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Site Planning and On-Board Collision Avoidance Software to Optimize Autonomous Surface Craft Surveys

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SITE PLANNING AND ON-BOARD COLLISION AVOIDANCE SOFTWARE TO OPTIMIZE AUTONOMOUS SURFACE CRAFT SURVEYS

BY

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MASTER OF SCIENCE IN OCEAN ENGINEERING

OF

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2013

ABSTRACT

Autonomous surface crafts (ASCs) have strong potential as platforms for repeat transect oceanographic surveys in coastal and estuarine systems. Good spatial and temporal coverage and resolution could be achieved by an ASC capable of weeks-long operations at average speed 5 knots, which is the design goal for the Surveying Coastal Ocean Autonomous Profiler (SCOAP) catamaran ASC. This project addresses operational challenges for long duration ASC deployments, to help minimize risk of collisions: site planning, and on-board collision avoidance (CA) software.

In anticipation of a Rhode Island Sound (RIS) SCOAP deployment, a site planning method was developed using archived Automatic Identification System (AIS) data. AIS is a real-time, radio-based system for sharing navigation information among vessels. Archived data were used to determine geographic and seasonal patterns of RIS vessel traffic, and associated frequency of potential collision encounters for various hypothetical repeat transect ASC surveys under consideration. Seasonal-mean AIS vessel traffic varied from as low as 0.01 tracks per day or less in southeastern RIS to about 8 tracks per day in shipping lanes near Narragansett Bay. Corresponding numbers of potential collision encounters for a month-long repeat transect ASC survey in these two areas are about 0-2 and 12-22, respectively, with lower/higher values in winter/summer. Crudely estimated non-AIS traffic suggests up to 3-4 times higher total (AIS and non-AIS vessels) potential encounters. The method provides quantitative information to enable site planning that best balances oceanographic sampling goals against associated collision risks.

On-board autonomy software capable of performing collision avoidance (CA) maneuvers is essential for long duration ASC operations. To demonstrate and evaluate its CA performance the Mission Oriented Operation Suite Interval Programming Helm autonomy software, to be implemented on SCOAP, was used to simulate repeat transect ASC surveys with traffic vessels. The CA algorithm used avoids collisions without attempting to comply with Coast Guard (CG) Collision Avoidance Regulations (COLREGS). Three categories of ASC CA maneuver were identified, in which nearly all encounters fall: large deflection, course-reversal, and leave/return to station keeping. ASC path disruptions are substantially reduced when traffic vessels perform CA in addition to the ASC; sensitivity of encounter statistics to other ASC and traffic vessel path configurations, and CA algorithm parameters, is modest. Overall the CA algorithm performed reliably, resolving at least 97% of encounters in 10s of seconds, including interactions with multiple traffic vehicles simultaneously.

A framework was developed for how ASCs can best approach compliance with COLREGS, the set of rules (prescribed behaviors and exceptions to them) applicable to vessels with human operators on board. The framework considers the ASC operating mode and its maneuverability relative to traffic vessels. For SCOAP, marked for restricted maneuverability and executing repeat transects, the recommendation is to always give way except when station-keeping with sensors overboard. The framework will be reassessed when CG requirements for ASC COLREGS compliance, currently under development, are completed. Regardless, it is suggested that on-board autonomy software include flexibility to implement different combinations of prescribed behaviors and exceptions, for different ASCs and applications.

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TABLE OF CONTENTS

LIST OF TABLES

TABLE PAGE

LIST OF FIGURES

Chapter 1. Introduction and Motivation

Potential of ASCs for Shallow-Water Oceanographic Sampling

Traditionally there have been two main methods for oceanographic sampling; vessel-based surveys using research vessels, and moorings. Vessel-based surveys have good spatial coverage but poor temporal coverage, as constrained by the high cost of research vessel operations. Conversely moorings offer good temporal coverage but do not achieve high spatial coverage. In coastal and estuarine settings, a common sampling need is the separation of tidal signals from subtidal variability (lower-frequency than tidal; including prominent weather-band changes). This separation typically requires surveys of long duration (at least a week) with frequent sampling (multiple times daily) at a given location, which is too costly to accomplish with a research vessel. Fields of oceanographic interest in coastal and estuarine settings vary on spatial scales of a few kilometers and to capture them would require more moorings than would be affordable, or would be operationally feasible given vessel traffic.

In recent years mobile platforms, including profiling floats and subsurface gliders, have been effective in helping overcome these limitations, particularly in deeper water. The ARGO program (Roemmich, 2009) is a good example of profiling float capabilities. ARGO floats descend through the water column in order to perform a Conductivity Temperature Depth (CTD) cast, and then ascend to the surface to transmit their data to shore via satellite, while providing information about ocean currents based on their drift. Subsurface gliders (Rudnick, Davis, Eriksen, Fratantoni, & Perry, 2004) are a mobile platform that can also make CTD profile measurements, as well as velocity observations throughout the water column using an acoustic Doppler current profiler (ADCP), and send the data to shore via satellite. Gliders have the advantage of self-propulsion based on wings that generate forward momentum from buoyancy forces, so they can target specific locations. Gliders are very energy-efficient so that while they are achieving spatial coverage they can sample persistently for long periods.

Autonomous surface crafts (ASCs), or unmanned surface vessels (USVs) as they have been traditionally known, have important potential advantages ((Manley, 2008) provides a review) as a mobile sampling platform in the challenging shallow water environment. Coastal and estuarine waters have strong tidal currents that can overpower floats and subsurface gliders. They also have complex bathymetric and coastline geometries to be avoided. In addition, vessel traffic is intense and must be actively avoided. ASCs can be equipped with sufficient energy resources for strong propulsion to overcome tidal currents. The persistent surface presence and stronger propulsion of ASCs makes possible the use of on-board autonomous navigation systems to perform collision avoidance (CA) maneuvers.

A combination of rapidly advancing technologies, that automate both the detection of other vessels and the performance of CA maneuvers, are helping open up the possibility for long duration ASC deployments. The Automatic Identification System (AIS) is a radio-based system (described in more detail in Chapter 2 below) for real-time communication of vessel navigation information, in which each vessel carries a transceiver. Equipping an ASC with AIS is straightforward and helps ensure it will be detected in real-time by other AIS-equipped vessels, and vice-versa. Also advancing rapidly are on-board autonomy software frameworks for robotic systems, which are applicable to ASCs. Examples include Control Architecture for Robotic Agent Command and Sensing (CARACaS) developed at the Jet Propulsion Laboratory (Kuwata, Wolf, Zarzhitsky, & Huntsberger, 2011), the T-Rex architecture developed at the Monterey Bay Aquarium Research Institute (Rajan, Py, McGann, & Ryan, 2009), and the Mission Oriented Operating Suite (MOOS) Interval Programming (IvP) Helm developed at Massachusetts Institute of Technology (Benjamin, Leonard, Schmidt, & Newman, 2012). The MOOS-IvP Helm (MIH) platform (described in more detail in Chapter 3 below) is freely-distributed open source software with a user community, and includes a capability to perform CA, that has been demonstrated in controlled field tests (Benjamin & Leonard, 2006).

Repeat Transect Sampling by ASCs

In addition to scientific rationales, operational constraints of ASCs motivate the use of repeat transect sampling. Protocols for ASC deployments remain under development by the United States Coast Guard (USCG) and it stands to reason that long-duration ASC deployments are more likely to be approved if they follow a "moving buoy" concept, because this approach involves only a minor shift away from the long established protocols for USCG management of oceanographic mooring deployments. The moving buoy concept is that the ASC is not operated unattended except at a designated transect to which it is either towed, or escorted. The ASC can move along the designated transect to accomplish its mission goals but is allowed to deviate away from the transect only by a specified distance. The USCG will alert mariners to the location of the transect using their Notice to Mariners publication, just as it does for specific sites where oceanographic moorings are deployed.

Repeat transect sampling, a central concept throughout this thesis, gathers oceanographic data at several points (spatial sampling) over a long period of time (temporal coverage). A given repeat transect (Figure **1**) can be defined by the following parameters: the average ASC speed, the transect length and orientation, the number of stations, and the duration of time the ASC spends at each station. The vessel will collect oceanographic data using a CTD, ADCP, and/or other sensors at each station. The ASC will hold position, or "station-keep", for the duration of the measurement. The duration on station varies depending on the sensor, with 5-10 minutes (maximum 10-30 minutes) typically long enough to enable, for example, a CTD cast (by a winch-equipped ASC) in 20-30 meters of water, or an ADCP averaging period long enough to reduce observation uncertainty due to ship motion. Station-keeping is only performed at stations during passage of the ASC along the transect in one direction, in order to create a dataset where each individual station will have times as nearly equispaced as possible. If the vessel were to stop in both directions it would produce different temporal distribution of samples from stations near the center of the transect compared to samples near the ends of the transect. This would make the data more difficult to interpret and analyze.

The potential of ASCs for oceanographic sampling is illustrated by considering what an ASC could achieve if it had operational capabilities to continue repeat transect sampling for a week or more. An ASC with an average speed of 5 knots (about 2.5 m/s), could sample each of 10 stations, 2 km apart on an 18-km long transect, for 10 minutes about 4 times a day. This would achieve the oceanographic sampling goals described above very well. This specific set of parameters for repeat transect sampling is the baseline used throughout this thesis. It is motivated by currently underway development (see below) of a catamaran ASC capable of month-long endurance in coastal waters at 5 knots average speed.

Approach and Purpose of this Study

This thesis addresses aspects of two key operational challenges that need to be overcome before ASCs can approach their full potential usefulness to oceanographers. The first is site planning of long duration deployments, which must balance oceanographic sampling goals against risk of collision with other vessel traffic in busy coastal waterways. The second is the capability for ASCs to perform collision avoidance with other vessels, using on-board software they host.

The ASC most relevant to this study is the Surveying Coastal Autonomous Profiler (SCOAP) (Figure **2**) which is an 11m long catamaran custom built by Searobotics (www.searobotics.com) with a design that emphasizes capabilities for long duration deployments (weeks at average speed of 5 knots) and seaworthiness in coastal waters.

In Chapter 2 an AIS-based site planning exercise is carried out as motivated by the culminating deployment (slated for later this year) of the current phase of SCOAP development. The target site is Rhode Island Sound (RIS) and the goal is for SCOAP to collect ADCP current observations on a repeat transect for a period of a few weeks or more. Archived historical AIS data from RIS are used to characterize traffic of AIS-equipped vessels in the area and guide the choice of location and sampling parameters for the repeat transect.

In Chapter 3, the MIH software framework is used to simulate an ASC carrying out repeat transect sampling in the presence of traffic vessels that cross the sampled transect. The characteristics of CA maneuvers carried out by the ASC are investigated and described. Sensitivity of the resulting CA encounter statistics to various parameters of the transect sampling, vessel traffic, and CA algorithm are also investigated.

In Chapter 4, practical implications of ASC operations are examined specifically as they relate to the USCG Collision Avoidance Regulations (COLREGS). A framework of optimum methods for attempted COLREG compliance by an ASCs is developed and applied to a few ASC applications. Associated implications for on-board CA software are considered.

A summary and conclusions are given in Chapter 5.

Figure 1 Schematic of repeat transect sampling.

The ASC first travels in one direction stopping at each station to station-keep, until reaching the end of the transect. It then proceeds directly to the first point before repeating the cycle.

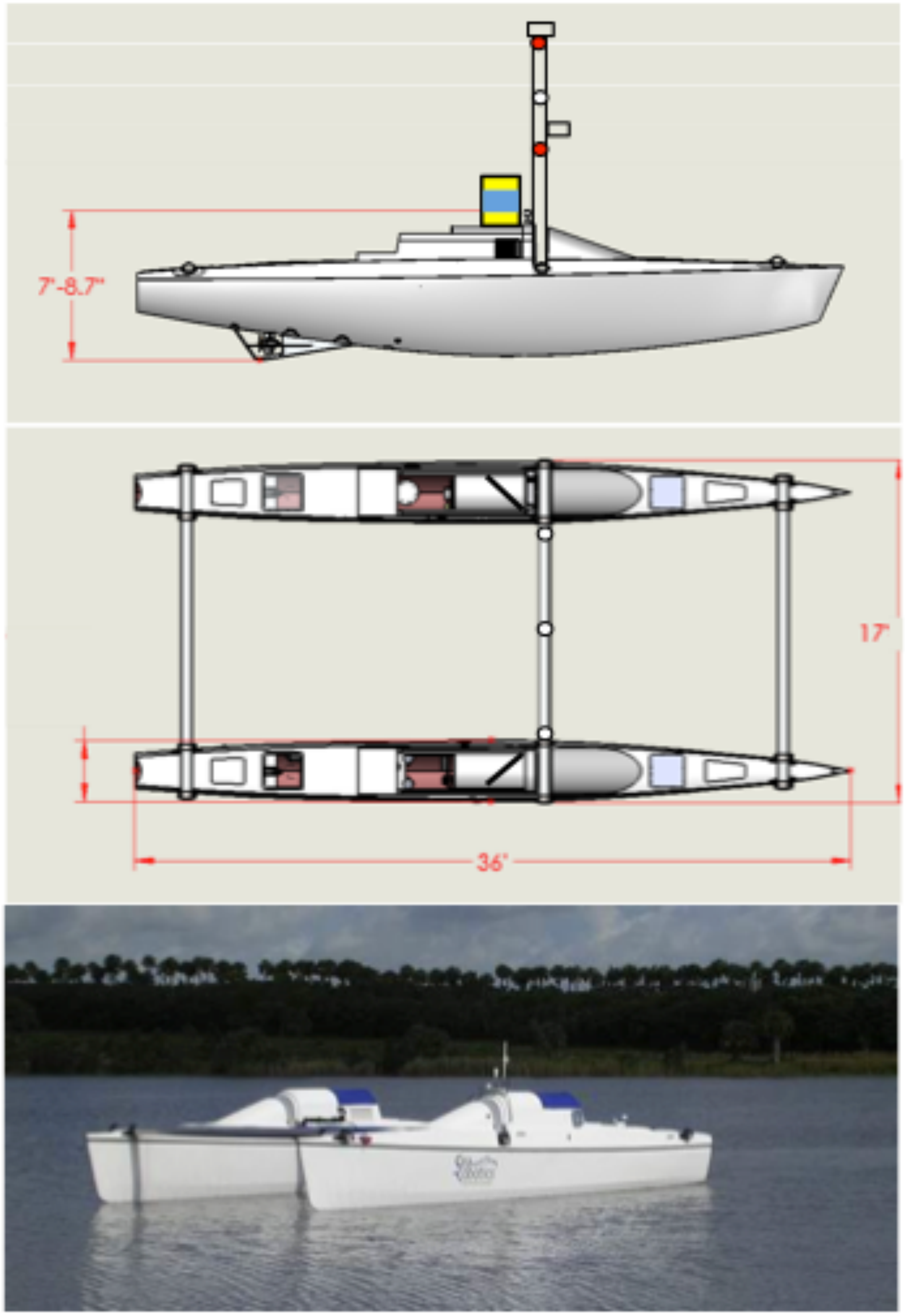


Figure 2 The SCOAP ASC.

Upper two frames are design drawings displaying tri-mast superstructure for lighting, and International Code Flag D rigid replicas, as required by the USCG. Bottom frame is a photo during trials (no tri-mast nor code flags) on a pond in Florida.

Chapter 2. Historical AIS Data for ASC Deployment Planning

Introduction

The Automatic Identification System (AIS) is a system for monitoring ship traffic by marine vessels, ground stations and aircraft using Very High Frequency (VHF) radio (Arroyo, 2011). AIS is required on commercial vessels over 300 tons and all passenger vessels, and is becoming more common on smaller recreational vessels. Each vessel is assigned a unique identification number known as a Maritime Mobile Service Identity (MMSI) and hosts an AIS transceiver. Vessel information such as position, speed, and heading is transmitted in real time to other vessels, where the course and closest point of approach for each vessel can be calculated and displayed, aiding vessel operators with navigation planning and CA.

Historical AIS data are useful for planning an ASC deployment. The spatial coverage allows areas with high traffic density, such as shipping lanes, to be identified and the frequency of passage of AIS-equipped vessels to be quantified. Time series historical data also allows the seasonality and inter-annual changes in vessel traffic to be determined.

Two concrete examples of hypothetical oceanographic sampling goals the SCOAP ASC could target in its RIS deployment are as follows (Figure **3**). First, observations to test the hypothesis of water entering southeastern RIS from the offshore shelf area of Nantucket Shoals (Codiga & Ullman, 2010) could be the aim. In order to sample this area the transect would be located in a far south and east position (E on Figure **3**). A second potential goal is to sample the exchange of water between northern RIS and Narragansett Bay. In this case the transect would be positioned at the farthest north and west location (A in Figure **3**).

Hypothetical ASC deployments can be used with historical AIS data to estimate the number of potential encounters with other vessels. Sensitivity to the location, speed, and station keep duration of the repeat transect the ASC will be sampling can be investigated.

The first purpose of this chapter is to use archived AIS data to characterize geographic and seasonal patterns in vessel traffic density for RIS and its surrounding areas. Using this information the number of encounters an ASC will have when executing a repeat transect survey is then quantified as a function of transect location and sampling parameters. The results are useful to guide optimal choices for location and sampling parameters of the ASC deployment to balance operational risk against desired oceanographic sampling.

Methods

Archived AIS data is publically available through the website MarineCadastre.gov, for the years 2009 and 2010, in the form of ARC GIS Geodatabase files (Taylor & Stein, 2012). Data were downloaded into ARC Map 10 using computing resources available at the Graduate School of Oceanography and the Marine Affairs Department of the University of Rhode Island. To create records of each ship position fix data, the raw AIS data were loaded into ARC Map and the clip tool was used to reduce it to the RIS area. The Add XY tool was used to add the XY coordinates to each data point followed by exporting as a table within a txt file that was loaded into Matlab. The result, which is referred to as "points" data, has a timestamp for each fix but the data is not organized into groups showing the paths and motions of individual vessels.

To create “tracks” data, or groups of fixes corresponding to the paths of specific vessels, tools for ARC Map created by Applied Science Associates (Kingston, RI) were used (Taylor & Stein, 2012). These tools clip the raw data into the same area of interest and create individual ship tracks from the raw points data provided. These ship tracks were then saved into shape files and exported from ARC Map in that format, then imported to Matlab. The result has fixes grouped by ship track, with a starting time for each track but no timestamp corresponding to each individual fix.

The “points” and “tracks” data were merged in order to generate the final raw dataset required for the potential encounter calculations. The merging was accomplished by identifying matches in the lat, lon, and MMSI number. This created a dataset of vessel tracks, each of which has a series of fixes with associated times.

The density of vessel traffic was quantified in terms of Track Frequency (TF), defined as the average number of tracks per day within a specified grid area during a specified time period. Square lat-lon grid areas with resolution 0.5 km were considered optimal based on comparisons to 1 km and 0.25 km treatments. TF was computed for individual month time periods first (see for example, Figure **4**), then groups of three months were averaged to produce seasonal Track Frequency (Winter = Jan, Feb, Mar; Spring = Apr, May, Jun; Summer = Jul, Aug, Sep; Fall = Oct, Nov, Dec). Each month included sampling every day except for June 2009, which only had four days of data; when the seasonal means were computed from monthly results, they were weighted based on the number of days sampled during each month. Seasonal results were computed for 2009 and 2010 individually, as well as for both years combined. For clarity in figures the quantity plotted is the base-10 logarithm of TF, $\log_{10}$(TF+C), where C = $1\text{x}10^{-5}$ is a small constant offset to prevent unbounded values where TF is zero. Values of 2,1,0, -1 for the $\log_{10}$(TF+C) in the figures thus correspond to TF of 100,10,1,and 0.1 ship-tracks per day, respectively.

Comparisons of TF from individual years 2009 and 2010 to each other were made using the fractional change (FC),

$$FC = \frac{(TF_{2010} - TF_{2009})}{(\frac{TF_{2010} + TF_{2009}}{2})}$$

Fractional change was only computed for 0.5km square grid regions for which both TF_{2009} and TF_{2010} were non-zero. FC is a unit-less value where a positive value indicates TF 2010 increased compared to TF 2009 and vice versa for negative values. For example, an FC value of 0.5 or 1 corresponds to increases of TF2010 relative to TF2009 by an amount equal to 50% or 100%, respectively, of the mean between TF2009 and TF2010.

Potential encounters of a hypothetical ASC on a repeat transect survey with historical AIS tracks were determined as follows. First, the time and position information for the ASC track was determined by specifying its average speed, the length of the transect, the number of stations along the transect, the duration of the station keep at each station (see Figure **3**), and the start time and duration (falling during the period of the historical AIS data) of the sampling. Next, for each timestep (using 0.5 minute resolution), the historical AIS data was searched for any track that passed within a threshold distance (800m, 400 m, 200m) of the ASC location at that timestep within a threshold time interval (4, 2, 1 minutes respectively) of that timestep. Such tracks represent potential encounters with other vessels that would require CA maneuvers, and were compiled. The baseline case was a one-month duration deployment with the ASC moving at 5 knots along an 18 km long transect with 10 stations and stopping for 10 minutes at each station, using the 400m and 2-minute thresholds.

To investigate sensitivity to the position of the transect, results were computed using July 2009 AIS data for 5 locations of the transect, spanning from southeastern RIS to near the mouth of Narragansett Bay (Figure **3**). To investigate sensitivity of the results to the seasonal and interannual variations, the results for the transect nearest to Narragansett Bay were computed using one-month intervals in January, April, July, and October of 2009 and 2010. To investigate sensitivity to the station-keep duration, the July 2009 results for this same transect location were compared to cases with 0, 20, and 30 minute station-keep durations. To investigate sensitivity to the ASC speed, the July 2009 case on the same transect was compared to an ASC at speeds of 1.5 m/s and 3.5 m/s, instead of 2.5 m/s.

Results

Geographic and seasonal patterns of variability in historical AIS data

Seasonal TF in the RIS area (Figure **5**, Figure **6**, and Figure 7) shows several clear patterns. The most heavily trafficked areas are concentrated in the shipping lanes into Narragansett Bay, consisting of north-south oriented inbound and outbound lanes to the east of Block Island The second primary shipping lane runs east west just to the south of the Rhode Island coastline, between Block Island Sound in the west and Buzzards Bay in the east, in which lies the Cape Cod Canal. Each of these primary-shipping lanes is heavily trafficked (Figure 7) with up to 5-8 tracks/day in all seasons of both 2009 and 2010.

There are also several secondary shipping lanes visible in the TF maps. These are primarily from Block Island to Point Judith and from the Atlantic Ocean into the East-West shipping lane. The Block Island to Point Judith lane has the most traffic due to the ferries that travel this route year round, as well as recreational vessels during the summer months (TF of 5-8 tracks/day). This route sees a significant reduction in traffic during the winter months (TF of 1-3 tracks/day), in response to reduced tourist visits to Block Island during that season. The next most travelled secondary lane is from the open ocean, joining the East-West travel lane to the Cape Cod Canal, with a secondary lane around the Elizabeth Islands in eastern RIS. These are slightly less traveled than the main shipping lanes with seasonal TF in the range of 0.5 to 1 tracks/day.

Beyond the shipping lanes there are several other patterns in seasonal TF. Common paths for ships lead from the ocean into Narragansett Bay and between many ports within Rhode Island Sound. However, in contrast to shipping lanes, these tracks are dispersed geographically, with seasonal TF in the range of 0.1 to 0.01 tracks/day or as low as one ship every hundred days over the course of a season.

A main component of seasonal variability is large increases to TF in the primary shipping lanes during the summer (range 5-8) compared to winter (range 1.25-2.5). TF is slightly higher in spring (range 2.5-4.5) than fall (range 2.0-4.0). In the primary shipping lanes, during the summer months more traffic goes into Narragansett Bay destined for Quonset, Providence, and Fall River ports, while during the winter more shipping traffic travels east-west through Rhode Island Sound to and from the Cape Cod Canal via Buzzards Bay. Outside the main shipping lanes, during the spring and summer the geographic spread of non-zero TF is enhanced compared to the fall and winter.

Differences in seasonal TF between 2010 and 2009 (Figure **8**) include a minor but notable decrease (FC range -0.5 to -1.0) in vessel traffic in the primary shipping lanes. However the secondary shipping lanes from the Atlantic Ocean to and from Buzzards Bay and the Cape Cod Canal experience an increase (FC range 0.5-1) from 2009 to 2010. This is most apparent in the spring season, which shows a large increase in traffic between the southwest and northeast corners of RIS, in 2010 compared to 2009. There is also an increase in 2010 TF relative to 2009 for ship traffic between the Atlantic southeast or RIS and Narragansett Bay. The most extreme increase in 2010 is in the area just south of the Rhode Island coast east of Newport where there is a large increase in ships leaving Narragansett Bay and traveling to the Cape Cod Canal. The area immediately west of Block Island also shows a significant increase even though this is not part of any specific shipping lane.

Encounter statistics of repeat transect ASC sampling

The number of encounters with historical AIS vessel tracks, for the base case ASC repeat transect sampling for one month during July 2009 along the five transects A-E in Figure **3**, was 24,6,6,1, and 1 respectively (Figure **9**a), with threshold values of 400m and 2 min. As expected, the number of encounters decreases when the transect moves from the area near the mouth of Narragansett Bay that includes multiple shipping lanes to the relatively low-traffic areas of southeastern RIS (see Figure 7).

For threshold values of 800m/4min or 200m/1min, the number of encounters increased and decreased approximately linearly (Figure **10**). Based on four seasonally-distributed one-month intervals, during both 2009 and 2010, at Transect A there was (Figure **9**b) a mean of 14.6 encounters and standard deviation of 6.3 encounters, with peak numbers of encounters occurring in summer of both years as consistent with the above descriptions of TF results. Based on the results of transect A the influence of station-keep duration (Figure **9**c) and ASC speed variations (Figure **9**d) on the number of encounters is minor compared to the temporal variability (given the 6.3 encounter standard deviation in Figure **9**b).

The AIS data also provide information about the characteristics of vessels the ASC is likely to encounter (Table **1**). The average length of AIS equipped vessels is greater than 60m and increases with distance from shore. More than 80% of vessels are underway using their engine, with only a small percentage underway sailing. The percentage of cargo ships, fishing vessels, and tankers increases with distance from shore. Pleasure craft, tugs, and tows are more prevalent near shore.

Discussion

The results for seasonal TF based on AIS (Figure **5**, Figure **6**, and Figure 7) suggest the area of southeastern RIS, where ASC sampling could target investigation of hypothesized inflow to RIS from the shelf (Transect E Figure **3**) has lower risk for collision than other nearby areas where there are shipping lanes. At Transect E, TF is about 0.01-0.1 tracks/day on average, or at most one track about every 10 days. The tracks are dispersed geographically and are more numerous in summer (0.01-0.1 tracks/day) than winter (0.001-0.05 tracks/day). Operational risk could be reduced by sampling during non-summer seasons if the oceanographic aims were consistent with that.

In contrast, if ASC deployments were to be attempted in the primary shipping lanes such as Transect A (Figure **3**), to investigate exchange between Narragansett Bay and northern RIS, they would see on average 5-8 tracks/day, with little variability from season to season. The secondary shipping lanes are more seasonally variable, but also see consistent traffic. The Block Island shipping lane has a great increase in traffic during the summer (TF 5-8 tracks/day), however the Cape Cod Canal has more traffic in the winter (TF 3-5 tracks/day). It is clear that during the winter traffic is more constrained to the commercial shipping lanes with the decrease in recreational traffic.

Most traffic in the targeted area of RIS travels on a northwest-southeast course from Narragansett Bay outbound to the Atlantic Ocean. As the deployment approaches the coast the traffic tends to align on a more North-South, or alternatively East-West course. To the extent that the targeted transect orientation (east-west and slightly northeast-southwest) travel nearly parallel to other vessels will be minimized and potential multiple contacts with individual vessels reduced. The further the sampling line could be relocated toward the south and east, away from shipping lanes; the number of potential vessel conflicts may be reduced, and vice versa.

Based on comparisons between 2009 and 2010 AIS data (Figure **8**), inter-annual variations in ship activity are significant. The main factors thought to be driving differences between these two years are changes in the level of economic activity, and the number of vessels equipped with AIS sensors. Economic activity can increase or decrease from year to year, while the number of vessels using AIS is expected to increase each year given that smaller vessels not required to use it are still increasingly adopting the technology. The general reduction in seasonal TF within shipping lanes, in 2010 relative to 2009, is likely due to changes in the economy. Outside shipping lanes, the increase in TF during 2010 relative to 2009 is consistent with increasing implementation of AIS technology on smaller vessels, for example west of Block Island (Figure **8**).

The quantitative calculations allow the operational constraints of each transect to be examined. Because of its position near shipping lanes the operational risk for sampling the NB-RIS exchange (transect A) is highest at about 15 +/- 6 potential collision avoidance encounters with other AIS-equipped vessels per month) than for sampling the Shelf-RIS inflow transect (about 0-2 potential encounters per month) which lies well outside the shipping lanes.

AIS is only required on commercial vessels of 300 tons or greater; therefore many smaller recreational vessels are not equipped with an AIS transponder. Vessels may also be equipped with receive only AIS transponders which are not counted in the collected data. Due to the nature of AIS the TF values within the data represent a lower bound of actual traffic an ASC would have to interact with. The targeted areas for SCOAP deployment could see substantially more ship traffic during the summer when recreational traffic is most active. The opinion of certain experienced RIS mariners (Pers. comm., P. LeBlanc, SafeSea Towing and Salvage, 2013) is that about 40-70% of vessels don’t have AIS, with higher percentages in summer. Based on the crude assumption that the geographic and temporal distributions of non AIS vessels are similar to those of AIS vessels, the number of total (AIS and non-AIS equipped vessels) encounters then scales up to about 40-90 per month at transect A and about 3-7 per month at Transect E.

AIS data provides important knowledge of vessel traffic patterns. It is clear that the percentage of pleasure craft is greatest closer to shore and decreases as the distance from shore increases. Most vessels offshore are large commercial vessels such as cargo ships and tankers. Tugs and tows are more common closer to shore. The average vessel size is much greater than the ASC in both areas but again increases with distance from shore. From this information it is clear that the near shore environment is much more crowded and challenging for the ASC with more numerous pleasure craft, tows, and smaller vessels.

The decision of whether to attempt oceanographic sampling at a given site should be based on the extent to which there is confidence that the CA capabilities of the ASC can successfully negotiate the corresponding estimated number of potential encounters per month. In combination the historical AIS observations and hypothesized repeat transect sampling scenarios have yielded a quantified measure of the extent to which operational risks differ between sites considered during the planning stages in preparation for an upcoming ASC deployment in RIS.

Table 1 AIS data vessel characteristics. Percentages do not sum to 100 because vessels not reporting or unassigned have been omitted.

Vessel Characteristics	Transect A	Transect E
Average Length	68.7m	93.9m
Status		
Underway Using Engine	81.2%	88.5%
Underway Sailing	1.6%	2.7%
Vessel Type		
Cargo Ships	10.4%	25.0%
Fishing	2.2%	12.5%
Pleasure Craft	31.7%	16.7%
Sailing	3.9%	12.5%
Tankers	11.3%	16.7%
Towing	6.5%	0%
Tugs	10.9%	0%

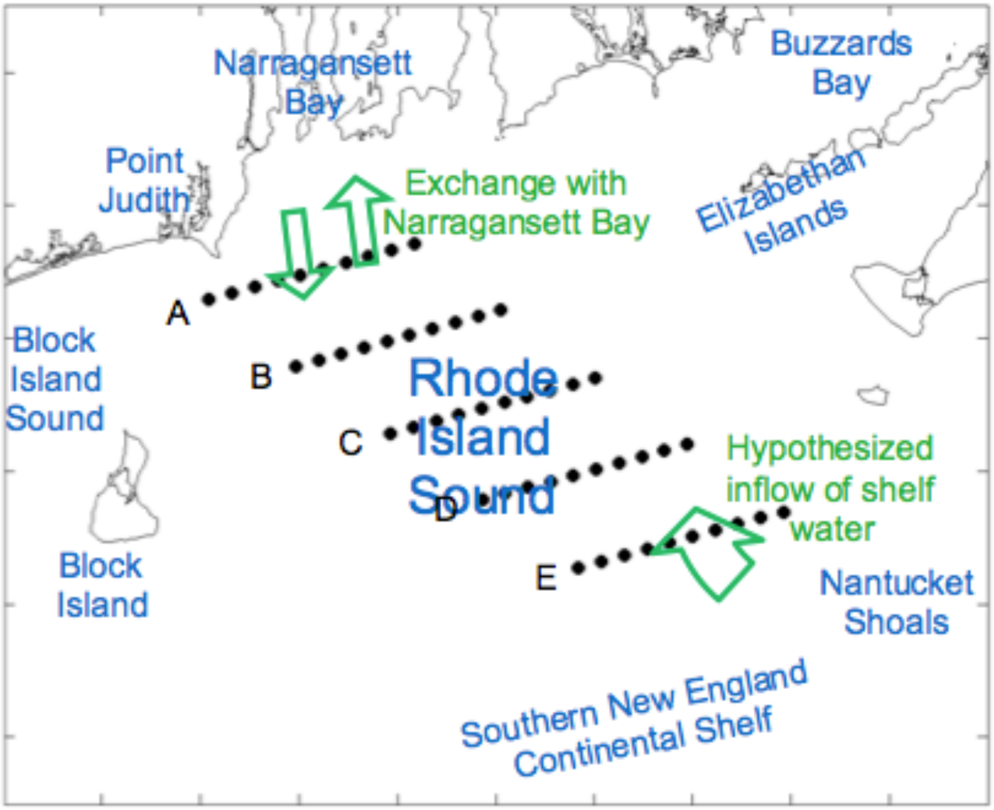


Figure 3 Map of hypothetical repeat transect sites for SCOAP deployment in RIS.

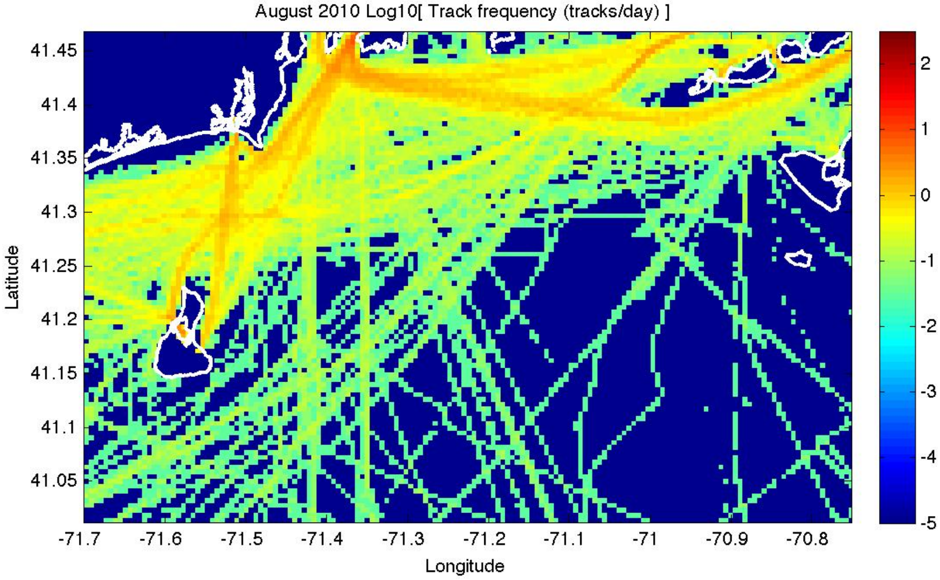


Figure 4 Track Frequency (TF), example from one month, August 2010.

The logarithm of the number of tracks per day during the one-month period August 2010. Values of 2, 1, 0, and -1 correspond to TF of 100, 10, 1, and 0.1 tracks per day.

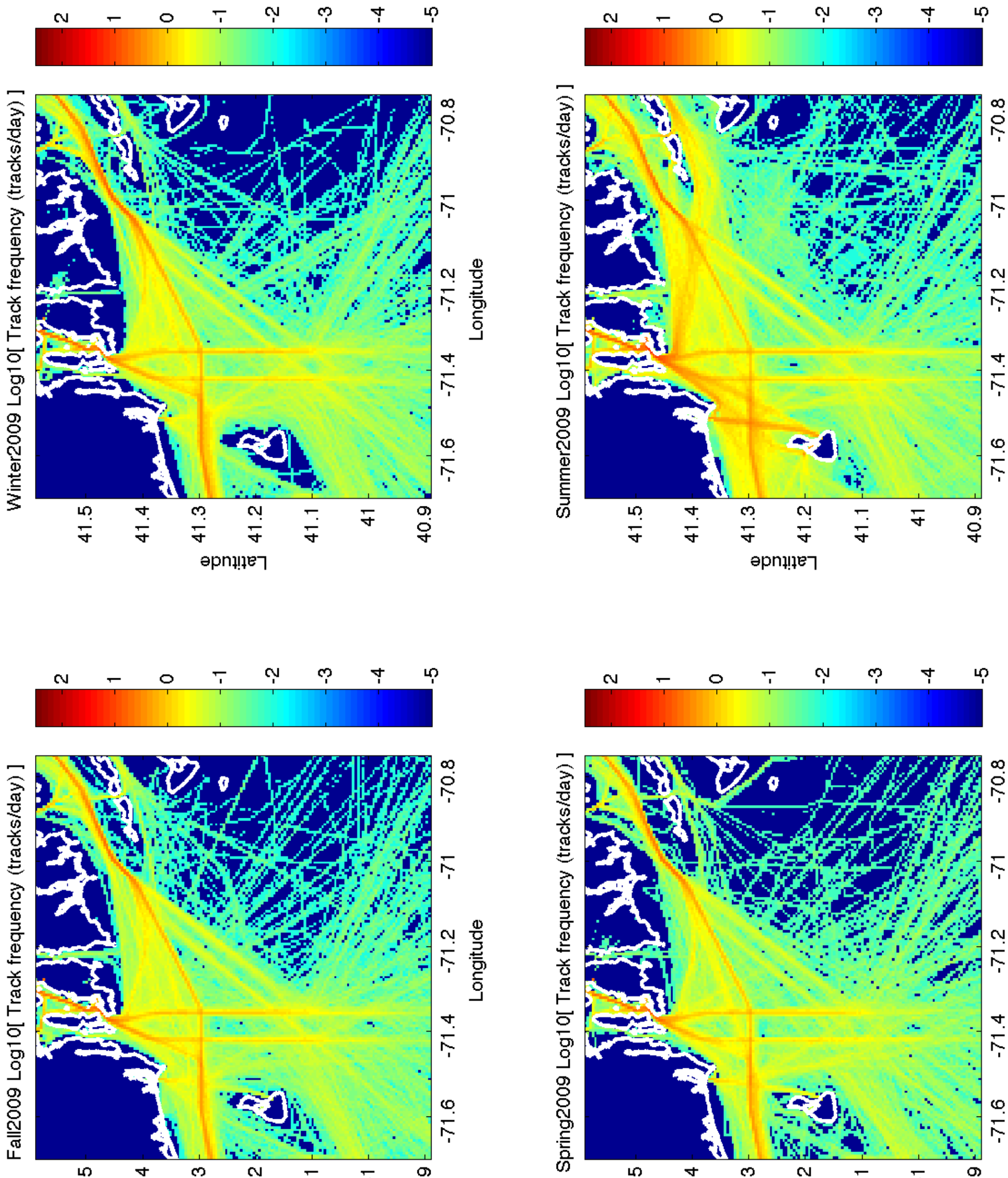


Figure 5 Seasonal Track Frequency using 2009 observations, shown as in Fig. 4.

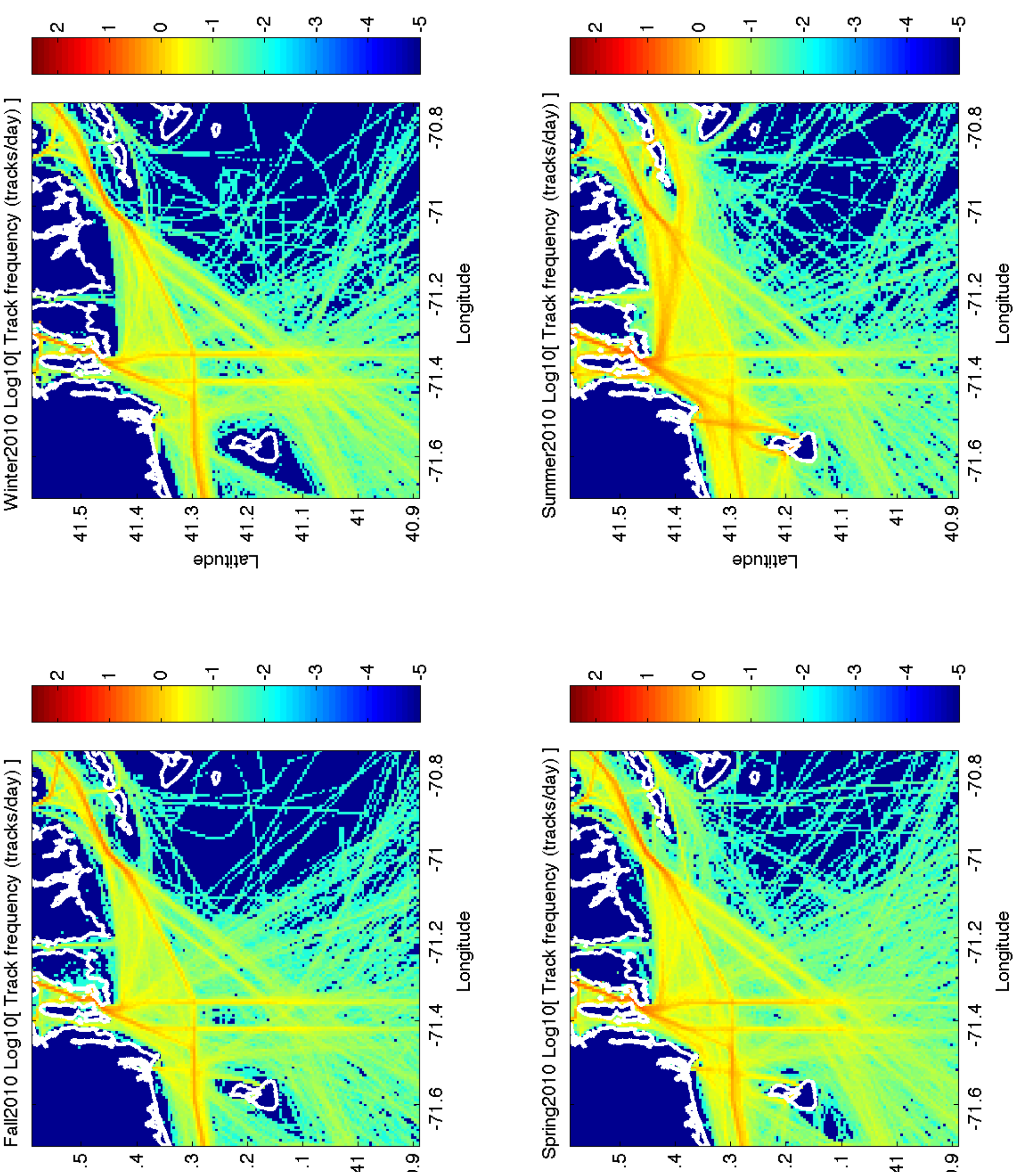


Figure 6 Seasonal Track Frequency using 2010 observations, shown as in Fig. 4.

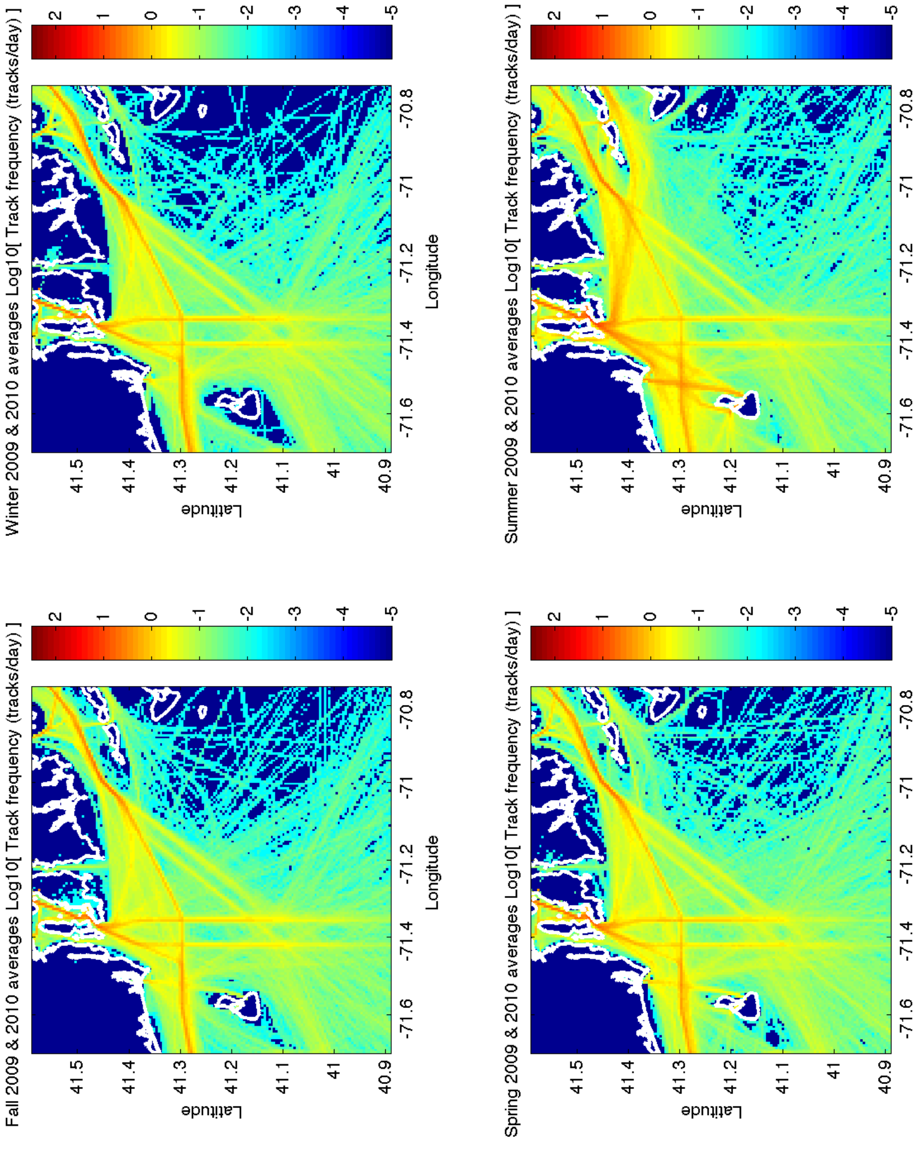


Figure 7 Seasonal TF of combined 2009 and 2010 observations, shown as in Fig. 4.

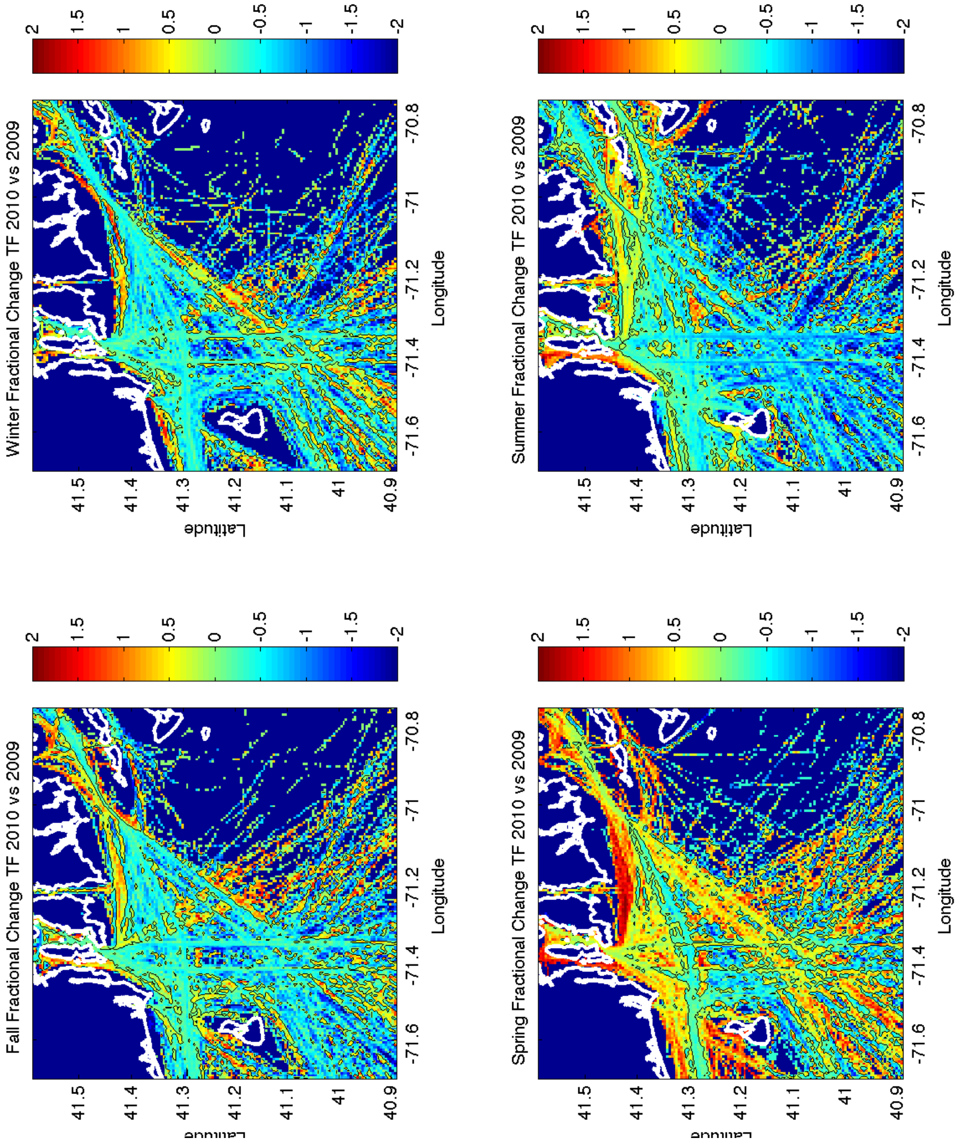


Figure 8 Fractional Change (FC) in TF 2010 vs 2009.

FC between 2010 and 2009 with the blue areas corresponding to a decrease in TF and the yellow and red areas showing an increase in TF. Black contour lines are plotted at the 1 and -1 levels (100% increase and decrease, respectively, of 2010 relative to 2009).

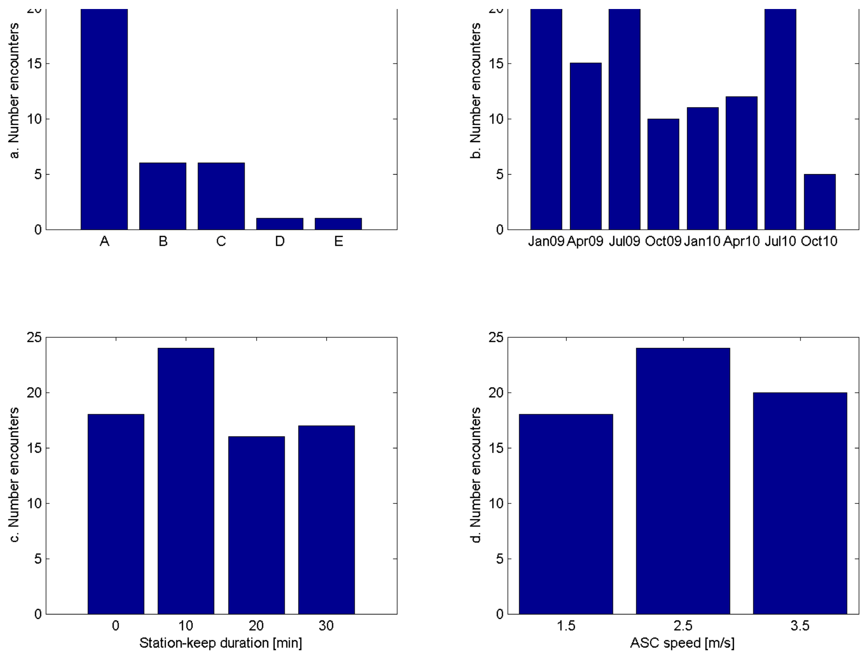


Figure 9 Number of potential vessel encounters for repeat transect ASC sampling.

(a) Geographically different transect locations (see Fig 3), for repeat transect sampling with 2.5 m/s ASC speed and 10 minute station-keep duration, using July 2009 historical AIS data. (b) Results for different one-month intervals, at Transect A, with speed and station-keep duration as in (a). (c) Dependence on station keep duration, for speed 2.5 m/s at Transect A, using July 2009. (d) Dependence on ASC speed variations, for 10 minute station keep at Transect A during July 2009.

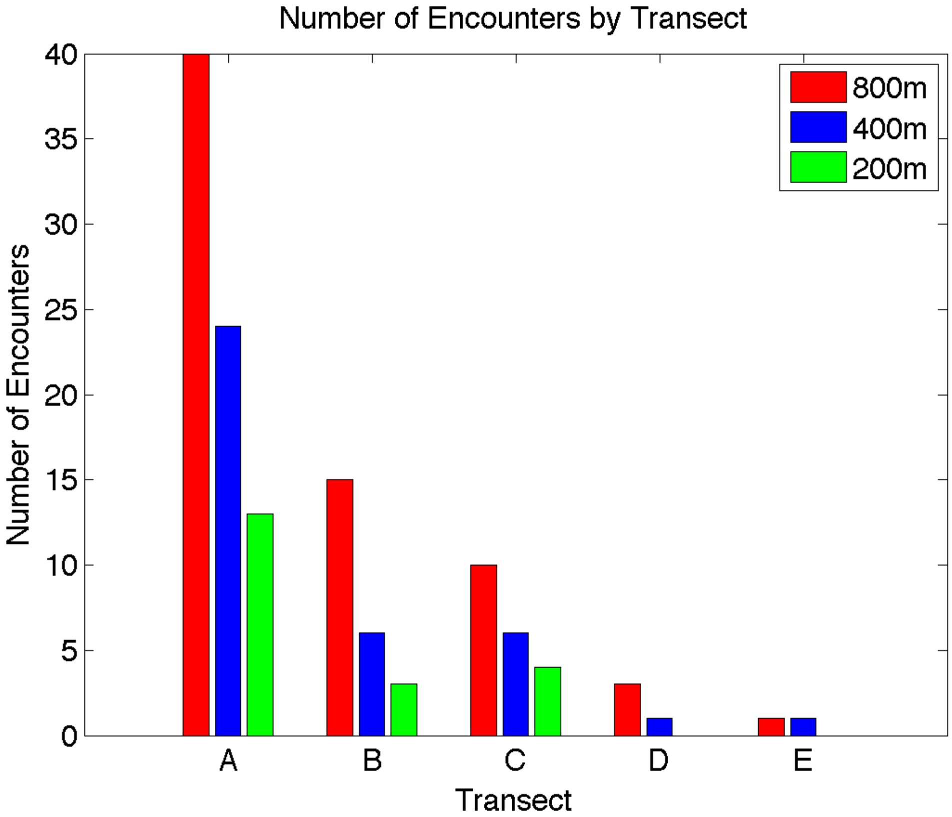


Figure 10 Sensitivity of potential encounters to threshold parameters, July 2009.

Results for 800m/4min, 400m/2min, and 200m/1min thresholds (blue bars are the base case shown in Fig 9).

Chapter 3. On-Board Collision Avoidance Software Simulations

Introduction

Mission Oriented Operating Suite (MOOS) is a robotics software framework developed in 2001, at Massachusetts Institute of Technology (MIT) with the US Navy to support operations with unmanned undersea vehicles, and later adapted to unmanned surface vehicles. MOOS follows a backseat driver paradigm (Figure 11) that effectively decouples vehicle control, such as the adjustment of actuators (rudders, motors, etc), and vehicle autonomy such as advanced decision making (heading, speed, etc). Individual modules each control a single area of the total vehicle system such as a PID (Proportional Integral Derivative) control or logging instruments. The modules are connected together and communicate using MOOS. Interval Programming Helm (IvP Helm) was developed in 2004 (Benjamin et al., 2012) as an autonomy suite for the MOOS which can determine vehicle path decisions based on simultaneously optimizing outcomes for multiple potentially competing objectives or "behaviors" (Figure 11).

The MOOS-IvP Helm (MIH) framework is an open source software platform that will be used on the SCOAP catamaran ASC. MIH-based autonomous CA software has been demonstrated using ASCs in simple scenarios (Benjamin, Curcio, Leonard, & Newman, 2006). In addition the MIH package includes tools for simulations of ASC maneuvers as determined by the IvP Helm algorithm, including multiple-vehicle scenarios that can be custom configured by the user. For these reasons, the MIH platform has been used here to simulate collision avoidance performance by an ASC carrying out oceanographic sampling along a repeat transect of the type described in the previous chapters.

Although collision avoidance at sea is governed by the US Coast Guard COLREGS (discussed in more detail in Chapter 4) the simulations performed in this chapter use CA algorithms that do not incorporate the COLREGS. As such these CA behaviors are neutral with respect to whether the ASC will alter course to the port or starboard side during encounters. The neutral behaviors also do not account for a determination of the give way and stand on vessel in an encounter situation. While not a complete solution for COLREGS compliance in practical applications the neutral CA software is a first step towards that, which can be built upon in order to implement a compliant solution.

What are the characteristics of CA maneuvers that an ASC will make, in order to avoid traffic vessels, when it carries out repeat-transect sampling? How does the number of CA encounters, and the time duration of each encounter, change as a function of (a) its station-keep duration, (b) whether traffic vessels pass through a station on its transect, (c) the angle of approach of the traffic vessels, and (d) whether or not the traffic vessels themselves are actively performing CA maneuvers? How reliable is the CA algorithm in resolving potential collision situations? The purpose of this chapter is to address these questions using MIH simulations.

Methods

The MIH vehicle simulation capability (Benjamin et al., 2012) is based on a simple vehicle state simulator (process “uSimMarine”) that operates based on present vehicle state and actuator inputs. Simulations rely on a contact manager utility process (“pBasicContactMgr”) that manages vessel contacts. In effect, the contact manager acts as a system for real-time transfer of vessel position and speed information among multiple vessels during simulation, akin to what AIS (see chapter 2) provides to a group of AIS-equipped vessels. Contact manager posts alerts based on vessel distance (Figure **12**) and calculated closest point of approach (CPA). A CPA-based “collision avoidance” behavior (Figure **13**) (Benjamin et al., 2006) can be spawned on a vessel by an alert, from the contact manager, of another vessel within range of potential collision. Once the avoid behavior is spawned its relative priority is given by the contact vessel’s distance according the priority weight radius (Figure **13**).

The baseline simulation configuration is as follows (Figure **14**). An ASC travels on a 4750 m long, east-west transect at a speed of about five knots (2.5 m/s). The ASC stops and station-keeps at waypoints at 0,250,1000,1750,2500,3250,4000 and 4750 meters when moving eastward along the transect, then returns directly to the westward end of the transect and repeats the cycle (see Figure **1**). The vessel transect and speed were chosen as a representation of a long duration ASC mission, but using a shorter inter-station distance (total transect length 4.75km instead of 15-20km) in order to make the simulation computationally faster by excluding long stretches when no vessel interactions could occur.

To generate numerous encounters with the ASC, nine traffic vessels are included. These traffic vessels travel on a north-south transect 1000 meters long, with each traffic vessel spaced every 500 meters apart, centered around the ASC transect (Figure **14**). The traffic vessel speeds (listed in Figure **14**) were purposefully chosen to be varying from vessel to vessel in an irregular way, but with an average across all vessels (~10 knots) and deviations from the average of a few knots, that are representative of real vessel traffic based on archived AIS data from southeastern RIS (see Figure 7).

The alert range was 50 meters and the CPA alert range was 75 meters (Figure **12**), the avoid behavior inner weighting distance was 50 meters and outer distance was 100 meters with a completed distance of 125 meters (Figure **13**). The duration of each simulated period was 24 hours, which was found to be long enough to generate a sufficiently high number of CA encounters for the purposes of this investigation.

An initial series of simulations was carried out using traffic vessels configured with no CA behaviors (Table **2**, upper section). The first simulation, BASE has the ASC stationkeeping for ten minutes at each station. The next two, SK0 and SK20 investigate the effect of varying ASC station-keep durations with times of 0, and 20 minutes. Next, simulations N22.5 and N45 investigate the effect of traffic vessel incidence angles of 22.5 and 45 degrees counter clockwise from due North, in contrast to the 0 degrees of BASE. To examine sensitivity to traffic vessel speeds that are (in contrast to BASE) slower than the ASC, a simulation (SLOW) was executed with ASC speed held at 2.5 m/s but traffic vessel speed reduced to a factor of 0.3, resulting in speeds of 1.65, 1.2, 1.5, 2, 1.35, 1.95, 1.65 and 1.2 m/s; to maintain the same frequency of crossing the ASC transect, the traffic vessel transect lengths were correspondingly reduced from 1000 to 300 meters. In another simulation, denoted LR for large radius, the collision avoidance radius parameters were all increased by 50 m.

A second group of simulations (Table **2**, lower section, suffix TCA for traffic CA) differed from the above runs only in that both the ASC and the traffic vessels actively performing CA maneuvers. The traffic vessel performed CA using the same algorithm as the ASC and radii parameters the same as in the BASE simulation.

Finally, a multivehicle simulation was created to force encounters with two traffic vessels at once. The ASC travelled back and forth at 2.5 m/s along an east-west transect 1km long which was intersected neat its center by two 1km long north-south transects 30m apart in the east west direction. A traffic vessel moved repeatedly back and forth on each north-south transect at 5m/s.

A MOOS utility (pLogger) recorded the navigation information and contact alerts of all vessels throughout the simulation, and other utilities (alogclip and alogrm) were used to isolate desired sections of the log files. The logs were loaded into Matlab where the vessel traffic alerts were parsed and used to determine the total number of contacts, the average time per contact, and the paths of the two vessels for each encounter.

Results

When traffic vessels are not actively performing CA three main types of ASC CA maneuver occur (Figure **15**): large deflection, course reversal, and leave/return station-keep. The large deflection encounter (Figure **15**a) occurs when two vessels are going to pass close to each other which forces a large deflection off course for the ASC, adjusting its course to go around the traffic vessel in order to prevent a collision.

In the course reversal encounter (Figure **15**b) the timing of the arrival of the traffic vessel causes it to effectively block the ASC path so the ASC changes heading until it turns around to keep a safe distance. Once the vessel passes the ASC turns back on its desired course and continues, in some cases requiring a 360 degree heading change.

The leave/return station-keep encounter (Figure **15**c) occurs when a traffic vessel approaches the ASC while the ASC is station keeping. The ASC is then forced to move away from the traffic vessel while attempting to maintain its station-keep position, usually resulting in a circle roughly starting and ending at the station-keep point. By following this circle the ASC can maintain as much distance as possible from the traffic vessel while staying as close as possible to the station keep point.

These CA paths change substantially when the traffic vessels are actively avoiding the ASC (Figure **16**). As expected the deflections tend to be smaller for the ASC, and greater for the traffic vessels (Figure **16**a). Since the vessel is actively avoiding the ASC the course reversal path effectively does not occur. A smaller displacement of the ASC occurs in the leave/return to stationkeep case, as the traffic vessel drives around the ASC (Figure **16**b); the avoidance of the traffic vessel can decrease the need for the ASC to leave its station keeping position so it will be able to stay much closer to the desired waypoint.

When the traffic vessel is incident at 22.5 or 45 degrees from North the above patterns are modified but generally in minor ways.

In 3% or fewer cases an atypical behavior occurs that leads to the ASC requiring a long period of time to depart from the traffic vessel, during which the two vessels are effectively "locked" with each other and moving together (Figure **17**). This behavior is more common in TCA cases but can also occur in non-TCA cases. It occurs more frequently when the speeds of the two vessels are similar to each other.

Statistics of the first group of simulations (non-TCA cases (Figure 18)) reveal that the number of encounters is approximately linearly related to the traffic vessel speed, leading to increases and decreases in the number of encounters of up to 25%. This is expected since the constant-length traffic vessel transects mean the number of times the traffic vessel will cross the ASC transect during the 24-hour simulation is proportional to the traffic vessel speed.

Comparing the base case of station keeping for 10 minutes to a non stationkeeping transect it is found (Figure **18**a) that stationkeeping for 10 minutes increases the number of contacts with the traffic vessels that are aligned with stations (TV2, TV5, and TV8) by approximately 100%. However since the ASC spends more time station keeping and the simulation duration is fixed, it reduces the number of contacts with the remaining vessels by approximately 25%. Taken in combination there is a net increase of contacts by approximately 20% when the ASC performs station-keeping. However, if none of the traffic vessels were aligned with a station-keep position the opposite would be true, as time spent station-keeping would decrease the time when encounters occur. Compared to the base case the number of contacts with vessels while station-keeping did not increase significantly in the longer station-keeping mission (SK20), but there were fewer contacts with traffic vessels that are not aligned with a station-keeping point. The 45-degree mission shows an increase in number of contacts and a decrease in time per encounter since the higher angle allows the traffic vessel to cover more horizontal distance therefore increasing the chances of an encounter at some point along the ASC transect.

The average time per encounter shows varying levels of sensitivity to the parameters that have been tested (Figure **18**b). There was little sensitivity to station keeping and station keep duration. Increasing the angle of traffic vessel encounters served to reduce time in contact. Increasing the alert radius (LR Simulations) served to increase the average time in contact from approximately 45 to 65 seconds since the longer distances of travel required to create more separation takes more time to resolve. Slower vehicle traffic vessels increase the average time per encounter to approximately 95 seconds per contact (Figure **18**b). This is due to the fact that slower vessels take much longer to resolve encounters, not only to cover ground, but also since speed differential does not create as much distance between the two vessels.

Similar trends hold true for the TCA avoidance simulations (Figure **19**). As expected, the station-keeping mission has much more contact with the vessels that intersect a station point and less contact with vessels that do not intersect the station points compared to the non station-keep simulation. The non-station-keeping mission has only slight variations in the amount of contacts with each vessel with 9 +/- 2 contacts with each vessel (Figure **19**). TCA creates minor differences in the number of contacts, and slight increases in time per encounter.

Finally an example (Figure **20**) from the multivehicle simulations illustrates the capability for the Helm autonomy software to trigger multiple instances of the CA algorithm simultaneously and prioritize them appropriately until they are resolved. The ASC first encounters the traffic vessel incident from the south, and responds by reversing toward the west and slightly north while the traffic vessel passes. Then the ASC detects the traffic vessel incident from the north and responds by moving southward and further west, until it also passes.

Discussion

The overall result of the simulations is that 97% or more of the CA maneuvers for an ASC doing repeat transect sampling do not substantially disrupt the mission of the ASC. Even those cases that cause relatively large disruptions to the ASC path, or force it away from its station-keep behavior, are nonetheless resolved without significant delay to the ASC on its sampling mission. The ability of the CA algorithm to reconcile multiple competing objectives and successfully avoid collisions while continuing to perform its oceanographic sampling mission shows the potential of the CA algorithm for real world encounters.

While the CA algorithm successfully resolves potential collisions it can cause ASC paths that are less efficient. An example is when the ASC vehicle reverses course (Figure **15**b) due to the fact that it is constrained to maintain a survey speed of 5 knots, which prevents it from slowing down, and it instead turns around and covers more ground to allow time for the traffic vessel to pass.

During 0-3% of the encounters a significantly longer time, during which the two vessels traveled together (Figure **17**), was required for the situation to be resolved. This behavior is thought mainly to be associated with the artificial nature of the identical CA behavior of the two vessels, and the fact that the simulations do not include conditions such as currents and winds, which would be expected to easily break the symmetry. If one vessel was not an ASC with the same CA algorithm, or if natural wind/current conditions were present, then these cases would be expected to occur less frequently.

The most pronounced change as a result of TCA is found when a traffic vessel interacts with a station-keeping vessel. Since the traffic vessel attempts to drive around the station-keeping vessel it does not require the station-keeping ASC to deviate greatly from its position, this is advantageous as it produces better quality data for oceanographic sampling.

The ASC was able to perform multiple vessel collision avoidance by prioritizing the vessels to avoid and performing the necessary collision avoidance maneuver for the vessel with the highest priority, then once that contact is resolved transitioning to avoid the next traffic vessel. This proves the CA algorithms to be capable of resolving multiple vessel encounters.

Table 2 Simulation parameters

Simulation Name	ASC Vessel Station Keep	Traffic Vessel Avoid	Notes
Non Traffic Collision Avoidance Simulations			
BASE	Yes	No	10 Min Station Keep
SK0	No	No	0 Min Station Keep
SK20	Yes	No	20 Min Station Keep
N22.5	Yes	No	Traffic transects 22.5 Degree from North
N45	Yes	No	45 Degree Angle
SLOW	Yes	No	Vessel Traffic Speed Reduced
LR	Yes	No	CA Radii Increased by 50 Meters
Multivehicle	No	No	See text for description
Traffic Collision Avoidance Simulations			
BASE_TCA	Yes	Yes	10 Min Station Keep
SK0_TCA	No	Yes	0 min Station Keep
SLOW_TCA	Yes	Yes	Vessel Traffic Speed Reduced
LR_TCA	Yes	Yes	CA Radii Increased by 50 Meters

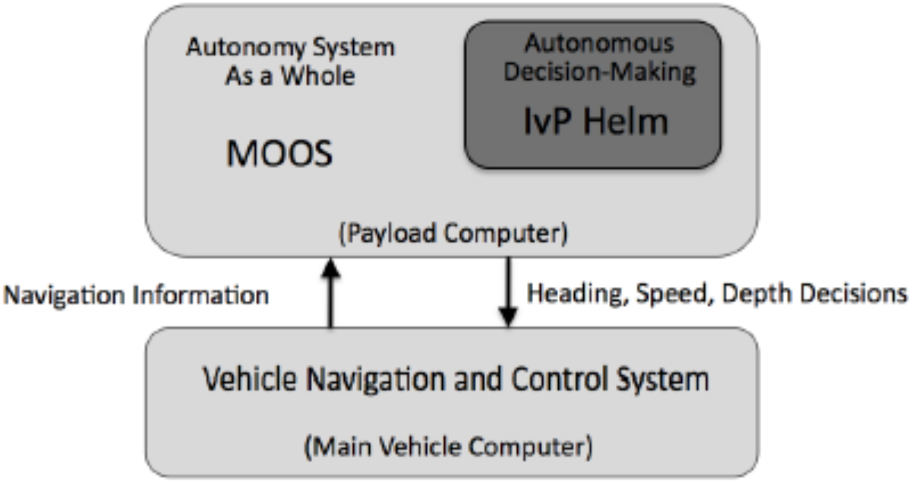


Figure 11 Overview Schematic of MOOS IvP Helm.

Backseat Driver System outlining main components. IvP Helm is an autonomous decision engine within MOOS. The MOOS autonomy system is driven by IvP Helm and interfaces with the control and navigation systems on the vehicle itself. From Benjamin et al. (2012).

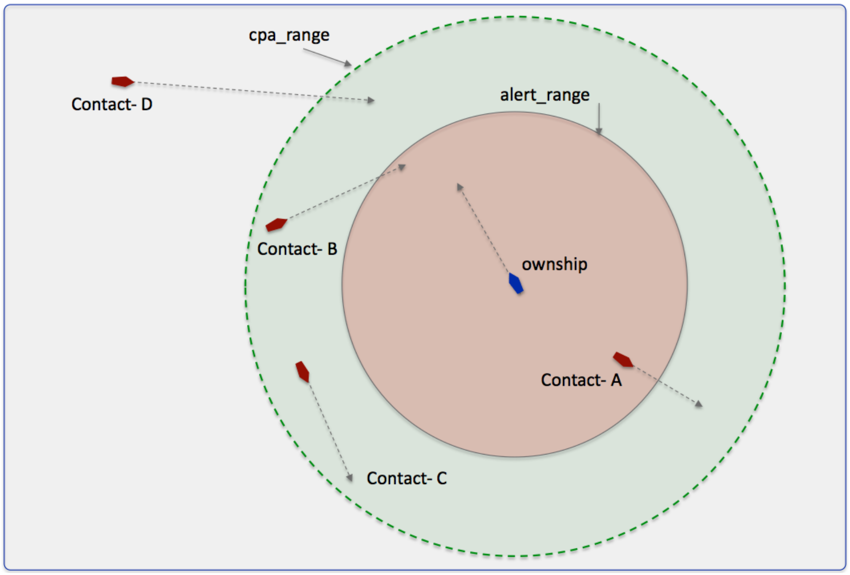


Figure 12 Illustration of the contact manager utility.

The red circle displays the Alert Range, vessels within this range create an alert. The green circle represents the Alert Closest Point of Approach Range, which triggers an alert if vessels are within this range and their calculated closest point of approach is within the alert range. From Benjamin et al. (2012).

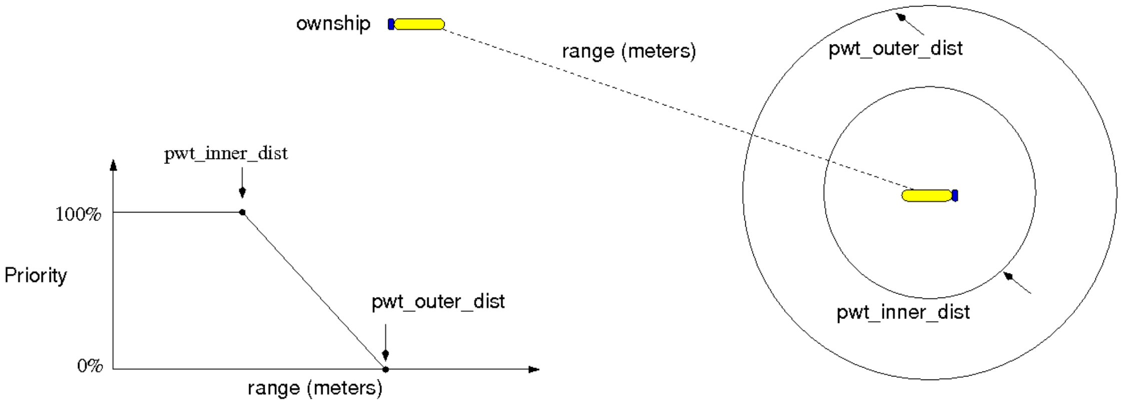


Figure 13 Priority weight radii definition in avoid behavior.

Avoid behavior uses an outer radius, beyond which the priority weight is 0% and an inner radius where the priority is 100% with the priority varying linearly between the two radii. From Benjamin et al. (2012).

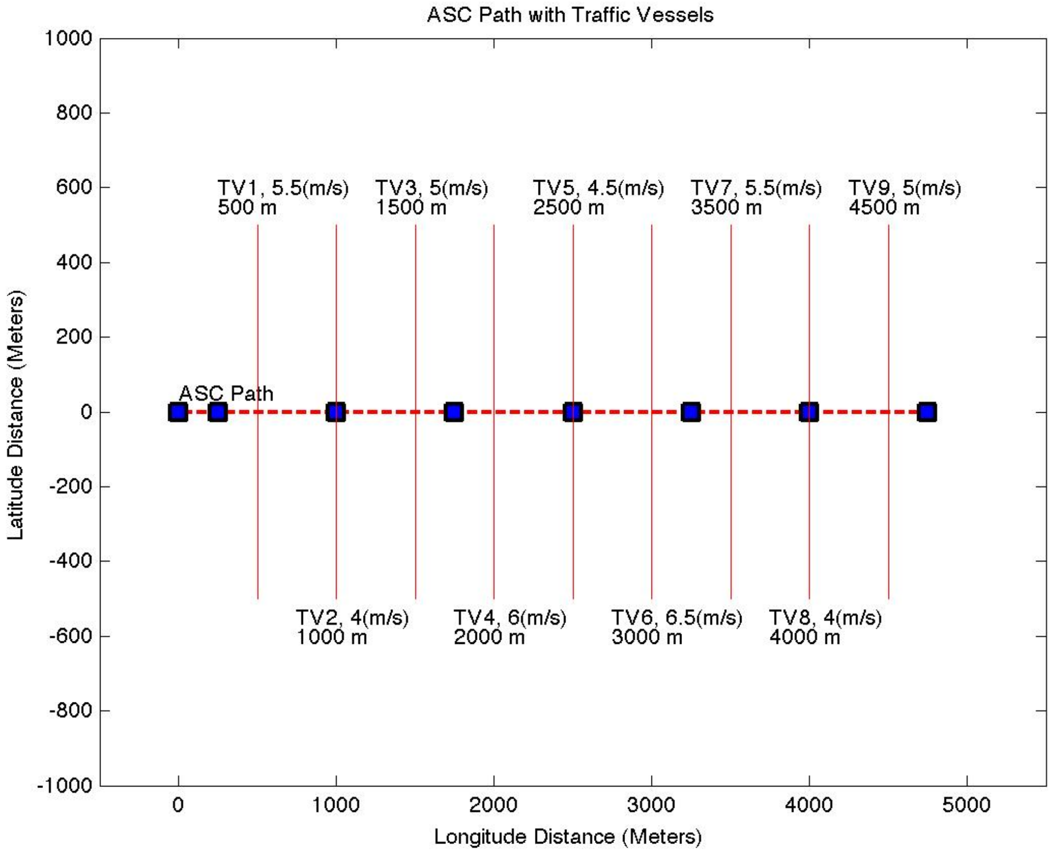


Figure 14 Configuration of repeat transect sampling CA simulations.

Blue boxes represent stationkeep points, the red dotted line is the travel path of the ASC and the red vertical lines are the paths of the traffic vessels. The ASC travels among the stations in the sequence shown in Figure 1. The traffic vessels travel back and forth from endpoint to endpoint along their tracks. Traffic vessel transects are labeled (odd above, even below) with vessel name, position and speed. Traffic Vessels 2, 5, and 8 intersect with an ASC stationkeep position.

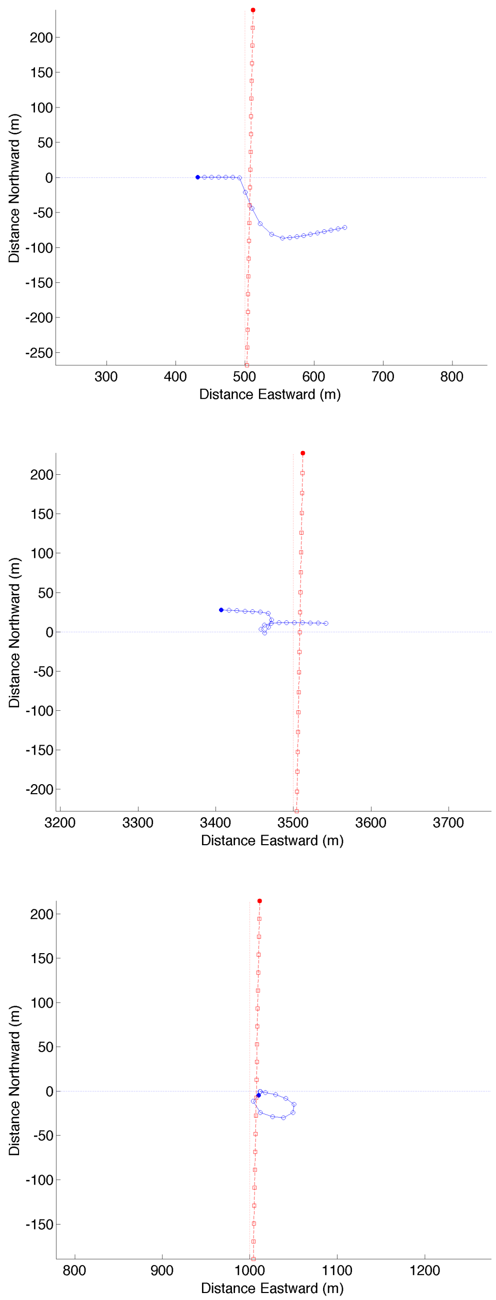


Figure 15 Three characteristic ASC CA maneuvers (non-TCA cases).

The ASC (blue) approaches from the east. The traffic vessel (red) approaches from the north. Solid circles show initial positions; other circles shown each 5 seconds. (a) Large Deflection encounter where ASC alters course around Traffic Vessel. (b) Course reversal encounter where ASC alters heading around in order to wait for traffic vessel to pass. (c) Station-keep encounter where ASC attempts to stay at station-keeping position while also avoiding traffic vessel.

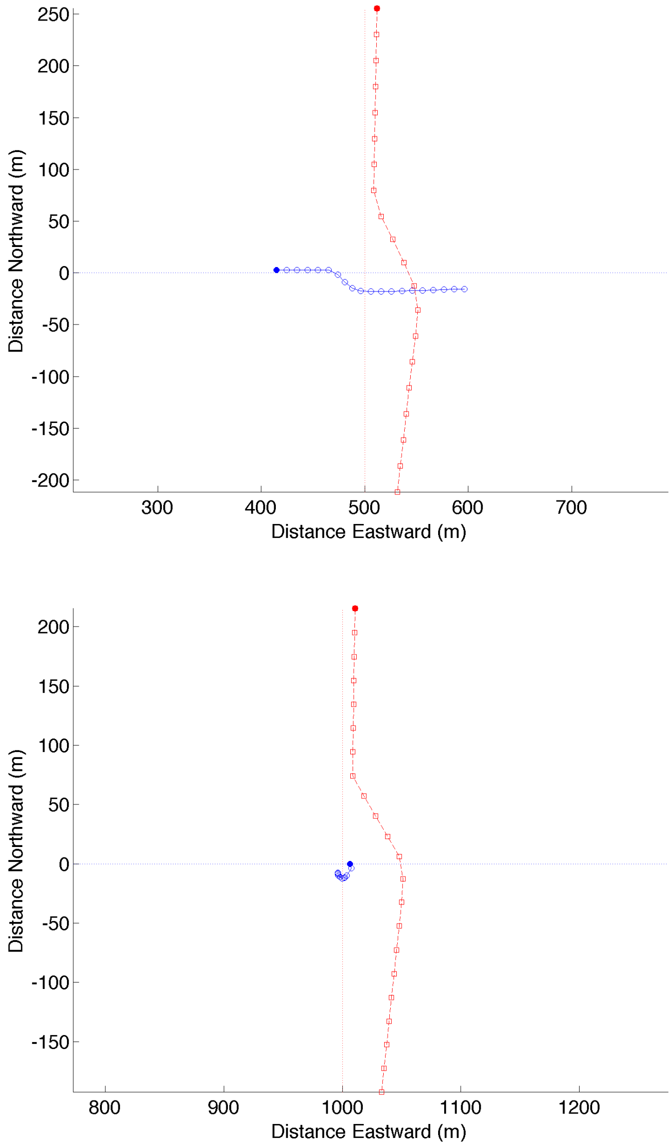


Figure 16 CA maneuvers, TCA cases, shown as in Fig 15.

(a) Large deflection encounter where both ASC and traffic vessel alter course to avoid each other. (b) Station-keep encounter where traffic vessel alters course to travel around ASC while ASC holds position at station-keeping point.

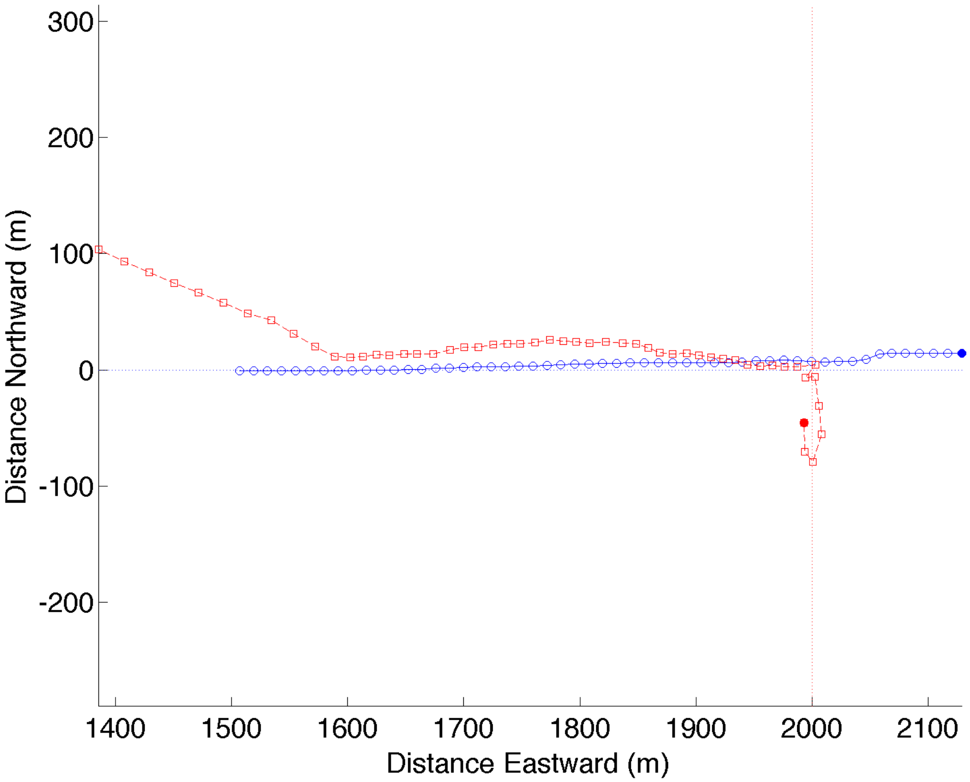


Figure 17 Atypical encounter.

TCA case in which the CA algorithm requires an extended period of time, during which the two vessels are “locked” with each other, before resolving the encounter.

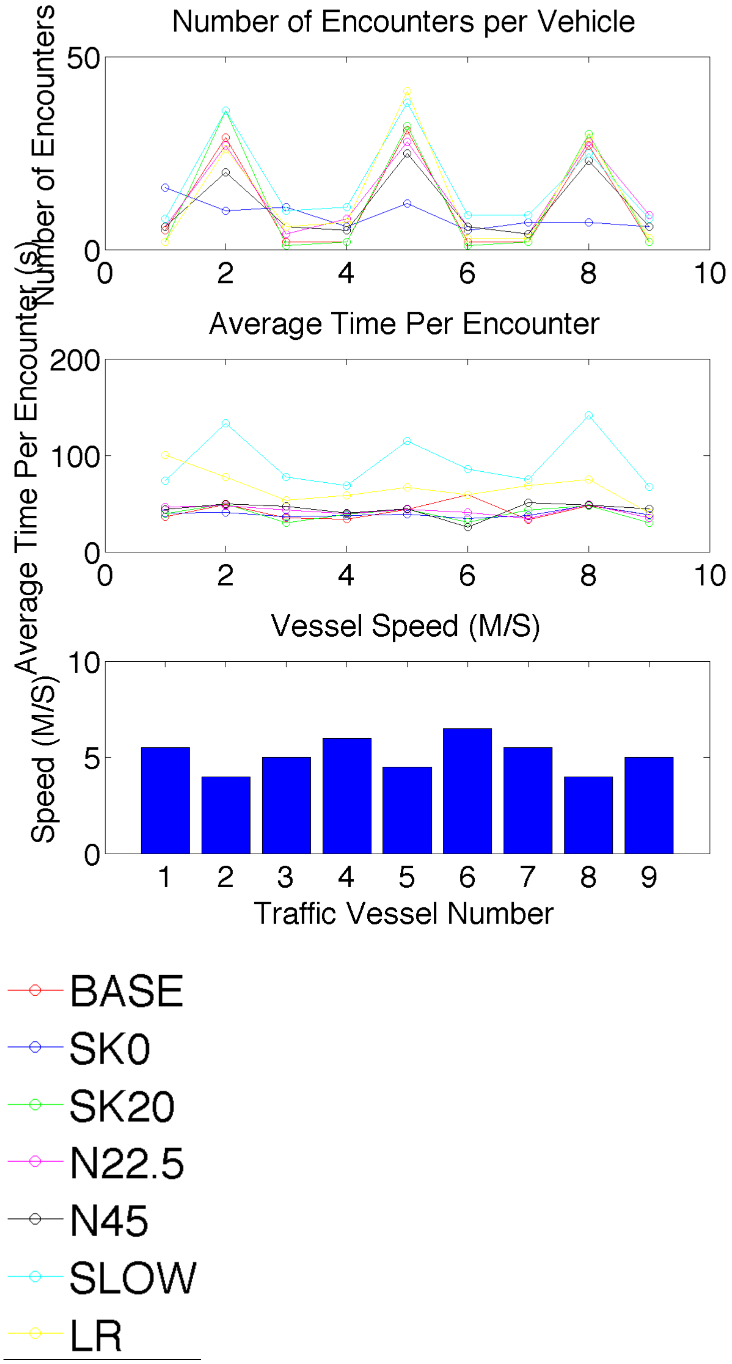


Figure 18 Encounter statistics of non-TCA simulations.

Legend refers to simulations denotations in Table 2. (a) The number of encounters with each traffic vessel during the simulation. (b) The average time of each encounter during the simulation in seconds. (c) Traffic Vessel Speed (in SLOW speeds are 0.3 times those shown).

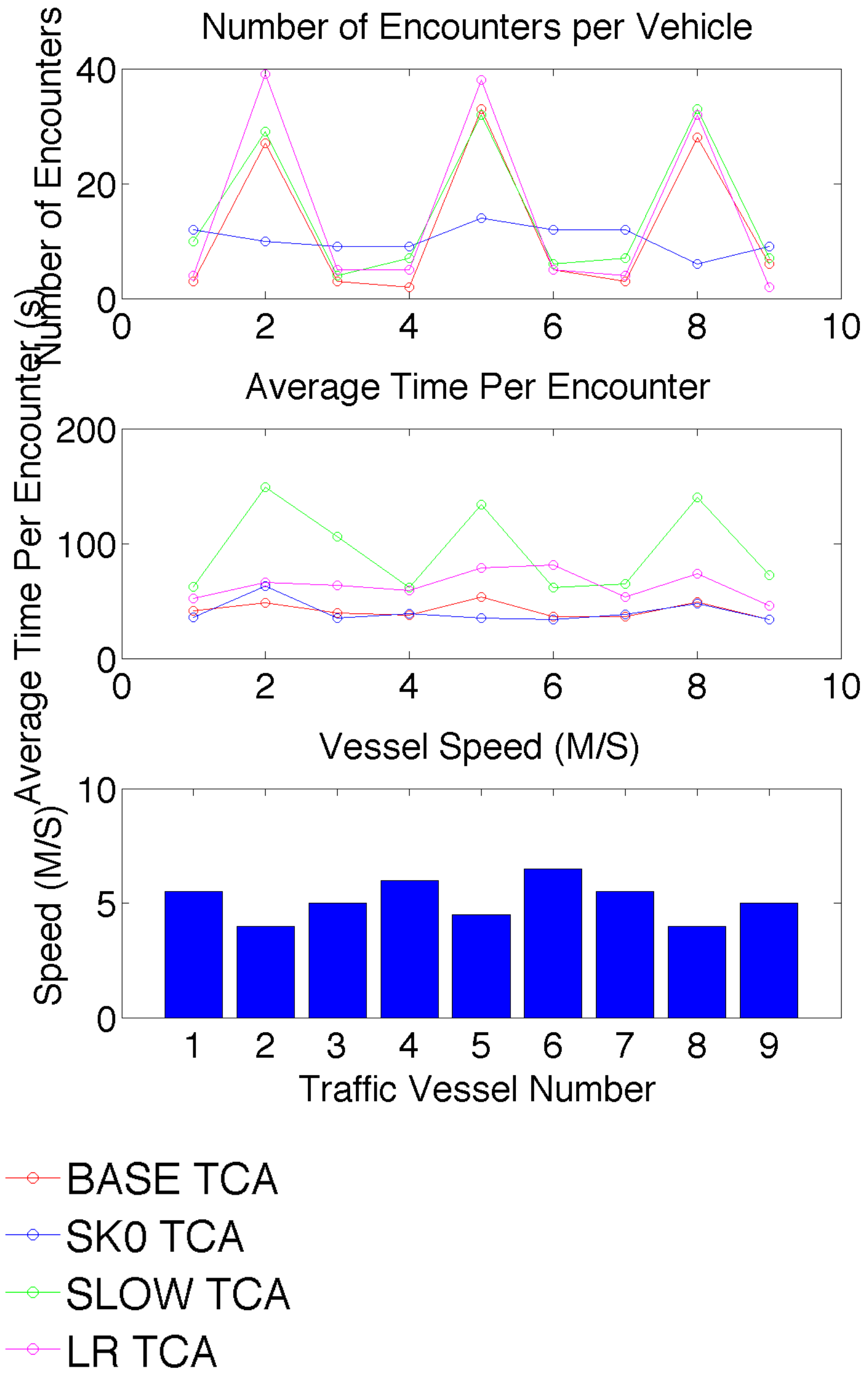


Figure 19 Encounter statistics of TCA simulations.

Shown as in Fig 18.

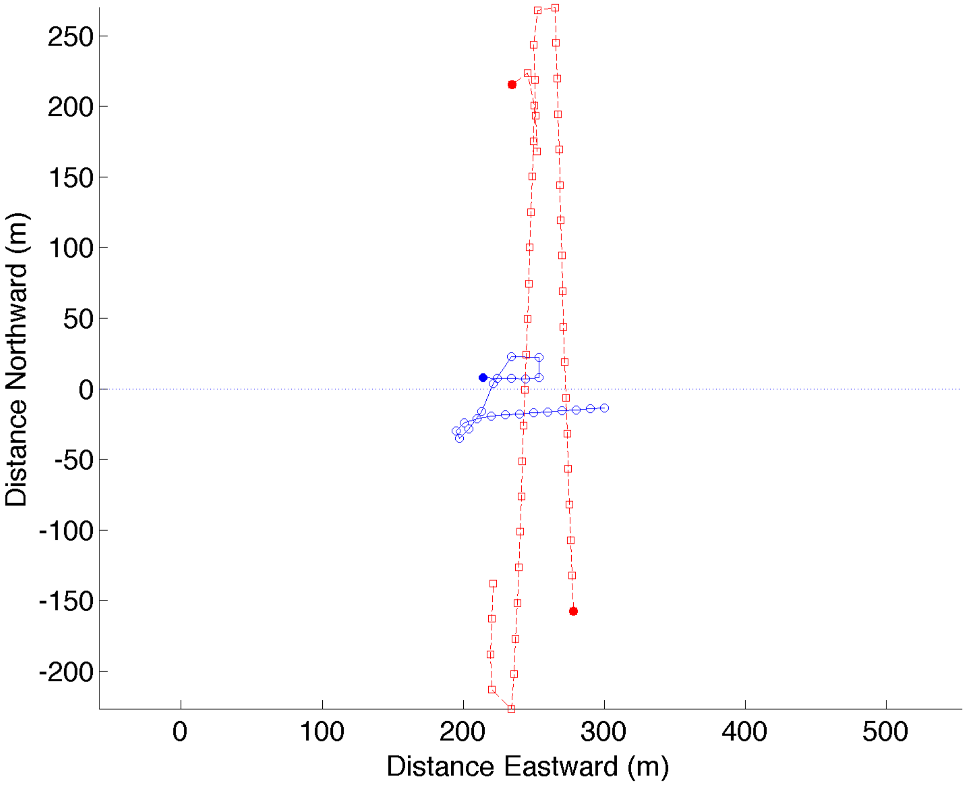


Figure 20 Multivehicle Encounter.

See text for description.

Chapter 4. ASC Operations in the Context of COLREGS

Introduction

The Collision Avoidance Regulations (COLREGS) developed by the US Coast Guard (USCG) (Commandant, 1999) are a collection of rules designed to prevent collisions at sea. They were developed prior to the existence of ASCs and have not yet formally been adapted for applicability to ASCs. Here, a framework of best practices to enable ASCs to operate in ways that would be most consistent with COLREGS compliance has been developed. The framework is applied to ASCs of multiple types and applications, with the prominent example of repeat transect oceanographic sampling as considered in earlier chapters. Recommendations are then made for desired capabilities of on-board autonomy software in the context of approaching COLREGS compliance.

Background on COLREGS

There are approximately 40 different sections or rules in the COLREGS covering varying aspects of shipping. They are explicitly written in order to allow for human judgment of relative maneuverability. The rules can be considered to fall into two groups: (a) prescribed navigation behaviors and (b) exceptions to the prescribed behaviors. In many potential collision scenarios, compliance with COLREGS is carried out through obeying a rule that consists of an exception to the prescribed behavior, as based on human judgment in the given situation.

The main prescribed behaviors of interest here are as follows. If two vessels are crossing each other at an angle, Rule 15 applies: the vessel that has the other vessel on its starboard (right) side is the "give way" vessel and must alter course to avoid collision; the other vessel, as the "stand-on" vessel, must hold its course (Figure **21**a, b). This situation places a large emphasis on relative speeds and maneuverability of the two vessels, which must be taken into account by their operators. If two vessels are approaching head-on Rule 14 applies, which has a prescribed behavior for both vessels to alter course to starboard (right) in order to avoid each other (Figure **21**d). In the case of a vessel holding station to perform a task other vessels must give way to it since it is stationary. All vessels must maintain a proper lookout at all times, consisting of a person watching for traffic vessels, such that human judgment can best be applied.

There are prominent examples of exceptions that are used to comply with the rules in practical situations. These include Rule 18, which establishes a precedence order for vessels having the highest priority to stand on. In order of decreasing precedence are vessels without an operator, vessels with restricted ability to maneuver, vessels engaged in fishing, sailing vessels, and power-driven vessels. Rule 8 is another important exception, covering levels of maneuverability: when a vessel otherwise expected to stand on is the more maneuverable of the two vessels, it can comply by instead giving way. This leads to the informal "Law of Gross Tonnage" where any vessel significantly larger than the other should be avoided as a practical solution that complies through exception. Other exceptions occur when due to specific situations vessels request a non-COLREGS resolution of encounters such as passing to starboard instead of to port as described by the rules, through real-time communication between vessel operators.

ASC Operations in the Context of COLREGS

The requirements for ASCs with respect to COLREGS compliance are currently unresolved and under active consideration by the CG and the Navigation Safety Advisory Council (NAVSAC). A large fraction of the COLREGS (not discussed above) involve horn signals, light signals, or other actions that it is unlikely ASCs will ever be engineered to carry out. It seems unlikely those components of COLREGS will ever be considered applicable to ASCs.

The recently passed NAVSAC Resolution 11-02 (NAVSAC, 2011) regarding unmanned vehicles addressed some COLREGS-relevant aspects of ASC operations. Its language implies (Allen, 2012) that unmanned vehicles which are making navigation decisions autonomously (i.e. by on-board software, “machine-controlled”) will be exempt from the lookout requirement, while those that are operated remotely or “tele-operated” (human controlled) will not. Resolution 11-02 also states that an ASC with size and characteristics of SCOAP must be marked (as shown in Figure **2**) with all-round red over white over red lights at 4m/3m/2m height above the gunwale, as well as the international code flag D, in order to signify that it is limited in its ability to maneuver.

These considerations lead to the conclusion that a key subset of the COLREGS has the most applicability to operations of ASCs and therefore their on-board autonomy software. The COLREGS of most relevance are the prescribed behaviors in rules 14 (head on situations, Figure **21**d), 15 (crossing situations Figure **21**, a, b), and the exceptions to them in rule 8 (based on relative maneuverability). However each ASC and its intended application (speed and maneuverability relative to other vessels it will typically encounter; whether it is station keeping or not) may lead to different choices for how best to approach compliance. For example, it may be best for one ASC in a given application to have on-board software that carries out a different combination of the prescribed behaviors and exceptions than would be best for a different ASC in a different application.

A framework for optimizing COLREG compliance for a given ASC application

A framework for how to determine the best route towards COLREG compliance for a given ASC application has been developed. The purpose is to help decide the safest balance between prescribed behaviors and exemptions. Several criteria are used to determine the proper collision avoidance plan, including how maneuverable the ASC is in relation to the typical traffic in the deployment area. This traffic information can be based on historical AIS data (as in Chapter 2, for example). Other criteria are the employment concept of the ASC such as a repeat transect or active patrol, and the speed and turning constraints imposed on the ASC, such as by any of the sensors it is operating. It is instructive to consider the framework criteria in the context of three ASC applications (Figure **22**).

The first case (Figure **22**, left column) is a harbor surveillance ASC (e.g, Colito, 2007). This ASC is relatively fast and maneuverable, and typically the traffic vessels it interacts with will also be similarly capable. The sensors onboard the ASC will not impose any limitations on its speed and maneuverability. Since the ASC has no restrictions and is in an area with similarly unrestricted vessels it is best for the ASC to obey the prescribed behaviors as closely as possible. This means giving way or standing on depending on the situation. For autonomy software this is challenging because it involves the capability to judge whether giving way or standing on is suitable.

The second case (Figure **22**, right column) is an ASC using equipment that restricts it, such as towing a plankton net. The ASC has sharply limited maneuverability because of the mission, making the typical traffic vessels more maneuverable than the ASC, so the ASC will not easily be capable of giving way. In this case it is recommended that the ASC follow the prescribed actions of the COLREGS and exercise its right as a vessel that is limited in its ability to maneuver, to hold its position and expect other vessels to avoid it. For autonomy software this is relatively simple, in the sense that judgment to discern between standing on or giving way is not expected.

A repeat transect survey such as the SCOAP deployment in RIS (third case, Figure **22**, middle columns) is a hybrid of these two scenarios. The traffic vessels to be avoided are typically much larger than SCOAP. While travelling between stations the ASC is not limited in its ability to maneuver, however when on station and actively sampling, if it has sensors in the water, it is limited. Under these circumstances, it is best for the ASC to always give way --even when it is the “stand on” vessel, as an exception to the prescribed behavior--except when it is actively sampling and limited in its ability to maneuver. For autonomy software the ability to actively avoid other vessels, by giving way, is required. However, because giving way is the default in all crossing situations, the ability to judge whether to stand on or give way is not required. In this sense this case is not as challenging for CA algorithms as the harbor patrol ASC case. It could suffice to activate a COLREGS-neutral CA algorithm, for example that applied in the simulations of Chapter 3.

The three cases illustrate that the particular combination of prescribed behaviors and exceptions that is best may differ for each ASC and application.

Conclusions and Discussion

In the case of an ASC carrying out repeat transect oceanographic sampling such as SCOAP in RIS, the recommended strategy for complying with COLREGS is different during the travelling and stationkeeping periods. When travelling, a "give way always" operative is adopted by the ASC, as an exception to the prescribed rules for giving way or standing on. When on station with instruments in the water that restrict maneuverability, the ASC can stand on, in accordance with its markings as "restricted in its ability to maneuver." A CA algorithm that is COLREGS-neutral (as described in Chapter 3) could suffice. In this context it would be advantageous for the CA algorithm to operate with larger radii parameters while the ASC is travelling and smaller values during station-keeping.

The framework developed here will need to be reassessed when formal CG requirements for ASC compliance with COLREGS, currently under development, are completed. However, recommendations can be made for autonomy software. Prior efforts include the use of velocity obstacles (Kuwata et al., 2011), fuzzy logic based decision-making (Perera, 2009), or multi object optimization (Benjamin et al., 2006), but the focus has generally been on obeying the prescribed actions rather than choosing to comply with COLREGS through exceptions to the prescribed actions. The investigation here suggests that the capability to flexibly implement different combinations of prescribed behaviors and exceptions should be a priority.

A potential future enhancement of autonomy software could also be to use live AIS information specific to each vessel (for example, vessel length) in order to help tailor CA responses, with respect to relative maneuverability rules, to each individual traffic vessel.

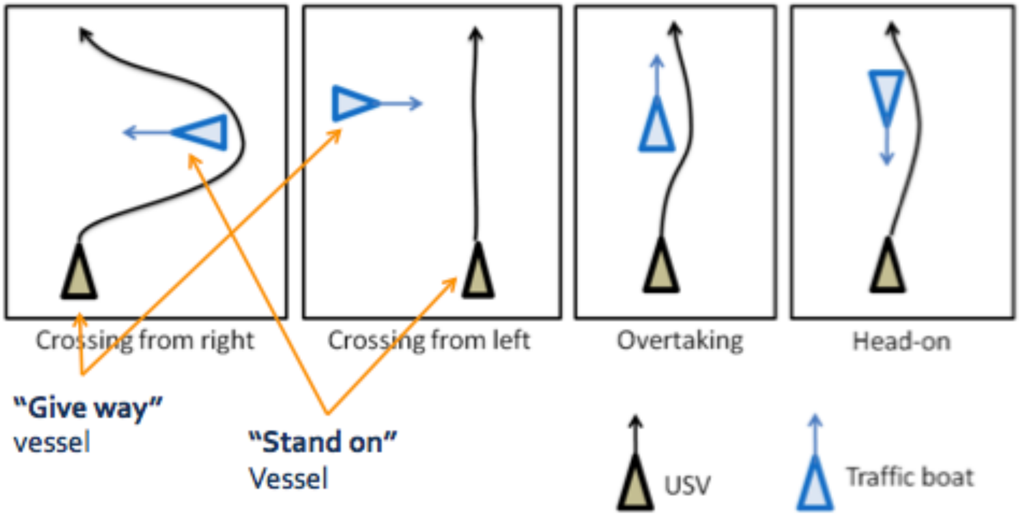
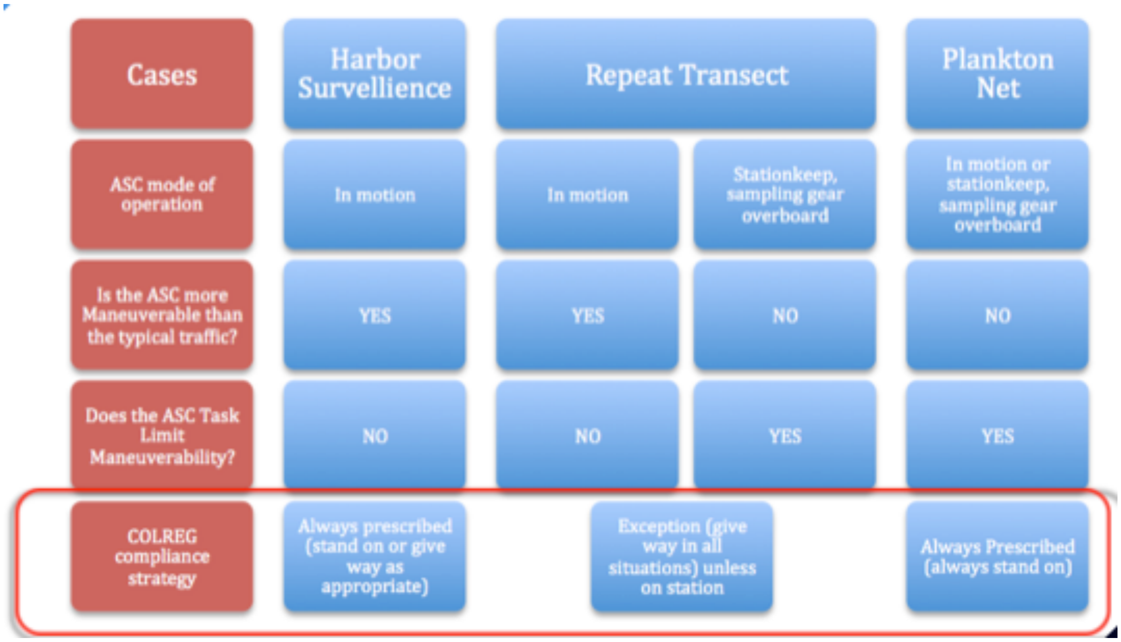


Figure 21 Illustration of COLREGS-governed encounter situations.

Illustrations where the ASC (USV) is brown triangle and Traffic Vessel is the blue triangle. From left to right (a) is a crossing situation where the ASC is the give way vessel and must alter course to pass behind the Traffic Vessel. (b) A crossing situation where the ASC is the stand on vessel and must hold its course while the Traffic Vessel must alter its course. (c) An overtaking situation where the ASC must alter its course to pass around the Traffic Vessel. (d) A head on encounter where both the ASC and the Traffic Vessel must alter course to starboard to avoid each other. (Modified from Kuwata et al., 2011).



Cases	Harbor Survellience	Repeat Transect		Plankton Net
ASC mode of operation	In motion	In motion	Stationkeep, sampling gear overboard	In motion or stationkeep, sampling gear overboard
Is the ASC more Maneuverable than the typical traffic?	YES	YES	NO	NO
Does the ASC Task Limit Maneuverability?	NO	NO	YES	YES
COLREG compliance strategy	Always prescribed (stand on or give way as appropriate)	Exception (give way in all situations) unless on station		Always Prescribed (always stand on)

Figure 22 Framework to determine strategy of ASC COLREG compliance.

Illustration of ASC decision-making tree as it relates to three types of ASC deployments. The red squares are criteria relating to the employment conditions of the ASC. The blue squares are the specific cases for ASC deployment where the criteria determine the proper COLREGS compliance scheme, shown in the bottom boxes.

Chapter 5. Summary and Conclusions

Repeat transect surveying, or traveling a line to several stations where measurements are taken (Figure **1**), is a valuable technique for oceanographic sampling. It is motivated by the need for both good spatial and temporal coverage. When designed for long-duration (weeks or more) operations, ASCs have strong potential to achieve this goal in a cost efficient manner. An ASC capable of 2.5 m/s average speed could sample 10 stations 2 km apart, along an 18km long transect, four times daily. Repeat transect sampling also helps reduce the operational risk to the ASC, as compared to other less structured survey plans, because it is effectively a "moving buoy". This project was motivated by the currently underway development of the SCOAP ASC (Figure **2**) and the intention to use it for a repeat transect oceanographic survey in RIS.

In order to best lay plans for the RIS deployment a method of using archived historical AIS data to quantify geographic and seasonal patterns in vessel traffic, and the risk of collision based on hypothetical configurations of repeat transect sampling, was developed and demonstrated. The frequency of individual AIS-equipped vessel tracks was determined over monthly intervals, during 2009 and 2010, at each cell in a 0.5 km resolution grid covering the region. The number of tracks per day ranged from about 0.01 or less, in areas of southeastern RIS far from shipping lanes, to about 8 tracks per day in the shipping lanes of northern RIS near the mouth of Narragansett Bay (Figure 7). The operational risk associated with a series of oceanographically motivated hypothetical locations for repeat transect sampling by ASC, configured with parameters as listed in the prior paragraph, was quantified by determining the number of potential collision encounters that would occur with historical AIS tracks during month-long intervals. The risk varied from 0-2 potential collision encounters per month in southeastern RIS, to a maximum of 15 +/- 6 encounters per day in the northern shipping lanes (Figure **3**, and Figure **9**) depending on the season. Scaling these up crudely for poorly known non-AIS vessel traffic yields a total (AIS and non AIS vessels) of 40-90 encounters close to Narragansett Bay and 3-7 encounters in southeastern RIS. These quantitative results facilitate optimal deployment planning to balance oceanographic sampling needs and operational risk.

The performance of on-board autonomy software during collision encounters was investigated using simulations of an ASC on a repeat transect survey in the presence of traffic vessels. The simulations were performed using the MIH autonomy software suite, which will be used on SCOAP. It includes a COLREG-neutral CA algorithm, which was used in the simulations. The CA maneuvers performed by the ASC when interacting with a crossing vessel fell into a small number of characteristic groups: a large deflection, course reversal, and leave/return to station keeping (Figure **15**, a, b, c). Sensitivity of the number and nature of encounters to variations in the parameters of the repeat transect sampling, the traffic vessel configuration, and CA algorithm was shown to be modest. Anomalous cases where the CA algorithm takes a substantially longer time to resolve (Figure **17**) account for less than 3% of cases not resolving efficiently. Overall, the autonomy software exhibited the ability to successfully manage multiple competing objectives and perform CA maneuvers, including multi-vehicle cases, efficiently while minimizing disruption to the repeat transect oceanographic sampling.

Applicability of the COLREGS to ASCs is currently not resolved, and a topic under consideration by NAVSAC. A framework based approach for attempted COLREG compliance using specific criteria has been developed. These criteria are based on the relative maneuverability of the ASC and vessel traffic as well as the ASC mission and employment concept and constraints. Historical AIS data can be used for guidance regarding typical traffic vessel characteristics. ASCs in different applications can approach COLREG compliance using varying combinations of prescribed behaviors and exceptions from them. Due to the method of employment an ASC performing an oceanographic repeat transect survey will "give way always" except when it is station-keeping and has instruments in the water. These conclusions will need to be revisited when formal CG requirements of ASCs, currently under development, are finalized. It is suggested that it will be advantageous for autonomy software to be capable of implementing CA algorithms that incorporate flexibility to comply with COLREGS using various combinations of prescribed behaviors and exceptions.

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