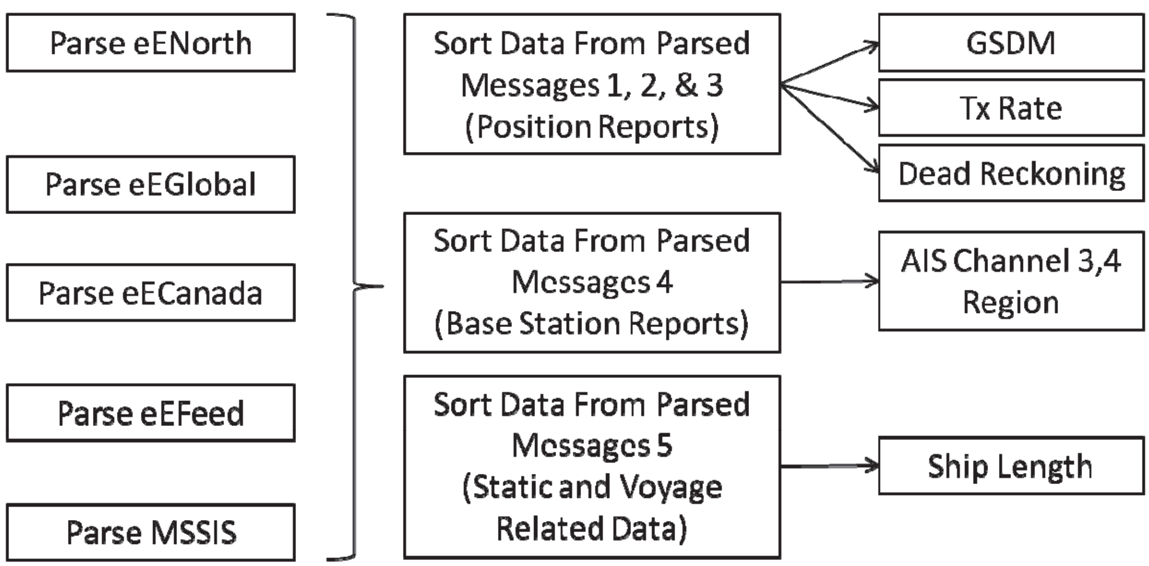


Figure 1: Processing chart for AIS data.

2.1 AIS Data Preparation

2.1.1 Parsing AIS Data

All AIS data was decoded using a modified version of an AIS parser written in C by Brian C. Lane [3]. The parser was modified to read AIS Message types 1, 2, 3, 4 and 5. Messages 1, 2 and 3 contain the ship position reports, Message 4 is the base station report, and Message 5 is the static and voyage related data report. All other AIS messages contained in the AIS datasets were ignored. The relevant parameters from each message type were written to text files organized by date. The extracted parameters are listed in Table 2. A complete description of all AIS Messages and parameters can be found in [4].

Although not included in the AIS messages themselves, a timestamp is applied to each message by the receiving system. The datasets listed in Table 1 use three different formats to add the timestamp to the encoded AIS message. Part of the modification to the AIS Parser was to read the timestamps from the different formats and output this with the AIS parameters.

During parsing, preliminary error checking was performed to reduce the amount of parsed data. Any message with an invalid Maritime Identification Digit (MID) (see Table 2) was dropped, as well as any ship or base station positions with invalid latitude and longitude. As described in [4], latitudes of 91° and longitudes of 181° mean the values were not available.

2.1.2 Sorting and Error Checking the Parsed Data

The output files from the parser for each AIS dataset were combined and sorted by Maritime Mobile Service Identity (MMSI) and timestamp using script files developed in MATLAB®. The parsed data from the ship position reports (Messages 1, 2, and 3), the static and voyage reports (Message 4), and the base station reports (Message 5) were processed separately.

2.1.2.1 Ship Position reports

The sorted position report data was written into text files based on MMSI. The MMSI grouping was set such that the size of the output files were not too large to read and process in MATLAB®.

Additional error checking was performed on the messages from each MMSI during this stage. It was observed that the position reports from a particular MMSI may contain errors in the reported positions. To detect and remove these position errors, the position reports from an MMSI were further separated into continuous time observations (CTO), which is defined as the positions from an MMSI with a time difference of less than two hours. A particular ship will be observed by an AIS receiver (satellite or ground based) while it is in the FOV of the receiver. As a result, the positions reported by an MMSI will have jumps in both time and location as the ship leaves one receiver's FOV and is picked up by another one at some other time and location. A position was considered an error if it varied by more than two degrees in longitude or latitude during one CTO. Furthermore, any CTO with only one position report was also removed. A description of each encountered position error and the action taken when found is listed in Table 3.

Table 2: Parameters Extracted from AIS Messages.

Message Parameter	AIS Message Type	Description
MMSI	1, 2, 3, 4 and 5	The MMSI is a unique number assigned to each ship that uses an AIS transmitter. The MMSI for ships are a 9-digit number of the format MID######, where # represents a digit. The MMSI for the AIS ground stations are of the format 00MID####. The MIDs are assigned regionally (Canada is 316). A complete listing of the MID can be found on the International Telecommunication Union (ITU) website [5]. Valid MIDs are between 201 and 775.
Latitude, Longitude	1, 2, 3 and 4	Latitude and longitude in decimal degrees. Messages 1, 2, and 3 are for ships, Message 4 is for base stations.
Speed over ground (SOG)	1, 2, and 3	Speed of ship in knots, between 0 and 102.1 knots. A speed of 102.2 indicates a speed greater than or equal to 102.2 knots.
Course over ground (COG)	1, 2 and 3	Ship heading in degrees from true north, between 0 and 359.9 degrees.
Rate of turn (ROT)	1, 2 and 3	Rate of turn. Values range between -127 and 127. The negative indicates turning to the left and positive is turning to the right. The +/-127 means turning at 5° per 30 seconds. 0 to 126 are mapped to turning 0° to 708° per minute to the right and 0 to -126 are 0° to 708° per minute to the left.
Navigational Status (NavStat)	1, 2 and 3	Navigation status of the ship. Includes such categories as under way by engine, fishing, at anchor, and moored. See [4] for a full list.
Distance to bow, Distance to stern	5	Distance from the ship AIS transmitter to the bow and stern in metres. Adding these two values gives the ship length.

Table 3: List of position errors encountered in AIS data.

Error Description	Numerical Example	Action
Single position error	1, 1, 1, 9, 1, 1	Message with error is removed.
Multiple position errors	1, 1, 12, 1, 4, 1, 8	It can be difficult to determine which points are the actual track. Therefore all messages in this CTO are removed.
Step in reported positions	1, 1, 1, 5, 5, 5	All messages in this CTO are removed
Two ships using the same MMSI at the same time in two different locations. The different positions were often alternating in time.	1, 4, 1, 4, 1, 4	Either position track could be valid. It is impossible to determine which positions correspond to the correct ship and which belong to the ship using the wrong MMSI, so all messages in the CTO are removed.

2.1.2.2 Static and Voyage Reports

The sorted length reported by each MMSI was checked for errors and the MMSI, length, and timestamp were saved to a MATLAB® save file (.mat). The length reported by each unique MMSI was checked for consistency and any ships reporting different lengths were removed.

2.1.2.3 Base Station Reports

The sorted positions of each base station MMSI were checked for consistency. Any position report for a MMSI that was not the same as the most common reported position (mode) rounded to the nearest degree was removed. Additionally, any MMSI with fewer than 100 position reports was removed. This number was determined experimentally and removed many error locations while keeping legitimate reports from ground stations.

The resulting MMSI, positions, and timestamp were saved to a MATLAB® save file (.mat).

2.2 Parameter Extraction

After the AIS data was sorted the databases required for input to the model were generated. A description of procedures used to generate the global ship density map (GSDM), the message transmit rates, dead reckoning, AIS Channels 3 and 4 region, and the ship length distribution are given in the following subsections.

These extracted parameters are used in the model.

2.2.1 Global Ship Density Map

The GSDM was derived from the parsed and sorted AIS datasets listed in Table 1 using the following procedure:

1. Read all position reports from a single MMSI (from the parsed and sorted data).

2. Sample the position reports for an MMSI at a five minute frequency.

3. Increment the 1° latitude by 1° longitude grid cell from each sampled position report by 1/(number of reports). This ensures that each MMSI adds one to the density map.

4. Repeat for each MMSI.

The resulting GSDM is shown in Figure 2 and Table 4 lists the total number of unique MMSIs in the GSDM, the maximum density cell, and the location of this cell. White areas in the GSDM contained no ships.

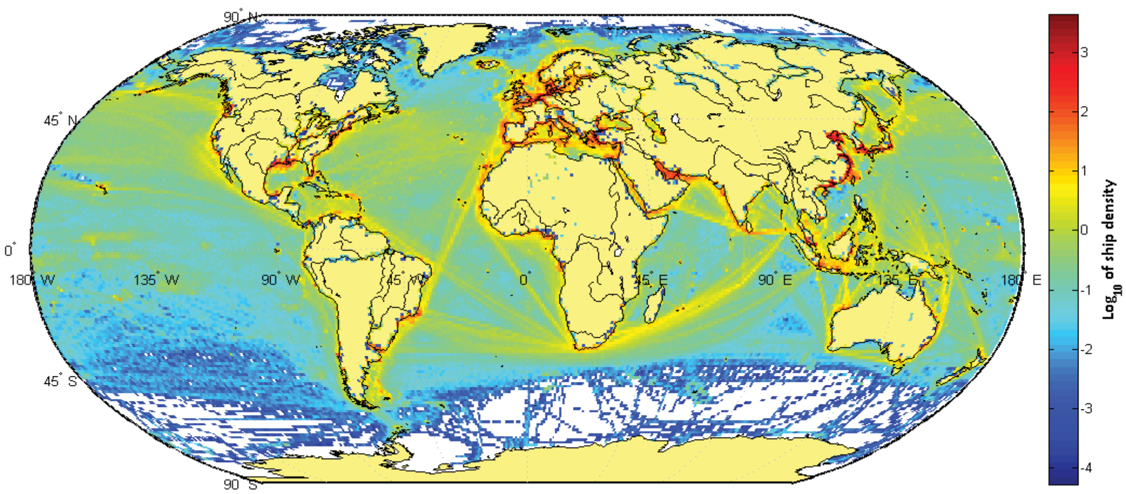


Figure 2: Global ship density map generated from the AIS datasets listed in Table 1.

Table 4: GSDM parameters.

Total Ships	Maximum Density	Cell with Maximum Density (lat, lon)
130784	4391.4	23,113 (Hong Kong)

2.2.2 AIS Message Transmit Rate

The transmit rate of the ship position reports (Messages 1, 2 and 3) are defined in [4] and reproduced in Table 5. To determine the transmit rate, the speed over ground, rate of turn, and navigation status are read from the AIS data. The calculation of the transmit rate was performed at the same time as the generation of the GSDM. The transmit rates were calculated from only those messages for which the speed over ground, rate of turn, and navigation status were defined; approximately 190 million out of 462 million parsed messages (41%). For the purposes of the transmit rate calculation, a ship was considered changing course if the rate of turn was not zero.

A histogram of the speed over ground from the position report messages is shown in Figure 3. The speeds were grouped into the three ranges used in the transmit rate calculation, as found in Table 5. Figure 4, Figure 5, and Figure 6 show the probabilities that a ship in a 1° latitude by 1° longitude grid cell is travelling at between 0 and 14 knots, 14 to 23 knots, and 23 or more knots, respectively. A cell where the probability is zero is empty in the figures. From the compiled data set, 89.5% of ships reported speeds of 0 to less than 14 knots, 9.7% of ships had speeds of 14 to less than 23 knots and 0.8% had speeds of 23 knots or more.

Table 5: AIS Message 1, 2 and 3 reporting intervals, from [4].

Ship's Dynamic Conditions	Nominal Reporting Interval
Ship at anchor or moored and not moving faster than 3 knots	180 s
Ship at anchor or moored and moving faster than 3 knots	10 s (a)*
Ship 0-14 knots	10 s (b)*
Ship 0-14 knots and changing course	10/3 s
Ship 14-23 knots	6 s
Ship 14-23 knots and changing course	2 s (a)*
Ship > 23 knots	2 s (b)*
Ship > 23 knots and changing course	2 s (c)*

Note: *The references (a), (b) and (c) are used to identify the different cases for the 2 s and 10 s reporting intervals as used in Figure 13.

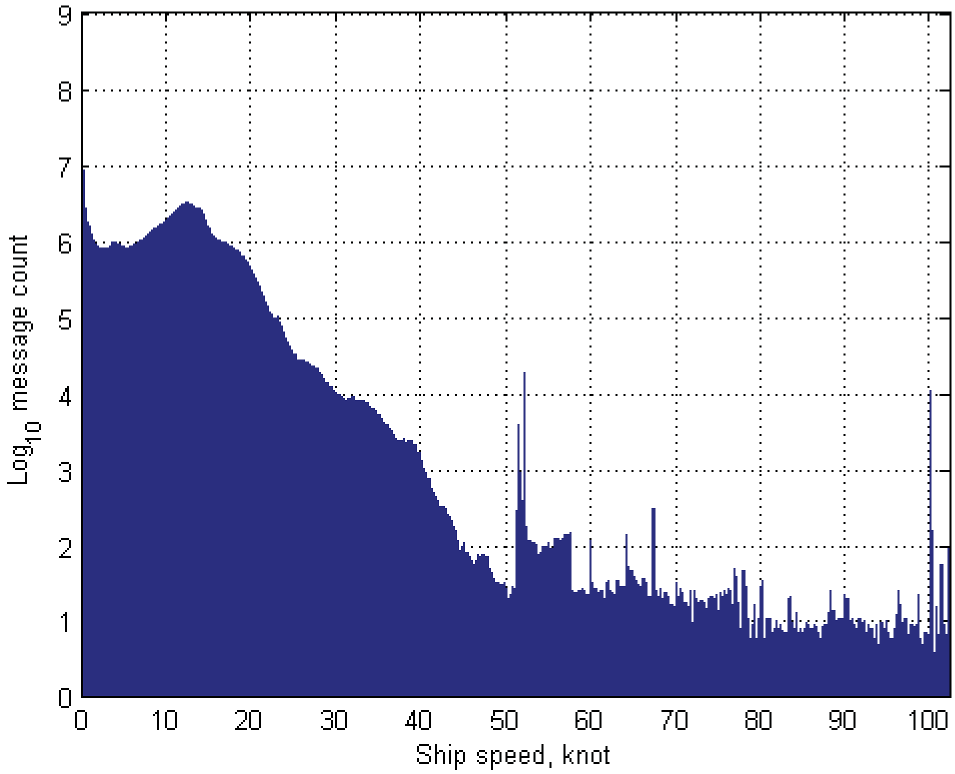


Figure 3: Distribution of speed over ground messages where speed over ground, rate of turn, and navigation status is defined.

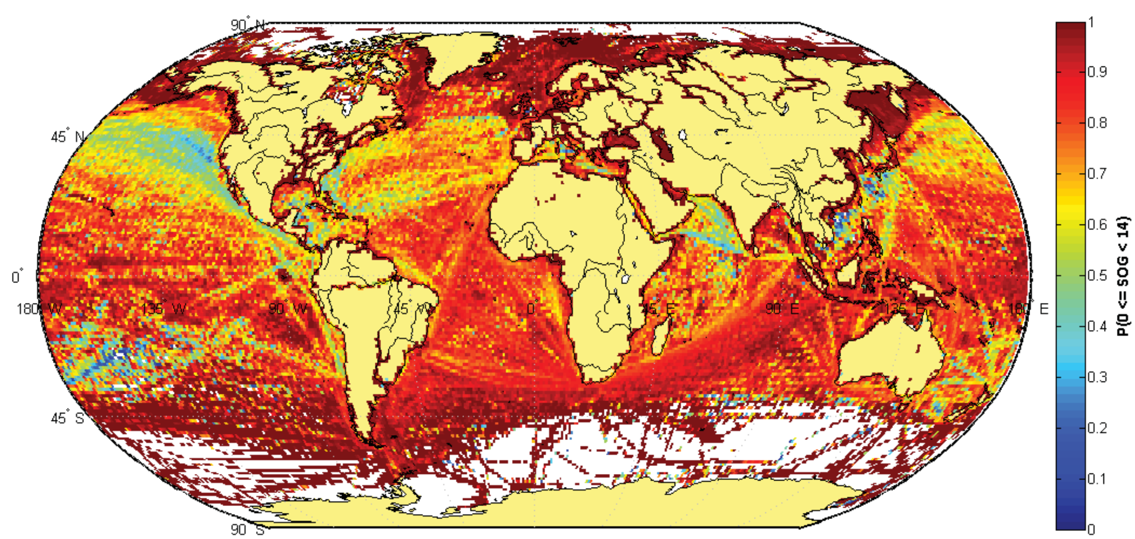


Figure 4: Probability that a ship in a grid cell is travelling greater than or equal to zero and less than 14 knots. These speeds represent 89.5% of all ships where the speed over ground, rate of turn, and navigation status were defined.

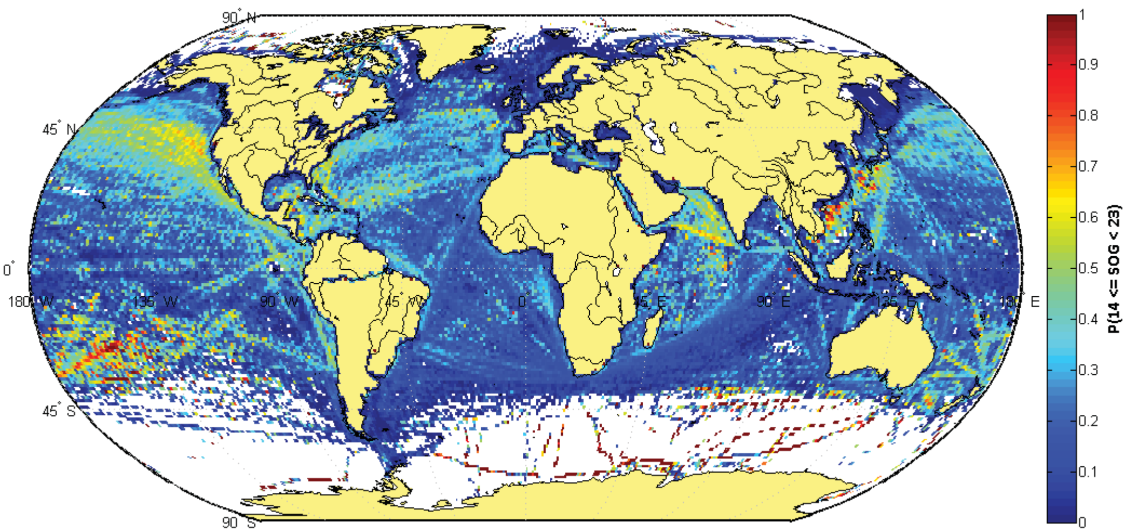


Figure 5: Probability that a ship in a grid cell is travelling greater than or equal to 14 and less than 23 knots. These speeds represent 9.7% of all ships where the speed over ground, rate of turn, and navigation status were defined.

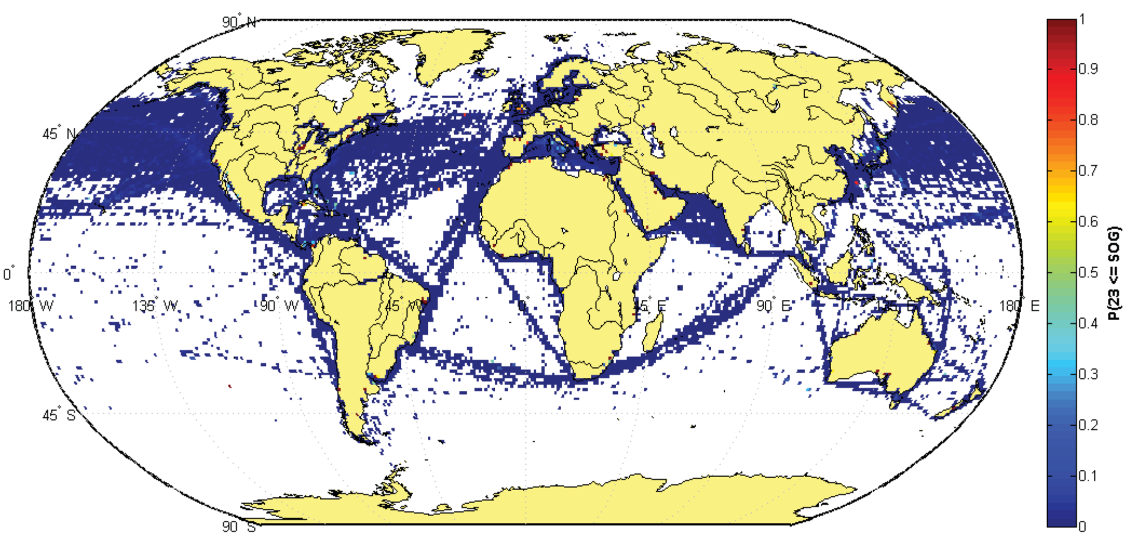


Figure 6: Probability that a ship in a grid cell is travelling greater than or equal to 23 knots. These speeds represent 0.8% of all ships where the speed, rate of turn, and navigational status were defined.

The navigation status was used to determine messages from ships that were moored or anchored. A histogram of the navigation statuses derived from the data and used to calculate the transmit rate is shown in Figure 7. The probability for each grid cell that a ship is not moored and not anchored is given in Figure 8 and the probability that a ship is moored or anchored is given in

Figure 9. From the data, 85.2% of ships were not moored and not anchored, leaving 14.8% that were moored or anchored.

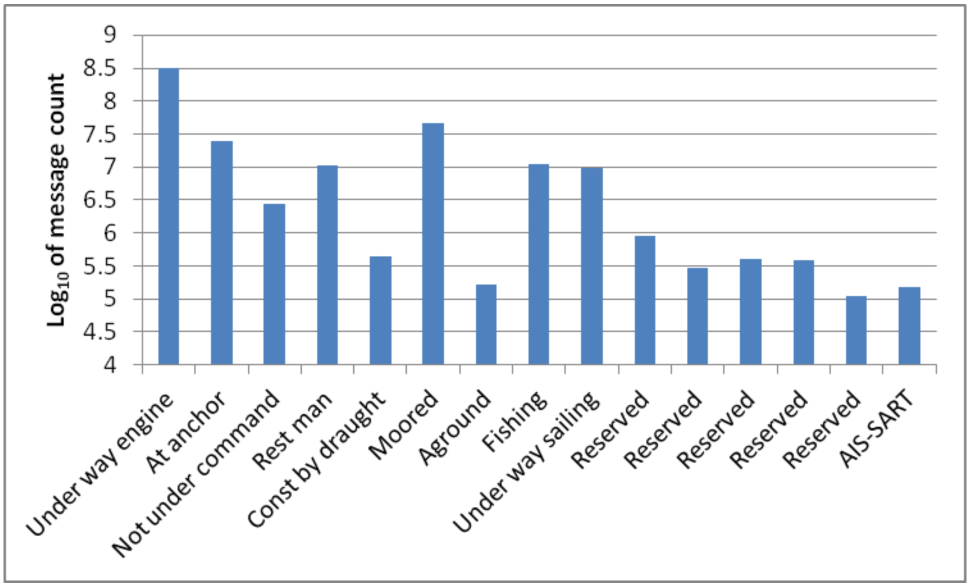


Figure 7: Histogram of navigation status messages where the speed over ground, rate of turn and navigation status were defined.

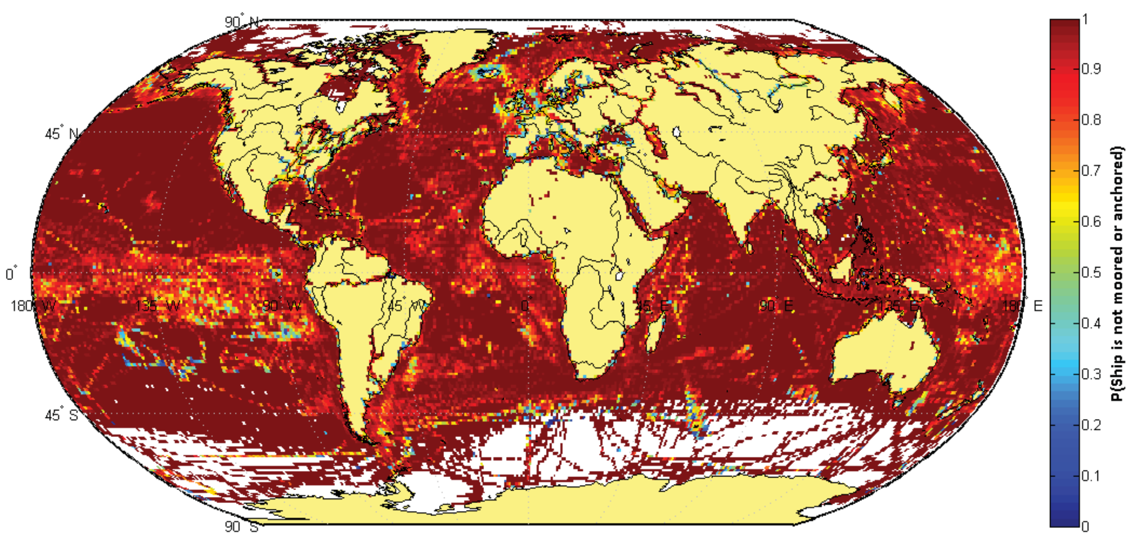


Figure 8: Probability that a ship in a grid cell is not moored and not anchored. These statuses represent 85.2% of all ships where the speed over ground, rate of turn and navigation status were defined.

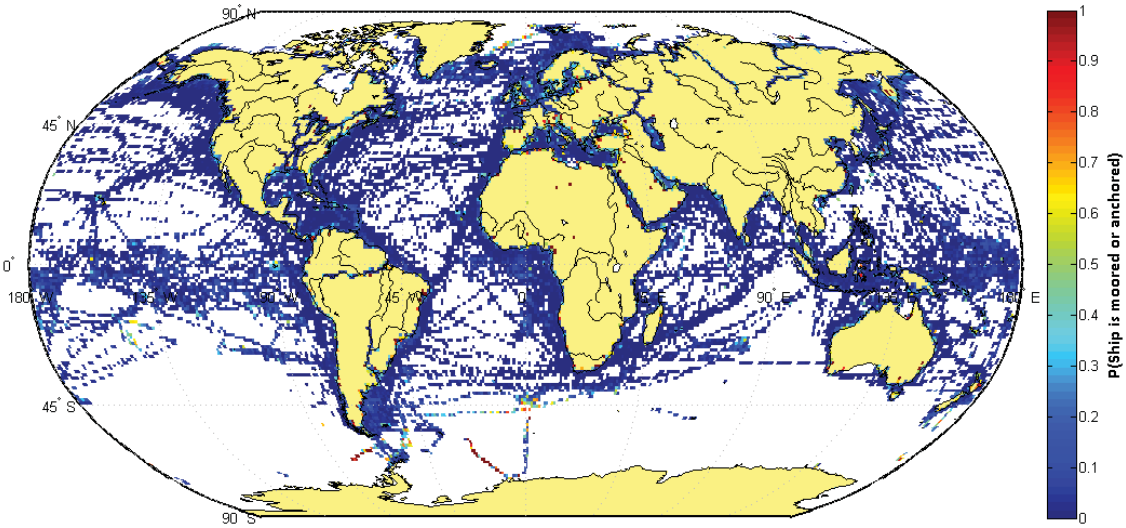


Figure 9: Probability that a ship in a grid cell is moored or anchored. These statuses represent 14.8% of all ships where the speed over ground, rate of turn and navigation status were defined.

A histogram of the rate of turn from the messages used to calculate the transmit rate is shown in Figure 10. A rate of turn of zero indicates that a ship is not changing course, while a rate of turn other than zero (and is defined) means that the ship was changing course. The probability that a ship in a grid cell is not changing course is shown in Figure 11 and the changing course case is found in Figure 12. The data shows that 58.6% of ships were not changing course, which means that 41.4% of ships were turning.

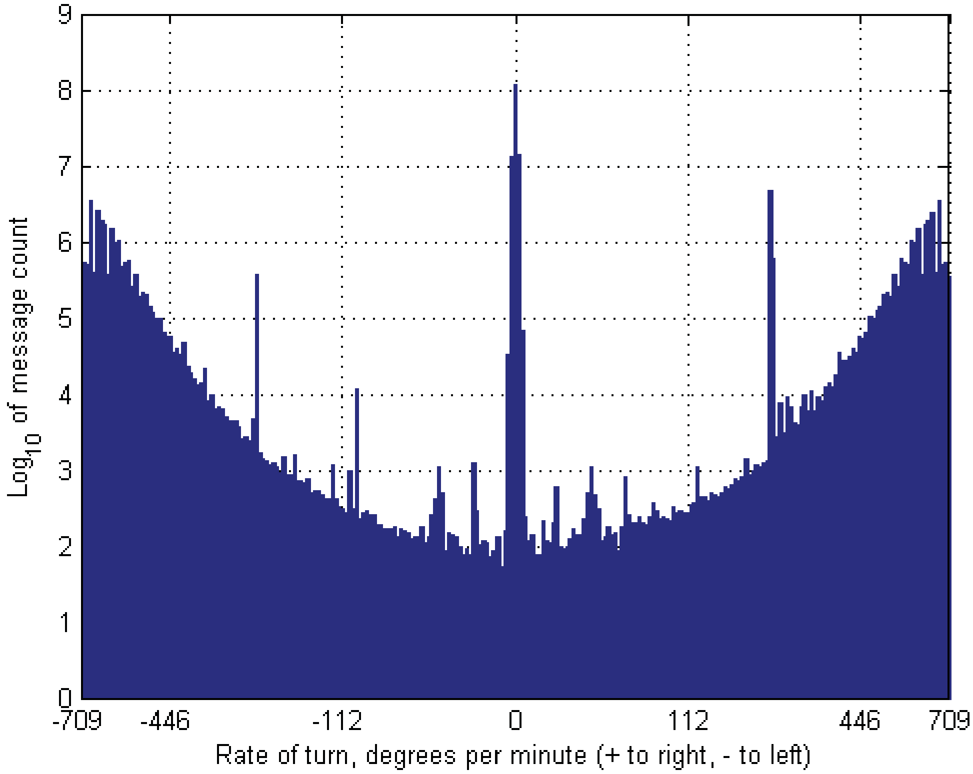


Figure 10: Histogram of rate of turn messages. Negative values mean the ship is turning to the left; positive is turning to the right.

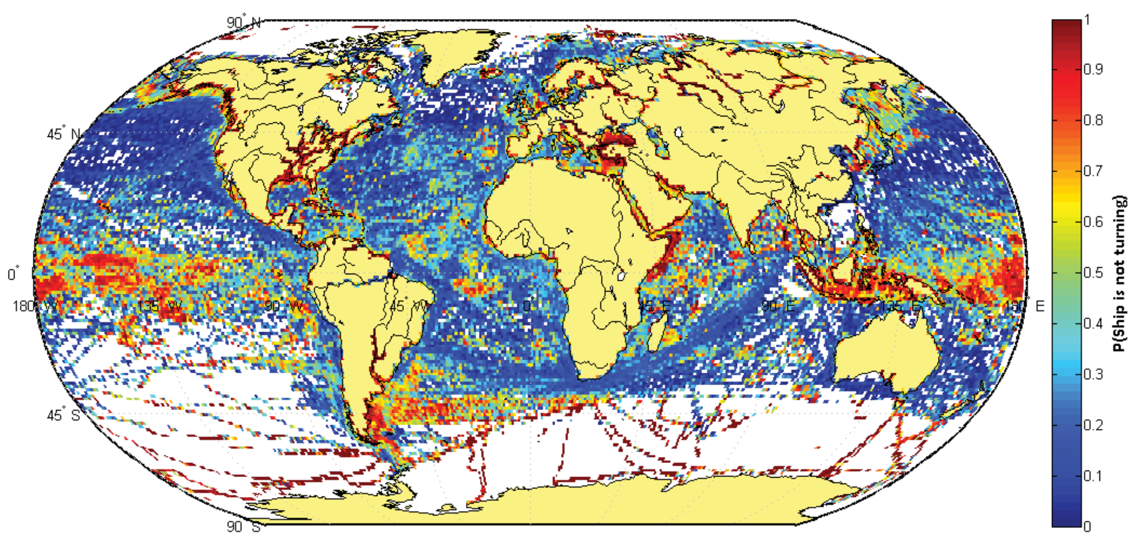


Figure 11: Probability that a ship in a grid cell is not turning. Ships that were not turning represent 58.6% of all ships where the speed over ground, rate of turn, and navigation status were defined.

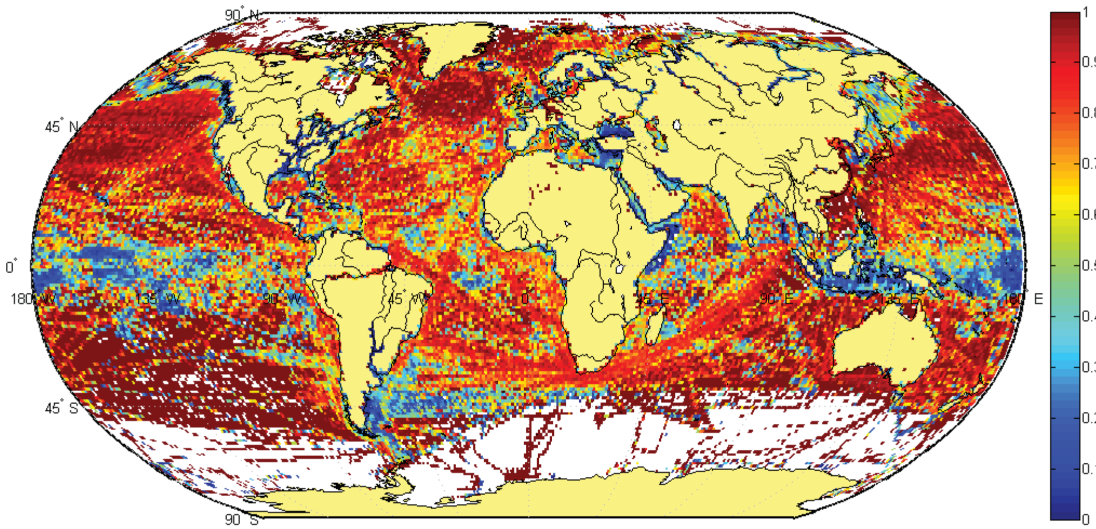


Figure 12: Probability that a ship in a grid cell is turning. Ships that were turning represent 41.4% of all ships where the speed over ground, rate of turn, and navigation status were defined.

The resulting probability distribution of the transmit rates calculated for the categories shown in Table 5 is found in Figure 13. Figure 14 gives the probability distribution for the actual transmit rate in seconds. Similarly, Figure 15 through Figure 19 shows the probability of a ship transmitting at the given rate on a per grid cell basis.

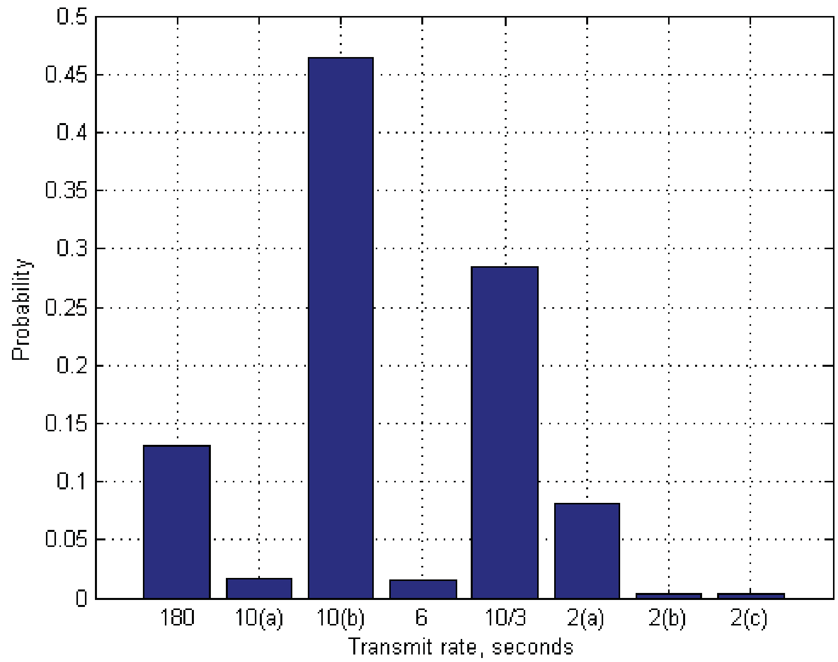


Figure 13: Probability distribution of AIS message transmit rates as described in Table 5.

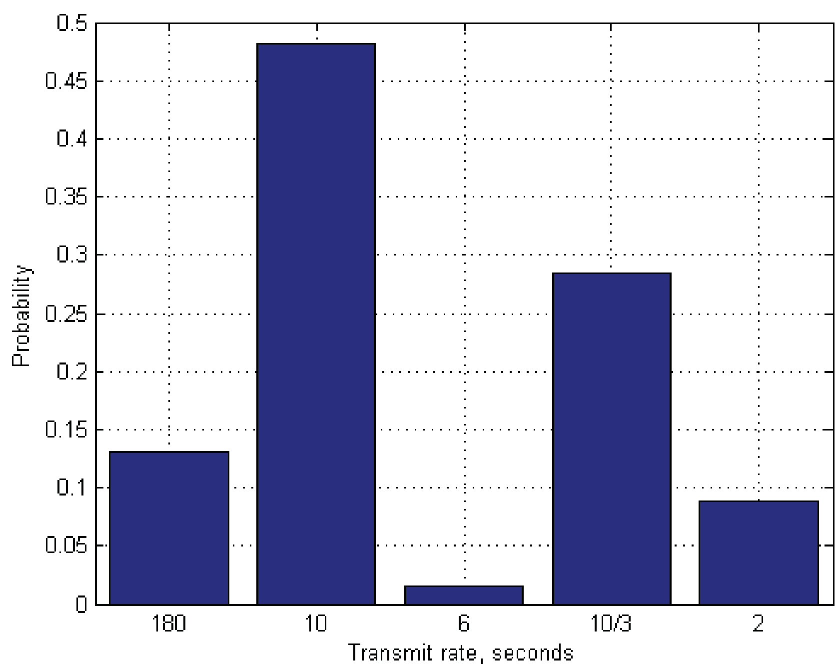


Figure 14: Transmit rate probability distribution of AIS Message 1, 2 and 3.

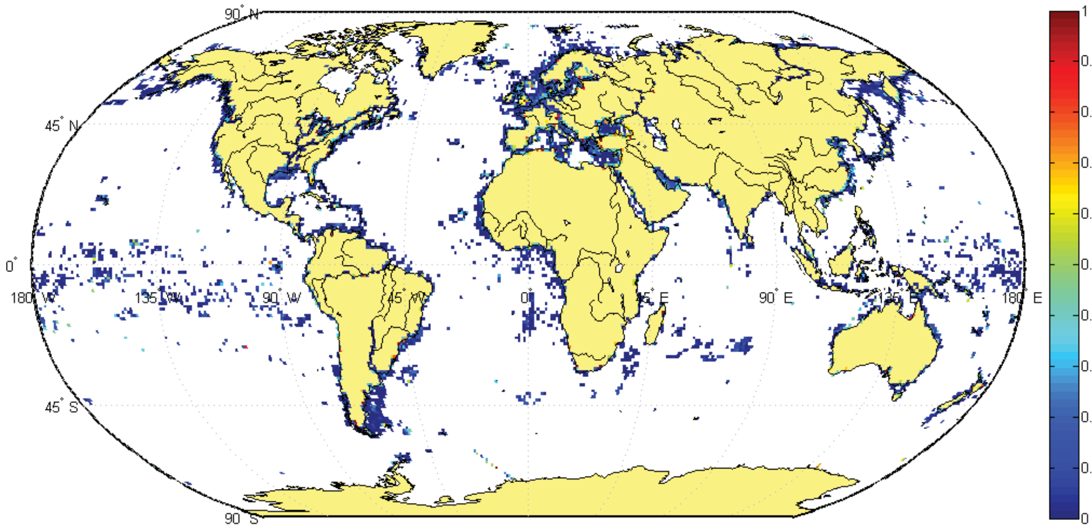


Figure 15: Probability that a ship in a grid cell is transmitting at a rate of 180 seconds. This rate represents 13.1% of all ships for which the transmit rate was calculated.

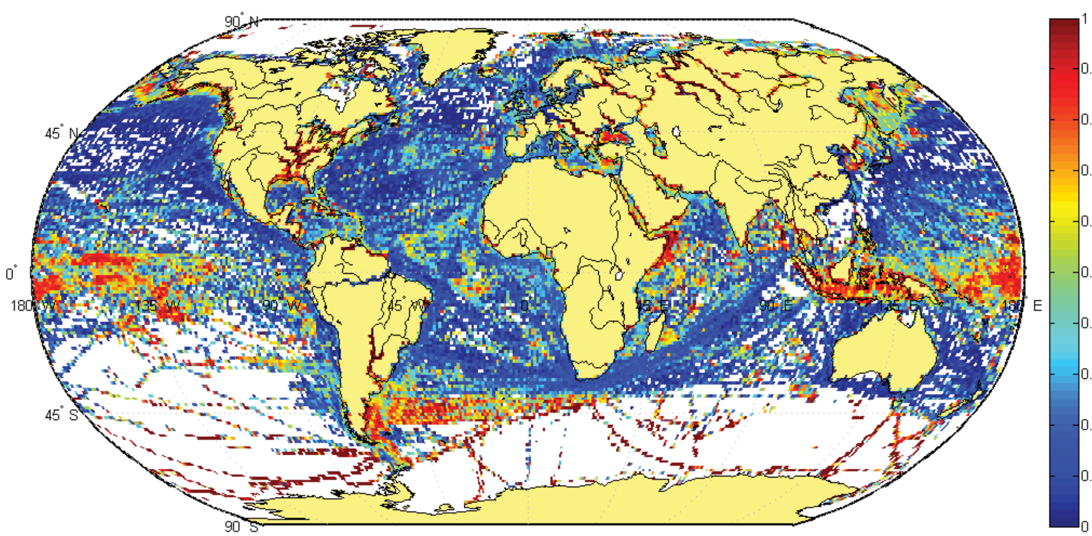


Figure 16: Probability that a ship in a grid cell is transmitting at a rate of 10 seconds. This rate represents 48.1% of all ships for which the transmit rate was calculated.

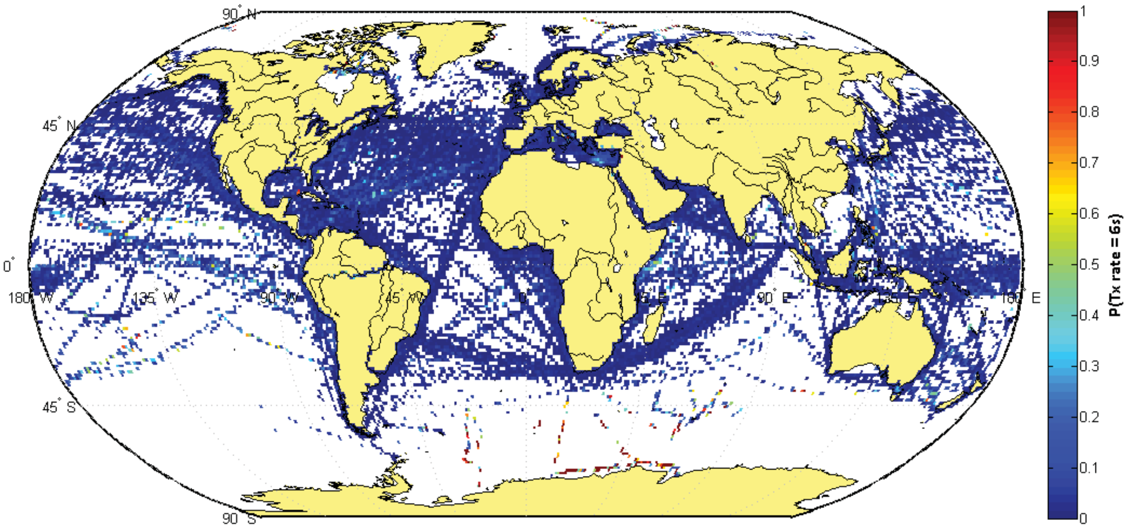


Figure 17: Probability that a ship in a grid cell is transmitting at a rate of 6 seconds. This rate represents 1.6% of all ships for which the transmit rate was calculated.

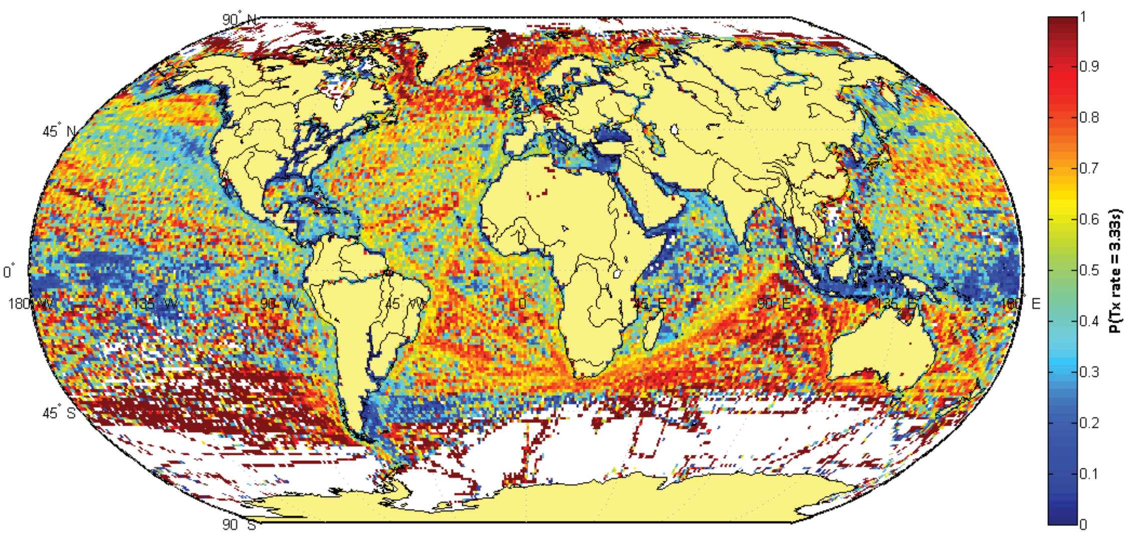


Figure 18: Probability that a ship in a grid cell is transmitting at a rate of 10/3 seconds. This rate represents 28.4% of all ships for which the transmit rate was calculated.

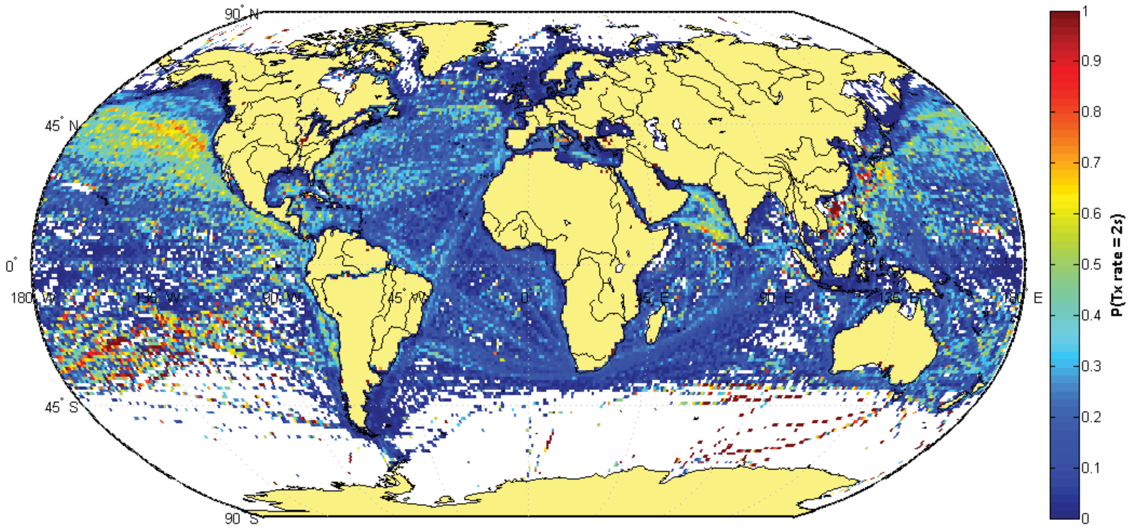


Figure 19: Probability that a ship in a grid cell is transmitting at a rate of 2 seconds. This rate represents 8.8% of all ships for which the transmit rate was calculated.

2.2.3 Dead Reckoning

Dead reckoning is a method of predicting the future position of a ship from the current position, speed, course (heading) and a time interval. Dead reckoning was calculated using the entire set of ships from the AIS database after error checking to remove ships with jumps (errors) in position reports. The process used is outlined as follows:

1. Get positions reports for current ship (ship track);

2. Calculate the dead reckoning for 5, 10, 15, 20, 25, 30, 45 minutes and 1, 2, 3, 4, 5 and 6 hours for each ship position report. The reckon() function in MATLAB® is used to calculate the dead reckoning;

3. Interpolate the position along the reported ship positions at the dead reckoning times for each ship position. If the dead reckoned time is after the last ship position the point is ignored; and

4. Calculate the distance between the dead reckoned and interpolated point on the ship track.

The dead reckoning deviations were then binned on the latitude, longitude grid using the position reports from each message for each time interval. Figure 20, Figure 21, and Figure 22 show the average dead reckoning deviations binned on the latitude, longitude grid for five minutes, one hour, and six hours. The cumulative distribution function for an example grid cell off the East Coast of Canada is shown in Figure 23. The horizontal line at 0.95 represents the confidence interval used for the probability of association discussed in Section 4.3.

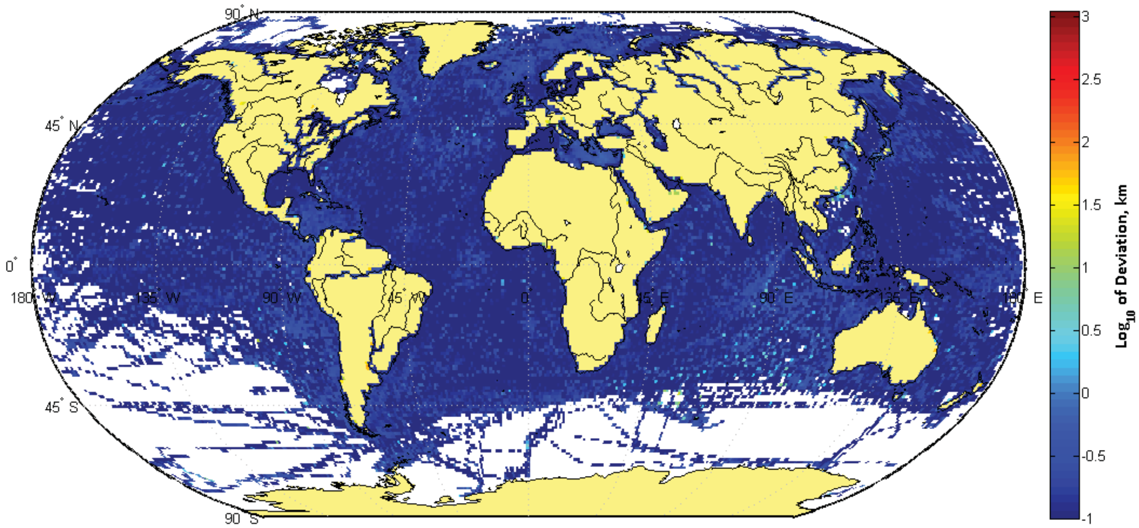


Figure 20: Average dead reckoning deviation for a five minute time difference

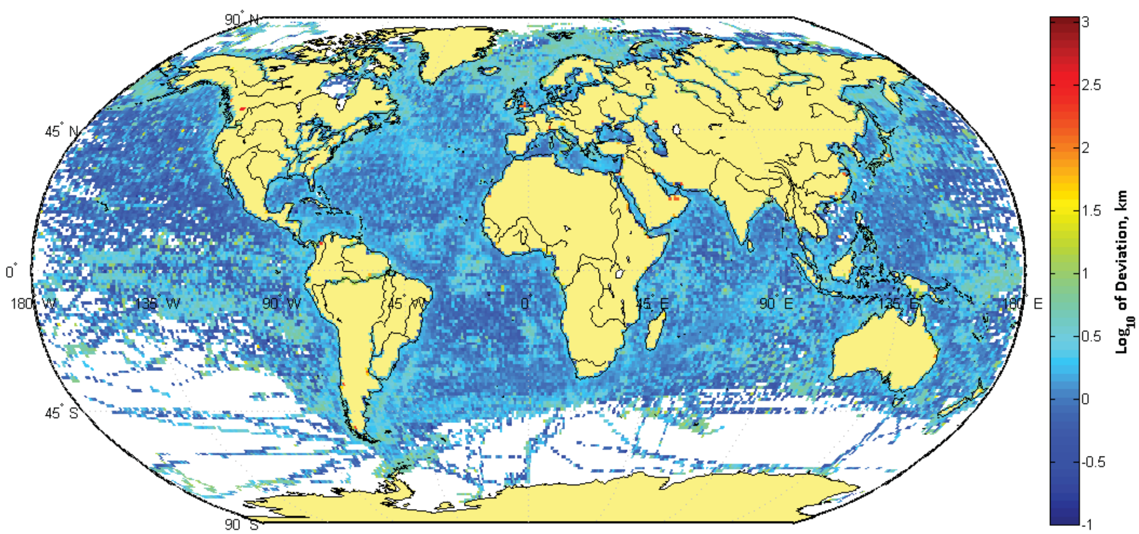


Figure 21: Average dead reckoning deviation for a 1 hour time difference

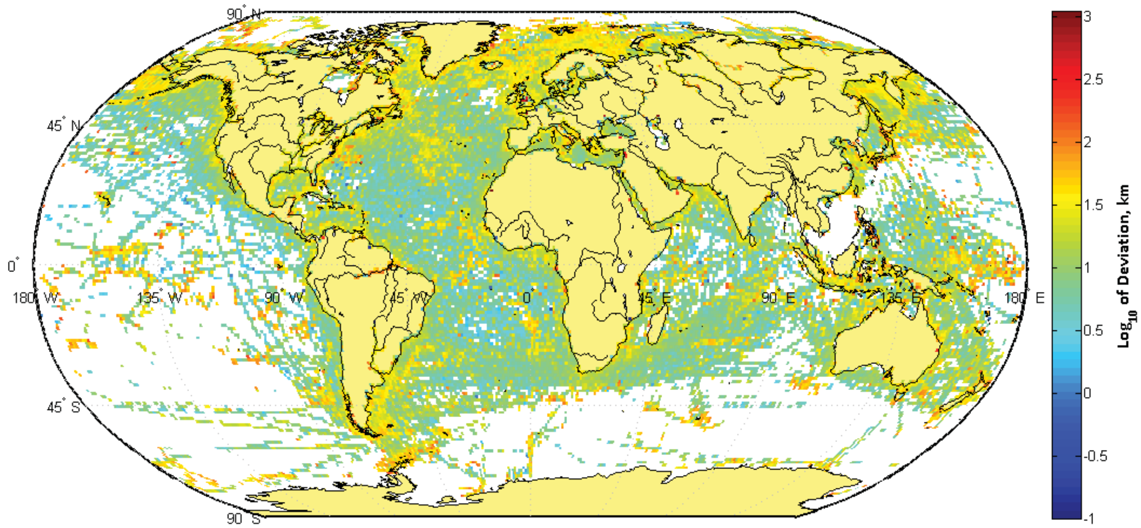


Figure 22: Average dead reckoning deviation for a 6 hour time difference

As an example, the cumulative distribution function for a latitude, longitude grid cell off the East Coast of Canada is shown for a time difference of five minutes, one hour, and six hours. Using a 95% confidence interval (the black dashed horizontal line) the dead reckoning deviation for a five minute time difference is less than one km, while at six hours the deviation is approximately 75 km.

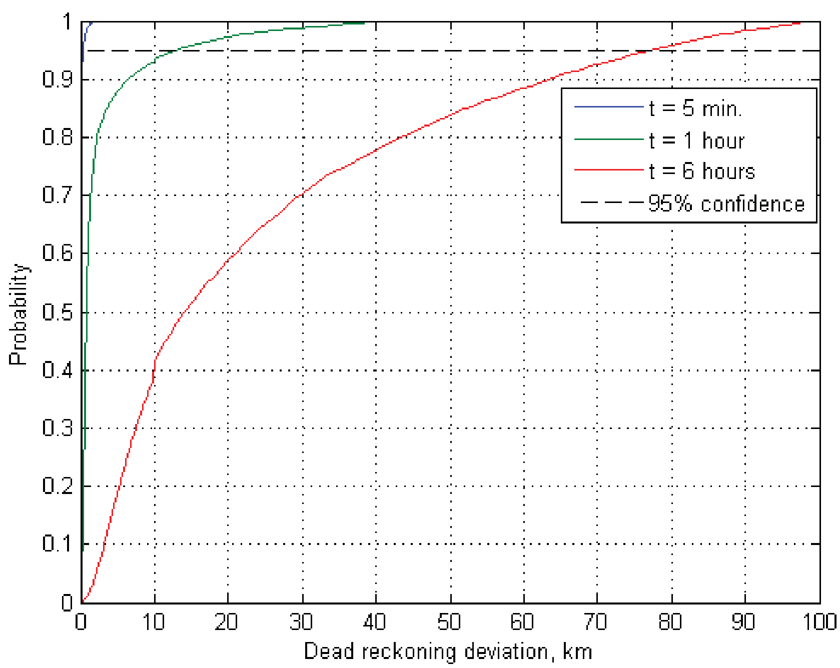


Figure 23: Cumulative distribution function for a lat, lon grid cell of the East Coast of Canada

2.2.4 AIS Channels 3 and 4 Exclusion Region

The AIS Channels 3 and 4 exclusion region refers to the areas within the FOV of an AIS terrestrial receiver. Ships within this area will not transmit using AIS Channels 3 and 4, which are intended for satellite reception.

A first attempt at creating a mask for the AIS Channels 3 and 4 exclusion region used the position reports from the MSSIS data. This dataset consists of messages from AIS ground stations and should represent only those ships in range of ground stations. However, as shown in the density map created from the MSSIS data in Figure 24, there are some regions (north-west Africa and the west coast of the United States) where the collected position reports extend far out into the oceans. It is assumed in [6] that ships within 50 nautical miles (nm) of an AIS ground station will not use AIS Channels 3 and 4, so a second iteration of the mask was created limiting the MSSIS data to 50 nm from land. The AIS Channels 3 and 4 exclusion zone is shown by the pink regions in Figure 24.

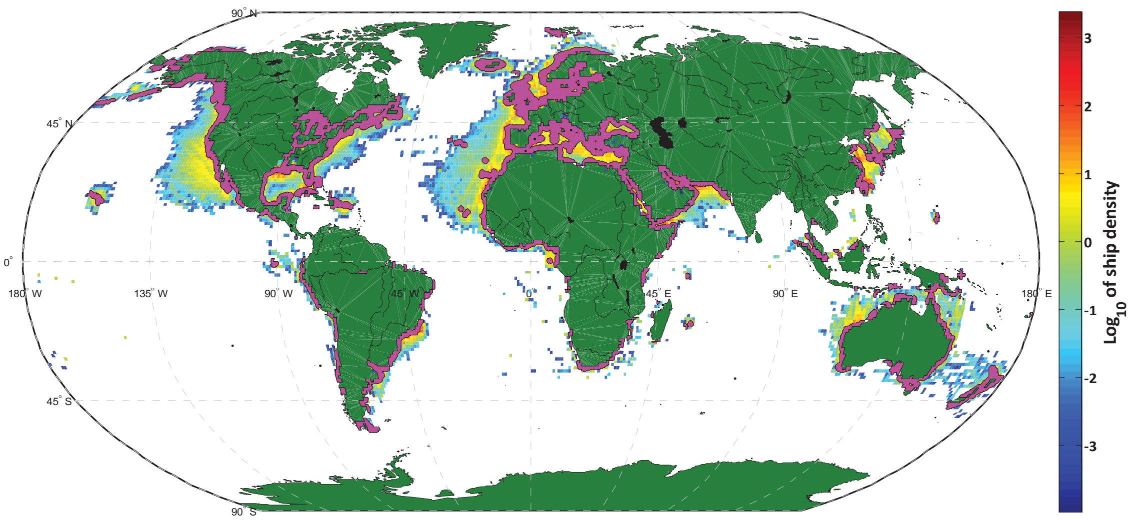


Figure 24: Ship density map from MSSIS AIS dataset, with AIS Channels 3 and 4 exclusion region shown in pink created from MSSIS data limited to 50 nm of land.

A second Channels 3 and 4 mask was created from the base station reports (AIS Message 4) which provide the latitude and longitude of the AIS ground stations. The MMSI, latitude, longitude and timestamp of the base station reports were extracted by the AIS parser and written into separate files. It was noted that the MSSIS AIS dataset, while taken from terrestrial base stations, contained a considerable number of positions located far offshore, well outside their normal reception range. These reports were considered to be erroneous. The following steps were used to generate the mask from the base station reports:

1. Read in all Message 4 data;

2. Sort by MMSI and timestamp;

3. For each MMSI, keep the most commonly reported position (mode). The reported positions of some base stations were observed to vary by less than one degree;

4. Remove base stations with a position more than 150 nm of land. This number was determined experimentally and eliminated many of the error positions in the oceans; and

5. Apply a 50 nm buffer around each remaining base station and merge with overlapping base station buffers.

The resulting AIS Channels 3 and 4 exclusion mask shown in Figure 25 still contains errors over land, such as Antarctica and a vertical line of errors in Western Canada. Because there are no ships in the land areas, these remaining errors will have no affect when using this mask. One issue with this mask is that there are some islands, such as the Azores and Hawaii, with no mask. A visual check against the ground stations found on [7] show that there are base stations on these islands.

The final AIS Channels 3 and 4 exclusion region mask was a combination of the two masks described above, and is shown in Figure 26. While this constitutes the final exclusion mask for the purposes of this project, it is expected that this mask will be regularly updated as more terrestrial base stations are implemented.

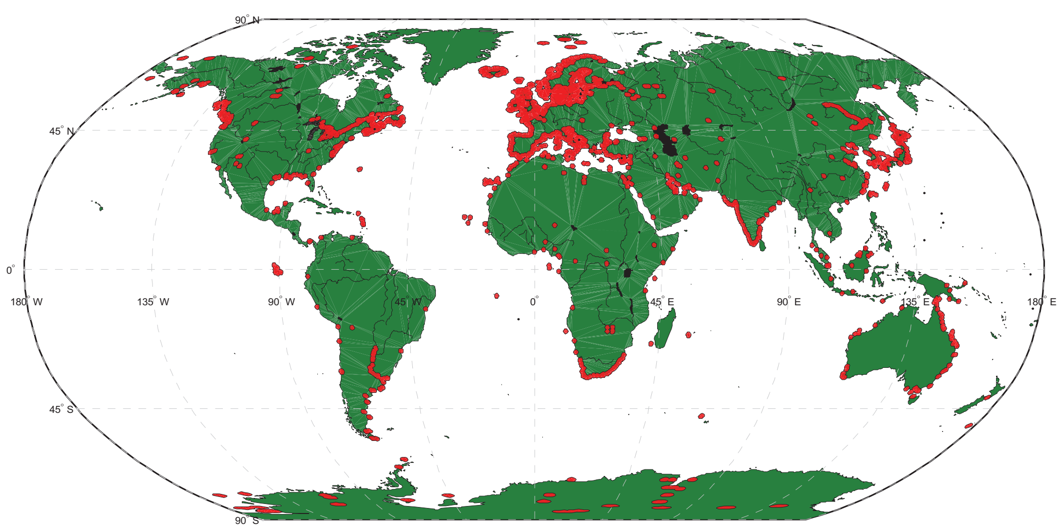


Figure 25: AIS Channels 3 and 4 exclusion region shown in red created from a 50 nm buffer around ground station positions from AIS Message 4 from all datasets.

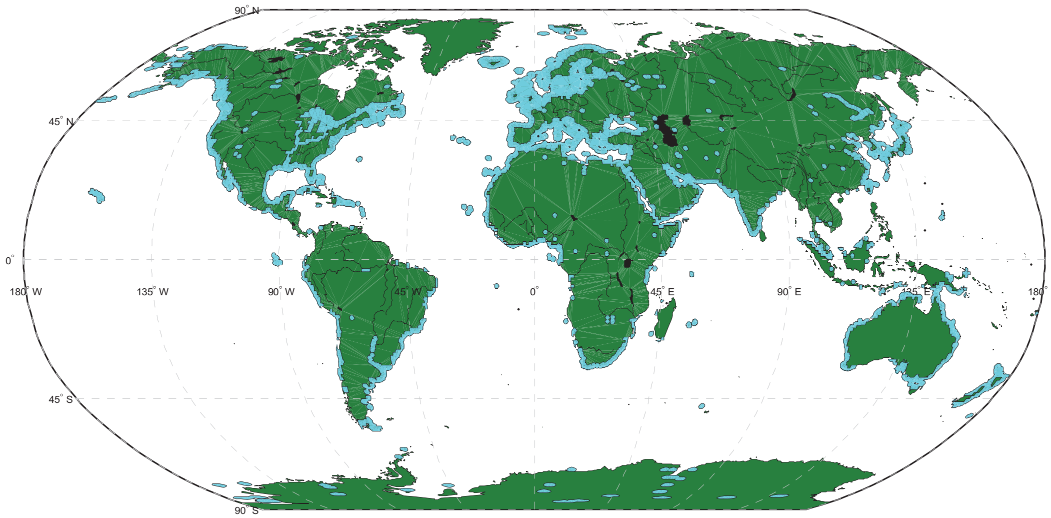


Figure 26: Final AIS Channels 3 and 4 region shown in blue, created from MSSIS data limited to 50 nm of land and the base station locations from AIS Message 4 and a 50 nm buffer.

2.2.5 Ship Length

The ship length distribution as a fraction of the total number of ships is shown in Figure 27 and was generated from 125,622 unique MMSIs from the AIS Message 5 data. The ship lengths were binned into 10 m groups for this figure. The ships in the 400 m bin represent reported ship lengths of 400 m or greater.

The ship lengths read from the AIS datasets were compared to the Canadian Maritime Network version of the Lloyd's Registry Fairplay ISR database available at DRDC Ottawa and the errors as a fraction of the ship length are shown in Figure 28. The reference database consisted of 56,188 unique MMSIs and 53,106 were matched to the 125,622 unique MMSIs read from the AIS Message 5 data set. From this, 86% of reported ship lengths were within 10% (0.1) of the actual ship length recorded in the registry. Although the comparison showed some errors in the AIS-derived ship lengths, the errors were minimal and the ship length distribution from the AIS data was used in the simulation.

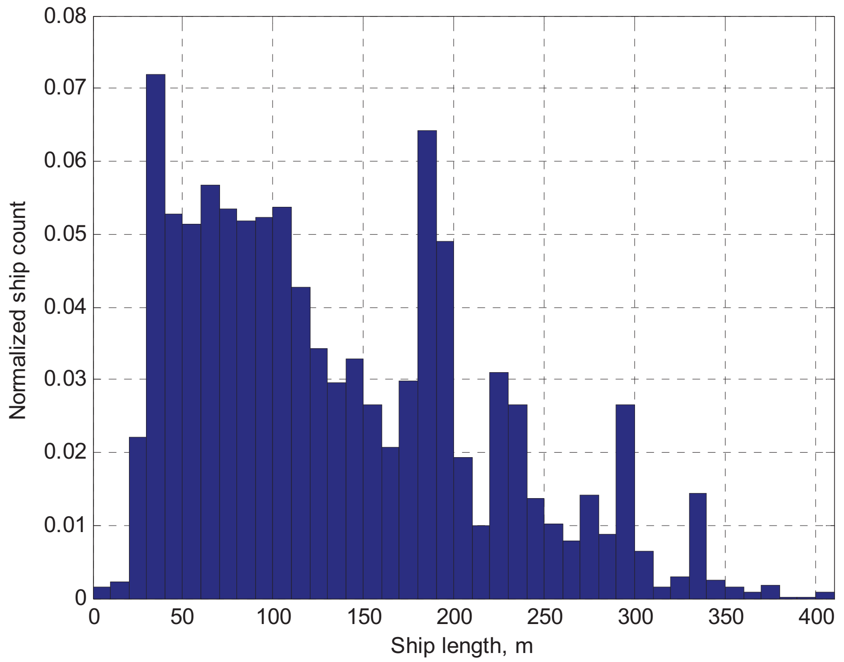


Figure 27: Ship length distribution from static and voyage-related reports (Message 5).

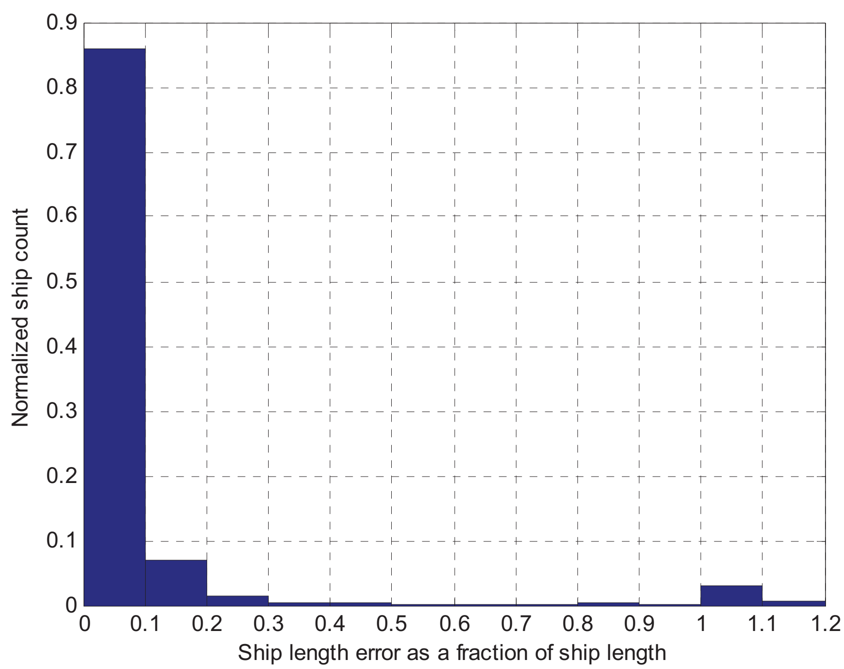


Figure 28: Ship length errors as a fraction of ship length, for the ships in both Message 5 and the reference database.

2.3 Errors in AIS Data

The problem of errors in AIS messages is known and well documented. DRDC Ottawa published a report [8] that investigated some of these errors. A list of the main errors encountered with the AIS data during this project and any resolution taken is listed in Table 6.

Table 6: List of AIS errors encountered.

Error	Related Messages	Description	Resolution
Invalid MMSI	1, 2, 3, 4 and 5	Table 2 explains the valid MMSI numbers for ships and base stations. An invalid MMSI could be due to human error when entering the MMSI into the AIS system or the equipment using a default value because the MMSI was not set.	Only MMSIs outside the valid range are removed. Any MMSI with errors inside the valid range and not detected as other errors could not be detected and therefore remained in the data.
Duplicate MMSI	1, 2, 3, 4 and 5	Multiple ships using the same MMSI.	If the same MMSI is used by multiple ships at the same time, the MMSI is detected and removed during the creation of the GSDM.
Parameters from equipment are not defined	1, 2, 3, 4 and 5	The latitude, longitude, SOG, COG, and ROT are transmitting a value of 'Not Defined'. These errors are likely due to equipment errors.	These messages were not used to create related products. Messages with valid latitude and longitude but with speed not defined are still used to create the GSDM.
Parameters are not set correctly	1, 2, 3 and 5	Values that are set (ship length, navigation status) are not set correctly for the actual situation. It was found that the ship length often contained errors, which could result from entering the length in the incorrect units (e.g., feet instead of metres) or from swapping the length and width measurements.	According to [9], the largest ship currently in service has a length of 397.1 m. Therefore any ship over 400 m was removed. Although a comparison of ship lengths from the AIS data was compared to a reference database, this was not used for removing errors.

2.4 Verification

The verification of the GSDM and derived parameters used in the simulation presented a difficult task largely because independent (non-AIS) and current global ship density data was not readily available. There are a number of data sources that measure the global ship density (both AIS and non-AIS sources) and are listed in Table 7. As noted in the table, only qualitative comparisons were made with the developed GSDM, where possible.

Table 7: List of ship density datasets for comparison.

Name	Comments
Automated Merchant Vessel Reporting program (Amver)	Non-AIS. Voluntary system used for search and rescue. The Amver website states that, on average, about 4000 ships are recorded by the system each day. The ship density maps are posted online, but access to the data used to generate the maps is limited to search and rescue use only, and only qualitative comparison was possible.
World Meteorological Services Voluntary Observing Ships (WMO VOS)	Non-AIS. Voluntary system used for ships to provide weather reports. The WMO VOS website states that currently only about 4000 ships participate globally. There is a ship density map available online based on WMO VOS data collected for a period of 12 months beginning in Oct-2004. Again only qualitative comparison was possible.
Historical Temporal Shipping (HITS) database	Non-AIS. Uses historical data collected from many different sources. For United States Department of Defence use only and not available for use in this project. No comparison to this dataset was possible.
IHS Fairplay	AIS based. IHS Fairplay offers AIS services. A GSDM would have to be purchased if it exists, or generated from purchased AIS data.
PASTA-MARE project	European Union (EU) project about satellite based AIS. The resulting GSDM is available free online in ShapeFile format [10] and was created from both satellite and terrestrial AIS data (satellite data from Pathfinder and Orbcomm between 01-Jan-2010 and 31-Mar-2010). A comparison with this dataset showed similarities. However, the PASTA-MARE used AIS data which would not provide independent verification.

As noted in the Progress Findings Report for this project [11], two attempts at validation were investigated early in the project and are briefly summarized here. The first looked at the number of ships found using AIS data from a single satellite pass and compared this to the expected number of ships from the model using the GSDM for the same area. The results were not as expected which was attributed to the GSDM being developed using a large dataset over time while the selected satellite pass could have a seasonal or time of day component.

The second approach looked at the probability of redetection of ships for two satellite passes close in time from the same sensor. As with the first validation attempt, there were issues relating to ships not being detected because they left the satellite FOV between passes that made this investigation inconclusive.

More recently, a third means of verification was investigated which involved comparing the number of ships detected using RSAT2 ScanSAR Narrow B imagery and comparing this with the number of ships generated by the model for the identical RSAT2 image area. Five areas were checked, as summarized in Table 8. The two Atlantic Ocean locations represent offshore areas while the three other sites (Vancouver, Gibraltar and Dover) represent coastal areas with high ship densities. The number of ships reported by the model was averaged from 16 runs for each area in order to have a good statistical sample size. The standard deviation of the 16 simulations is also given in Table 8. The ship detections on the first two locations in the Atlantic Ocean were processed by C-CORE and the detections from the three other locations were provided by DRDC Ottawa.

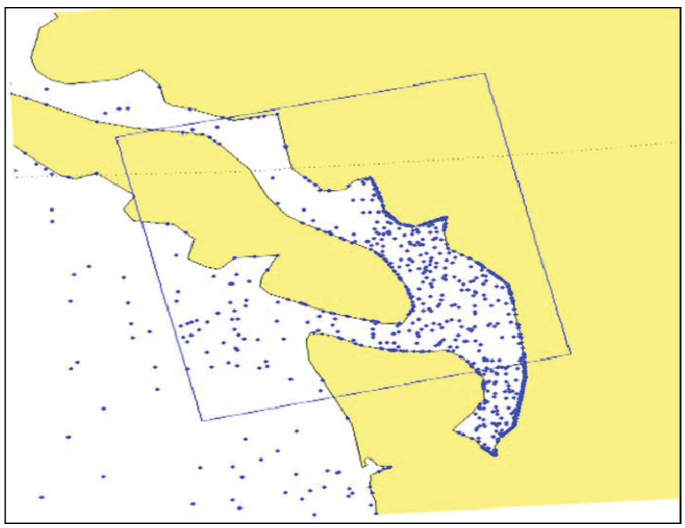
Table 8: Number of ships detected by SAR image vs. number of ships calculated from the GSDM in five experiment areas delimited by the footprints of RSAT2 SCNB images.

Area (Latitude, longitude)	**RSAT2 image date**	**Number of Ships in SAR**	**Mean, standard deviation of ships in Model**
Atlantic Ocean (45.04, -38.85)	08-Jul-2012	5	4.5, 1.03
Atlantic Ocean (44.60, -37.89)	15-Jul-2012	6	4.2, 0.75
Vancouver (50.19, -126.62)	25-Oct-2010	58	640.6, 6.01
Gibraltar (37.31, -7.62))	01-Aug-2008	122	651.1, 5.16
Dover (52.65, -0.45)	03-Aug-2008	343	1911.6, 20.25

The number of ships obtained from the RSAT2 image and that developed by the model for the two offshore Atlantic Ocean areas are in good agreement. However, the results from the coastal areas are not. Further investigation of these coastal cases highlights a number of potential issues that may make this verification approach difficult for such areas. Taking the Vancouver case as an example, Figure 29 displays the ships detected in the SAR image (a) and the model (b) for this case. The model implementation for ship placement is uniformly distributed over the entire one degree grid square. For coastal regions where the grid square includes land, all ships placed on land are moved to the coast. This maintains the correct number of ships in the grid square but bunches them near the coast, as shown in Figure 29(b). From a SAR perspective, vessel detections near the coast can be problematic also. The ability to detect vessels in the SAR image is influenced by a number of factors including shadowing near shore at shallow incidence angles, vessel length, sea state and imaging mode. One of the more prevalent factors in coastal areas is the increased number of smaller vessels. Depending on the actual vessel length and other mitigating factors, a significant number of vessels may not be detected by the SAR. In such cases, taking the SAR detections as a basis of comparison may not be viable.

While the offshore cases seem to be in good agreement, it is recommended that a number of additional cases be tested and confirmed before using this approach for verification going forward. For the coastal areas, this approach is not recommended. A better approach would be to collect ground truth data over an extended period as a reference rather than using SAR detections. This data may be able to be collected by direct observation over a period of time or through comparison with alternate datasets not based on AIS reports to provide a better basis of comparison.

(a)



(b)

Figure 29: Ship maps in Vancouver area. (a) Ships detected by RSAT2 SCNB image of 20-Oct-2010, (b) ships simulated from ship density map.

This verification work using RSAT2 imagery was expanded with additional locations and detections provided by Polar Epsilon via DRDC Ottawa. Figure 30 shows the locations of the RSAT2 imagery and the summary of the results are shown in Table 9. The results are grouped into three different categories. Group A represents cases where there was generally good agreement between the Polar Epsilon detections and the number of ships generated by the model. Group B were cases where the model made more ships than were detected in the RSAT2 imagery, and were locations that either contained land in the SAR image, or images close to the coastline. The higher number of ships for group B is possibly due to the same reasons as discussed for the Vancouver case. The group C cases had higher ships detected in the RSAT2 imagery than created by the model. These images were all from the South China Sea and indicates that there is a lack of coverage of this area in the AIS datasets used to generate the GSDM.

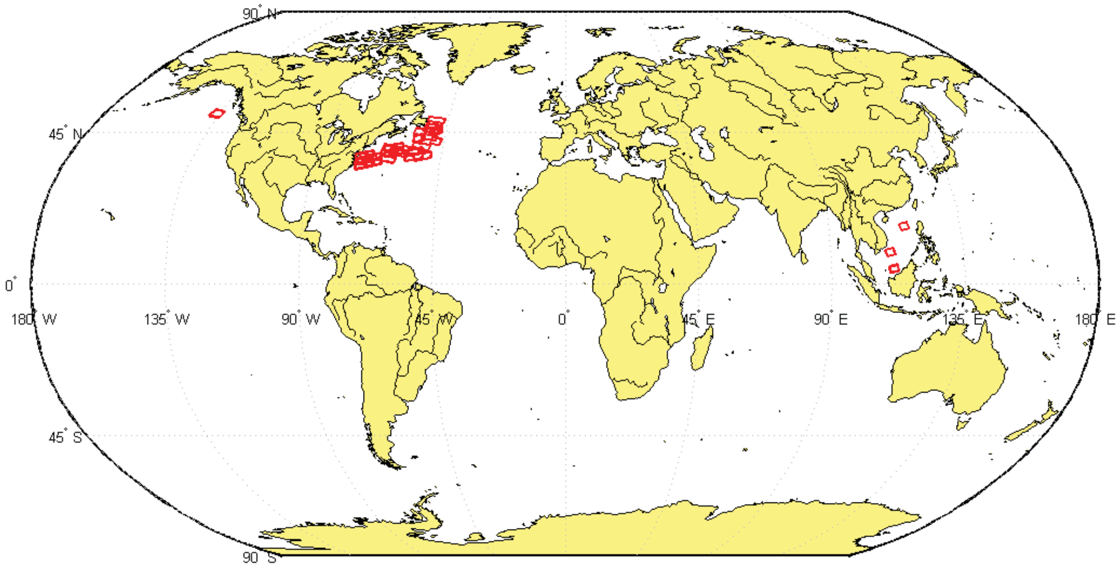


Figure 30: Location of RSAT2 images used for verification.

Table 9: Number of ships detected by SAR image vs. number of ships calculated from the GSDM in five experiment areas delimited by the footprints of RSAT2 SCNB images.

	Location	Date	RSAT2 Beam	Detections from Polar Epsilon	Ships in Density Map	Difference
A	East Coast Canada (ocean)	17-Dec-12	SCNB	9	5	-4
	East Coast US (ocean)	13-Dec-12	SCWA	4	4	0
	East Coast US (ocean)	13-Dec-12	SCWA	6	5	-1
	East Coast US (ocean)	14-Dec-12	SCWA	10	4	-6
	East Coast US (ocean)	14-Dec-12	SCWA	3	3	0
	East Coast US (ocean)	14-Dec-12	SCWA	8	5	-3
	East Coast US (ocean)	15-Dec-12	SCWA	7	2	-5
	East Coast US (ocean)	15-Dec-12	SCWA	5	9	4
	East Coast US (ocean)	16-Dec-12	SCWA	9	8	-1
	East Coast US (ocean)	16-Dec-12	SCWA	8	6	-2
	East Coast US (ocean)	16-Dec-12	SCWA	4	6	2
	East Coast US (ocean)	16-Dec-12	SCWA	3	1	-2
	East Coast US (ocean)	16-Dec-12	SCWA	5	4	-1
	East Coast US (ocean)	17-Dec-12	SCWA	7	6	-1
	West Coast Canada	23-Dec-12	SCNB	9	6	-3
	East Coast Canada (near NL)	18-Dec-12	DVWF	2	5	3
	East Coast Canada (near NL)	18-Dec-12	DVWF	8	5	-3

	Location	Date	RSAT2 Beam	Detections from Polar Epsilon	Ships in Density Map	Difference
	East Coast Canada (ocean)	18-Dec-12	DVWF	5	2	-3
	East Coast Canada (ocean)	23-Dec-12	SCNB	6	2	-4
	East Coast Canada (near NL)	24-Dec-12	SCNB	8	9	1
	East Coast Canada (ocean)	25-Dec-12	SCNB	5	5	0
B	East Coast US (near coast)	15-Dec-12	SCWA	14	33	19
	East Coast US (near coast)	15-Dec-12	SCWA	8	24	16
	East Coast US (near coast)	17-Dec-12	SCWA	6	17	11
	East Coast US (near coast)	17-Dec-12	SCWA	14	48	34
	East Coast US (near coast)	17-Dec-12	SCWA	12	114	102
C	South China Sea	17-Dec-12	SCNB	24	14	-10
	South China Sea	17-Dec-12	SCNB	24	10	-14
	South China Sea	18-Dec-12	SCNB	22	1	-21

2.5 Summary

The GSDM, transmit rate, dead reckoning errors, AIS Channels 3 and 4 exclusion region, and ship length distribution used in this project were generated from the available AIS datasets. Ideally, the statistical distributions derived for these parameters would be generated from a much larger set of AIS data covering a long time period and augmented by other relevant data sources where available. However it was realized early in the project that these activities could easily consume a considerable amount of time and effort. As a result, the products derived from the available AIS data were deemed to be sufficiently representative for use in this project. Caution should be exercised in using these products for applications beyond this project unless careful consideration is given to the limitations discussed previously.

The derived products also contain errors inherent in the AIS data. Where possible, these errors have been identified and removed. Given the nature of manual data input in many AIS messages, errors arising from incorrect entries as a result of human error are not always detectable and remain in the data.

3 AIS Model Development

3.1 Background Review

There have been many studies and reviews on the potential of satellite reception of AIS messages. Notable among these have been the modelling and simulation work done by the Norwegian Defence Research Establishment (FFI) (see, for example [15], [16] and [17]), and the stochastic model presented by J.K.E. Tunaley ([18], [19] and [20]). An overview of satellite detection of AIS messages, including a discussion of the work mentioned above, has been given by the ITU ([4] and [6]).

Beyond the basic models that have been developed for the satellite reception of AIS messages, of interest here is the detection of AIS messages that has been reported by COM DEV and their subsidiary exactEarth (eE). An overview of their work has been given, for example, by D'Souza and Martin [22], and more recently by D'Souza [23]. An interpretation of the performance presented in the latter work has been given by Tunaley [20] based on a stochastic model.

3.1.1 Parameters

The basic parameters of AIS are summarized in Table 10, as presented by the ITU [21]. Of note here are the message slots of length 256 bits transmitted in 26.7 ms, with 2250 time-slots in each frame. The message interval varies from two seconds to six minutes depending on the dynamic status of the ship, with the average interval for all ships being about seven seconds [21].

The ITU [21] has also summarized the nominal signal parameters and effective link margin, as shown in Table 11 and Figure 31. For a satellite altitude of 950 km considered within the ITU report, a margin of 10 dB is obtained out to about 500 km from the sub-satellite point.

Table 10: Overview of shipboard AIS technical parameters, from [21].

AIS parameters	Values
Frequencies	AIS Channel 1(161.975 MHz) and AIS Channel 2 (162.025 MHz)
Channel bandwidth	25 kHz
Platforms	Class A ships, Class B ships, coastal stations, navigation aids
Power	12.5 W (Class A); 2 W (Class B)
Antenna type(1)	½ λ dipole
Antenna gain(1)	2 dBi with cosine-squared vertical elevation pattern; Minimum gain = −10 dBi
Receiver sensitivity	−107 dBm for 20% packet error rate (PER) (minimum) −109 dBm for ≤20% PER (typical)
Modulation	9600 bits GMSK
Multiple access mode	TDMA (self-organizing, random, fixed and incremental)
TDMA frame length	1 min; 2250 time-slots

AIS parameters	Values
TDMA slot length	26.7 ms; 256 bits
Message types	22 types
Message length	1 to 5 slots with 1 slot being the dominate type
Periodic message interval	2 s to 6 min transmit intervals
Required *D/U* protection ratio	10 dB at PER = 20%[(2)]

[(1)] Typical parameters not defined in Recommendation ITU-R M.1371.

[(2)] Parameter specified in IEC 61993-2.

Table 11: Ship-to-satellite link budget at maximum range [21].

Parameters	Values
Geometry	
Satellite altitude (km)	950
Minimum transmit elevation angle (degrees)	0
Satellite antenna off-axis angle (degrees)	60.5
Maximum slant range (km)	3 281
Power	
Transmit power (dBm)	41.0
Transmit gain (dBi)	2.0
Transmit cable and miscellaneous losses (dB)	3.0
Free space propagation loss at maximum range (dB)	147.8
Polarization mismatch loss (dB)	3.0
Satellite antenna gain at the horizon (dBi)	1.6
Satellite RF line/filter losses (dB)	2.5
Received power at satellite (dBm)	−117.7
Satellite sensitivity for 20% PER (dBm)	−120.0
Net margin (dB)	8.3

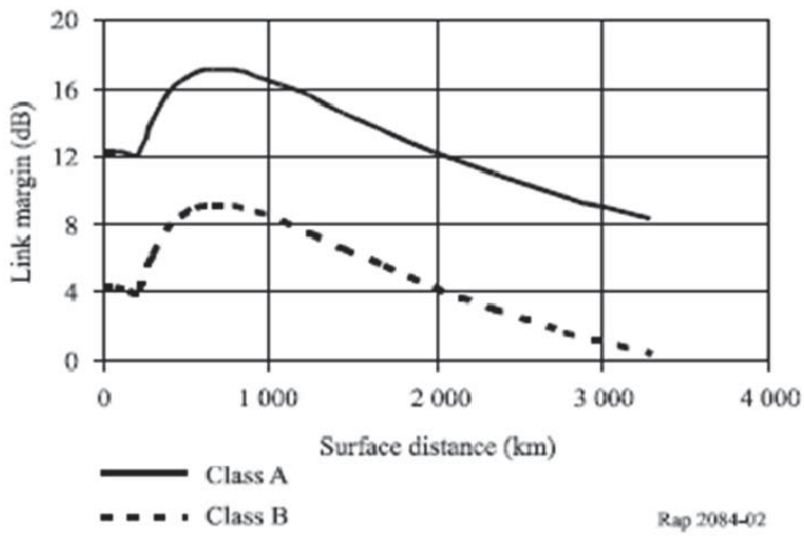


Figure 31: Ship-to-satellite link margin vs. surface distance from sub-satellite point [21].

3.2 Modeling Approaches

Several approaches to modelling the satellite detection of AIS messages have been reported in the literature. A so-called analytical method uses basic probability analysis over the various regions of the FOV to derive probability of detection expressions for various scenarios, and has been extensively developed by FFI [16], [17]. The problem has also been considered by Tunaley [20] in terms of random transmission of messages described by Poisson statistics, yielding results in agreement with the analytical method. More detailed analyses based on simulation of the transmission and detection characteristics have been performed, for example, by FFI [17] and ITU [21]. For most straightforward scenarios, the simulations yield results similar to the other approaches, although simulations remain a useful method to look at more complex characteristics within the AIS analyses.

3.2.1 Analytical models

FFI has developed two approaches, the first dealing with relatively small antenna footprints (< 800 km) and a second extended model. The first approach assumes only one type of message collision considering the maximum relative propagation delay for messages among different ship transmitters of two milliseconds. The second approach considers larger satellite antenna footprints including a second type of message collision caused by relative delays among messages coming from vessels in the FOV, which are longer than the maximum value allowed by self-organized cells.

The first FFI approach [15] defines the detection probability, *P*, for a given ship within the observation area as:

$$P = 1 - \left[1 - \left(1 - \frac{N_{tot}}{75M\Delta T}\right)^{M-1}\right]^{\frac{T_{obs}}{\Delta T}} \quad (1)$$

where M is the number of self-organized areas (size 40x40 nm was used for modelling), N_{tot} is the total number of ships, ΔT is reporting interval and T_{obs} is the observation time.

The second FFI approach [16] defines ship detection probability as:

$$P = 1 - \left[1 - e^{\left(\frac{-(1+s)N_{tot}}{37.5 n_{ch} \Delta T}\right)}\right]^{\frac{T_{obs}}{\Delta T}} \quad (2)$$

where s is the overlap factor depending on the sensor's altitude and FOV, N_{tot} is the total number of ships, n_{ch} is the number of independent channels used for transmission, ΔT is the reporting interval and T_{obs} is the observation time.

The ITU analytical model is based on identifying the instances when message signals may collide at the receiver, as shown in Figure 32 of the ITU document [21]. Zone 0 corresponds to the region in which the self-organizing capability of the TDMA signal would prevent collisions with the signal under consideration. In contrast, Zones 1 and 2 correspond to the regions where there is no coordination of the signal transmission, and therefore the signals may collide, with Zone 1 being limited to the area in which the maximum propagation delay is less than two milliseconds so that only a single time slot is affected, and Zone 2 is the remaining area within the FOV in which the propagation delay is greater than two milliseconds so that two time slots will be affected by a signal collision.

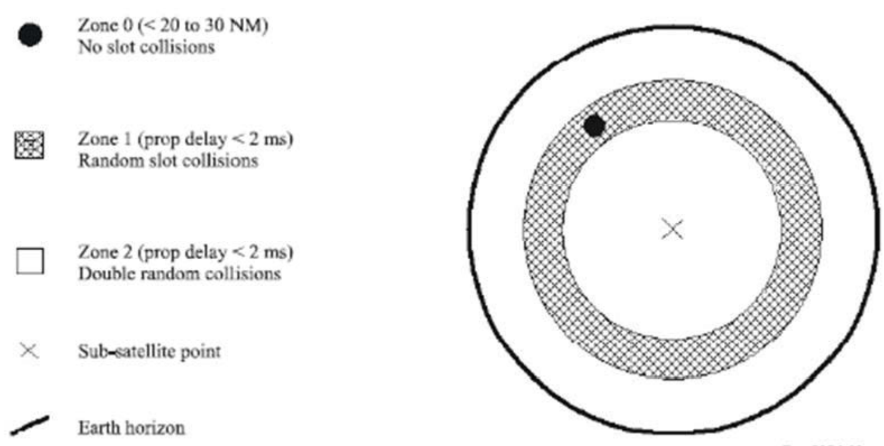


Figure 32: Illustration of time-slot collision zones [21].

The probability that at least one AIS message is detected out of *M* transmitted is then:

$$P_{M,N} = 1 - \left[1 - \left(1 - \frac{k\left(\frac{\tau}{\Delta T}\right)}{2}\right)^{N-1}\right]^{M} \quad (3)$$

where *N* is the total number of ships within the FOV, τ is the time for the message transmission, ΔT is the period of the message transmissions, and *k* is 0, 1, or 2 according to the zone of interference as illustrated in Figure 32.

3.2.2 Stochastic model

Tunaley [18] has described the probability of detection (POD) of an AIS message in terms of a Poisson random process, with a mean rate of message transmission, λ. Thus, the probability of at least one correct AIS message being received is:

$$p = 1 - \left(1 - e^{-\lambda \tau_0 (1-q)(1+s)}\right)^{\frac{T_{obs}}{\Delta T}} \quad (4)$$

where τ is the time for the message transmission, ΔT is the period of the message transmissions, and T_{obs} is the time during which the AOI is being viewed. The parameter *q* is the probability that a message is uncorrupted by another single message, and *s* is an overlap factor that accounts for the three zones of interference as outlined in Figure 32. For small values of the argument, $\lambda\, \tau_0\, (1 - q)(1 + s)$, the expression for the detection probability obtained by Tunaley is identical to that given by the analytical model above.

3.2.3 Simulations

Simulation of the satellite reception of AIS signals is useful for verifying the detection behaviour, and is especially useful for analyzing non-uniform characteristics. The Monte Carlo simulation is based on characterizing the ship distribution, the message transmissions, propagation, and reception. Additional factors, such as interference from terrestrial sources may be included. Both FFI and ITU, as well as COM DEV, have simulated the behavior of AIS satellite reception under various assumptions.

An example of the results obtained from the ITU [21] for the basic scenario of uniform ship distribution and random AIS transmissions is shown in Figure 33, along with the corresponding results from the analytical model.

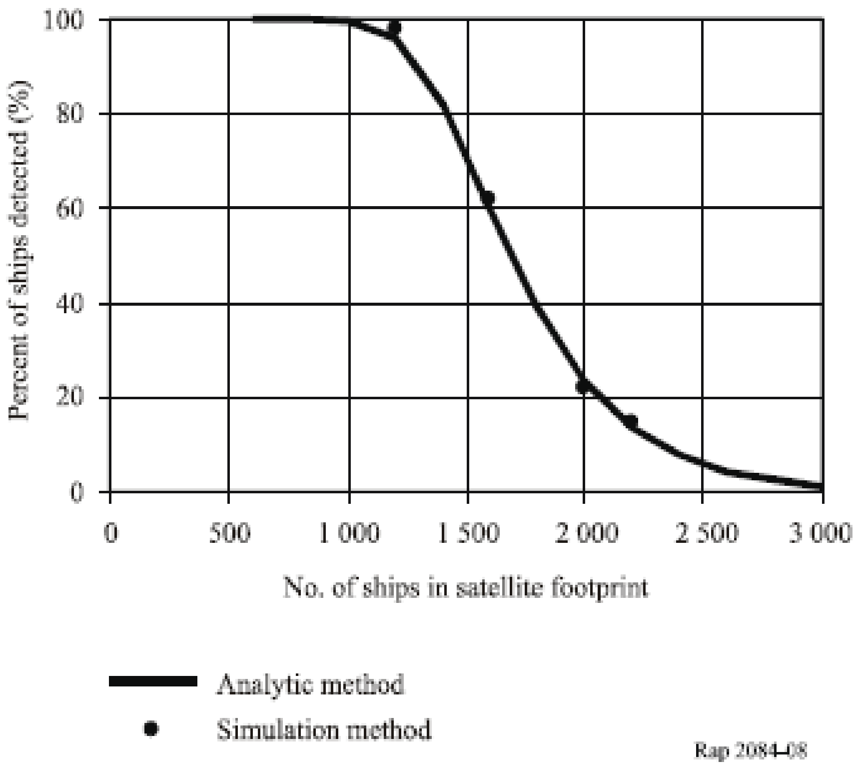


Figure 33: AIS satellite detection baseline curve using simulation method [21].

The ITU report [21] has also considered the various interference effects, from both Class A and Class B signals, and the effects of non-uniform ship distribution. The results for various observation times are presented in the report, and a few figures are reproduced here for reference. Figure 34 shows the probability of detection for an AIS signal considering Class A interference only, while Figure 35 includes interference from Class B signals. The results shown in Figure 36 are based on a global ship distribution, and illustrate one example of the detection probability for the North Atlantic shipping lanes.

Interference from terrestrial sources is considered in the review by the ITU [21], in particular VHF public correspondence stations (VPCS) and land mobile radio (LMR). Since these signals generally have higher signal levels, they can readily swamp the AIS signals at the satellite receiver. Successful reception of AIS signals in this instance therefore depends on the duty cycle of the terrestrial source, such that the AIS message can be received between terrestrial transmissions.

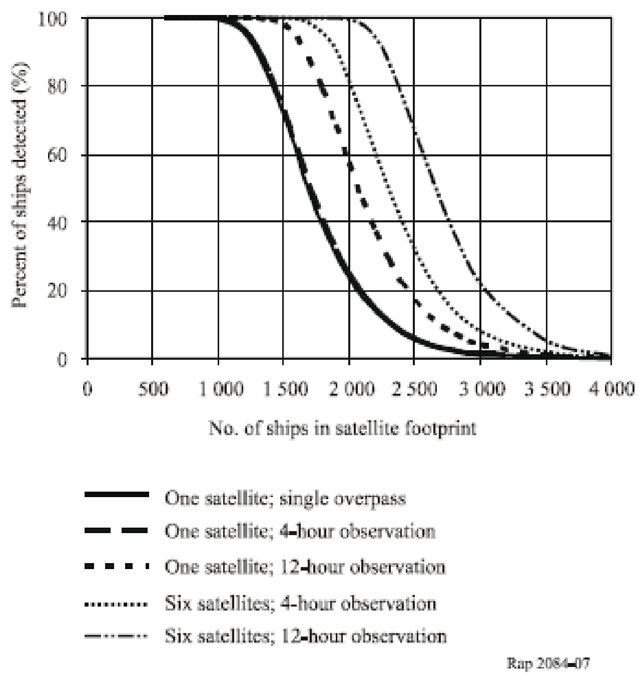


Figure 34: AIS satellite detection (One-and-six-satellite scenarios) [21].

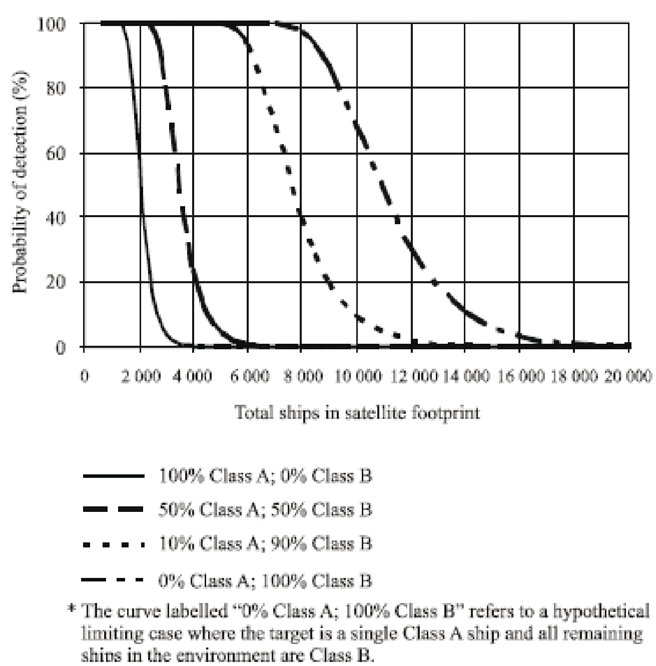


Figure 35: Detection probability in a mixed Classes A and B environment (One satellite; 12 h observation period) [21].

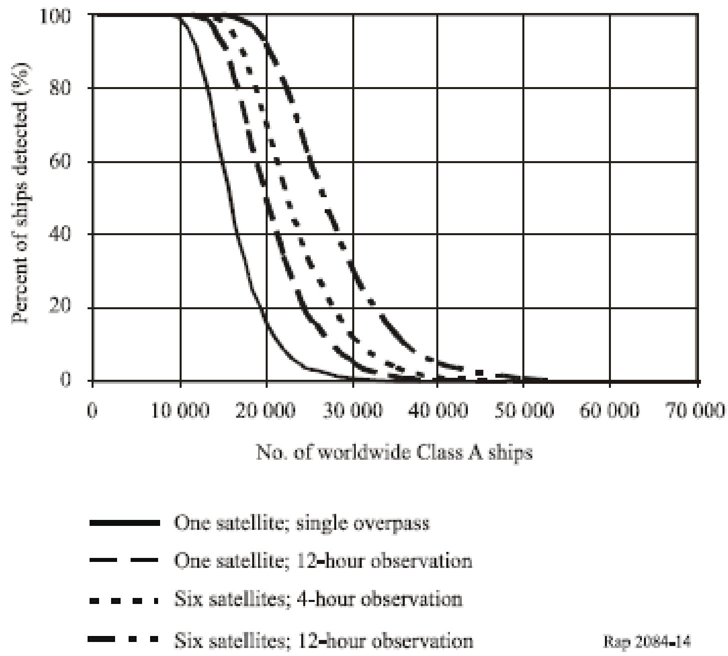


Figure 36: Detection statistics using worldwide ship data (Target ship located 1000 km off coast of New York, NY, USA) [21].

The reception of standard AIS messages at a satellite may be improved by using one or more enhanced methods. The satellite antenna pattern can be altered to focus on a reduced FOV, although this, in general, will also limit the observation time, thereby offsetting potential gains in reduced message collisions. One can also take advantage of the difference in the Doppler shift from the ships in varying parts of the satellite footprint to separate colliding messages, or use the differences in the polarization from Faraday rotation to separate messages along different propagation paths. The redundancy in the AIS messages from a given ship can be used in a correlation processor to help separate such messages from noise, and may be of particular value in excluding the lower power Class B signals.

3.2.4 Satellite Specific AIS — Message 27

To improve the detection of AIS messages received by satellites, new message parameters have been proposed to help overcome the message collisions. These proposed changes, which would define a new Message 27, are summarized in ITU-R M.2169 [6]. They include transmitting the messages on two channels (AIS Channels 3 and 4) that are restricted to maritime use, and reducing the message length to 96 bits and increasing the reporting interval to 3 min. This standard would be limited to Class A vessels only, and furthermore a transmission would be suppressed if a vessel is within range of an AIS base station. The introduction of this standard, including the upgrade of existing AIS transmitters, has been recently discussed at the World Radiocommunication Conference 2012. Approval has now been given for the allocation of AIS Channels 3 and 4 for long range AIS broadcast messages; however no timeline for implementation has been established to date.

An example of the probability of detection for the satellite specific AIS, as determined by the ITU [6], is shown in Figure 37. These results show that the detection is around an order of magnitude better than that for the standard AIS messages.

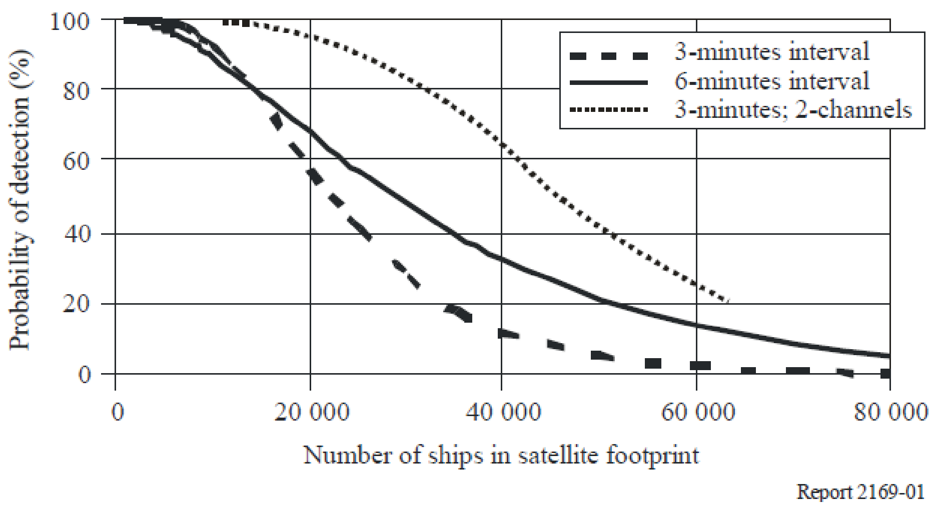


Figure 37: Detection statistics with 3rd AIS satellite channel (assuming uniform ship distribution) [6].

3.3 Interference

It has been demonstrated in the literature that AIS signals received in space are subject to potential interference by electromagnetic signals in the VHF bands transmitted by land-based transmitters. As a result, the overall performance of the AIS system may be negatively impacted depending on the location and output power of the interference sources [24],[25]. To comprehensively evaluate the performance of SAIS, it is necessary to consider interference.

This section describes the identification of potential interference sources to the AIS frequencies. The International Telecommunication Union Radio Regulation (ITU-RR) allocates AIS frequencies in different spectrum regions around the world. A survey of the official spectrum allocation for ITU dedicated AIS frequencies in selected countries has been conducted. The interference sources in each country are considered for equipment which operates in accordance with an individual country's regulations; however use of the ITU dedicated AIS frequencies over land areas for mobile or fixed services may be permitted where they do not interfere with the AIS system. Ideally, an exhaustive survey of the spectrum allocation for each country would be required to identify all potential interference sources; however, this level of investigation is beyond the scope of this project. Therefore, the investigation is limited to selected representative countries in each spectrum region.

Other potential interference sources originate from powerful VHF (from 30 MHz to 300 MHz) radar installations in some countries [24]. These VHF transmitters are mainly used for military purposes. Additionally, information was also found to indicate that electromagnetic radiation from high voltage power transmission lines can interfere with AIS systems. Both of these situations will be further discussed in the following subsections.

In addition to the sources previously mentioned, there is also the possibility of interference due to illegal transmitters in the AIS frequency range of interest. Illegal interference sources are difficult to identify due to uncertainties in operating time and locations. There is little information available in the literature dealing with illegal sources. An experimental AIS project, the LuxSpace AIS (LUXAIS) receiver installed on the International Space Station (ISS), was intended to provide an ability to detect illegal interference sources from space. The sampling devices on the LUXAIS receiver were designed to provide snapshots of the whole AIS frequency range. When combined with the well-defined orbital information of the ISS, the sampled data can be geographically positioned within an accuracy of several kilometres. From this, interference sources can be identified and localized by analysing the sampled data [24]. Unfortunately, no experimental results are available because of the communication failure between the LUXAIS receiver and the ISS interfaces after launch. The failed LUXAIS receiver was returned to Earth on March 16, 2012 [26].

3.3.1 AIS1 and AIS2: AIS Frequencies Allocated in ITU-RR

The Radio Regulations (RRs) published by ITU contain the complete text of the RR as adopted by the World Radiocommunication Conference (WRC) (Geneva, 1995) (WRC-95) subsequently revised and approved by all at the following WRC. The latest Edition (2012) was approved at WRC-12 in Geneva, Switzerland. Since the online access of the 2012 Edition is not currently available, all the quotations in this section are adopted from ITU-RR Edition of 2008 (WRC-07) [27]. However, the ITU *Provisional Final Acts* of WRC-12 are available at this time. The new regulations and allocations for AIS frequencies are discussed in this report in Section 3.3.2.

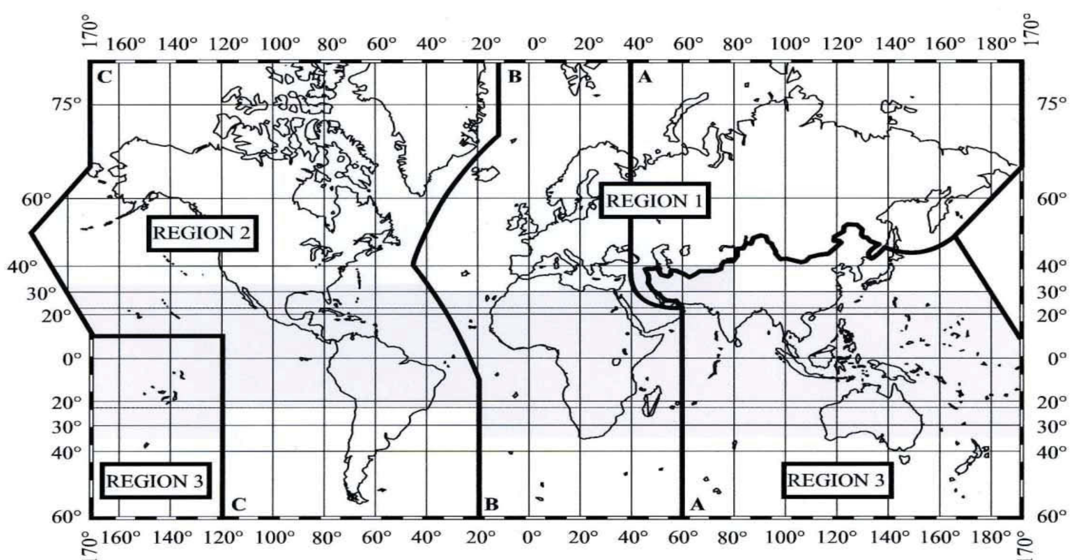


Figure 38: World spectrum regions (Adopted from [27], ARTICLE 5).

The world has been divided into three regions by ITU-RR as shown in Figure 38. The frequency allocation in each region is specified separately. Footnotes 5.3 to 5.9 of ARTICLE 5 define the region boundaries as follows:

5.3 *Region 1: Region 1 includes the area limited on the east by line A (lines A, B and C are defined below) and on the west by line B, excluding any of the territory of the Islamic Republic of Iran which lies between these limits. It also includes the whole of the territory of Armenia, Azerbaijan, the Russian Federation, Georgia, Kazakhstan, Mongolia, Uzbekistan, Kyrgyzstan, Tajikistan, Turkmenistan, Turkey and Ukraine and the area to the north of Russian Federation which lies between lines A and C.*

5.4 *Region 2: Region 2 includes the area limited on the east by line B and on the west by line C.*

5.5 *Region 3: Region 3 includes the area limited on the east by line C and on the west by line A, except any of the territory of Armenia, Azerbaijan, the Russian Federation, Georgia, Kazakhstan, Mongolia, Uzbekistan, Kyrgyzstan, Tajikistan, Turkmenistan, Turkey and Ukraine and the area to the north of Russian Federation. It also includes that part of the territory of the Islamic Republic of Iran lying outside of those limits.*

5.6 *The lines A, B and C are defined as follows:*

5.7 *Line A: Line A extends from the North Pole along meridian 40° East of Greenwich to parallel 40° North; thence by great circle arc to the intersection of meridian 60° East and the Tropic of Cancer; thence along the meridian 60° East to the South Pole.*

5.8 *Line B: Line B extends from the North Pole along meridian 10° West of Greenwich to its intersection with parallel 72° North; thence by great circle arc to the intersection of meridian 50° West and parallel 40° North; thence by great circle arc to the intersection of meridian 20° West and parallel 10° South; thence along meridian 20° West to the South Pole.*

5.9 *Line C: Line C extends from the North Pole by great circle arc to the intersection of parallel 65° 30'North with the international boundary in Bering Strait; thence by great circle arc to the intersection of meridian 165° East of Greenwich and parallel 50° North; thence by great circle arc to the intersection of meridian 170° West and parallel 10° North; thence along parallel 10° North to its intersection with meridian 120° West; thence along meridian 120° West to the South Pole.*

The AIS frequencies are defined in ITU-RR ARTICLE 5 and APPENDIX 18. The frequency allocation table in ARTICLE 5 is adopted in Figure 39.

The detailed specification for AIS frequency range between 156.8375 to 174 MHz is described by the footnotes 5.226 and 5.227A of ARTICLE 5 as below:

5.226 ... *In the bands 156-156.4875MHz, 156.5625-156.7625 MHz, 156.8375-157.45 MHz, 160.6-160.975 MHz and 161.475-162.05 MHz, each administration shall give priority to the maritime mobile service on only such frequencies as are assigned to stations of the maritime mobile service by the administration.*

5.227A *Additional allocation: the bands 161.9625-161.9875 MHz and 162.0125-162.0375 MHz are also allocated to the mobile-satellite service (Earth-to-space) on a* *secondary basis for the reception of automatic identification system (AIS) emissions from stations operating in the maritime-mobile service (see Appendix **18**) (WRC-07).*

148-223 MHz

Allocation to services		
Region 1	**Region 2**	**Region 3**
148-149.9 FIXED MOBILE except aeronautical mobile (R) MOBILE-SATELLITE (Earth-to-space) 5.209 5.218 5.219 5.221	**148-149.9** FIXED MOBILE MOBILE-SATELLITE (Earth-to-space) 5.209 5.218 5.219 5.221	
149.9-150.05	MOBILE-SATELLITE (Earth-to-space) 5.209 5.224A RADIONAVIGATION-SATELLITE 5.224B 5.220 5.222 5.223	
150.05-153 FIXED MOBILE except aeronautical mobile RADIO ASTRONOMY 5.149	**150.05-156.4875** FIXED MOBILE 5.225 5.226	
153-154 FIXED MOBILE except aeronautical mobile (R) Meteorological Aids		
154-156.4875 FIXED MOBILE except aeronautical mobile (R) 5.226		
156.4875-156.5625	MARITIME MOBILE (distress and calling via DSC) 5.111 5.226 5.227	
156.5625-156.7625 FIXED MOBILE except aeronautical mobile (R) 5.226	**156.5625-156.7625** FIXED MOBILE 5.225 5.226	
156.7625-156.8375	MARITIME MOBILE (distress and calling) 5.111 5.226	
156.8375-174 FIXED MOBILE except aeronautical mobile 5.226 5.227A 5.229	**156.8375-174** FIXED MOBILE 5.226 5.227A 5.230 5.231 5.232	

Figure 39: ITU-RR frequency allocation table, 148-223 MHz (Adopted from [27], ARTICLE 5).

APPENDIX 18 of ITU-RR defines the two central frequencies for AIS (AIS Channel 1 and AIS Channel 2 are referenced in the ITU documents as AIS 1 and AIS 2 respectively), as displayed in Figure 40. The footnotes *f, l, p and o* state:

f) The frequencies 156.300 MHz (channel 06), 156.525 MHz (channel 70), 156.800 MHz (channel 16),161.975 MHz (AIS 1) and 162.025 MHz (AIS 2) may also be used by aircraft stations for the purpose of search and rescue operations and other safety-related communication. (WRC-07);

l) These channels (AIS 1 and AIS 2) are used for an automatic identification system (AIS) capable of providing worldwide operation, unless other frequencies are designated on a regional basis for this purpose. Such use should be in accordance with the most recent version of Recommendation ITU-R M.1371. (WRC-07);

p) Additionally, AIS 1 and AIS 2 may be used by the mobile-satellite service (Earth-to-space) for the reception of AIS transmissions from ships. (WRC-07);

o) These channels may be used to provide bands for new technologies, subject to coordination with affected administrations. Stations using these channels or bands for new technologies shall not cause harmful interference to, and shall not claim protection from, other stations operating in accordance with Article 5. The design of such systems shall be such as to preclude the possibility of interference to the detection of AIS signals on 161.975 or 162.025 MHz. (WRC-07);

Channel designator	Notes	Transmitting frequencies (MHz)		Inter-ship	Port operations and ship movement		Public corres-pondence
		From ship stations	From coast stations		Single frequency	Two frequency	
15	*g)*	156.750	156.750	x	x		
75	*n)*	156.775	156.775		x		
16	*f)*	156.800	156.800	DISTRESS, SAFETY AND CALLING			
76	*n)*	156.825	156.825		x		
17	*g)*	156.850	156.850	x	x		
77		156.875		x			
18	*m)*	156.900	161.500		x	x	x
78	*m)*	156.925	161.525			x	x
19	*m)*	156.950	161.550			x	x
79	*m)*	156.975	161.575			x	x
20	*m)*	157.000	161.600			x	x
80	*m)*	157.025	161.625			x	x
21	*m)*	157.050	161.650			x	x
81	*m)*	157.075	161.675			x	x
22	*m)*	157.100	161.700		x	x	x
82	*m), o)*	157.125	161.725		x	x	x
23	*m), o)*	157.150	161.750		x	x	x
83	*m), o)*	157.175	161.775		x	x	x
24	*m), o)*	157.200	161.800		x	x	x
84	*m), o)*	157.225	161.825		x	x	x
25	*m), o)*	157.250	161.850		x	x	x
85	*m), o)*	157.275	161.875		x	x	x
26	*m), o)*	157.300	161.900		x	x	x
86	*m), o)*	157.325	161.925		x	x	x
27		157.350	161.950			x	x
87		157.375	157.375		x		
28		157.400	162.000			x	x
88		157.425	157.425		x		
AIS 1	*f), l), p)*	161.975	161.975				
AIS 2	*f), l), p)*	162.025	162.025				

Figure 40: ITU-RR Table of transmitting frequencies in VHF Maritime mobile band (Adapted from [27], APPENDIX 18).

Summarizing the relevant ITU-RR information provided previously, the following AIS frequency information is concluded:

1. 161.975 (AIS 1) and 162.025 (AIS 2) MHz with 25 KHz bandwidth (161.9625-161.9875 MHz and 162.0125-162.0375 MHz) are specifically allocated for AIS service for worldwide operation (maritime mobile service);

2. 161.975 MHz (AIS 1) and 162.025 MHz (AIS 2) with 25 KHz bandwidth (161.9625-161.9875 MHz and 162.0125-162.0375 MHz) can be also used for AIS satellite reception (mobile-satellite service) on a secondary basis with regard to mobile service;

3. In the mobile service, 161.975 MHz (AIS 1) and 162.025 MHz (AIS 2) can also be used by aircraft stations for the purpose of search and rescue operations and other safety-related communication. This is the only other approved use of the AIS 1 and AIS 2 frequencies except for AIS service mentioned in ITU-RR; and

4. For the fixed service, no specific application mentioned in ITU-RR use AIS 1 and AIS 2 frequencies.

3.3.2 AIS Channels 3 and 4: New AIS Frequencies for Receiving AIS Signals From Space

As the potential for long-range AIS ship detection continues to increase for applications such as better handling of hazardous cargoes, countering illegal operations and tracking ships globally, space-based AIS is becoming an effective means to meet these demands.

Unlike conventional terrestrial AIS systems which are less susceptible to interference through geographical separation, the space-based AIS receivers cover a much larger geographic area thus receiving AIS signals from numerous AIS transmitters simultaneously. As well, mobile systems operating inland are typically within the range of space-based AIS receivers. As a result, space-based AIS must be able to operate in an interference environment. To address the space-based AIS service, ITU has published several study reports discussing the technical limitations of using the conventional AIS Channels 1 and 2 for satellite detection of AIS signals. These reports also provide recommendations for technical solutions [4], [6] and [28].

Some of the conclusions in [6] are as follows:

> *A special short AIS message (proposed Message 27, of only 96 bits) that is tailored for satellite reception would solve the problem of blurred reception.*
>
> *Ships within range of an AIS base station should suppress transmission of this message.*

Satellite detection of the shipborne AIS should be limited to the AIS Class A (SOLAS Class) because the AIS Class B population is too large to be included.

Separate operating frequencies in addition to AIS 1 and AIS 2 are needed that are not subject to terrestrial use.

Frequencies should be considered only from RR AP18 due to the limited tuning range of the shipborne AIS.

RR AP18 contains only 4 frequencies (channels 16, 70, 75 and 76) that are exclusively dedicated to maritime use. Channels 16 and 70 cannot be considered because of their specific status. Should channels 75 and 76 of RR AP18 be considered together with the transmission mode described in this report, studies show the requirement of footnote n) to RR AP18 is met.

The detailed recommendations for long-range AIS broadcast message 27 content are specified in [4].

In essence, ITU proposed to add a mobile satellite service (Earth-to-space) allocation using VHF maritime mobile Channels 75 and 76 (156.775 MHz and 156.825 MHz) for improved AIS satellite detection using message 27 (please note that references to VHF maritime mobile Channels 75 and 76 are equivalent to AIS Channels 3 and 4 used elsewhere in this document). This proposed allocation is compatible with the existing navigation-related communications of the frequencies as designated in ITU-RR APPENDIX 18, note *n* which states, *"The use of these channels (75 and 76) should be restricted to navigation-related communications only and all precautions should be taken to avoid harmful interference to channel 16, e.g. by limiting the output power to 1 W or by means of geographical separation."* Channels 75 and 76 serve as guard-bands for channel 16, which is the safety and distress calling frequency used around the world. This is exclusively dedicated to maritime use and restricted from terrestrial use on a global basis; therefore it is protected from interference from all legally operating transmitters. Precautions to avoid harmful interference to Channel 16 will be achievable by prohibiting message 27 transmissions from ships within the range of an AIS base station.

According to the recently published "*PROVISIONAL FINAL ACTS*" of the WORLD RADIOCOMMUNICATION CONFERENCE (WRC-12) [31], Channel 75 and 76 have been approved to be used for the mobile-satellite service (Earth-to-Space) limited to the reception of AIS emissions of long-range AIS broadcast messages (Message 27). With the exception of AIS transmissions, emissions in these frequency bands by systems operating in the maritime mobile service for communications shall not exceed 1 W.

Beside its traditional allocations, AIS 1 and AIS 2 frequencies have also been allocated to the Mobile-satellite (Earth-to-Space) service limited only for AIS emissions.

Table 12 provides a summary of the AIS frequencies used for the mobile-satellite service.

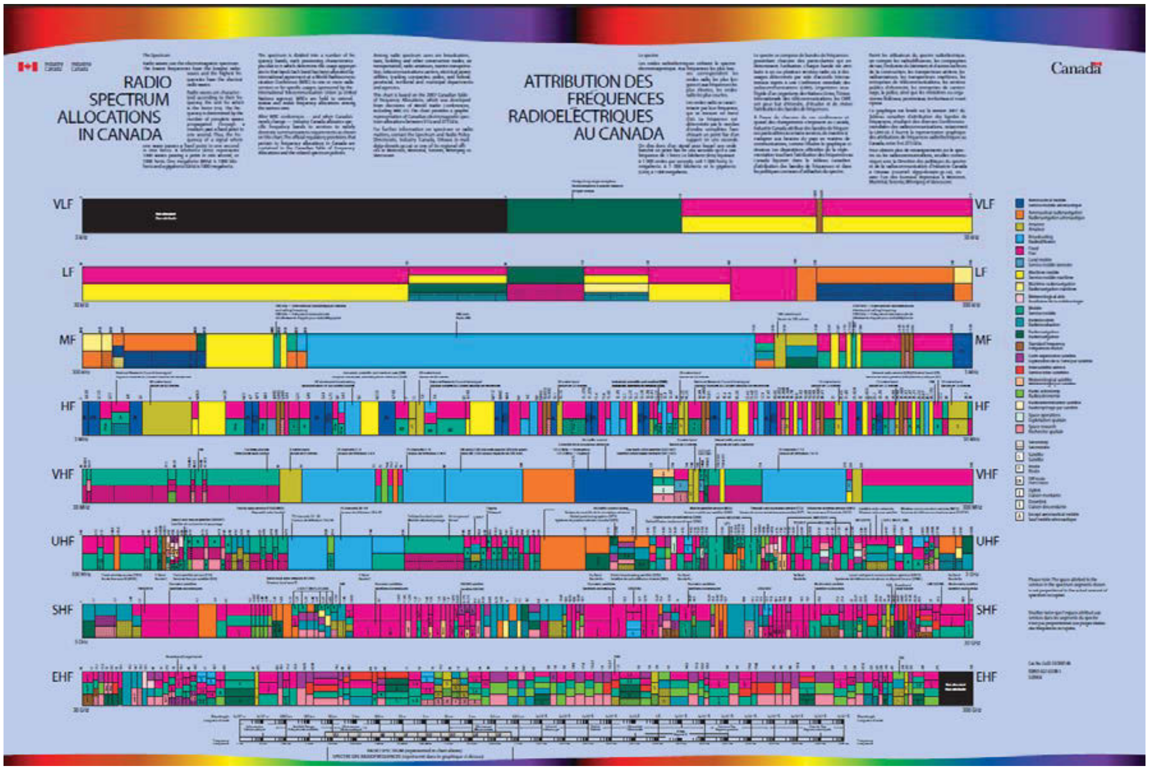
Table 12: AIS frequencies and bandwidths.

Channel	Center Frequency MHz	Bandwidth KHz	Frequency Range MHz
AIS 1 (Ch. 87)	161.975	25	161.9625 - 161.9875
AIS 2 (Ch. 88)	162.025	25	162.0125 - 163.0375
AIS 3 (Ch. 75)	156.775	25	156.7625 - 156.7875
AIS 4 (Ch. 76)	156.825	25	156.8125 - 156.8375

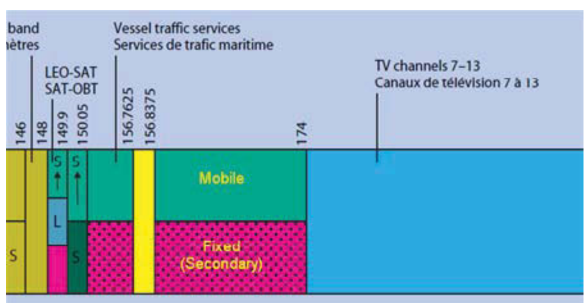
3.3.3 Spectrum Allocation for AIS Frequencies in Selected Countries

In 2007, the ITU conducted a survey aiming to gather information on the most important issues related to spectrum management policies around the world, including details of the initiatives undertaken by authorities responsible for the allocation of radio frequencies in each ITU Member State. The survey constitutes a brief introduction explaining the spectrum policy and planning efforts of each country, the relevant laws and the authority responsible for dealing with radio spectrum management. The internet addresses, together with the contact information listed in the survey, provide a portal to obtain a much more complete set of information for each country [29]. Starting from the portals, spectrum allocations are investigated on a per country basis although some of the website addresses listed may not be active. As a supplement, the European Communication Office Frequency Information System (EFIS) [30] of the European Communications Office is also referred to for access to spectrum use in each country in Europe.

The spectrum allocation of a given country is usually published in two formats: chart and table. The table version usually gives footnotes for each allocation. Examples of spectrum wall charts for Canada [32] and the USA [33] are displayed in Figure 41.


RADIO
SPECTRUM
ALLOCATIONS
IN CANADA
ATTRIBUTION DES
FRÉQUENCES
RADIOÉLECTRIQUES
AU CANADA
Canada
VLF
LF
MF
HF
VHF
UHF
SHF
EHF

(a)


band
mètres
LEO-SAT
SAT-OBT
Vessel traffic services
Services de trafic maritime
TV channels 7–13
Canaux de télévision 7 à 13
146
148
149.9
150.05
156.7625
156.8375
174
S
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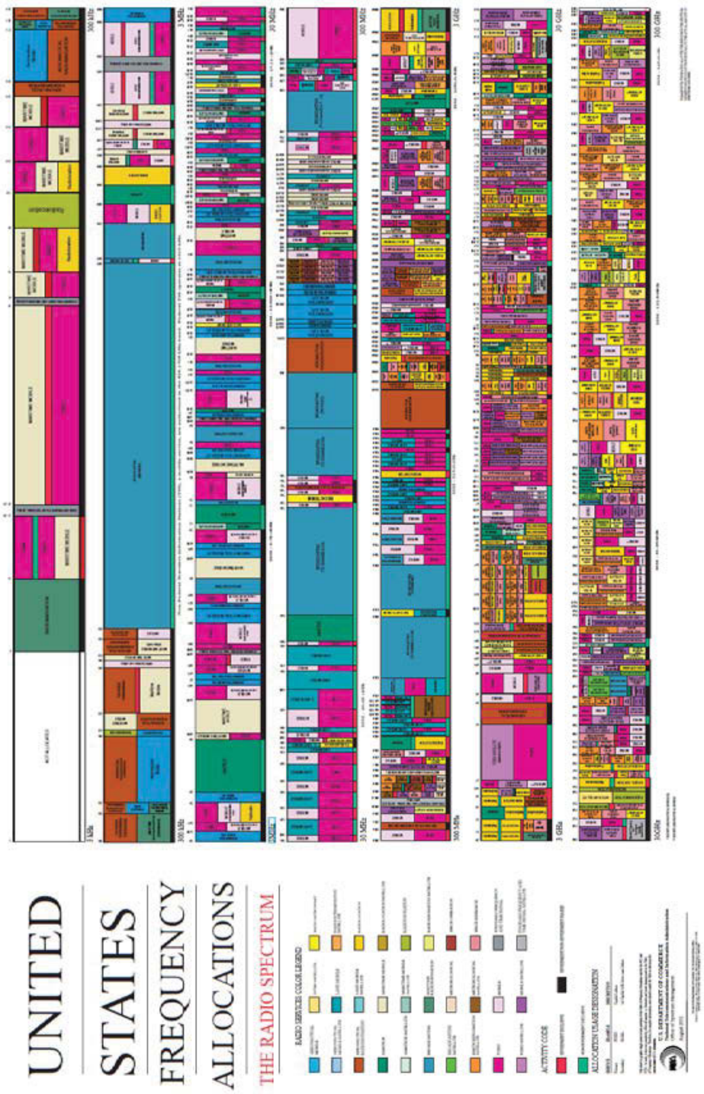
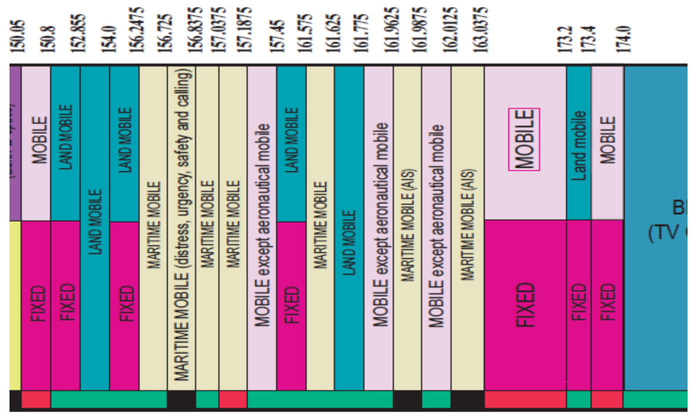
S
S
S
Mobile
Fixed
(Secondary)

(b)



(c)



(d)

Figure 41: Spectrum Allocation Wall Charts. (a) Canada chart. (b) sub-section of VHF band of (a). (c) USA chart. (d) Sub-section of VHF band of (c).

Comparing the two wall charts, the Canadian allocation for the VHF frequency range between 156.8375 MHz and 174 MHz follows the ITU allocation and does not provide any further details in this range. The USA wall chart clearly allocates two AIS channels consistent with the ITU allocation on AIS Channels 1 and 2. At the time of publication, AIS Channels 3 and 4 frequencies were still under discussion, so no specific allocations are indicated for these two frequencies on the charts shown.

Comparing the spectrum allocation in various countries with the ITU-RR allocations for AIS frequencies provides some insight into the potential for interference sources on AIS Channels 1 and 2 frequencies. Although a comprehensive investigation of all countries is not within the scope of this project, the spectrum allocation of selected countries from each of the ITU-defined spectrum allocation regions were investigated. A summary of these findings is provided in Table 13.

Table 13: Spectrum usages for ITU-RR AIS frequencies in some countries.

Jurisdiction	Region 1	Region 2	Region3
ITU	156.8375-174MHz Fixed, Mobile (except aeronautical) AIS1: 161.9625-161.9875 MHz AIS2: 162.0125-162.0375 MHz *5.226, 5.227A* [27]	156.8375-174MHz Fixed , Mobile AIS1: 161.9625-161.9875 MHz AIS2: 162.0125-162.0375 MHz *5.226, 5.227A* [27]	
UK	160.6125-163.03125 MHz mobile, *maritime* and international maritime services *5.226, 5.227A* [35]		

Jurisdiction	Region 1	Region 2	Region3
Egypt	156.8375-174MHz Fixed and mobile (except aeronautical) [37]		
Canada		156.8375-174MHz Mobile and Fixed (Secondary) *5.226, 5.227A* [32]	
USA		161.9625~161.9875MHz 162.0125~162.0375MHz Maritime mobile (AIS) [33]	
P. R. China			161.475~162.05MHz Maritime mobile Land mobile(Secondary) *5.226, 5.227A* [38]
Japan			161.475~162.06MHz Maritime mobile AIS1:161.9625~161.9875MHz AIS2: 162.0125~162.0375MHz [36]
India			156.8375-174MHz Fixed and mobile *5.226, 5.227A* [39]
Australia			156.8375-174MHz Fixed and mobile *5.226 5.227A* [34]
New Zealand			161.5-162.2 MHz Maritime Mobile AIS1:161.9625~161.9875MHz AIS2:162.0125~162.0375MHz [40]

Details on specific radio frequency allocations for Egypt are not readily available from the "National Telecommunication Regulatory Authority" website for the country [37] but the general information shown was available in chart form. As a result, specific allocations for AIS frequencies in frequency range 156.8375-174 MHz in Egypt is unknown. For all the other countries listed in Table 13, all allocations are as per ITU-RR guidance for AIS 1 and AIS 2 frequencies for the AIS services as indicated either by citing footnotes 5.226 and 5.227A of ITU-RR ARTICLE 5 or by specifying the frequency ranges.

The representative spectrum surveys listed in Table 13 can be considered a positive indicator that through proper adherence to spectrum management rules, interference from regulated transmitters should not be a major disturbance for AIS signal communication in the world. While a survey of all spectrum allocations for all countries is not possible within this project, the representative countries investigated provide good insight. Where potential interference sources are possible, it would require a detailed search of all radio licenses in the jurisdiction to determine technical details such as location, output power, duty cycle and specific frequency to determine the level of interference, if any. Further to this, WRC-12 has approved that fixed and mobile services (other than maritime mobile) that operate in the frequency bands of AIS Channels 1 and 2 will be discontinued as of January 1, 2025 [31]. As such, all administrations are asked to make all reasonable efforts to do this during the transition period.

The new AIS frequencies (AIS Channels 3 and 4) have not been reflected in each country's current spectrum plan. New allocations for these two channels in each country should be expected in the near future with the release of ITU-RR WRC-12. As previously discussed, no inference sources should be expected if ITU-RR (WRC-12) resolutions are adhered to.

3.3.4 Worldwide Interference Sources Search

3.3.4.1 Long Range VHF Radars

In addition to spectrum allocation issues posing potential interference sources, another possible interference source for AIS signals are large, powerful surveillance radars operated by various countries for military purposes. Long range detection and tracking radars operating in the VHF band have the potential to provide significant interference. An example of this kind of interference was observed and shown in [1]. The interference signal was believed to be transmitted by Russian anti-ballistic missile radars. The time domain interfered AIS signals captured by LUXPACE's PATHFINDER2 is provided in Figure 42.

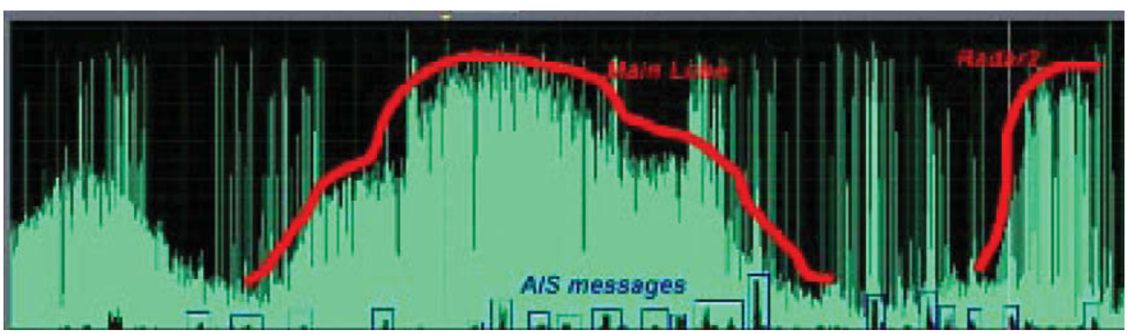


Figure 42: Interfered AIS signals received by PATHFINDER2 on 4 January 2010 with FOV covering North of Germany (Adopted from [1]).

The radar waveforms are shown in red and the AIS messages are marked in blue. The demodulation of the AIS messages was a problem given the much higher amplitude of the interference signal.

Given the example demonstrated, a search for long range radars was conducted. Given the sensitive nature of information related to military radar installations, limited information was found. The "List of radar" page from WIKIPEDIA [42] provides a limited list of countries operating long range radars. Table 14 summarizes the information retrieved.

Table 14: Long Range Radars in some countries.

Country	Long Range Radar	Frequency Band	Location info	Range
Iran	Yes	VHF	-	480 km
Soviet/Russia	Yes	VHF, UHF	Yes	1900 - 4200 km
Argentina	Yes	L	Yes	-
Australia	Yes	HF	Yes	3000 km
France	Yes	X	-	-
German	Yes	X	-	-
Norway	Yes	X	Yes	41,000 km
UK	Yes	X	-	-
USA	Yes	UHF	Yes	5600 km
Brazil	Yes	-	-	-
India	Yes	-	-	-
P. R. China	Yes	-	-	-

The long range radars in these countries are mainly used for military purposes. For the purposes of this project, the VHF radars are those of interest. Russia operates the most VHF radars found in this study. Three networks of VHF radars, reflecting three generations of development (first generation: Dnestr radars, second generation: Daryal radars, current generation: Voronezh radars) are still active as a part of the country's antiballistic missile surveillance network [43]. Iran also has one VHF early warning radar. It was stated that this radar can cover the whole Persian Gulf though the location of this installation is not available [44]. Table 15 provides available details pertaining to these particular VHF radars.

Table 15: VHF long range radars found in the world.

<table>
<tr><th>Country</th><th>Radar</th><th>Frequency MHz</th><th>Output power</th><th>Range km</th><th>Latitude</th><th>Longitude</th></tr>
<tr><td rowspan="8">Russian</td><td rowspan="4">Dnestr Radars</td><td rowspan="4">154-162</td><td rowspan="4">1.25 MW</td><td rowspan="4">1,900 to 3,000</td><td>52.877574° N</td><td>103.273323° W</td></tr>
<tr><td>52.874829° N</td><td>103.260791° W</td></tr>
<tr><td>46.603076° N</td><td>74.530985° W</td></tr>
<tr><td>68.114100° N</td><td>33.910200° W</td></tr>
<tr><td rowspan="2">Daryal Radars</td><td rowspan="2">150-200</td><td rowspan="2"></td><td rowspan="2">6000</td><td>40.871283°N</td><td>47.808958°W</td></tr>
<tr><td>65.210164°N</td><td>57.295383°W</td></tr>
<tr><td>Voronezh Radars</td><td>150-200</td><td>0.7 MW</td><td>4200</td><td>60.275458°N</td><td>30.546017°W</td></tr>
<tr><td>Iran</td><td>Matla-ul-fajr</td><td></td><td>4 KW</td><td>480</td><td></td><td></td></tr>
</table>

Figure 43 displays the Russian VHF radar locations. Two of the Dnestr Radars are very close to each other thus are merged into one yellow circle on the right side of the figure.

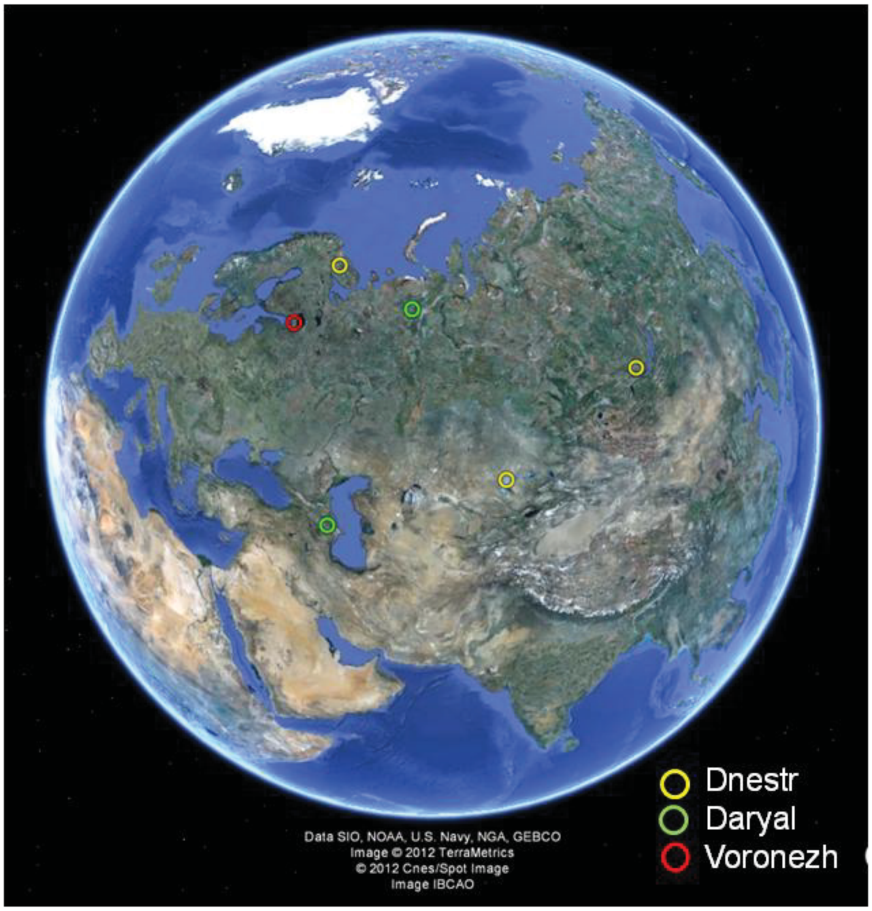


Figure 43: Long range VHF Radar locations in Russia, displayed on Google earth.

3.3.4.2 Cross-Sea Power Transmission Lines

A study published in the journal of "China Water Transport" in April of 2012 [45] indicates that there is a potential AIS interference issue arising from electromagnetic emissions from high voltage power transmission cables. The purpose of the study was to investigate interference from the high-voltage cross-sea power transmission lines on AIS signals received by ships. The conclusions from the study were translated and are summarized below:

1. The electrical radiation from the power transmission line (220KV) can cause interference to radio communication signals in VHF and lower frequencies.

2. Based on experiments, the impact area can be several thousand meters around the power line.

3. Based on the experiment, the AIS signals in the impacted area either cannot be detected or are received with errors.

It is not readily apparent if this interference source would be significant for space-based AIS receivers, however, if the interference results in not only reception errors but also transmission errors, then signal reception in space would certainly be impacted.

3.3.4.3 Transmitters Using AIS Frequencies (Canada, USA)

In some countries the relevant spectrum management organizations maintain a publicly accessible database of the country's licensed radio stations or frequencies. Users can obtain information such as the licensee names, type of radio stations, frequency, output power, locations and other information by searching the database. Information from these databases can provide details pertaining to potential interference sources.

The Spectrum Directorate of Industry Canada has such a system called "Radio Frequency Search". Various search tools provide real-time access to Canada-wide frequency information from Industry Canada's Assignment and Licensing System database [46]. A review of the licenses listed the vast majority as Canadian Coast Guard AIS base stations as part of the national AIS system or base stations operated by various major port authorities and the St. Lawrence Seaway authority. Figure 44 plots the locations of these transmitters on a map.

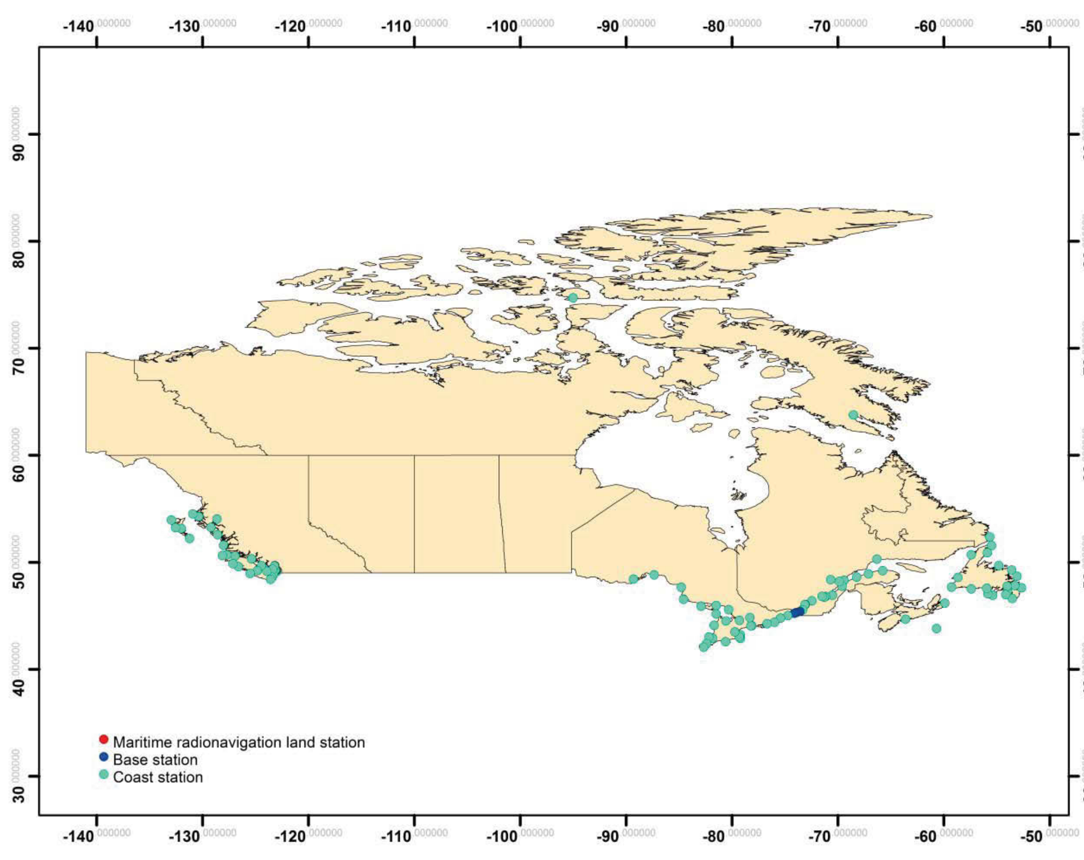


Figure 44: AIS Base Station Transmitters in Canada.

The Federal Communication Commission of the United States also maintains a similar database called "Universal Licensing System" [47]. Table 16 lists the transmitters found in the USA using this search engine.

Table 16: Licensed radio stations transmitting AIS frequencies in USA [47].

Licensee Name	Transmitter Location	Lat/Long	Station Class	Frequencies	Output Power W
ARIZONA, STATE OF	24601 N 29TH AVE PHOENIX MARICOPA AZ	33.7075N / 112.1207W	FX1	161.975 MHz	25
ARIZONA, STATE OF	14500 N ORACLE RD TUCSON PIMA AZ	32.5659N / 110.919W	FX1	161.975 MHz	25
ARIZONA, STATE OF	2800 W PINNACLE PEAK RD PHOENIX MARICOPA AZ	33.7022N / 112.1182W	FX1	161.975 MHz	25
ARIZONA, STATE OF	AZ		FX1T	161.975 MHz	50
ARIZONA, STATE OF	AZ		MO	161.975 MHz	50
Frontier Refining LLC	2700 E 5TH ST CHEYENNE LARAMIE WY	41.7694N / 104.7544W	FB2	161.975 MHz	50
AT&T CALIFORNIA	ROUND TOP HILL 5.3 MI NE OAKLAND CONTRA COSTA CA	37.8506N / 122.1926W	FC	161.975 MHz	50
GARDENHIRE, PAT L	HWY 879 ONE MI W BOYCE ELLIS TX	32.3796N / 96.7619W	FC	161.975 MHz	50
AVALON COMMUNICATIONS CORP	SIGNAL HILL SAINT THOMAS VI	18.3552N / 64.9468W	FC	161.975 MHz	50
WHIDBEY TELEPHONE COMPANY	S OF CLASSIC RD 7.4 KM NNW FREELAND ISLAND WA	48.0665N / 122.5782W	FC	161.975 MHz	50
Raymarine, Inc. a FLIR Company			FCA2	161.975 MHz, 162.025MHz	2

Licensee Name	Transmitter Location	Lat/Long	Station Class	Frequencies	Output Power W
BRUNSWICK NEW TECHNOLOGIES - MARINE ELECTRONICS	23868 HAWTHORNE BLVD., SUITE 201 TORRANCE LOS ANGELES CA	33.8139N / 118.35W	FCA	161.975 MHz, 162.025MHz	12
Applied Research Laboratory / The Pennsylvania State University	CENTRE PA		FCA2	161.975 MHz, 162.025MHz	2
NAVICO INC.	23868 HAWTHORNE BLVD, SUITE 201 TORRANCE LOS ANGELES CA	33.8139N / 118.35W	FCA	161.975 MHz, 162.025MHz	12
Raymarine, Inc. a FLIR Company	9 TOWNSEND WEST NASHUA HILLSBOROUGH NH	42.7879N / 71.5209W	FCA	161.975 MHz, 162.025MHz	2

Note: FC: Public Coast; FCA: Maritime support-Testing and Training; FX1T: Control Temporary; FX1: Control; MO: Mobile; FB2: Mobile Relay; FCA2: Marine Support-Testing and Training Temporary

The US licenses listed in Table 16 are for transmitters that are not readily identified as a part of the US nationwide AIS system. As a result, some of these may be considered potential interference sources, but details on the usage of each transmitter must be further investigated to clarify if it is a real source of interference.

3.3.5 Interference Summary

An investigation of the global electromagnetic spectrum allocation in the VHF band has been carried out to assess the potential for interference sources that may impact AIS reception. While an exhaustive investigation was beyond the scope of this project, the information gathered indicates that potential AIS interference sources are limited as many jurisdictions adhere to ITU-RR for license allocation, which regulates spectrum use to avoid interference. One of the more serious potential interference sources are military surveillance radars operating in the VHF band. These are operational in some countries for long range missile detection and have powerful transmitters. Detailed specifications are generally unavailable for these systems so a proper assessment is difficult. Additionally, a local source of AIS interference has been reported due to high voltage power transmission lines in a case near the coast of China. This has been shown to disrupt AIS receptions for vessels within several kilometres of the site; however, little impact is expected for SAIS receivers.

4 Model Implementation

The model implementation relies on the AIS database and derived products, as discussed in Section 2, the satellite orbit and resulting footprint and various AIS and SAR sensor options to generate probability of detection values for AIS and SAR on an area basis. The specific functionality pertaining to input parameters, file dependencies and model output are outlined in the following subsections. A discussion on the layout of the program and its major sections is also included in this section.

4.1 Functionality

4.1.1 Input

The simulation program obtains the required input from an input parameter file that is listed in the function argument list. Within the file, key parameter variable names are used to identify and assign parameter values. The format of each assignment statement is "parameter_name = parameter_value", with the option of including comments after the "%" identifier.

At the present time, AIS information is obtained from database files whose names are coded directly within the simulation function. These file names could easily be included within the input file as well.

4.1.1.1 Parameters

The key parameters that are defined within the input parameter file are shown in Figure 45 below. The example shown is one used for a RCM run at a location along the west coast of Canada. The required parameters specify the options for the SAR sensor, the SAR ship detectability modelling and the AIS sensor including the receiver modelling. Parameters are further discussed in Section 5

```
%% AIS Simulator Parameter file
% Horn of Africa

%% SAR setup
SAR_Sensor      = 'RCM1';
SAR_Mode        = 'SHIPDET';
SAR_BeamNum     = [];
SAR_StartTime   = '20120108T015739.000';  % using dateFormat3F = 'yyyymmddTHHMMSS.FFF';
SAR_ImagingTime = 120;  % seconds

%% AIS setup
AIS_Sensor    = 'RCM1';
AIS_Duration  = 7;      % minutes
AIS_StepTime  = 1;      % minutes
AIS_StartTime = '20120108T015239';     % using dateFormat = 'yyyymmddTHHMMSS';

%% Simulator setup
AIS12Flag            = 1;  % Channels 1 & 2
AIS34Flag            = 1;  % Channels 3 & 4
AIS12MaxReceivedMsgs = 7;
AIS34MaxReceivedMsgs = 2;

noiseFlag            = 0;  % interference
noisePower           = 0;  % W
noiseDutyCycle       = 0;  % percent
noiseLocations       = []; % Lat, Lon

transmitProbFlag    = 0; %
transmitProbability = 1; %

%% Ship Detectability Parameters
SAR_Ship_POD         = 0.9;      % probability of detection
RCM_NESZ             = 1;        % flag
SAR_Pol              = 0;        % flag HH polarization
Ocean_WindSpeed      = 10.833;   % m/s
Ocean_WindDirection = 0;         % towards sensor
Ocean_KNu            = 4;        % shape parameter
PFA                  = 2.5e-9;   % probability of false alarm
Det_Margin           = 3;        % dB
```

Figure 45: Sample input file.

4.1.1.2 Required Files

The simulation is developed for use in the MATLAB® programming environment and as such requires a working copy of this application. Development was done using MATLAB® release R2012a. In addition to the primary simulation code, the program also requires access to a series of supporting files and folders. These required dependencies are summarized in Table 17.

Table 17: File dependencies.

File	Description
Simulation file	
AIS_Simulation.m	Main application file
Parameter Files:	
Text file (e.g. *.txt or *.m)	Input file defining the parameters for ship detection probability and SAR, AIS, simulator setups.
Database files:	
den.mat	Ship density map
ship_lengths_grid.mat	Ship length distributions for each grid cell
combined_ais34_poly.mat	Exclusion regions for AIS channel 3 and 4 transmissions
norm_tx.mat	AIS signal transmission period distributions for dynamic messages, for each grid cell
norm_cog.mat	Ship COG distributions for each grid cell
norm_sog.mat	Ship speed over ground distributions for each grid cell
dead_reckoning_errors_pdf.mat	Dead reckoning probability density functions for each grid cell
Function files:	
sat_track_from_tle.m	Satellite orbit track from the Two Line Element (TLE), for the specified timeframe
gen_sar_beam_footprint.m	SAR swath for beam mode and specified acquisition time

File	Description
get_incidence_from_pos.m	SAR incidence angle for ships within swath
get_minShipLength.m	Minimum detectable ship length at specified SAR incidence angles (from DRDC Ottawa code)
move_to_coast.m	Ship positions that are initially generated over land are moved to the nearest water body
time_uncertainty.m	Calculates probability of association between AIS and SAR acquisition times
Orbit folder:	
req_files_orbit_propagation	Files in this folder are used for SAR and AIS satellite orbit calculations
Ship length folder:	
req_files_pod_from_ship_lengths	Files in this folder are used for ship SAR detectability calculations

4.1.2 Output

The output from the simulation consists of a text file containing information specific to the particular simulation run and two graphics illustrating the region covered and the ships generated for the simulation. Details pertaining to these outputs are described in the following subsections.

4.1.2.1 File

Figure 46 shows a sample output file. The first part of the output file contains a list of the input parameters (not shown in Figure 46), while the latter half contains some of the results of the SAR and AIS simulations as well as the probabilities of detection. The AIS Channels 1 and 2 outputs are given first followed by the AIS Channels 3 and 4 (if run). The output includes the number of ships in the SAR swath and in the AIS FOV and the average transmit rate for Channels 1 and 2. The probability of detection for ships within the SAR swath includes those listed in Table 18. The probabilities of detection for the AIS are given for those ships within the overlap region and for ships that are covered for at least five minutes of the AIS observation timeframe. This is meant to give an indication of the AIS detection capabilities beyond any restrictions that may exist within the limited area of the SAR swath. The reason for the two overlap areas is that the scenarios presented in Section 5 use a seven minute AIS on time but the specification for AIS on

RCM refers to ships within the AIS FOV for five minutes. The output also contains the probability of association based on the time difference between the AIS and SAR acquisition times.

Table 18: Probability of detection for ships within the SAR swath.

Probability of Detection	**Description**
P(SAR)	Ship detected by SAR, only considering ships larger than 25 metres
P(~SAR)	Ship not detected by SAR
P(AIS)	Ship detected by AIS
P(~AIS)	Ship not detected by AIS
P(AIS|SAR)	Ship detected by AIS given that it is detected by SAR
P(AIS|~SAR)	Ship detected by AIS given that it is not detected by SAR
P(SAR|AIS)	Ship detected by SAR given that it is detected by AIS
P(SAR|~AIS)	Ship detected by SAR given that it is not detected by AIS
P(SAR∩AIS)	Ship detected by SAR and AIS
P(SAR∪AIS)	Ship detected by SAR or AIS

```
number of ships in SAR swath: 85

number of ships in SAR swath and AIS 3&4 region: 64

average tx rate: 36.902
average tx rate (ignoring 180s): 6.901

orbit iteration      number of ships in AIS fov
          1             AIS 1&2: 1573     AIS 3&4: 1126
          2             AIS 1&2: 1737     AIS 3&4: 1121
          3             AIS 1&2: 1687     AIS 3&4: 1005
          4             AIS 1&2: 1655     AIS 3&4: 776
          5             AIS 1&2: 4118     AIS 3&4: 949
          6             AIS 1&2: 4760     AIS 3&4: 1005
          7             AIS 1&2: 5178     AIS 3&4: 1005


AIS channels 1 & 2 for ships within SAR swath
   P(SAR) = 0.99
   P(~SAR) = 0.01
   P(AIS) = 0.91
   P(~AIS) = 0.09
   P(AIS|SAR) = 0.90
   P(AIS|~SAR) = 1.00
   P(SAR|AIS) = 0.99
   P(SAR|~AIS) = 1.00
   P(SARnAIS) = 0.89
   P(SARuAIS) = 1.00

ship detection within AIS 1&2 field of view
   duration:  7.00 minutes
   number of ships:    603
   P(AIS) =  0.94

5 minute overlap
   number of ships:    971
   P(AIS 5min) =  0.94

Probability of association of AIS and RSAT2 for region 1,2 =  1.000

AIS channels 3 & 4 for ships within SAR swath
   P(SAR) = 0.98
   P(~SAR) = 0.01
   P(AIS) = 1.00
   P(~AIS) = 0.00
   P(AIS|SAR) = 1.00
   P(AIS|~SAR) = 1.00
   P(SAR|AIS) = 0.98
   P(SAR|~AIS) =  NaN
   P(SARnAIS) = 0.98
   P(SARuAIS) = 1.00

ship detection within AIS 3&4 field of view
   duration:  7.00 minutes
   number of ships:    263
   P(AIS) =  1.00

5 minute overlap
   number of ships:    454
   P(AIS 5min) =  1.00

Probability of association of AIS and RSAT2 for region 3,4 =  1.000

number of false alarms:     4

19-Mar-2013 13:30:52
```

Figure 46: Sample output file (input parameters not shown)

4.1.2.2 Figures

Two standard output figures are generated to illustrate the results of the simulation. The first figure is a map view of the SAR swath and AIS FOVs as the satellite steps along the specified track. An example is shown in the upper left of Figure 47. Also shown are the simulated locations of the ships, which are indicated according to whether they are within the AIS Channels 3 and 4 region. Ships within the SAR swath are denoted by either closed or open triangles, depending on whether or not they are detected by the SAR. Ships detected on either AIS Channels 1 and 2 or Channels 3 and 4 are indicated by different colour circles. A zoomed-in version of the output figure showing these features is shown in the upper right of Figure 47.

The second figure shows the ship length versus the SAR incidence angle, as well as the corresponding minimum detectable ship length as a function of the incidence angles. Ship lengths greater than the minimum detectable ship length are distinguished as being detected. An example is shown in the bottom of Figure 47.

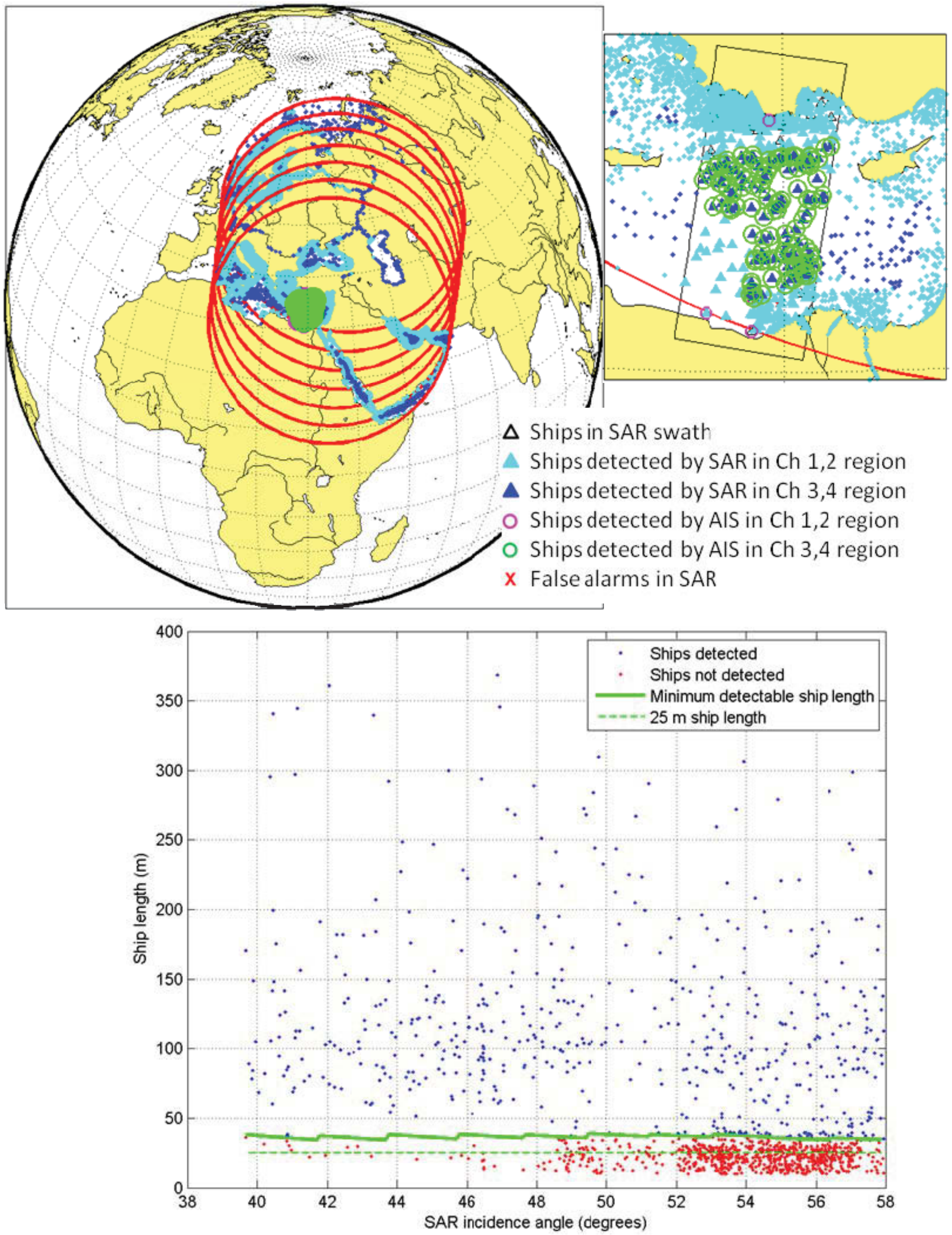


Figure 47: Sample output graphics.

4.2 Program Sections

The simulation is organized into sections dealing with the major elements of the program. The main sections include ship characterization, SAR setup, AIS setup, AIS message transmission, AIS message reception and probability of detection characterization. An overview of each of these sections is provided in the following subsections.

4.2.1 Ship Characterization

The number of ships within the SAR swath and AIS FOV is based on the GSDM (see Figure 2). The contribution from each degree square cell is taken from the database, and then the integer number of ships for each cell is then determined so that the cumulative residual round-off error does not exceed 0.5. The resulting ships in each degree square are then distributed uniformly within the cell. For cells that are partially overlapping the SAR swath, the corresponding ships are tagged as either being within or outside the SAR swath. For the AIS FOV, ship locations are generated for degree squares with centres within the FOV, and then the specific ship locations are checked as to whether they are in the FOV. For grid cells along the coast or along rivers, ship locations are also checked to verify if they are on water. If any location is on nearby land, the location is moved to the nearest available water body. While this approach may result in some bunching of ship locations near the coast, it retains the ship density for the grid cell as determined from the GSDM. From an AIS performance perspective, it is critical to maintain the appropriate ship density in the grid cell. If ships generated over land were omitted, this would introduce a bias in the ship density for the grid cell. Although this is a limitation in the current implementation, moving the ships within the grid cell to the nearest water body, does not introduce any issues in terms of the actual AIS POD calculation. Ideally, the locations should be generated so that they are uniformly distributed only over the water bodies in the grid cell.

The length of each ship is determined based on the length distributions for each degree square obtained from the global ship density database. This distribution is comprised of forty 10-metre bins up to 400 m, the upper range including the longest ships that exist at present (see Figure 27).

For the computation of the ship position dead reckoning, the SOG and COG are also obtained from the global ship database.

4.2.2 SAR Swath

The location of the SAR swath is based on the satellite position as determined by the propagation of the TLE to the specific start time and duration of the acquisition, and the SAR incidence angles as determined from the SAR beam mode and beam number. The SAR swaths for RSAT2 were verified against the standard RSAT2 Acquisition Planning Tool provided by McDonald Dettwiler and Associates (MDA) [48].

4.2.3 SAR Ship Detection

For the ships located within the SAR swath, the detection by the specified SAR beam mode is determined using the DRDC Ottawa ship detectability code [49]. First, the SAR incidence angle is calculated at each ship location, and then the DRDC Ottawa code is used to calculate the minimum detectable ship length at the given incidence angles, which is then compared to the corresponding ship lengths to determine if a ship would likely be detected. The simulation only considers ships larger than 25 m for the SAR POD. The DRDC ship detectability is based on the SAR beam mode characteristics, detection margin and probability of false alarm (PFA) parameters, and the sea state properties. The code is normally run using Sea State 5 with a corresponding wind speed of 10.833 m/s. The actual parameters used for the specific scenarios run in this project are outlined in Table 24. The parameters selected represent a near worst case situation for SAR ship detection.

Within the SAR swath, the number of false alarms is also indicated based on the PFA specified and the number of SAR image pixels.

4.2.4 AIS Satellite FOV

The AIS FOV is calculated based on the view from the satellite to the geometrical horizon. The satellite position is obtained by the propagation of the TLE along the orbit to the required time. The FOV is calculated at the centre point for each step along the satellite track.

Within the AIS FOV, ships within the region of the FOVs that are visible for the entire specified duration of the AIS acquisitions are identified and used as the basis for calculating the AIS POD. This region is referred to as the “snowman area”, or overlap area and is shown in Figure 48. AIS POD within the overlap area is calculated for vessels that remain in this area for five minutes. The area of the five minute overlap is shown in green for an AIS on time of seven minutes. The AIS probability of detection for ships within the SAR swath may differ from that for the overlap area, due to either the variation in the type of ships or the limited statistics available within the SAR swath.

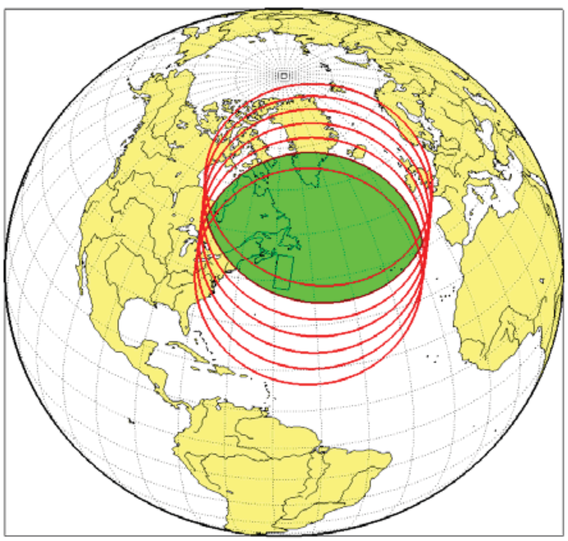


Figure 48: Snowman (overlap) area in green where ships remain in the FOV for five minutes.

4.2.5 AIS Message Properties

For AIS Channels 1 and 2, the dynamic message transmission period for each ship is obtained from the corresponding distributions for each degree square from the global ship database. The distribution thus contains the probabilities for message transmission at 180, 10, 6, 10/3, and 2 seconds as shown in Figure 14. The static messages for each ship are broadcast at an interval of six minutes, and require two message slots. For the proposed AIS Channels 3 and 4, the message transmission interval is three minutes.

The initial message transmission for each ship is assigned randomly to a slot within the message transmission period, as well as to one of Channels 1 or 2, and Channels 3 or 4. Since both dynamic and static messages are transmitted on AIS Channels 1 and 2, the transmission assignments are checked for potential conflict, with the static messages being shifted if required.

Since the AIS messages on Channels 3 and 4 are suppressed when a ship is within reception range of an AIS base station, ships within a specified coastal region are excluded from transmitting these messages. The exclusion region includes most coastal regions outside of the high latitudes.

4.2.6 AIS Message Reception and Detection

The reception and detection of the AIS messages was modelled using two different approaches. The first method is used for the basic and enhanced receivers and the second is used for the receiver that was tuned to the COM DEV simulation and eE decollider as run by DRDC Ottawa (referred to from this point forward as the decollider receiver). DRDC Ottawa's basic process was to simulate the transmission and reception of AIS messages for a particular number of ships transmitting at a set average transmission rate. The AIS POD was calculated for the ships that remain in the AIS FOV for more than five minutes. By changing the number of ships in the simulation, a performance curve relating POD to the number of ships in the AIS FOV is generated.

For AIS Channels 1 and 2, RCM and exactView-1 (EV1) use the decollider receiver, while other AIS satellites available in the model (i.e., Aprizesat-3 (AS3)) use the enhanced receiver implementation. All AIS Channels 3 and 4 use the basic receiver. The different implementations are discussed in the following subsections.

4.2.6.1 Basic and Enhanced Receiver

The stream of AIS messages arriving at the satellite AIS receiver is checked for message collisions both within the same slot and with the previous and next adjacent slots. Collisions with messages in adjacent slots can arise due to the path delays to the satellite associated with the ships throughout the AIS FOV. The simulation allows for a specified number of messages that could be tolerated without loss by the receiver in order to account for the complexity of various receivers. This simple approach is meant to enable consideration of receivers that provide various levels of message discrimination based on processing, for example, of Doppler shifts, polarization, or multiple signal extraction.

Of particular interest in the present study is the capabilities provided by the COM DEV receiver. To satisfy the specification of 90% probability of detection for an observation time of five minutes for 2,200 ships in the FOV, the number of required messages that must be received without loss was determined to be seven. The representative model output illustrating this is provided in Figure 49.

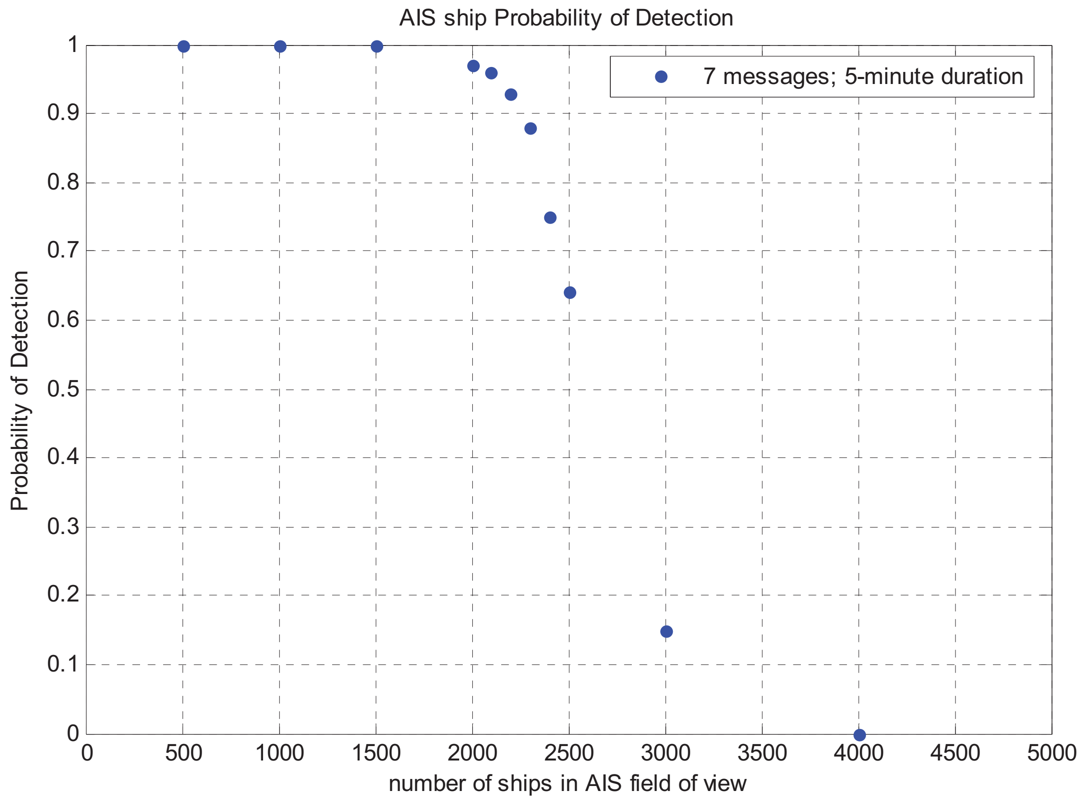


Figure 49: Determination of number of messages received before collisions encountered to match RCM specifications.

4.2.6.2 Decollider Receiver

The decollider receiver uses an implementation of a statistical model from [19], which gives the probability of extracting an uncorrupted message as:

$$\gamma = \gamma_0 e^{-\lambda\tau_0(1-q)^{(1+s)}} \qquad (5)$$

where

- γ_0 is the probability of receiving an uncorrupted message;
- $-\lambda\tau_0$ is the number of messages received;
- q is the probability a single message will be uncorrupted by the simultaneous arrival of another message; and

- s is the effect of message overlap and is a function of altitude.

This equation is used by the simulation to determine the number of messages from the received messages that are used for the AIS detections. The surviving messages are chosen randomly from the received messages. The number of messages received by the decollider, $\lambda\tau_0$, is set by the transmit rate of the ships in the current AIS FOV step. The s term was taken from Table A.7 of [16] based on the satellite altitude, 0.6362 for RCM and 0.6744 for EV1. The parameters γ_0 and q were tuned to the results provided by DRDC Ottawa that were generated using the COM DEV simulator and eE decollider for an average message transmit rate of two seconds and seven seconds, using the same average transmission rates. Figure 50 shows the performance curves from DRDC Ottawa for the two second and seven second curves (black and blue) and the performance curve from the tuned decollider receiver (green and red) for the same transmit rates. For other transmission rates the tuning parameters are interpolated or extrapolated from the two second and seven second cases. Ideally additional decollider performance curves from DRDC Ottawa at different transmission rates would be used for more accurate values of γ_0 and q. Table 19 lists the values of the parameters used for average transmit rates between two and ten seconds.

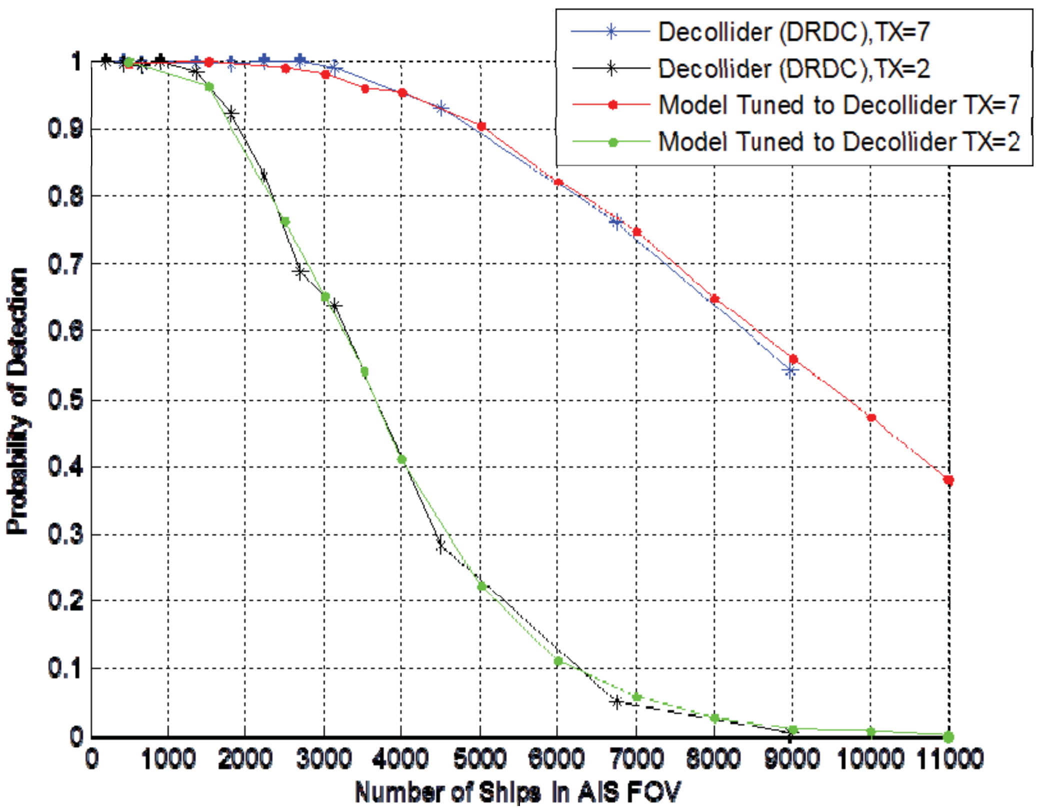


Figure 50: Performance curves from DRDC Ottawa and tuned decollider receiver.

Table 19. Tuned parameters for statistical model

Average Transmit Rate (seconds)	γ_0	q
2	0.0700	0.9250
3	0.1036	0.9208
4	0.1372	0.9166
5	0.1709	0.9124
6	0.2045	0.9082
7	0.2381	0.904
8	0.2717	0.8998
9	0.3053	0.8956
10	0.3390	0.8914

4.2.7 POD Characterization

The POD of ships within the SAR swath and AIS FOV is calculated and written to the output file. For the SAR swath, the various joint, marginal and conditional distributions are computed for the SAR and AIS detections. For the AIS, the probability of detection within the snowman region is also computed and given in the output file.

In interpreting the detection capabilities, the number of ships in the AIS FOV for each step along the AIS satellite track is the most significant factor in determining the POD. Within the SAR swath, P(SAR), P(AIS), P(AIS|SAR), P(AIS∪SAR), and P(AIS∩SAR), in particular, all readily indicate the detection capabilities.

The SAR POD only considers ships larger than 25 m in the calculation, and the AIS POD for dynamic messages on Channels 1 and 2 exclude ships transmitting at 180 seconds (ships that are moored or anchored).

4.3 SAR and AIS Time Difference

RSAT2 simulations differ from those of RCM in that SAR acquisitions and AIS receptions are obtained from different satellites. This introduces the issue of dealing with temporal differences between observations, creating a challenge for target association that is not as significant for the RCM case with co-located sensors.

From an operational perspective, it is desirable to match or associate SAR targets with corresponding AIS targets wherever possible. One approach for doing this is to use dead reckoning where navigational parameters (speed and heading) taken from AIS reports are used to predict the ship position over some elapsed period of time. The intent is to use such an approach to compare SAR target locations with predicted ship locations dead reckoned from AIS report information. There is an uncertainty associated with the predicted ship position that can be determined from some knowledge of along track (speed variations) and cross track (course or heading) uncertainties. There are a large number of factors that can influence these uncertainties ranging from vessel activity, region of operation, weather conditions and vessel traffic conditions just to name a few. A dead reckoning uncertainty analysis was performed as described in Section 2.2.3.

A simple association method was used to determine a probability of association between AIS and SAR targets. The details of this approach are outlined below:

1. Using speed, heading, and time difference between the AIS and SAR acquisitions, dead reckon the AIS detected ships;

2. Using the ship speed and SAR acquisition geometry calculate the azimuth shift of the ship as seen by the SAR and apply to the dead reckoned positions from the previous step;

3. Using a 95% confidence interval, the dead reckoning analysis probability distribution functions (Section 2.2.3) for the latitude, longitude grid cell of each ship, and the time difference between the AIS and SAR acquisitions, calculate uncertainty in the position calculated in step 2 and draw a circle of uncertainty around this point;

4. The probability of association for a ship is one divided by the number of detected ships (from AIS) in the uncertainty circle; and

5. The probability of association for each ship is averaged to get an overall probability of association for the run.

Figure 51 shows an example of the probability of association approach. The original AIS detected ships are shown by the blue *, the dead reckoned positions are indicated by the green line and circle. The azimuth shifted positions are represented by the blue triangles and the error circle is the dashed blue circle. Because the azimuth shifts were small relative to the dead reckoned distance, the blue triangle hides the green circles.

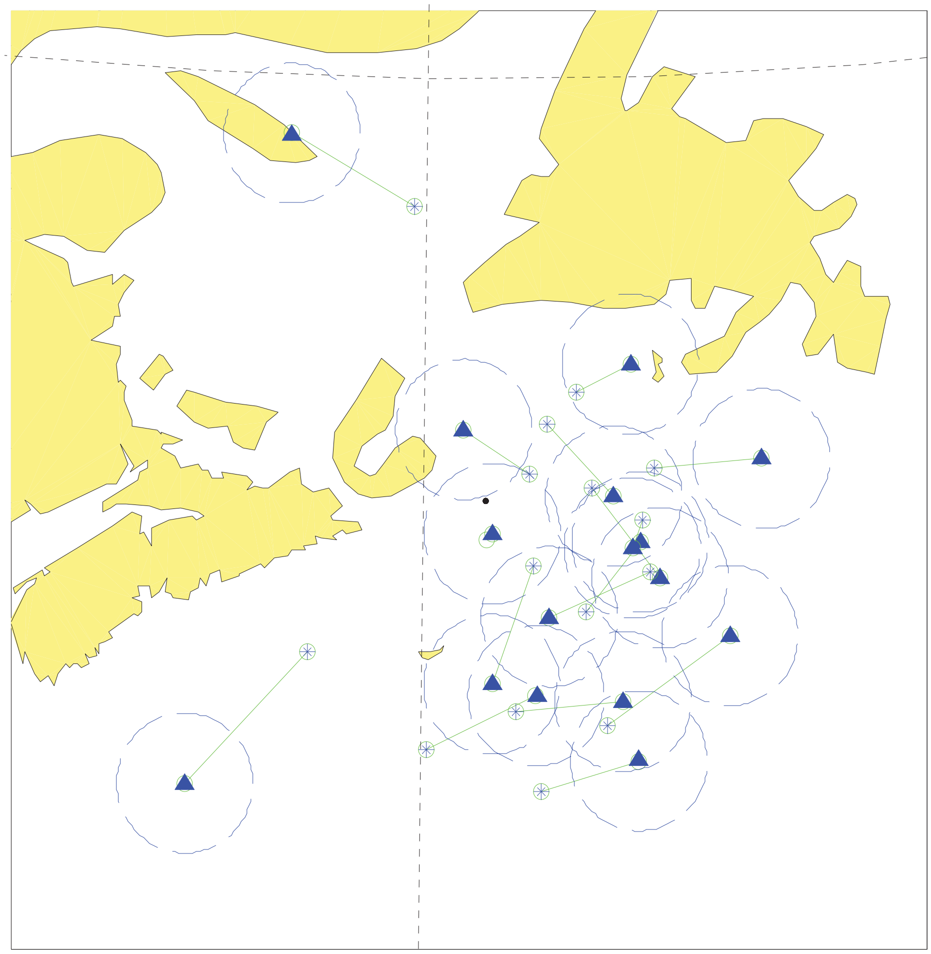


Figure 51: Illustration of probability of association. Original AIS detected ships are blue '+', dead reckoned position shown by green line and green circle, azimuth shifted position shown by blue triangle, and the error circle is the dashed blue circle.

5 Scenario Development

Scenarios developed for this project are based on the intended concept of operations for the use of RCM sensor data (SAR imagery and AIS ship reports) in support of surveillance and reconnaissance activities by DND/CF. From this perspective, scenarios are generated in alignment with the major priorities of DND/CF with regard to the use of RCM data to provide wide area surveillance over the Canadian land mass, ocean approaches to Canada and to support DND/CF operations globally. The following sub-sections outline the specific details used for scenario development as generated in consultation with DRDC personnel.

While the scenarios described outline those run for the purposes of this particular project, it is important to note that the model is easily adaptable to develop many different scenarios at the discretion of the user. The model provides an excellent tool for further analysis well beyond that provided in the scope of this particular project.

5.1 Key Parameters

The key parameters modelled in this project are summarized in Table 20. The table provides an overview of the parameters used in the scenarios developed for this project.

Table 20: Input parameter list.

Parameter	Description	Units	Values
SAR Setup			
SAR_Sensor	This is a user entered parameter that is used to select the SAR sensor to be used in the simulation. Two choices are implemented, RCM (1 to 3) and RSAT2.	N/A	RCM[1-3] RSAT2
SAR_Mode	This is a user selectable parameter that is set for each given scenario run. The modes available are defined for each of the RCM and RSAT2 imaging modes relevant to vessel detection applications.	N/A	SHIPDET MR50SW [1-4] MSSRDV MSSROS
SAR_BeamNum	Beam number of beam mode (if more than one beam mode exists)	N/A	
SAR_StartTime	This is a user entered parameter that defines when the SAR image acquisition is to begin. This is entered using the following date format, yyyymmddTHHMMSS.FFF	N/A	

Parameter	Description	Units	Values
SAR_ImagingTime	This is a user specified parameter and is input in units of one second. For RCM scenarios, this is set to two minutes as per the concept of operations. Similarly, two minutes on time are used for the SAR in RSAT2 simulations.	seconds	120
AIS Setup			
AIS_Sensor	This parameter is used to specify the AIS sensor to be used in the simulation. At present, RCM, AS3, AS4 and EV1 are implemented, however, others can be readily defined using appropriate TLE data.	N/A	RCM EV1
AIS_Duration	This is a user specified parameter and can be input in increments of one minute. For the purpose of RCM scenario development, this value is taken from the RCM Concept of Operations (ConOps) and is set to seven minutes (five minutes before SAR on and then off when SAR off). The same AIS on time duration is used for the AIS satellite for simulations run for RSAT2.	minutes	7
AIS_StepTime	Time interval for steps within the AIS simulation	minutes	1
AIS_StartTime	This is a user entered parameter that defines when the SAR image acquisition is to begin. This is entered using the following date format, yyyymmddTHHMMSS	N/A	
Simulator Setup			
AIS12Flag	These parameters are selectable by the user and allow for the use of various AIS channel combinations in the scenario. The model allows for the use of Channels 1 and 2 or Channels 3 and 4 separately, or the use of all four channels simultaneously.	N/A	1 (on)
AIS34Flag	See above		1 (on)

Parameter	Description	Units	Values
AIS12MaxReceivedMsgs	This parameter refers to the basic and enhanced AIS receiver capability as defined by the number of messages that can be received at the receiver before message conflicts occur. This is a user defined parameter. For enhanced receivers the number of messages is derived to be seven. For basic receivers the number is two. This is only used for AIS other than RCM and EV1 as these sensors use the decollider receiver.	N/A	7
AIS34MaxReceivedMsgs	See above. Number of messages received without loss for AIS Channels 3 and 4. This typically assumes a basic receiver.	N/A	2
noiseFlag	Flag to enable the user to input an interference source in the model. Not used.		0 (off)
noisePower	User entered transmit power for the interference source. Not used.	dB	
noiseDutyCycle	User entered duty cycle for the interference source. Not used.	percent	
noiseLocations	Latitude and longitude of the interference sources. Not used.	degrees	
transmitProbFlag	Flag: Account for AIS transmissions not reaching the SAIS receiver. Not used.		0 (off)
transmitProbability	Probability of AIS transmitted message reaching the SAIS receiver. Not used.		
Ship Detectability Parameters			
SAR_Ship_POD	Probability of detection		0.9
RCM_NESZ	Flag		1
SAR_Pol	SAR polarization		0 (HH)
Ocean_WindSpeed	Wind speed	m/s	10.833
Ocean_WindDirection	Wind direction with respect to sensor (0 is towards the sensor)	degrees	0
Ocean_KNu	Shape parameter		4
PFA	Probability of false alarm		2.5e-9
Det_Margin	Detection margin	dB	3

5.2 Areas of Interest

A total of ten Areas of Interest (AOIs) were used as the basis for scenario development in consultation with the project authority. The AOIs selected are based on DND/CF operational needs domestically and internationally where DND/CF forces have surveillance and reconnaissance interests. The AOIs used for this project are provided in Table 21. The AOIs also represent regions of varying ship density. One of the primary factors influencing performance is the number of vessels in the antenna footprint of both the SAR and AIS receivers. The scenarios provide this ship density variation with low density areas represented by the Canadian Arctic and to some extent Australia, moderate density areas represented by Canada's East and West coasts and the Horn of Africa and high density areas represented by the North Sea, English Channel, Persian Gulf, Japan and the Mediterranean. For the purposes of this report, low ship density areas are those with an average number of ships in the AIS FOV of up to 3,000, moderate density areas are those with 3,000 to 6,000 ships on average in the AIS FOV and high density areas have over 6,000 ships in the AIS FOV. It should be noted that these numbers are intended as relative reference values. The actual number of ships in the AIS FOV for any given AOI can vary substantially depending on acquisition geometry and other factors as discussed in Section 6.

Table 21: Scenario AOIs.

Number	Area of Interest	Ship Density
1	Australia	Low – Moderate
2	Canada East Coast	Moderate
3	Canada West Coast	Moderate
4	Canada Arctic	Low
5	Horn of Africa	Moderate
6	Persian Gulf	High
7	North Sea	High
8	English Channel	High
9	Japan	High
10	Mediterranean	High

5.3 RCM Scenario Summary

Scenarios have been developed for the RCM arrangement where the AIS receiver and the SAR are co-located on the same satellite. The scenarios run for RCM during this project are summarized in Table 22. A total of 10 iterations for each scenario are run to ensure a good statistical sample size. Two different acquisition geometries for each location were run for a total number of model runs completed for RCM of 200.

Table 22: RCM scenario summary.

AOI	SAR Mode	SAR on time	AIS on time	AIS Channels 1 and 2	AIS Channels 3 and 4	Orbit Orientation
All 10 as listed in Table 21	SHIPDET	2 mins	7 mins	Decollider receiver	On with 2 collisions	Ascending and descending

5.4 RSAT2 Scenario Summary

RSAT2 scenarios deal with the SAR and AIS receivers located on separate satellites. The intent is to evaluate the effects of spatial and temporal differences in data acquisition and how this impacts the ability to use these data together effectively for target association.

The scenarios run for RSAT2 are summarized in Table 23. Two different acquisition geometries for each location were run, but only using Channels 1 and 2. Since AIS Channels 3 and 4 do not currently exist, these were not considered for RSAT2 scenarios. The total number of model runs completed for RSAT2 was 200.

Table 23: RSAT2 scenario summary.

AOI	SAR Mode	SAR on time	AIS on time	AIS Channels 1 and 2	Time difference	AIS Satellite
All 10 as listed in Table 21	MSSRDV	2 mins	7 mins	On with 2 collisions	Variable depending on orbits	EV1

5.5 RCM Constellation Scenarios

Scenarios were developed around using the three RCM satellites as a constellation for improving the performance over single satellite operations. The approach for these scenarios was to acquire two AIS passes and then a third AIS pass with concurrent SAR acquisition. The three passes by the RCM satellites were consecutive observations of the same ground region using the same orbit direction, and were framed such that the final SAR footprint was inside the five minute overlap of each AIS pass. Each of the 10 AOIs from Table 21 were run with one iteration each. The process used for the constellation scenarios are:

1. Generate all ships required by the scenario. The GSDM is used to populate the grid cells covered by the three AIS passes.

2. Run the model using the created ships for the first AIS pass. The ships detected by AIS are recorded and the AIS POD in the SAR footprint of the final pass is calculated. The probability of association between this first pass and the time of the SAR acquisition is also calculated.

3. The ships are dead reckoned (using the speed and course) to the time of the second AIS pass.

4. The model is run a second time using the new ship locations and the detections and probabilities are handled as in the first pass.

5. The ships are dead reckoned to the time of the third AIS pass.

6. The model is run a third time using the new ship locations and the detections and probabilities are handled as in the previous passes.

6 Results and Analysis

6.1 RCM and RSAT2 Model Runs

As previously discussed, each of the RCM and RSAT2 scenarios listed in Section 5 were run 10 times to achieve a good statistical sample size. Additionally, two different acquisition geometries were run for each scenario. The intent of this was to run each scenario with a best and worst case with respect to the number of ships in the AIS FOV. Some scenarios had a large variation in the possible number of ships in the AIS FOV based on different acquisition geometries, while for other scenarios the difference was minimal. The number of ships in the total AIS FOV for the AIS reception duration was used to determine the two acquisition geometries. The number of acquisition geometries for RCM is limited because the AIS and SAR are located on the same satellite. For RSAT2 cases, there are a very large number of different combinations depending on which AIS satellite is chosen. To limit the possible combinations, only one AIS satellite, EV1, was used in this project.

The ship detectability parameters of the input files for all RCM and RSAT2 scenarios were set as listed in Table 24. These values are the default values used by the DRDC Ship Detectability code, except for the ocean wind speed. The specification for AIS on RCM used a Sea State of five, which was taken to correspond to a wind speed of 10.833 m/s.

The same simulator setup input parameters were used for all RCM and RSAT2 model runs and are listed in Table 25.

The SAR and AIS setup input parameters for RCM runs are given in Table 26 and Table 27, respectively. The start times for the SAR and AIS can be found in the input parameter files provided to the Project Technical Authority.

Table 24: Ship detectability parameters used for all RCM and RSAT2 model runs.

Parameter	Description	Value
SAR_Ship_POD	Probability of detection	0.9
RCM_NESZ	Flag (not used if RSAT2)	1
SAR_Pol	Selects which polarization to use (0 is HH)	0
Ocean_WindSpeed	Wind speed in m/s. The value used here corresponds to Sea State 5.	10.833
Ocean_WindDirection	Wind direction with respect to sensor, in degrees. 0 is towards the sensor.	0

Parameter	Description	Value
Ocean_KNu	Shape parameter	4
PFA	Probability of false alarm	2.5e-9
Det_Margin	Detection margin in dB	3

Table 25: Simulator setup parameters used for all RCM and RSAT2 model runs.

Parameter	Description	RCM Value	RSAT2 Value
AIS12Flag	Flag to run AIS Channels 1 and 2	1	1
AIS34Flag	Flag to run AIS Channels 3 and 4	1	0
AIS12MaxReceivedMsgs	Number of allowed collisions for AIS Channels 1 and 2. Not used in this case as both RCM and EV1 use decollider receiver.	7	2
AIS34MaxReceivedMsgs	Number of allowed collisions for AIS Channels 3 and 4	2	2
noiseFlag	Flag for using interference	0	0
noisePower	Power of interference in Watts	0	0
noiseDutyCycle	Duty cycle for interference as a percent	0	0
noiseLocations	Latitude and longitude of interference sources	[ ]	[ ]
transmitProbFlag	Flag to use transmit probability	0	0
transmitProbability	Probability that a transmitted message reaches the receiver.	1	1

Table 26: SAR setup parameters for RCM and RSAT2 model runs.

Parameter	Description	RCM Value	RSAT2 Value
SAR_Sensor	SAR sensor	RCM1	RSAT2
SAR_Mode	Beam mode of SAR sensor	SHIPDET	MSSRDV
SAR_BeamNum	Beam number of beam mode, if more than one beam exists.	[ ]	[ ]
SAR_StartTime	SAR image start time	Various	
SAR_ImagingTime	SAR imaging time in seconds	120	120

Table 27: AIS setup parameters for RCM and RSAT2 model runs.

Parameter	Description	RCM Value	RSAT2 Value
AIS_Sensor	Selected AIS sensor. For RCM, use same name as RCM sensor	RCM1	EV1
AIS_Duration	Duration of AIS sensor, in minutes	7	7
AIS_StepTime	Time for AIS iteration in the model, in minutes	1	1
AIS_StartTime	Start time for AIS.	5 minutes before SAR start time	Various

6.2 Model Outputs

The following subsections show the results of the scenario runs for each of the ten locations. The runs were set-up so that the first orientation presented represents a situation with more ships in the AIS FOV than the second case. Running the ten scenarios for RCM with two different acquisition geometries each and for ten iterations results in 200 outputs.

For each location, two figures representing the two acquisition geometries are presented, as well as a table listing the average values for each output parameter calculated during the ten iterations. The table columns list results for the two orientations for each of the AIS Channels 1 and 2 and

Channels 3 and 4 cases. For example, the number of ships in the SAR swath of the Channels 1 and 2 columns represents the ships in the SAR footprint that are using Channels 1 and 2. Similarly, the information provided in the Channels 3 and 4 columns represents the same data generated from the reduced subset of ships generated from the GSDM with the Channels 3 and 4 exclusion mask applied. For the RSAT2 and EV1 cases, the last two columns in each table show results for two different acquisition geometries representing the highest and lowest total number of ships in the AIS FOV. While the RCM cases use an ascending and descending satellite pass, the RSAT2 and EV1 cases do not necessarily use this arrangement.

The first three rows of Table 28 to Table 37 are the average, minimum, and maximum number of ships in the AIS FOV steps represented by the large red circles in Figure 52 to Figure 85. The number of ships in the AIS FOV during each one minute time step can vary significantly. The fourth row gives the number of ships in the SAR swath. Rows five to 10 represent the various detection probabilities calculated. Rows 11 and 12 list the number of ships in the AIS FOV overlap area (previously referred to as the snowman area) and the probability of detection for AIS in this area. The AIS FOV overlap area is the intersection of the AIS FOV steps illustrated in Figure 48. The last two rows are more applicable to the RSAT2 scenarios and list the acquisition time difference between AIS and SAR and the probability of association between the AIS and SAR. For all RSAT2 scenarios discussed in the following subsections, EV1 is the satellite used as the AIS platform.

6.2.1 Australia

The Australia location is an area of low to medium ship density. The location for the RCM footprint was off the southeast coast, as seen in Figure 52 and Figure 53 and similarly for RSAT2 in Figure 54 and Figure 55. The average number of ships in the AIS FOV was lower for the ascending RCM orbit then the descending RCM and the two RSAT2 orbits. Both the RCM AIS swath and EV1 AIS used with RSAT2 did not cover other areas of high ship density, except those ships around Australia and New Zealand.

The results of the ten iterations of the descending and ascending RCM scenarios are shown in columns two to five of Table 28, and the two orbit scenarios of RSAT2 are shown in columns six and seven. Because of the low number of ships in the AIS FOV for both RCM AIS Channels 1 and 2 and Channels 3 and 4 regions, the probabilities of AIS detection are high. The decollider receiver used for EV1 results in lower probabilities of AIS detection for the second RSAT2 orbit scenario.

In this location, and areas with similar distributions of ships inside the AIS FOV, AIS using Channels 1 and 2 performs just as well as AIS using Channels 3 and 4 when a decollider receiver is used.

Table 28: Average from 10 iterations of Australia scenario outputs.

Output	RCM				RSAT2 and EV1	
	Descending		Ascending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Mean ships in AIS FOV steps	1353.2	542.6	898.7	211.0	1281.4	1247.8
Min. ships in AIS FOV steps	1221.2	377.5	284.5	51.6	743.3	822.6
Max. ships in AIS FOV steps	1433.4	694.4	1358.4	409.3	1807.6	1603.2
Ships in SAR swath	3.9	3.9	4.0	4.0	6.3	4.7
SAR POD (ships > 25 m)	1.00	1.00	1.00	1.00	1.00	1.00
AIS POD for ships in SAR swath	1.00	1.00	1.00	1.00	1.00	0.96
Probability of AIS given SAR detection for ships in SAR swath	1.00	1.00	1.00	1.00	1.00	0.96
Probability of SAR AND AIS detection for ships in SAR swath	1.00	1.00	1.00	1.00	1.00	0.96
Probability of SAR OR AIS detection for ships in SAR swath	1.00	1.00	1.00	1.00	1.00	1.00
Number of ships in AIS FOV 5 minute overlap	1073.4	381.2	622.5	93.5	893.1	1004.7
AIS POD in AIS FOV 5 minute overlap	0.99	1.00	0.99	1.00	0.98	0.99
AIS and SAR time difference (hours)	0.08	0.08	0.08	0.08	4.89	5.74
Probability of association for AIS and SAR	1.00	1.00	1.00	1.00	1.00	1.00

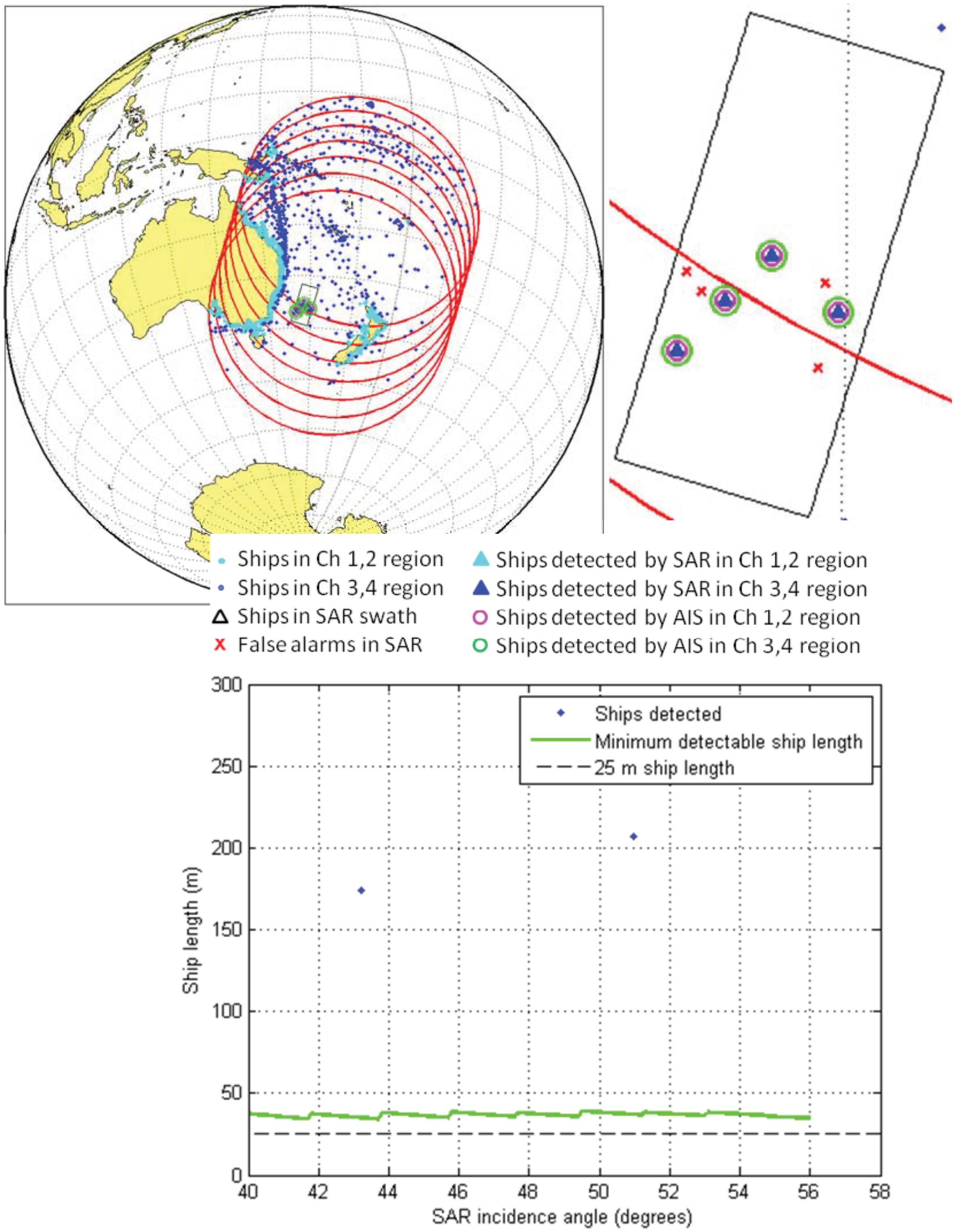


Figure 52: Example of descending RCM output for Australia (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

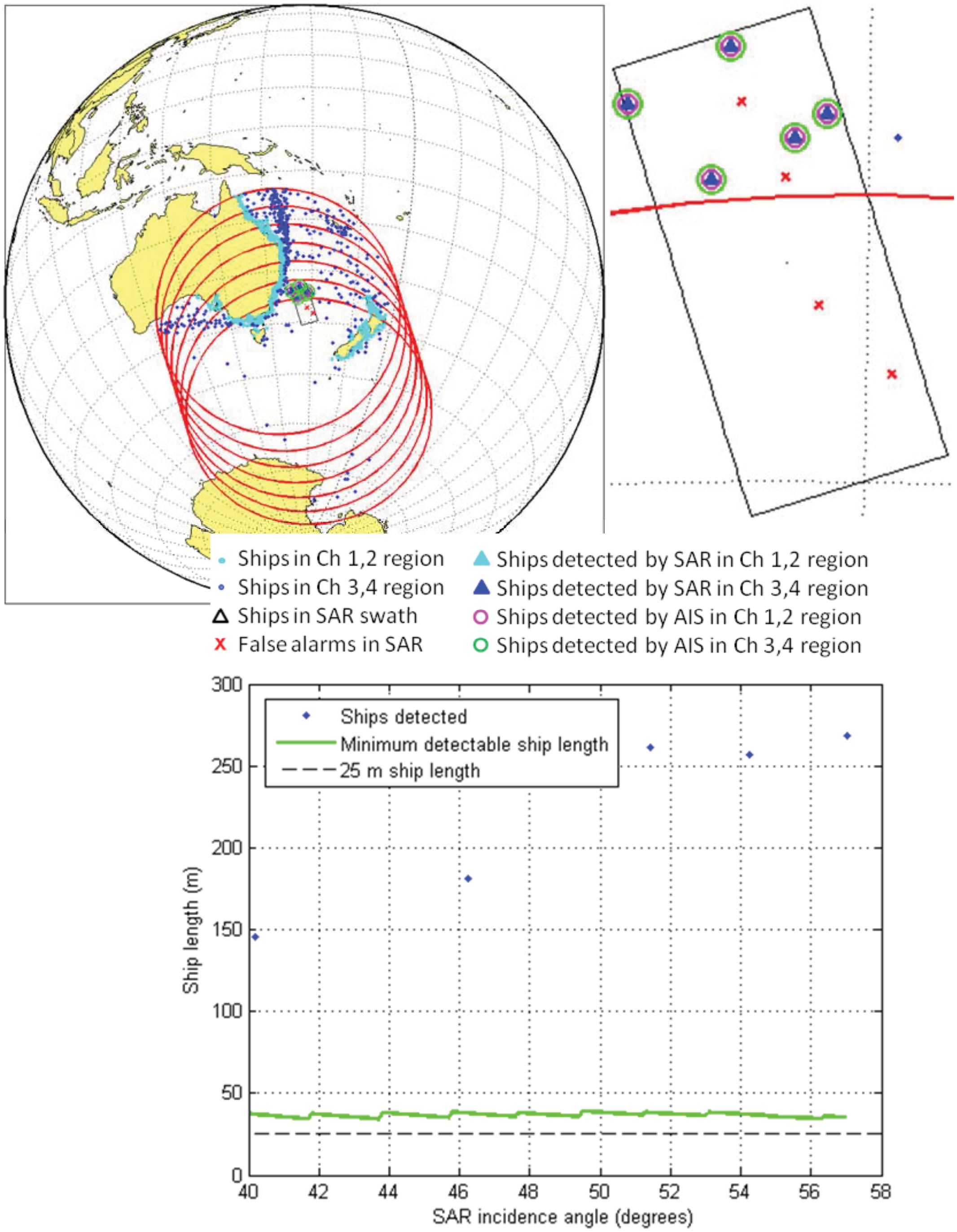


Figure 53: Example of ascending RCM output for Australia (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

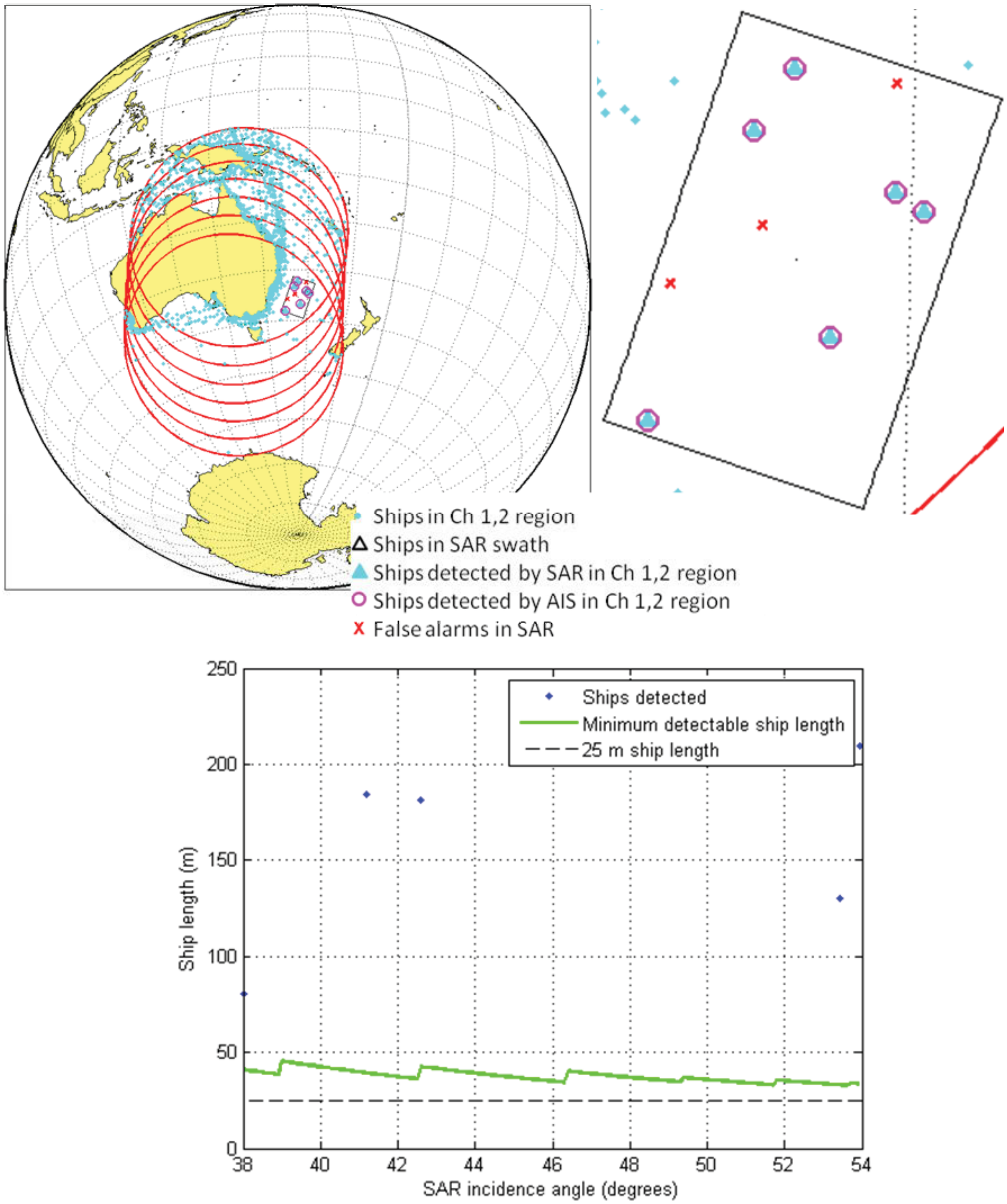


Figure 54: Example of RSAT2 orbit 1 output for Australia (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

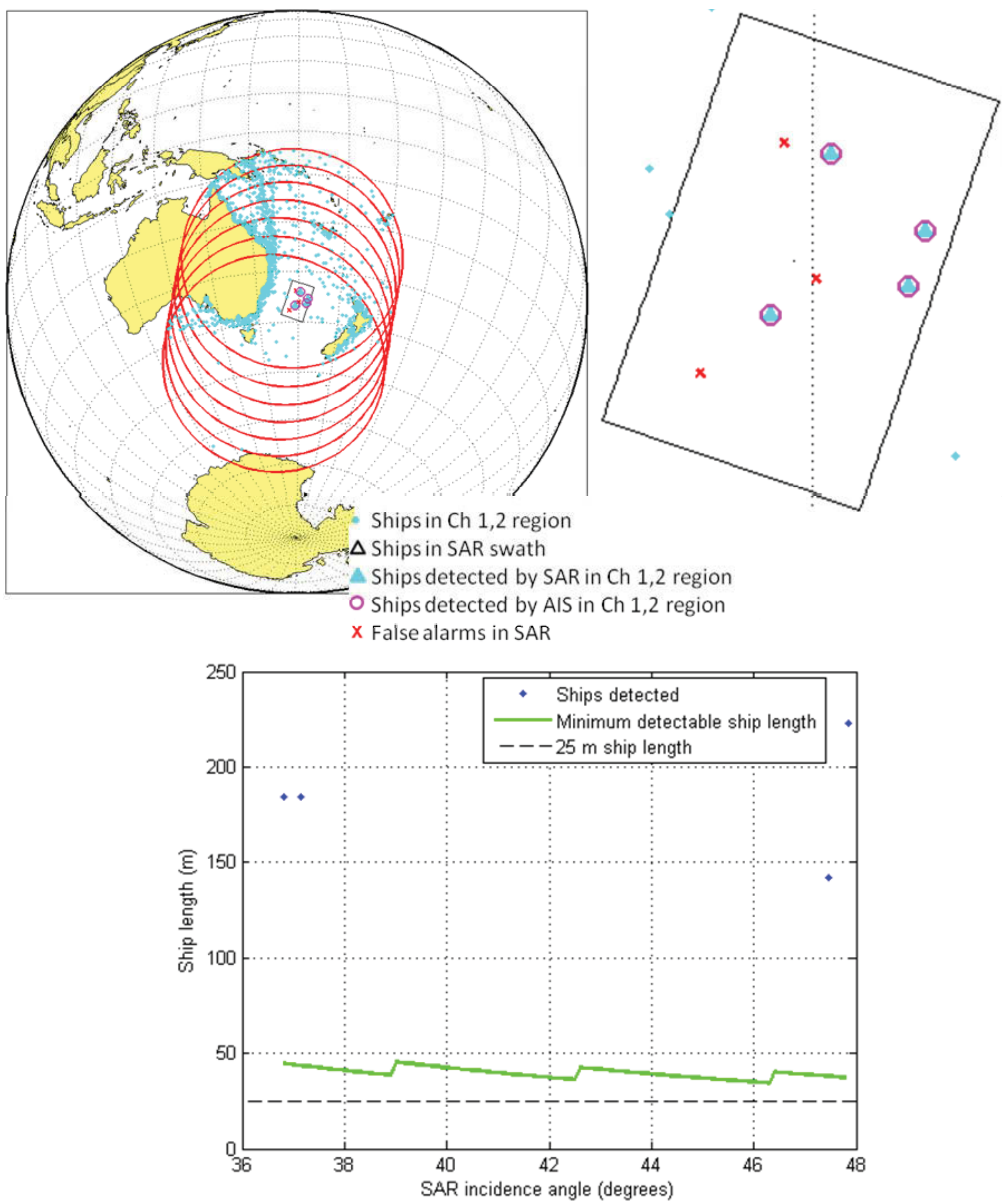


Figure 55: Example of RSAT2 orbit 2 output for Australia (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

6.2.2 Canadian Arctic

The Canadian Arctic scenarios present an area of very low ship density within the SAR footprint with high ship densities at the ends of the AIS FOV steps. The ascending AIS orientations cover the high density areas on the east and west coasts of Canada and the United States. The descending AIS orbit scenarios cover the high number of ships near Iceland and northern Europe.

The result of the ten iterations for the two RCM and two RSAT2 scenarios are shown in Table 29. The ascending and descending RCM orbits are shown in Figure 56 and Figure 57 and the two RSAT2 orbits are in Figure 58 and Figure 59. For the AIS Channels 1 and 2 regions there is a large variation in the number of ships in the AIS FOV steps, with maximums above 7000 ships. The decollider receiver used with RCM and EV1 for the RSAT2 runs returns a probability of AIS detection of one for all cases except the ascending RCM case. The number of ships in the SAR footprint for the ascending RCM case is one and the 0.9 POD for AIS in the SAR footprint results from one run of ten not detecting the ship. There is a significant reduction in the number of ships in the Channels 3 and 4 region and accordingly the probability of AIS detection in the Channels 3 and 4 region is one for all cases. The orbit geometry of EV1 for the second RSAT2 orbit was able to avoid the higher density areas along the east coast of Canada and the United States, but is unnecessary as the probability of AIS detection for both RSAT2 geometries is 1.

Table 29: Average from 10 iterations of the Canadian Arctic scenario outputs.

Output	**RCM**				**RSAT2 and EV1**	
	Ascending		**Descending**		**Orbit 1**	**Orbit 2**
	Ch.1,2	**Ch.3,4**	**Ch.1,2**	**Ch.3,4**	**Ch.1,2**	**Ch.1,2**
Mean ships in AIS FOV steps	2735.3	309.8	3289.7	462.6	1799.6	361.6
Min. ships in AIS FOV steps	532.8	137.9	1420.9	359.8	680.2	287.4
Max. ships in AIS FOV steps	7035.9	620.3	4486.4	533.1	3400.1	423.4
Ships in SAR swath	1.0	1.0	1.8	1.8	8.9	2.8
SAR POD (ships > 25 m)	1.00	1.00	1.00	1.00	0.87	0.95
AIS POD for ships in SAR swath	0.90	1.00	1.00	1.00	1.00	1.00
Probability of AIS given SAR detection for ships in SAR swath	0.90	1.00	1.00	1.00	1.00	1.00

Output	RCM				RSAT2 and EV1	
	Ascending		Descending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Probability of SAR AND AIS detection for ships in SAR swath	0.90	1.00	1.00	1.00	0.81	0.90
Probability of SAR OR AIS detection for ships in SAR swath	1.00	1.00	1.00	1.00	1.00	1.00
Number of ships in AIS FOV 5 minute overlap	343.4	113.5	2140.7	283.5	167.9	119.7
AIS POD in AIS FOV 5 minute overlap	0.98	1.00	0.92	1.00	1.00	1.00
AIS and SAR time difference (hours)	0.08	0.08	0.08	0.08	5.75	5.78
Probability of association for AIS and SAR	0.90	1.00	1.00	1.00	0.62	0.94

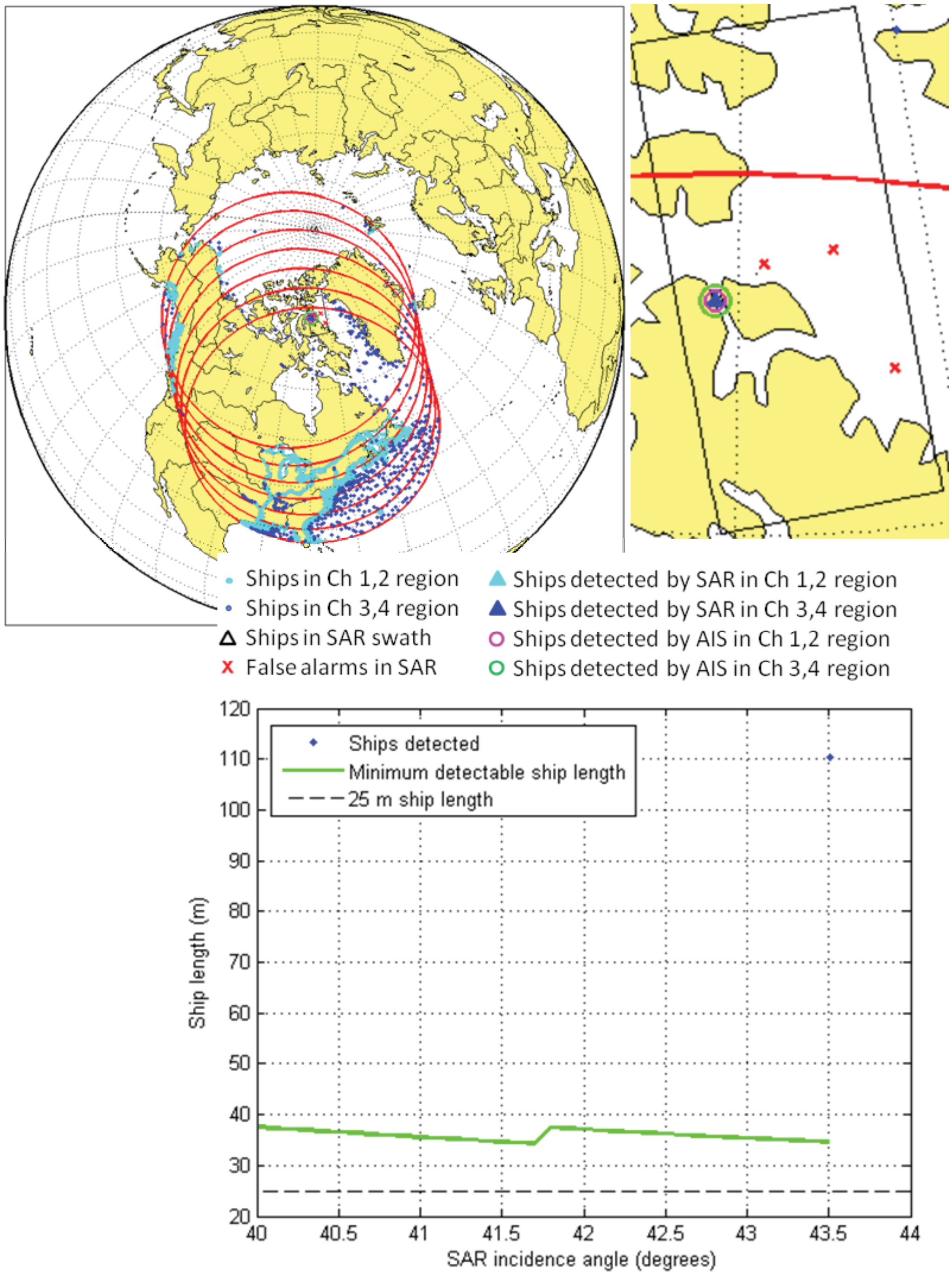


Figure 56: Example of ascending RCM output for the Canadian Arctic (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

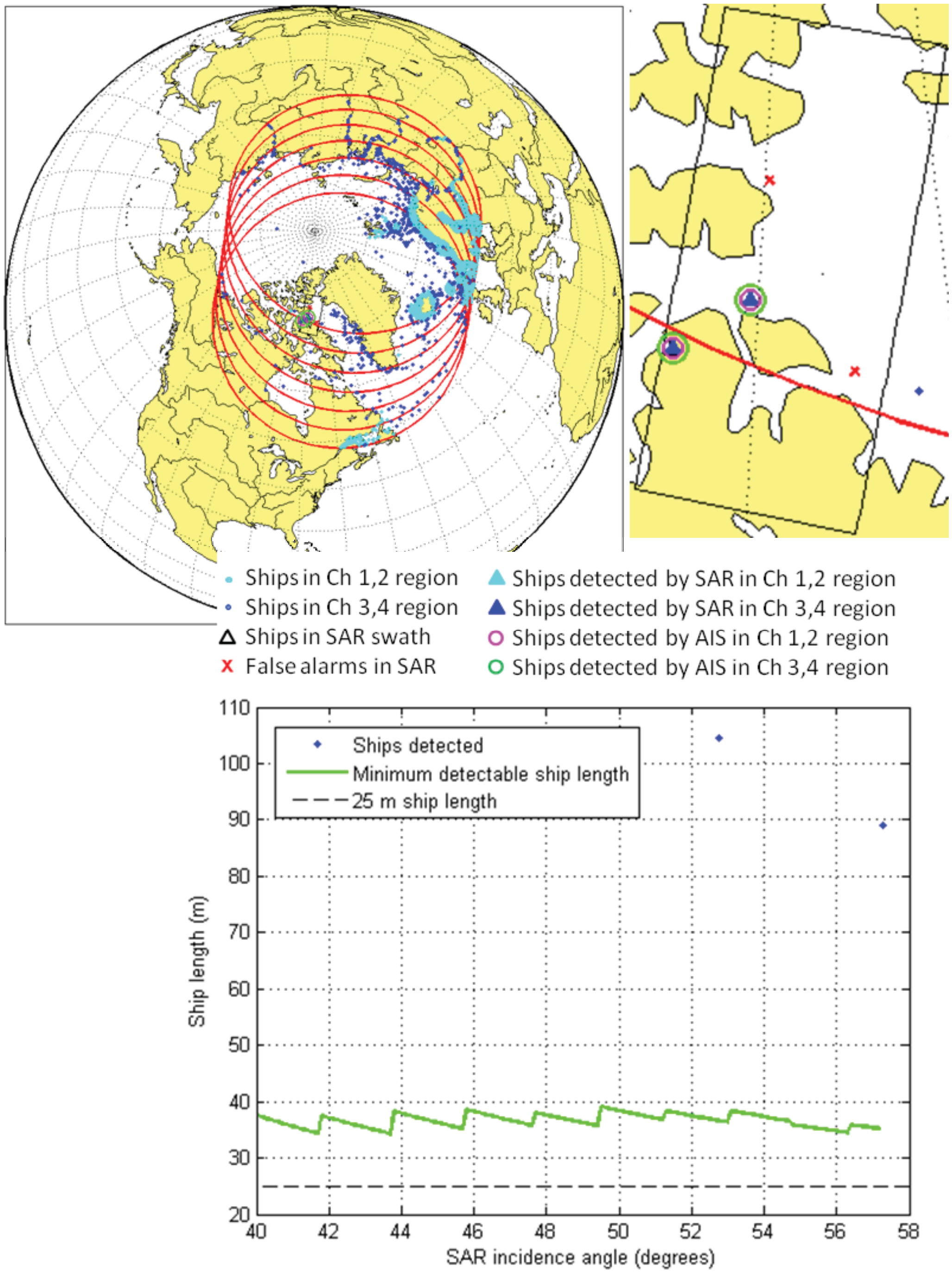


Figure 57: Example of descending RCM output for the Canadian Arctic (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

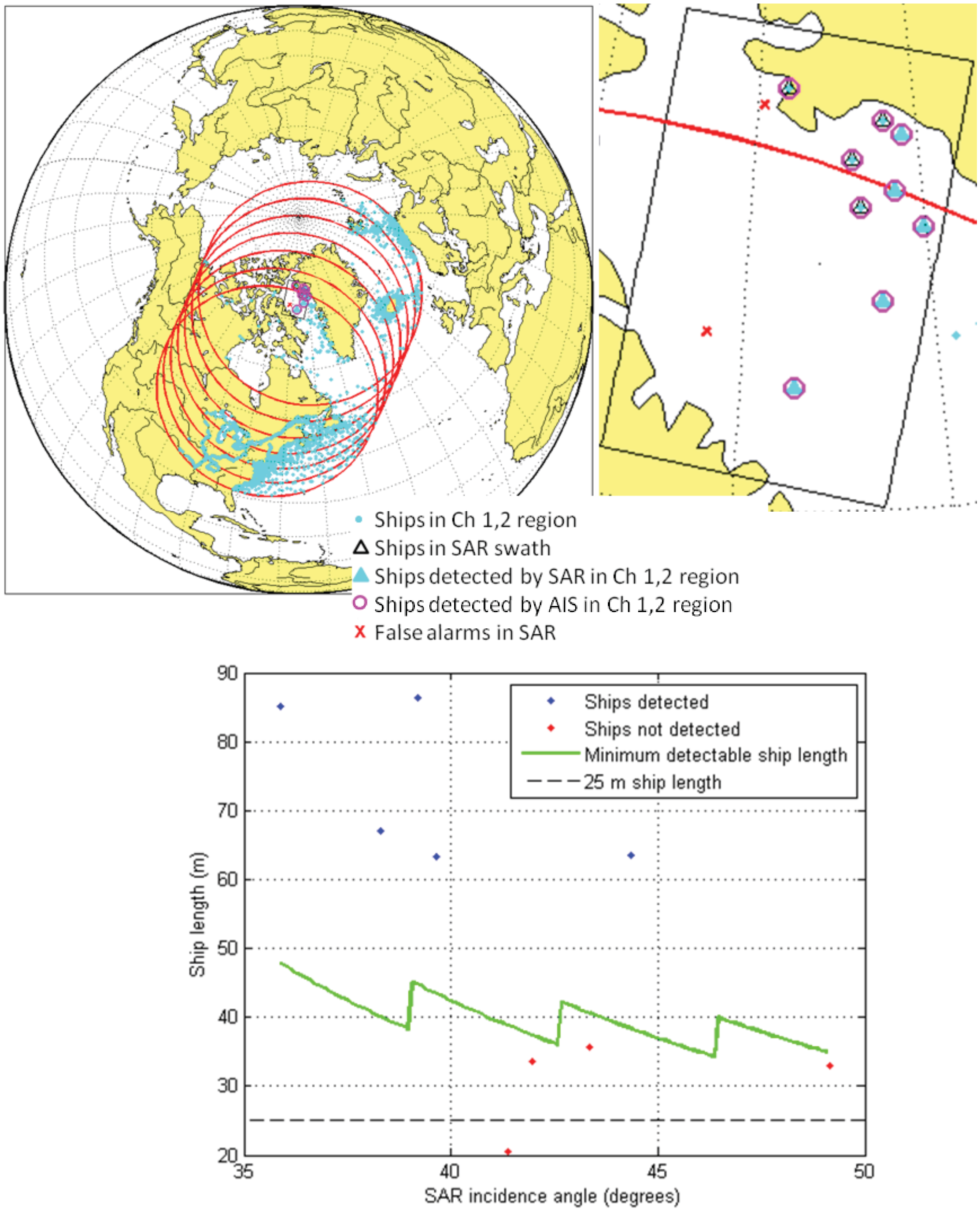


Figure 58: Example of RSAT2 orbit 1 output for the Canadian Arctic (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

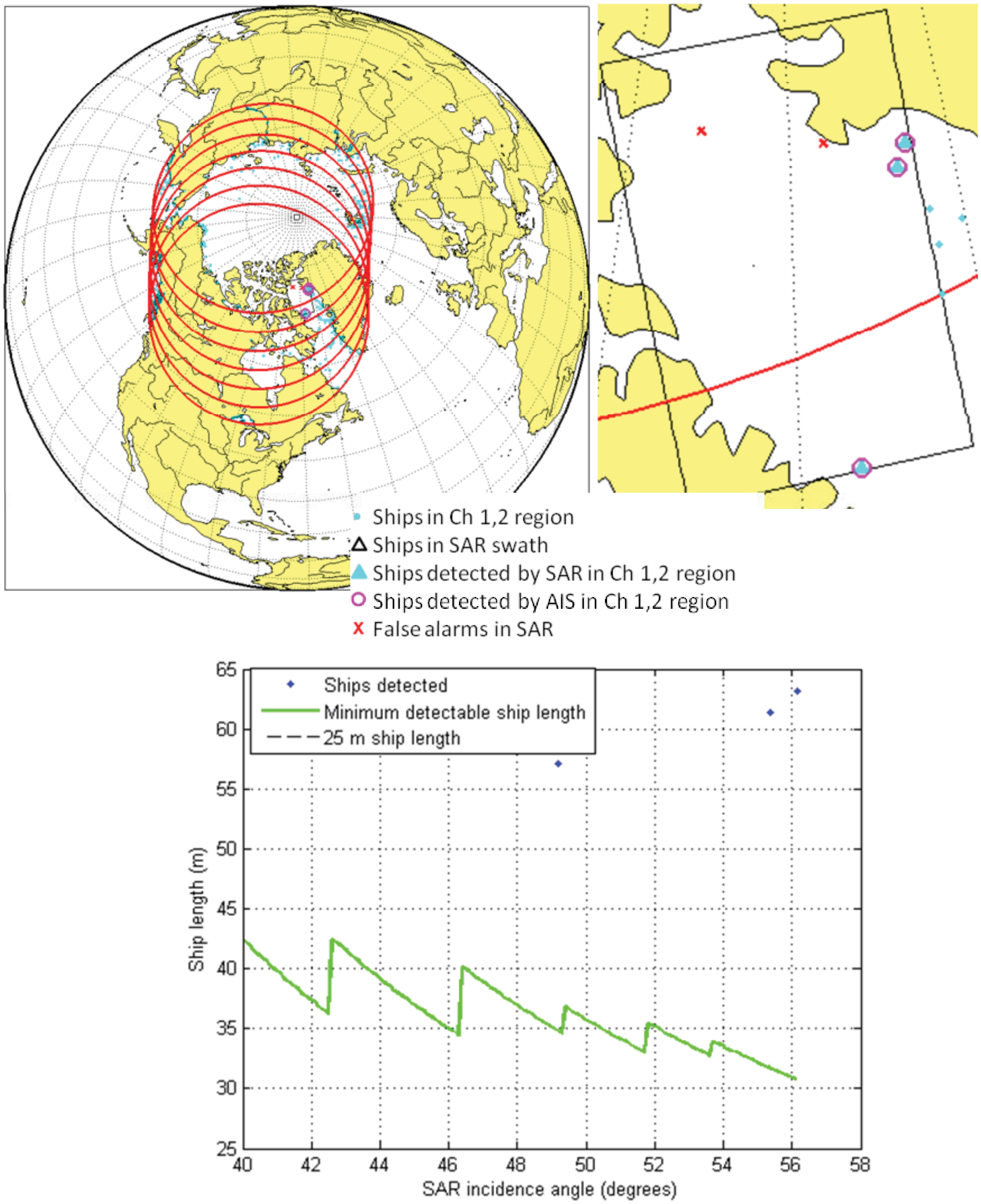


Figure 59: Example of RSAT2 orbit 2 output for the Canadian Arctic (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

6.2.3 Canadian East Coast

The Canadian East Coast scenarios represent a medium ship density case for the SAR and a high ship density for the AIS, with the RSAT2 scenarios having higher densities. Similar to the Canadian Arctic scenarios, the AIS for the RCM descending scenario covers the higher density area of eastern Canada and the United States and northwestern Europe. The ascending RCM orbit avoids Europe, but covers more of the East Coast of Canada and the United States and includes the Great Lakes and inland waterways. Both RSAT2 AIS orbits were similar but have an average difference in the number of ships in the FOV of almost 2000 ships.

Table 30 summarizes the results from the average of the ten iterations for the descending and ascending RCM orbits and the RSAT2 orbits. Figure 60 and Figure 61 shows one of the iterations for the descending and ascending RCM scenarios and Figure 62 and Figure 63 show the RSAT2 scenarios. The probability of AIS detection for Channels 1 and 2 is high for all RCM and RSAT2 orbit cases. The probability of AIS detection is one with Channels 3 and 4 due to the reduced number of ships in the RCM AIS FOV. The probability of AIS detection for the RCM ascending Channels 1 and 2 case is lower than the other cases due to the consistently higher number of ships in each of the AIS FOV steps.

The probability of SAR detection is lower for RCM ascending Channels 1 and 2 and RSAT2 orbit 2 due to a higher number of ships below the minimum detectable ship length in the SAR footprint.

Table 30: Average from 10 iterations of the Canadian East Coast scenario outputs.

Output	**RCM**				**RSAT2 and EV1**	
	Descending		**Ascending**		**Orbit 1**	**Orbit 2**
	Ch.1,2	**Ch.3,4**	**Ch.1,2**	**Ch.3,4**	**Ch.1,2**	**Ch.1,2**
Mean ships in AIS FOV steps	3514.0	853.0	4791.9	1328.1	5974.6	3904.7
Min. ships in AIS FOV steps	3001.1	768.5	4144.9	863.2	2966.9	3002.5
Max. ships in AIS FOV steps	5005.1	919.2	5197.0	1613.5	9207.5	4935.8
Ships in SAR swath	25.5	24.0	56.6	17.6	105.0	90.6
SAR POD (ships > 25 m)	0.97	0.96	0.85	0.91	0.93	0.86
AIS POD for ships in SAR swath	0.98	1.00	0.81	1.00	0.91	0.91

Output	RCM				RSAT2 and EV1	
	Descending		Ascending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Probability of AIS given SAR detection for ships in SAR swath	0.99	1.00	0.86	1.00	0.92	0.93
Probability of SAR AND AIS detection for ships in SAR swath	0.94	0.96	0.59	0.91	0.77	0.68
Probability of SAR OR AIS detection for ships in SAR swath	0.99	1.00	0.91	1.00	0.98	0.97
Number of ships in AIS FOV 5 minute overlap	1123.7	465.1	3680.6	837.3	3312.4	2882.8
AIS POD in AIS FOV 5 minute overlap	0.92	1.00	0.80	1.00	0.81	0.88
AIS and SAR time difference (hours)	0.08	0.08	0.08	0.08	5.45	5.91
Probability of association for AIS and SAR	1.00	1.00	1.00	1.00	0.36	0.40

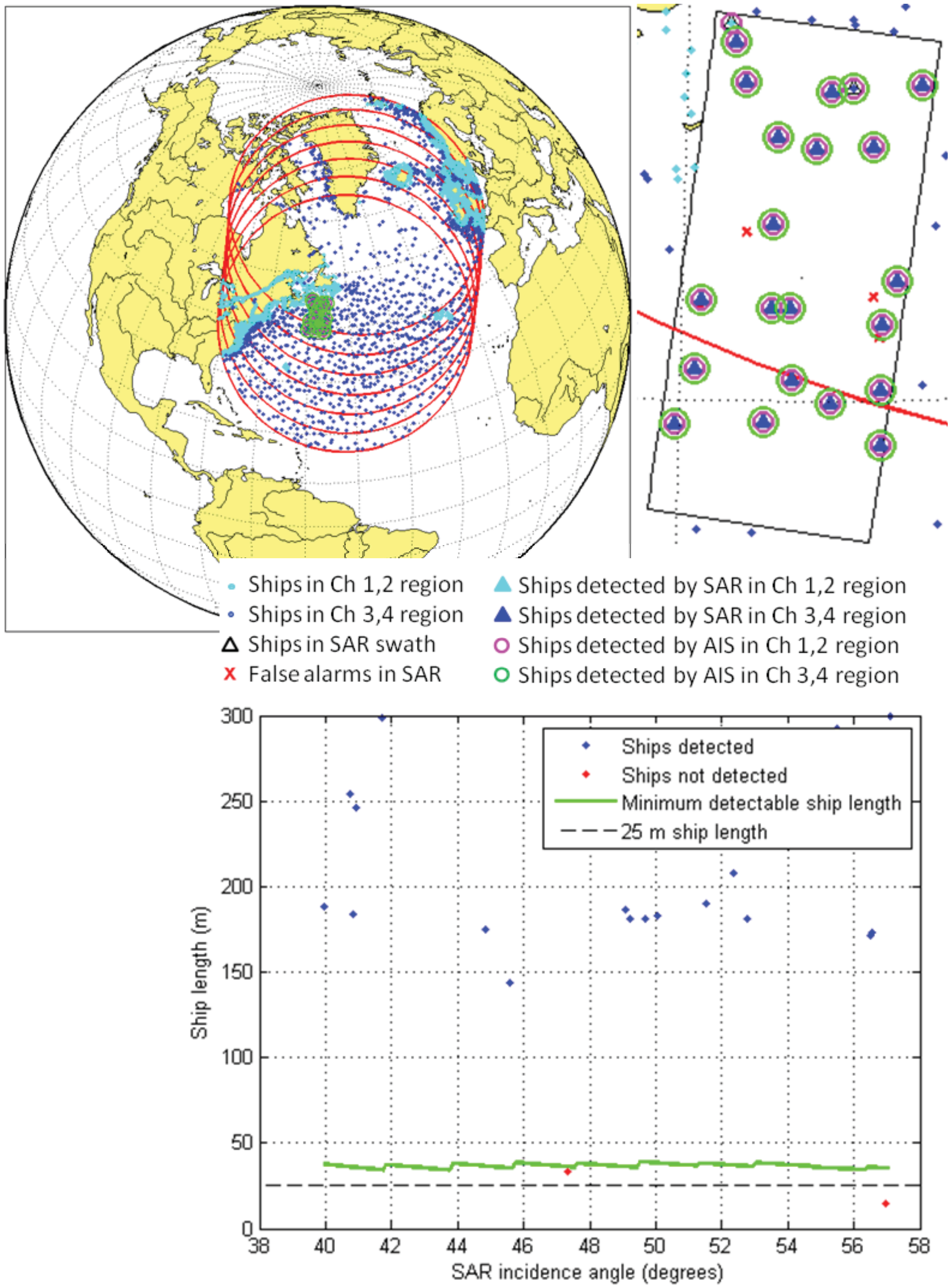


Figure 60: Example of descending RCM output for Canadian East Coast (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

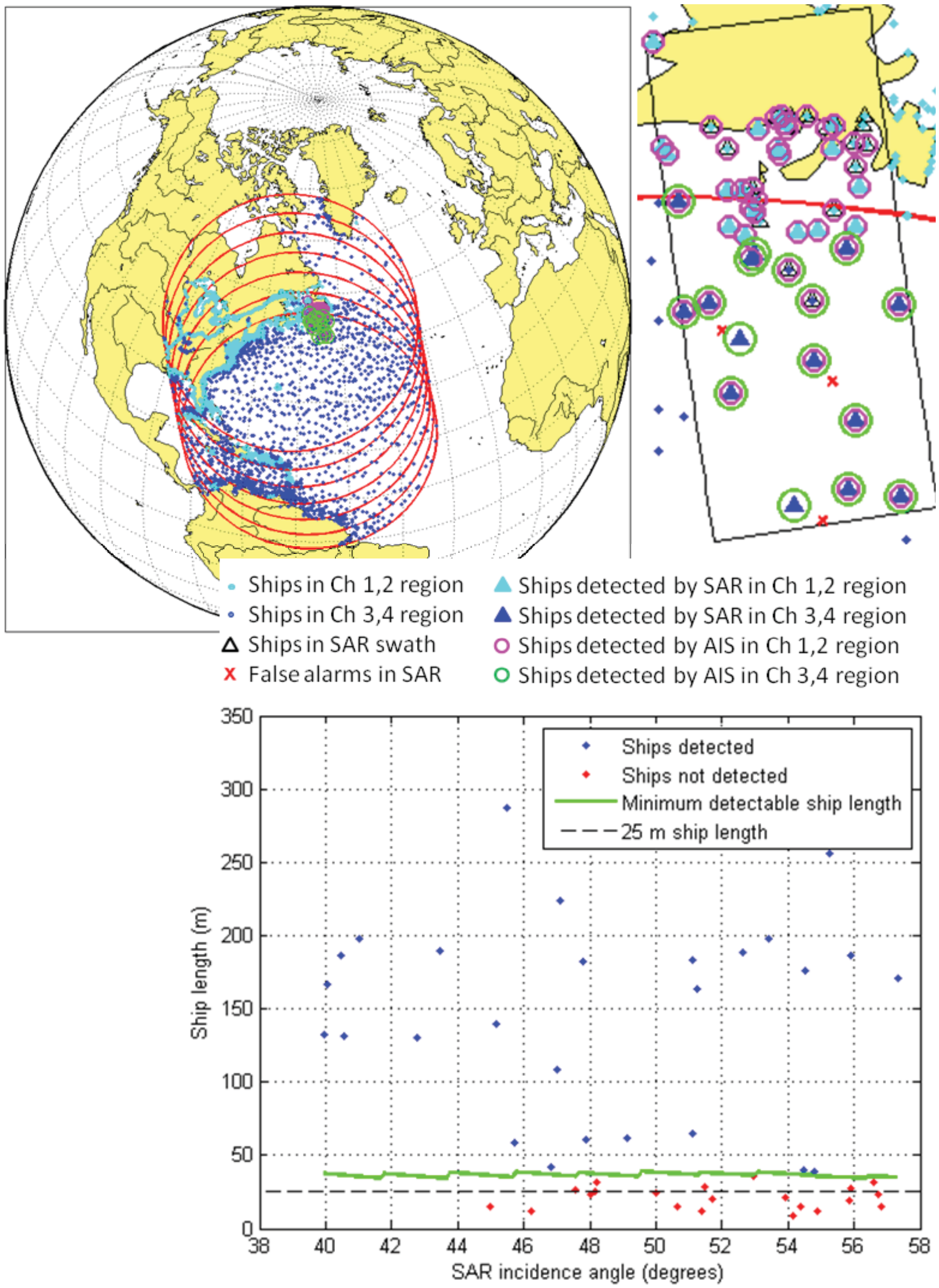


Figure 61: Example of ascending RCM output for Canadian East Coast (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

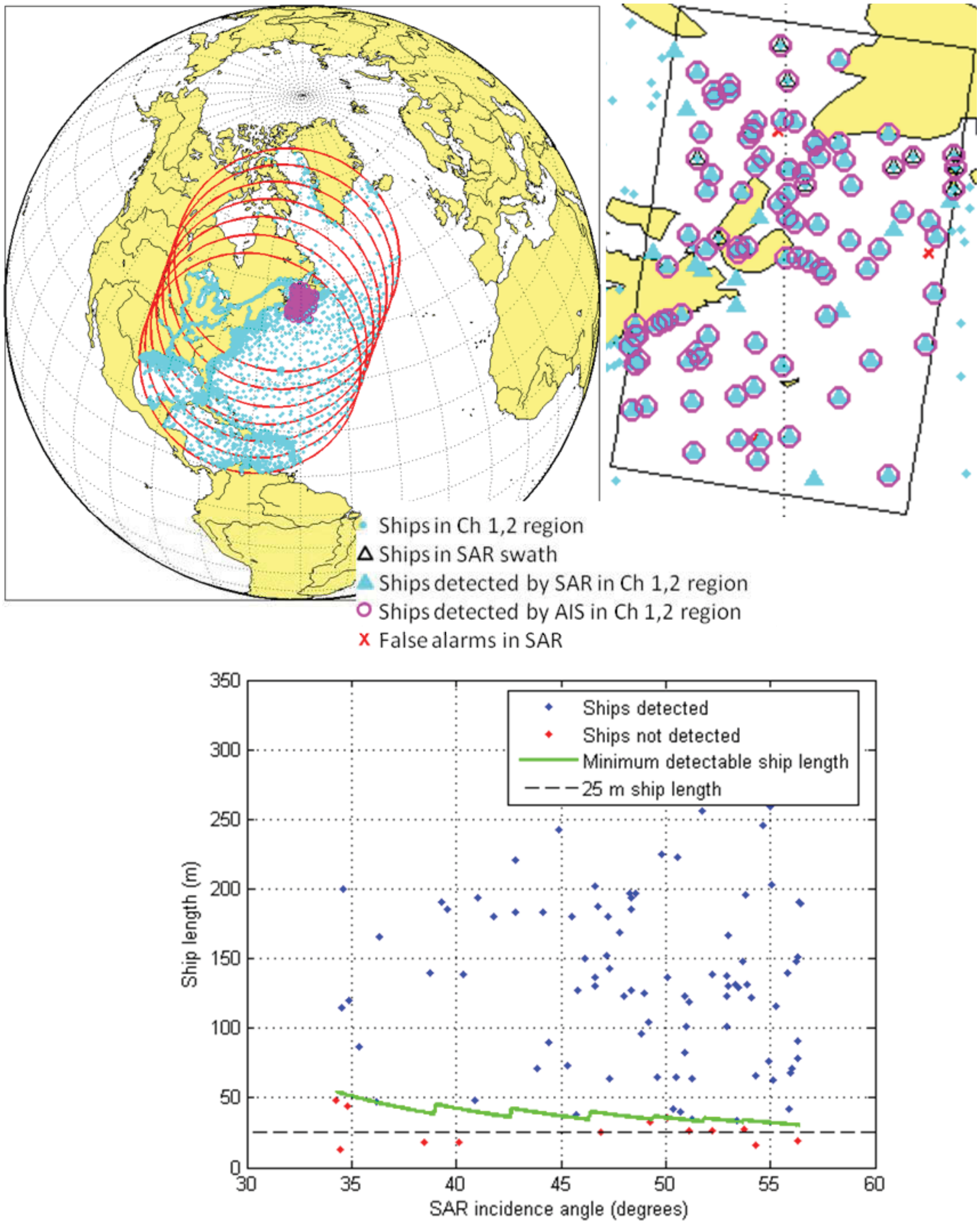


Figure 62: Example of RSAT2 orbit 1 output for the Canadian East Coast (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

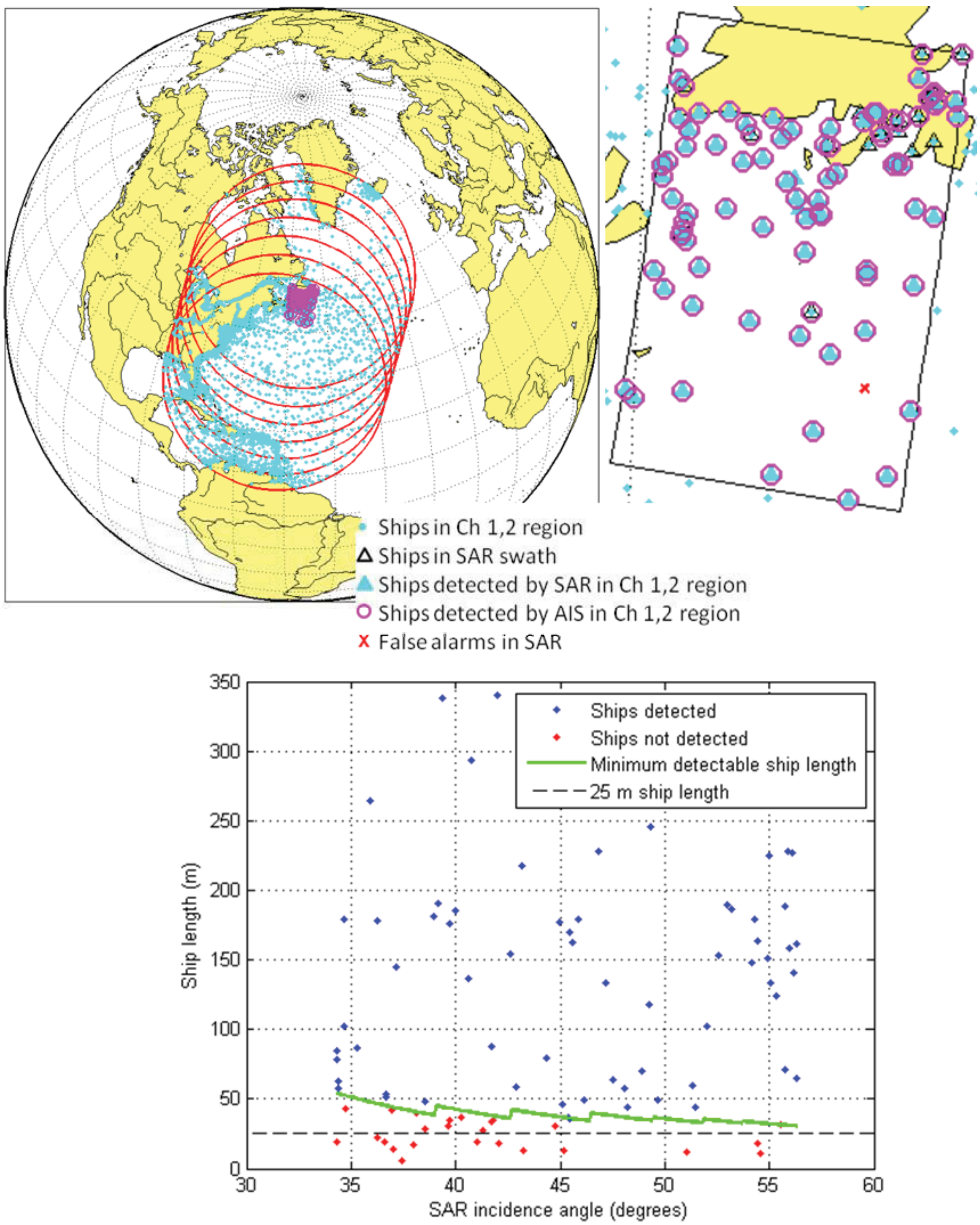


Figure 63: Example of RSAT2 orbit 2output for the Canadian East Coast (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

6.2.4 Canadian West Coast

The Canadian West Coast scenarios represent regions of medium ship density. The AIS swath for both the RCM and RSAT2 orbit cases covered the west coast of Canada and the United States, with the ascending RCM case having a slightly higher ship density. The two RSAT2 orbit cases were similar in acquisition geometry, but the first case covered more of the higher density areas of the western United States.

The averages of the ten iterations for RCM and RSAT2 are summarized in Table 31 and examples of the iterations for both cases are shown in Figure 64 and Figure 65 for RCM and Figure 66 and Figure 67 for RSAT2. In general, the probability of detection for AIS in the SAR footprint using Channels 1 and 2 of RCM and EV1 with RSAT2 were high.

The probability of SAR detection is lower within the Channels 1 and 2 area cases of both RCM and RSAT2 than within the Channels 3 and 4 areas because of the increased number of ships below the detection threshold for SAR in these coastal regions.

Table 31: Average from 10 iterations of the Canadian West Coast scenario outputs.

Output	RCM				RSAT2 and EV1	
	Ascending		Descending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Mean ships in AIS FOV steps	3115.7	988.7	2090.5	445.7	2927.2	1538.8
Min. ships in AIS FOV steps	2686.5	904.0	673.3	155.9	2397.6	1346.1
Max. ships in AIS FOV steps	3416.5	1046.1	2971.9	730.0	3245.1	1664.5
Ships in SAR swath	49.8	26.4	140.3	21.0	118.5	88.4
SAR POD (ships > 25 m)	0.82	0.97	0.61	0.96	0.68	0.67
AIS POD for ships in SAR swath	0.94	1.00	0.99	1.00	0.93	0.96
Probability of AIS given SAR detection for ships in SAR swath	0.98	1.00	0.99	1.00	0.95	0.98
Probability of SAR AND AIS detection for ships in SAR swath	0.68	0.97	0.44	0.96	0.49	0.53

Output	RCM				RSAT2 and EV1	
	Ascending		Descending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Probability of SAR OR AIS detection for ships in SAR swath	0.95	1.00	0.99	1.00	0.96	0.98
Number of ships in AIS FOV 5 minute overlap	2461.6	729.7	1590.9	208.7	2531.5	1329.8
AIS POD in AIS FOV 5 minute overlap	0.92	1.00	0.98	1.00	0.93	0.98
AIS and SAR time difference (hours)	0.08	0.08	0.08	0.08	5.73	4.15
Probability of association for AIS and SAR	1.00	1.00	1.00	1.00	0.36	0.49

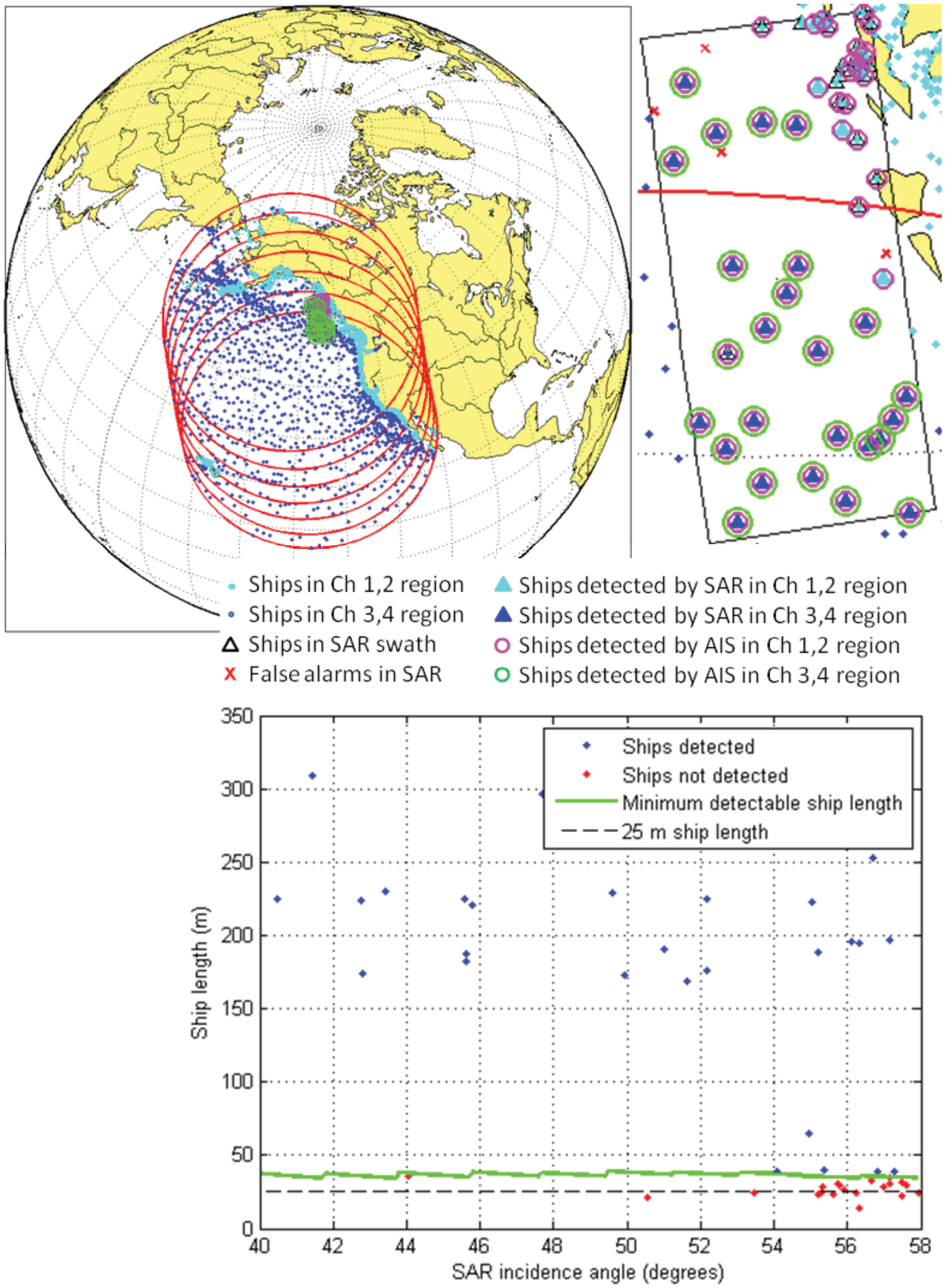


Figure 64: Example of ascending RCM output for Canadian West Coast (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

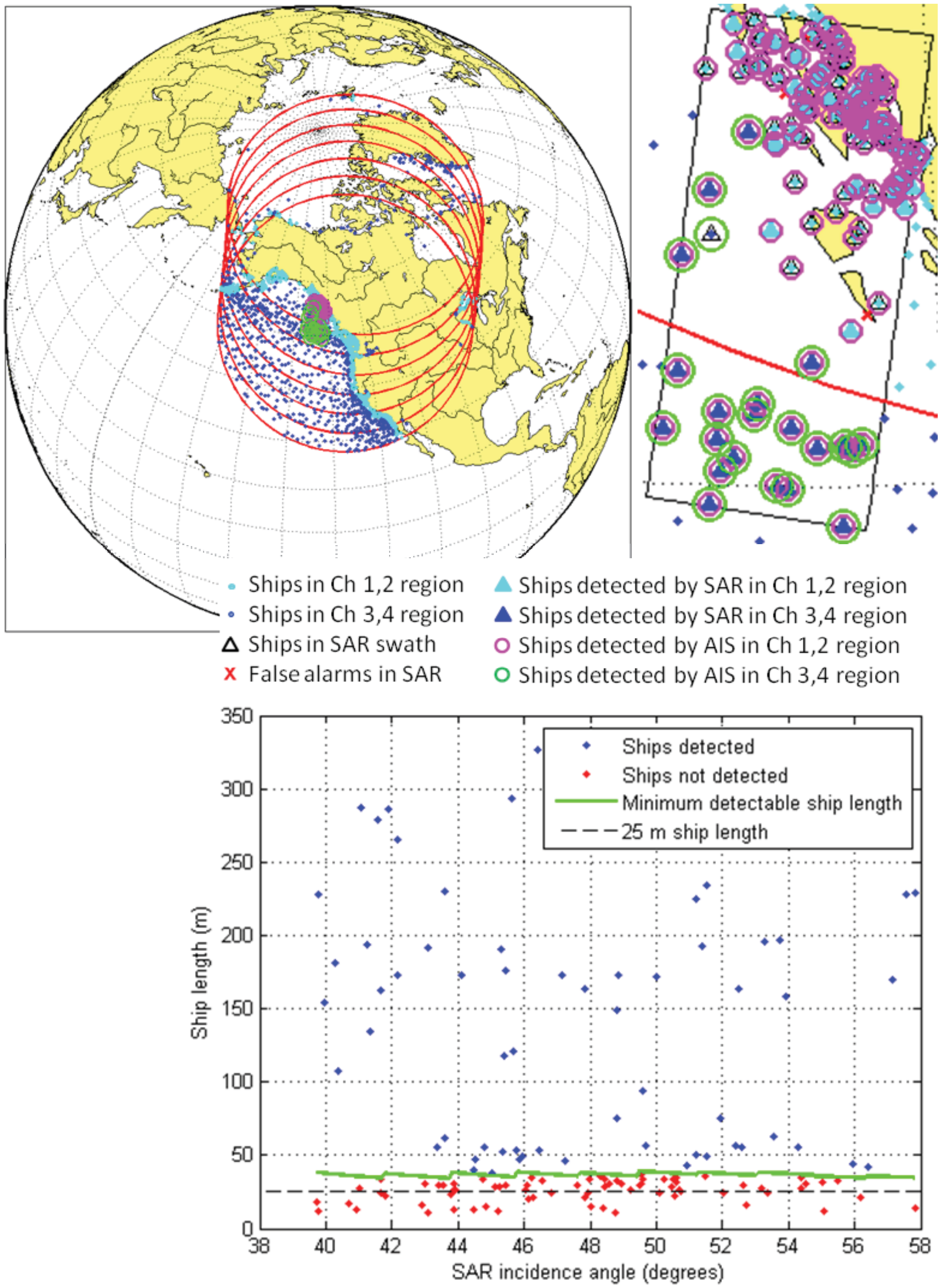


Figure 65: Example of descending RCM output for Canadian West Coast (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

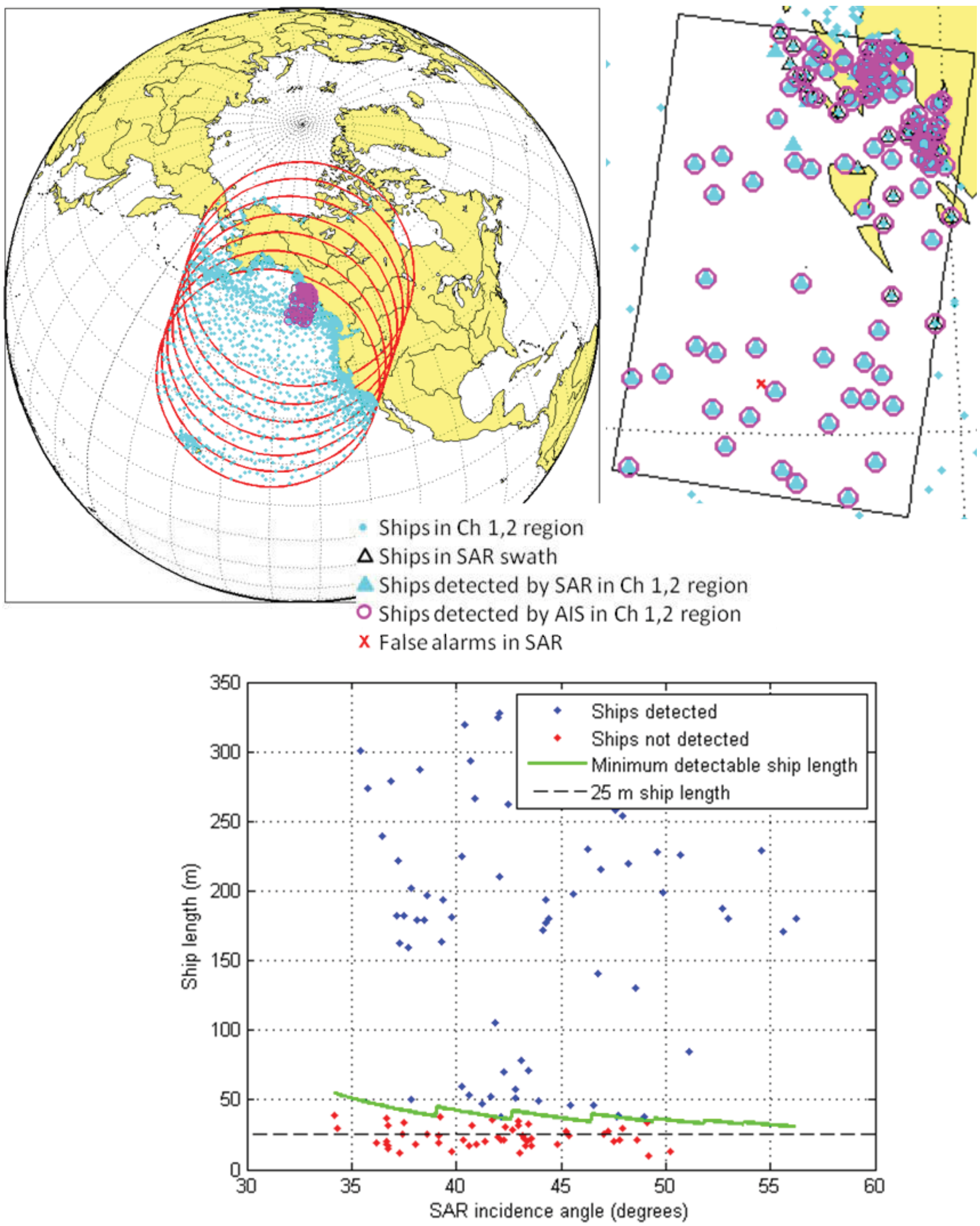


Figure 66: Example of RSAT2 orbit 1 output for the Canadian West Coast (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

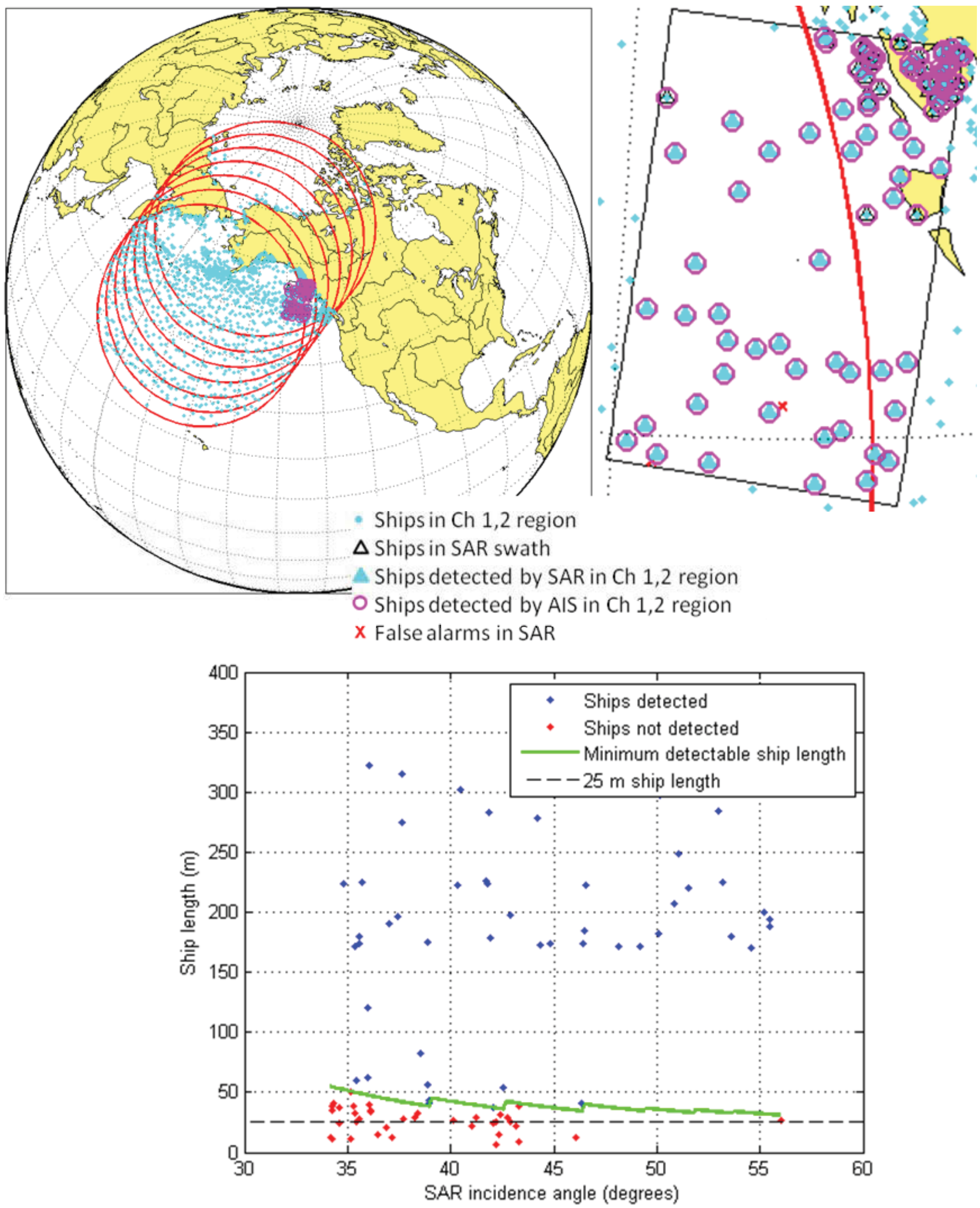


Figure 67: Example of RSAT2 orbit 2 output for the Canadian West Coast (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

6.2.5 English Channel

The English Channel location is an area of very high ship density. The orbit geometries of all scenarios contain a large number of ships in both the AIS and SAR footprints. Much of the area covered by the SAR footprint for RCM and RSAT2 is within the AIS Channels 1 and 2 region that is monitored by coastal base stations (ships excluded from Channels 3 and 4 transmission), with the descending RCM case and first orbit case of RSAT2 including more ships than the other cases.

Table 32 lists the average of the ten scenario iteration outputs for the RCM and RSAT2 orbits. Figure 68 and Figure 69 show an example of these ten iterations for RCM and Figure 70 and Figure 71 for the RSAT2 scenarios. Due to the very high number of ships in each AIS FOV step, all the probabilities of AIS detection (including the AIS FOV overlap area) for Channels 1 and 2 for RCM and EV1 with RSAT2 are near zero (the EV1 and RSAT2 orbit 2 has a higher probability of 0.21). The number of ships for the AIS Channels 3 and 4 region is much smaller and as a result, the probabilities of detection from AIS are very high.

The probability of detection by SAR for both RCM and RSAT2 AIS Channels 1 and 2 regions are affected by the large number of ships below the minimum detectable ship length. For the Channels 3 and 4 cases, the probability of detection by SAR is higher for the descending case, yet very low for the ascending orientation. The ships in the RCM Channels 3 and 4 region in the northern part of the SAR swath for the descending pass (top right of Figure 68) must be larger than those found in the southwest part of the SAR swath in the ascending pass (Figure 69).

Table 32: Average from 10 iterations of the English Channel scenario outputs.

Output	RCM				RSAT2 and EV1	
	Descending		Ascending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Mean ships in AIS FOV steps	23368.0	1743.8	20124.3	2253.4	21424.4	15136.3
Min. ships in AIS FOV steps	13993.9	698.3	9214.3	1738.8	8295.5	5437.4
Max. ships in AIS FOV steps	29761.3	2326.9	24392.8	2396.9	26862.5	19559.9
Ships in SAR swath	1414.3	69.8	958.9	8.4	6561.1	1195.3
SAR POD (ships > 25 m)	0.81	0.82	0.75	0.14	0.78	0.72
AIS POD for ships in SAR swath	0.00	1.00	0.04	0.98	0.01	0.21

Output	RCM				RSAT2 and EV1	
	Descending		Ascending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Probability of AIS given SAR detection for ships in SAR swath	0.00	1.00	0.04	1.00	0.01	0.20
Probability of SAR AND AIS detection for ships in SAR swath	0.00	0.81	0.02	0.14	0.00	0.09
Probability of SAR OR AIS detection for ships in SAR swath	0.81	1.00	0.75	0.98	0.60	0.58
Number of ships in AIS FOV 5 minute overlap	18584.6	1315.1	16819.0	1991.7	17035.2	5937.9
AIS POD in AIS FOV 5 minute overlap	0.01	1.00	0.02	0.99	0.03	0.14
AIS and SAR time difference (hours)	0.08	0.08	0.08	0.08	5.90	4.59
Probability of association for AIS and SAR	1.00	1.00	0.99	1.00	0.30	0.16

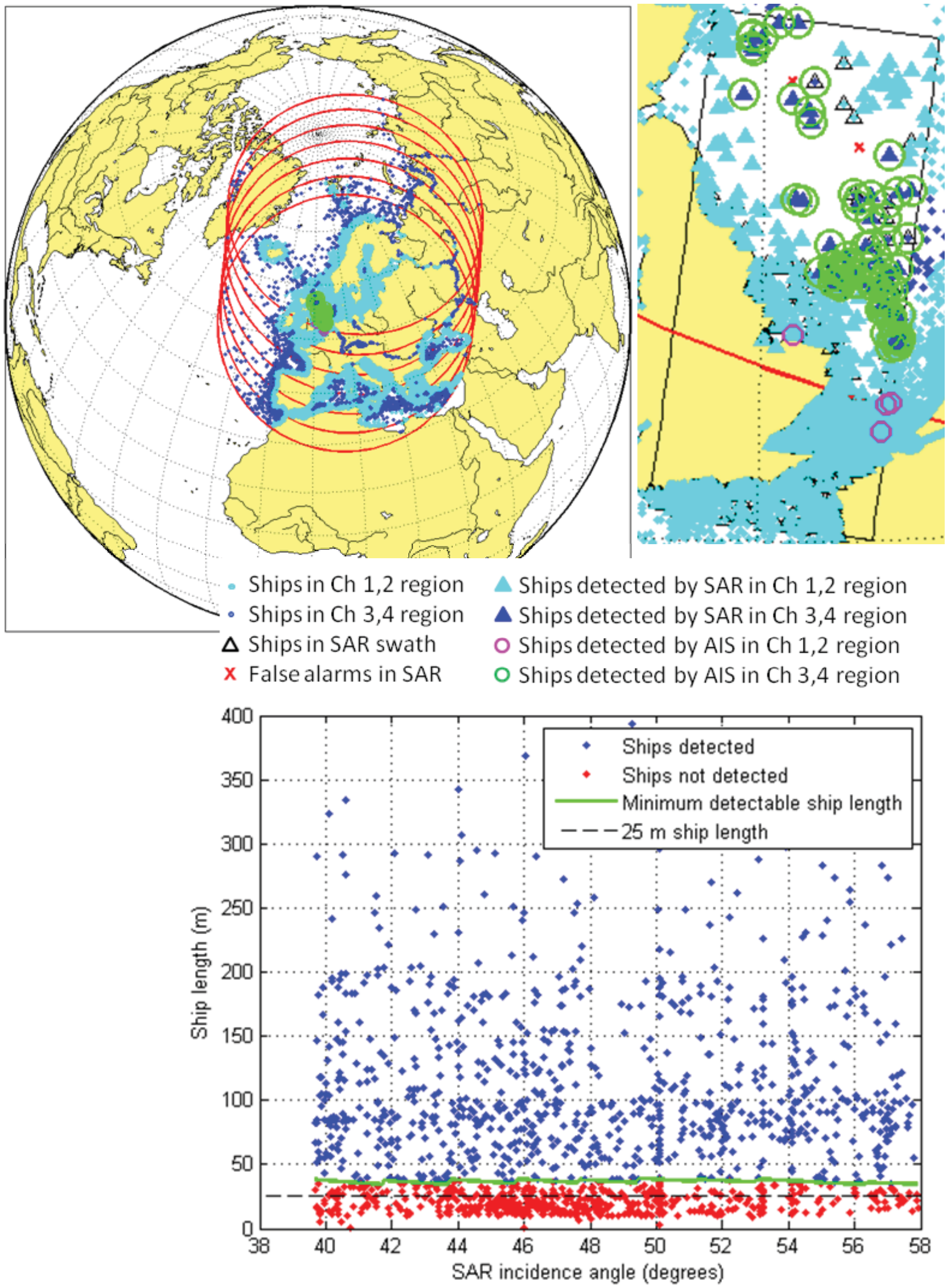


Figure 68: Example of descending RCM output for the English Channel (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

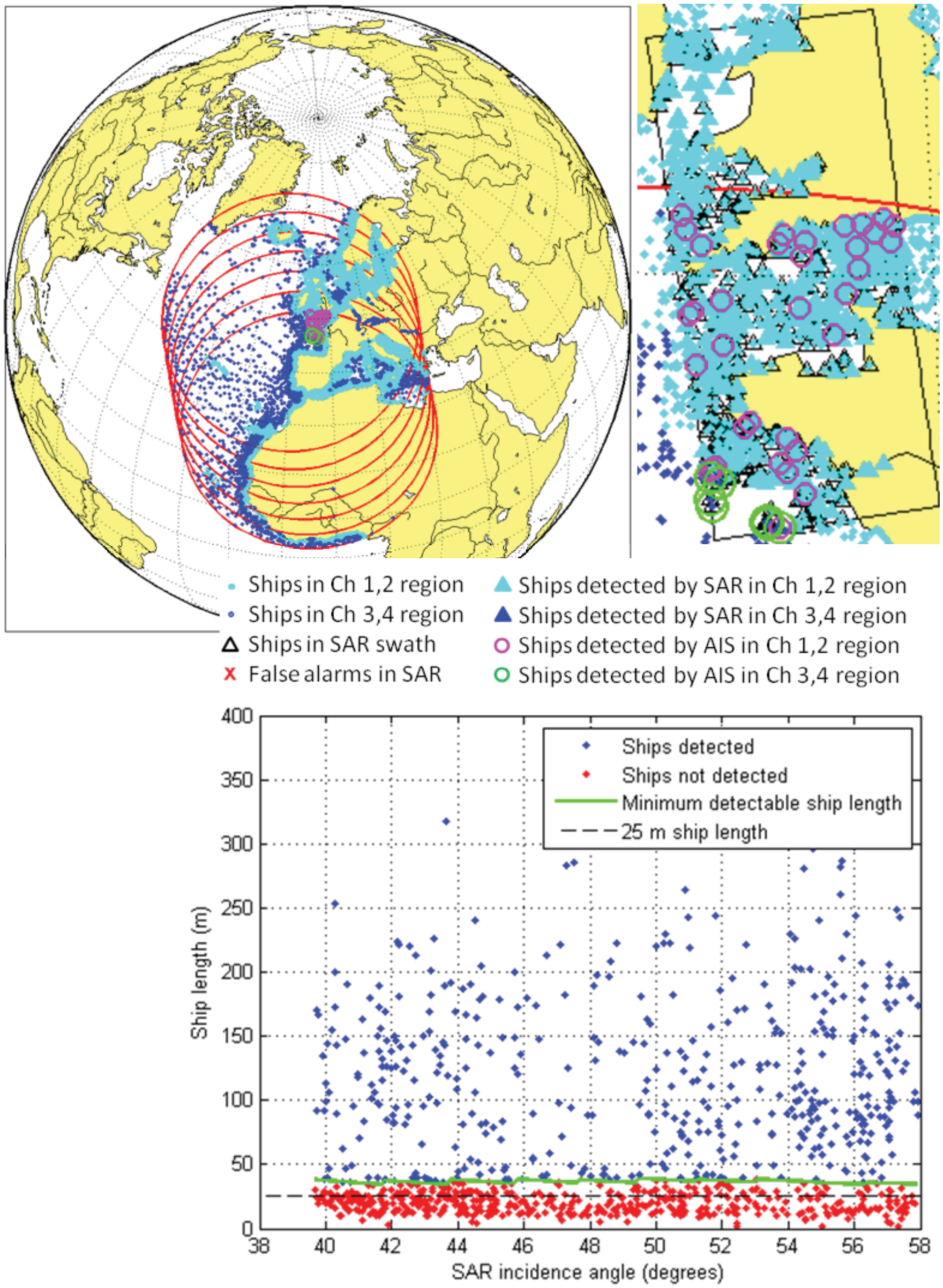


Figure 69: Example of ascending RCM output for the English Channel (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

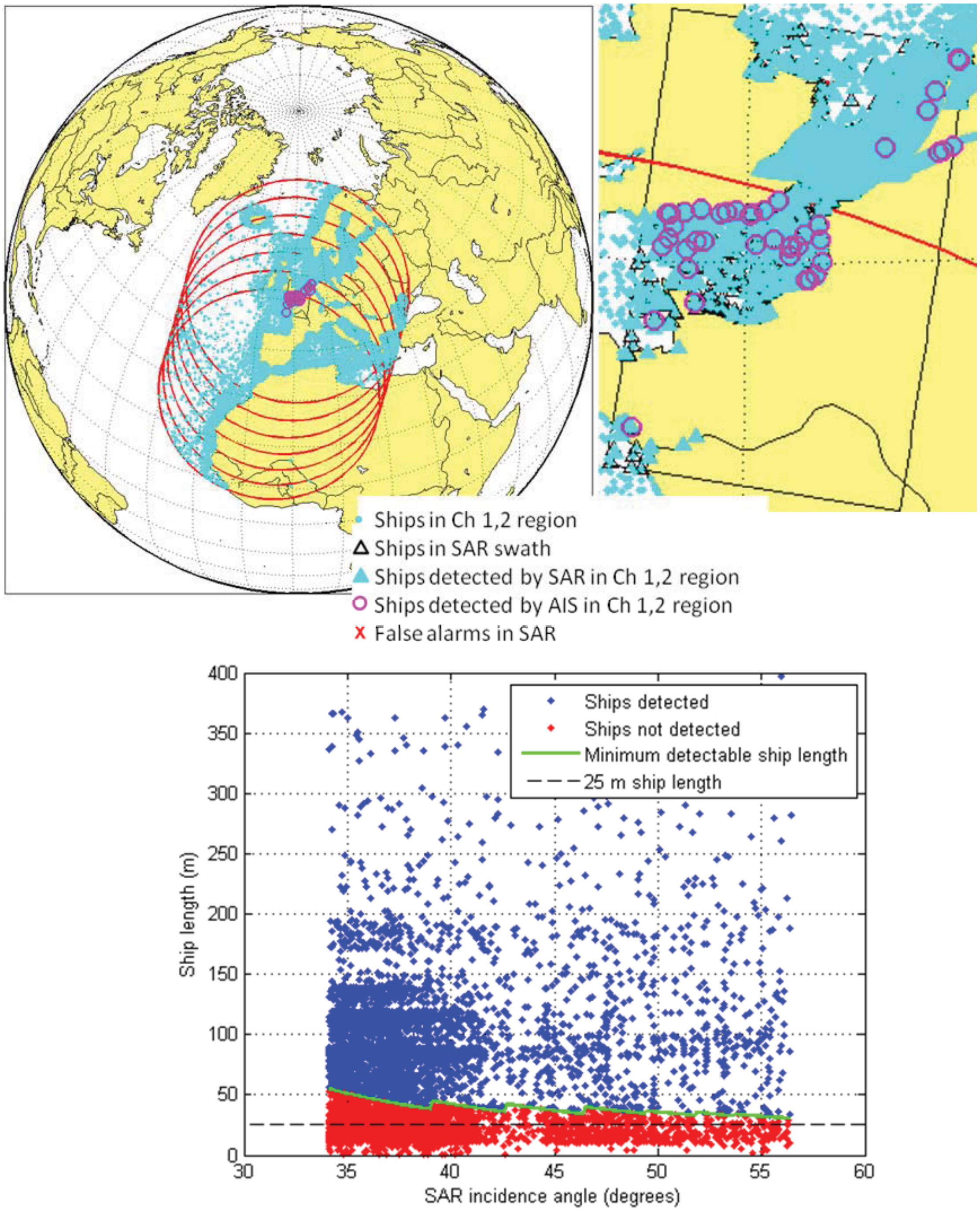


Figure 70: Example of RSAT2 orbit 1output for the English Channel (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

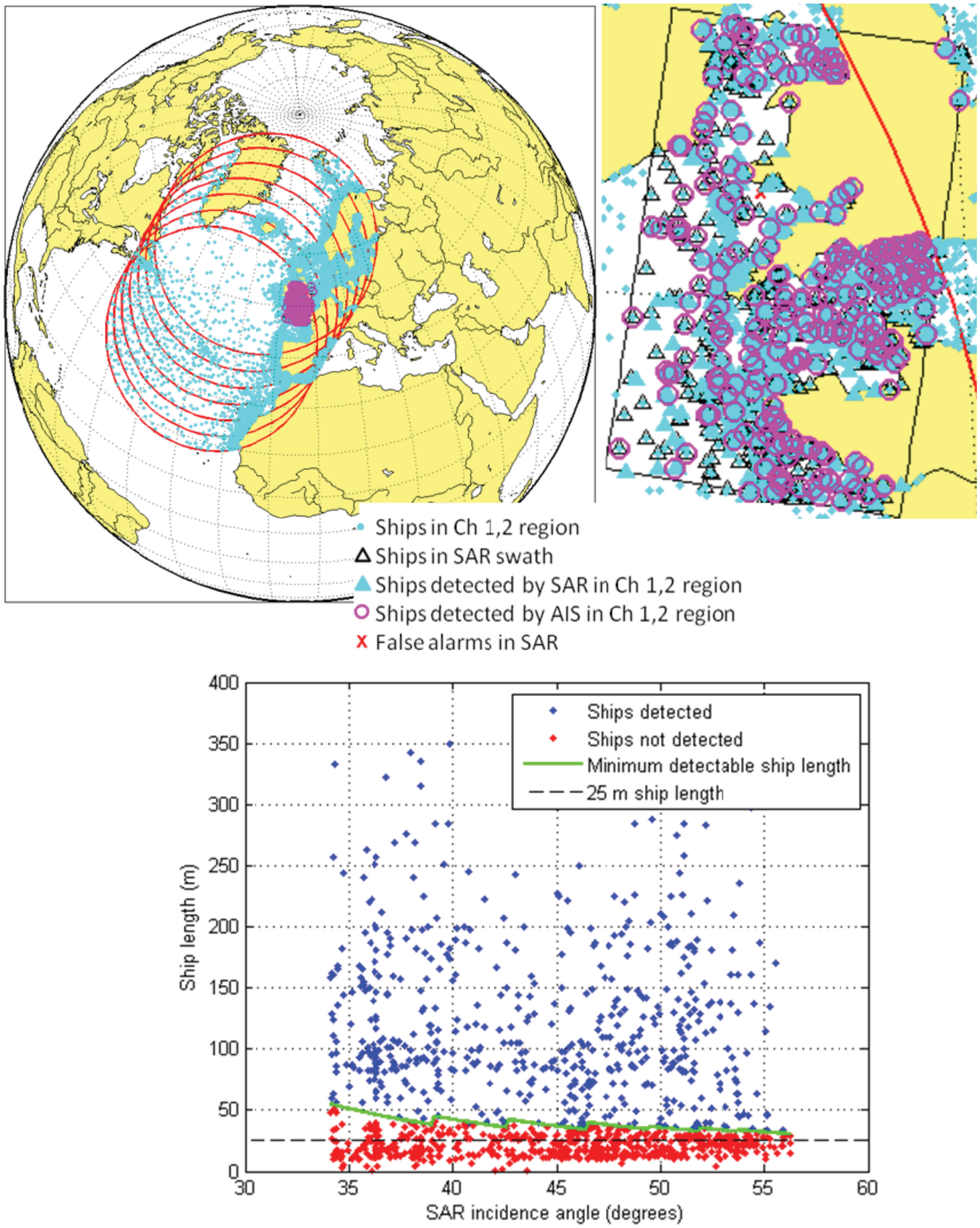


Figure 71: Example of RSAT2 orbit 2output for the English Channel (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

6.2.6 Horn of Africa

The Horn of Africa scenarios are examples of medium ship density. The descending RCM and RSAT2 orbit cases had more ships in the AIS FOV, including more ships around India and include the Caspian and parts of the Black Seas. The ascending case covers the less dense regions near the southeast coast of Africa. Both orbits cover the Red Sea and the Persian Gulf.

Table 33 gives the average results for the ten scenario iterations for both acquisition geometries of RCM and RSAT2. Figure 72 and Figure 73 show examples of the output for the ten iterations of RCM and similarly Figure 74 and Figure 75 show output examples for RSAT2.

The probability of AIS detection for the RCM Channels 3 and 4 cases are all high. Additionally, the probability of AIS detection for the ascending RCM Channels 1 and 2 case and both EV1 and RSAT2 orbits are also high due to the lower number of ships for much of the AIS FOV steps. The probabilities of AIS detection for the descending RCM Channels 1 and 2 are lower due to the consistently higher number of ships in each of the AIS FOV steps.

The Horn of Africa is a location where the performance of AIS using Channels 1 and 2 can vary widely depending on the framing of the SAR and AIS.

Table 33: Average from 10 iterations of the Horn of Africa scenario outputs.

Output	RCM				RSAT2 and EV1	
	Descending		Ascending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Mean ships in AIS FOV steps	6022.4	1589.8	2968.4	1012.6	4745.2	3257.9
Min. ships in AIS FOV steps	5605.2	1346.5	1576.3	786.7	1165.6	1307.4
Max. ships in AIS FOV steps	6315.3	1753.8	5196.2	1140.1	9907.3	5400.9
Ships in SAR swath	89.2	61.5	87.4	63.7	130.5	71.2
SAR POD (ships > 25 m)	0.98	0.98	0.97	0.97	0.97	0.98
AIS POD for ships in SAR swath	0.70	1.00	0.93	1.00	0.95	0.95
Probability of AIS given SAR detection for ships in SAR swath	0.69	1.00	0.93	1.00	0.95	0.95
Probability of SAR AND AIS detection for ships in SAR swath	0.67	0.98	0.90	0.97	0.92	0.92

Output	RCM				RSAT2 and EV1	
	Descending		Ascending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Probability of SAR OR AIS detection for ships in SAR swath	0.99	1.00	1.00	1.00	0.99	1.00
Number of ships in AIS FOV 5 minute overlap	5042.5	1146.9	967.7	465.5	1040.3	929.0
AIS POD in AIS FOV 5 minute overlap	0.68	1.00	0.95	1.00	0.94	0.94
AIS and SAR time difference (hours)	0.08	0.08	0.08	0.08	5.16	6.00
Probability of association for AIS and SAR	1.00	1.00	1.00	1.00	0.44	0.46

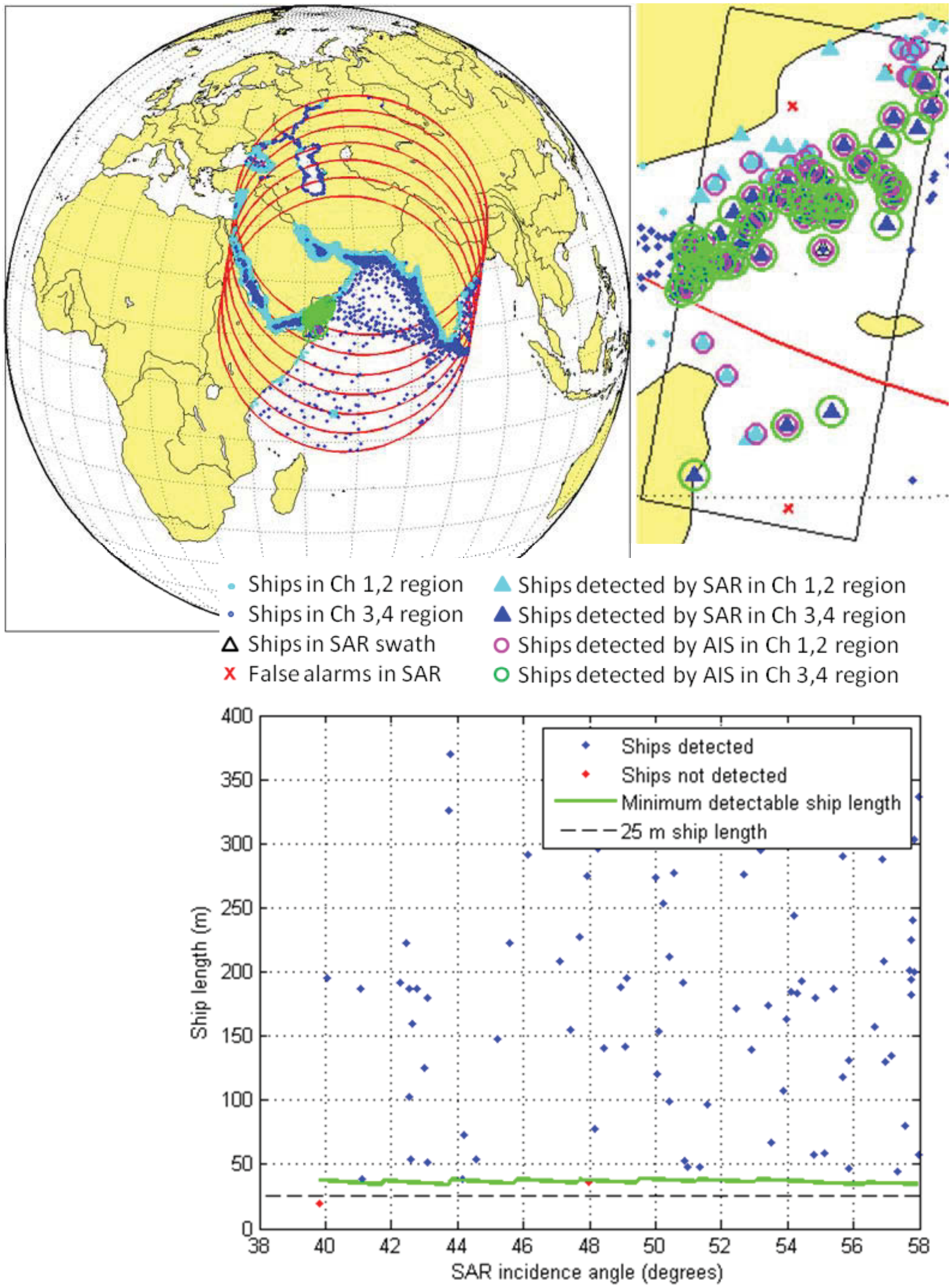


Figure 72: Example of descending RCM output for the Horn of Africa (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

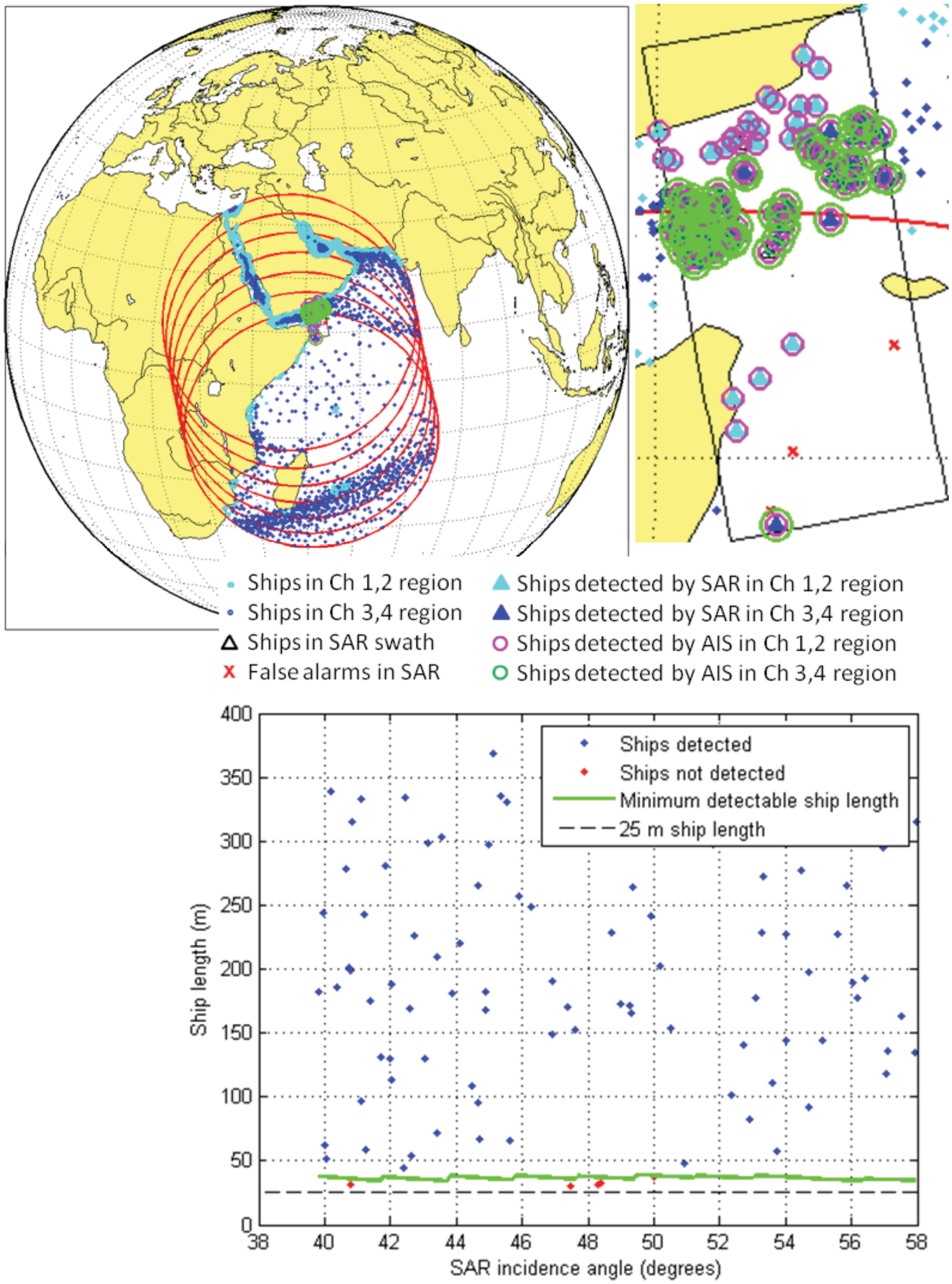


Figure 73: Example of ascending RCM output for the Horn of Africa (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

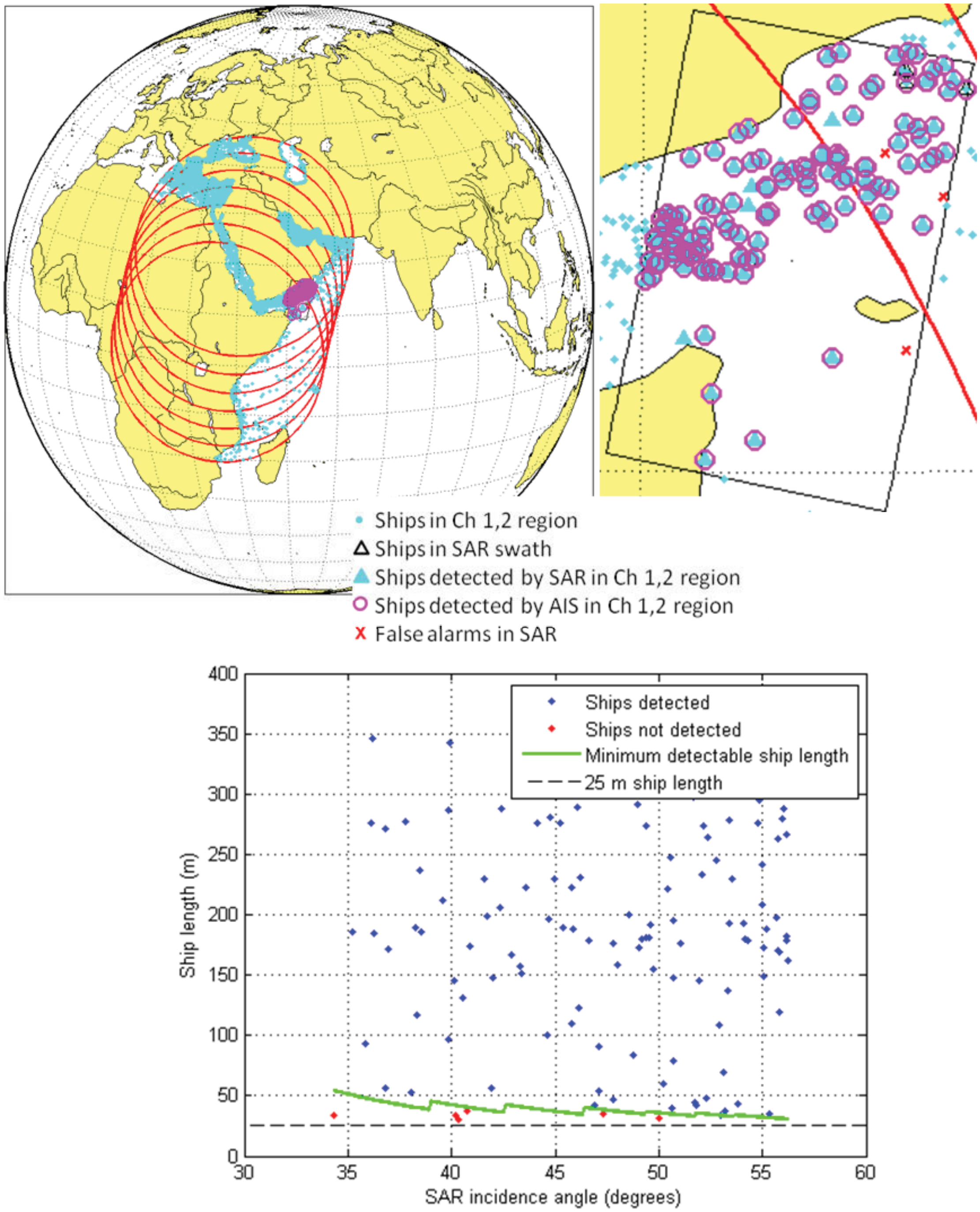


Figure 74: Example of RSAT2 orbit 1 output for the Horn of Africa (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

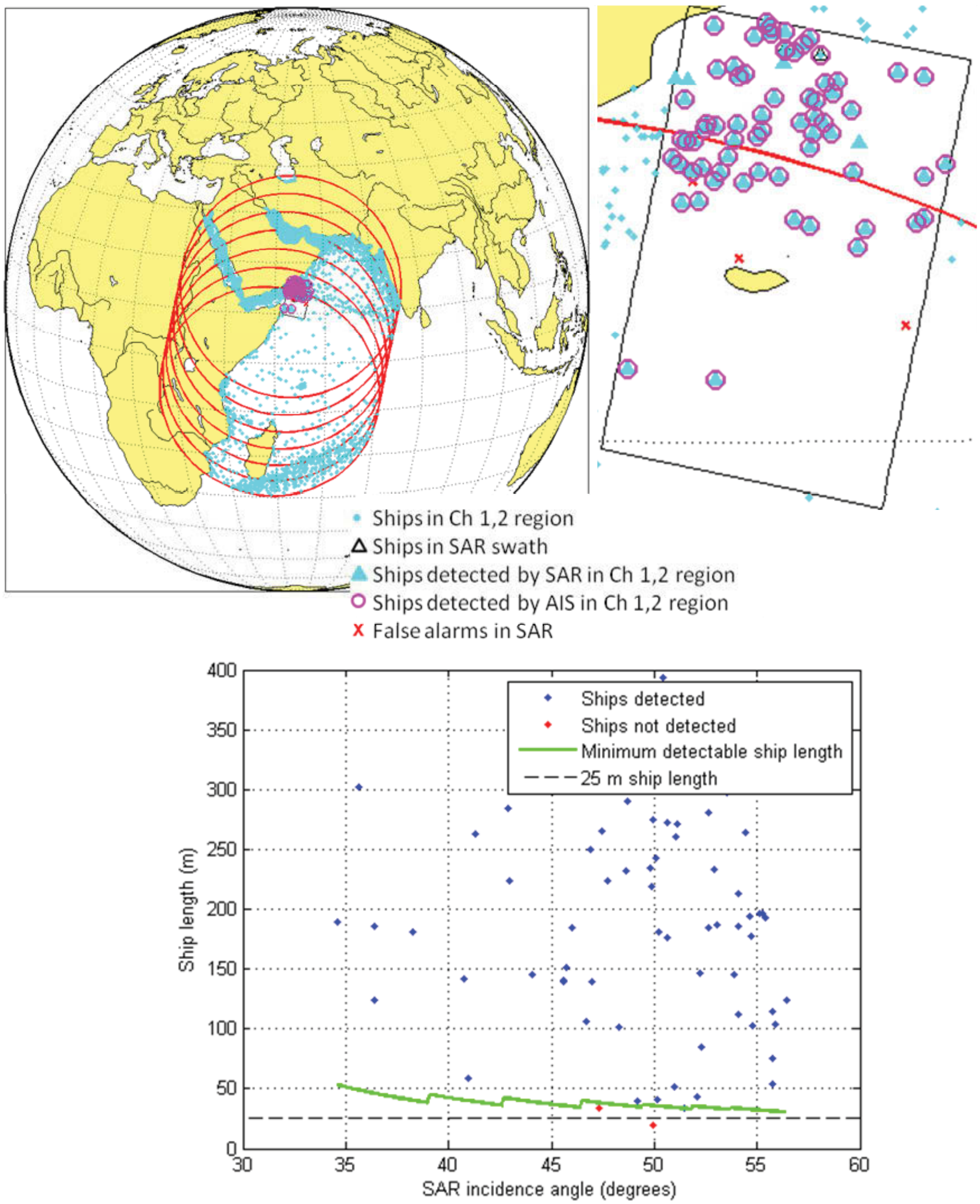


Figure 75: Example of RSAT2 orbit 2 output for the Horn of Africa (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

6.2.7 Japan

The Japan case studies have high ship density in both the SAR and AIS footprints. There was very little difference in the number of ships in the AIS FOV for the RCM and RSAT2 scenarios, with an exception for the descending RCM.

The average of the ten scenario iterations for the RCM and RSAT2 cases are listed in Table 34. Examples of one of the ten iterations for both RCM orbit cases are shown in Figure 76, Figure 77, Figure 78 and Figure 79 for RSAT2. The probability of detection by AIS for all Channels 1 and 2 orbits (RCM and RSAT2) are near zero while the probabilities for the Channels 3 and 4 are higher at 0.86 and 0.97 for the ascending and descending cases.

The POD by SAR for all cases within the regions of Channels 1 and 2 and Channels 3 and 4 are also high, with that for the Channels 1 and 2 region being slightly lower. This would indicate that the majority of the ships in this region are above the minimum detectable length, and supported by the plots in lower part of Figure 76 to Figure 79.

Table 34: Average from 10 iterations of the Japan scenario outputs.

Output	RCM				RSAT2 and EV1	
	Ascending		Descending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Mean ships in AIS FOV steps	33790.4	10647.1	23985.7	5202.0	33965.2	31752.5
Min. ships in AIS FOV steps	28089.4	9962.6	11880.0	2700.4	29987.8	23463.3
Max. ships in AIS FOV steps	35473.9	11291.6	34305.9	9880.5	34791.9	33898.0
Ships in SAR swath	3330.9	23.7	3134.4	27.0	3406.6	3541.6
SAR POD (ships > 25 m)	0.87	0.99	0.88	0.97	0.89	0.87
AIS POD for ships in SAR swath	0.00	0.86	0.01	0.97	0.00	0.00
Probability of AIS given SAR detection for ships in SAR swath	0.00	0.86	0.01	0.97	0.00	0.00
Probability of SAR AND AIS detection for ships in SAR swath	0.00	0.86	0.01	0.95	0.00	0.00
Probability of SAR OR AIS detection for ships in SAR swath	0.87	1.00	0.88	1.00	0.82	0.80

Output	RCM				RSAT2 and EV1	
	Ascending		Descending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Number of ships in AIS FOV 5 minute overlap	30688.8	9304.4	13542.7	3515.6	33106.7	32167.8
AIS POD in AIS FOV 5 minute overlap	0.00	0.85	0.02	0.97	0.00	0.00
AIS and SAR time difference (hours)	0.08	0.08	0.08	0.08	5.93	5.83
Probability of association for AIS and SAR	0.00	1.00	0.99	1.00	0.00	0.20

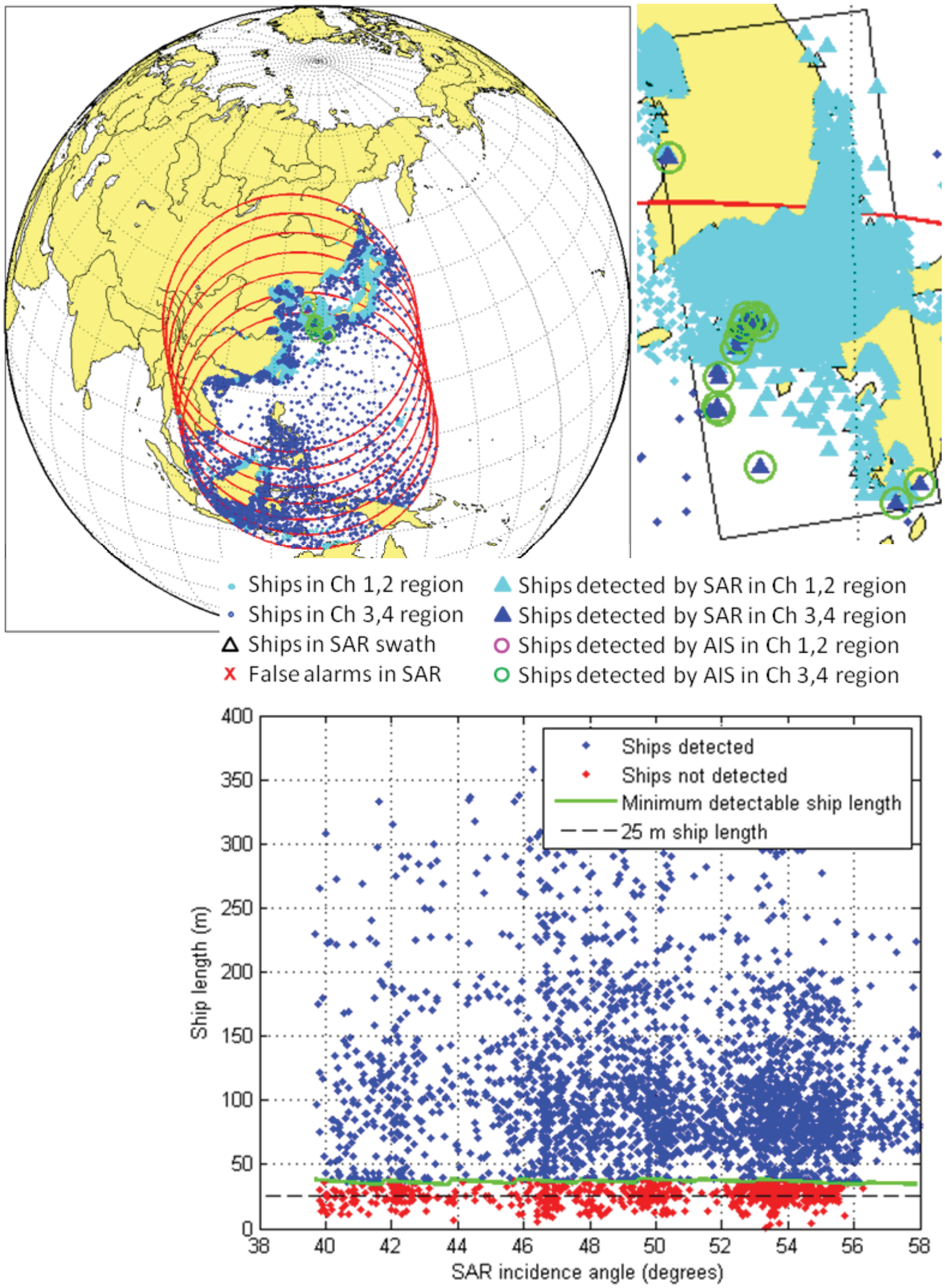


Figure 76: Example of ascending RCM output for Japan (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

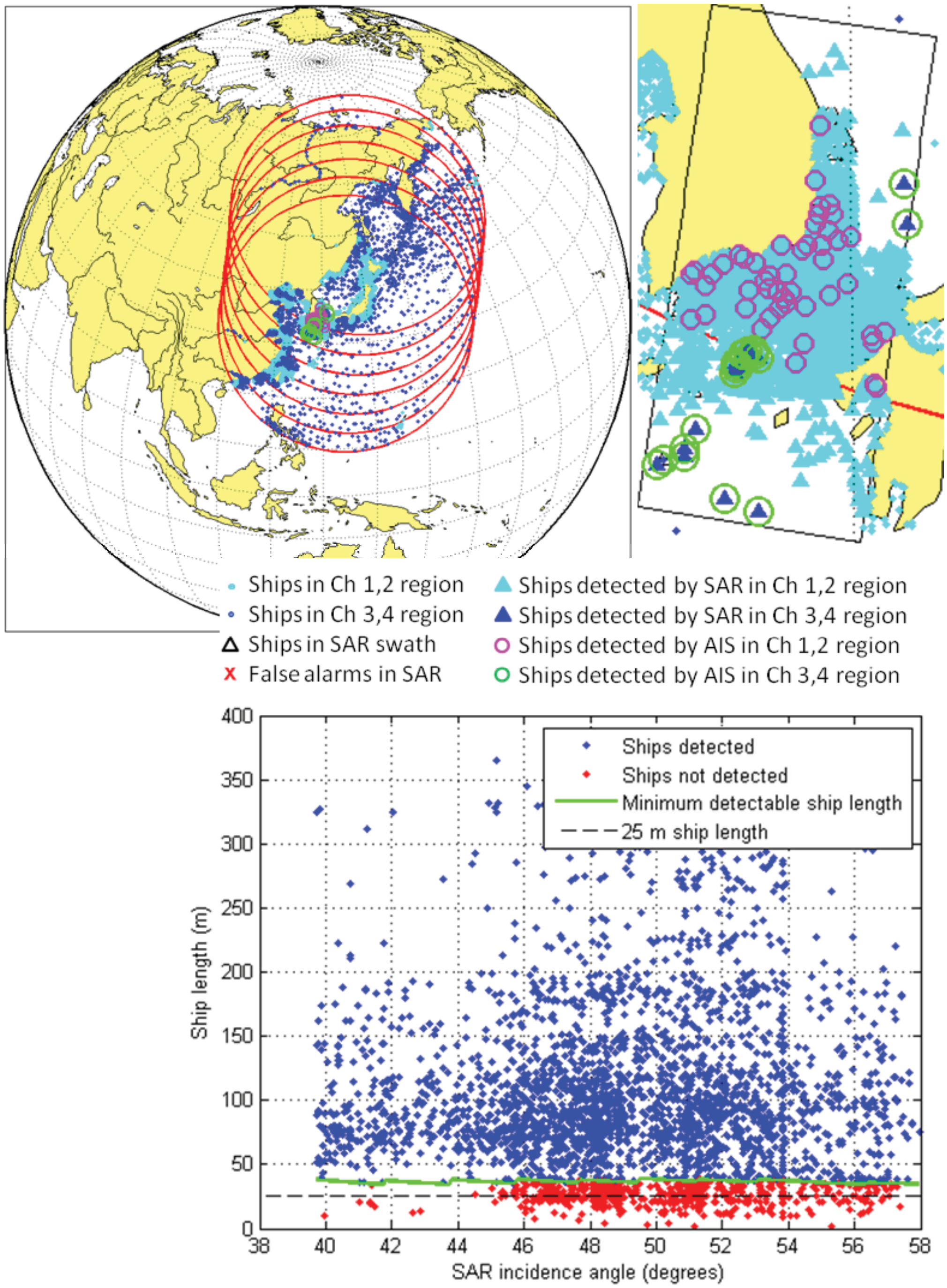


Figure 77: Example of descending RCM output for Japan (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

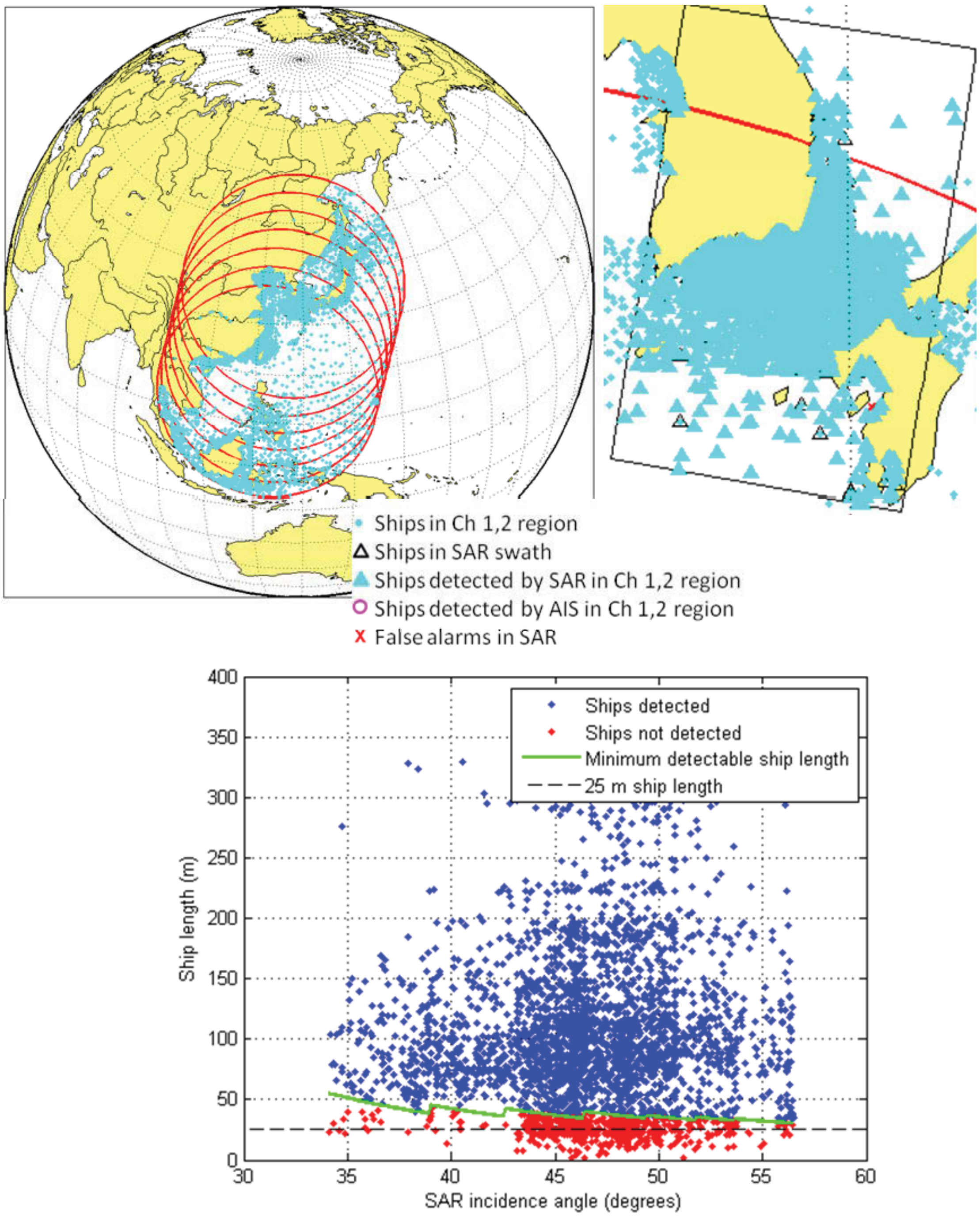


Figure 78: Example of RSAT2 orbit 1 output for Japan (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

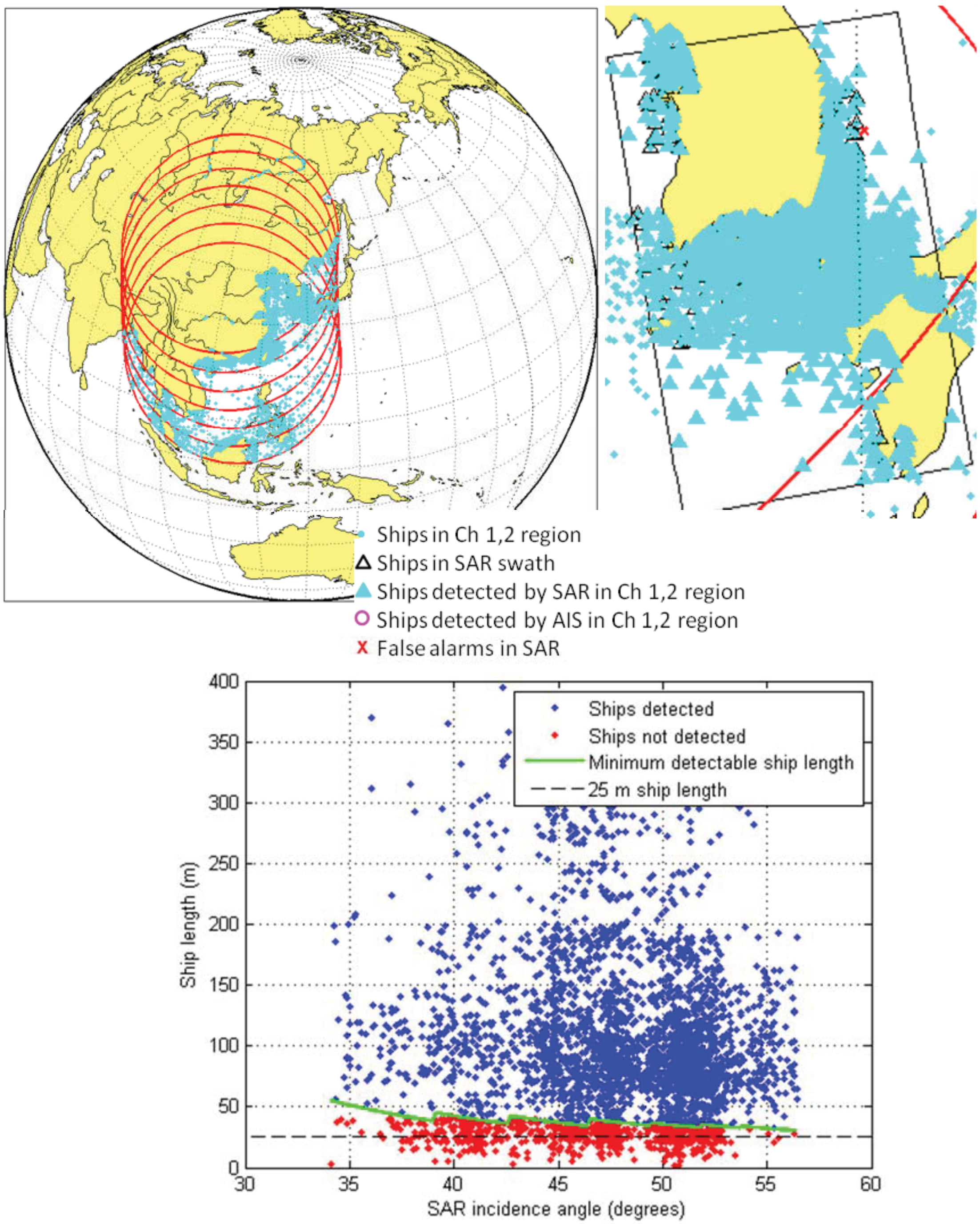


Figure 79: Example of RSAT2 orbit 2 output for Japan (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

6.2.8 Mediterranean

The Mediterranean scenarios are also cases of high density. However, unlike the Japan cases, a significant difference in the number of ships exists between the descending and ascending RCM geometries and between the two RSAT2 orbit geometries. The descending RCM case covers high density areas in all AIS FOV steps as the satellite passes over Eastern Europe. The ascending RCM orientation starts in an area of lower density over Africa and ends in the higher density region of Western Europe. Both RSAT2 orbit geometries cover much of Europe, with orbit two covering the north-western waters and orbit two covering the Red Sea and parts of the Persian Gulf.

Table 35 gives the average of the ten scenario iterations for both orbit geometries of RCM and RSAT2. Figure 80 and Figure 81 show examples of the ten iterations for the RCM orbits and Figure 82 and Figure 83 for RSAT2.

There is a wide difference in the probability of AIS detection in the SAR footprints for the Channels 1 and 2 cases for RCM and RSAT2, from 0.03 to 0.52. The fewer ships in the ascending RCM case is reflected in the higher probability of AIS detection (0.46). The probability of detection for AIS with Channels 3 and 4 is high in all scenarios. The mid to high probability of SAR detections (higher for the Channels 3 and 4 region) are a result of a high number of ship in this area that are below the minimum detectable threshold.

Table 35: Average from 10 iterations of the Mediterranean scenario outputs.

Output	RCM				RSAT2 and EV1	
	Descending		Ascending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Mean ships in AIS FOV steps	19092.7	1954.7	9604.6	977.5	18553.6	9513.3
Min. ships in AIS FOV steps	12766.4	1695.3	2833.2	689.0	7006.4	2923.9
Max. ships in AIS FOV steps	24101.6	2087.1	21848.4	1726.9	28948.9	21010.2
Ships in SAR swath	815.5	104.8	971.6	113.2	1138.0	733.0
SAR POD (ships > 25 m)	0.72	0.96	0.73	0.97	0.76	0.92
AIS POD for ships in SAR swath	0.03	1.00	0.46	1.00	0.13	0.52
Probability of AIS given SAR detection for ships in SAR swath	0.03	1.00	0.53	1.00	0.14	0.56

Output	RCM				RSAT2 and EV1	
	Descending		Ascending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Probability of SAR AND AIS detection for ships in SAR swath	0.01	0.96	0.25	0.97	0.07	0.45
Probability of SAR OR AIS detection for ships in SAR swath	0.72	1.00	0.73	1.00	0.57	0.88
Number of ships in AIS FOV 5 minute overlap	9805.9	1301.4	3611.3	468.0	8891.4	4613.4
AIS POD in AIS FOV 5 minute overlap	0.04	0.99	0.56	1.00	0.17	0.51
AIS and SAR time difference (hours)	0.08	0.08	0.08	0.08	5.21	5.66
Probability of association for AIS and SAR	1.00	0.98	0.96	0.98	0.25	0.17

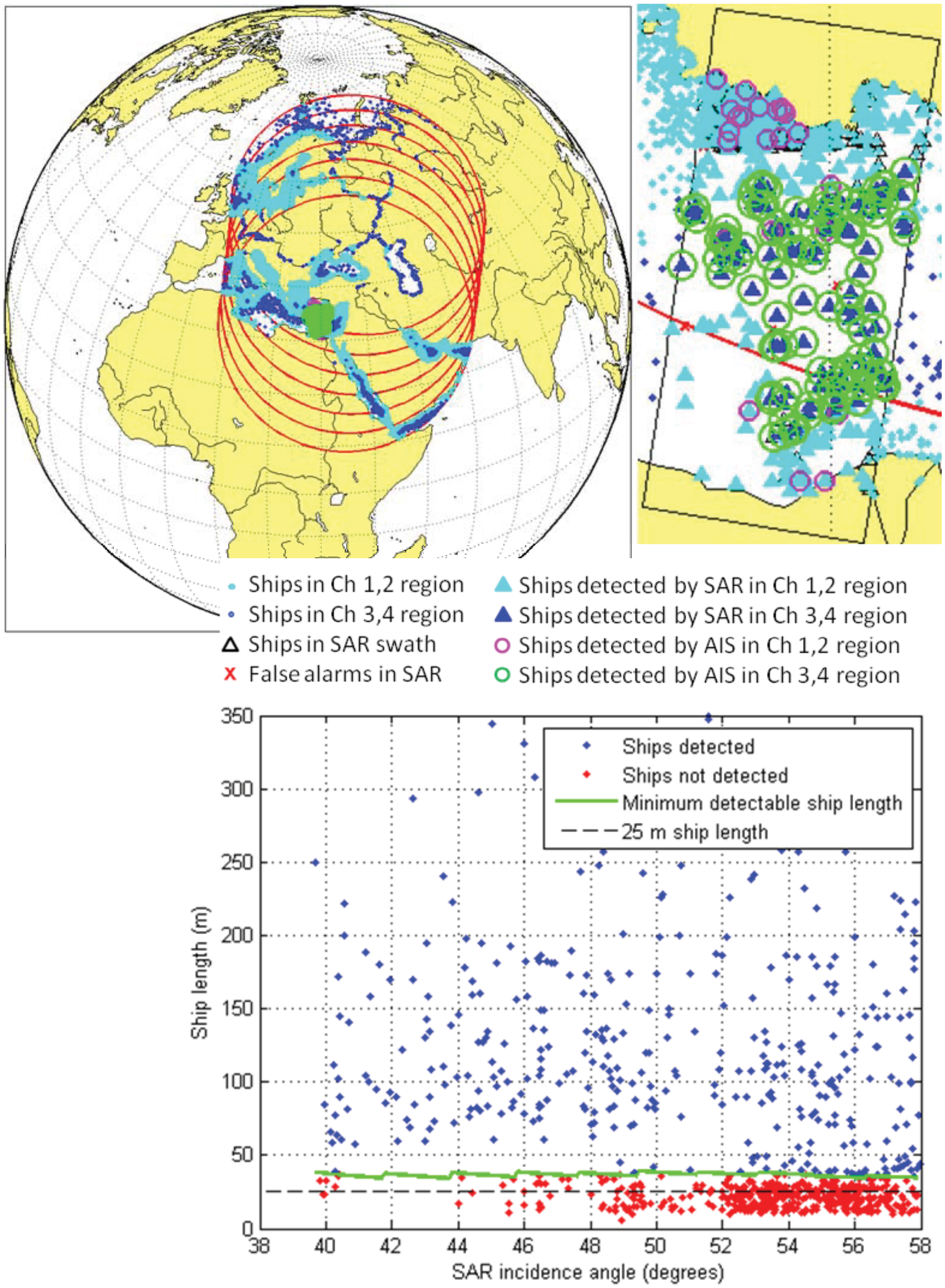


Figure 80: Example of descending RCM output for the Mediterranean (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

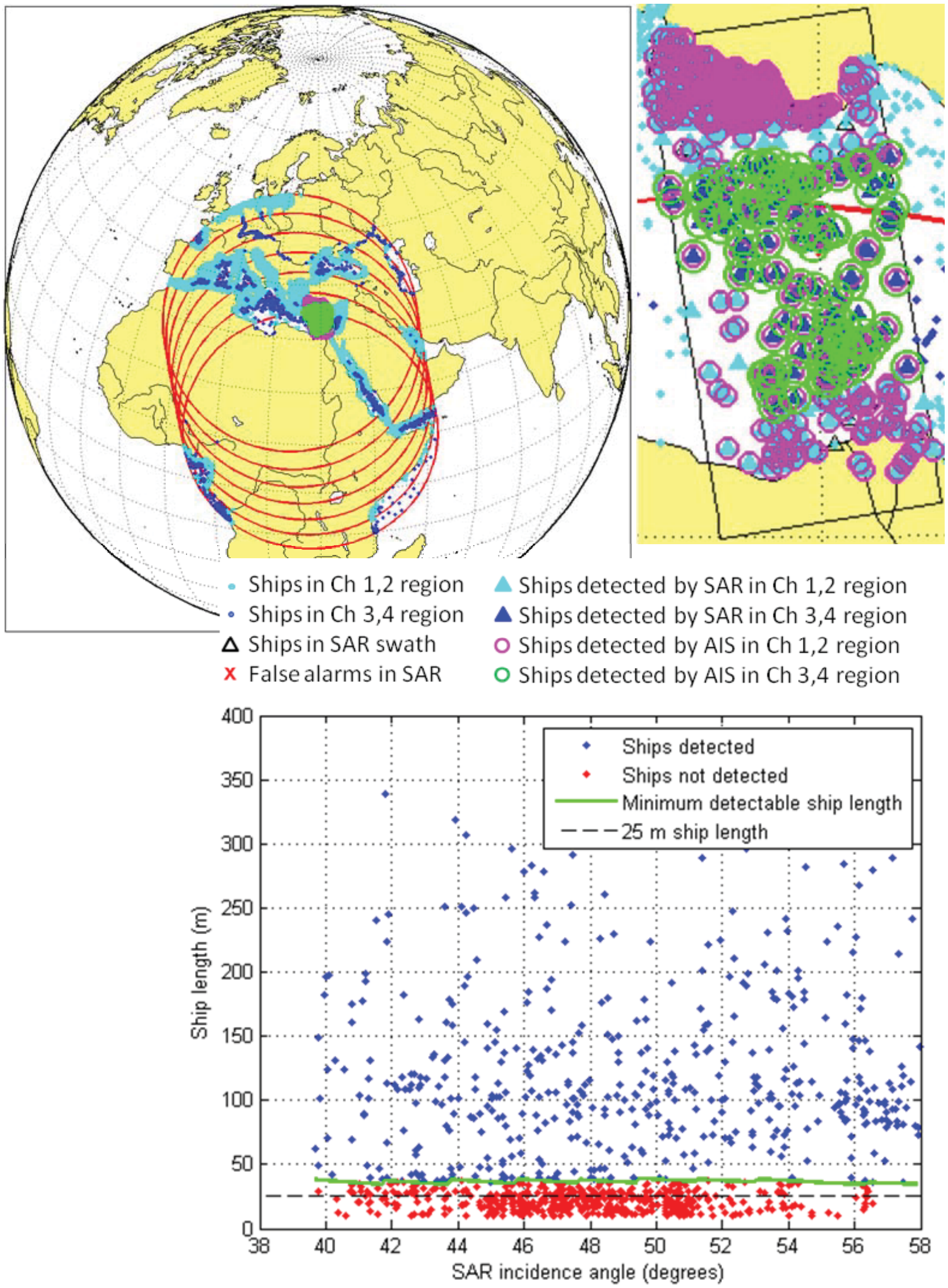


Figure 81: Example of ascending RCM output for the Mediterranean (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

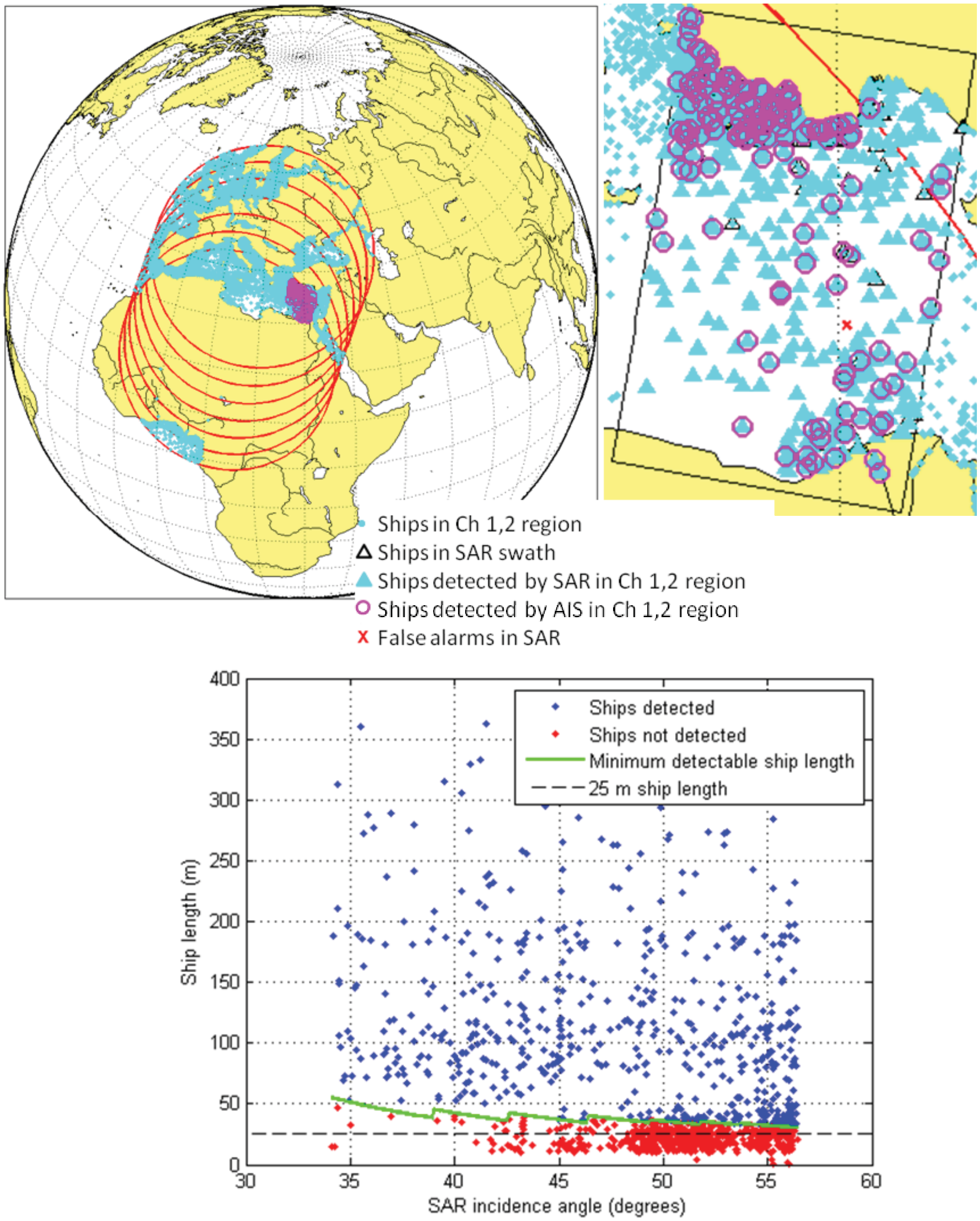


Figure 82: Example of RSAT2 orbit 1 output for the Mediterranean (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

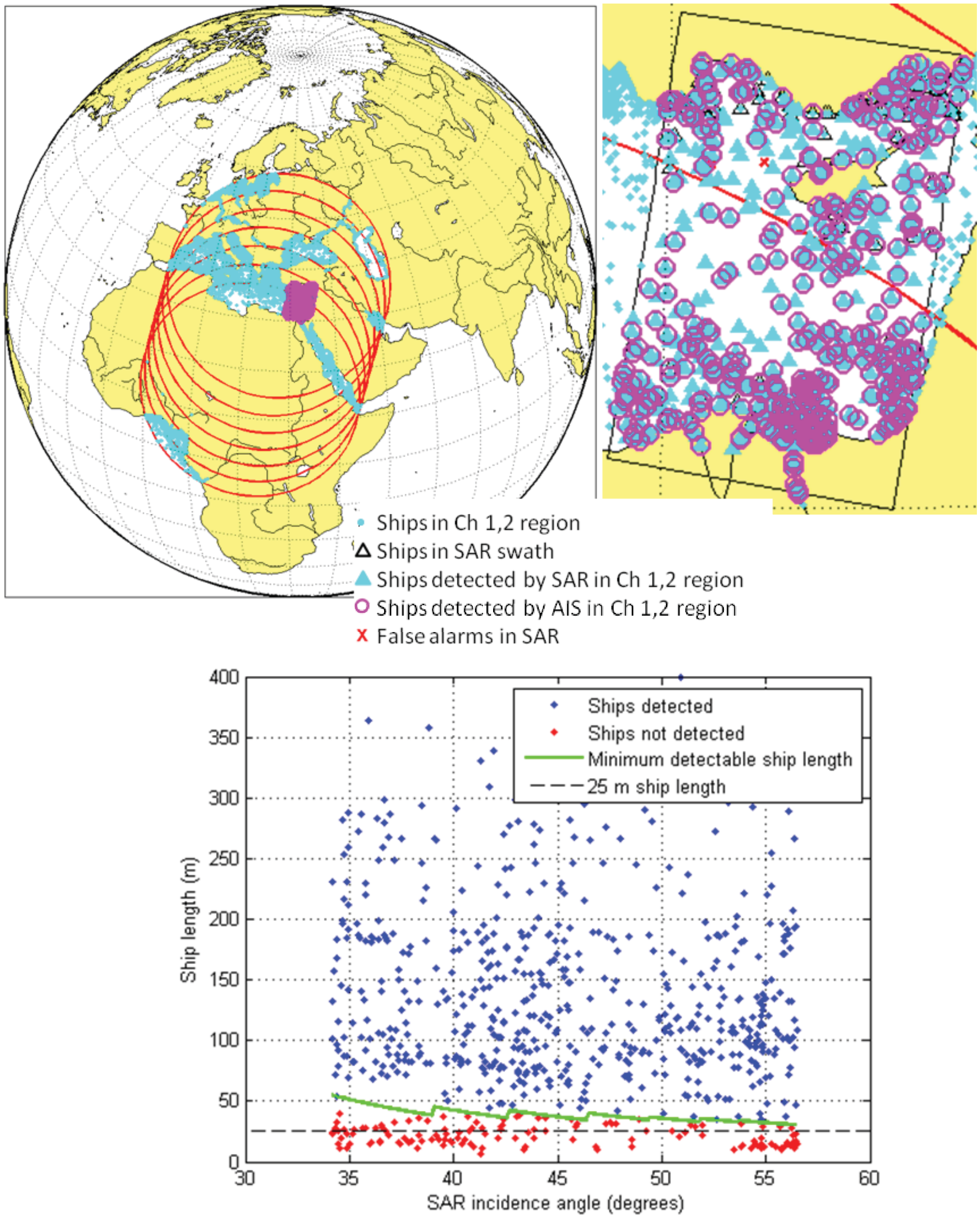


Figure 83: Example of RSAT2 orbit 2 output for the Mediterranean (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

6.2.9 North Sea

The North Sea represents areas of high ship density in both the AIS FOV and the SAR footprint. Both the RCM descending and ascending passes cover most of Europe, with the descending case having the higher maximum number of ships in the AIS FOV steps and the ascending having a higher average number of ships in the FOV steps. The second RSAT2 case was able to cover significantly fewer ships than the first orbit geometry and is reflected in the POD.

An average of the ten output results from the RCM and RSAT2 cases are given in Table 36. Examples of the iterations are shown in Figure 84 and Figure 85 for the RCM orbits and Figure 86 and Figure 87 for the RSAT2 scenarios. The probability of AIS detection is zero for the ascending RCM Channels 1 and 2 case and the orbit 1 case of RSAT2 and EV1. The descending RCM Channel 1 and 2 case has a higher probability of AIS detection of 0.20, while the second orbit geometry of RSAT2 and EV1 has a much higher probability at 0.78. The RCM Channels 3 and 4 cases, with the reduced number of ships in the regions have high probabilities of AIS detection.

The high probabilities of SAR detection within both AIS Channels 1 and 2 and Channels 3 and 4 regions (higher for 3 and 4) are because the ships in this area are generally large. The probability of SAR detection for the descending RCM Channels 3 and 4 is lower than the Channels 1 and 2 case because of a proportionately higher number of smaller ships in the Channels 3 and 4 region.

Table 36: Average from 10 iterations of the North Sea scenario outputs.

Output	RCM				RSAT2 and EV1	
	Descending		Ascending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Mean ships in AIS FOV steps	18691.8	1405.9	25010.1	2210.9	25979.1	5204.4
Min. ships in AIS FOV steps	5878.0	526.4	23602.3	2046.6	23035.3	2987.3
Max. ships in AIS FOV steps	28572.0	2174.4	26001.3	2308.8	27870.7	6442.7
Ships in SAR swath	777.8	11.3	458.3	31.1	1077.5	582.6
SAR POD (ships > 25 m)	0.87	0.77	0.86	0.87	0.81	0.85
AIS POD for ships in SAR swath	0.20	1.00	0.00	0.99	0.00	0.78
Probability of AIS given SAR detection for ships in SAR swath	0.20	1.00	0.00	0.99	0.00	0.77

Output	RCM				RSAT2 and EV1	
	Descending		Ascending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Probability of SAR AND AIS detection for ships in SAR swath	0.15	0.77	0.00	0.86	0.00	0.55
Probability of SAR OR AIS detection for ships in SAR swath	0.87	1.00	0.86	1.00	0.68	0.93
Number of ships in AIS FOV 5 minute overlap	9165.5	572.2	22068.3	1856.0	23571.1	2398.4
AIS POD in AIS FOV 5 minute overlap	0.16	1.00	0.00	0.99	0.00	0.73
AIS and SAR time difference (hours)	0.08	0.08	0.08	0.08	5.93	3.47
Probability of association for AIS and SAR	0.96	1.00	0.20	1.00	0.50	0.16

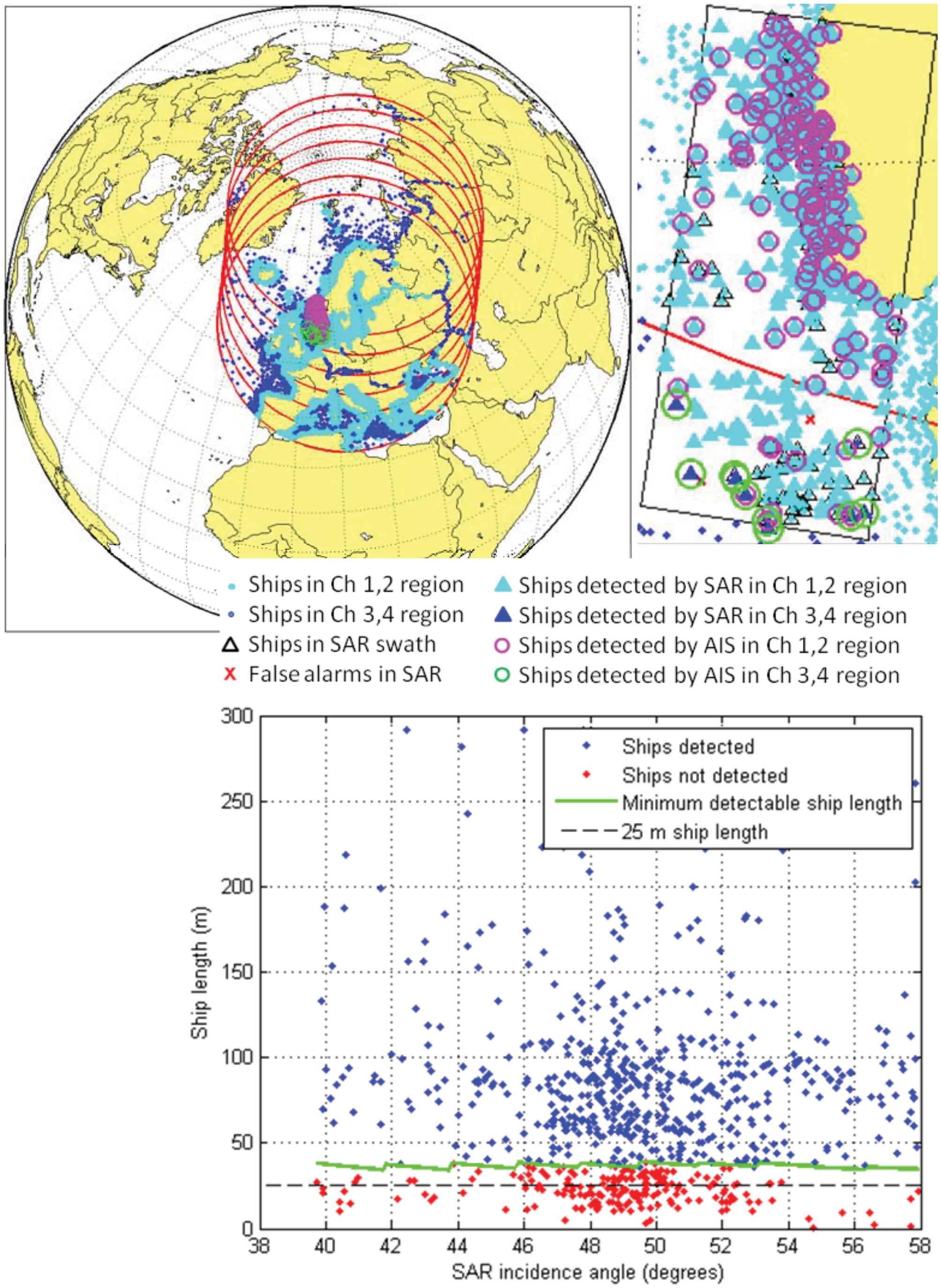


Figure 84: Example of descending RCM output for the North Sea (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

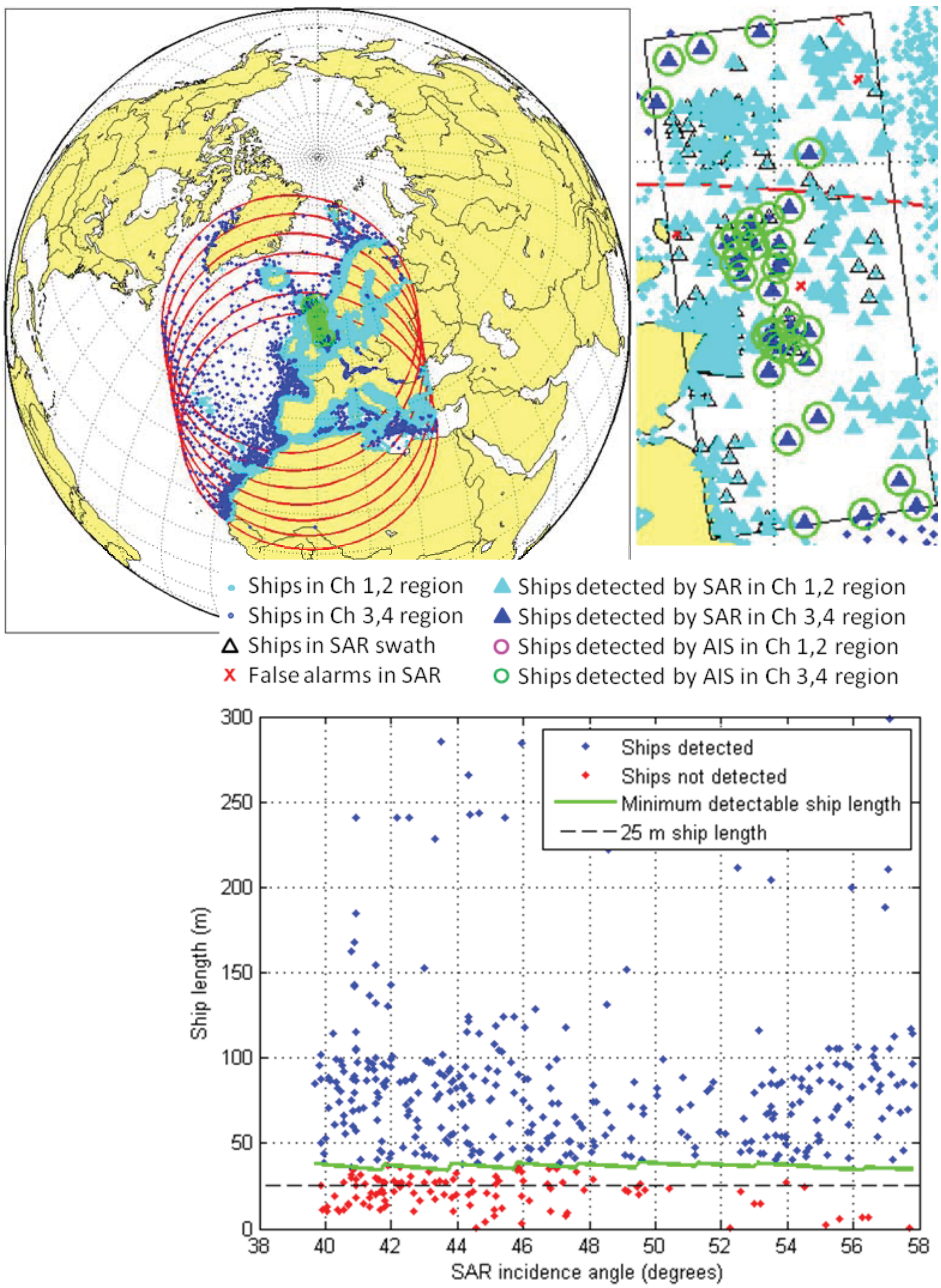


Figure 85: Example of ascending RCM output for the North Sea (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

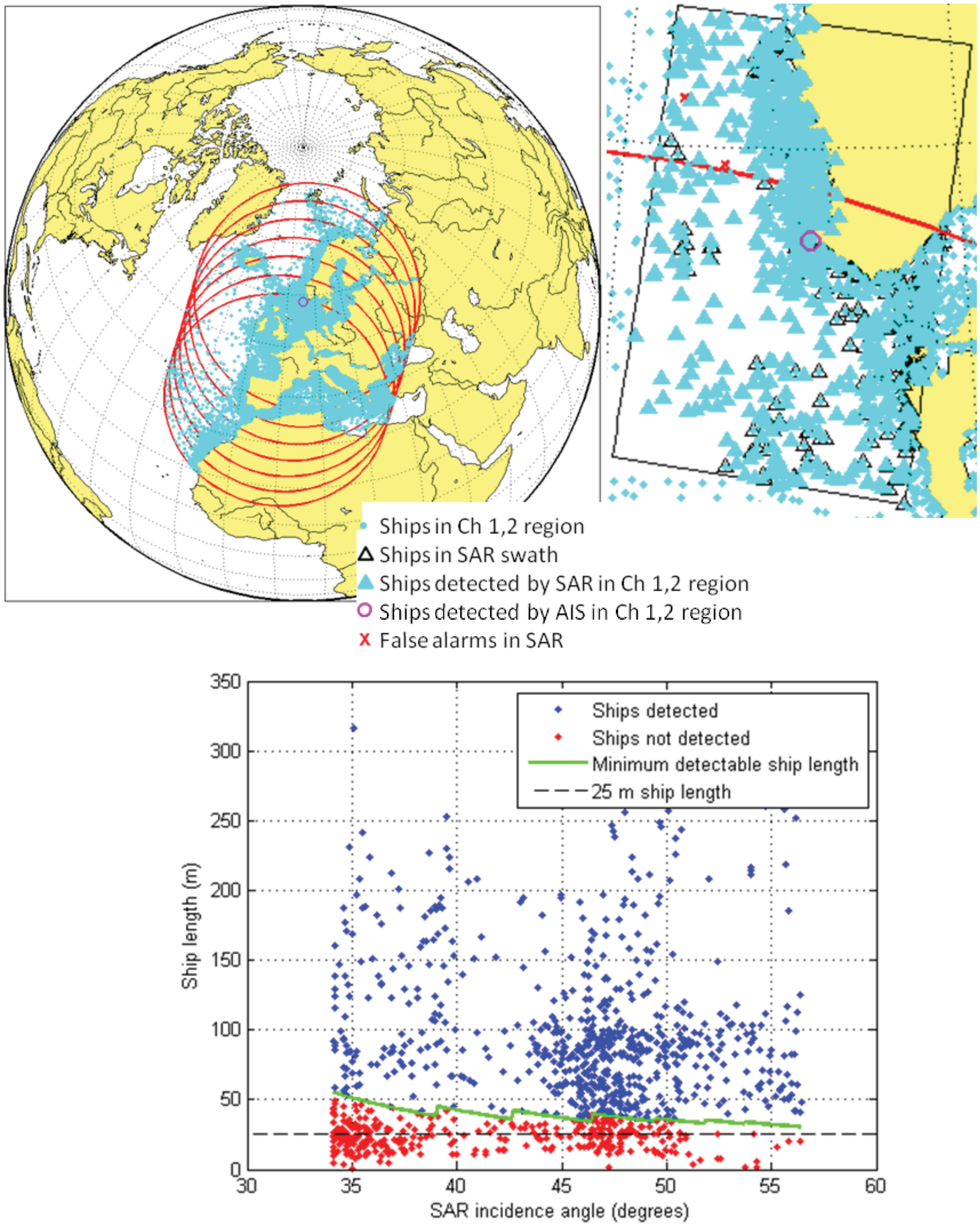


Figure 86: Example of RSAT2 orbit 1 output for the North Sea (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

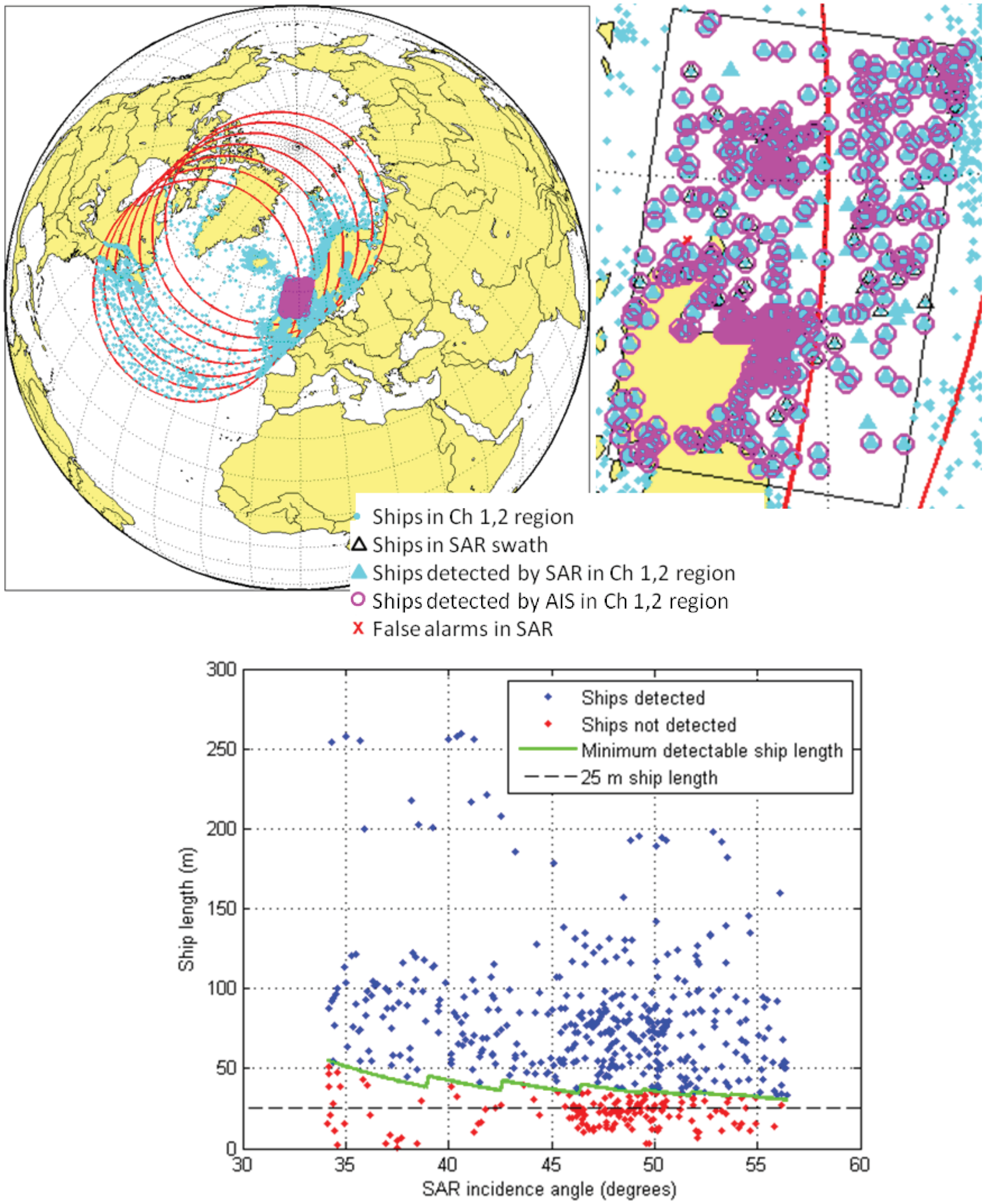


Figure 87: Example of RSAT2 orbit 2 orbit for the North Sea (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

6.2.10 Persian Gulf

The Persian Gulf scenarios represent areas of high ship density in the AIS FOV. The RCM ascending case covers more of the Mediterranean than the descending and has more ships overall in the AIS FOV steps. The second RSAT2 case covers an area slightly to the south and avoiding the ships in northern Europe.

Table 37 gives the average of the ten iterations for both RCM and RSAT2. Figure 88 and Figure 89 show examples of the outputs for RCM and Figure 90 and Figure 91 for RSAT2. The probability of AIS detections for both RCM and RSAT2 with EV1 Channels 1 and 2 results range between 0.49 and 0.7. The RCM Channels 3 and 4 cases have an AIS probability of detection for the SAR footprint of 1.

The probability of SAR detection within the Channels 1 and 2 regions are slightly higher than for the RCM Channels 3 and 4 regions. This is likely because the Channels 3 and 4 region contains proportionately more ships below the minimum detectable ship length than in the Channels 1 and 2 region. While this is as at first glance counter intuitive, a closer look at the Channels 3 and 4 exclusion zone shows only small pockets of the Gulf outside the exclusion zone. If the few ships in these pockets include a couple of small vessels, the SAR POD is impacted significantly.

Table 37: Average from 10 iterations of the Persian Gulf scenario outputs.

Output	RCM				RSAT2 and EV1	
	Ascending		Descending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Mean ships in AIS FOV steps	6715.7	1389.0	5932.4	1343.4	9698.4	7446.2
Min. ships in AIS FOV steps	4351.8	1174.0	4287.2	990.3	4628.2	4307.3
Max. ships in AIS FOV steps	10707.8	1716.5	6988.8	1657.6	12067.3	10541.0
Ships in SAR swath	1158.2	124.7	892.6	111.6	1180.2	1452.9
SAR POD (ships > 25 m)	0.87	0.76	0.88	0.78	0.87	0.87
AIS POD for ships in SAR swath	0.66	1.00	0.70	1.00	0.49	0.63
Probability of AIS given SAR detection for ships in SAR swath	0.66	1.00	0.70	1.00	0.49	0.63
Probability of SAR AND AIS detection for ships in SAR swath	0.53	0.76	0.58	0.78	0.40	0.51

Output	RCM				RSAT2 and EV1	
	Ascending		Descending		Orbit 1	Orbit 2
	Ch.1,2	Ch.3,4	Ch.1,2	Ch.3,4	Ch.1,2	Ch.1,2
Probability of SAR OR AIS detection for ships in SAR swath	0.93	1.00	0.94	1.00	0.91	0.93
Number of ships in AIS FOV 5 minute overlap	4639.7	972.5	4663.8	899.4	6969.0	4820.0
AIS POD in AIS FOV 5 minute overlap	0.68	1.00	0.71	1.00	0.40	0.65
AIS and SAR time difference (hours)	0.08	0.08	0.08	0.08	5.09	5.54
Probability of association for AIS and SAR	0.98	1.00	0.99	1.00	0.05	0.04

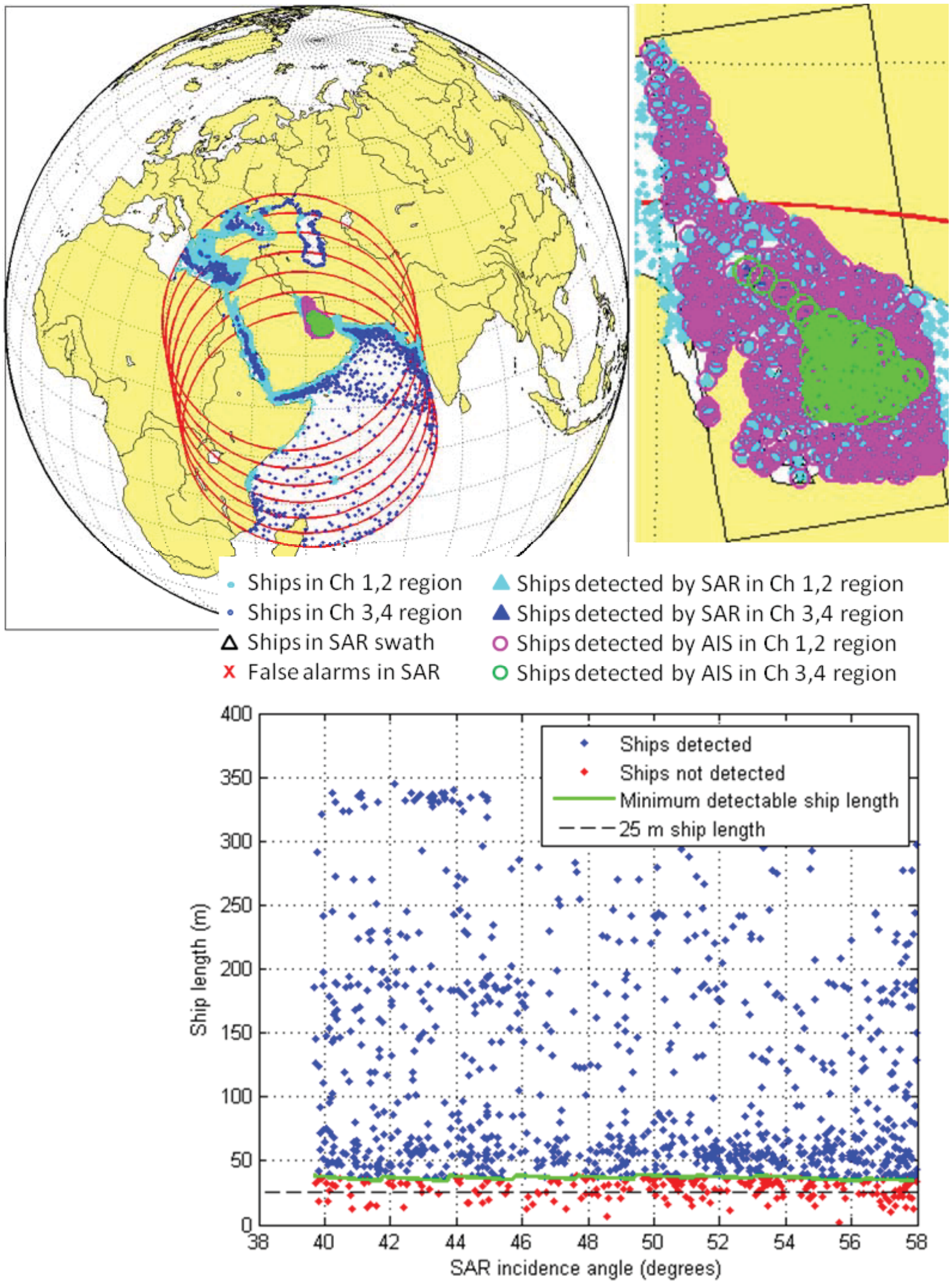


Figure 88: Example of ascending RCM output for the Persian Gulf (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

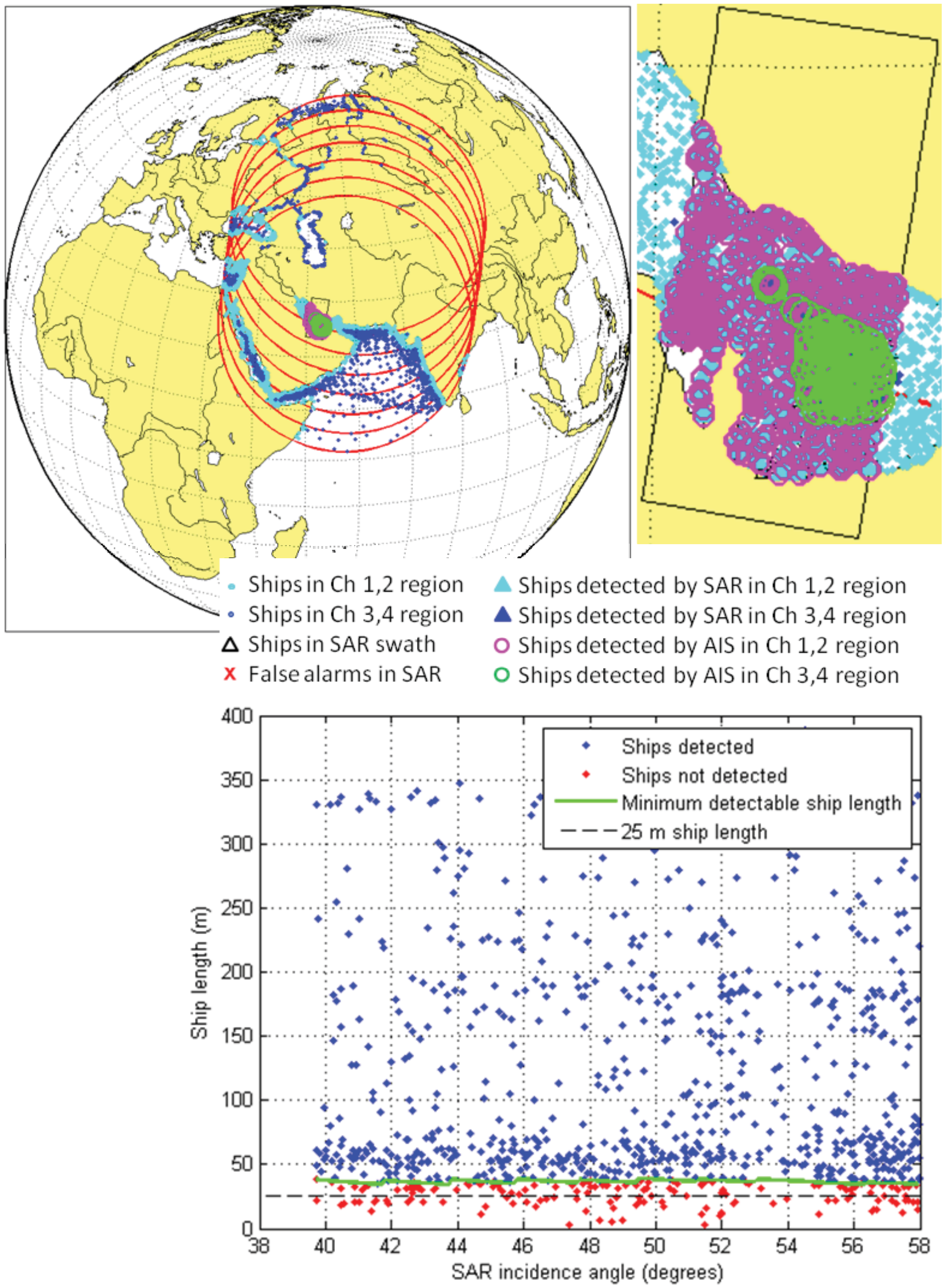


Figure 89: Example of descending RCM output for the Persian Gulf (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

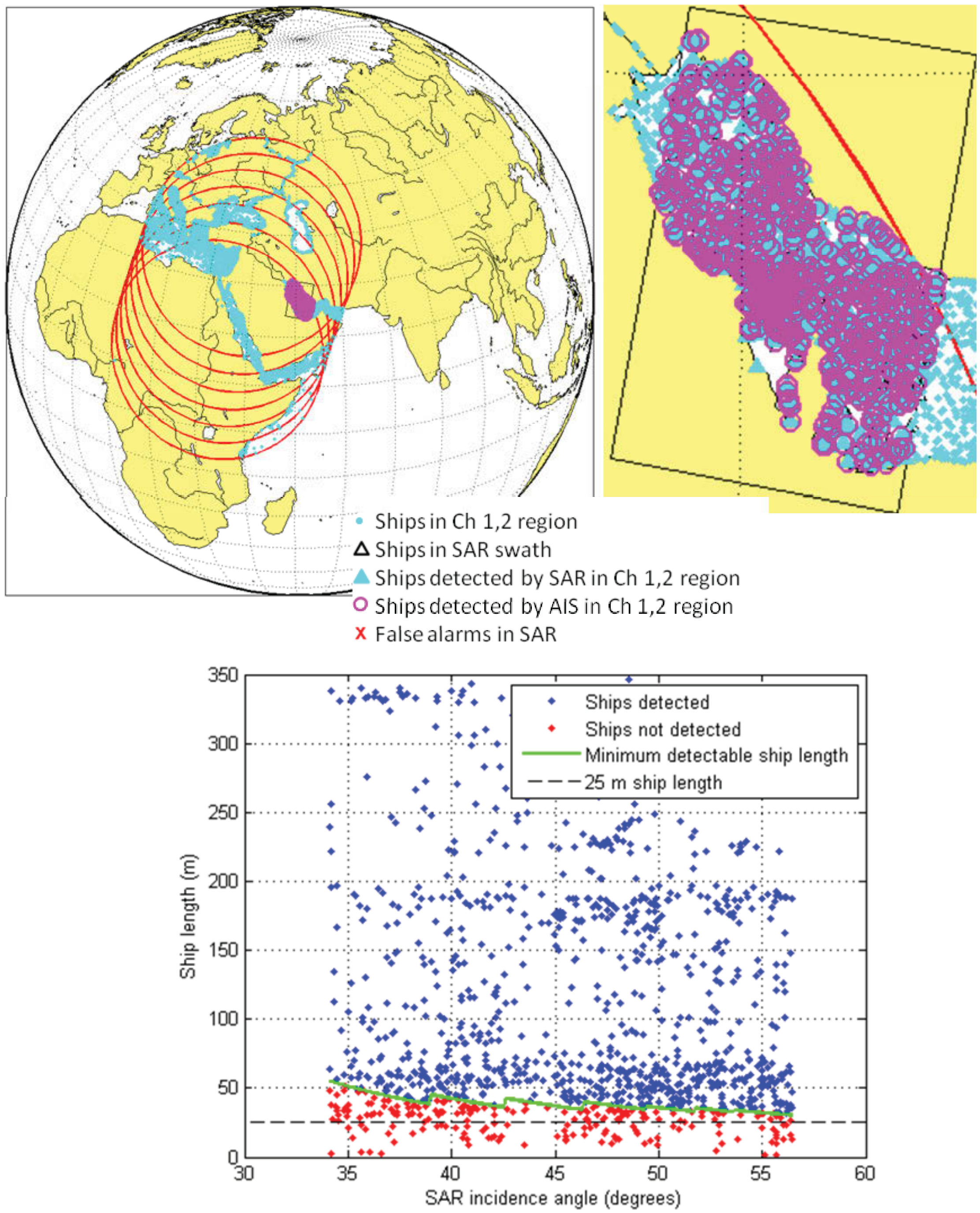


Figure 90: Example of RSAT2 orbit 1 output for the Persian Gulf (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

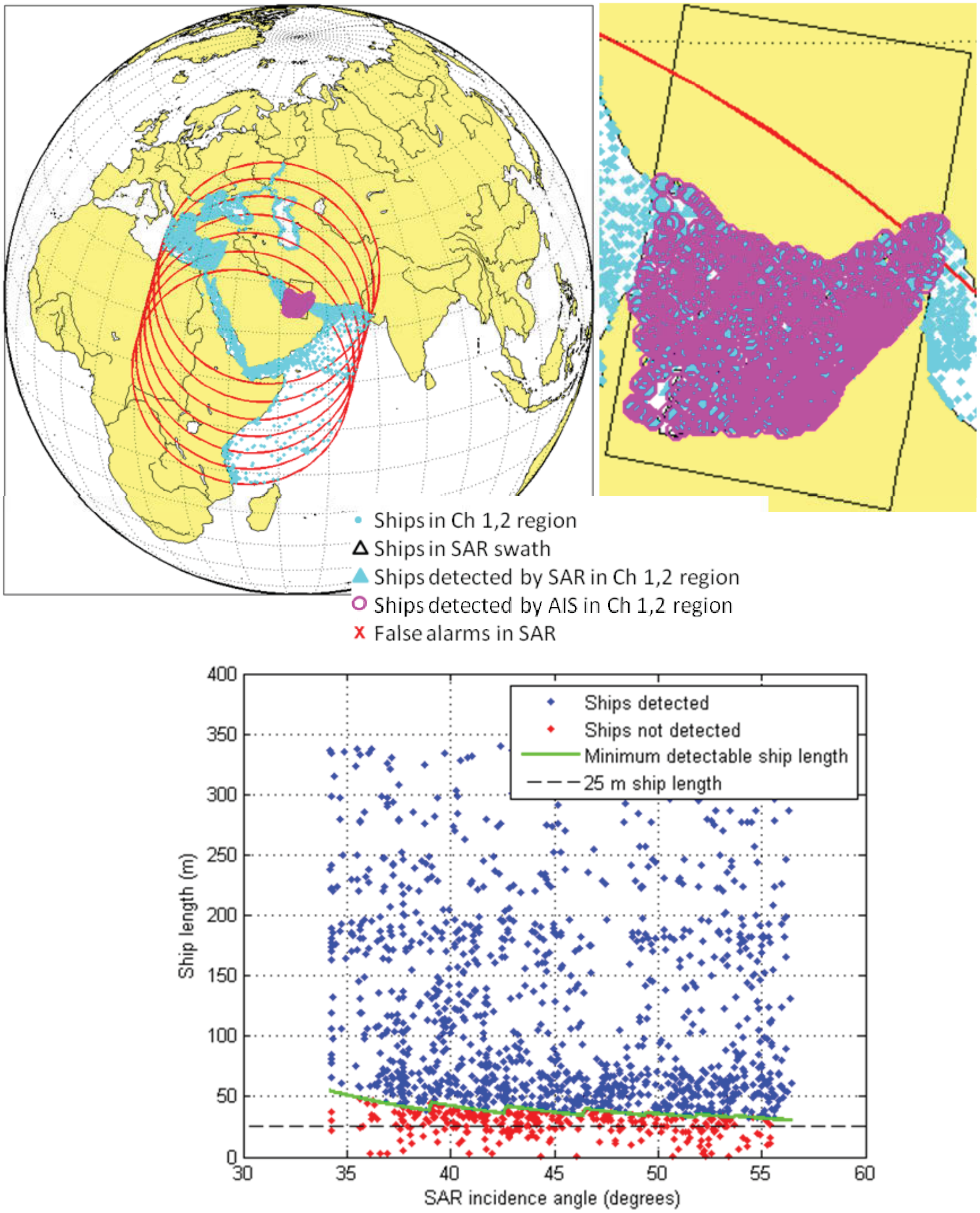


Figure 91: Example of RSAT2 orbit 2 orbit for the Persian Gulf (top left). The top right is a magnified view of the model output to show the SAR swath. The lower plot shows the length of the ships vs. SAR incidence angle.

6.2.11 Model Output Summary

The results obtained from the various scenarios run are summarized in Table 38 and Table 39 for RCM and Table 40 for RSAT2 and EV1.

Table 38: Summary of RCM results for AIS Channels 1 and 2.

	RCM Results for AIS Channels 1 and 2 (Decollider Receiver)									
		AIS Swath			SAR Swath				5 Minute Overlap	
Location	Time Diff (hrs)	Mean Ships	Min. Ships	Max. Ships	Num. Ships	Prob. SAR	Prob. AIS	Prob. Assoc.	Num. Ships	Prob. AIS
Canadian Arctic	0.08	2735.3	532.8	7035.9	1.0	1.00	0.90	0.90	343.4	0.98
	0.08	3289.7	1420.9	4486.4	1.8	1.00	1.00	1.00	2140.7	0.92
Canadian East Coast	0.08	3514.0	3001.1	5005.1	25.5	0.97	0.98	1.00	1123.7	0.92
	0.08	4791.9	4144.9	5197.0	56.6	0.85	0.81	1.00	3680.6	0.80
Canadian West Coast	0.08	3115.7	2686.5	3416.5	49.8	0.82	0.94	1.00	2461.6	0.92
	0.08	2090.5	673.3	2971.9	140.3	0.61	0.99	1.00	1590.9	0.98
Australia	0.08	1353.2	1221.2	1433.4	3.9	1.00	1.00	1.00	1073.4	0.99
	0.08	898.7	284.5	1358.4	4.0	1.00	1.00	1.00	622.5	0.99
English Channel	0.08	23368.0	13993.9	29761.3	1414.3	0.81	0.00	1.00	18584.6	0.01
	0.08	20124.3	9214.3	24392.8	958.9	0.75	0.04	0.99	16819.0	0.02
Horn of Africa	0.08	6022.4	5605.2	6315.3	89.2	0.98	0.70	1.00	5042.5	0.68
	0.08	2968.4	1576.3	5196.2	87.4	0.97	0.93	1.00	967.7	0.95
Japan	0.08	33790.4	28089.4	35473.9	3330.9	0.87	0.00	0.00	30688.8	0.00
	0.08	23985.7	11880.0	34305.9	3134.4	0.88	0.01	0.99	13542.7	0.02
Mediterranean	0.08	19092.7	12766.4	24101.6	815.5	0.72	0.03	1.00	9805.9	0.04
	0.08	9604.6	2833.2	21848.4	971.6	0.73	0.46	0.96	3611.3	0.56
Persian Gulf	0.08	6715.7	4351.8	10707.8	1158.2	0.87	0.66	0.98	4639.7	0.68
	0.08	5932.4	4287.2	6988.8	892.6	0.88	0.70	0.99	4663.8	0.71
North Sea	0.08	18691.8	5878.0	28572.0	777.8	0.87	0.20	0.96	9165.5	0.16
	0.08	25010.1	23602.3	26001.3	458.3	0.86	0.00	0.20	22068.3	0.00

Table 39: Summary of RCM results for AIS Channels 3 and 4.

	RCM Results for AIS Channels 3 and 4 (Basic Receiver)									
		AIS Swath			SAR Swath				5 Minute Overlap	
Location	**Time Diff (hrs)**	**Mean Ships**	**Min. Ships**	**Max. Ships**	**Num. Ships**	**Prob. SAR**	**Prob. AIS**	**Prob. Assoc.**	**Num. Ships**	**Prob. AIS**
Canadian Arctic	0.08	309.8	137.9	620.3	1.0	1.00	1.00	1.00	113.5	1.00
	0.08	462.6	359.8	533.1	1.8	1.00	1.00	1.00	283.5	1.00
Canadian East Coast	0.08	853.0	768.5	919.2	25.5	0.96	1.00	1.00	465.1	1.00
	0.08	1328.1	863.2	1613.5	56.6	0.91	1.00	1.00	837.3	1.00
Canadian West Coast	0.08	988.7	904.0	1046.1	49.8	0.97	1.00	1.00	729.7	1.00
	0.08	445.7	155.9	730.0	140.3	0.96	1.00	1.00	208.7	1.00
Australia	0.08	542.6	377.5	694.4	3.9	1.00	1.00	1.00	381.2	1.00
	0.08	211.0	51.6	409.3	4.0	1.00	1.00	1.00	93.5	1.00
English Channel	0.08	1743.8	698.3	2326.9	1414.3	0.82	1.00	1.00	1315.1	1.00
	0.08	2253.4	1738.8	2396.9	958.9	0.14	0.98	1.00	1991.7	0.99
Horn of Africa	0.08	1589.8	1346.5	1753.8	89.2	0.98	1.00	1.00	1146.9	1.00
	0.08	1012.6	786.7	1140.1	87.4	0.97	1.00	1.00	465.5	1.00
Japan	0.08	10647.1	9962.6	11291.6	3330.9	0.99	0.86	1.00	9304.4	0.85
	0.08	5202.0	2700.4	9880.5	3134.4	0.97	0.97	1.00	3515.6	0.97
Mediterranean	0.08	1954.7	1695.3	2087.1	815.5	0.96	1.00	0.98	1301.4	0.99
	0.08	977.5	689.0	1726.9	971.6	0.97	1.00	0.98	468.0	1.00
Persian Gulf	0.08	1389.0	1174.0	1716.5	1158.2	0.76	1.00	1.00	972.5	1.00
	0.08	1343.4	990.3	1657.6	892.6	0.78	1.00	1.00	899.4	1.00
North Sea	0.08	1405.9	526.4	2174.4	777.8	0.77	1.00	1.00	572.2	1.00
	0.08	2210.9	2046.6	2308.8	458.3	0.87	0.99	1.00	1856.0	0.99

Table 40: Summary of RSAT2 and EV1 results for AIS Channels 1 and 2.

	RSAT2 and EV1 Results for AIS Channels 1 and 2 (Basic Receiver)									
	AIS Swath				SAR Swath				5 Minute Overlap	
		Mean Ships	Min. Ships	Max. Ships	Ships	Prob. SAR (>25m)	Prob. AIS	Prob. Assoc.	Num Ships	Prob. AIS
Canadian Arctic	5.75	1799.6	680.2	3400.1	8.9	0.87	1.00	0.62	167.9	1.00
	5.78	361.6	287.4	423.4	2.8	0.95	1.00	0.94	119.7	1.00
Canadian East Coast	5.45	5974.6	2966.9	9207.5	105.0	0.93	0.91	0.36	3312.4	0.81
	5.91	3904.7	3002.5	4935.8	90.6	0.86	0.91	0.40	2882.8	0.88
Canadian West Coast	5.73	2927.2	2397.6	3245.1	118.5	0.68	0.93	0.36	2531.5	0.93
	4.15	1538.8	1346.1	1664.5	88.4	0.67	0.96	0.49	1329.8	0.98
Australia	4.89	1281.4	743.3	1807.6	6.3	1.00	1.00	1.00	893.1	0.98
	5.74	1247.8	822.6	1603.2	4.7	1.00	0.96	1.00	1004.7	0.99
English Channel	5.90	21424.4	8295.5	26862.5	6561.1	0.78	0.01	0.30	17035.2	0.03
	4.59	15136.3	5437.4	19559.9	1195.3	0.72	0.21	0.16	5937.9	0.14
Horn of Africa	5.16	4745.2	1165.6	9907.3	130.5	0.97	0.95	0.44	1040.3	0.94
	6.00	3257.9	1307.4	5400.9	71.2	0.98	0.95	0.46	929.0	0.94
Japan	5.93	33965.2	29987.8	34791.9	3406.6	0.89	0.00	0.00	33106.7	0.00
	5.83	31752.5	23463.3	33898.0	3541.6	0.87	0.00	0.20	32167.8	0.00
Mediterranean	5.21	18553.6	7006.4	28948.9	1138.0	0.76	0.13	0.25	8891.4	0.17
	5.66	9513.3	2923.9	21010.2	733.0	0.92	0.52	0.17	4613.4	0.51
Persian Gulf	5.09	9698.4	4628.2	12067.3	1180.2	0.87	0.49	0.05	6969.0	0.40
	5.54	7446.2	4307.3	10541.0	1452.9	0.87	0.63	0.04	4820.0	0.65
North Sea	5.93	25979.1	23035.3	27870.7	1077.5	0.81	0.00	0.50	23571.1	0.00
	3.47	5204.4	2987.3	6442.7	582.6	0.85	0.78	0.16	2398.4	0.73

6.3 RCM Constellation Scenarios

The results of the ten RCM constellation scenarios are shown in Sections 6.3.1 to 6.3.10. For each of these scenarios an overview of the AIS coverage and magnified view of the SAR footprint are shown in Figure 92 through Figure 101. A table showing the order of the RCM passes and the results are also presented in Table 41 to Table 50. The location of each scenario is similar, but not necessarily the same as was used in the previous RCM scenarios.

The order of the RCM passes are given in the tables and are colour coded as RCM1 as a red outline, RCM2 as a green outline and RCM3 as a blue outline. The colour of the SAR footprint also matches that of the third pass for each scenario. The AIS ship detections shown in the SAR footprint of each figure represents the AIS detected ships (from any pass) that is in the SAR footprint at the time of the third pass.

The tables list the time difference between each AIS pass and the SAR footprint, the probability of AIS detection of the current pass to the SAR footprint of the final pass, the cumulative probability of the AIS detection, and the probability of association between the current pass and the time of the SAR acquisition. The cumulative probability of AIS detection combines the ships detected in the previous passes by AIS with the ships detected by AIS in the final SAR footprint, and represents the performance increase by using the three RCM satellites as a constellation.

For the purposes of comparing the constellation results to a single satellite system, the third pass will be considered as the single satellite case. Therefore, the probability of AIS detection for the single satellite observation will be the last sensor pass of the fourth column of the output tables for each location. Similarly, the overall constellation probability of AIS detection will be the last sensor pass of the fifth column.

Only the results for AIS Channels 1 and 2 are shown as the probabilities for Channel 3 and 4 were always 100%, except for two of the Persian Gulf passes, where the probability of AIS detection was zero. The results of the ten scenarios are discussed in Section 6.3.11.

6.3.1 Canadian Arctic

The Canadian Arctic had probability of AIS detections of 100% for all passes, so the constellation provided no additional benefit over the single satellite case as all ships are detected. Due to the low number of ships in the SAR footprint, the probability of association for all passes was 100% for this scenario.

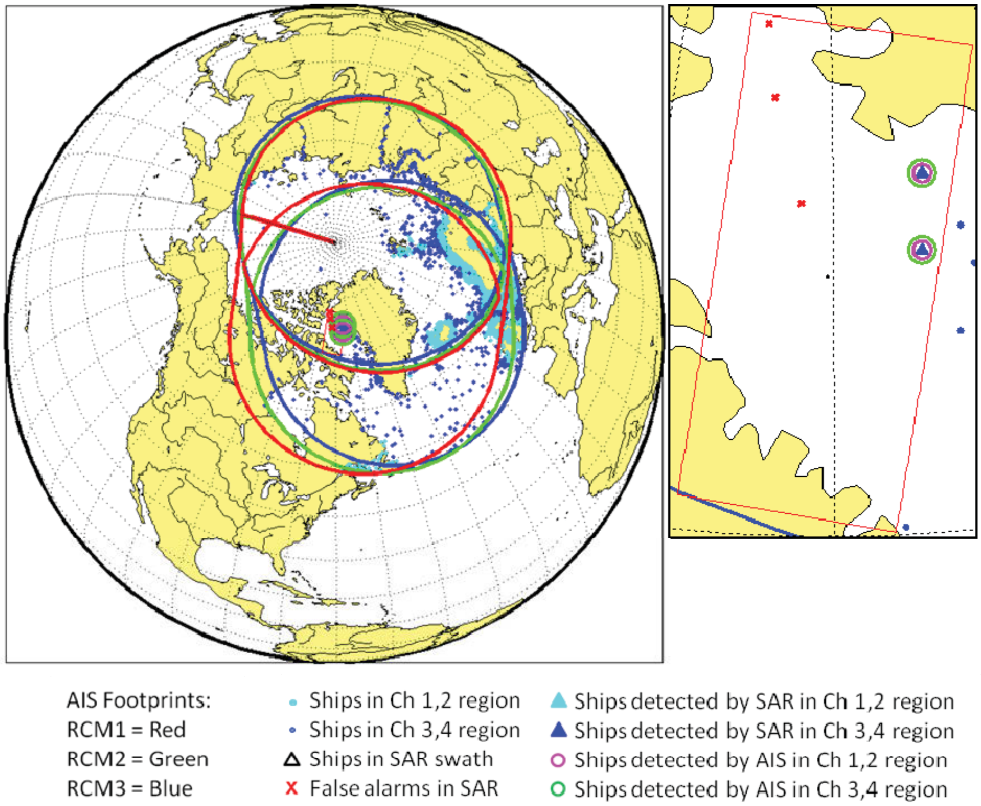


Figure 92: Canada Arctic RCM constellation scenario output

Table 41: Canada Arctic RCM constellation scenario results for Channel 1 and 2

Location	Sensor	Time Difference (minutes)	Prob. AIS Detection in SAR	Cumulative Prob. AIS Detection in SAR	Prob. of Association
Canada Arctic	RCM3	65	1.00	1.00	1.00
	RCM2	32	1.00	1.00	1.00
	RCM1	3	1.00	1.00	1.00

6.3.2 Canadian East Coast

The Canadian East Coast also had a high probability of detection in all three passes. The probability of association for the three passes was also 100%. Using the constellation for this location will provide a minimal performance improvement.

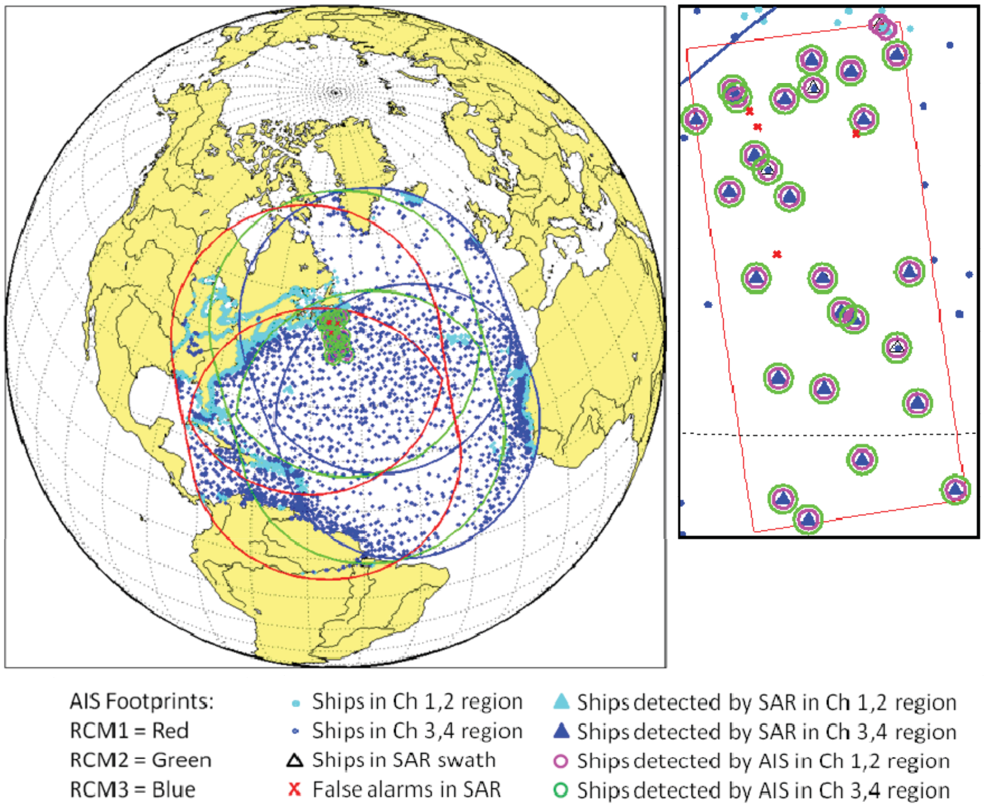


Figure 93: Canada East RCM constellation scenario output

Table 42: Canada East RCM constellation scenario results for Channel 1 and 2

Location	Sensor	Time Difference (minutes)	Prob. AIS Detection in SAR	Cumulative Prob. AIS Detection in SAR	Prob. of Association
Canada East	RCM3	57	0.93	0.93	1.00
	RCM2	32	1.00	1.00	1.00
	RCM1	3	0.96	1.00	1.00

6.3.3 Canadian West Coast

Due to the acquisition geometry, the AIS coverage over water increases for each pass of the Canadian West Coast scenario resulting in an increased number of vessels in the AIS FOV each time. Consequently, the probability of AIS detection decreased from 100% to 87%. Using the three sensors as a constellation increases the final probability of AIS detection to 96%. The probability of association starts at 89% for the first pass and increases to 100% due to the decreasing time difference and fewer ships detected in the SAR footprint by the AIS. Although 100% of the ships were detected in the first pass, the probability of association was only 89%. This results in a degradation of the overall performance because some of the detected ships cannot be reliably associated.

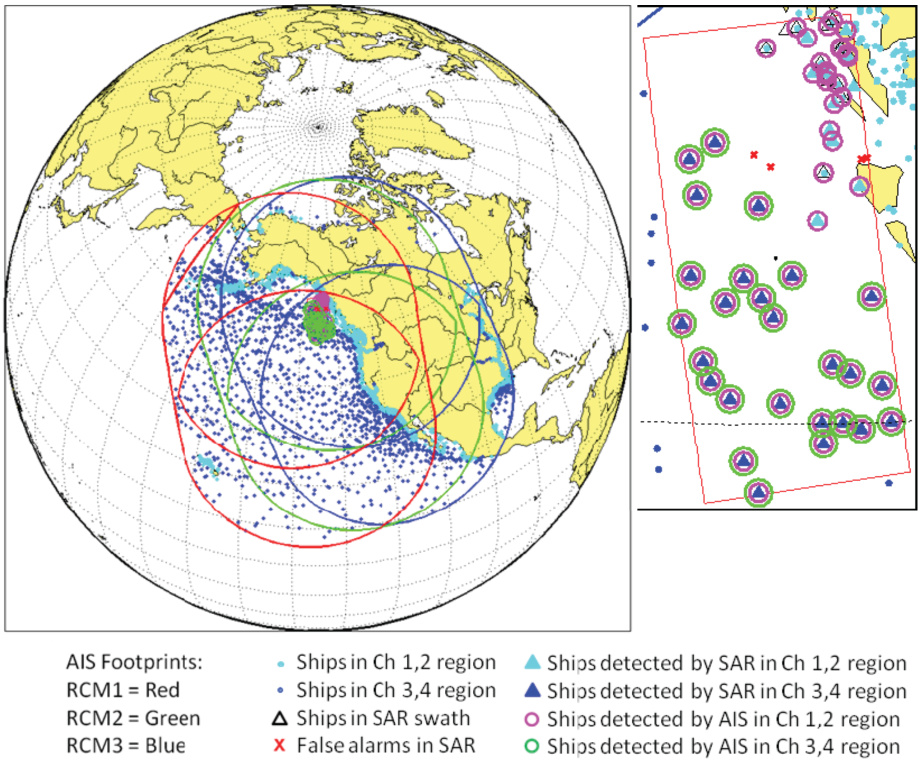


Figure 94: Canada West RCM constellation scenario output

Table 43: Canada West RCM constellation scenario results for Channel 1 and 2

Location	Sensor	Time Difference (minutes)	Prob. AIS Detection in SAR	Cumulative Prob. AIS Detection in SAR	Prob. of Association
Canada West	RCM3	67	1.00	1.00	0.89
	RCM2	32	0.96	0.98	0.96
	RCM1	3	0.87	0.96	1.00

6.3.4 Australia

The Australia scenario had probabilities of AIS detection of 100% for all passes so the constellation provided no additional benefit over the single satellite case as all ships are detected. The probability of association was 100% for all passes in this scenario.

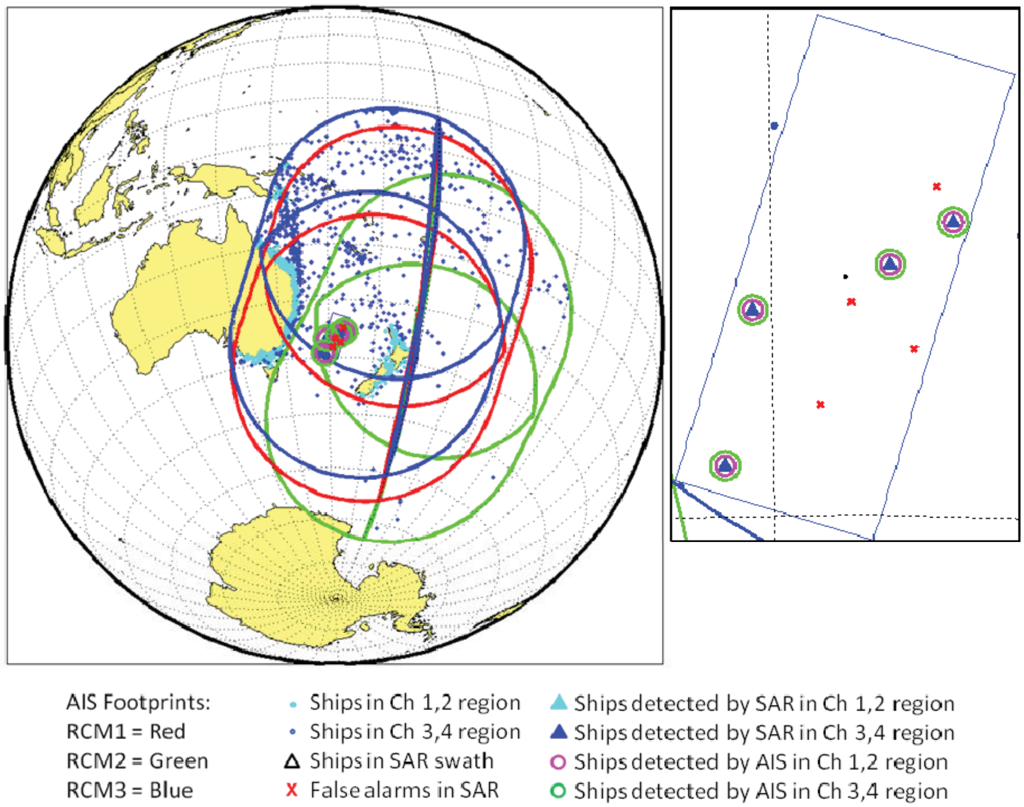


Figure 95: Australia RCM constellation scenario output

Table 44: Australia RCM constellation scenario results for Channel 1 and 2

Location	Sensor	Time Difference (minutes)	Prob. AIS Detection in SAR	Cumulative Prob. AIS Detection in SAR	Prob. of Association
Australia	RCM2	61	1.00	1.00	1.00
	RCM1	36	1.00	1.00	1.00
	RCM3	3	1.00	1.00	1.00

6.3.5 English Channel

The probability of AIS detection in the SAR footprint of the final pass is very low for all passes. The 0% detection probability for the first pass is due to rounding as the probability of association is 100% (the probability of association will be 0% when no ships are detected). The probabilities of association for the passes are high, but this is because very few ships are actually detected. Adding the constellation has a negligible improvement on the AIS detection performance for Channels 1 and 2.

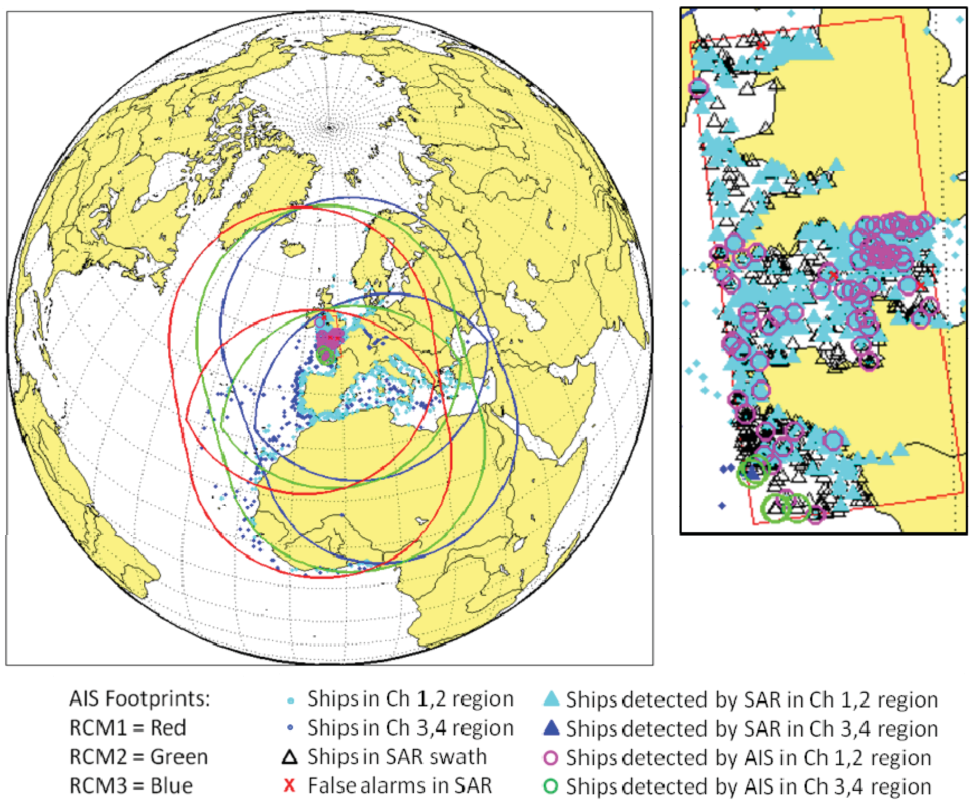


Figure 96: English Channel RCM constellation scenario output

Table 45: English Channel RCM constellation scenario results for Channel 1 and 2

Location	Sensor	Time Difference (minutes)	Prob. AIS Detection in SAR	Cumulative Prob. AIS Detection in SAR	Prob. of Association
English Channel	RCM3	49	0.00	0.00	1.00
	RCM2	32	0.02	0.02	1.00
	RCM1	3	0.06	0.07	0.98

6.3.6 Horn of Africa

The probability of AIS detection was improved for the Horn of Africa, from 88% to 99%, and the probabilities of association for the three passes are high. Using the constellation approach for this location would improve the AIS detection.

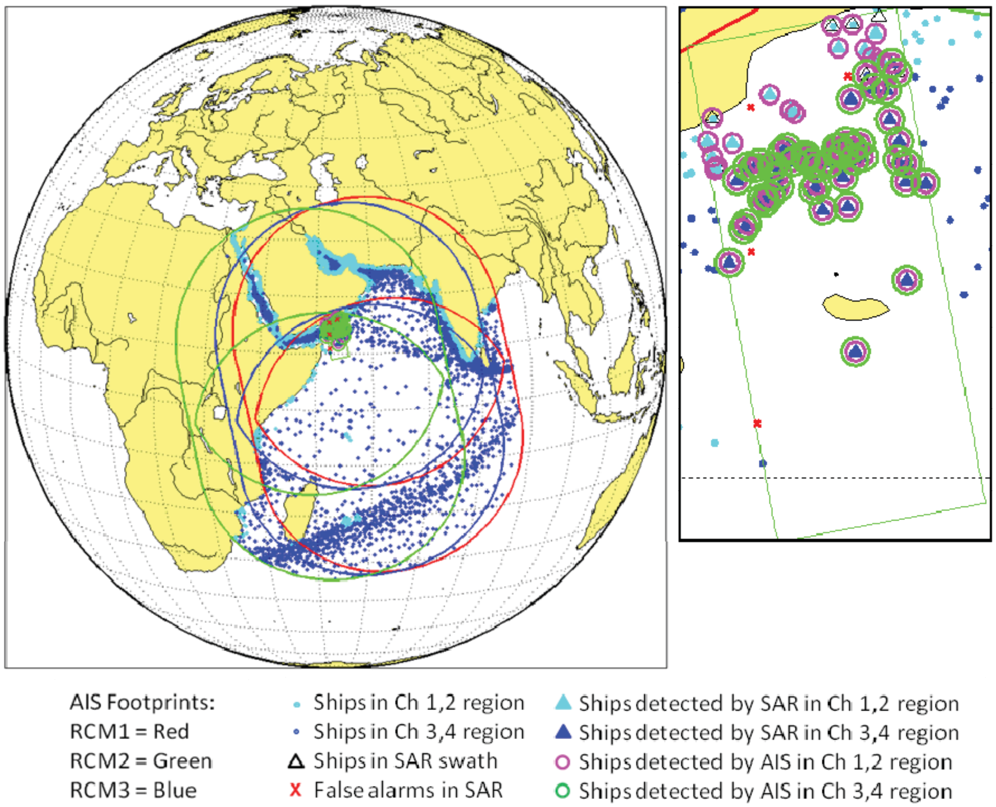


Figure 97: Horn of Africa RCM constellation scenario output

Table 46: Horn of Africa RCM constellation scenario results for Channel 1 and 2

Location	Sensor	Time Difference (minutes)	Prob. AIS Detection in SAR	Cumulative Prob. AIS Detection in SAR	Prob. of Association
Horn of Africa	RCM1	62	0.81	0.81	0.96
	RCM3	31	0.85	0.93	0.98
	RCM2	3	0.88	0.99	1.00

6.3.7 Japan

The probability of AIS detection for the Japan scenario decreases from 30% in the first pass to 0% in the third. Although the cumulative probability of AIS detection shows an improvement of 30% over the single satellite case, the inability to associate ships in the earlier passes to the final pass due to the time difference means that the constellation performance will be worse.

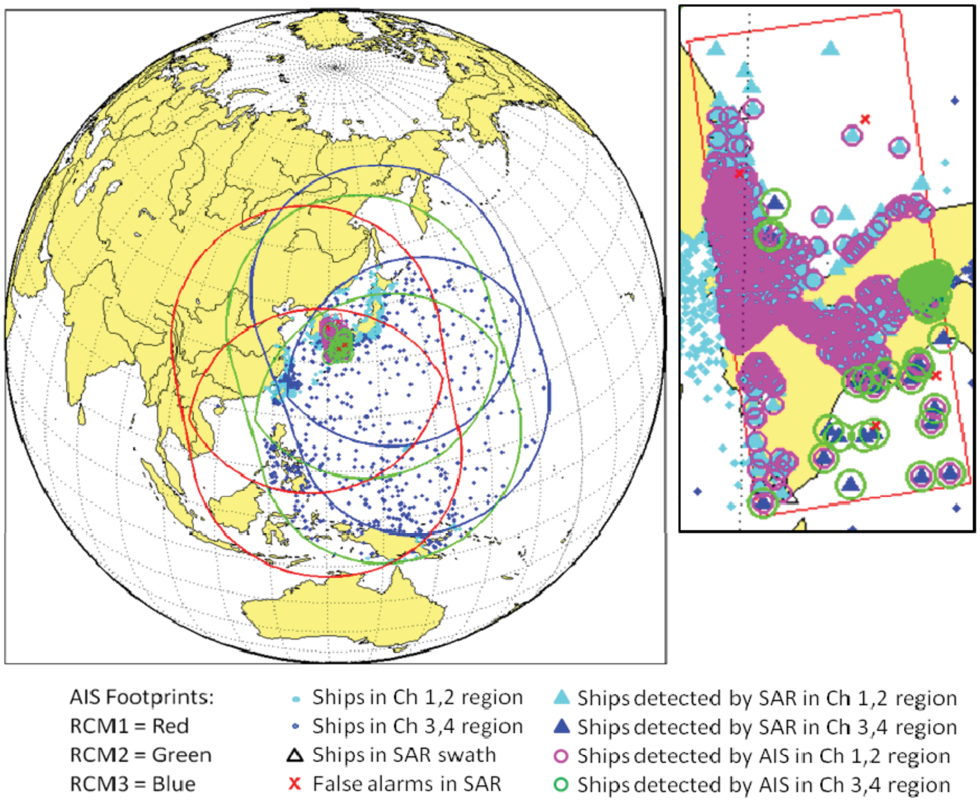


Figure 98: Japan RCM constellation scenario output

Table 47: Japan RCM constellation scenario results for Channel 1 and 2

Location	Sensor	Time Difference (minutes)	Prob. AIS Detection in SAR	Cumulative Prob. AIS Detection in SAR	Prob. of Association
Japan	RCM3	68	0.30	0.30	0.23
	RCM2	32	0.13	0.33	0.64
	RCM1	3	0.00	0.30	0.00

6.3.8 Mediterranean

The Mediterranean scenario shows a small improvement by using the constellation over a single satellite. However, due to the lower probability of association in the earlier passes, the actual performance benefit will be lower.

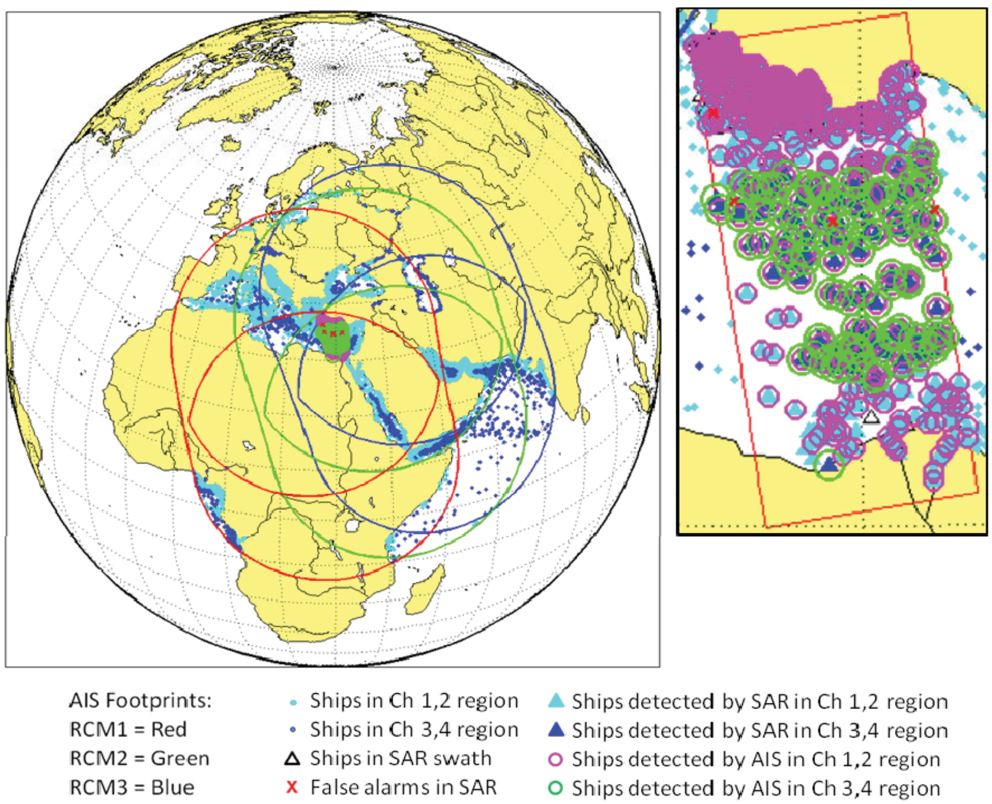


Figure 99: Mediterranean RCM constellation scenario output

Table 48: Mediterranean RCM constellation scenario results for Channel 1 and 2

Location	Sensor	Time Difference (minutes)	Prob. AIS Detection in SAR	Cumulative Prob. AIS Detection in SAR	Prob. of Association
Mediterranean	RCM3	77	0.25	0.25	0.58
	RCM2	32	0.25	0.34	0.85
	RCM1	3	0.36	0.44	0.95

6.3.9 Persian Gulf

The Persian Gulf constellation had about a 20% improvement in the AIS probability of detection over a single satellite (55% to 74%). As with the Mediterranean scenario, the probability of association is lower for the earlier passes, therefore, the constellation performance will be reduced because the ships cannot be correctly associated.

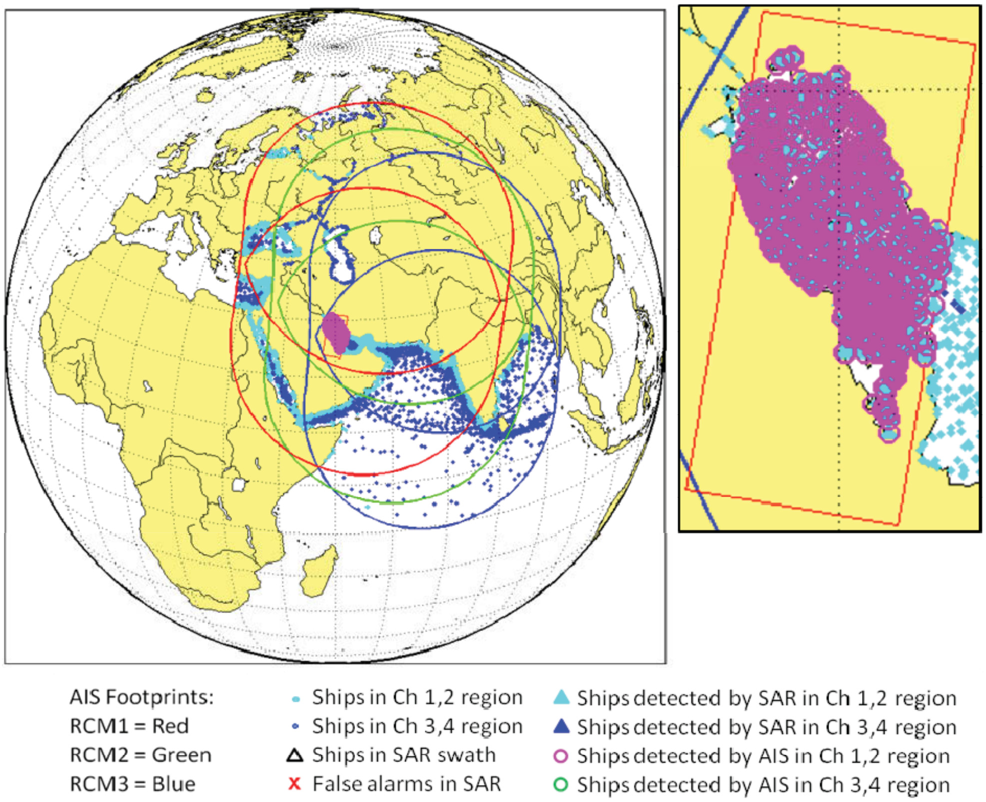


Figure 100: Persian Gulf RCM constellation scenario output

Table 49: Persian Gulf RCM constellation scenario results for Channel 1 and 2

Location	Sensor	Time Difference (minutes)	Prob. AIS Detection in SAR	Cumulative Prob. AIS Detection in SAR	Prob. of Association
Persian Gulf	RCM3	43	0.71	0.71	0.62
	RCM2	31	0.66	0.77	0.76
	RCM1	3	0.55	0.74	0.98

6.3.10 North Sea

The North Sea results are similar to the Persian Gulf case. The constellation provides approximately a 20% increase over the single satellite case, but because of the lower probability of associations in the earlier passes, the final performance will be somewhat lower.

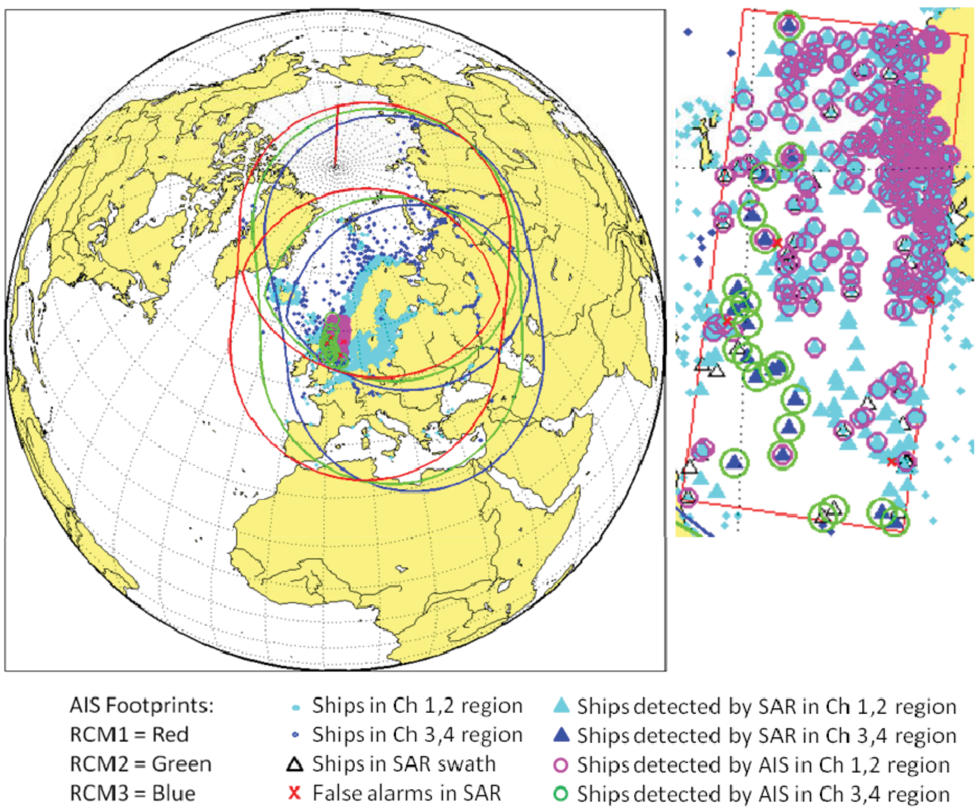


Figure 101: North Sea RCM constellation scenario output

Table 50: North Sea RCM constellation scenario results for Channel 1 and 2

Location	Sensor	Time Difference (minutes)	Prob. AIS Detection in SAR	Cumulative Prob. AIS Detection in SAR	Prob. of Association
North Sea	RCM3	54	0.17	0.17	0.71
	RCM2	31	0.24	0.34	0.76
	RCM1	3	0.24	0.44	0.98

6.3.11 RCM Constellation Output Summary

Table 51 and Table 52 summarize the results of the RCM Constellation scenarios for AIS Channels 1 and 2, and Channels 3 and 4, respectively. For the purposes of comparing the constellation results to a single satellite system, the third pass will be considered as the single satellite case. Therefore, the probability of AIS detection for the single satellite observation will be the last sensor pass of the fourth column for each location. Similarly, the overall constellation probability of AIS detection will be the last sensor pass of the fifth column.

Table 51: RCM constellation scenario summary for AIS Channels 1 and 2

Location	Sensor	Time Difference (minutes)	Prob. AIS Detection in SAR	Cumulative Prob. AIS Detection in SAR	Prob. of Association
Canada Arctic	RCM3	65	1.00	1.00	1.00
	RCM2	32	1.00	1.00	1.00
	RCM1	3	1.00	1.00	1.00
Canada East	RCM3	57	0.93	0.93	1.00
	RCM2	32	1.00	1.00	1.00
	RCM1	3	0.96	1.00	1.00
Canada West	RCM3	67	1.00	1.00	0.89
	RCM2	32	0.96	0.98	0.96
	RCM1	3	0.87	0.96	1.00
Australia	RCM2	61	1.00	1.00	1.00
	RCM1	36	1.00	1.00	1.00
	RCM3	3	1.00	1.00	1.00
English Channel	RCM3	49	0.00	0.00	1.00
	RCM2	32	0.02	0.02	1.00
	RCM1	3	0.06	0.07	0.98
Horn of Africa	RCM1	62	0.81	0.81	0.96
	RCM3	31	0.85	0.93	0.98
	RCM2	3	0.88	0.99	1.00
Japan	RCM3	68	0.30	0.30	0.23
	RCM2	32	0.13	0.33	0.64
	RCM1	3	0.00	0.30	0.00
Mediterranean	RCM3	77	0.25	0.25	0.58
	RCM2	32	0.25	0.34	0.85
	RCM1	3	0.36	0.44	0.95
Persian Gulf	RCM3	43	0.71	0.71	0.62
	RCM2	31	0.66	0.77	0.76

Location	Sensor	Time Difference (minutes)	Prob. AIS Detection in SAR	Cumulative Prob. AIS Detection in SAR	Prob. of Association
	RCM1	3	0.55	0.74	0.98
North Sea	RCM3	54	0.17	0.17	0.71
	RCM2	31	0.24	0.34	0.76
	RCM1	3	0.24	0.44	0.98

Table 52: RCM Constellation scenario summary for AIS Channels 3 and 4

Location	Sensor	Time Difference (minutes)	Prob. AIS Detection in SAR	Cumulative Prob. AIS Detection in SAR	Prob. of Association
Canada Arctic	RCM3	65	1.00	1.00	1.00
	RCM2	32	1.00	1.00	1.00
	RCM1	3	1.00	1.00	1.00
Canada East	RCM3	57	1.00	1.00	1.00
	RCM2	32	1.00	1.00	1.00
	RCM1	3	1.00	1.00	1.00
Canada West	RCM3	67	1.00	1.00	1.00
	RCM2	32	1.00	1.00	1.00
	RCM1	3	1.00	1.00	1.00
Australia	RCM2	61	1.00	1.00	1.00
	RCM1	36	1.00	1.00	1.00
	RCM3	3	1.00	1.00	1.00
English Channel	RCM3	49	1.00	1.00	1.00
	RCM2	32	1.00	1.00	1.00
	RCM1	3	1.00	1.00	1.00
Horn of Africa	RCM1	62	1.00	1.00	0.96
	RCM3	31	1.00	1.00	0.98
	RCM2	3	1.00	1.00	1.00
Japan	RCM3	68	1.00	1.00	0.36
	RCM2	32	1.00	1.00	0.50
	RCM1	3	1.00	1.00	0.83
Mediterranean	RCM3	77	1.00	1.00	0.93
	RCM2	32	1.00	1.00	0.99
	RCM1	3	1.00	1.00	1.00
Persian Gulf	RCM3	43	1.00	1.00	1.00
	RCM2	31	0.00	0.00	0.00

Location	Sensor	Time Difference (minutes)	Prob. AIS Detection in SAR	Cumulative Prob. AIS Detection in SAR	Prob. of Association
	RCM1	3	0.00	0.00	0.00
North Sea	RCM3	54	1.00	1.00	1.00
	RCM2	31	1.00	1.00	1.00
	RCM1	3	1.00	1.00	1.00

6.4 Analysis

6.4.1 AIS Channels 1 and 2

One of the most interesting aspects of this work is the sheer volume of messages being transmitted by the large number of ships in the AIS FOV. Even in the more sparse shipping areas near the poles and in the large open ocean areas, the FOV of the AIS sensors is sufficiently large such that large numbers of ships are visible. The AIS receiver performance specification for RCM states that a 90% POD must be achieved when there are 2,200 ships in the FOV for five minutes. Based on the GSDM developed and simulation results, it is readily apparent that the number of ships in the FOV for most areas is greater than 2,200 and in many cases much greater. The scenario cases presented focus on AOIs of interest to DND/CF and represent areas of varying ship densities considered as low, moderate or high.

The initial AIS sensor model implementation was based on the RCM AIS receiver performance specifications and the resulting PODs calculated were very low. This is not surprising given the large number of vessels in the AIS FOV, typically much greater than 2,200. These results were not in alignment with expected performance, but were used as the basis for analysis in the absence of any receiver performance specifications.

A subsequent model implementation was later introduced based on better receiver performance modelling as run by DRDC using the COM DEV simulator and eE decollider. Details on this implementation are discussed in Section 4.

Model and simulation results using the decollider implementation produced improved results. In low and moderate density AOIs, POD was typically very good. Low density areas in the Canadian Arctic and Australia resulted in POD values well over 90% and in many cases, nearly 100%. Similarly, moderate density AOIs showed excellent AIS POD with values around 90%, except in a couple of cases where significantly higher numbers of ships in the FOV resulted in lower values. In these cases, the number of ships in the FOV reached as high as 6,300. For the most part, high density AOIs showed very low AIS POD due to the very high numbers of ships in the FOV. In these cases, POD can be expected to be less than 20% with many results much less than that. In the highest density locations, the number of ships in the FOV can exceed 35,000 with a resultant POD of effectively 0%.

The model runs show that the extent of the AIS FOV can heavily influence the number of ships visible even in areas considered to have low to moderate ship density. This is further discussed in the following subsections.

6.4.1.1 FOV and Acquisition Geometry

The ascending and descending scenarios shown in the previous section covers a large geographic variation in ship density. One of the most interesting results demonstrated by the scenarios depicted is the significant impact that slight differences in orbit geometries can have on detection performance. Taking the West Coast Canada scenario as an example, several interesting observations can be made. As previously discussed, the AIS POD is very sensitive to the number of ships in the AIS FOV. Given the large coverage extents of this FOV, in almost all scenarios, the number of ships visible to the AIS receiver is impacted by a high density area well removed from the local area of interest. The only scenario which did not show this impact was the Australian scenario. As the footprint coverage for RCM covers such a large area, the overall number of ships in the FOV can become very large, completely swamping the receiver resulting in negligible PODs. This is readily demonstrated in the East Coast Canada scenario where the ship density is considered moderate, but the AIS are seeing ships on the European West Coast and into the Gulf of Mexico during the acquisition period. This results in a high number of visible ships leading to lower AIS POD.

Acquisition geometry can also play a role in SAR POD. Using the West Coast Canada example once again, the number of ships inside the SAR swath doubled in the descending pass compared to the ascending pass (see Table 31). Taking a closer look at the swaths (see Figure 64 and Figure 65), the general areas covered are similar; however, the key difference is that the descending SAR swath covers more of the coastline. This results in a greater number of ships in the SAR swath and a greater overall number of smaller ships below the SAR detection threshold. This is also seen in the English Channel and North Sea scenarios, albeit to a lesser degree.

6.4.1.2 Canadian AOIs

A closer look at the Canadian AOIs shows that acquisition geometry can make a significant difference to AIS POD for the west coast, as previously discussed. The Arctic and east coast situations are more challenging. Although the Arctic has a very low ship density over a large geographical area, the polar orbit combined with the large AIS FOV usually results in a large number of ships with contributions to ship count from the east and west coasts of North America and Europe. The east coast scenario offers a little better situation for adjusting the acquisition geometry, and AIS PODs may be somewhat improved here.

6.4.2 AIS Receiver Model

As described in Section 4.2.6, the capability of the AIS receiver is modelled using a number of implementations to account for different types of receiver performance. Using the RCM ascending Horn of Africa scenario as an example, the difference in POD detection from the basic receiver model, enhanced receiver model and decollider model is demonstrated with the output results summarized in Table 53. The three cases are run with the same orbit geometry and the resulting number of ships in the FOV for each time step is similar. The POD calculated for the basic receiver in this case is 1%, while the performance of the enhanced receiver is 67% and the decollider result is 91%.

Table 53: Comparison of basic and enhanced receiver POD using the RCM ascending Horn of Africa scenario.

AIS Time Step	Number of Ships in FOV		
	Basic	Enhanced	Decollider
1	1572	1589	1552
2	1730	1731	1705
3	1675	1677	1676
4	1658	1654	1637
5	4183	4149	4138
6	4839	4791	4754
7	5256	5199	5163
AIS POD	**Basic**	**Enhanced**	**Decollider**
	1%	67%	91%

The decollider model implementation shows a sharp roll-off as the number of ships increases, as shown in Figure 50. This characteristic explains why in many of the scenario runs, the AIS POD drops off when the number of ships in the FOV reaches the roll-off point. Looking at the Horn of Africa case this effect can be easily seen as shown in Table 54. This shows two model runs with two different orbit geometries, one descending (Case 1) and one ascending (Case 2) resulting in differences in the number of ships in the FOV. The corresponding PODs in these two cases are significantly different with a POD of 68% for Case 1 and 95% for Case 2.

Table 54: Horn of Africa ships in the FOV by time step for ascending and descending satellite passes.

AIS Time Step	Number of Ships in the FOV	
	Case 1	Case 2
1	5608	1565
2	6182	1737

	Number of Ships in the FOV	
3	6325	1681
4	6138	1643
5	6165	4161
6	5967	4808
7	5888	5226

6.4.3 AIS Channels 3 and 4

The use of AIS Channels 3 and 4 consistently shows excellent performance for all scenarios run. Given that the proposed operating scheme for these channels is to have messages transmitted on these channels only when a vessel is beyond the range of an AIS base station, the number of ships expected in the AIS FOV is greatly reduced. The greatest areas of ship density shown by the GSDM are typically in coastal regions near major port facilities or in restricted navigational areas. This distribution of ships places a much higher number near shore within the range of coastal stations. Using the English Channel scenario case as an example, the number of ships in the AIS FOV for Channels 1 and 2 is significantly higher than the corresponding numbers in the FOV for Channels 3 and 4. The number ranges from 29,761 to 13,994 and 2,327 to 698, respectively. Not surprisingly, the AIS POD for Channels 1 and 2 is nil, while the POD for Channels 3 and 4 is near 100%. This high POD is achieved with just a basic receiver model. This result is repeated for all scenarios.

6.4.4 SAR Performance

SAR detection performance has been included in the simulation using the DRDC Ottawa ship detectability code. Results from the simulation are provided for all scenarios. SAR POD is based only on ships greater than 25 m in length as per the RCM requirement. The simulation output figures for SAR detection show all ships generated from the GSDM that fall within the SAR swath. As ship lengths are derived from the length distributions in the AIS database on a per degree cell basis, the number of small ships tends to be higher near the coast and is reduced farther from shore. As a result, SAR swaths near shore may contain a large number of small ships, many below 25 m in length. To avoid any bias in SAR POD results, only vessels greater than 25 m are considered in the calculation, reflective of the RCM specification for SAR ship detection. It should be noted that in the scenario cases run, near worst case SAR sensor parameters and environmental conditions were used, effectively raising the detection threshold. SAR POD results under these conditions were found to be very good.

6.4.5 RCM AIS Constellation Performance

The performance of the RCM constellation scenarios for AIS Channels 1 and 2 were found to be higher than those of a single satellite scenario for some locations, while in other locations the constellation offered minimal or no benefit. For Channels 3 and 4, the probability of any single pass was 100% and the additional constellation passes offer no detection improvement. The exception to this is two of the Persian Gulf passes which had a Channel 3 and 4 AIS POD of 0%. This result is an anomaly produced as a result of the SAR footprint containing an extremely small portion of the Channel 3 and 4 region (seen by the dark blue dots just outside the SAR footprint in Figure 100). This produces cases where there are no ships generated within the intersecting regions thereby giving a nil result.

Looking more closely at AIS Channels 1 and 2 constellation results show the benefit in AIS POD possible over a single sensor pass. In low density AOIs such as the Canadian Arctic and Australia, the single RCM satellite scenario had a 100% AIS POD for ships in the SAR footprint. The constellation in these areas offered no benefit. In other areas of low to moderate ship densities, such as the Canadian East Coast, there was a slight improvement realized when using the three satellite detections. In this case, some ships not detected by AIS in the first pass were subsequently detected in the following two passes improving AIS POD for the constellation to 100%. In these locations the probability of association was 100% meaning that there was no issue in associating ships in earlier passes to the time of the SAR image.

In locations with higher ship densities (Canadian West Coast, Horn of Africa, and Persian Gulf), there was a small improvement in constellation AIS POD ranging from 9% to 19%. For the highest density locations (English Channel, Mediterranean, Japan, and North Sea) the AIS PODs of any single pass was very low or effectively nil in most cases. Here, the advantage of the constellation showed improved results with AIS PODs increasing by as much as 30%.

The RCM constellation scenarios have the same FOV and acquisition geometry factors as discussed in Section 6.4.1.1. Acquisitions of the three constellation passes could be framed to minimize the ship density within the AIS FOV and thus optimize AIS detection performance. As was seen in the two different scenario geometries of the single satellite RCM scenario results, different framing of the acquisitions can result in a wide variation in performance.

Planning an RCM constellation for optimum performance in this respect is a much more difficult task, but could be made easier through well developed RCM planning software and GSDM.

6.4.6 Overall AIS Performance

Based on the results produced from the simulation, it is apparent that the expected performance of the new AIS receiver to be used on RCM will provide good performance in areas of low to moderate ship density. This includes the Canadian domestic AOIs where expected performance is typically greater than 90%. From a Canadian security perspective, two-channel AIS will enable users to provide very good coverage with expected PODs of 90% for maritime approaches in all areas. When four-channel AIS capability is considered, PODs increase to nearly 100% for approaches beyond the limit of base station coverage.

For the other AOIs considered, particularly those of high ship density, expected PODs are significantly lower for two-channel AIS; however, four-channel AIS raises POD for offshore areas to well over 80% in even the highest density areas. Near shore regions tend to be of higher ship density than those on the open ocean. SAIS performance is not expected to be very good in these high density locations; however, from an operational point of view, these regions tend to be well covered by terrestrial base station networks. This is particularly true of the highest ship density areas around major ports and shipping lanes.

Overall, two-channel AIS capability on RCM is expected to perform well and provide a significant contribution to domestic Recognized Maritime Picture (RMP) realization. Adding the capability to receive Channel 3 and 4 messages will enhance domestic POD performance, but, will be a critical element in providing reliable ship detection capacity in foreign AOIs.

While Radio Frequency spectrum allocation for AIS Channels 3 and 4 have been recently approved at WRC-12, there is no established timeline for their integration. It is expected that once a timeline is in place, there will be a transition period over which commercial vessels will adopt the required equipment for use. Full integration is likely several years away.

6.4.7 SAR and AIS Time Differences

The time difference between the acquisition of separate AIS and SAR satellites introduces confusion in the association of a target found in the AIS with the correct target in the SAR image acquired some time later. This confusion is represented by the probability of association calculated for each scenario.

The probability of association for RCM Channels 1 and 2 are generally high, with exceptions in the highest density cases for Japan and the North Sea. The probability of association for the ascending Japan scenario is zero because no ships were detected by AIS. The ascending North Sea case has a probability of 20% because in some of the ten runs a small number of ships were detected by AIS and had a probability of association of 100%. When the ten runs are averaged together the probability of AIS detection (to two decimal places) is zero, while the probability of association is 20%. The probability of association for RCM Channels 3 and 4 are all 100% except for the Mediterranean where the probability is 98%.

The results from the simulations using RSAT2 show that the probability of association decreases with increasing time and increasing ship density in the SAR footprint. These results are not surprising and are a known problem when fusing data from two different instances in time. Except for the Canadian Arctic and Australia, the probabilities of association for the RSAT2 and EV1 cases were below 50%, and in many cases were very low.

When looking at the RCM constellation configuration, the temporal separation between each of the three satellites is on the order of 30 minutes allowing for three “looks” at an AOI within a one hour time period. The probability of association for the constellation was evaluated for the case where AIS detections from the preceding two satellite passes were associated with the SAR detections from the last satellite pass. In general, the trend of increasing temporal difference between AIS and SAR acquisition resulting in lower probabilities of association holds for the constellation cases even with the relatively small time differences (on the order of 30 min and one hour) afforded by the constellation. The same effect is demonstrated as the number of ships in the FOV increases.

6.4.8 Comparison of RCM and RSAT2 Capabilities

The performance of the individual SAR and AIS sensors on RCM as compared to equivalent sensors currently available on other satellites for the most part offer comparable performance. The proposed AIS receiver for RCM offers some performance improvements due to the decollider provisions; however, this design will be forthcoming on new AIS satellites as they come online. A big advantage for RCM will be the inclusion of an AIS Channels 3 and 4 capable receiver. As demonstrated in the simulation results, this capability significantly improves ship detection capability in areas of high ship density.

Perhaps the biggest capability improvement offered by RCM is through co-location of AIS and SAR sensors on a single satellite followed closely by the three satellite constellation arrangement. This arrangement offers several advantages over the current capability of sensors available on separate satellites. One advantage is in terms of planning and coordination of data acquisitions. The three RCM satellites will allow for frequent coverage of most areas and allows for possible resource queuing to avail of targeted image acquisitions for following satellites if a target of interest is noted in a preceding satellite pass. This type of ready queuing and resource tasking is not always possible with sensors on separate satellites.

The constellation aspect of RCM also affords an advantage with multiple “looks” at an AOI within a short time period. Simulation results show that AIS vessel detection performance can be improved over an AOI, particularly where ship densities are high. Each individual satellite will detect a percentage of vessels in the AOI depending on the number of vessels in view. While these individual detection rates may be low in high traffic areas, each satellite will be detecting a number of different vessels in each pass. When combined, these detections effectively provide an increased detection probability for the AOI. Additionally, the multiple look aspect offers an improved target tracking capacity where multiple detections of the same ship over a one hour period provides better track establishment and maintenance opportunities. This is a capability not readily available when using sensors of opportunity over an AOI.

One of the key aspects of SAIS is the ability to detect and identify targets. Ship identification is inherent in AIS message information as each vessel has a unique MMSI assigned. The fusion of SAR and AIS information to provide positive target identification is a crucial aspect of Intelligence, Surveillance and Reconnaissance (ISR) activities. A significant advantage is provided by co-location of AIS and SAR sensors in this regard. As demonstrated, the capacity to properly associate AIS and SAR detections is drastically diminished as the time difference between each acquisition type increases and the number of ships in the FOV increases. Co-location of sensors virtually eliminates the temporal difference effect as acquisitions are virtually simultaneous allowing for very high probability of association between SAR and AIS detections. Positive identification offers a significant contribution to securing and maintaining the RMP.

Looking at the results calculated for the RSAT2 and EV1 probabilities of association shown in Table 40, it is evident that the ability to positively identify or associate AIS detections with SAR targets is difficult when there is a significant time difference between the respective acquisitions.

As the time difference increases, the probability of association decreases. The RCM case with co-located sensors and effectively zero time difference is a best case scenario for this situation.

6.4.9 RCM SAR and AIS Concept of Operations

The usual ConOps for the AIS on RCM is that the AIS will be turned on five minutes before the SAR on time and turned off when the SAR is turned off. The developed simulation provided the ability to test various ConOps for the SAR on RCM. Two approaches were undertaken, the first using a uniform distribution of ships in the Pacific Ocean to generate performance curves without the influence of the geographic distribution of ship, and the second approach used the Canadian East Coast scenario as an example. In both cases, the scenarios used a SAR on time of two minutes.

A few representative AIS durations and time offsets from the SAR, as listed in Table 55, were used to generate performance curves for the area in Figure 102 and are shown in Figure 103. For this general case with a uniform distribution of ships and without the influence of land changing the time offset of the SAR and AIS had no effect on the performance curves (red and blue curves for the seven minute case and the cyan and magenta curves for the five minute case). The only requirement is that the SAR footprint remains in the AIS FOV for at least five minutes. The AIS duration clearly changed the performance, with the performance increasing as the AIS duration increases. The blue dots in the figure are the performance curve of the enhanced receiver, and the green curve is the performance curve of the decollider receiver (with an average transmit rate of seven seconds).

Table 55: AIS duration and time offset from SAR used for the Pacific Ocean ConOps analysis

AIS Duration (min)	**AIS start time before SAR (min)**
7	5
7	3
5	3
5	0
3	1

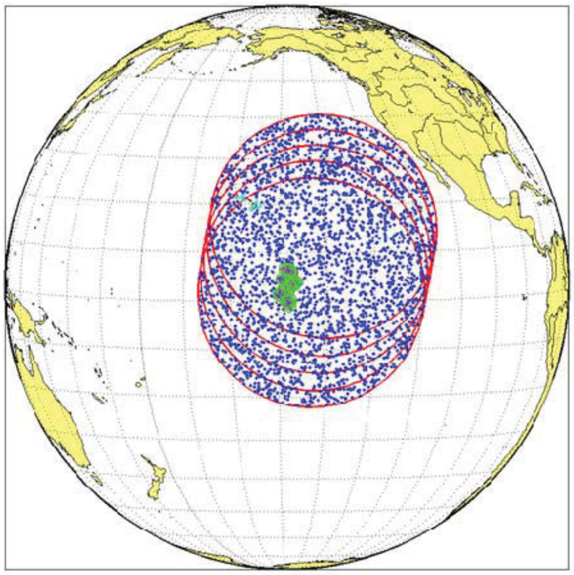


Figure 102: Location of coverage for Pacific Ocean analysis

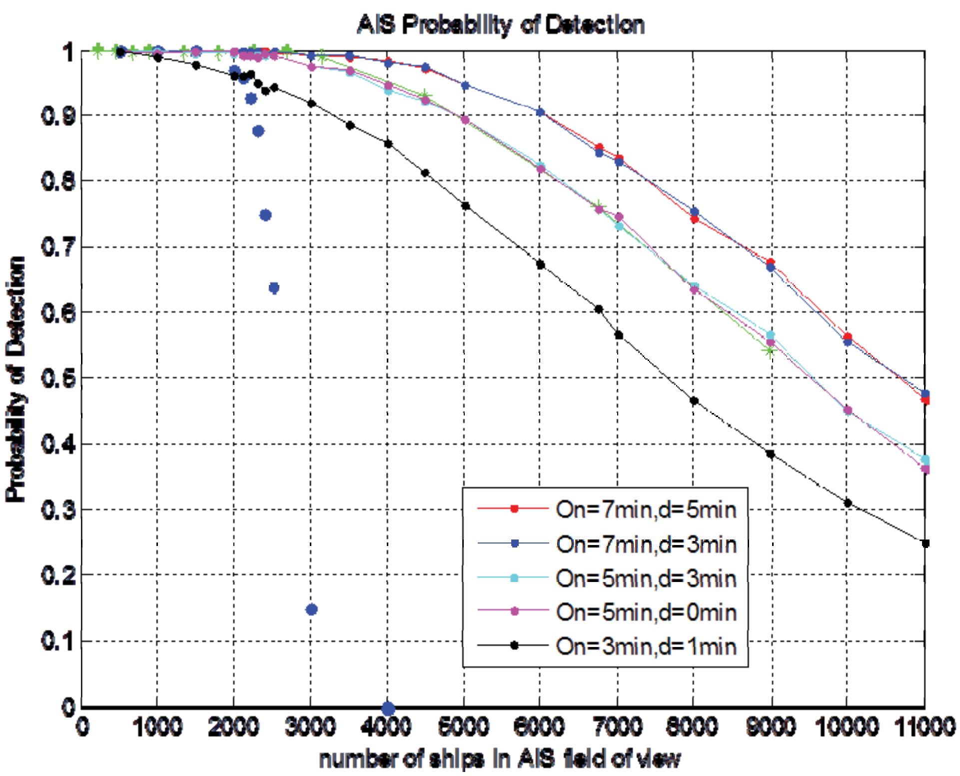


Figure 103: Performance curves for various RCM SAR and AIS ConOps for a location in the Pacific Ocean

The second case looked at the Canadian East Coast and the AIS durations, time offset from SAR, and AIS POD for a five minute overlap are shown in Table 56. The results show that the AIS POD for the five minute overlap increases as the AIS duration increases. Unlike the general case in the Pacific Ocean, varying the AIS start time offset does have an effect on the POD. Figure 104 shows the output of the simulation for the AIS duration of seven minutes with a time offset of zero minutes (left image) and five minutes (right image). The zero minute offset case has a lower POD due to the higher number of ships in the overlap region, while the five minute offset case has fewer ships in the overlap and thus a higher AIS POD. Based on this, it is possible to use the ship density in the AOI to determine the optimum AIS time offset from the SAR.

Table 56: Results of ConOps analysis for Canadian East Coast

AIS Duration (min)	**AIS start time before SAR (min)**	**AIS POD for 5 min overlap**
3	0	0.708
3	1	0.732
5	0	0.797
5	3	0.827
7	0	0.829
7	3	0.876
7	5	0.897

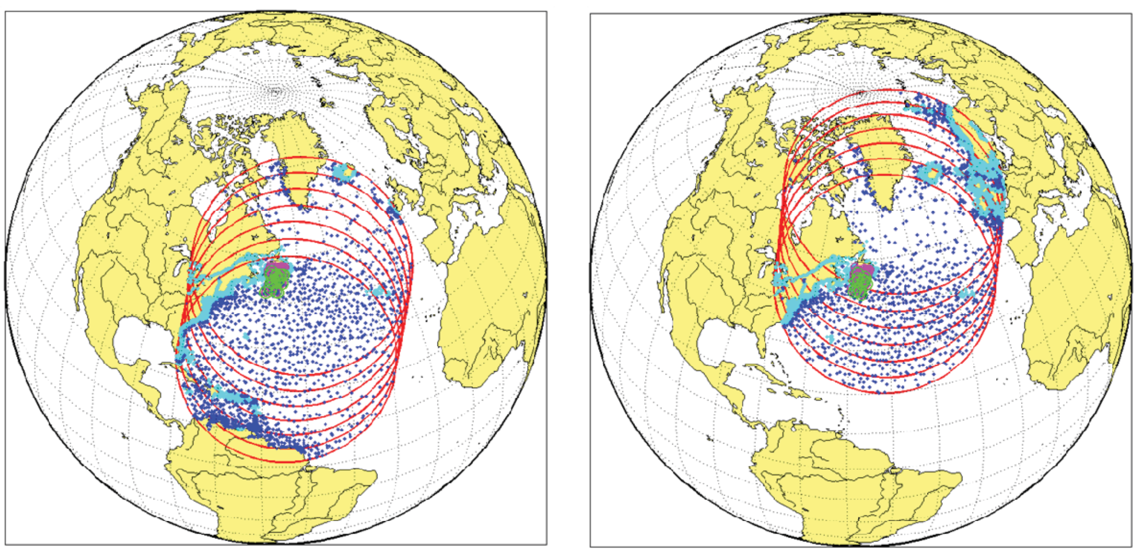


Figure 104: Locations of the seven minute AIS duration runs with time offset of 0 for the left image and 5 minutes for the right image.

6.5 Performance Metrics

In this project, an assessment of the expected AIS sensor performance on RCM is performed using a statistical based model combined with a SAR model provided by DRDC. As such, evaluations can be made of AIS and SAR sensor performance. While the analysis presented in the previous sections provides an assessment of performance available through the sensor systems considered, it may not be readily apparent how these performance indicators translate into operational differences. An important aspect of this type of assessment is how the sensor systems of interest compare in a "real-world" context. The following subsections outlines and applies a methodology used for this purpose and provides valuable insights on how these performance indicators may be interpreted.

6.5.1 Measures of Performance

Based on the modelling and simulation efforts undertaken, a number of results and outcomes have been realized for a range of scenarios as described in the preceding sections. Based on the modelling performed, the merits of various system configurations can be assessed on the basis of measures of performance (MOP) concepts. A significant amount of work has been done to develop a means to provide operational evaluation of various sensors and sensor systems used for ISR purposes. An overview of a standardized approach to metric selection and augmentations thereof is summarized in [50] and provides a discussion of applying such a methodology to DIASRS.

Definitions of individual metrics and categories of metrics are found in [50]. A number of these metrics such as detection performance and association performance are calculated and discussed as outputs of the modelling activities undertaken. These outputs provide a quantitative evaluation of capabilities. For the purposes of this assessment, MOP concepts used for evaluation are a combination of individual sensor MOPs and fusion MOPs.

6.5.2 Value-Added Benefits

In addition to the insight provided directly through MOP evaluation, a contextual analysis based on operational needs provides useful insight into the expected capabilities of the sensor or sensor system to meet these needs. A methodology known as "Value-Added Benefits" (VAB) has been previously defined [51] as a qualitative means to assess the relative contribution that a system can provide in the context of "real world" scenarios. The scenarios used as a basis for analysis are taken from Canadian Forces Planning Scenarios (CFPS) used in strategic planning. Scenarios used are those most relevant to ISR.

This approach has been used to evaluate a number of ISR sensors including the SAR capability of RCM and is recommended as a means of evaluating RCM with AIS in comparison with alternative systems. An interpretation of this approach is used to provide a comparative means of evaluating the RCM system of sensors to alternative systems, particularly with regard to AIS and SAR sensor co-location and the proposed four-channel AIS capability on RCM.

An overview of the VAB definition process is outlined in [50] and is repeated below for convenience. The proposed steps to define VABs are:

1. Select the CFPS for which the sensor system is potentially relevant (for the evaluation of maritime surveillance systems, the Search and Rescue, Surveillance, National Sovereignty, and Defence of North America scenarios have been previously used and are used here as well).

2. Produce maritime vignettes that best represent each ISR scenario that would involve the sensor under consideration. Each vignette is a series of scripted events designed to test the systems under consideration in a realistic application.

3. Determine the ISR objectives for each vignette.

4. Identify VABs for each scenario that best match the objectives. Five VABs have been typically chosen for each scenario, however the exact number is flexible. Note that the matching of VAB and ISR objectives is not intended to be one-to-one, but rather the VAB combined should largely encompass all of the ISR objectives.

5. Score the benefits using the scoring system as follows:

    a. 0.0 indicates that the system provides no improvement beyond current capabilities (it has been suggested that an extra step should be added before this one to formally identify what “current capabilities” are);

    b. 0.1 indicates a “slight to moderate improvement”; and

    c. 1.0 indicates “significant improvement”.

6. Provide a concise justification of the scores provided.

6.5.3 VAB Evaluation

The VAB approach is taken in this project to provide a basis of comparison to evaluate the respective benefits offered by combinations of three satellite-based sensor systems analyzed through the modelling and simulation work described herein. The three systems of interest include,

1. The combination of RSAT2 SAR platform and the EV1 AIS platform;

2. The RCM satellite configuration with SAR and a two-channel AIS receiver; and

3. RCM with SAR and a four-channel AIS receiver.

As previously discussed, the scenarios used as a basis for analysis are taken from the broad CFPS used in strategic planning. Scenarios used are those most relevant to ISR. For this project, the scenarios and vignettes used are those employed in [51] with slight modification. These are summarized in Table 57.

Table 57: ISR scenarios and objectives

ISR CFPS	Maritime Vignette	ISR Objectives
Search & Rescue (S&R)	Distress signal received - general search area known	• Identify S&R vessel • Establish accurate position and time • Track S&R vessel and direct response units
	Vessel reported missing - route known but no specific location	• Establish search area • Develop a vessel profile to determine capabilities and likely intentions • Establish prior track history for search planning
Surveillance	Smuggling into the country - known identity, origin, departure time and probable destination	• Establish surveillance area • Establish contact box • Discriminate between a vessel of interest (VOI) and other vessels in the vicinity • Maintain track on VOI
	Smuggling activity identified but no knowledge of vessel identification or route	• Define a surveillance area and coverage plan • Identify suspicious activity
	Pollution slick sighted, polluter unknown	• Identify VOIs • Establish track history • Collect evidence
National Sovereignty	Illegal fishing within the exclusive economic zone (EEZ)	• Detect presence and level of activity inside the EEZ • Develop profile of VOIs
	Vessel transit through Northwest Passage	• Detect presence of vessels • Develop profile of VOI

ISR CFPS	Maritime Vignette	ISR Objectives
Defence of North America	Interdiction of vessel involved in a hostile act after the act has been committed	• Obtain and maintain track on the VOI • Coordinate and report to responding unit
	Prevention of hostile activity, no ID of forces	• Establish an AOI • Establish situational awareness • Identify combatants and non-combatants
	On-going incident (hostage, etc.)	• Problem definition • Establish vessel profile • Identify combatants and non-combatants
	Operational support to naval activity	• Provide situational awareness outside of vessel/air asset sensor range

Following the methodology outlined above, VABs are now defined for each scenario to best account for the ISR objectives outlined in Table 57 and then scored for each system. Defining VABs is not an exact process and the translation of scenario objectives into VABs may not be the same for two different evaluators. As with the scenario and vignette definitions, the VABs used here are taken from [51] with slight modification.

The scoring results are shown in Table 58, Table 59 and Table 60. With regard to the scoring scheme, the basis for scoring changes for each evaluation. The intent is to assess the potential of each system under consideration against existing capabilities that contribute to developing and maintaining the RMP. In the case of RCM with four-channel AIS evaluated here, it is presupposed that this case is an additional capability over the previous RCM two-channel AIS case; thereby scores are awarded using that case as the basis. For RSAT2 and EV1 and RCM with two-channel AIS, the basis is RSAT2 and a current generation AIS satellite such as AS3. However, the basis for RCM with four-channel AIS scoring is RCM with two-channel AIS.

In all cases, the substantiation for each score is based on the simulation and modelling results previously discussed in this report. It should be noted that scoring is very much subjective and may vary between different evaluators. The scoring is intended to provide a relative evaluation of the contribution a particular sensor or system can make towards establishing the RMP.

For the Search and Rescue scenarios, please note that the VABs and associated scoring consider only maritime cases where vessels are the potential search targets. Maritime search cases involving aircraft or other non-AIS-equipped targets are not factored into the scoring.

The evaluation for RSAT2 and EV1 is provided in Table 58. This case considers a next generation AIS receiver and SAR on separate satellites as compared with an earlier generation AIS receiver and SAR on separate satellites.

Table 58: VAB evaluation for RSAT2 and EV1

ISR CFPS	Value-Added Benefit	RSAT2 & EV1 Score	ISR Objectives
Search & Rescue	Increase positional accuracy	0.1	• Positional accuracy from vessel GPS at time of AIS transmission
	Detect all vessels in an area	0.1	• Greater than 80% AIS detection probability in Canadian AOIs
	Reduce response time	0.1	• Improved knowledge of vessels of opportunity to task to response, especially far offshore • Sensors are not real-time, latency from AIS transmission to reception by SAR coordinator
	Identify vessel	1.0	• AIS detected vessels are identified (unique vessel MMSI included in AIS messages)
	Timely data reception	0.1	• Data available to Search and Rescue personnel within a few minutes for Canadian AOIs
	S&R Capability Improvement	**1.4**	
Surveillance	Detect all vessels in AOI	0	• Greater than 80% AIS detection probability in Canadian AOIs • Very low detection probability for other AOIs giving little gain overall
	Identify vessels	1.0	• AIS detected vessels are identified (unique vessel MMSI included in AIS messages)
	Optimize resource tasking	0.1	• Some capability to associate SAR and AIS targets
	Establish track	0.1	• AIS information on course and speed allows for track initiation
	Surveillance planning	0.1	• Track information allows for some level of planning
Surveillance Capability Improvement		**1.4**	

ISR CFPS	Value-Added Benefit	RSAT2 & EV1 Score	ISR Objectives
National Sovereignty	Detect violators	1.0	• Greater than 80% AIS detection probability in Canadian AOIs
	Collect irrefutable evidence	0.1	• Some capability to associate SAR and AIS targets
	Minimal use of tasked resources	0.1	• Some capability to associate SAR and AIS targets
	Accessible data to third party	0.1	• Data available to DND and other government agencies (OGAs) as needed to support security operations • Data latency may result in information not getting where needed in a timely manner
	Direct authorities to location	0.1	• Track information allows for some level of localization
National Sovereignty Capability Improvement		**1.4**	
Defence of North America	Covert tracking	0	• Occasional coverage
	Tracking continuously	0	• No capacity for continuous tracking
	Detect all vessels in an area	0.1	• Greater than 80% AIS detection probability in Canadian AOIs
	Accessible data to third party	0.1	• Data available to DND and allies as needed. Some latency depending on AOI
	Identify vessel	1.0	• AIS detected vessels are identified (unique vessel MMSI included in AIS messages)
Defence of North America Capability Improvement		**1.2**	

Table 59 summarizes the evaluation for RCM with two-channel AIS. This case considers a next generation AIS receiver and SAR on the same satellite as compared with an earlier generation AIS receiver and SAR on separate satellites.

Table 59: VAB evaluation for RCM with two-channel AIS

ISR CFPS	Value-Added Benefit	RCM 2 Channel Score	ISR Objectives
Search & Rescue	Increase positional accuracy	0.1	• Positional accuracy from vessel GPS at time of AIS transmission
	Detect all vessels in an area	1.0	• Greater than 90% AIS detection probability in Canadian AOIs • RCM constellation offers 3 looks in a short time period (~ 1 hour)
	Reduce response time	0.1	• Improved knowledge of vessels of opportunity to task to response, especially far offshore • Sensors are not real-time, latency from AIS transmission to reception by SAR coordinator
	Identify vessel	1.0	• AIS detected vessels are identified (unique vessel MMSI included in AIS messages)
	Timely data reception	0.1	• Data available to S&R personnel within a few minutes for Canadian AOIs
S&R Capability Improvement		**2.3**	
Surveillance	Detect all vessels in AOI	1.0	• Greater than 90% AIS detection probability in Canadian AOIs
	Identify vessels	1.0	• AIS detected vessels are identified (unique vessel MMSI included in AIS messages) • High Probability of Association allows better identification of S&R targets • High Probability of Association allows localization of "dark" targets (not transmitting AIS)
	Optimize resource tasking	1.0	• Substantial POD improvement in high density areas outside Canadian AOIs • Wide area coverage on a daily

ISR CFPS	Value-Added Benefit	RCM 2 Channel Score	ISR Objectives
			basis with RCM
	Establish track	1.0	• Improved RMP with RCM constellation having 3 looks at AOI at ~30 minute intervals to establish track • RCM probability of association near 100% for co-located AIS and SAR
	Surveillance planning	0.1	• Improved tracking with RCM allows better planning
Surveillance Capability Improvement		**4.1**	
National Sovereignty	Detect violators	1.0	• Greater than 90% AIS detection probability in Canadian AOIs
	Collect irrefutable evidence	1.0	• RCM probability of association near 100% for co-located AIS and SAR
	Minimal use of tasked resources	1.0	• Improved RMP with RCM • Wide area coverage daily allows better resource tasking
	Accessible data to third party	0.1	• Data available to DND and OGAs as needed to support security operations • Data latency may result in information not getting where needed in a timely manner
	Direct authorities to location	1.0	• Better tracking with RCM constellation having 3 looks at AOI at ~30 minute intervals • Better assessment of target intentions and direction to responders • High Probability of Association allows localization of "dark" targets (not transmitting AIS)
National Sovereignty Capability Improvement		**4.1**	

ISR CFPS	Value-Added Benefit	RCM 2 Channel Score	ISR Objectives
Defence of North America	Covert tracking	0.1	• RCM constellation provides once daily coverage over Canadian AOIs
	Tracking continuously	0.1	• Improved RMP with RCM constellation having 3 looks at AOI at ~30 minute intervals to establish track
	Detect all vessels in an area	1.0	• Greater than 90% AIS detection probability in Canadian AOIs • High Probability of Association allows localization of “dark” targets (not transmitting AIS)
	Accessible data to third party	0.1	• Data available within minutes for Canadian AOIs , increased latency for other global AOIs
	Identify vessel	1.0	• AIS detected vessels are identified (unique vessel MMSI included in AIS messages) • High Probability of Association allows better identification of SAR targets • High Probability of Association allows localization of “dark” targets (not transmitting AIS)
Defence of North America Capability Improvement		**2.3**	

Table 60 summarizes the evaluation for RCM with four-channel AIS. This case considers the addition of a second AIS receiver on RCM tuned to receive messages on the pending AIS Channels 3 and 4. This four-channel AIS capability is evaluated on the basis of improvements to the two-channel RCM case as indicated earlier.

Table 60: VAB evaluation for RCM with four-channel AIS

ISR CFPS	Value-Added Benefit	RCM 4 Channel Score	ISR Objectives
Search & Rescue	Increase positional accuracy	0	• No improvement over RCM 2 channel
	Detect all vessels in an area	0.1	• RCM with AIS Channels 3 and 4 offers near 100% detection in offshore areas
	Reduce response time	0.1	• Improved knowledge of vessels of opportunity to task to response, especially far offshore
	Identify vessel	0	• No improvement over RCM 2 channel
	Timely data reception	0.1	• Data available to SAR personnel within a few minutes for Canadian AOIs
S&R Capability Improvement		**0.3**	
Surveillance	Detect all vessels in AOI	1.0	• AIS Channels 3 and 4 near 100% detection in Canadian AOIs • AIS Channels 3 and 4 give high POD in all other AOIs as well
	Identify vessels	0.1	• High Probability of Association allows better identification of SAR targets • High Probability of Association allows localization of “dark” targets (not transmitting AIS)
	Optimize resource tasking	0.1	• Improved RMP with RCM especially with AIS Channels 3 and 4 in offshore areas • Substantial POD improvement in high density areas outside Canadian AOIs
	Establish track	0	• No improvement over RCM 2 channel
	Surveillance planning	0	• No improvement over RCM 2 channel

ISR CFPS	Value-Added Benefit	RCM 4 Channel Score	ISR Objectives
Surveillance Capability Improvement		**1.2**	
National Sovereignty	Detect violators	0.1	• RCM with AIS Channels 3 and 4 near 100% detection
	Collect irrefutable evidence	0	• No improvement over RCM 2 channel
	Minimal use of tasked resources	0.1	• Improved RMP with RCM especially with AIS Channels 3 and 4 in offshore areas • Wide area coverage daily allows better resource tasking
	Accessible data to third party	0	• No improvement over RCM 2 channel
	Direct authorities to location	0.1	• Better assessment of target intentions and direction to responders • High Probability of Association allows localization of “dark” targets (not transmitting AIS)
National Sovereignty Capability Improvement		**0.3**	
Defence of North America	Covert tracking	0	• No improvement over RCM 2 channel
	Tracking continuously	0	• No improvement over RCM 2 channel
	Detect all vessels in an area	1.0	• RCM with AIS Channels 3 and 4 near 100% detection • AIS Channels 3 and 4 give high POD in all AOIs • High Probability of Association allows localization of “dark” targets (not transmitting AIS)
	Accessible data to third party	0	• No improvement over RCM 2 channel

ISR CFPS	Value-Added Benefit	RCM 4 Channel Score	ISR Objectives
	Identify vessel	0.1	• High Probability of Association allows better identification of SAR targets • High Probability of Association allows localization of “dark” targets (not transmitting AIS)
Defence of North America Capability Improvement		**1.1**	

Based on the VAB evaluation presented, the RCM sensor configuration with co-located SAR and AIS sensors offers significant advantages over comparable systems with AIS and SAR sensors on different satellites. The most profound advantages are seen in the Surveillance and National Sovereignty scenarios with lesser, but nonetheless significant, advantages demonstrated for the Search and Rescue and Defence of North America scenarios. When the additional capability of AIS Channel 3 and 4 receptions is factored in, there are additional benefits gained, particularly in the Surveillance scenario where benefits are shown to be significant.

Table 61 provides a VAB evaluation scoring summary. As indicated previously, the RCM four-channel AIS case is scored based on the RCM two-channel AIS case as the addition of AIS Channels 3 and 4 are an added capability to the RCM configuration. As a result, the scores for RCM four-channel are added to the scores for RCM two-channel to illustrate benefit improvement over existing capabilities. As an example, if an RCM two-channel score is 0.1 and RCM four-channel offers a moderate improvement, the resultant score for RCM four-channel would be 0.1 + 0.1 = 0.2.

It is important to note that this cumulative scoring method is being used just for the purpose of relative comparison between the three cases analyzed in this project. Typically, the maximum score that is achievable in this type of VAB analysis would be 5.0, corresponding to five significant improvements. In this case, the two RCM cases look at incremental capability improvements and the cumulative scoring represents a qualitative means of showing the relative change this capability affords to the system. These cumulative scoring results should not be taken directly as a basis of comparison against other VAB analysis outcomes.

Table 61: VAB evaluation summary

Canadian Forces Planning Scenarios	VAB Scoring Summary			Comments
	RSAT2 and EV1	RCM 2 Channel	RCM 4 Channel	
Search & Rescue	1.4	2.3	2.5	• RCM constellation provides moderate improvement over RSAT2 and EV1 for S&R • RCM 4 Channel adds a slight additional improvement for this CFPS
Surveillance	1.4	4.1	5.3	• RCM constellation provides significant improvement over RSAT2 and EV1 for the Surveillance CFPS • RCM 4 Channel adds a significant additional improvement for this CFPS, particularly with regard to the high POD improvement in high vessel density AOIs
National Sovereignty	1.4	4.1	4.4	• RCM constellation provides significant improvement over RSAT2 and EV1 for the National Sovereignty CFPS • RCM 4 Channel adds a moderate additional improvement for this CFPS
Defence of North America	1.2	2.3	3.4	• RCM constellation provides significant improvement over RSAT2 and EV1 for the Surveillance CFPS • RCM 4 Channel adds a significant additional improvement for this CFPS, particularly with regard to the high POD improvement in high vessel density AOIs

Given one of the primary missions for RCM is maritime surveillance, the VAB evaluation demonstrates a much improved potential capability in this capacity over current system capabilities. This evaluation supports the premise that an AIS capability on RCM will enhance the Canada First Defence Strategy goals of conducting national and continental operations and defending Canada. Including the capability to receive and process all four AIS channels, when available, will provide greater enhancement not realizable with only a two-channel option.

7 Conclusions

7.1 Overview

The primary objective of this project is to provide information as a means to support or contradict the hypothesis that the RCM configuration with co-located AIS and SAR sensors will enhance identification of vessels of interest in maritime approaches in a timely manner by significantly reducing the number of unidentified detected vessels in an operational AOI. This was investigated through:

1. Development of a model that will incorporate statistical models from space-based AIS data sources and simulate the major factors affecting the quality of the AIS radio frequency link;

2. Identify issues and expected performance associated with the combination of space-based AIS and RSAT2 vessel detection data; and

3. Establish the expected performance for AIS on RCM.

This report documents the effort undertaken to address the analysis of expected performance of AIS on RCM through the use of a statistics-based model and simulation. The work extends ship detection performance assessment capability for not only RCM, but also other combinations of AIS and SAR sensors on different satellites. Overall, the objectives of this project have been achieved with the simulation and modelling tool providing a good basis for further evaluation.

7.2 Findings

7.2.1 Modelling and Simulation Summary

The project has realized a statistics-based model and simulation tool that provides a means to evaluate detection probabilities for a range of AIS and SAR sensor combinations. A significant database of AIS messages has been compiled, from which a number of characteristic statistical distributions of ship data has been derived. While these derived results are required to use the simulation tool, the database and derived products constitute a very useful data set in their own right.

Model development evolved to include three different implementations to simulate, basic, enhanced and decollider type AIS receiver implementations. The basic and enhanced receiver implementation use a simplified approach utilizing a tolerable number of collisions applied on a per message slot basis. The number of allowed collisions is a variable set by the user to simulate varying levels of receiver sophistication. The decollider implementation uses a statistical based model as a basis for determining AIS receiver performance. A number of parameters are used in the model and are available to allow specific aspects of a receiver to be tuned to match actual receiver performance as simulated or represented by actual performance data as it becomes available. The end result provides a good basis for assessment of SAIS and SAR detection capabilities.

Several model runs were executed to provide an assessment of AIS performance on RCM looking at both the two-channel and four-channel configurations planned. Various scenarios were developed to provide a level of understanding of expected detection performance. Results were generated and analyzed for ten specified AOIs of interest to DRDC. Model runs were also conducted in each AOI to evaluate the potential impact of the three satellite constellation arrangement for RCM.

Work has also been done to provide an assessment of the performance expected when temporally disparate AIS and SAR sensor data are used for target identification. A probability of association metric is developed and calculated for this purpose.

Based on the various performance metrics calculated through simulation and modelling, a methodology has been applied to provide an interpretation of these results in the context of "real-world" maritime surveillance needs.

Electromagnetic interference from ground-based transmitters was identified as a potential issue impacting performance and was investigated as a part of this work. Originally, this capability was to be included in the model implementation, but was unable to be completed at project end.

Given the extensive effort required for model development, less time was available to conduct an extended set of model runs to facilitate in-depth performance evaluations for all AOIs. However, sufficient runs were performed to provide a fair characterization of expected RCM performance and how that compares with the current capabilities offered by RSAT2 and various AIS satellites. The work carried out in this project provides a valuable tool and baseline to extend this investigation to additional AOIs, sensor platforms and specific cases, as required.

7.2.2 Summary of Results

The results of this work give a clear indication that the AIS decollider receiver planned for RCM will provide very good ship detection performance on AIS Channels 1 and 2 for the Canadian domestic AOIs and other low to moderate density AOIs modelled. For the Canadian domestic AOIs extending out to 1,200 nm from the east and west coasts, two-channel AIS will provide very good coverage with expected PODs on the order of 90%. For high ship density locations in other global AOIs, performance is shown to be significantly lower as the number of ships in the field of view increases. In the highest density areas with ship counts in excess of 30,000 with the AIS FOV, the POD for two-channel AIS is effectively nil.

Conventional two-channel AIS systems using AIS Channels 1 and 2 are significantly influenced by the number of ships in the FOV. The transmission rates for vessels transmitting on these channels are quite high when under way resulting in extremely high message volume, particularly in high traffic areas. Based on the results obtained using the simulation tool, the use of an AIS decollider receiver planned for RCM significantly improves AIS POD over the basic receiver designs currently deployed; however, simulation outputs indicate that the decollider receiver is still easily overwhelmed in high density areas. This can be somewhat mitigated by using the combined AIS detections from the three satellite constellation acquired within a short (approximately one hour) time period for a given AOI to improve AIS POD. Simulation results using the pending AIS Channels 3 and 4 result in consistently high AIS PODs for all AOIs. As these channels will only be used beyond the range of coastal base stations and utilize lower transmission rates, performance is much better than the case with AIS Channels 1 and 2. The advent of this capability offers extremely good vessel detection results for areas beyond coastal station coverage. As such, four-channel AIS on RCM will be a critical element in achieving very reliable ship detection performance in or around high density areas beyond terrestrial base station coverage. Complete operational coverage, especially in high traffic densities near shore, will require terrestrial AIS base station networks to augment SAIS coverage offshore.

Co-location of AIS and SAR sensors, as with RCM, is shown to offer much better target association probabilities than that of sensors located on separate satellites. As the temporal difference between the AIS and SAR acquisitions increases, probability of association declines quickly. Maintaining target tracks using this data becomes difficult as a result.

Overall, two-channel AIS co-located with the SAR on RCM offers very good ship detection performance under most circumstances for low to moderate ship density AOIs. With the advent of AIS Channels 3 and 4, the built-in four-channel AIS capability planned for RCM will provide improved ship detection performance in all AOIs, with the most profound impact in areas with very high ship density. When combined with terrestrial networks, four-channel SAIS will provide excellent ship detection performance in most all AOIs.

7.3 Future Efforts to Consider

A number of gaps and weaknesses are apparent from this work that could benefit from additional investigation. These include the following:

1. Improve tuning of the statistical model through the use of simulated detection performance data generated for the planned RCM receiver derived from raw AIS signals as a means to improve tuning of the statistical model when it becomes available;

2. Investigate other approaches to target track association for implementation in the model;

3. Update the AIS database and derived distributions used in the model;

4. Update the random ship generation approach for grid cells containing land areas;

5. Complete implementation for the inclusion of external interference sources;

6. Implement a MATLAB® graphical user interface for the simulation.

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List of acronyms

AIS	Automatic Identification System
AOI	Area of Interest
Amver	Automated Merchant Vessel Reporting program
AS3	AprizeSat-3
AS4	AprizeSat-4
BLOS	Beyond line-of-sight
CFPS	Canadian Forces planning scenarios
COG	Course over ground
ConOps	Concept of operations
CSA	Canadian Space Agency
CSTDMA	Carrier-sense time domain multiple access
CTO	Continuous time observations
DIASRS TDP	Design of an Integrated AIS Sensor on a Radar Satellite Technology Demonstration Program
eE	exactEarth
EEZ	Exclusive economic zone
EV1	exactView-1
EFIS	European Frequency Information System
EU	European Union
FFI	Norwegian Defence Research Establishment
FOV	Field of view
GPS	Global positioning system
GSDM	Global ship density map
HITS	Historical Temporal Shipping
IMO	International Maritime Organization
ISR	Intelligence, Surveillance and Reconnaissance
ISS	International Space Station
ISR	Intelligence, Surveillance, Reconnaissance
ITU	International Telecommunication Union
ITU-RR	International Telecommunication Union Radio Regulations

LMR	Land Mobile Radio
LOS	Line of sight
LUXAIS	LuxSpace Automatic Identification System
MDA	MacDonald, Dettwiler and Associates
MID	Maritime Identification Digit
MMSI	Maritime Mobile Service Identity
MOP	Measures of performance
MSSIS	Maritime Safety and Security Information System
NavStat	Navigational status
OGA	Other government agency
PER	Packet error rate
PFA	Probability of false alarms
POD	Probability of detection
R&D	Research and Development
RCM	RADARSAT Constellation Mission
RDE	Radar Data Exploitation
RMP	Recognized maritime picture
ROT	Rate of turn
RR	Radio regulations
RSAT	RADARSAT
RSAT2	RADARSAT-2
SAIS	Satellite based automatic identification system
SAR	Synthetic aperture radar
S&R	Search and rescue
SOG	Speed over ground
SOLAS	Safety of life at sea
SOTDMA	Self-organizing time domain multiple access
TDMA	Time domain multiple access
TDP	Technology demonstration program
TLE	Two line element
UNCTAD	United Nations Conference on Trade and Development
VAB	Value added benefits

VHF	Very high frequency
VOI	Vessel of interest
VPCS	VHF public correspondence stations
WMO VOS	World Meteorological Services Voluntary Observing Ships
WRC	World Radiocommunication Conference

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.) C-CORE, Captain Robert A. Bartlett Building, Morrissey Road, St. John's, NLCanada A1B 3X5	2. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.) UNCLASSIFIED (NON-CONTROLLED GOODS) DMC A REVIEW: GCEC APRIL 2011

3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)

Satellite Automatic Identification System (SAIS) Performance Modelling and Simulation: Final Findings Report

4. AUTHORS (last name, followed by initials – ranks, titles, etc. not to be used)

Parsons, G.; Youden, J.; Yue, B.; Fowler, C.

5. DATE OF PUBLICATION (Month and year of publication of document.) December 2013	6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.) 226	6b. NO. OF REFS (Total cited in document.) 51

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Contract Report

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

Defence R&D Canada – Ottawa, 3701 Carling Avenue, Ottawa, Ontario K1A 0Z4

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.) 15eu01	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.) W7714-091149/001/SV
10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.) R-12-112-987	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.) DRDC Ottawa CR 2013-096

11. DOCUMENT AVAILABILITY (Any limitations on further dissemination of the document, other than those imposed by security classification.)

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An Automatic Identification System (AIS) capability on the RADARSAT Constellation Mission (RCM) will enhance the Canada First Defence Strategy goals of conducting national and continental operations and defending Canada. Key to understanding this is the ability to model and simulate satellite AIS (SAIS) performance characteristics. This report provides an overview of a statistical simulation implemented by C-CORE to evaluate SAIS performance. Included is a discussion on the approach and methodology employed with results presented for the specific case of the proposed AIS payload on the RCM. The model is driven by a global ship density map (GSDM) derived from an AIS database developed over the course of this project. The database and derived products are generated from data provided by Defence Research and Development Canada – Ottawa (DRDC Ottawa) for this purpose including both SAIS data (from exactEarth (eE)) and terrestrial AIS data from the Maritime Safety and Security Information System (MSSIS). C-CORE has implemented a model based on previous analytical and stochastic model approaches reported in the literature. Model implementation relies on the AIS database and derived products, the satellite orbit and resulting field of view (FOV) for the AIS and synthetic aperture radar (SAR) sensors to generate probability of detection values for AIS and SAR on an area basis. Various options are available to select various imaging modes of the sensor and to vary the ability of the AIS sensor to handle message collisions. Additionally, the model incorporates the ability to utilize the two existing AIS channels (Channels 1 and 2) and the pending new AIS channels (Channels 3 and 4) dedicated to SAIS reception and not transmitted by vessels near shore (i.e., within the range of coastal base stations). A series of scenarios for RCM and RADARSAT-2 (RSAT2) with exactView-1 (EV1) have been run in various areas of interest (AOIs). Results show that the RCM configuration with co-located SAR and AIS sensors, utilizing four-channel AIS, will provide very good ship detection performance for most areas beyond base station coverage areas.

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Performance Modelling; AIS; Ship Density; RADARSAT Constellation Mission; RADARSAT-2