Raytheon

TP #13803E

Search and Rescue Tracker

Radar Data Processing and Performance Analysis

Prepared for:

Transportation Development Centre
Transport Canada

by:

Raytheon Canada Limited

July 2001

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16. Abstract

The Raytheon Search and Rescue Tracker (SAR Tracker) uses a rugged, inexpensive multi-CPU computer to process radar signals from any normal marine radar and thus enables standard commercial marine radars to detect and track small targets, such as swimmers and liferafts, in heavy seas. These targets are so frequently obscured behind waves and buried in radar clutter that even experienced radar operators are often unable to detect them.

This report quantifies the performance of the SAR Tracker in detecting small awash targets in 3.5 metre waves in Sea States ranging from smooth to very rough (Sea States 1 to 5). Tests used radar data recorded in 1997 off the east coast of Newfoundland from a Canadian Coast Guard ship sailing at 10 knots. The tethered and drifting targets had calibrated radar cross sections from 0.03 to 0.47 square metres.

Swimmers and liferafts are reliably detected to 3 and 7.2 kilometres respectively, with fewer than 5 false tracks per hour. The SAR Tracker increases the marine radar search rate two to four times for liferafts and even more for the smallest targets, such as swimmers and persons in survival suits, that are not normally detectable in any wind by radar alone.

This performance improvement offers immediate benefits in faster, less expensive searches and in lives saved.

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16. Résumé

Le pisteur de recherche et sauvetage Raytheon (pisteur SAR) fait appel à un ordinateur robuste et peu coûteux, doté de plusieurs processeurs, pour traiter les signaux d'un radar de bord classique. Il devient ainsi possible, avec un radar de bord ordinaire vendu dans le commerce, de détecter des petites cibles, comme des personnes à la mer et des radeaux de sauvetage, dans de fortes mers. Or, ces cibles sont si souvent cachées par les vagues et noyées dans le brouillage radar que même des radaristes d'expérience arrivent rarement à les détecter avec un radar seul.

Ce rapport quantifie les performances du pisteur SAR enregistrées lors d'essais de détection de petites cibles dérivant à fleur d'eau dans des vagues d'une hauteur pouvant atteindre 3,5 mètres, dans des états de mer variant de calme à très forte (degrés 1 à 5). Les analyses ont porté sur les données radar recueillies en 1997 au large de la côte est de Terre-Neuve par un navire de la Garde côtière canadienne évoluant à une vitesse de 10 noeuds. Les cibles captives et dérivant au fil de l'eau avaient une surface équivalente étalonnée variant de 0,03 à 0,47 mètre carré.

Les personnes à la mer, avec et sans combinaison de survie, et les radeaux de sauvetage sont détectés avec un degré élevé de fiabilité à des distances de 3 et de 7,2 kilomètres, respectivement; moins de cinq fausses détections à l'heure sont enregistrées. Par rapport au radar de bord, le pisteur SAR accélère la recherche de deux à quatre fois pour la détection de radeaux de sauvetage, et encore plus pour la détection de cibles plus petites, comme les personnes à la mer avec et sans combinaison de survie, qui demeurent habituellement indétectables par un radar seul, quelle que soit la direction du vent.

De telles performances procurent des avantages immédiats : recherches moins longues et moins coûteuses, plus de vies sauvées.

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The support and assistance of numerous individuals made the SAR Tracker a practical reality. Charles Gautier of the Transportation Development Centre has believed in and supported the project from its earliest days and contributed greatly to the overall system design. Max Johnson and Joe Ryan of Sigma Engineering willingly extended the Sea Scan software to connect to the Automatic Threshold Control. Reg Fitzgerald of Oceans Limited contributed the information on comparable sweep widths that helped place the SAR Tracker performance in perspective.

EXECUTIVE SUMMARY

The Raytheon Search and Rescue Tracker (SAR Tracker) enables standard commercial marine radars to detect and track small targets, such as swimmers and liferafts, in heavy seas. These targets are so frequently obscured behind waves and buried in radar clutter that even experienced radar operators are often powerless to discern and track them.

This report quantifies the performance of the SAR Tracker under the wide range of conditions encountered in practical SAR operations in the Atlantic off Newfoundland.

Functions and Description

The basis of the SAR Tracker design is that conventional marine radars such as the Raytheon Pathfinder II and AN/SPS-73 have sufficient transmitter power, receiver sensitivity and resolution (in range and azimuth) to raise even very small targets above the clutter and thereby detect them. Unfortunately, numerous clutter features are necessarily detected along with the desired targets. The situation is usually complicated by the presence of waves that often hide awash targets.

The SAR Tracker works by correlating the few target detections amidst the many clutter detections over 1 or 2 minutes to accumulate a statistical basis for declaring a high confidence target track. The SAR Tracker is designed to enable the shipboard radar to reliably detect and track swimmers and liferafts in 3.5 m waves at ranges up to 3 and 7.2 km, respectively, with fewer than 5 false tracks per hour. Larger targets with more freeboard, such as open boats, can be tracked at much longer ranges.

The SAR Tracker uses one or more personal computers (PCs) to process the radar video signal into high confidence tracks. The entire SAR Tracker is therefore connected in parallel with the marine radar as shown in Figure 1. This loosely coupled architecture enables the operator to use the radar without worrying about the SAR Tracker, which quietly operates in the background using a completely independent signal processor. The SAR Tracker uses a single monitor, which can be shared with other systems, to set up and control the processing and to display the radar picture, plots, M of N detections and tracks.

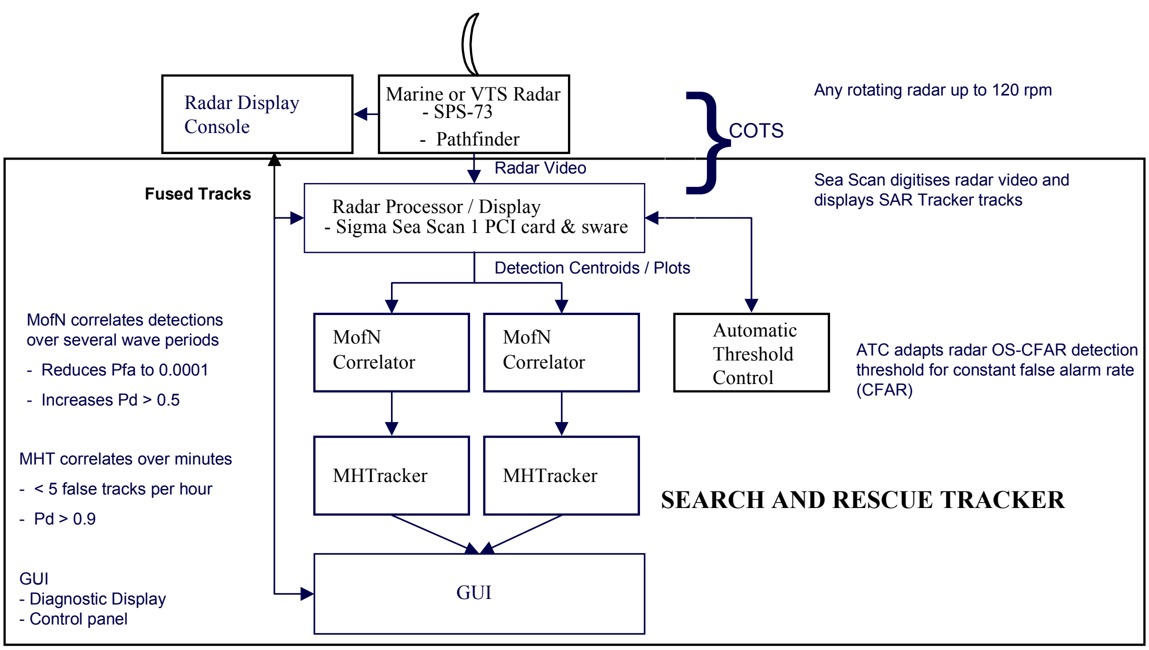

Figure 1 Search and Rescue Tracker Functional Block Diagram

Inexpensive Expandable Open Architecture Implementation

The SAR Tracker uses simple and readily available PC hardware to facilitate growth and limit cost. The radar processor and each parallel Correlator-Tracker require a single dual-Pentium III PC. The SAR Tracker performance is largely defined by the available processing power and will therefore benefit from the rapid trend to higher CPU clock rates, wider bus bandwidths and less expensive multi-processor servers.

The defined performance is for two Correlator-Trackers, but significant increases in detection range are expected as further Correlator-Trackers are added, up to the tentative limit of four. All inter-PC communications are over 100T Ethernet. A hub or router can be added should the tracks or radar data be sent to other systems.

All software is written in platform-independent, object-oriented code that runs under Windows NT. The SAR Tracker code can therefore be loaded without modification onto whatever size computers are required for the mission. Being object-oriented, the SAR Tracker software has proven particularly simple to extend and modify in response to operator requests for different functions or displayed information.

Longer Detection Ranges Against Smaller Targets

The measured 90 percent cumulative probability of detection (Pd_{cum}) range for a single sail-past in 3.2 to 3.8 m seas far exceeds that of any conventional radar or of a visual observer, even in good visibility. As shown in Figure 2, the smallest (0.03 m^2) targets, corresponding to a fully immersed swimmer, can be detected from 3 to 0.8 km in Sea States 1 to 3. Such small targets are normally impossible to detect in anything but a flat, calm sea. The largest (0.6 m^2) target, corresponding to a 4- to 6-man liferaft, could be detected from 7.2 to 3.2 km in Sea States 1 to 5. Fewer than 5 false tracks per hour were observed in all cases.

Up to 40 percent longer ranges were typically attained by slowing the search rate from 10 to 5 kn, particularly at higher sea states. Moreover, the 50 percent Pd_{cum} ranges are 1 to 2 km further out and will contribute detections on about half the targets in this outer annulus. These detections are not usually considered sufficient to extend the search sweep width but do serve to usefully augment the more reliable 90 percent-certain detections.

The SAR Tracker performance is largely governed by the clutter and the waves:

- The percentage visibility of awash targets behind waves equally reduces the number of detections for both short and medium pulse. Smaller waves hide awash targets less frequently than larger ones. Target visibility is highest looking along the troughs (i.e., crosswind for wind-driven waves) and lowest looking into and away from the waves (i.e., upwind and downwind). In the long swells typically observed offshore Newfoundland, the effect is often masked by irregularities in the wave fronts.
- Medium pulse clutter (with 40 m range resolution) is about 6 times stronger than short pulse clutter (6 m resolution).
- Clutter strength increases with wave steepness and is typically highest upwind and lowest downwind.

The measured detection ranges shown in Figure 2 are those where the Pd_{cum} reaches 90 percent on a single sail-past at 10 kn. Equivalent curves for 5, 15 and 20 kn searches can be extracted from the detailed tables in Section 9 of the report.

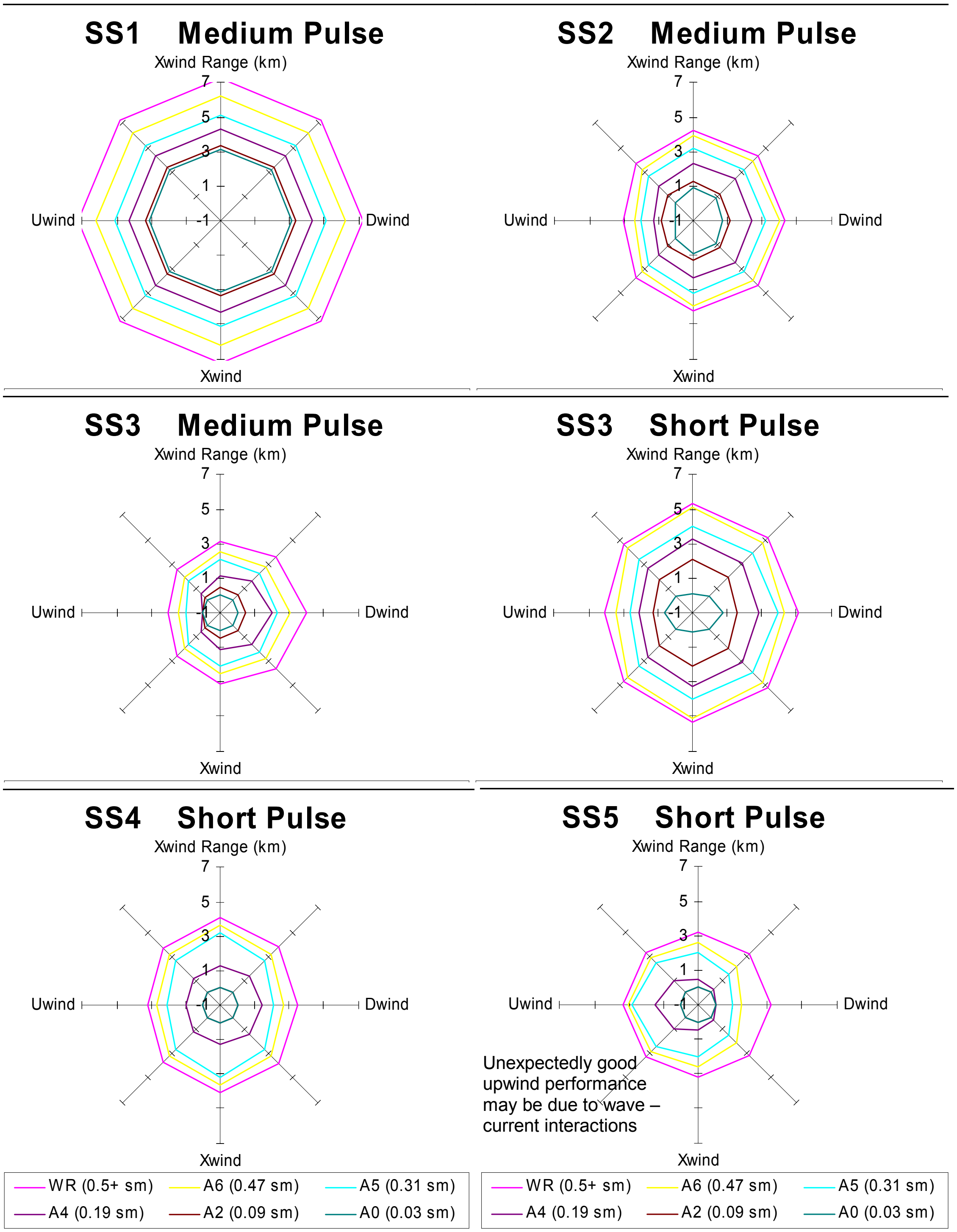

Figure 2 Range for 90% Pd_{cum} in 3.2 to 3.8 m waves versus wind direction (10 kn search)

Medium pulse detection range is seen to be highly dependent on the sea state and the resulting clutter strength. At Sea State 1, the clutter is negligible and so the detection range is independent of wind direction. As the winds increase above 7 kn, the clutter rises to Sea State 2 and reduces the detection range by 30 percent for the largest (0.5 m^2) targets and by 75 percent for the smallest (0.03 m^2) ones. At Sea State 3, the detection range is reduced by a further 30 to 50 percent, depending on target size. For all targets, the maximum detection range is downwind, followed closely by crosswind. Upwind range is much less and falls faster with sea state, particularly for the smaller targets, because the increased clutter from the steeper-faced waves in this sector force the automatic threshold control to locally increase the detection threshold. For medium pulse operation above Sea State 1, the benefits of increased crosswind visibility are therefore being increasingly outweighed by the increased crosswind clutter intensity.

Short pulse is less affected by clutter; the detection range therefore benefits from the increased crosswind visibility. At Sea State 3, the maximum detection range for all targets is crosswind, followed closely by downwind and upwind. The relative crosswind advantage is steadily reduced with sea state as the increasing clutter offsets the constant improved crosswind visibility until the maximum range is observed to be downwind. The sea state at which this transition occurs is proportional to the target radar cross section. Higher sea states are expected to rapidly reduce first the upwind range and then the crosswind range as was observed with the medium pulse.

Short pulse is therefore recommended for Sea State 2 and higher searches, where clutter effectively masks the targets. Medium pulse is only superior in Sea States 0 and 1, where no appreciable clutter intrudes.

Smaller wave heights are confidently expected to increase target visibilities and therefore detection ranges, but more data is required to quantify the improvement. Higher floating targets such as 20-person liferafts and small boats are both larger and much more visible and should be detected at much longer ranges than the small awash targets used in this project.

Increased Search Sweep Widths

The exact layout of search patterns should be matched to the desired Pd_{cum} for the expected target type and wind direction. For simplicity, the SAR Tracker average sweep width is plotted in Figure 3 for 90 percent Pd_{cum} searches at 5, 10, 15 and 20 kn in 3.2 to 3.8 m seas.

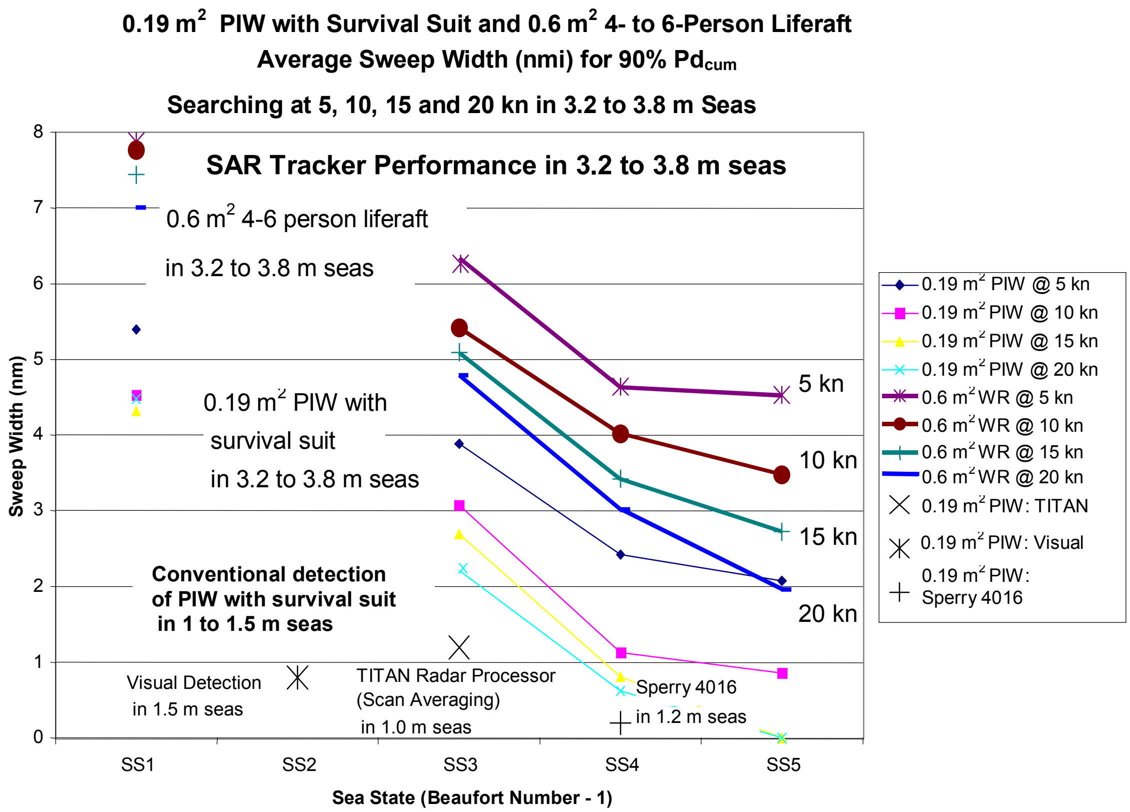

Figure 3 Sweep widths for 90% Pd_{cum} detection of 0.6 and 0.19 m^2 targets in 3.2 to 3.8 m seas

The SAR Tracker detects the 0.19 m2 person in water (PIW) with survival suit in far higher (1.5 to 3 times) seas than conventional techniques and does this at much longer ranges. The SAR Tracker delivers sweep widths that are 2 to 4 times wider than the TITAN Radar Processor (digitally processed scan averaging) and 3 to 5 times wider than visual searches. Much more significant improvements would be likely if the comparisons were made at similar wave heights.

The 0.6 m^2 Wave Rider buoy has approximately the same radar cross section as a 4- to 6-person liferaft, but is physically much smaller and rides lower in the water. The Wave Rider is therefore more frequently buried under water or hidden behind waves than any liferaft. Despite this, the SAR Tracker detects the Wave Rider in 3.2 to 3.8 m seas with sweep widths that are comparable to visual searches in 1.6 to 1.9 m waves against 4- to 6-person liferafts (without lights). Of course, the SAR Tracker works equally well at night and in fog and is much less affected by weather.

The SAR Tracker is far superior to conventional analog radar searches. The measured sweep width for a Sperry 127E is only 0.8 nmi in 0.9 m seas (assumed to be Sea State 3). In contrast, the SAR Tracker sweep width in waves that are 4 times larger is 4.8 to 6.3 nmi, which is 6 to 8 times better.

The SAR Tracker consistently detects the 0.6 m^2 Wave Rider buoy with 2.5 nmi wider sweep widths than it does the 0.19 m^2 PIW.

These loose comparisons suggest that the SAR Tracker will dramatically increase the sweep widths that can be used in marine search and rescue. Moreover, the SAR Tracker detects swimmers and other awash targets smaller than 0.19 m2 in sea states where they have hitherto been undetectable.

At a 10-kn search speed in 3.5 m seas, the recommended sweep widths for 90 percent certainty detection, with fewer than 5 false detections per hour, are summarized in Table 1.

Table 1 Average sweep widths for 90% certainty detection at 10 kn in 3.5 m seas

Target Type	Estimated Radar Cross-Section (m^2)	Equivalent Target Buoy	Sweep Width (nmi) for Sea State		
			SS 1	SS 3	SS 5
4- to 6-person liferaft	0.6	Wave Rider	7.8	5.4	3.5
4-person liferaft	0.47	A6	6.7	4.8	2.6
Swamped 4-person liferaft	0.31	A5	5.4	3.9	2.1
Person in water with survival suit	0.19	A4	4.5	3.1	0.85
PIW swimmer (max)	0.09	A2	3.5	2.3	-
PIW swimmer (min)	0.03	A0	3.2	0.5	-

Faster Search Reduces Costs

If you double the sweep width while maintaining the probability of success, then you can cover twice the area in the same time and thereby halve the cost of the search. The SAR Tracker has been demonstrated to increase the 90 percent confident sweep width by 2 to 4 times when compared to conventional visual and radar techniques. This was achieved in much larger seas than the conventional techniques and is therefore a conservative estimate of the improvement offered by the SAR Tracker.

Faster searches are particularly beneficial because they limit the enlargement of the search area due to the unknown drift of the survivors. Off Newfoundland, the Labrador Current plus the wind can easily push survivors by several nmi each hour they are adrift. Unfortunately, the direction and speed of drift are neither predictable nor constant.

The SAR Tracker has the added advantage of being completely automatic. Visual searchers will be able to focus their efforts on confirming and identifying SAR Tracker detections and on augmenting the SAR Tracker where required. Fatigue will be reduced so searchers will not need to be relieved as frequently. Alarms can be set up to automatically alert the watch-stander when a target is detected.

Faster Rescue Saves Lives

Two to four times faster searches mean that survivors will be rescued much earlier and will therefore be less exposed to the killing cold of the North Atlantic or North Pacific.

The number of deaths due to exposure and ensuing hypothermia should therefore be significantly reduced.

Of course, in some cases the search vessel must transit for many hours to reach the search area and it is this delay that dominates the time to rescue. The SAR Tracker could be mounted in a helicopter or aircraft to greatly reduce the transit time to the search area and further increase the search rate. The SAR Tracker already digitizes radars up to 120 rpm and computes accurate 2-D motion compensation so the changes required to digitize a high-speed airborne radar and add height to the motion compensation would be modest.

Inexpensive Operational Trials Demonstrate Benefits

With a few inexpensive improvements to make the SAR Tracker easier to use, operational trials are expected to bring immediate benefits in faster and more reliable searches. This will save lives and, at the same time, reduce SAR costs. The costs of these trials would be modest because the SAR Tracker uses off-the-shelf PC technology as well as existing radar.

Conclusion

The SAR Tracker dramatically extends the small target detection range of conventional marine radars. These radars are already used in most of the world's coast guards and navies and would not need to be replaced or modified in any way. The radar operator uses the radar as usual and need only refer to the SAR Tracker display when looking for small targets.

The SAR Tracker reliably detects and tracks swimmers and liferafts at ranges up to 3 and 7.2 km respectively, with fewer than 5 false tracks per hour. Compared to conventional marine radars, the SAR Tracker search rate is two to four times greater for larger targets such as liferafts. The increase is even greater for the smallest targets, such as swimmers and persons in survival suits, that are not normally detectable in any wind by radar alone.

This performance improvement offers immediate benefits in faster, less expensive searches and in lives saved.

SOMMAIRE

Le pisteur de recherche et sauvetage Raytheon (pisteur SAR) permet, à l'aide d'un radar de bord classique vendu dans le commerce, de détecter et pister des petites cibles, comme des personnes à la mer et des radeaux de sauvetage ballottés par une mer agitée. Or, ces cibles sont si souvent cachées par les vagues et noyées dans le brouillage radar que même des radaristes d'expérience arrivent rarement à les détecter avec un radar seul.

Ce rapport quantifie les performances du pisteur SAR dans le large éventail des conditions de mer qui régnaient lors d'opérations de recherche-sauvetage menées dans l'Atlantique, au large de Terre-Neuve.

Fonctions et description

Le pisteur SAR mise sur le fait que les radars de bord classiques, comme le Raytheon Pathfinder II et l'AN/SPS-73, possèdent une puissance d'émission, une sensibilité de réception et un pouvoir séparateur (en angle et en portée), suffisants pour dégager des cibles, même très petites, du clutter et ainsi les détecter. Malheureusement, de nombreuses réflexions associées au clutter sont ainsi détectées en même temps que les cibles recherchées. Sans compter la présence des vagues, qui complique habituellement la situation en cachant les cibles à fleur d'eau.

Le pisteur SAR établit des corrélations entre les quelques détections de cibles qui ressortent au milieu des nombreuses détections de clutter issues d'une ou deux minutes d'observation, créant ainsi une base statistique qui l'autorise à déclarer trajectoire de cible un ensemble de détections, avec un degré élevé de confiance. Le pisteur SAR est conçu pour permettre au radar de bord de détecter et pister des personnes à la mer sans combinaison de survie et des radeaux de sauvetage dans des vagues de 3,5 m et à des distances allant jusqu'à 3 et 7,2 km, respectivement, avec moins de cinq fausses détections à l'heure. Les cibles plus grosses, à franc-bord plus important, comme les embarcations non pontées, peuvent être repérées de beaucoup plus loin.

Le pisteur SAR utilise un ou plusieurs ordinateurs personnels (PC) pour extraire du signal vidéo-radar des trajectoires de haute fiabilité. Tout le pisteur SAR est ainsi connecté en parallèle avec le radar de bord, comme le montre la Figure 1. Une telle architecture à couplage lâche permet à l'opérateur d'exploiter le radar sans se préoccuper du pisteur SAR, qui fonctionne discrètement en arrière-plan, avec un processeur de signaux complètement indépendant. Le pisteur SAR utilise un seul moniteur, qu'il partage volontiers avec d'autres systèmes, pour piloter le traitement et afficher l'imagerie radar, les plots, les détections M de N et les trajectoires.

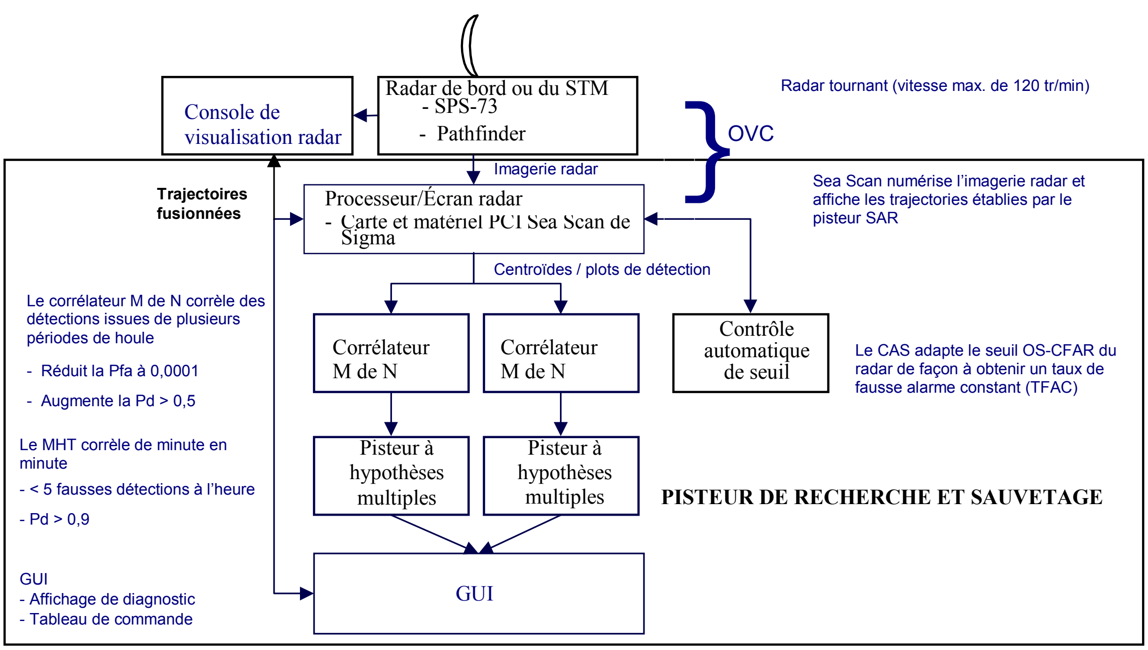

Figure 1 Diagramme des blocs fonctionnels du pisteur de recherche et sauvetage

Système à architecture ouverte, économique et extensible

Le pisteur SAR utilise de simples ordinateurs PC, peu coûteux et facilement disponibles, ce qui facilite les extensions éventuelles et limite les coûts du système. Le processeur radar et les pisteurs-corrélateurs parallèles sont articulés sur un seul Pentium III à deux processeurs. Les performances du pisteur SAR dépendent grandement de la puissance de traitement disponible et elles ont tout à gagner de la tendance actuelle à l'accroissement des fréquences d'horloge des processeurs et des largeurs de bandes des bus, et à l'abaissement des coûts des serveurs de processeurs multiples.

Les performances nominales valent pour deux corrélateurs-pisteurs, mais l'ajout de corrélateurs-pisteurs, jusqu'à un maximum provisoire de quatre, devrait augmenter de façon importante la portée de détection. Toutes les communications entre les PC utilisent le protocole Ethernet 100T. Un concentrateur ou routeur peut être ajouté au système pour la transmission des trajectoires ou des données radar à d'autres systèmes.

Le logiciel utilise un langage indépendant du système d'exploitation, il est orienté objet et il tourne sous Windows NT. Il est donc possible de charger le code du pisteur SAR sans aucunement modifier les ordinateurs utilisés pour la mission, quelle que soit leur puissance. Du fait que le logiciel est orienté objet, il est éminemment simple de faire des extensions et d'apporter des modifications lorsque les opérateurs réclament des fonctions ou des affichages différents.

Portées de détection plus grandes, cibles plus petites

La portée associée à une probabilité de détection (Pd_{cum}) cumulative mesurée de 90 p. 100, pour un seul passage du navire de recherche dans des vagues de 3,2 à 3,8 m, dépasse de beaucoup la portée de détection de n'importe quel radar classique ou d'une recherche visuelle, même lorsque la visibilité est bonne. Comme le montre la Figure 2, les cibles les plus petites (0,03 m^2 de surface équivalente) représentant une personne à la mer dont la tête émerge de l'eau, peuvent être détectées à une distance de 3 à 0,8 km, dans des états de mer variant de 1 à 3. De si petites cibles sont normalement impossibles à détecter, si ce n'est dans une mer calme. La cible la plus grosse (0,6 m^2 de surface équivalente), représentant un radeau de sauvetage pour 4 à 6 personnes, a été détectée à une distance de 7,2 à 3,2 km dans des états de mer variant de 1 à 5. Dans tous les cas, moins de cinq fausses détections à l'heure ont été enregistrées.

La portée de détection s'est accrue jusqu'à 40 p. 100 lorsque le navire de recherche évoluait non plus à 10 kt mais à 5 kt, notamment dans une mer forte. De plus, à vitesse plus faible, la portée associée à des Pd_{cum} de 50 p. 100 est de 1 à 2 km supérieure, et environ la moitié des cibles se trouvant dans cet anneau périphérique sont détectées. Habituellement, ces détections ne sont pas considérées suffisantes pour justifier l'augmentation de la portée de la recherche, mais elles servent de complément utile aux détections de la zone plus fiable de 90 p. 100.

Les performances du pisteur SAR sont largement fonction du clutter et des vagues :

- Peu importe la longueur des impulsions (courtes ou moyennes), la visibilité intermittente des cibles à fleur d'eau dissimulées par les vagues réduit le nombre des détections. Les petites vagues cachent moins souvent les cibles à fleur d'eau que les grosses. La visibilité des cibles est maximale lorsque celles-ci se déplacent perpendiculairement au sens de la houle (c.-à-d. par vent traversier, dans le cas de vagues générées par le vent) et minimale lorsqu'elles se déplacent dans le sens de la houle (c.-à-d., par vent amont ou vent aval). Dans les longues lames caractéristiques de l'état de la mer au large de Terre-Neuve, cet effet est souvent imperceptible en raison des fronts de houle irréguliers.
- Avec des impulsions moyennes (pouvoir séparateur en portée de 40 m) le clutter est environ 6 fois plus intense qu'avec des impulsions courtes (pouvoir séparateur de 6 m).
- L'intensité du clutter augmente avec la pente de la houle et elle est habituellement à son maximum par vent amont et à son minimum par vent aval.

Les portées de détection mesurées représentées à la Figure 2 sont celles qui correspondent à une Pd_{cum} de 90 p. 100 à la suite d'un seul passage du navire de recherche évoluant à une vitesse de 10 kt. Des courbes équivalentes pour des recherches effectuées à des vitesses de 5, 15 et 20 kt peuvent être dérivées des tableaux détaillés présentés à la section 9 du rapport.

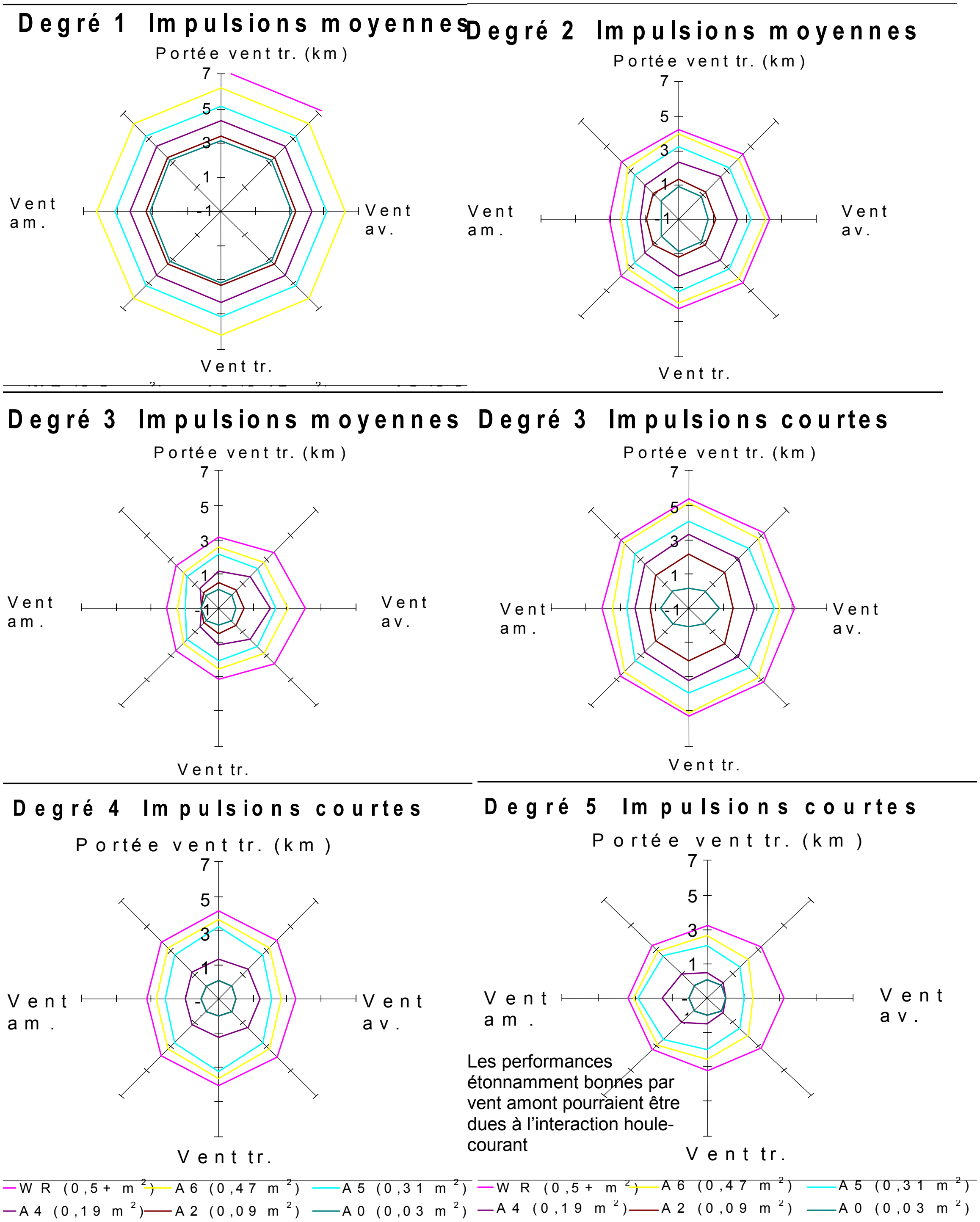

Figure 2 Portée associée à une Pd_{cum} de 90 % dans des vagues de 3,2 à 3,8 m, selon la direction du vent (navire de recherche évoluant à une vitesse de 10 kt)

Comme on peut le voir, la portée de détection avec des impulsions moyennes dépend fortement de l'état de la mer et, corollairement, de l'intensité du clutter. Dans une mer calme (degré 1), le clutter est négligeable et la portée de détection est donc indépendante de la direction du vent. Lorsque les vents atteignent une vitesse supérieure à 7 kt, le clutter s'intensifie, produisant un état de mer de degré 2, ce qui entraîne une réduction de 30 p. 100 de la portée de détection des cibles les plus grosses (0,5 m^2) et de 75 p. 100 des cibles les plus petites (0,03 m^2). Dans un état de mer de degré 3, la portée de détection diminue encore de 30 à 50 p. 100, selon les dimensions de la cible. Pour toutes les cibles, la portée de détection maximale est enregistrée par vent aval, et est légèrement moindre par vent traversier. Plus la mer est forte, plus la portée de détection est réduite par vent amont, notamment dans le cas des petites cibles, car le clutter généré par des vagues à versant abrupt dans ce secteur oblige la commande automatique de seuil à accroître localement le seuil de détection. Donc, lorsque le radar émet des impulsions moyennes dans un état de mer supérieur au degré 1, les avantages d'une meilleure visibilité par vent traversier se trouvent amoindris par l'augmentation de l'intensité du clutter par vent traversier.

Comme le clutter influe moins sur les impulsions courtes, la portée de détection est d'autant plus grande que la visibilité est meilleure par vent traversier. Dans un état de mer de degré 3, c'est par vent traversier qu'est enregistrée la portée de détection maximale pour toutes les cibles. La portée par vent amont suit de près, elle-même suivie de la portée par vent aval. L'avantage relatif du vent traversier diminue régulièrement avec l'état de la mer, car le clutter de plus en plus intense annule l'avantage associé à l'amélioration constante de la visibilité par vent traversier, jusqu'à ce que la portée de détection maximale soit enregistrée par vent aval. L'état de mer auquel la transition s'opère est proportionnel à la surface équivalente de la cible. Ainsi, on peut penser qu'une mer forte réduit rapidement, dans un premier temps, la portée de détection par vent amont, puis la portée de détection par vent traversier, comme il a été constaté avec des impulsions moyennes.

Il est donc recommandé d'utiliser des impulsions courtes pour des recherches dans des états de mer de degré 2 et supérieurs, où les cibles sont effectivement noyées dans le clutter. Les impulsions moyennes ne s'avèrent supérieures aux impulsions courtes que dans des états de mer de degrés 0 et 1, soit lorsque le clutter est négligeable.

On peut penser que moins les vagues sont hautes, plus les cibles sont visibles et plus les portées de détection augmentent; mais davantage de données sont nécessaires pour quantifier cette relation. Intuitivement, toutefois, des cibles qui émergent davantage au-dessus de l'eau, comme des radeaux de sauvetage pour 20 personnes et des petites embarcations, sont à la fois plus grosses et beaucoup plus visibles, et devraient donc être détectées à des distances beaucoup plus grandes que les petites cibles utilisées aux fins de la présente recherche.

Augmentation des largeurs de balayage

Les plans de ratissage devraient correspondre à la Pd_{cum} souhaitée selon le type de cible recherchée et la direction du vent. Pour plus de simplicité, on trouvera à la Figure 3 les largeurs de balayage moyennes du pisteur SAR pour une Pd_{cum} de 90 p. 100 à des vitesses de 5, 10, 15 et 20 kt, dans des vagues de 3,2 à 3,8 m.

PAM avec combinaison de survie (0,19 m²) et radeau pour 4 à 6 personnes (0,6 m²)

Largeur de balayage moyenne (NM) pour une Pd_{cum} de 90 %

Recherche menée à des vitesses de 5, 10, 15 et 20 kt, dans des vagues de 3,2 à 3,8 m

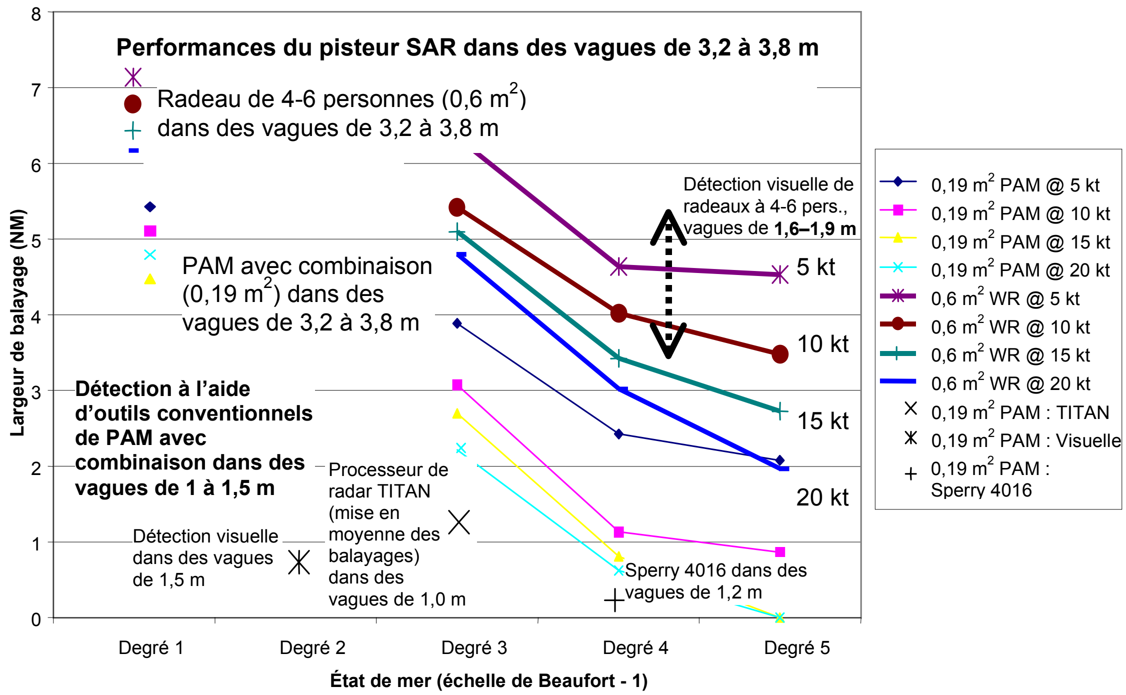

Figure 3 Largeurs de balayage pour une Pd_{cum} de 90 % de cibles de 0,6 et de 0,19 m² dans des vagues de 3,2 à 3,8 m

Le pisteur SAR détecte des personnes à la mer (PAM) revêtues d'une combinaison de survie (surface équivalente de 0,19 m²) dans des vagues beaucoup plus hautes (de 1,5 à 3 fois) que les techniques classiques et ce, à des distances beaucoup plus grandes. Le pisteur SAR explore des couloirs de deux à quatre fois plus larges que ceux couverts par le radar TITAN (mise en moyenne de balayages numérisés) et de trois à cinq fois plus larges que le permettent les recherches visuelles. Des comparaisons à des hauteurs de vagues semblables feraient vraisemblablement ressortir encore plus les avantages du pisteur SAR.

La bouée Wave Rider, d'une surface équivalente de 0,6 m², équivaut à peu près aux dimensions d'un radeau de sauvetage pour 4 à 6 personnes, mais elle est beaucoup plus petite et s'enfonce plus profondément dans l'eau. Elle est donc plus souvent submergée ou cachée derrière les vagues que n'importe quel radeau de sauvetage. Malgré cela, le pisteur SAR détecte le Wave Rider dans des vagues de 3,2 à 3,8 m en couvrant des largeurs de balayage comparables à celles couvertes par des recherches visuelles de radeaux de sauvetage pour 4 à 6 personnes (sans feux) dans des vagues de 1,6 à 1,9 m. Bien sûr, le pisteur SAR travaille aussi bien dans l'obscurité et dans la brume et fait peu de cas des conditions météorologiques.

Le pisteur SAR est de beaucoup supérieur aux radars de recherche analogiques classiques. La largeur de balayage mesurée d'un Sperry 127E est de 0,8 NM dans une mer de 0,9 m (degré 3). Par contraste, la largeur de balayage du pisteur SAR dans des vagues quatre fois plus grosses est de 4,8 à 6,3 NM, soit 6 à 8 fois supérieure.

Le pisteur SAR détecte de façon constante la bouée Wave Rider (0,6 m² de surface équivalente) dans des couloirs plus larges de 2,5 NM que lorsqu'il détecte la PAM (0,19 m² de surface équivalente).

Ces analyses en vrac donnent à penser que le pisteur SAR augmentera de façon marquée les largeurs de balayage que pourront couvrir les navires de recherche-sauvetage. De plus, le pisteur SAR détecte les personnes à la mer sans combinaison de survie et d'autres cibles à fleur d'eau de surface équivalente inférieure à 0,19 m², dans des états de mer où elles demeuraient jusqu'à présent indétectables.

Pour une vitesse d'exploration de 10 kt dans des vagues de 3,5 m, les largeurs de balayage recommandées pour une détection avec une certitude de 90 p. 100, avec moins de cinq fausses détections à l'heure, sont résumées au Tableau 1.

Tableau 1 Largeurs de balayage moyennes pour un taux de détection de 90 % à 10 kt dans des vagues de 3,5 m

Type de cible	Surface équivalente estimative (m^2)	Bouée cible équivalente	Largeur de balayage (en NM) selon l'état de la mer		
			Degré 1	Degré 3	Degré 5
Radeau de sauvetage pour 4 à 6 personnes	0,6	Wave Rider	7,8	5,4	3,5
Radeau de sauvetage pour 4 personnes	0,47	A6	6,7	4,8	2,6
Radeau de sauvetage pour 4 personnes envahi par l'eau	0,31	A5	5,4	3,9	2,1
Personne à la mer revêtue d'une combinaison de survie	0,19	A4	4,5	3,1	0,85
PAM sans combinaison (max.)	0,09	A2	3,5	2,3	-
PAM sans combinaison (min.)	0,03	A0	3,2	0,5	-

Accélération de la recherche = diminution des coûts

En doublant la largeur de balayage sans diminuer la probabilité de détection, il est possible de couvrir une superficie deux fois plus grande dans un même temps, et de réduire ainsi de moitié le coût d'une opération de recherche-sauvetage. Il a été démontré que le pisteur SAR permet d'augmenter de 2 à 4 fois la largeur de balayage associée à une probabilité de détection de 90 p. 100, par rapport aux techniques classiques de recherche visuelle et de recherche radar. Comme les recherches à l'aide du pisteur SAR ont été faites dans des mers beaucoup plus grosses que celles qui faisaient appel aux techniques classiques, il s'agit là d'une estimation prudente des avantages offerts par le pisteur SAR.

Autre avantage des recherches rapides, elles peuvent dispenser de la nécessité d'étendre la zone d'exploration, lorsque des victimes dérivent dans une direction inconnue. Au large de Terre-Neuve, le courant du Labrador combiné au vent peut facilement faire dériver des personnes à la mer sur plusieurs milles marins à l'heure. Malheureusement, la direction et la vitesse de cette dérive ne sont ni prévisibles ni constantes.

Autre avantage non négligeable, le pisteur SAR est complètement automatique. Les vigies pourront consacrer leurs efforts à confirmer et identifier les détections du pisteur SAR et à le compléter, au besoin. Comme la fatigue sera moindre, les vigies n'auront pas besoin d'être relevées aussi fréquemment. Des alarmes peuvent être installées pour prévenir automatiquement l'officier de quart lorsqu'une cible est détectée.

Plus le sauvetage est rapide, plus grandes sont les chances de sauver des vies

Des recherches de deux à quatre fois plus rapides signifient que les personnes naufragées seront rescapées beaucoup plus tôt et seront donc exposées moins longtemps au froid mortel de l'Atlantique Nord ou du Pacifique Nord.

Le nombre de décès dus au séjour en mer et à l'hypothermie qui s'ensuit devrait diminuer de façon importante.

Naturellement, dans certains cas, il faut de nombreuses heures au navire de recherche pour atteindre la zone d'exploration, et c'est ce délai qui explique le temps mis pour effectuer le sauvetage. Il est pensable de monter le pisteur SAR dans un hélicoptère ou un avion, de façon à réduire de façon marquée le temps de transit vers la zone d'exploration et d'accélérer d'autant la recherche. Le pisteur SAR numérise déjà les images radar jusqu'à 120 tr/min et calcule avec précision une compensation cinétique bidimensionnelle. Il serait donc relativement simple de numériser un radar aéroporté grande vitesse et d'ajouter la hauteur aux paramètres de compensation cinétique.

Des essais peu coûteux en service réel démontreront les avantages du pisteur SAR

Moyennant quelques améliorations peu coûteuses pour rendre le pisteur SAR plus facile à utiliser, des essais en service réel devraient apporter des avantages immédiats, soit des recherches plus rapides et plus efficaces. Plus de vies seront ainsi sauvées et les opérations SAR seront moins coûteuses. Les coûts de ces essais seront modestes, car le pisteur SAR utilise des PC ordinaires et des radars existants.

Conclusion

Comparé aux radars de bord classiques, le pisteur SAR augmente de beaucoup la portée de détection des petites cibles. Les radars de bord nécessaires équipent déjà la plupart des navires des gardes côtières et des marines du monde et n'auraient pas besoin d'être remplacés ni modifiés. Le radariste utilise le radar comme d'habitude et ne doit se reporter à l'écran du pisteur SAR que pour repérer des petites cibles.

Le pisteur SAR peut détecter et poursuivre de façon fiable des personnes à la mer et des radeaux de sauvetage à des distances atteignant 3 et 7,2 km respectivement, avec moins de cinq fausses détections à l'heure. Comparativement aux radars de bord classiques, le pisteur SAR prend deux à quatre fois moins de temps pour explorer une zone à la recherche de cibles plus grosses, comme des radeaux de sauvetage. Les avantages du pisteur SAR sont encore plus remarquables dans le cas des petites cibles, comme des personnes à la mer, revêtues ou non d'une combinaison de survie, qu'un radar seul ne réussit habituellement pas à détecter, quelle que soit la direction du vent.

Ces performances accrues entraînent des avantages immédiats : accélération des recherches, diminution des coûts, plus de sauvetages.

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GLOSSARY OF ACRONYMS AND ABBREVIATIONS

Acc	Acceleration
AI	Artificial Intelligence
ATC	Adaptive Threshold Control
Az	Azimuth
CCGS	Canadian Coast Guard Service
CFAR	Constant False Alarm Rate
ConfCoast	Confirmed track coast interval
COTS	Commercial Off The Shelf
CPA	Closest Point of Approach
CPU	Central Processing Unit
D	Detections
db	decibel
DGPS	Differential Geographic Positioning System
DLL	Dynamic Link Library
DW	Downwind
E	Extent
FA/Hr	False Alarms per Hour
GPS	Geographic Positioning System
GUI	Graphical User Interface
IMO	International Maritime Organization
IR	Infrared
km	kilometre
kn	knot
m	metre
M of N	Correlator - M detections out of N scans
MB	Megabyte
MHT	Multiple Hypothesis Tracker
MHz	Megahertz
MND	M of N Detector
MRI	Modular Radar Interface
MRSA	Modern Radar System Analysis
MV	Motor Vessel
nmi	nautical mile
PC	Personal Computer
PCI	Personal Computer Interface
Pd	Probability of detection
Pd_{cum}	Cumulative probability of detection
Pfa	Probability of false alarm
PIW	Person In Water
PPI	Plan Position Indication (radar screen)
R	Range bin
RCS	Radar Cross Section
Rfa	Rate of false alarm
rpm	Revolutions per minute
S/(C+N)	Signal to Clutter plus Noise (ratio)
SAR	Search And Rescue

GLOSSARY OF ACRONYMS AND ABBREVIATIONS CONTINUED

SARAIT	Search And Rescue AI Tracker
sdev	Standard Deviation
SIR	Signal-to-Interference Ratio
sm	Square metre
SNR	Signal-to-Noise Ratio
STC	Sensitivity Time Control
Tc	Time to confirm
TDC	Transportation Development Centre
TentCoast	Tentative track coast interval
Tv	Visibility time
Tvm	Total measured visibility time
Tvs	Total simulation visibility time
USCG	U.S. Coast Guard
USCGC	U.S. Coast Guard Cutter
UTB	U.S. Coast Guard Utility Boats
UTC	Universal coordinated time
UW	Upwind
V	Velocity
VTS	Vessel Traffic Services
W	Wind sector
WPB	USCG Work Patrol Boats
WR	Wave Rider (buoys)
XW	Crosswind

1. Overview

The Raytheon Search and Rescue Tracker (SAR Tracker) enables most commercial marine radars to detect and track small targets such as swimmers and liferafts in heavy seas. These are targets that are so frequently obscured behind waves and buried in radar clutter that even experienced radar operators are usually powerless to discern and track them.

The SAR Tracker uses one or more personal computers (PCs) to process the radar video signal into high confidence tracks. The entire SAR Tracker is therefore connected in parallel with the marine radar. This loosely coupled architecture enables the operator to use the radar without worrying about the Tracker, which quietly operates in the background using a completely independent signal processor. The Tracker uses a single monitor, which can be shared with other systems, to set up and control the processing and to display the radar picture, plots, M of N detections and tracks.

The purpose of this contract was to quantify the performance of the SAR Tracker under the wide range of conditions encountered in practical SAR operations.

To this end a substantial body of radar data was recorded off the east coast of Newfoundland in late 1997 using a 120 rpm geared-up Raytheon Pathfinder II and a Sigma Sea Scan radar processor. Radar observations of both tethered and drifting calibrated targets were recorded in wave heights from 1.5 to 4.5 m as described in Section 2.

Preliminary analysis of this data[1] in early 1998 demonstrated that small SAR targets could indeed be detected by the Pathfinder-Sea Scan-SAR Tracker system at operationally useful ranges. While sailing at 10 kn in 3.2 to 3.8 m seas, the SAR Tracker detected targets the size of a person-in-water (PIW) at 2 to 4 km and the size of a small four-man liferaft at 4 to 7 km. Maximum range was achieved when the wind-blown clutter was lowest. This performance was achieved with fewer than five false detections per hour.

These preliminary tests also showed how to double the detection range in higher sea states, by controlling the Sea Scan detection threshold in range and azimuth. Such an adaptable threshold could be set to detect small targets both in the intense clutter to windward, in the weaker crosswind and downwind clutter, and in the low clutter conditions at long range. In early 1999 Sigma Engineering effected the necessary Sea Scan upgrades and Raytheon Canada developed an adaptive threshold-setting algorithm called the Adaptive Threshold Control (ATC). With these improvements in place, a rigorous assessment of the SAR Tracker performance has been completed and is documented in this report.

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[1] P. Scarlett, et al., *AI Radar Tracker Upgrades for SAR Target Detection*, Transport Canada Publication TP 13322E, June 1998.

2. Theory of Operation

The basis of the SAR Tracker design is that conventional marine radars such as the Raytheon Pathfinder II and AN/SPS-73 have sufficient transmitter power, receiver sensitivity and resolution (in range and azimuth) to raise very small targets above the clutter and thereby detect them.

The problem for conventional IMO trackers is that small targets such as 0.5 m^2 liferafts have a very low probability of detection (typically 0.2 to 0.5) in anything but a flat calm. At the same time, the probability of false alarm (P_{fa}) will be high, at 0.01 to 0.001, depending on sea state. Smaller targets such as 0.03 m^2 swimmers are even less detectable. Moreover, for a masthead radar, such awash targets will be frequently hidden behind waves where they are completely undetectable. Coastal installations can mount the radar much higher to minimize wave blockage but this further increases the radar clutter.

The SAR Tracker works by correlating the sparse target detections amidst the more numerous clutter detections over many scans to accumulate a statistical basis for declaring a high confidence target track. The Tracker is designed to enable the shipboard radar to reliably detect and track swimmers and liferafts in Sea State 3 and 3 m swells at 1 and 3 nmi with fewer than five false tracks per hour. Larger targets with more freeboard, such as open boats, are tracked at longer ranges.

The SAR Tracker uses the Sea Scan[2] radar interface cards and software to digitize the radar video and then minimize the effects of sea clutter while detecting target-like features. Sea Scan implements the following processing stages:

- Pulse Filtering – integrates across the beamwidth to maximize the signal-to-noise ratio (SNR) and remove impulsive noise.
- Scan Averaging – integrates over several scans to further improve SNR (in low clutter conditions) and smooth out sea spikes.
- Ordered Statistic CFAR Detector – reliably detects small features in clutter and is less affected by clutter statistics than simpler cell averaging constant false alarm rate (CFAR). Detection threshold varies in range and azimuth as set by the Raytheon ATC. The CFAR parameters (rank, window length and offset) are set independently for the operator-defined upwind, downwind and crosswind sectors.
- Centroiding Plot Extractor – locates the centre of mass for contiguous detections and excludes those plots that are too large or small to be the target of interest. The Sea Scan software allows the operator to specify the minimum and maximum target extent in four operator-set range bands.

Plots (i.e., centroids) from the Sea Scan are then processed by two parallel Correlator-Tracker computers implementing the following processing functions:

- M of N Correlator – correlates over several scans to identify clusters of plots that are sufficiently close to be from a target and declares them as M of N Detections. Slower targets can be correlated over longer intervals than fast ones.
- Multiple Hypothesis Tracker (MHT) – correlates M of N Detections into tracks using rigorous Bayesian association logic and Kalman filtering. Multiple hypotheses enable the tracker to maintain several candidate tracks and thereby resist confusion from the numerous clutter detections and missed target detections.
- User Interface and Diagnostic Display – drop-down menu configuration of the M of N Correlator and MHT processing, display of M of N detections and tracks, and display of tracking statistics.

The overall system is controlled by four common functions:

- Adaptive Threshold Control – computes the appropriate detection threshold in each range-azimuth to maintain a constant false alarm rate irrespective of the local clutter strength and statistics. The map is updated every minute or so, to track changes in clutter intensity and statistics as rain cells and other features move through the field of view and as the radar blockage moves due to ship manoeuvres.
- Track Fusion (in development) – fuses multiple tracks from the same target into one composite track.
- Automatic Setup (in development) – automatically selects processing parameters based on the key operational requirements selected by the operator (target size, maximum manoeuvrability, maximum speed, sea state, swell period and desired false track rate)
- Radar Display – the Sea Scan display overlays track vectors onto the radar plan position indication (PPI) display and allows the operator to pop up each track’s speed, course, range, bearing and ID. Track quality is available but not yet displayed.

Typically each Correlator-Tracker is configured for:

- a particular class of target, for example, fast or slow, high or low manoeuverability, high or low visibility (i.e., freeboard); or
- a different parsing of the expected visibility (e.g., 6/40 and 2/10, 3/4) to better detect targets with differing wave-induced visibilities; or
- a look direction, for example upwind or downwind; or
- a geographic area.

[2] Sea Scan is the trademark of Sigma Engineering, St. John’s, Newfoundland.

This division of labour works well because the smallest awash targets, such as swimmers and debris, are typically drifting at 1 kn or less. Such drifting targets can therefore be correlated for longer intervals to compensate for their reduced visibility (due to waves) and low average probability of detection (due to the low radar cross section (RCS)). Targets with more freeboard, such as liferafts, have more windage and therefore drift faster, but are more visible behind waves and have larger RCS.

Similarly, in serious seas (and clutter), small 5 to 6 m open boats and inflatables have to slow down to avoid swamping or flipping. Conversely, the larger 15 m cigarette-style offshore power boats can go faster but are also much more detectable.

The overall signal processing chain is shown below.

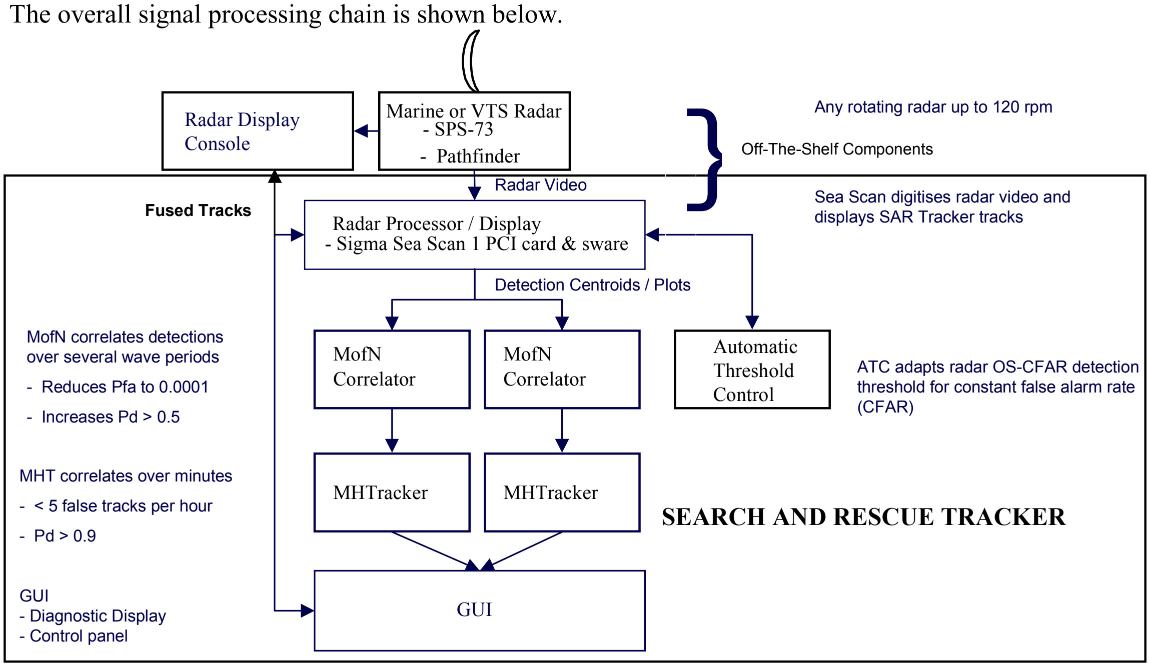

Figure 2-1 Search and Rescue Tracker functional block diagram

To summarize, the SAR Tracker reliably detects and tracks small targets with very few false tracks because:

- the Sea Scan processing maximizes target detectability on each scan;
- the M of N Correlator dramatically reduces the number of false detections entering the MHT;
- the advanced MHT association techniques follow strict Bayesian logic that minimizes the chances of spurious associations; and
- the conservative MHT track promotion logic postpones confirming tracks until the confidence is sufficiently high. For a track to be confirmed, two consecutive M of N detections must be close enough to be associated into a potential track, which must then have several (typically three to five) updates to be confirmed. If several updates pass with no association, then the tentative track is deleted and never confirmed. The odds of sea clutter passing these criteria and being confirmed is extremely low under normal operating conditions.

A typical reduction in the false alarm rate from the input detections with Pfa = 0.01 to the final SAR Tracker output with 3 false tracks per hour is shown below. This data was gathered using a Raytheon Pathfinder II radar, detecting targets ranging in size from 0.03 to 0.5 m^2 at maximum ranges from 1.2 to 3 nmi in moderate wind-driven clutter. The radar was mounted 20 m above sea level on a buoy tender sailing at 10 kn in 3.2 m seas.

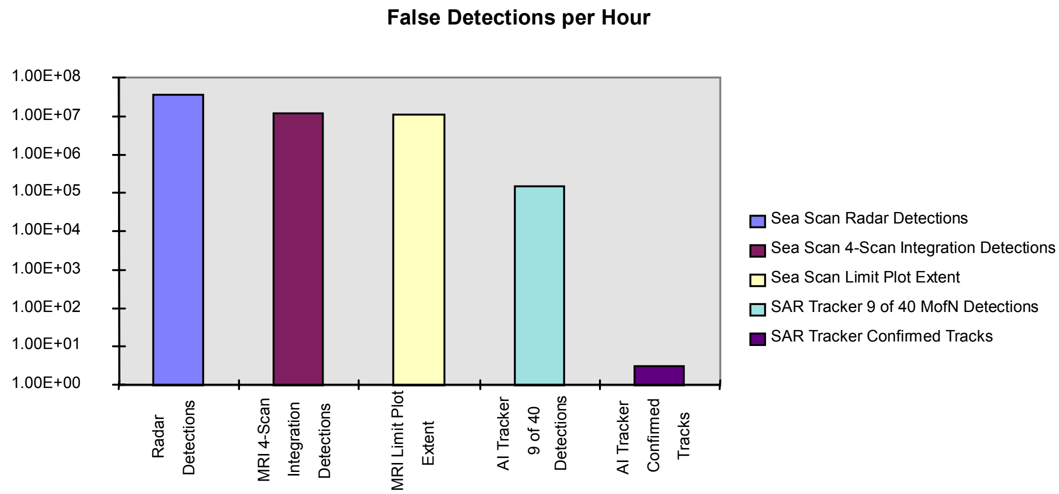

Figure 2-2 Reduction in false alarms with successive SAR Tracker processing stages

3. Key Processing Functions

3.1 Adaptive Threshold Control (ATC) and OS-CFAR Detector

The processing load of the M of N Correlator and the MHT are determined mainly by the number and density of input plots. Plots and existing tracks (or M of N correlations) that could potentially interact must be treated together in a cluster if the association and assignment is to be at all optimal. The processing load rises exponentially with cluster size, which is therefore a key determinant of the processing load. The ideal approach to limiting the processing load is to maintain a constant plot density throughout. The SAR Tracker approximates this by maintaining a constant detection density; since most detections are by definition due to clutter, this is the same as maintaining CFAR.

To this end, the Sea Scan was improved to allow the CFAR detection threshold to be set in range and azimuth. The thresholds are computed by the SAR Tracker and entered into the Sea Scan plot extractor as a threshold matrix of 360 azimuth cells by 128 range cells mapped onto whatever size image the Sea Scan is generating. The SAR Tracker controls the Sea Scan threshold by a simple proprietary algorithm, implemented in C-code, called the Adaptive Threshold Control.

Marine clutter environment is in constant flux as winds shift direction and speed, as rain cells move through the field of view and as the ship manoeuvres (shifting the azimuth of any (ship-centred) radar blockage). New thresholds are regularly computed every one to three minutes to better track the clutter as it moves and as it changes intensity and statistical behaviour. The ATC does not remove clutter but it does maximize the detection performance therein. Local increases in clutter power unavoidably degrade the local S/(C+N) ratio; since the ATC adapts to maintain a constant Pfa, the local probability of detection (Pd) will necessarily drop. The SAR Tracker can usually initiate and maintain tracks in a cluttered environment with Pfa of 0.001 even when the Pd drops to 10 to 20 percent. In essence, maintaining CFAR lets the M of N Correlator and the MHT work to maximum capacity.

The ATC determines the threshold matrix that provides a constant median Pfa throughout the field of view. The Pfa is measured at the CFAR output prior to centroiding. The assumption made here is that almost all detections in any scan are false alarms due to clutter and noise. This assumption is most valid for the SAR Tracker's intended operational environment, where a few small targets are buried in strong clutter.

Extensive trials off Newfoundland have demonstrated that true CFAR detections are maintained, irrespective of the local clutter intensity and statistical characteristics. CFAR is maintained even as rain cells drift through the field of view. Strong returns from land, large vessels and buoys in light clutter can slightly increase the detection threshold for up to 100 m around, but improvements to the ATC are underway to remove this effect.

The Sea Scan radar processor implements a sliding window OS-CFAR that operates on CFARWindow range samples on both sides of each range-azimuth cell. The amplitude of these 2*CFARWindow samples and the central cell under test are ordered and the CFARRank percent largest is taken as the local CFARBackground for the central cell. The CFAR filtered image is computed as CentralCell – CFARBackground + CFAROffset for each cell in the image. The Sea Scan plot extractor merely applies a threshold to this CFAR-filtered image and then centroids contiguous detections into plots.

The resulting plot density depends on the size of the clusters. Areas with large features (e.g., at short range upwind in heavy clutter) have large average extent and will typically have lower plot densities than areas where the features are smaller (e.g., at longer ranges where clutter is modest).

The Pathfinder II used in these trials has a nominal radar range resolution of 40 m on medium pulse and 6 m on short pulse. The azimuth resolution with the 7-ft. X-band antenna is 1 deg. In these trials, the Sea Scan was configured to record the medium pulse data by sampling every 15 m and 0.352 deg. A point target detected in the absence of noise will ideally span 40/15 x 1/0.352 or 2.7 x 2.8 range azimuth cells and have an extent (E) of about 8 cells. With noise, the detection threshold is increased, which reduces the measured target extent to typically about 4 to 6 cells. The desired Pfa is calculated thus:

$$\text{Pfa } \% = P * E / (\text{RangeCells} * \text{AzimuthCells}) * 100\%$$

For a desired plot count (P) of 1000 on 768 x 1024 medium pulse images with an average target extent of 4, the required Pfa is 0.005 or 0.5 percent.

The ATC algorithm processes several radar scans to estimate the threshold matrix and then smooths the result to limit abrupt threshold changes that would otherwise introduce plot extraction artifacts. The threshold matrix is thereby adapted to dynamic features such as rain cells and sharp-edged features such as land.

The ATC algorithm is implemented in C-code and communicates independently with the Sea Scan server using sockets and the Sea Scan Dynamic Link Library (DLL).

3.2 M of N Correlator

The M of N Correlator must typically process up to one minute of plots in real time. Even longer correlations are possible against slowly drifting or stationary targets. The M of N Correlator implements three nested correlations to combat bursts of plots from short-lived but strong sea spikes and breaking waves that would otherwise appear target-like.

In marine search and rescue, the radar may be rotated at 120 rpm so the M of N Correlator must handle up to 120 scans of plot data in real time. The SAR Tracker implements two (or more) parallel M of N Correlator-MHT chains. If both are looking for similarly small drifting targets in a 120 rpm marine search and rescue application, one might be configured for 6/20,1/1,2/2 and the other for 5/15,1/2,2/2. Both are correlating more than 60 scans but are parsing the data space differently to increase the aggregate probability of detection.

For coastal surveillance applications with a conventional 25 rpm vessel traffic services (VTS) radar, a more typical division might be 2/6,1/1,2/2 focussing on small open boats and 2/3,1/1,1/1 looking for faster, more detectable targets. As usual, the longer correlations are used for the slower, less detectable targets.

The M of N Correlator uses balanced tree techniques to build and prune the large dynamic database. In some cases, the M of N Correlator has run successfully with over 60,000 plots in its database.

3.3 Multiple Hypothesis Tracker (MHT)

The greatest problem associated with tracking multiple targets, based on large numbers of radar detections, is the possibility of incorrect association. In other words, if an established target track is assigned an incorrect detection, the update of its trajectory could send it in the wrong direction, resulting in a false or deceiving target track. Since such tracking is inherently a causal system, these problems can not be recovered from. In the last 20 years, and with the advent of more powerful computers, new techniques have been developed that allow better association decisions to be made, even allowing for the possibility of incorrect assignments. One of the most advanced is the multiple hypothesis tracking algorithm.

The MHT was conceived in its most complete form by Reid[3]. It is a statistical approach, incorporating false targets, new tracks, missed detections and finite track lifetimes. The basic premise is that, through the application of Bayes' rule, the probability of any track/detection combination, over a given number of radar updates, is solely dependent on the probability of the combination from the previous scan and the probability of the current track-detection updated association. The algorithm thus does not make any "hard" assignments at each step; it instead keeps all possible track/detection associations, ranking them by their probabilities (i.e., how likely a given association actually is). Such hypotheses may be efficiently updated at each step merely by calculating the current probabilities for association. Thus, a combination of tracks and detections that looks very likely at one stage may, at a later time, be revealed to be less feasible as its updated probability decreases. The correct (or more likely) association hypotheses will then predominate, allowing incorrect decisions to be prevented.

MHT processing assumes that each new M of N plot is either an extension of an existing track, a new target or a false alarm (these last two options are combined). These possibilities, together with a missed detection scenario for each of the tracks, account for the additions to the hypothesis set at each update time. The combination and extension of tracks and hypotheses implies that there is exponential growth as new hypotheses are formed at each update. Our implementation of the MHT propagates several of the most likely possible track/detection scenarios forward, thus still allowing for the likelihood of missed detections, crossing tracks and false alarms. Efficiency is further maintained by clustering the data, whereby the multiple hypotheses are considered only for groups of tracks and detections that are close to each other. This enables the gross complexity of the problem to be reduced. These clusters encompass hypotheses that share common reports and are separate from those in other clusters. In this way, clusters may be processed independently and in parallel, preventing unconstrained growth of the hypothesis tree. The best track/detection hypotheses are determined as solutions to a linear assignment problem, where the elements or "costs" are determined (probabilistically) by the closeness of targets and detections.

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[3] D.B. Reid, *An Algorithm for Trading Multiple Targets*, IEEE Transactions on Automatic Control, Vol. 24, No. 6, pp. 843-854, 1979.

In the MHT, the auction algorithm is used (repeatedly) to solve these problems. Once under track, the target trajectories are propagated using a Kalman filter.

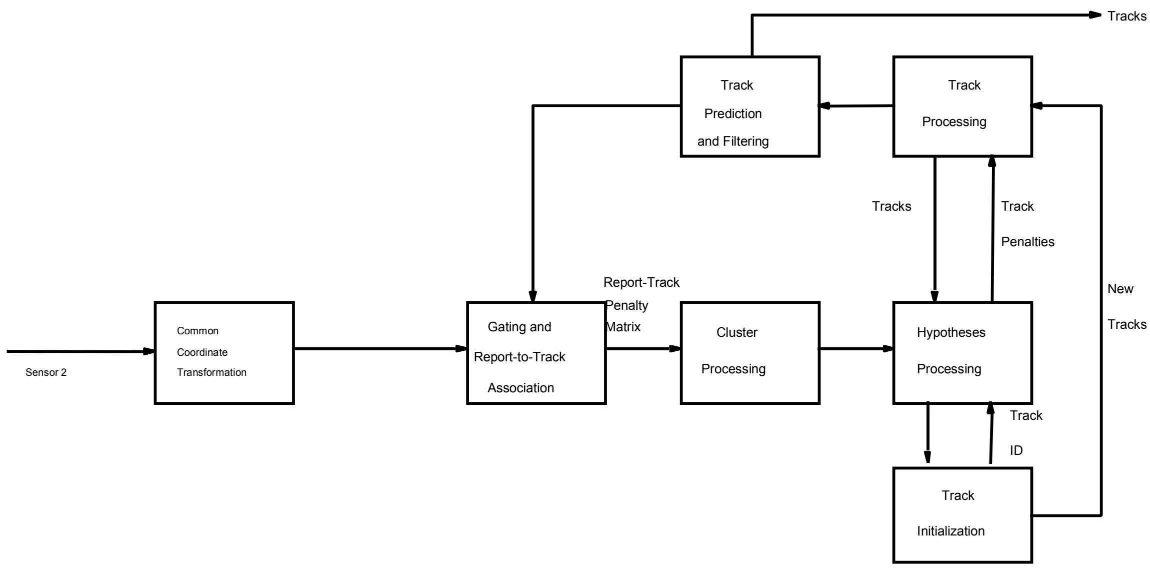

Figure 3-1 Multiple Hypothesis Tracker functional block diagram

The MHT automatically initiates high confidence tracks on all targets meeting the user-defined criteria for track initiation. M of N detections from several scans are required to ensure high confidence (and low false tracks) before initiating a confirmed track. The track initiation process is extremely resistant to false alarms, yet is very rapid when there is clear evidence of a track.

All tracks are confirmed through two lower-confidence intermediate stages:

1. Potential tracks result when plots on two consecutive updates (i.e., of M of N Detections) are close enough that they can be associated.
2. Tentative tracks are the extension of potential tracks through successive updates. Each tentative track is maintained with a count of the number of updates having valid associations (i.e., hits) and the number of consecutive updates with no valid associations (i.e., consecutive misses). The user defines how many hits are required for a confirmed track and how many consecutive misses are needed to delete the tentative track. Good results were achieved in Tarifa when the MHT was configured to confirm tracks after three hits and delete them after four consecutive misses. A separate user-configurable parameter defines the number of consecutive misses to delete a confirmed track (typically five or six updates).

Only confirmed tracks are shown to the operator because of their much greater confidence when compared with the tentative and potential tracks.

A new feature under development lets the operator manually cue the tracker to initiate either a confirmed track at a specified location, speed and course, or a potential track at a specified location.

The MHT implements full Bayesian association logic and uses Kalman filters to predict and smooth the track. Estimated track and measurement errors are used to size the association gates and calculate the probabilities of association.

It is normal with MHT that each new set of plots causes an explosive growth in the tree of potential and tentative track associations followed by a re-clustering and a pruning down to the retained (most likely) hypotheses. Typically, the MHT is operated with two to four hypotheses per track. Implementing this dynamic database in a modest computer is central to the success of the SAR Tracker.

The SAR Tracker can be configured so that on average less than 1 percent of pre-existing tracks will have lost track at any time. Once confirmed, tracks will be coasted for a user-set number of M of N updates to bridge periods of poor detections, target overlap and other problems. Confirmed tracks are always coasted further than tentative tracks as befits the greater confidence expressed in them. Detections that were good enough to initiate a confirmed track will almost always sustain the track through normal degradations so the probability of track loss is typically low.

The SAR Tracker is particularly tolerant of crossing targets because of the use of multiple hypotheses and rigorous Bayesian association logic. Should two crossing targets be blurred into one plot, the tracker associates the plot with both of the candidate tracks. As long as successive scans eventually resolve the targets before the tracker has reached 50 percent of its coasting limit, then in 95 percent of cases, the tracks will be unambiguously associated again. Problems typically arise with very slow targets or extremely acute convergence angles where the targets stay merged beyond the tracker's coasting limit. A typical example of successful tracking is shown below with the underlying detections and the resulting tracks.

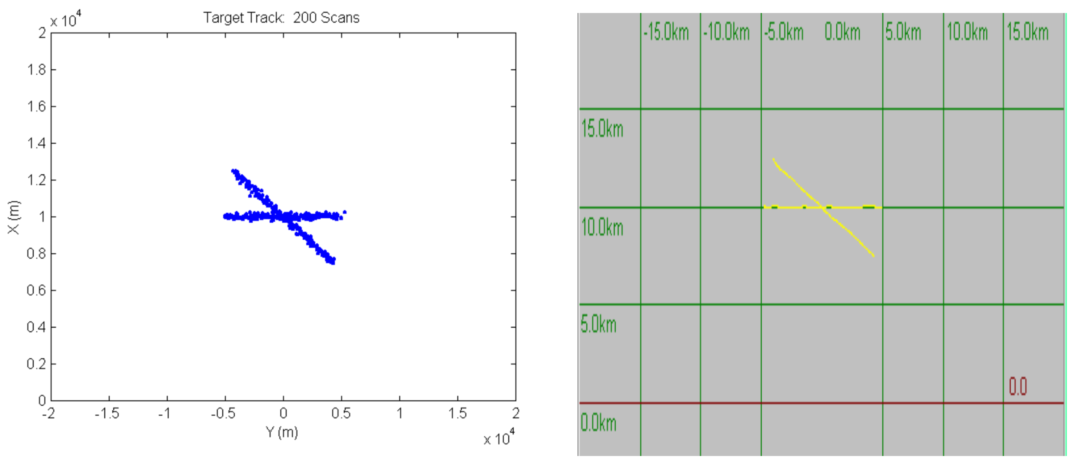

Figure 3-2 Multiple Hypothesis Tracking of crossing targets

Phantom tracks (or track seductions) are exceedingly rare because the MHT allows only the two to four most likely hypotheses to propagate. Even if a false detection is close enough to be the most likely association (e.g., on an update with no true target detection), the likelihood of this false track continuing with further detections is much lower than the likelihood of a valid target detection pulling the track back on course.

False tracks receiving updates are also rare and short-lived because of:

1. the limited number of false detections passing the M of N Correlator, and
2. the Bayesian association logic that is rigorously tied to the radar error ellipses and the estimated Kalman filter error.

4. Implementation

The entire SAR Tracker is implemented on two dual-CPU PCs linked by Ethernet. The Sigma Engineering Sea Scan radar processor software and the associated PCI Radar Interface card are installed either on one of the SAR Tracker PCs or on a separate PC linked by Ethernet. Industrial enclosure PCs can be used for a more rugged installation on a ship's bridge. Maintenance and upgrades are facilitated by the use of standard PC hardware and software.

All software is in object-oriented code. This facilitates both system maintenance and improvement at a reasonable cost. New features can be added with much less effort than would be normal with lower level languages such as C.

PC implementation of these sophisticated M of N Correlation and MHT algorithms is only possible because of the careful algorithm design, extensive trials and a tailored coding for computational efficiency. To put things in perspective, the 1996 version of the MHT was tested for the Transportation Development Centre (TDS) at the Vancouver VTS Centre, where it ran in real time on a 486DX4 processing 100 plots every 2.5 seconds. The current implementation uses dual Pentium 700 MHz CPUs with 500 MB of memory and can process up to 1000 plots every half-second.

The operator controls the SAR Tracker parameters using the Sea Scan Graphical User Interface (GUI) and the SAR Tracker GUI shown in Figure 4.1. All parameters are set by means of drop-down menus. A diagnostic display of current and past M of N detections and tracks is provided to facilitate tuning the system to the particular site, mission and sensor characteristics.

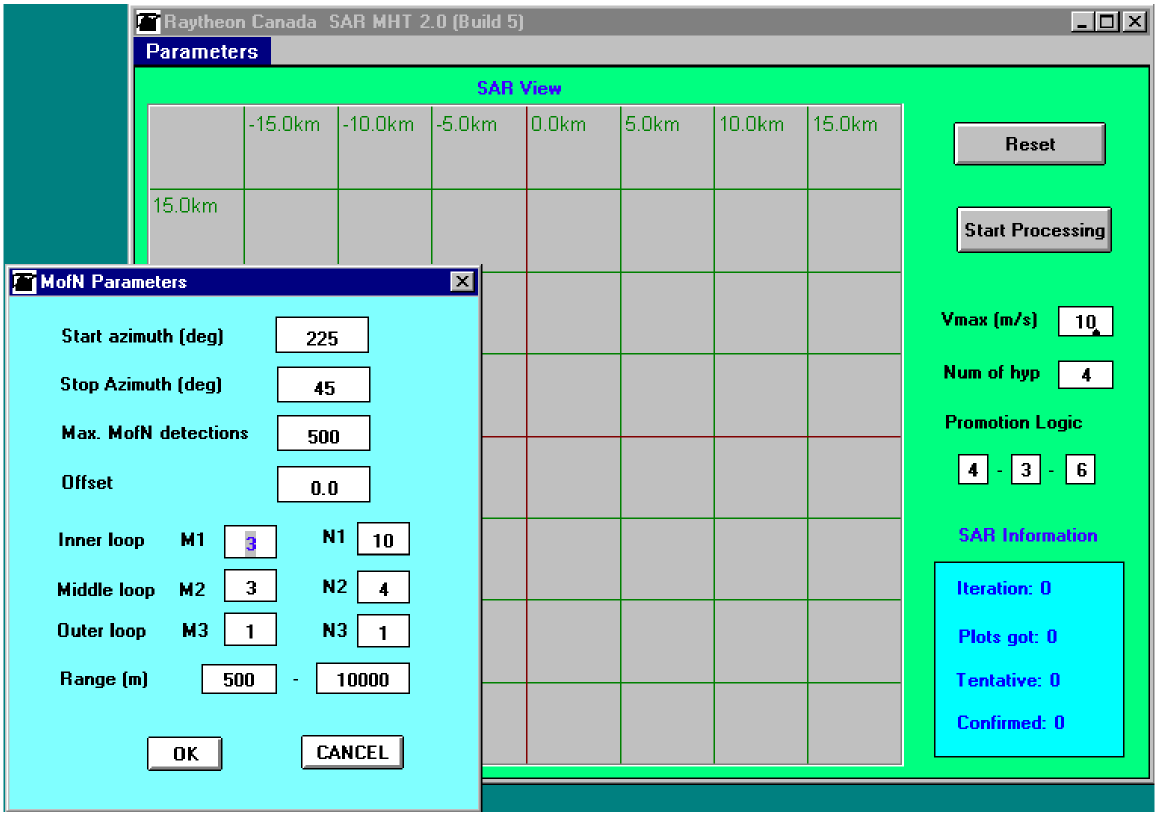

Figure 4-1 SAR Tracker graphical user interface showing M of N Correlator drop-down menu

5. Recorded SAR Data

Oceans Limited of St. John's, Newfoundland, was separately contracted by TDC to prepare for and carry out a field trial off the east coast of Newfoundland with the support of the CCGS *J.E.Bernier*. An extensive set of radar data was recorded of calibrated targets in both tethered and drifting configurations. Staff from Sigma Engineering were on board to operate the Sea Scan and from Raytheon Canada to test the SAR Tracker with live and recorded Sea Scan data.

The performance of any radar processing technique is initially determined by the radar data and the experimental conditions. To accurately assess performance, data was gathered that spanned all the acquisition variables summarized in Table 5-1.

Table 5-1 Data acquisition variables

Variable	Range	Notes
Sea Characteristics		
Sea State	0 to 5	Depends on weather
Wave Shape	Uniform to Steep	Depends on wind/wave/current geometry
Target Characteristics		
Radar Cross Section	0.03 to 0.15 m^2 0.2 to 0.6 m^2	Typical unaugmented PIW Typical liferafts and augmented PIWs
Extent	1 resolution cell	Point targets
Drift Velocity	0 to 1 kn	Tethered and drifting targets (both move)

Dispersion	Tethered targets are 0.4 nmi apart Drifting targets are typically 100 m apart	All tethered targets can be resolved Multiple survivors and debris fields
Search Vessel Characteristics		
Speed	6 to 10 kn	Typical search speeds
Bearing to Target versus Wave Direction	360 deg.	Test all geometries (large differences between upwind, downwind and crosswind)
Radar Mast Blockage	Ahead vs. Astern Port vs. Starboard	Test targets at both to quantify degradation Radar on centre-line; so no difference
Radar Mast Height	25 m	CCGS *J. E. Bernier*
Radar Processing		
STC	On or Off	Test both
Pulse Length	Short and Medium 1	3 and 6 nmi range

5.1 Radar Target Characteristics and Ground Truth Data

Twenty-five calibrated radar targets were tethered 0.4 nmi apart in a 5 x 5 square array with a wave-rider buoy (of approximately 0.6 m^2 uncalibrated RCS) tethered 1.5 nmi to the north. Six sizes of target were used:

- 1x Wave-Rider 0.6 m^2 estimated 4- to 6-man liferaft (estimated)
- 1x A6 Target 0.47 m^2 4-man liferaft (measured)
- 6x A5 Target 0.31 m^2 swamped 4-man liferaft (estimated)
- 6x A4 Target 0.19 m^2 PIW in survival suit (estimated)
- 6x A2 Target 0.09 m^2 PIW swimmer (maximum measured)
- 6x A0 Target 0.03 m^2 PIW swimmer (minimum measured)

Additional A0, A2 and A4 targets were deployed in various drifting constellations throughout the trial. Flashing lights and a radio beacon were used on the A4 and larger targets to facilitate recovery.

Tests at Cape Spear, Newfoundland, indicated that an unaugmented diver's head had an RCS between 0.03 and 0.09 m^2 and a diver in a lifevest an RCS of about 0.14 m^2. A PIW with a survival suit floats higher and exposes both legs and arms to the radar, and therefore has an estimated RCS of 0.19 m^2. The A0, A2 and A4 targets should therefore have spanned the expected range of worst-case PIW SAR targets.

All targets were moored with 191 m anchor cables in about 145 m of water. Allowing for water depth variations, and with no a prior knowledge of the direction of target drift, Oceans Limited calculated the maximum expected "watch circle" radius to be 130 m. The centre of this watch circle had a maximum deployment error of about one ship length, or 70 m. The maximum error in the ground truth array positions was therefore 200 m.

5.2 Tethered Array Data Gathering

Target detectability with marine radars varies greatly depending on the viewing angle relative to the waves and the wind; visibility is lowest into or away from the prevailing waves and highest across them (i.e., along the troughs). Sea clutter is highest looking upwind, where the waves are steep-faced and most reflective, particularly if the sea is building. Slightly lower clutter is measured downwind but the lowest clutter is crosswind looking along the troughs of the wind-driven waves. To complicate matters, the ocean swell and the wind-driven waves are usually from different directions. Performance was also expected to vary with ship speed and blockage effects. A scripted search pattern was therefore sailed that examined all targets in the square array from all possible viewing geometries and ranges in two stages:

1. Two perimeter searches offset 0.25 nmi from the array using first medium and then short pulse. The objective was to test how targets are acquired at different ranges and viewing geometries relative to the waves. Target range varied much more slowly than did the viewing geometry. On any leg of the perimeter search, the furthest targets were 2 to 2.5 nmi distant and therefore around the expected limit of detectability. The closest targets were 0.25 to 0.5 nmi distant and therefore highly likely to be detected.
2. A stepped search with 3 nmi extensions at each corner as shown in Figure 5-1. The objective was to test how quickly targets are acquired and lost as the range (but not the geometry) changes rapidly. The pulse length was changed at the end of each radial to compare short and long pulse performance under comparable geometries and sea states.

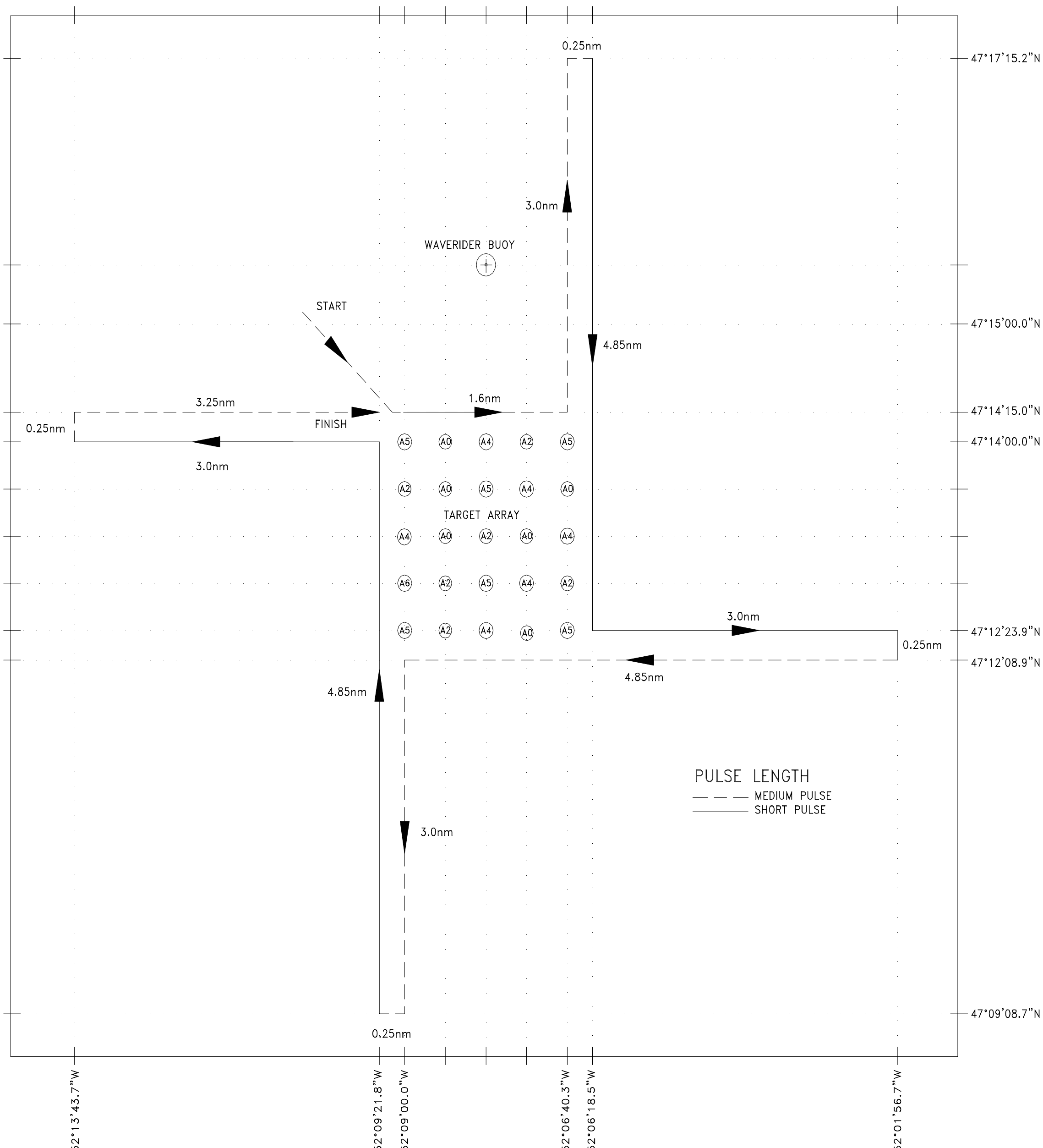

Figure 5-1 Stepped search data gathering sailing pattern

5.3 Drifting Targets Data Collection

Disposable targets were cast adrift en route to (and from) the tethered array and monitored as they receded astern and as they were approached on recovery. DGPS deployment and recovery positions were accurately recorded in a log along with the estimated speed and direction of drift (from experience or charts).

The objective was to measure the performance against drifting targets, both individually and in clusters (both resolved and seen from differing geometries relative to the wind and swell). To this end, the targets were deployed and recovered from different directions and in a wide variety of sea states, winds and currents. The target displacement from deployment to recovery was used by Oceans Limited to estimate the average drift rate and interpolated position fixes.

5.4 Environmental and Radar Data Log

The following environmental measurements were logged every half-hour throughout the trial:

- Local time;
- Visibility (nmi);
- Cloud (tenths);
- Weather;
- Combined significant wave height and period;
- Significant wind wave height and period;
- Predominant swell height and period;
- Wind speed and direction;
- Air temperature;
- Dew point temperature;
- Sea temperature; and
- Ship speed (kn) and heading.

Throughout the sailing pattern, scrupulous records were kept by Oceans Limited of the timing and nature of all changes to the radar settings, Sea Scan processing and Sea Scan taping.

5.5 Radar Recordings

Twenty-four Exabyte tapes were recorded during the trials as summarized below in Table 5-2. The focus of this project was on the higher sea states, particularly in high winds where the clutter is most severe. These conditions imposed the most stress on the SAR Tracker and served to best delineate its performance limits.

Table 5-2 Radar recordings grouped by wave height

Tape / Segment	Search Type	Combined Sea (m)	Wind Speed (kn)	Pulse	Notes Clutter Level
	Tethered Array	**>3.5 m**			
14 / 0 - 2	Step, Step, Circuit	3.6 – 4.4 m	40 – 44 kn	S, M, M	Very High
15 / 0, 1	Circuit, Leave Area	3.8 m	44 kn	S, M	Very High
	Tethered Array	**3.0 to 3.5 m**			
12 / 1, 2	Approach, Circuit	3.3 – 3.0 m	34 – 38 kn	M, S	Very High
13 / 0 - 2	Circuit, Step, Step	3.2 – 3.3 m	38 – 43 kn	S, M, S	Very High
19 / 1 - 2	Circuit, Circuit-Step	3.2 – 3.4 m	12 – 23 kn	M, S	High
20 / 0 - 2	Step	3.4 – 3.2 m	15 – 10 kn	M, S, M	Medium
21 / 0, 1	Circuit	3.3 – 3.0 m	10 – 2 kn	S, M	Medium - Low
22 / 0	Circuit (cont'd)	3.0 m	1 kn	M	Low

22 / 1 - 5	Step	3.1 – 3.5 m	1 – 8 kn	M, S, S, M, M	Low
23 / 0, 1	Step (cont'd)	3.5 m	8 kn	S, M	Low
	Tethered Array	**2.5 to 3.0 m**			
16 / 0 - 3	Step, Step, Step, Circuit	2.8 – 3 – 2.6 m	28 – 24 kn	M, S, M, S	High
17 / 0 - 2	Circuit	2.6 – 2.8 m	24 – 29 kn	S, S, M	High
18 / 0 - 2	Return	N/A	N/A	S	High
	Tethered Array	**2.0 to 2.5 m**			**Azimuth Spokes**
8 / 1, 2	Step	2.1 – 2.3 m	25 – 33 – 29 kn	M, S	High
9 / 0	Step cont'd	2.3 m	32 kn	M	High
9 / 1 - 2	Circuit	2.3 m	32 – 23 kn	S, M	High
9 / 3	Step	2.3 m	20 – 27 kn	S	High
10 / 0 - 3	Step cont'd	2.3 – 2.4 m	27 – 24 – 28 kn	M, S, M, S	High
	Tethered Array	**< 2.0 m**			**Azimuth Spokes**
7 / 2 - 4	Circuit	1.7 – 1.8 m	20 – 28 kn	M, M, S	High
8 / 0	Circuit	1.8 – 1.9 m	25 – 33 – 29 kn	S	High
	Drifters	**1.5 to 3.5 m**			
12 / 0	Deploy Drifters	3.1 m	31 kn	S	High (Spokes)
11 / 0	Recover Drifters	2.4 m	28 kn	M	High (Spokes)
7 / 1	Deploy Drifters	1.7 m	23 kn	S	Medium (Spokes)
19 / 0	Deploy Drifters	3.1 m	12 kn	S	Medium
24 / 0, 1	Recover Drifters	3.5 m (est)	10 kn (est)	S, M	Medium
	Other Data				**Heading Error**
1 / 0, 1	Circuit	1.8 – 1.9 m	10 – 14 kn	S, M2	Heading Error
1 / 2 - 5	Step	1.7 – 2.2 m	11 – 18 kn	S, M, S, S	Heading Error
2 / 0	Step	2.2 – 2.0 m	18 – 17 kn	M	Heading Error
3 / 0 - 6	Approach	2.2 m	19 – 14 kn	M	Heading Error
4 / 0 - 2	Circuit and Step	2.2 m	15 – 13 kn	SA, M, SA2	Heading Error
5 / 0 - 2	Step and Return	2.5 m	12 kn	M2, M, SA2	Heading Error
6 / 0 - 4	Testing			S, S, S, M, S	Testing

Regrettably, Tapes 1 to 5 have occasional heading errors that limit the SAR Tracker performance while Tapes 8 to 11 have free-rotating radial spokes of reduced sensitivity that prevent the ATC from setting a useful median CFAR. These problems with the data precluded any useful analysis of SAR Tracker performance in waves under 2.5 m.

6. Preliminary Results

The original non-adaptive SAR Tracker system underwent a limited set of testing in 1998 on a small subset of the extensive recorded data set. The preliminary tests demonstrated that, while sailing at 8 to 10 kn in 3.3 to 3.8 m seas, the SAR Tracker detected very small PIW-sized targets at 1 to 2 nmi (depending on the clutter intensity) and small liferaft-sized targets at 2 to 3.5 nmi, all with fewer than 5 false detections per hour. The testing on these two data sets probed the interrelationships between the many processing parameters but there was insufficient time to explore the performance limits.

The SAR Tracker was tested on two small sets of data gathered in 3.8 and 3.3 m seas; the first data set has very little clutter and the second a great deal. For these preliminary tests, the measure of performance was the maximum detection range for each class of target that was achieved with a SAR Tracker false alarm rate of under 10 per hour.

6.1 Low Clutter Tests

Under **low clutter conditions** most false alarms are due to relatively uncorrelated receiver noise and sea spikes; therefore, the MND can detect even the least visible SAR targets by correlating over several wave periods. Because of this, the maximum SAR Tracker detection range is approximately the same at all bearings. Under these conditions, the SAR Tracker processing is particularly robust and insensitive to the exact choice of processing. Figure 6-1 demonstrates that the Wave-Rider buoy is consistently detected at 3.5 nmi whether 2, 4 or 8 scans are integrated in the Sea Scan. Similarly, the SAR array targets are all detected at around 2 to 2.5 nmi irrespective of the processing or their size. This confirms that target visibility is the main limitation under low clutter conditions such as these.

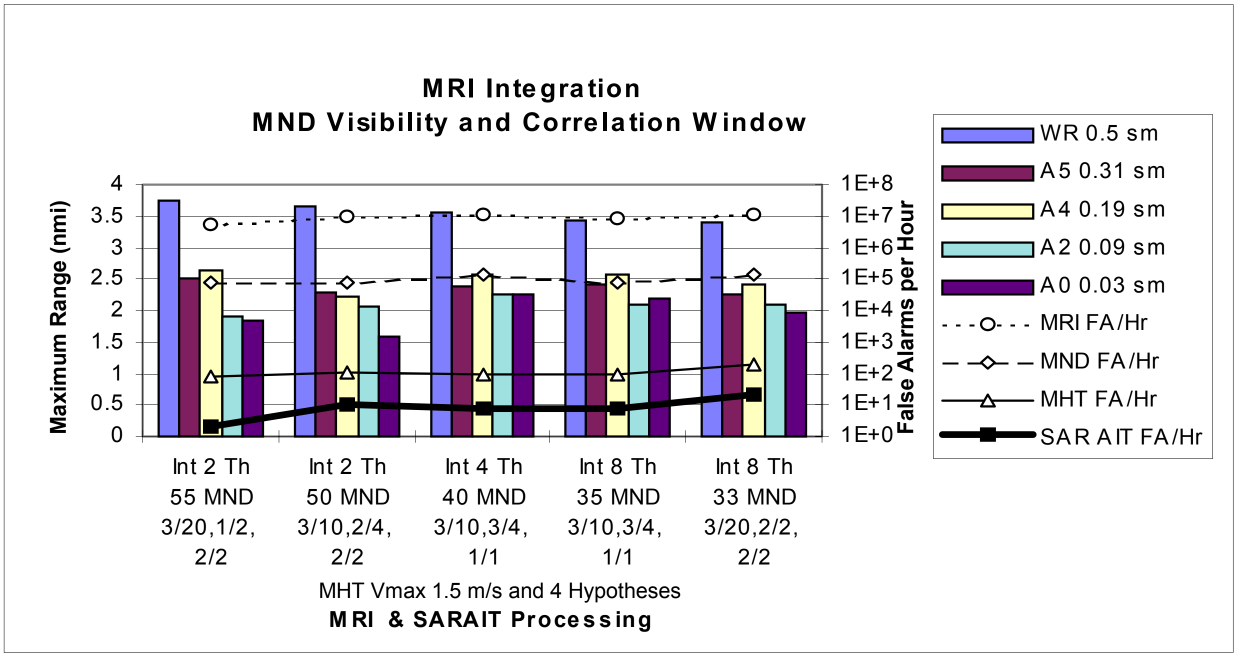

Figure 6-1 Non-adaptive Pathfinder-Sea Scan-SAR Tracker performance in 3.8 m seas and low clutter

Reasonable detection ranges with 2 to 20 false tracks per hour were therefore achieved under these low clutter conditions:

- by setting the Sea Scan threshold for 750 to 1500 plots per scan (Rfa = 1e7);
- with an MND ratio from 7.5 to 25 percent giving 200 to 500 MND detections per interval (Rfa = 1e5/hr);
- with an inner MND window less than or equal to the average wave period (10 seconds or 20 scans);
- with an overall MND window spanning several wave periods; and
- with a maximum track velocity of 1.5 m/s (3 kn) to allow for sudden wave-driven motion.

6.2 Moderate Clutter Tests

The SAR Tracker also reliably detected awash SAR targets in **moderate sea clutter** and similarly high 3.2 m swells albeit at shorter ranges and not into the face of steep wind-driven 0.3 m waves where the clutter is most intense. In high winds, the sea clutter varies enormously in range and azimuth while the tested Sea Scan settings were global. In the absence of the ATC, the Sea Scan was therefore set to compromise between dense detections at close range and upwind, and sparser detections at longer ranges and downwind. Nonetheless, the Wave-Rider buoy and the A6 and A5 targets were typically detected at 1.5 nmi, and the A0 targets at 0.5 to 1 nmi.

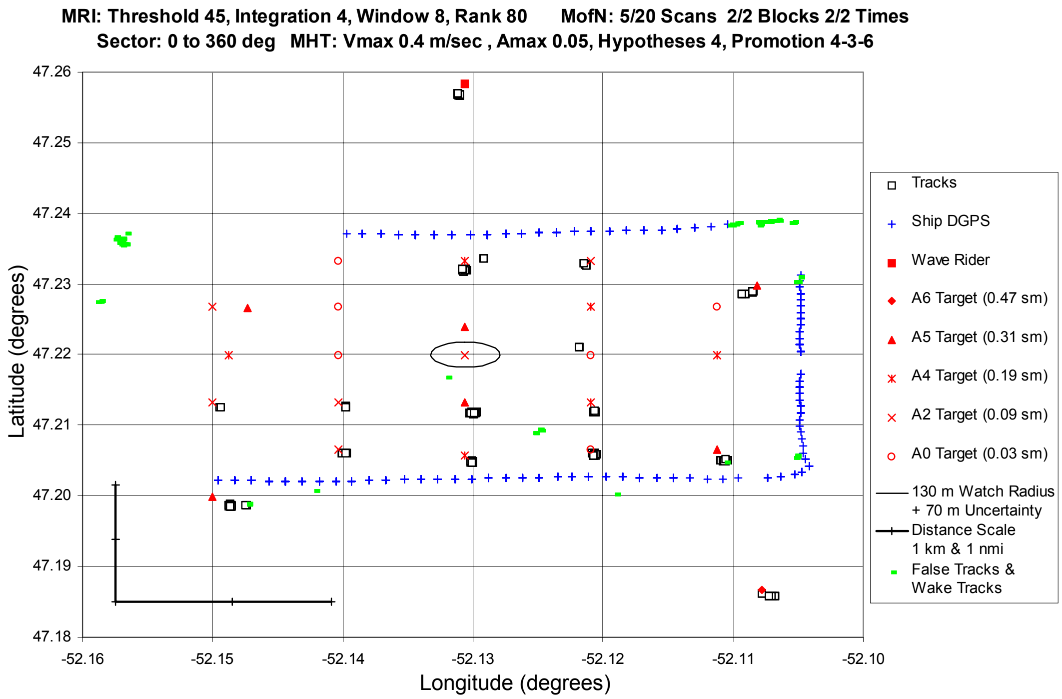

Figure 6-2 SAR target tracks superimposed on the array ground truth (medium clutter)

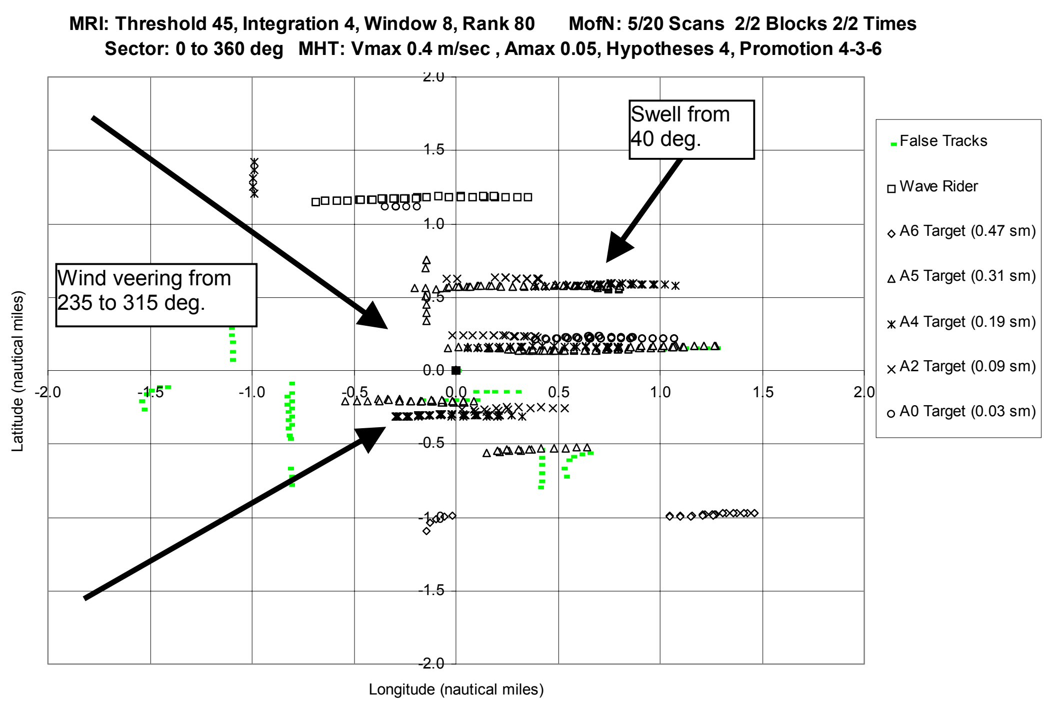

Figure 6-3 SAR target tracks, range and bearing from the ship (medium clutter)

There were many ways to set up the original non-adaptive system to detect the SAR targets with operationally acceptable false alarm rates. Figure 6-4 illustrates several examples of successful SAR processing that expose the broad trends that will lead to the best possible performance in this, the next phase:

- Sea Scan integration over the number of scans targets will be at each wave crest (2 to 4 in this case);
- Sea Scan CFAR window set to 8 for lowest Rfa overall and to 4 for maximum small target range;
- Sea Scan CFAR rank of 30 for nearby small targets to 80 for larger distant targets;
- MND inner window matched to the expected target visibility (10 to 25 percent depending on range, size and azimuth) and the wave period (20 in this case);
- Total MND correlation interval of 2 to 6 wave periods (40 to 120 scans in this case);
- MHT hypotheses set to 4 or more in SAR environments;
- MHT and MND maximum velocity reduced to 0.5 m/s (i.e., 1 kn) to limit SAR Tracker false alarms;
- AI rejection of obvious wake tracks.

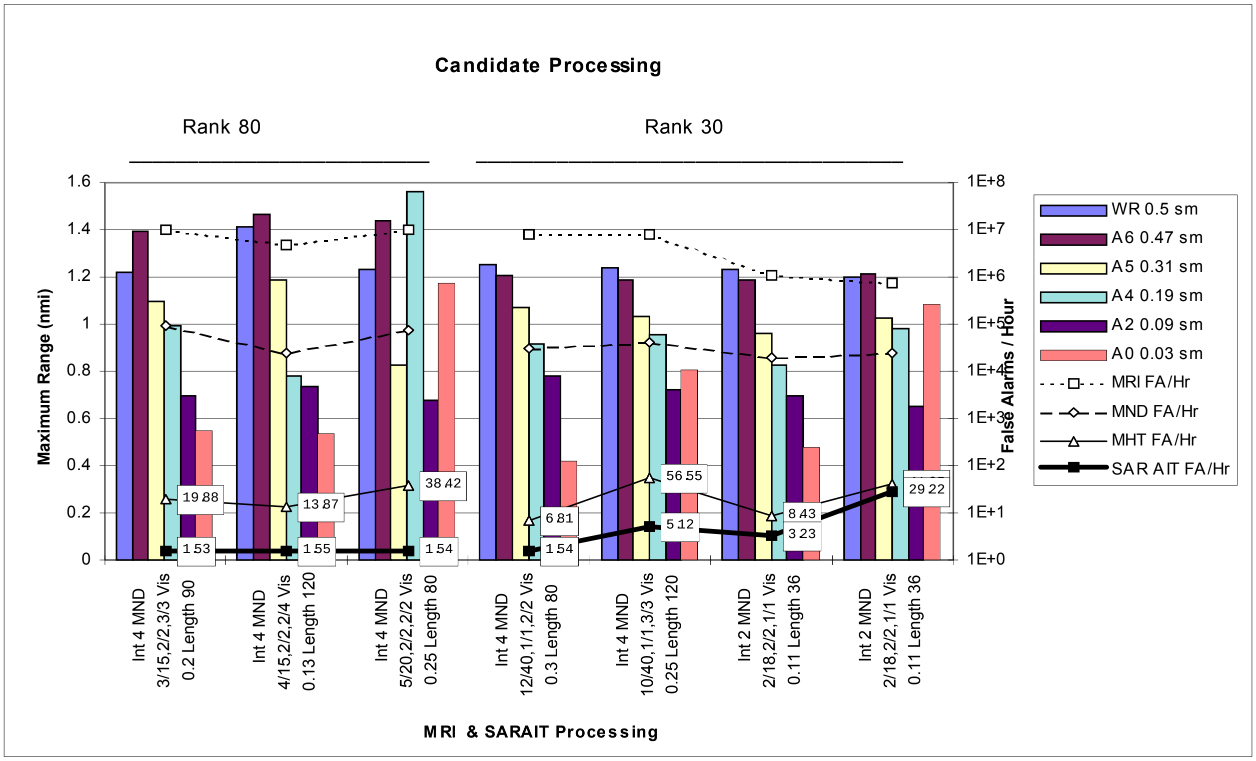

Figure 6-4 Non-adaptive SAR Tracker performance in 3.3 m seas and medium clutter

The main lesson from these preliminary tests was that the Sea Scan and SAR Tracker processing needed to vary with range and azimuth. Globally setting the processing parameters forced compromises that limited the SAR Tracker performance. This led to the upgrade of Sea Scan to incorporate range-azimuth plot extraction thresholds and the development of the SAR Tracker ATC to set these thresholds.

6.3 Improved Performance with ATC

The ATC delivered the expected improvement in target detection range and track quality as can be seen by comparing for Tape 21 the performance of the non-adaptive SAR Tracker (Figures in Section 6.2) with the adaptive SAR Tracker (Figures 6-5, 6-6, 6-7).

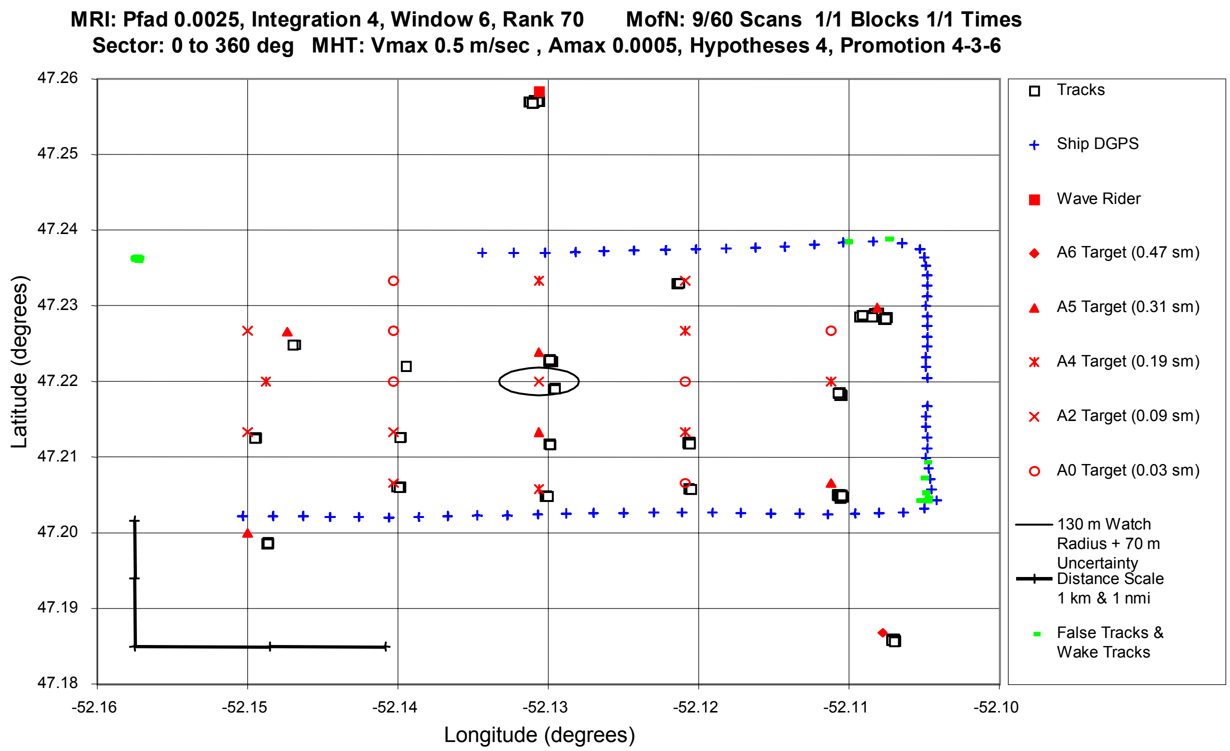

Figure 6-5 Adaptive SAR Tracker tracks superimposed on the array ground truth (medium clutter)

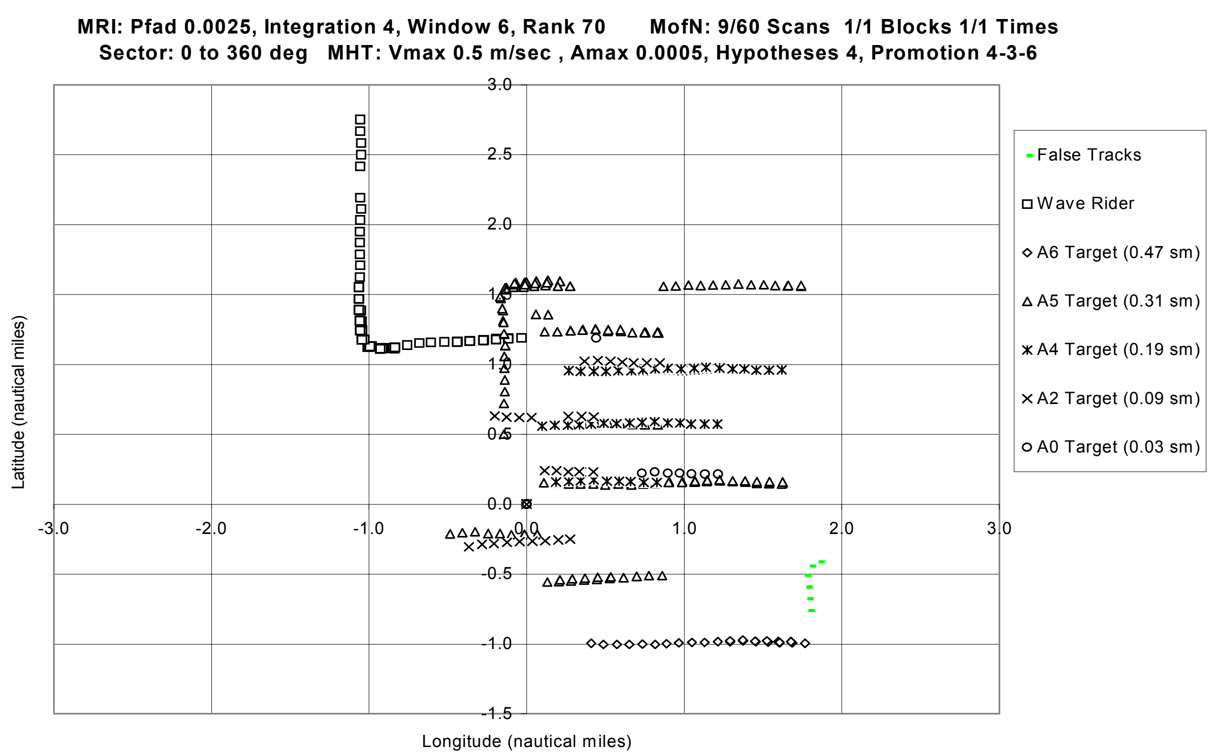

Figure 6-6 Adaptive SAR target tracks, range and bearing from the ship (medium clutter)

Comparing Figure 6-7, below, with Figure 6-4 illustrates that the ATC approximately doubles the SAR Tracker range for these representative processing parameters. Moreover, the false track rate is approximately halved to only one per hour.

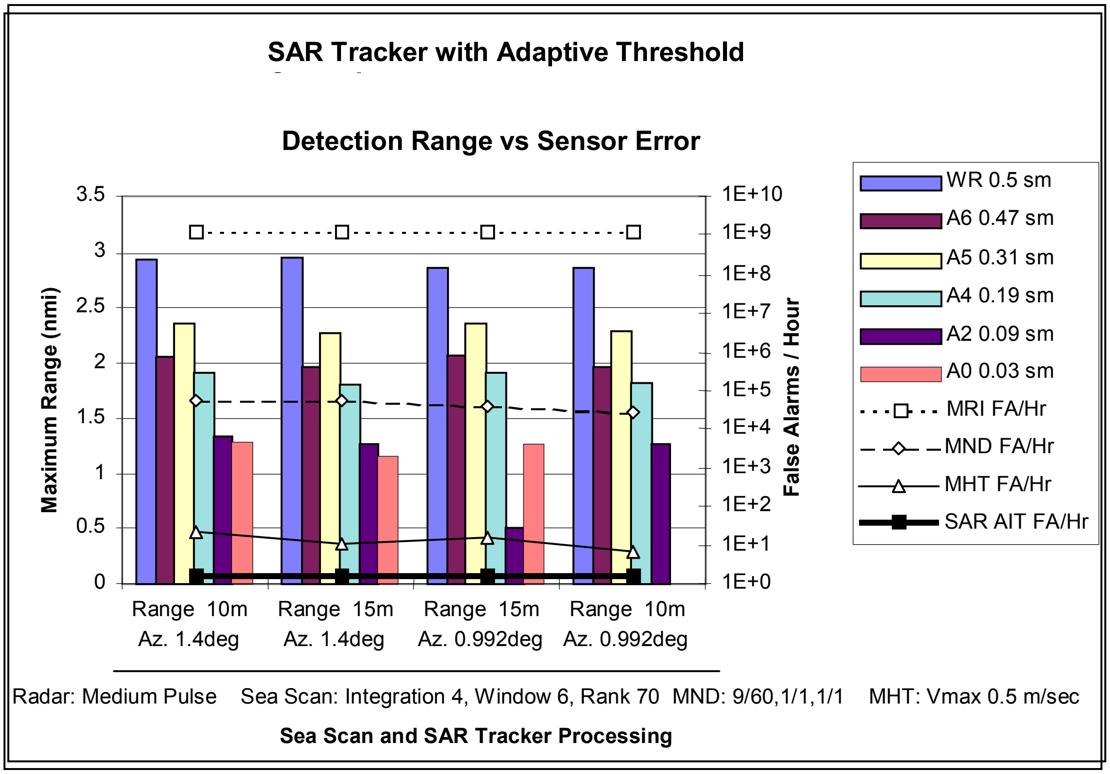

Figure 6-7 SAR Tracker with ATC performance in 3.3 m seas and medium clutter

7. Performance Predictions

The SAR Tracker detects small awash targets in clutter by correlating over many scans to pick out locations with more detections than could be caused by clutter alone. For the targets of interest, the Pd for a single scan where the target is at a wave crest or otherwise visible is under 0.5. For a scan where the target is masked by intervening waves, the Pd is zero. The median Pfa is set by the ATC and is typically between 0.01 and 0.001. The expected performance of the radar against detectable targets (i.e., at wave crests or with sufficient freeboard to be above the waves) is calculated in this section using the well accepted Modern Radar System Analysis (MRSA) tool.[4]

Radar performance in sea clutter is largely dependent on the wind-driven roughness of the sea surface, referred to as the "sea state". The relationship between sea state and wind speed is complicated since the roughness depends on how long the wind has been blowing (the "duration") and over how wide a region of open water (the "fetch"). For every wind speed, there is a limit to the attainable sea state, called a "fully developed sea", that is eventually reached with sufficient wind duration and fetch. The accepted definition of fully developed sea states is summarized in Table 7-1.

[4] W. Barton and D. Barton, *Modern Radar System Analysis – Software*, Artech, Norwood, MA, 1990.

Table 7-1 Fully developed sea state versus wind speed, fetch and duration[5]

Wind Speed (kn)	< 7	7 - 12	12 - 15	15 - 19	19 - 25	25 - 30	> 30
Beaufort # *Description*	2 Light Breeze	3 Gentle Breeze	4 Moderate Breeze	5 Fresh Breeze	6 Strong Breeze	7 Moderate Gale	8+ Gales, Storms, etc.
Sea State # *Description*	1 Smooth	2 Slight	3 Moderate	4 Rough	5 Very Rough	6 High	7 - 8 Very High
Fetch (km)	50	80	160	240	300	500	> 500
Duration (h)	< 3	3 - 10	10 - 20	20 - 24	24 - 26	26 -28	> 28
Wave Height (m) ($H_{1/3}$)	< 0.3	0.3 - 1	1 - 1.6	1.6 - 2.4	2.4 - 3.6	3.6 - 6	> 6
Relative Frequency %	20		20	20	15	10	15

In practice, swell and other waves will block awash targets from radar detection most of the time. Against awash targets, this analysis establishes the *peak* Pd that is attainable with a specified average Pfa. The *average* Pd is therefore the peak Pd multiplied by the average visibility, typically 15 to 25 percent for awash targets in 3 m swells at 5 km. The predicted detection ranges are therefore only accurate for higher targets, such as small boats, that are not appreciably masked by waves.

The best performance requires maximizing the peak Pd for a specified median Pfa. This analysis therefore serves to establish the appropriate radar pulse length for different sea states and target radar cross-sections, whether the targets are awash or not.

Marine radars such as the Pathfinder II can reduce the effects of sea clutter by operating with shorter pulses. This reduces the area of a range-azimuth resolution cell and therefore the amount of clutter energy against which the target must be detected. A shorter pulse necessarily has a lower average transmitted power and therefore a reduced performance outside the cluttered region. This is not an issue for small SAR targets, which are only detectable within the cluttered region anyway.

As can be seen in Figure 7-1, the best detection performance[6] at sea states 0 to 2 is clearly achieved with a medium pulse length. For sea state 3, the medium pulse has a slightly higher range than the short pulse but this is more than offset in tracker performance by a 4 times greater range standard deviation that will leave the SAR Tracker's MofN Correlator and MHT association gates more exposed to false alarms. By sea state 4, the medium pulse is restricted to a narrow annulus that effectively precludes reliable tracking except at very slow search speeds. At sea states 4 and above, the short pulse is clearly best, particularly for operating at higher probabilities of detection.

The smallest 0.03 m^2 target (i.e., the PIW) is more quickly masked by rising clutter levels. The medium pulse is therefore only effective to sea state 1 and the short pulse is superior at sea state 2 and higher.

To be conservative, all analysis in this section is based on the target being upwind where the clutter is most severe. Somewhat greater detection ranges are expected for both crosswind and downwind targets.

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[5] F. E. Nathanson, *Radar Design Principles*, 2nd ed., McGraw Hill, New York, 1991.

[6] Note that the MRSA tool uses a simplified sea state description (see Table 7-1) that is most valid for fully developed seas where the winds have blown steadily for several hours over many miles of sea. The higher the sea state, the longer the time and the greater the fetch required for full development.

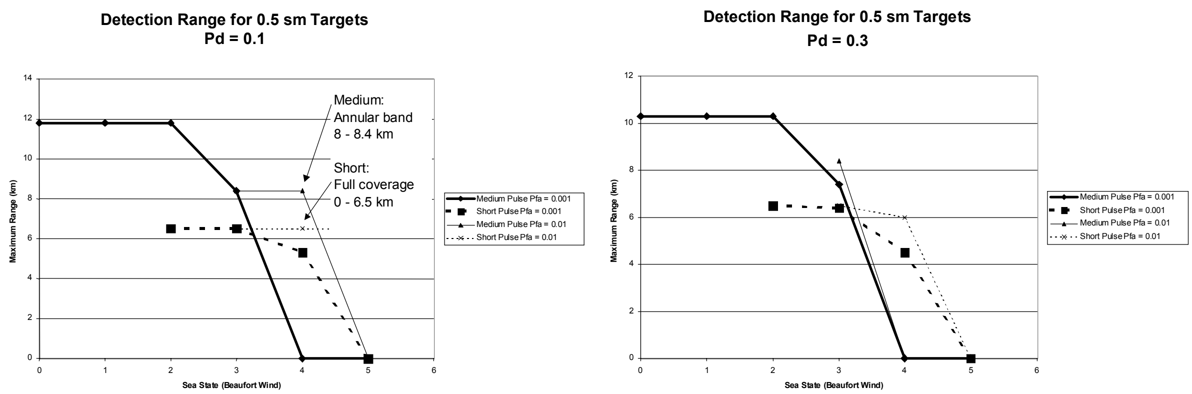

Figure 7-1 Maximum detection range of a 0.5 m^2 target at peak Pd = 0.1 and 0.3 versus pulse length and Pfa

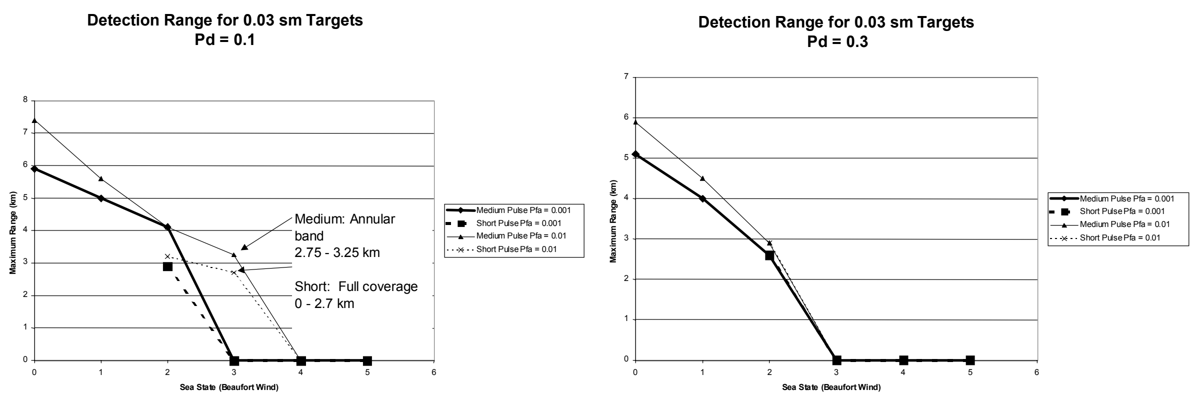

Figure 7-2 Maximum detection range of a 0.03 m^2 target at Pd = 0.1 and 0.3 versus pulse length and Pfa

In summary, theory predicts the following peak detection ranges for a 0.1 Pd and 0.01 Pfa:

- 0.5 m^2 targets (i.e., small 4-man liferafts) in sea state 5: 6.5 km (or 3.5 nmi)
- 0.03 m^2 targets (i.e., PIWs and swimmers) in sea state 3: 2.7 km (or 1.5 nmi)

Testing shows that the SAR Tracker can indeed detect such targets, even in 3 to 4 m waves, as will be shown in Section 9.

7.1 Sea States 0 and 1

Sea State 0 or 1 conditions are unusual in the North Atlantic but the near absence of any clutter enables the SAR Tracker to achieve its maximum detection range. Figure 7-3 illustrates the absence of any appreciable clutter at Sea State 1. This means that the radar should be operated with:

- medium pulse mode to maximize the average transmitted power;
- 2- to 6-scan integration to maximize the signal-to-noise ratio, depending on average target visibility at wave crests;
- 25- to 33-sample CFAR window to minimize detection losses.

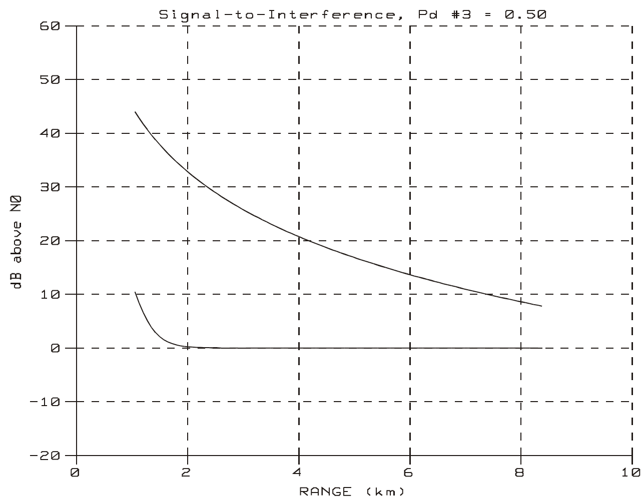

Figure 7-3 Medium pulse signal and interference levels for 0.5 m^2 target in Sea State 1

Table 7-2 indicates the expected detection ranges of 0.5 and 0.03 m^2 targets with single-scan processing.

Table 7-2 Sea State 0 and 1 medium pulse single-scan detection range for 0.5 and 0.03 m^2 targets

Probability of Detection	Required S/(C+N) at Pfa = 0.001	0.01	0.5 m^2 Detection Range Pfa = 0.001	0.03 m^2 Detection Range Pfa = 0.001	0.03 m^2 Detection Range Pfa = 0.01
0.1	7.0	3.0	8.4 km	2.9 km	4.1 km
0.3	9.5	7.0	7.6 km	2.7 km	4.1 km
0.5	10.8	8.6	7.1 km	2.5 km	4.0 km
0.7	11.9	9.9	6.6 km	2.4 km	3.7 km
0.8	12.5	10.6	6.4 km	2.3 km	3.5 km
0.9	13.2	11.5	6.2 km	2.2 km	3.4 km

Small point targets such as liferafts and swimmers will not fluctuate greatly from scan to scan unless they are being occluded by intervening waves. In Sea State 0, the waves are usually long swells that will reveal the targets at wave crests . During a typical 8 to 10 second swell period, the target is likely to be detectable for two seconds or four scans of the radar. It is therefore expected that averaging (i.e., integrating) for four scans will improve the SNR by approximately 5 db (a factor of 3.2). The expected performance with 4-scan integration is shown in Table 7-3. As expected, the maximum detection range increases with the Pfa.

Table 7-3 Sea State 0 medium pulse 4-scan integration detection range for 0.5 and 0.03 m^2 targets

Probability of Detection	Required S/(C+N) at Pfa = 0.001	0.01	0.5 m^2 Detection Range Pfa = 0.001	0.03 m^2 Detection Range Pfa = 0.001	0.03 m^2 Detection Range Pfa = 0.01
0.1	7.0	3.0	11.8 km	5.9 km	7.4 km
0.3	9.5	7.0	10.3 km	5.1 km	5.9 km
0.5	10.8	8.6	9.5 km	4.7 km	5.4 km
0.7	11.9	9.9	9.0 km	4.4 km	5.0 km
0.8	12.5	10.6	8.7 km	4.3 km	4.8 km
0.9	13.2	11.5	8.3 km	4.1 km	4.5 km

7.2 Sea State 2

Sea State 2 is attained at a wind speed of 8 kn. The clutter levels are significantly higher than at Sea State 1, as shown in Figure 7-4, but the medium pulse is still superior.

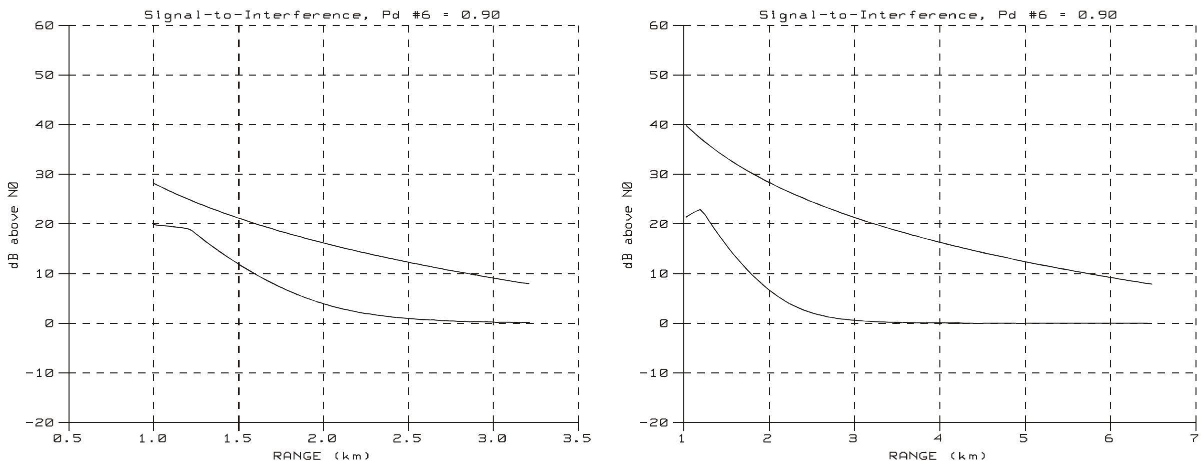

Figure 7-4 Short pulse signal and interference levels for 0.03 and 0.5 m^2 targets in Sea State 2

The clutter levels are already such that the smallest targets, such as swimmers, can only be reliably detected with 0.01 Pfa. The detection performance of the medium pulse (Table 7-4) is still superior to that of the short pulse (Table 7-5), but the gap is narrowing.

Table 7-4 Sea State 2 medium pulse detection range for 0.5 and 0.03 m^2 targets

Probability of Detection	Required S/(C+N) at Pfa = 0.001	0.01	0.5 m^2 Detection Range Pfa = 0.001	0.03 m^2 Detection Range Pfa = 0.001	0.03 m^2 Detection Range Pfa = 0.01
0.1	7.0	3.0	11.8 km	4.1 km	4.1 km
0.3	9.5	7.0	10.3 km	3.5 km	4.1 km
0.5	10.8	8.6	9.5 km	0 km	3.9 km
0.7	11.9	9.9	9.0 km	0 km	3.6 km
0.8	12.5	10.6	8.7 km	0 km	3.4 km
0.9	13.2	11.5	8.3 km	0 km	3.1 km

Table 7-5 Sea State 2 short pulse detection range for 0.5 and 0.03 m^2 targets

Probability of Detection	Required S/(C+N) at Pfa = 0.001	0.01	0.5 m^2 Detection Range Pfa = 0.001	0.03 m^2 Detection Range Pfa = 0.001	0.03 m^2 Detection Range Pfa = 0.01
0.1	5.6	1.7	6.5 km	2.9 km	3.2 km
0.3	8.0	5.4	6.5 km	2.6 km	3.2 km
0.5	9.2	7.1	6.0 km	0 km	3.2 km
0.7	10.2	8.4	5.7 km	0 km	3.1 km
0.8	10.8	9.0	5.5 km	0 km	3.0 km
0.9	11.5	9.8	5.3 km	0 km	2.8 km

7.3 Sea State 3

Sea State 3 is reached with a 12 kn wind. The short and medium pulses have similar detection ranges but the short pulse has fewer false alarms and is therefore likely to be operationally superior.

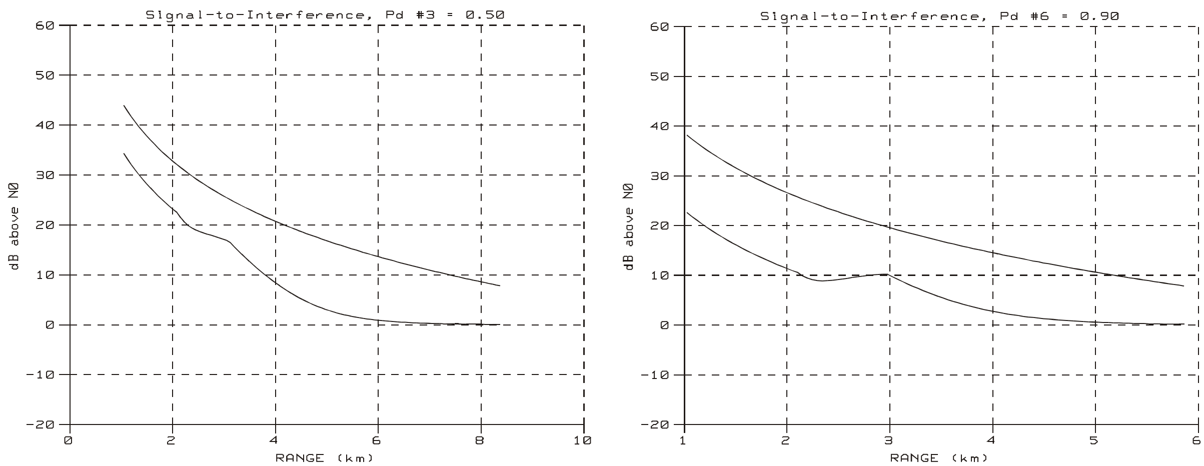

Figure 7-5 Medium and short pulse signal and interference levels for 0.5 m^2 targets in Sea State 3

The medium pulse detects the 0.5 m^2 targets at longer ranges but this is of limited use because either the Pd is low (under 0.5) or the Pfa is high (0.01). The short pulse is therefore a more effective detector overall because it combines a high Pd of 0.9 with a low Pfa of 0.001. Neither pulse can detect the smallest 0.03 m^2 targets at a Pd better than 0.1 but the short pulse at least detects these targets at all ranges out to 2.75 km rather than in a thin annular band.

Table 7-6 Sea State 3 medium pulse detection range for 0.5 and 0.03 m^2 targets

Probability of Detection	Required S/(C+N) at Pfa = 0.001	0.01	0.5 m^2 Detection Range Pfa = 0.001	0.5 m^2 Detection Range Pfa = 0.01	0.03 m^2 Detection Range Pfa = 0.01
0.1	7.0	3.0	8.4 km	8.4 km	2.75 – 3.25 km
0.3	9.5	7.0	7.4 km	8.4 km	0 km
0.5	10.8	8.6	6.7 km	8.0 km	0 km
0.7	11.9	9.9	0 km	7.3 km	0 km
0.8	12.5	10.6	0 km	7.0 km	0 km
0.9	13.2	11.5	0 km	6.6 km	0 km

Table 7-7 Sea State 3 short pulse detection range for 0.5 and 0.03 m^2 targets

Probability of Detection	Required S/(C+N) at Pfa = 0.001	0.01	0.5 m^2 Detection Range Pfa = 0.001	0.5 m^2 Detection Range Pfa = 0.01	0.03 m^2 Detection Range Pfa = 0.01
0.1	5.6	1.7	6.5 km	6.5 km	2.7 km
0.3	8.0	5.4	6.4 km	6.5 km	0 km
0.5	9.2	7.1	5.9 km	6.5 km	0 km
0.7	10.2	8.4	5.5 km	6.3 km	0 km
0.8	10.8	9.0	5.2 km	6.0 km	0 km
0.9	11.5	9.8	4.9 km	5.7 km	0 km

7.4 Sea State 4

Sea State 4 is reached with an 18 kn wind, given enough fetch and duration for a fully developed sea. Because of the increased clutter reflectivity, the short pulse (with ¼ the resolution cell area) is now seen in Figure 7-6 to be clearly superior to the medium pulse for all targets.

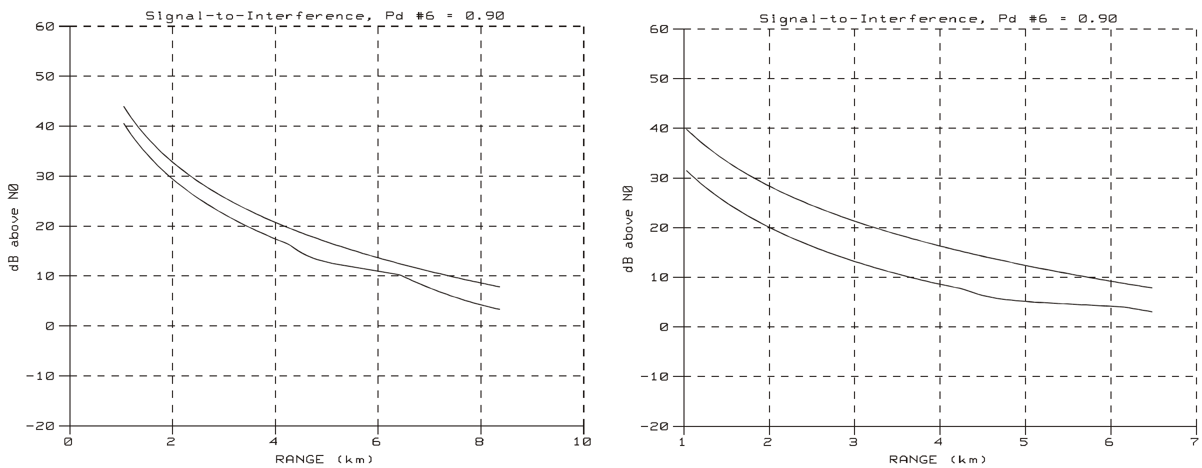

Figure 7-6 Medium and short pulse signal and interference levels for 0.5 m^2 targets in Sea State 4

Table 7-8 Sea State 4 medium pulse detection range for 0.5 and 0.03 m^2 targets

Probability of Detection	Required S/(C+N) at Pfa = 0.001	0.01	0.5 m^2 Detection Range Pfa = 0.001	0.5 m^2 Detection Range Pfa = 0.01	0.03 m^2 Detection Range Pfa = 0.01
0.1	7.0	3.0	0 km	4.2 to 5 and 8 to 8.4 km	0 km
0.3	9.5	7.0	0 km	0 km	0 km
0.5	10.8	8.6	0 km	0 km	0 km
0.7	11.9	9.9	0 km	0 km	0 km
0.8	12.5	10.6	0 km	0 km	0 km
0.9	13.2	11.5	0 km	0 km	0 km

Table 7-9 Sea State 4 short pulse detection range for 0.5 and 0.03 m^2 targets

Probability of Detection	Required S/(C+N) at Pfa = 0.001	0.01	0.5 m^2 Detection Range Pfa = 0.001	0.5 m^2 Detection Range Pfa = 0.01	0.03 m^2 Detection Range Pfa = 0.01
0.1	5.6	1.7	5.3 km	6.5 km	0 (SIR = -3 db)
0.3	8.0	5.4	4.5 km	6.0 km	0 km
0.5	9.2	7.1	0 km	5.2 km	0 km
0.7	10.2	8.4	0 km	2.6 km	0 km
0.8	10.8	9.0	0 km	0 km	0 km
0.9	11.5	9.8	0 km	0 km	0 km

7.5 Sea State 5

At Sea State 5 (wind speed 24 kn), only the short pulse is effective and only against the larger targets of 0.2 m^2 or larger. Halving the Pfa to 0.005 increases the SIR for Pd = 0.1 from 1.7 db to 3.1 db, which is shown in Figure 7-7 to be far beyond the maximum SIR of 2.2 db in the first 2 nmi.

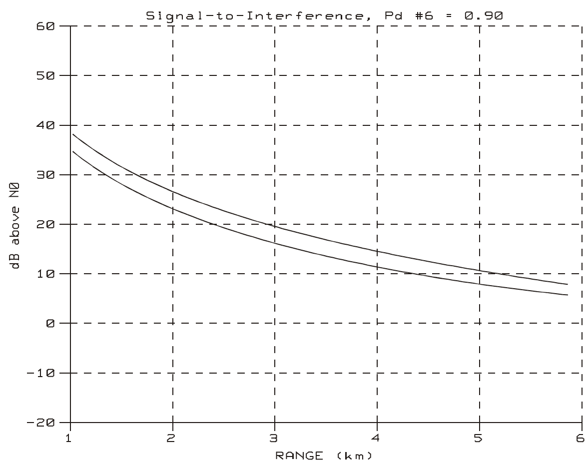

Figure 7-7 Short pulse signal and interference levels for 0.5 m^2 targets in Sea State 5

Table 7-10 Sea State 5 short pulse detection range for 0.5 m^2 targets

Probability of Detection	Required S/(C+N) at Pfa = 0.001	0.01	0.5 m^2 Detection Range Pfa = 0.001	0.5 m^2 Detection Range Pfa = 0.005	0.5 m^2 Detection Range Pfa = 0.01
0.1	5.6	1.7	0 km	0 km	6.5 km
0.3	8.0	5.4	0 km	0 km	0 km
0.5	9.2	7.1	0 km	0 km	0 km
0.7	10.2	8.4	0 km	0 km	0 km
0.8	10.8	9.0	0 km	0 km	0 km
0.9	11.5	9.8	0 km	0 km	0 km

8. Analysis Methodology

Marine search and rescue is conducted by sailing in search patterns. Legs of the search pattern are spaced and a ship speed chosen to achieve the required balance between area search rate (in nmi^2 per hour) and probability of detection. To illustrate the balance consider the two extremes. A very slow, careful search with overlapping coverage between legs will have a high probability of detection but only if the target is in the small search area that can be covered. Conversely, a high-speed search with no overlap will cover a much larger area but the radar is within detection range of the target for such a short time that the probability of detection is low.

To design a search, SAR operators will need to know the probability versus range that the SAR Tracker will detect the expected target as it sails by and the expected number of false tracks per hour. This requires calculation of the Cumulative Probability of Detection (Pd_{cum}) for targets at different ranges and look angles, and for different ship speeds and courses relative to the wind.

The most difficult task for the SAR Tracker is to initiate a confirmed track from the stream of clutter detections. It is during track initiation that the estimated track errors (and therefore the track gates) are largest and the risk of track seduction by false alarms greatest. To detect small SAR targets, the SAR Tracker is typically operated in a very sensitive mode where there are 50 to 100 tentative tracks for every confirmed one. To avoid swamping the system, the MHT must prune the less likely tentative tracks after a few missed updates. Conversely, confirmed tracks are coasted significantly longer as befits their greater confidence.

Fortunately, most SAR targets are drifting at no more than 1 to 3 kn and only manoeuvre in response to changes in the prevailing currents and winds. Target speed and manoeuvrability are therefore so low that even a short high-confidence target track will usually permit the SAR vessel to close, confirm the target identity and effect the rescue. The SAR Tracker is a particularly effective detector because every new track and track update provides the operator with an estimated target location, course, speed and track quality. A SAR vessel sailing at 20 kn to investigate a detection at 4 nmi will be beside the target within 12.5 minutes but would usually have visual or IR confirmation and further radar tracks long before then. Even a target drifting rapidly at 3 kn will only have moved 0.6 nmi during this 12.5 minute interval, so little damage will ensue if the estimated target speed or course are in error. It is much more dangerous to miss the target entirely than to declare false detections. The most important task is to initiate high confidence tracks at the target's location and the second is to estimate the target's speed and direction of drift.

The first measure of SAR Tracker performance is therefore the number of track initiations (each having an estimated target location, speed and course) that can be achieved while the searching vessel sails past the target. A target that is repeatedly tracked at differing ranges and look geometries is more reliably detected than a target that is detected but once. The acceptable number of false alarms will depend on the search conditions but is estimated to vary from five per hour when visibility permits rapid visual confirmation to one per hour when fog or night precludes confirmation beyond a few hundred metres.

The actual radar recordings were gathered sailing around a tethered array of targets and, in a few cases, to or from a small number of drifting targets. To translate the SAR Tracker performance measured from these situations into an estimated Pd_{cum} is not straightforward.

1. Experiment to find effective SAR Tracker processing parameters. The SAR Tracker implements at least two (and up to four) parallel Correlator-Tracker chains, each of which should be optimized for a subset of the coverage range, wind compass or target size. It is neither necessary nor likely that a single Correlation-Tracker processing chain will be optimal for all targets at all ranges and look geometries. Even at lower sea states there are advantages to maintaining two or more independent Correlator-Trackers.
2. Run the SAR Tracker with each of the M (typically two to four) processing chains N times using the same Sea Scan settings for all. Configure the MHT to drop all confirmed tracks immediately so that only track initiations are counted.
3. Accumulate the number of track initiations (i.e., Detections - D) of each target type and the average time to confirm (Tc), in each range bin (R) (every 0.5 nmi) and sectoral position relative to the wind (Upwind (UW), Downwind (DW) and Crosswind (XW) in 90 deg. sectors).
4. Accumulate detectability measures for each of the 25 targets for the particular course sailed: visibility time (Tv) per range bin (R) and wind sector (UW, DW and XW).
5. Remove times when the radar would never be able to initiate a track under normal circumstances because of:
   - R outside the M of N Correlation range interval;
   - Sea Scan radar sector blanking (most of the short pulse data was recorded with a 180 deg. sector that changed on every leg to point at the array);
   - M of N Correlation sector blanking;
   - too short an interval within the coverage region (assumed minimum was twice the average Tc).
6. Accumulate the total measured visibility time (Tvm) for each target type, in each range bin and wind sector.
7. Calculate the average Probability of Detection Pd = D * Tc / (N * Tvm) for each range bin and wind sector.

The average Pd and Tc are then used to synthesize the Pd_{cum} as the ship sails from 4 nmi before the target past the closest point of approach and on to 4 nmi past the target. The assumed test is a 4-nmi long line of targets spaced every 0.5 nmi at 90 deg. to starboard (i.e., east) of the ship. For simplicity, the ship is assumed to be moving north. Since tracker performance varies with wind sector, simulations must be run for winds from the west, north and east (by symmetry, a south wind is equivalent to a north wind); the targets are therefore classified as Downwind, Crosswind or Upwind at their closest point of approach (CPA).

For each wind direction and ship speed (5, 10, 15 and 20 kn), calculate Pd_{cum} for each target type A:

1. Calculate the total simulation visibility time (Tvs) for each offset distance, in each range bin R and wind sector W
2. For each target type, $Pd_{cum}(A) = 1 - \prod(1 - Pd(A,R,W))^{Tvs/Tvm}$

8.1 Testing Methodology

Accurate log records were kept manually for each test run using the form in Table 8-1. The plot counts are an estimated average that are later translated into the false alarm rate Sea Scan, MND and SAR Tracker Rfa.

Table 8-1 Test log

		Sea Scan Parameters								**SAR Tracker MND Parameters**							**SAR Tracker MHT**			
File / Segment	Time	Pfa	MinExtent	MaxExtent	Integration	Window	Offset	Rank	# Plots	M1	M2	M2	N2	M3	N3	# MND Plots	Vmax	Amax	Track	R/Az Var

The following data are output to the screen (and optionally logged) by the SAR Tracker MND processor once per scan:

- number of input Sea Scan plots;
- M of N processing time (for diagnosis);
- ship position and time (UTC);
- number of output MND detections (every N1*N2 scans).

The MHT processor receives the accumulated M of N detections every N1*N2 scans and implements MHT for which the following data are output to the screen (and optionally logged):

- location in latitude and longitude of current (blue) and past (grey) MND detections, confirmed tracks (yellow) and ship position history (blue) on a map;
- number of input MND detections;
- number of MHT deleted, potential, tentative and confirmed tracks;
- MHT image size and processing time (for diagnosis);
- elapsed time to process and time stamp interval.

The following critical intermediate and final products are saved to file for later analysis:

- current ATC map (rewritten each update);
- history of MND detections (appended after each update);
- history of MHT states and tracks (appended after each update);
- history of MHT confirmed tracks and ship positions.

The results of each playback are a machine-readable MHT state history, an MHT output file (Table 8-2) and an optional large MND data file (Table 8-3).

Table 8-2 SAR Tracker track output file

Init #	*Trk #*	*X*	*Y*	*Xdot*	*Ydot*	*Xvar*	*Yvar*	*Track Length*	*Track Update*	*Track Misses*
1	1	3123.81	-3472.67	0.0202	-0.6966	513.034	559.563	4	4	0
1	1	3117.88	-3469.92	-0.4335	-0.0179	652.955	774.335	5	5	0

Mon	*Day*	*Yr*	*Hr*	*Min*	*Sec*	*Start Lat*	*Start Long*	*Ship Lat*	*Ship Long*
11	17	97	2	27	18	47.2019	-52.0649	47.2019	-52.0716
11	17	97	2	27	38	47.2019	-52.0649	47.202	-52.0729

Table 8-3 MND detection file

X (m)	Y (m)	Average X var	Average Y var	Average XY var	Least Squares Fit X var	Least Squares Fit Y var	Least Squares Fit XY var	Scan #

These two test files are then analysed as required by the separate Analysis System. The Analysis System is implemented in Microsoft Excel and scripted to automatically process the SAR Tracker Track Output file to compare the separate ground truth data with the tracks and, if required, with the M of N detections. The number of targets detected and their range and azimuth are automatically extracted along with the false alarm rates (Rfa in false detections per hour) at the outputs of the Sea Scan, MND, MHT and, after automatically rejecting obvious wake and edge artifacts, the SAR Tracker. Rain clutter is largely controlled by the adaptive threshold but any residue would be obvious to the operator and easily ignored.

The Analysis System accumulates by range bin, wind direction and target size the following statistics for calculating the Pd_{cum}:

- number of track initiations,
- average track length,
- target visibility, and
- measured average probability of detection.

8.2 Optimize Key Processing Parameters

The broad effects of each of the key Sea Scan and SAR Tracker processing parameters are summarized in Table 8-4.

Table 8-4 Key processing parameters

Sub-System	Variable Parameter	Typical Values	Notes
Sea Scan	CFAR Window	4, 6, 8, 16	Shorter window detects smaller extent targets but increases Pfa and position error
Sea Scan	CFAR Rank	30, 50, 70, 80	Lower rank detects weaker features but increases Pfa and position error
Sea Scan	Integration (scans)	1, 2, 4, 8	Longer integration detects large targets at longer range but weakens smaller, less visible targets
Sea Scan	Threshold (Pfa %)	0.01 – 0.001	Higher Pfa detects smaller targets and false alarms so MND or Vmax used to control
SAR Tracker	Vmax (m/s)	0.5, 0.75, 1, 1.5	Faster Vmax opens tracker to both detections and false alarms
SAR Tracker	Range Std Dev (m)	10, 15, 20 m 5, 7.5, 10 m	Range error is higher than normal due to masthead gyrations and low SIR
SAR Tracker	Azimuth Std Dev (deg.)	0.65, 1.0, 1.4 deg.	Azimuth error is higher than nominal 0.2 to 0.5 deg. due to post-processed corrections and low SIR
SAR Tracker	Tentative Promotion	4/3/*, 6/4/*	Longer coasts bridge detection gaps but promote more false tracks unless confirmations increase
SAR Tracker	Confirmed Coast	*/6, */8, */12	Longer coasts bridge detection gaps but any false tracks are retained longer
SAR Tracker	MND Visibility	10 – 25%	Lower visibility can offset lower Pfa

9. Performance in 3.2 to 3.8 m Waves

To quantify the SAR Tracker performance, we have processed the cross section of the data shown in Table 9-1. These recordings were selected for significant 3.2 to 3.8 m waves, Sea States from 1 to 5, wind strengths from 3 to 44 kn, multiple look angles and long enough test runs for meaningful statistics. Two parallel Correlator-Tracker chains were used for analysis because such a system delivers a good balance between performance and physical size and is therefore ideally suited for shipboard use. Targets missed by one Correlator-Tracker are usually picked up by the other one and the system requires only two dual-CPU PCs. Improved performance will result from adding further Correlator-Tracker chains (and PCs).

Table 9-1 Data sets used for detailed analysis

Tape / Segment	Wave Height	Beaufort Number Wind Speed	Estimated Sea State	Pulse Length
15 / 2	3.8 m	Bf 7-9 44 kn rising	Very Rough SS5	Short
19 / 2	3.4 m	Bf 6 23 kn	Rough SS4	Short
21 / 0	3.3 m	Bf 3-4 10 kn	Moderate SS3	Short
19 / 1	3.2 m	Bf 4 11 kn rising	Moderate SS3	Medium
21 / 1	3.3 m	Bf 3-4 10 kn falling	Slight SS2	Medium
22 / 4	3.4 m	Bf 2-3 3–8 kn rising	Smooth SS1	Medium

It is not possible to exactly match the wind speeds or wave heights to Sea States because the constantly changing winds and limited fetch meant that the seas were never fully developed. Throughout the recording period, the seas were usually building or declining. In addition, the winds were typically from the southwest against a tongue of the Labrador Current from the north. One consequence of this was that waves were frequently steep-faced both upwind and upcurrent. The resulting clutter often varied substantially between upwind, downwind and crosswind look angles.

Approximate equivalent sea states were, however, estimated from the radar display and can be used with caution to extrapolate to other situations. As an example, Segment 15/2 was estimated as Sea State 5 because the 44 kn gale-force winds had not yet blown long enough or over sufficient fetch to build to the theoretical limit of 10 m and Sea State 7. Conversely, Segment 22/4 had a large running swell that obscured targets but produced little clutter and was therefore estimated as Sea State 1.

9.1 Short Pulse Mode

Section 7 illustrated the importance of increasing the radar resolution at higher sea states. The short pulse recordings were therefore used to characterize the SAR Tracker performance in (equivalent) Sea States 3, 4 and 5.

All short pulse data was recorded with a 180 deg. 3 nmi sector that was always oriented toward the array. For this reason, the A6 and wave rider targets were rarely in the field of view. The SAR Tracker performance against these targets was therefore interpolated from the sparse measured data in proportion to the measured A5 and A4 performance. Another consequence of this sectoral recording was that edge effects had to be minimized by running the ATC with less smoothing than was optimal, which slightly degraded CFAR detection performance.

The SAR Tracker long-range performance beyond 2.5 nmi was significantly under-estimated by the absence of any recorded data beyond 3 nmi. The problem is best shown by showing how four targets at 3 nmi would be tracked by a 10 kn searching vessel and the effect on the calculated performance:

- A target abeam of the ship will only be detectable for a few scans as the ship sails past. At these ranges, the tracker typically requires 3 minutes to initiate track and will therefore stand no chance of detecting the target.
- A target 10 degrees ahead of the ship would be detectable for 6 minutes and therefore represents the first good chance the SAR Tracker has of initiating a track.
- A target ahead of the ship will be repeatedly detected as the ship sails toward it and will typically be tracked within 3 minutes, by which time the range has dropped to 2.5 nmi. The longest-range track initiation would therefore be reported as 2.5 nmi.
- A target astern will also be tracked as the ship recedes. The last, and therefore longest-range, track initiation could be reported anywhere between 2.5 and 3 nmi (depending on the previous initiation) and would therefore have a median value of 2.75 nmi.

The net effect of the 3 nmi recording limit is to limit the maximum range to approximately 2.5 nmi and to reduce the number of targets that can contribute to the performance analysis. These conditions were particular to the recording equipment used during the 1997 trial and would not constrain the SAR Tracker as currently implemented.

9.1.1 Sea State 5 Very Rough Seas: 3.8 m Waves and 44 kn Winds

This data set was notable for the freshening 44 kn winds that drove the clutter to very high levels that dominated the radar PPI out to 2 nmi. The 3.8 m waves were mostly wind-driven with little or no swell. The 7.3 second wave period had been lengthening as the waves grew more developed before the winds and can be seen clearly on the radar display below. The waves were steep-faced looking upwind as can be seen by the bright clutter at 240 degrees.

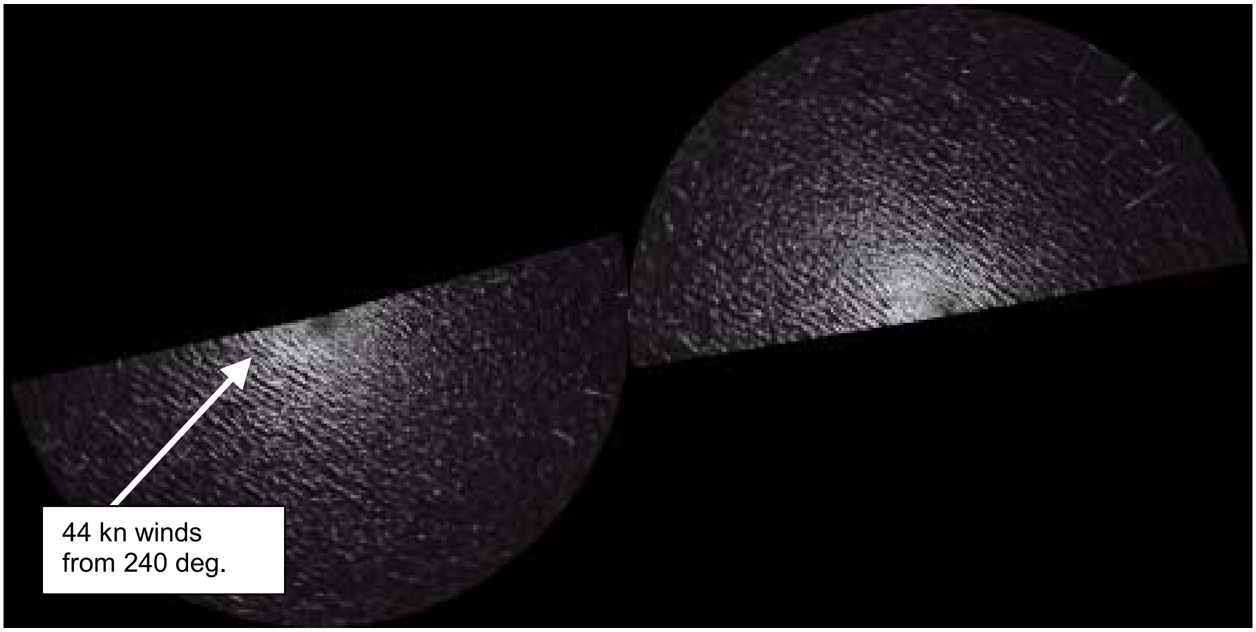

Figure 9-1 Short pulse PPI in Sea State 5: 3.8 m combined sea (3 nmi scale)

The two processing chains shown in Table 9-2 were used to maximize the overall probabilities of detection of all sizes of target at all azimuths. Figure 9-2 illustrates the approximate uniformity of the target detections from 1 to 2 nmi. The surprising lack of downwind detections under 1 nmi may be due to building waves washing over the targets, possibly with some help from a strong downwind current.

Table 9-2 Representative SAR Tracker processing for Sea State 5 on short pulse

Sea Scan Processing Parameters											
Pfa	Integration	CFAR Window	CFAR Rank	Min Extent	Max Extent						
0.001	3	12	40	6,5,4,4	20						
SAR Tracker Processing Parameters											
M1	N1	M2	N2	M3	N3	V max (m/s)	Acc max (m/s^2)	R var (m^2)	Az var (rad^2)	Hypotheses	Initiation (TentCoast Confirms ConfCoast)
5	15	1	2	2	2	0.5	0.005	400	3e-4	2	4/3/0
8	60	1	1	2	2	0.5	0.005	900	6e-4	2	4/3/0

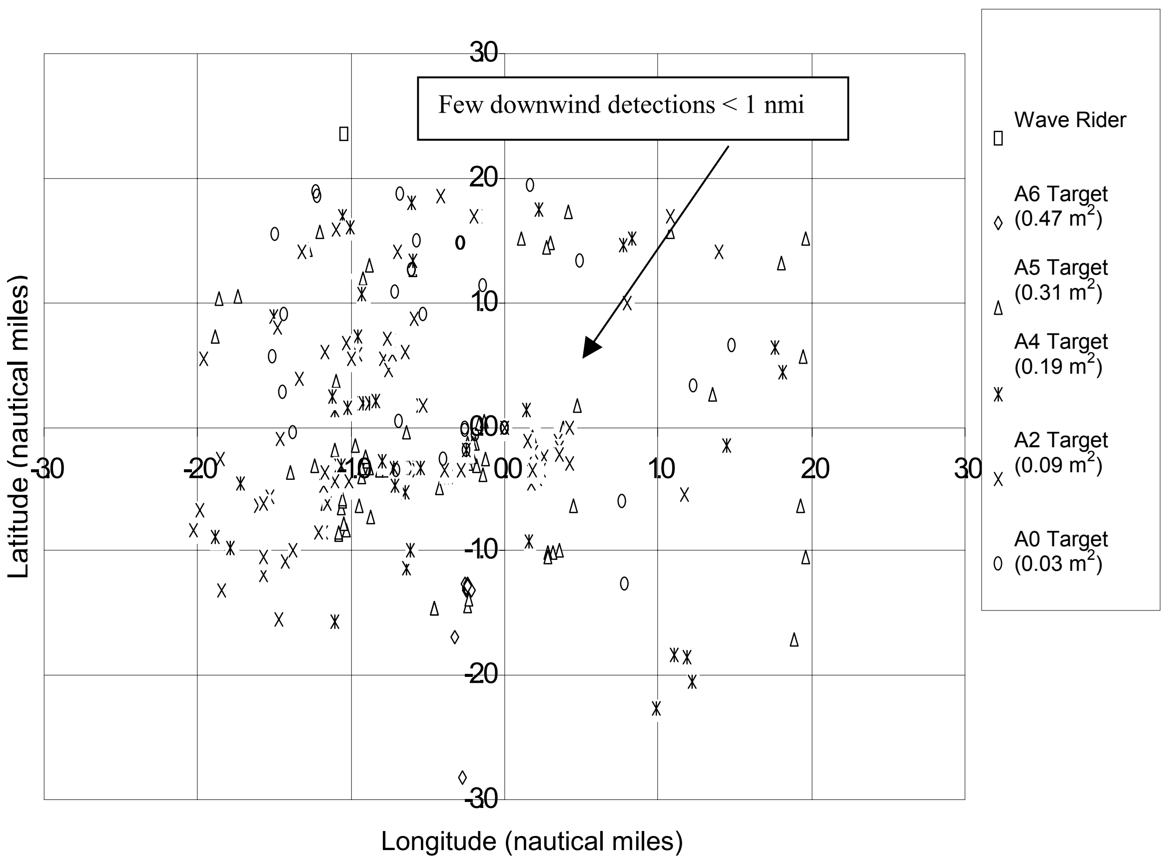

Figure 9-2 Track initiations relative to ship from four runs

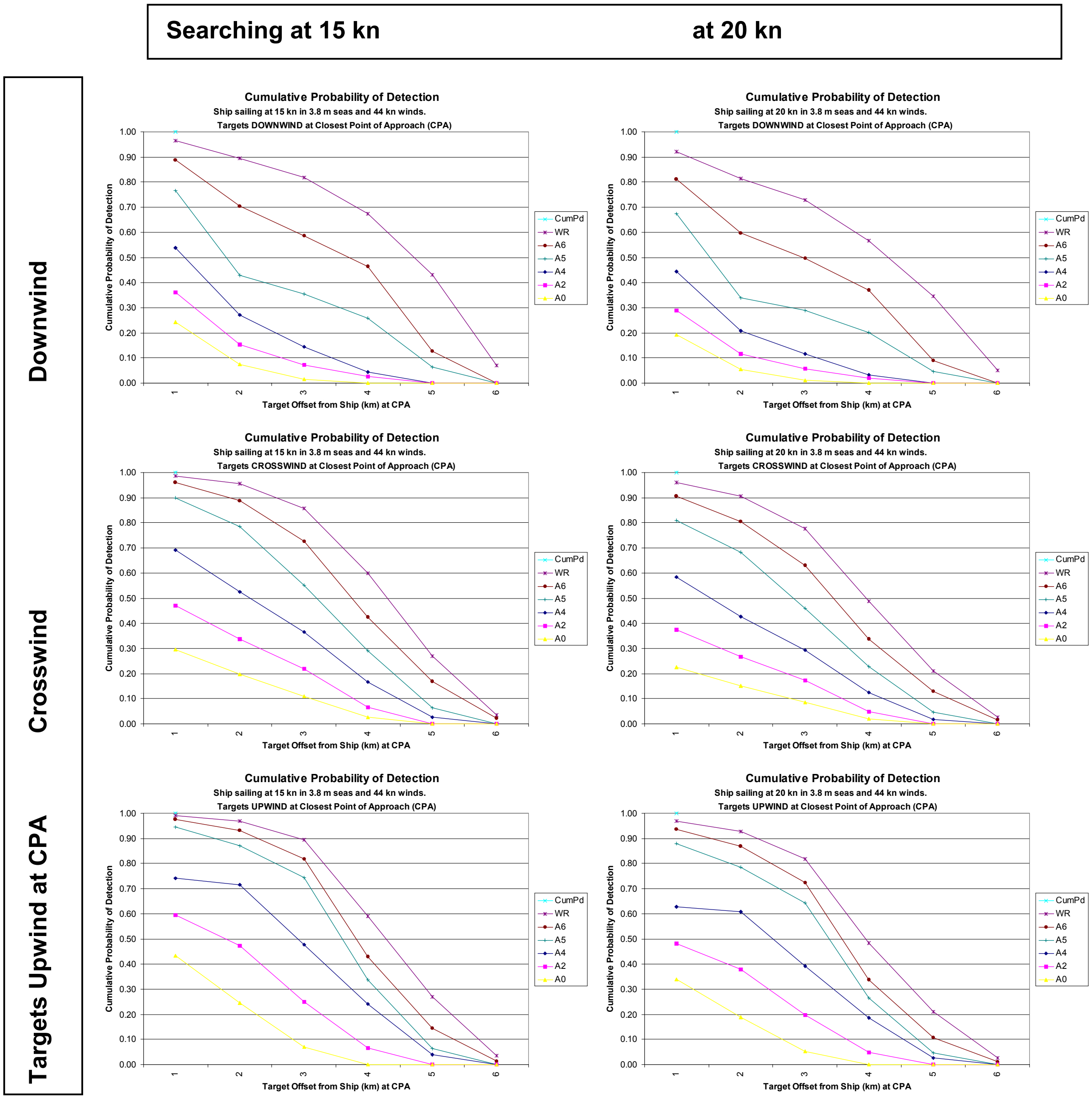

Figure 9-3 Short pulse in Sea State 5: Pd_{cum} for 15 and 20 kn searches

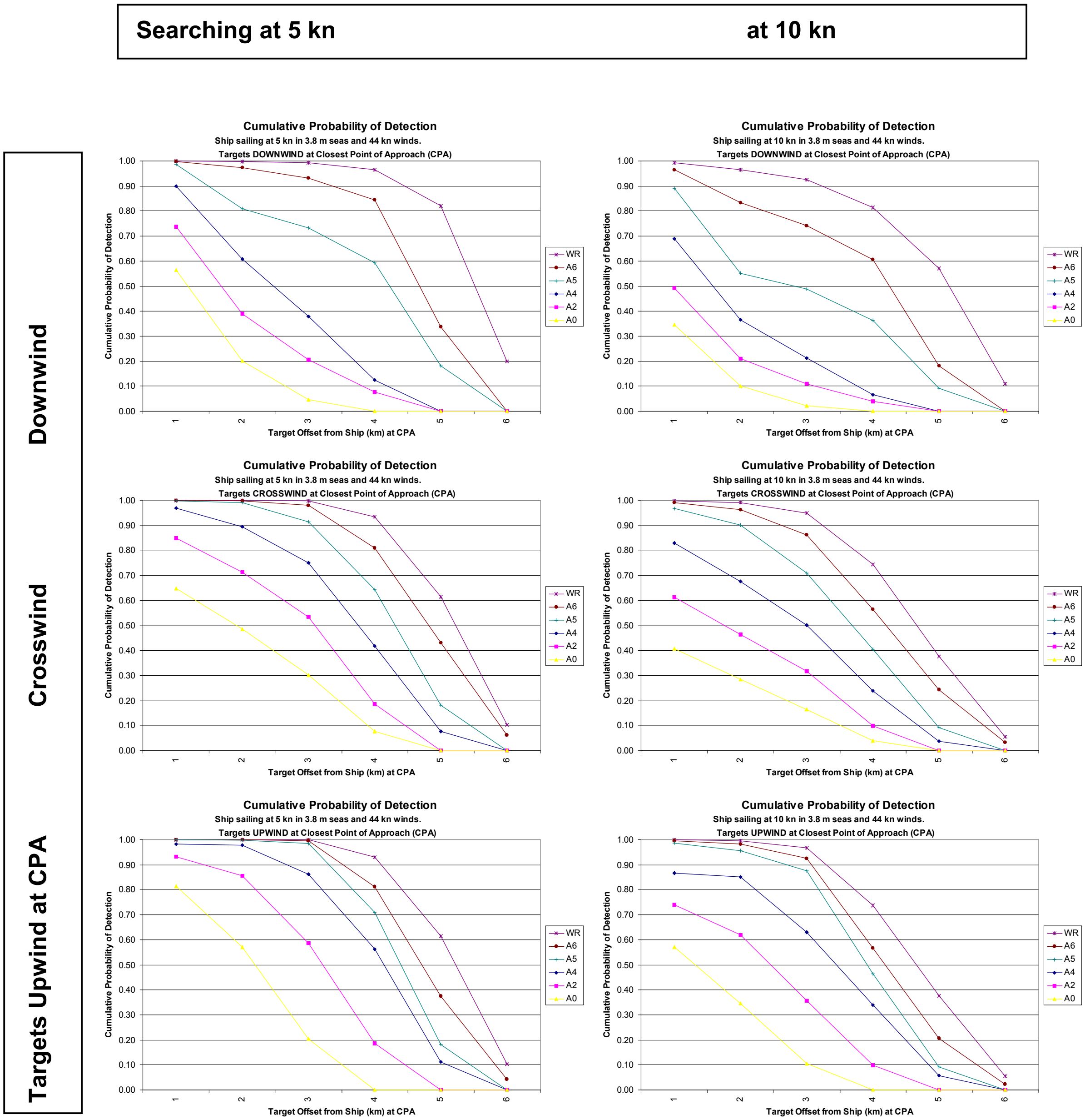

Figure 9-4 Short pulse in Sea State 5: Pd_{cum} for 5 and 10 kn searches

9.1.2 Sea State 4 Rough Seas: 3.0 m Swell, 0.5 m Waves and 23 kn Winds

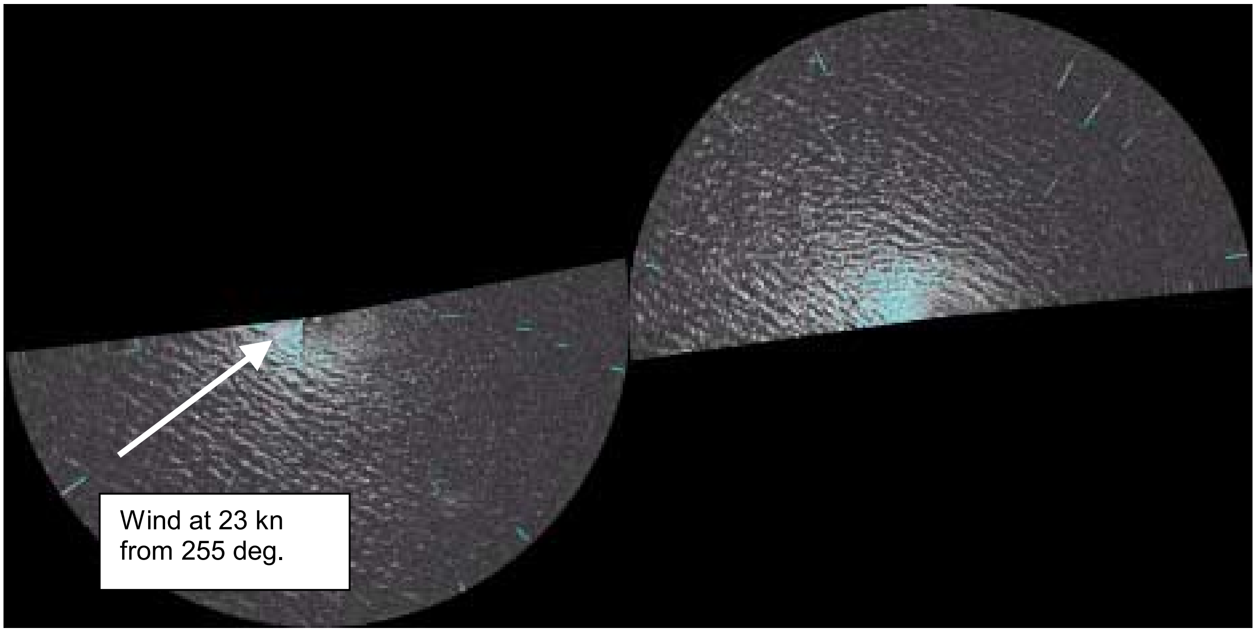

Figure 9-5 Short pulse PPI in Sea State 4: 3.4 m combined sea (3 nmi scale)

The sea clutter at Sea State 4 is significantly lower than at Sea State 5, the ship's wake is clearly visible and the clutter only dominates the display out to 1 nmi.

Table 9-3 Representative SAR Tracker processing for short pulse in Sea State 4

Sea Scan Processing Parameters											
Pfa	Integration	CFAR Window	CFAR Rank	Min Extent	Max Extent						
0.001	4	12	40	6,5,4,4	20						
SAR Tracker Processing Parameters											
M1	N1	M2	N2	M3	N3	V max (m/s)	Acc max (m/s^2)	R var (m^2)	Az var (rad^2)	Hypotheses	Initiation (TentCoast Confirms ConfCoast)
5	40	1	1	3	3	0.5	0.005	900	6e-4	2	4/3/0
8	60	1	1	2	2	0.5	0.005	900	6e-4	2	4/3/0

Track initiations from three runs are plotted in Figure 9-6. Downwind detections predominate as is usual.

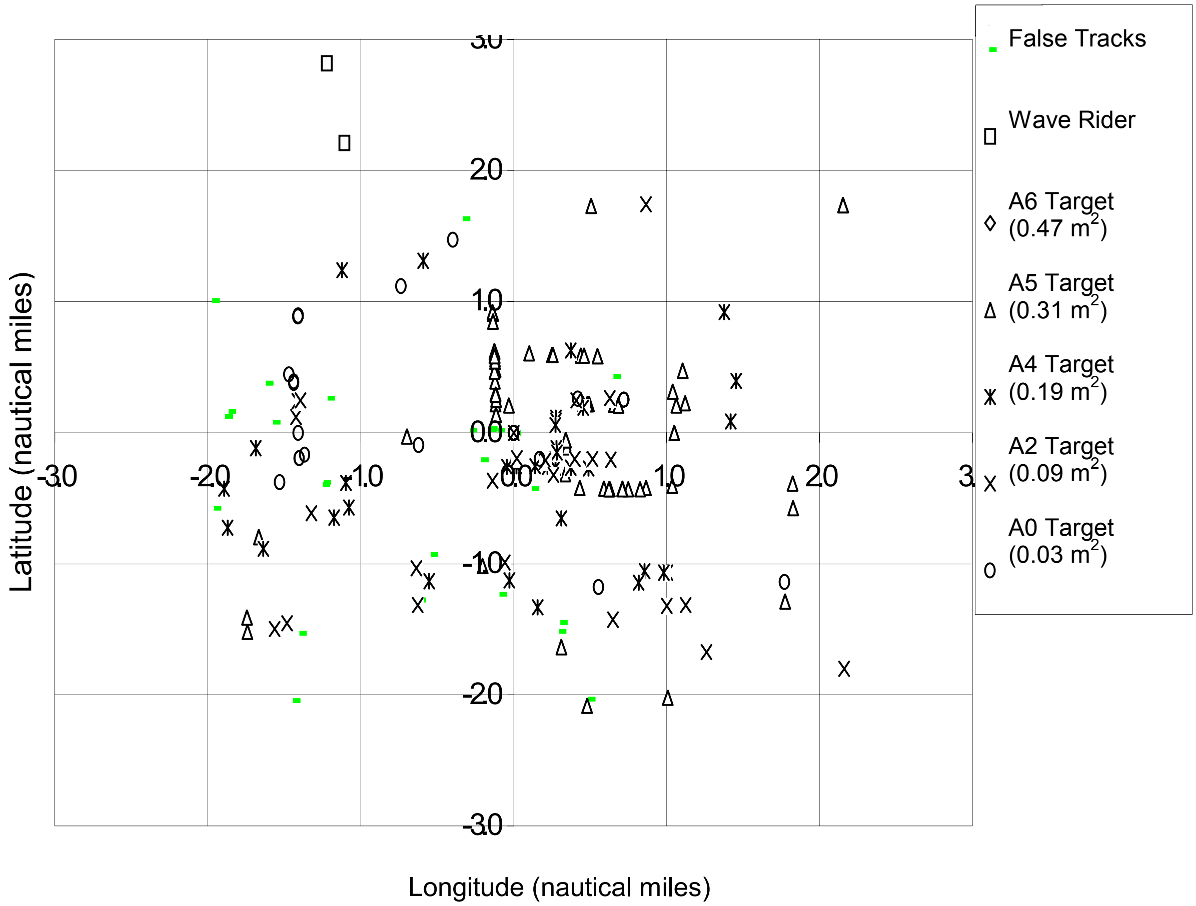

Figure 9-6 Track initiations relative to ship from three runs

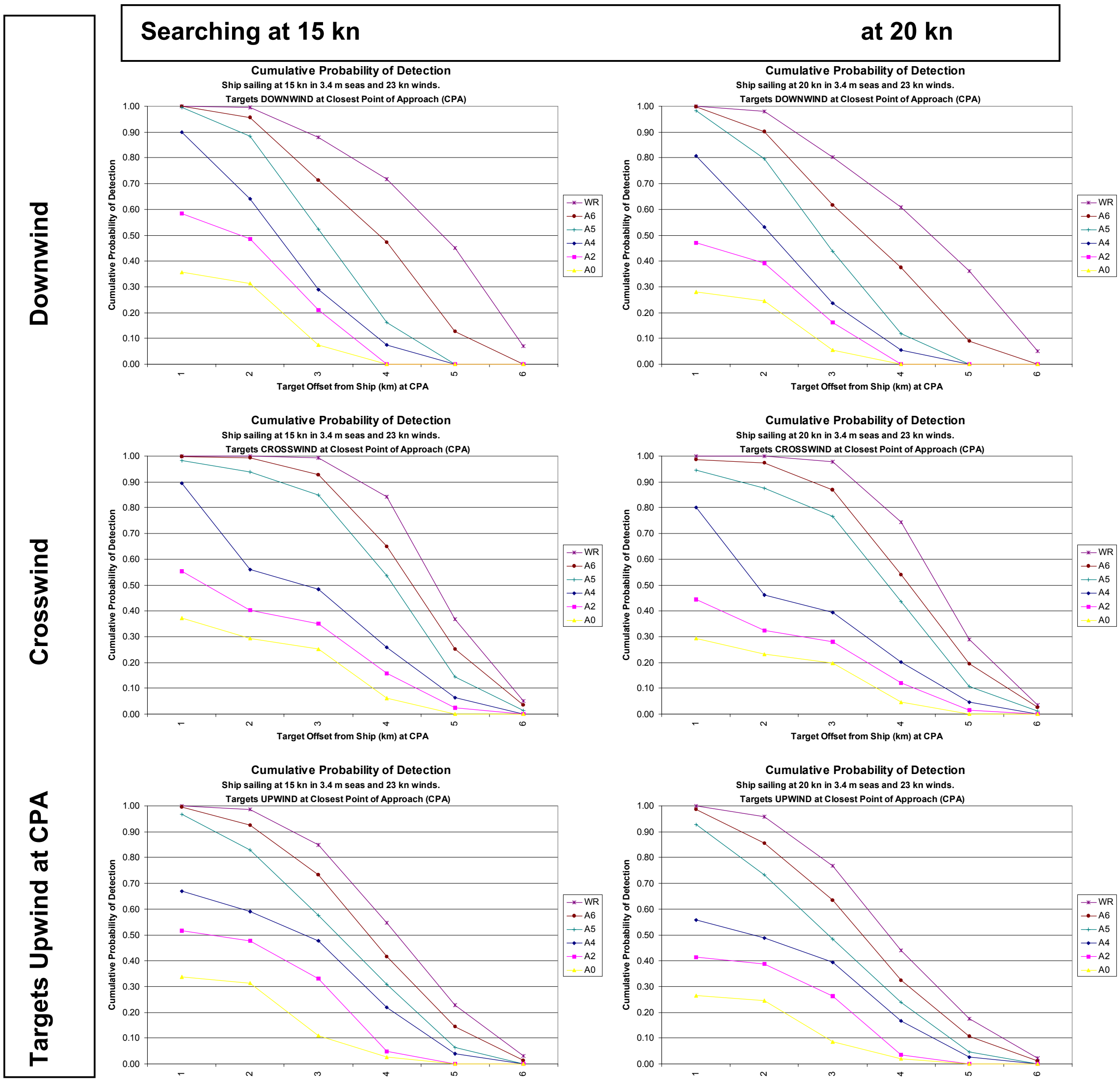

Figure 9-7 Short pulse in Sea State 4: Pd_{cum} for 15 and 20 kn searches

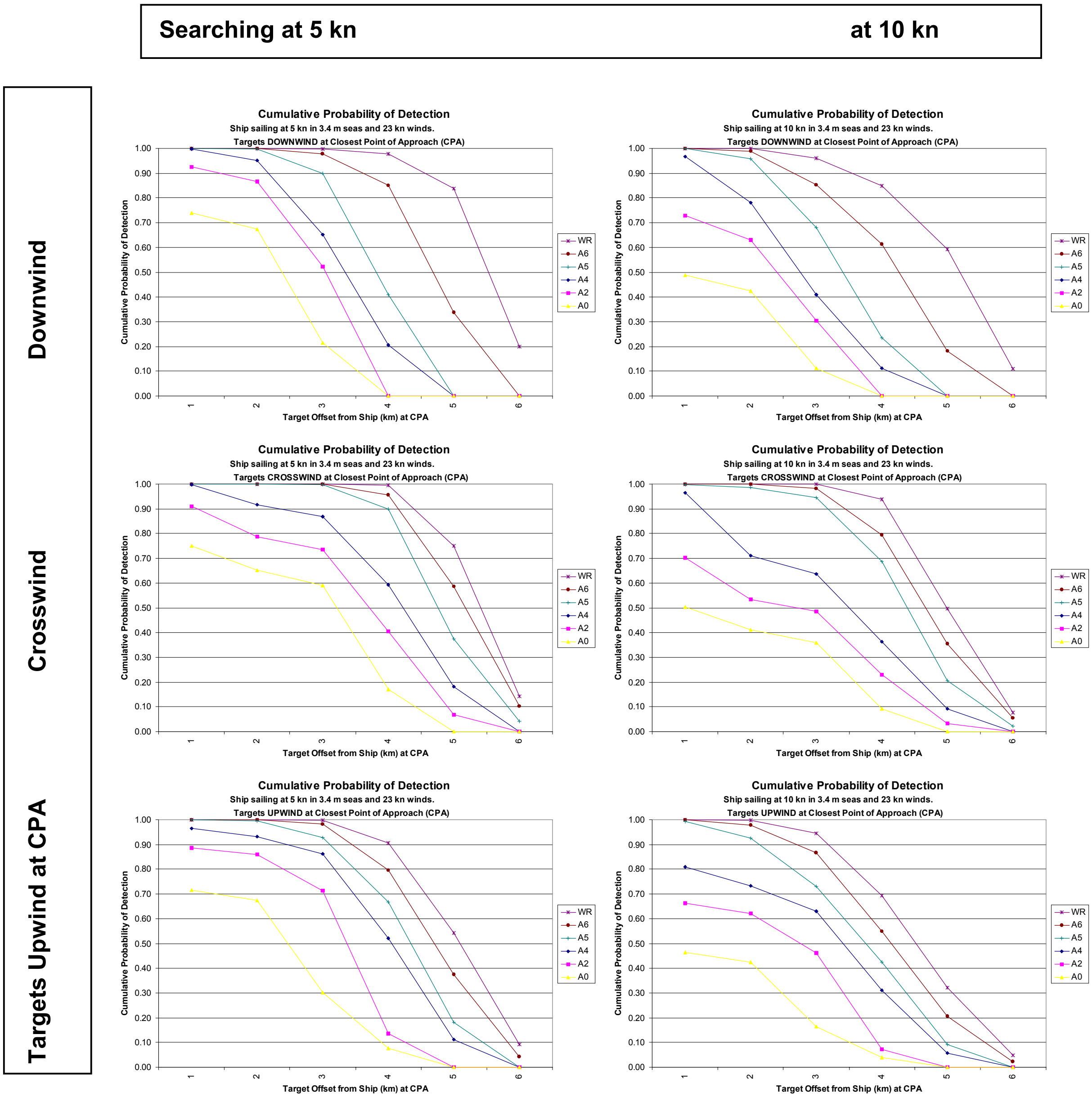

Figure 9-8 Short pulse in Sea State 4: Pd_{cum} for 5 and 10 kn searches

9.1.3 Sea State 3 Moderate Seas: 3.2 m Swell, 0.3 m Waves and 10 kn Winds

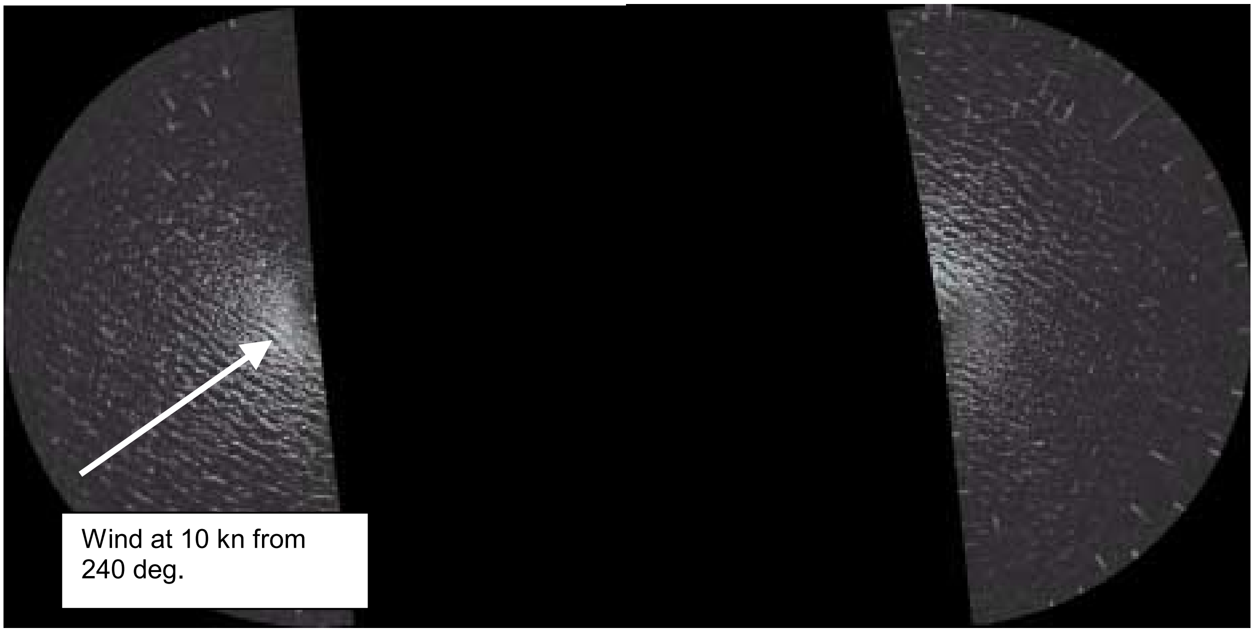

Figure 9-9 Short pulse PPI in Sea State 3: 3.5 m combined sea (3 nmi scale)

Table 9-4 Representative SAR Tracker processing for short pulse in Sea State 3

Sea Scan Processing Parameters											
Pfa	Integration	CFAR Window	CFAR Rank	Min Extent	Max Extent						
0.002	3	12	40	5,4,4,4	20						
SAR Tracker Processing Parameters											
M1	N1	M2	N2	M3	N3	V max (m/s)	Acc max (m/s^2)	R var (m^2)	Az var (rad^2)	Hypotheses	Initiation (TentCoast Confirms ConfCoast)
3	15	2	3	2	2	0.5	0.005	400	3e-4	2	4/3/0
8	60	1	1	2	2	0.5	0.005	400	3e-4	2	4/3/0

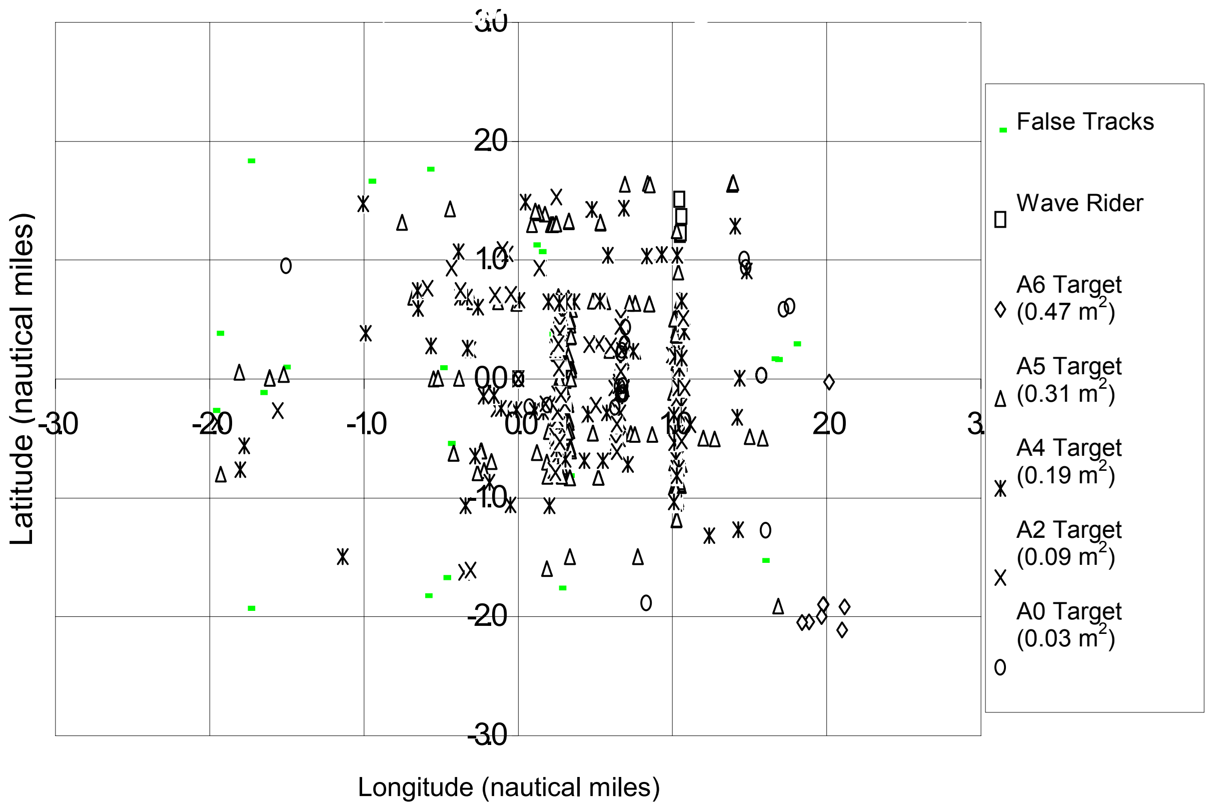

Figure 9-10 Track initiations relative to ship from two runs

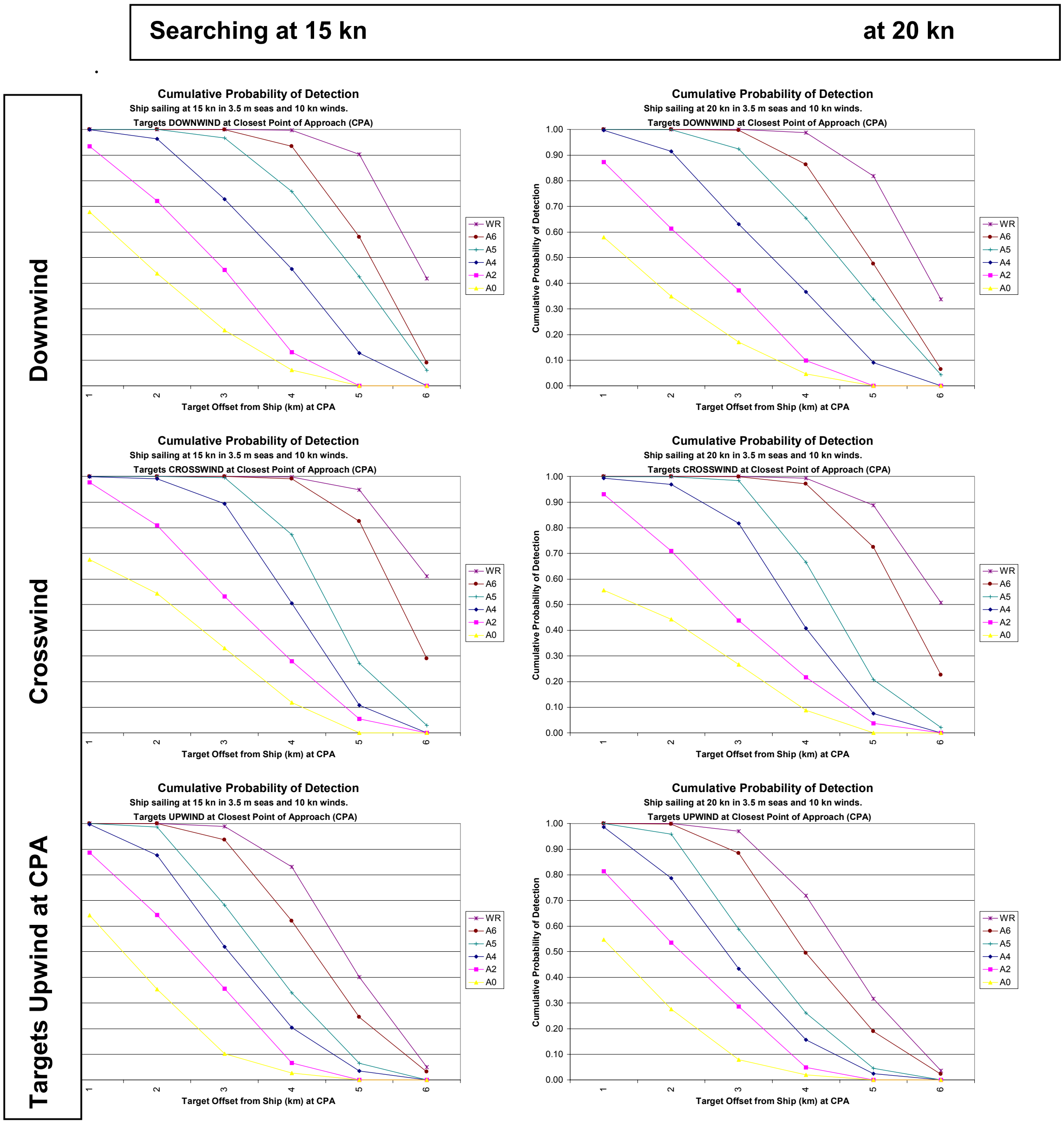

Figure 9-11 Short pulse in Sea State 3: Pd_{cum} for 15 and 20 kn searches

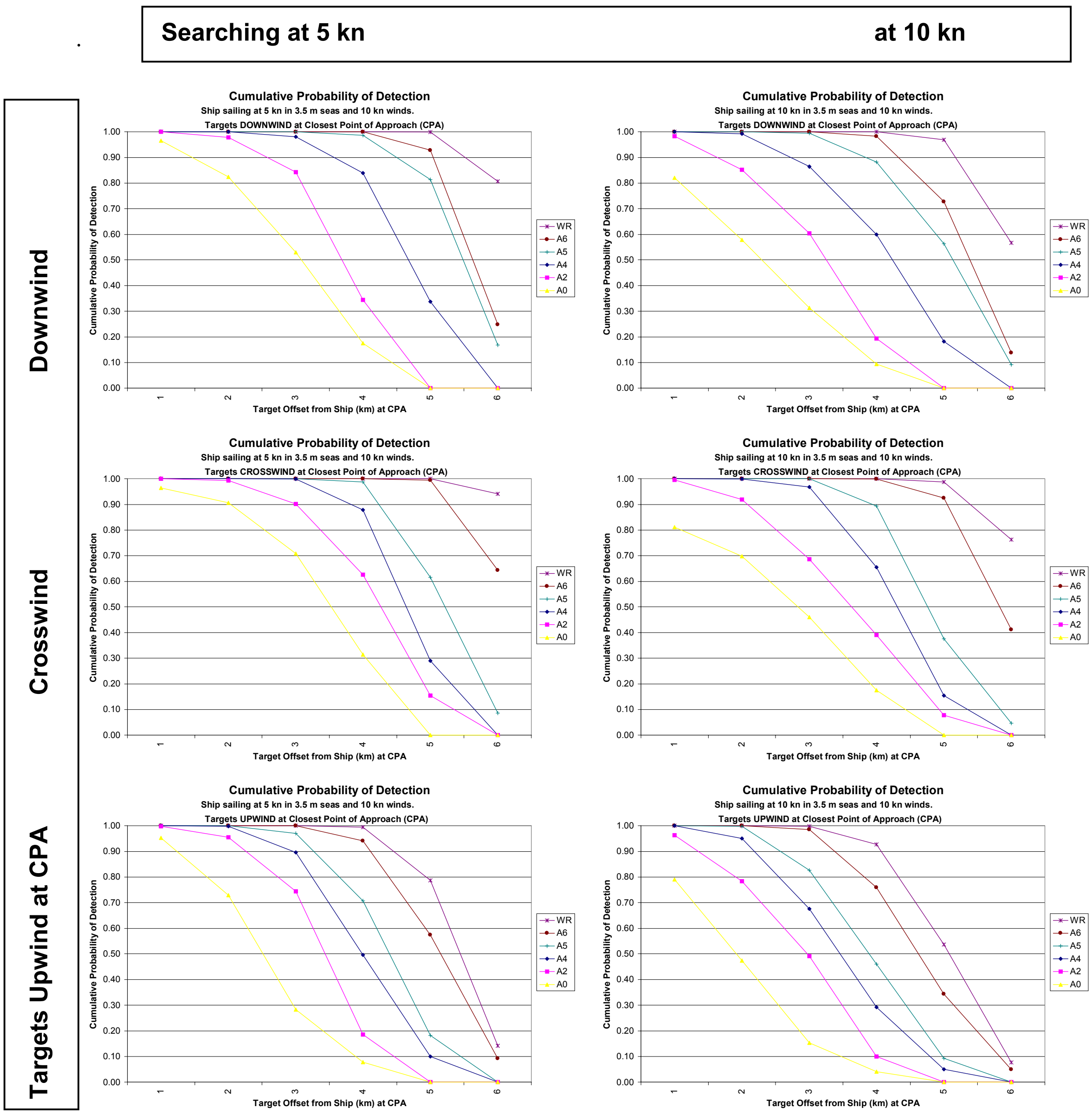

Figure 9-12 Short pulse in Sea State 3: Pd_{cum} for 5 and 10 kn searches

9.2 Medium Pulse Mode

Medium pulse operation is expected to deliver its best performance at Sea States 1 and 2 as shown in Section 7. Sea State 3 is expected to mark the transition where the slightly longer medium pulse detection range is more than offset in the SAR Tracker by the four times greater range errors.

9.2.1 Sea State 3 Moderate Seas: 3.0 m Swell, 0.3 m Waves and 11 kn Winds

This data set was recorded a disturbed sea with a rapidly rising 11 kn wind that would soon reach 23 kn. Numerous white caps created a high false alarm environment typical of Sea State 3. Significant clutter is evident even at 6 nmi.

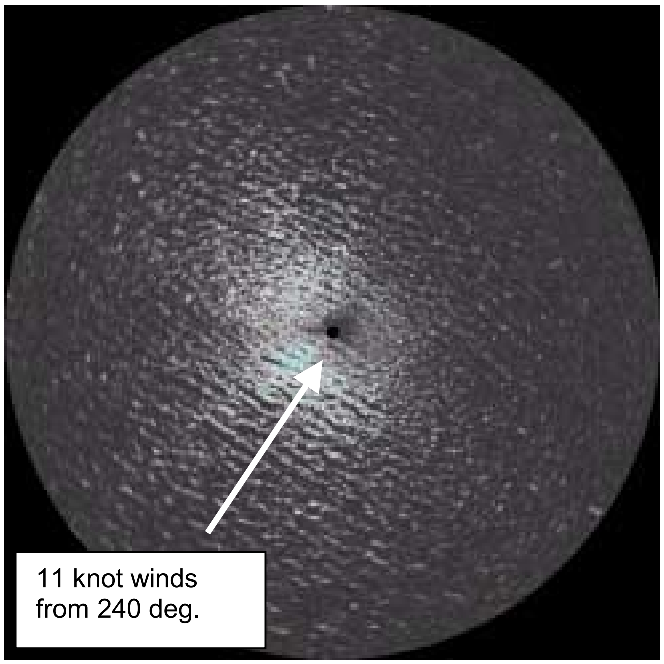

Figure 9-13 Medium pulse PPI in Sea State 3: 3.3 m combined sea (6 nmi scale)

Table 9-5 Representative SAR Tracker processing for medium pulse in Sea State 3

Sea Scan Processing Parameters											
Pfa	Integration	CFAR Window	CFAR Rank	Min Extent	Max Extent						
0.001	4	12	40	6,5,4,4	20						
SAR Tracker Processing Parameters											
M1	N1	M2	N2	M3	N3	V max (m/s)	Acc max (m/s^2)	R var (m^2)	Az var (rad^2)	Hypotheses	Initiation (TentCoast Confirms ConfCoast)
5	40	1	1	3	3	0.5	0.005	900	6e-4	2	4/3/0
8	60	1	1	2	2	0.5	0.005	900	6e-4	2	4/3/0

Figure 9-14 shows where the SAR Tracker initiated tracks as the ship sailed around the target array. Note the relative sparseness of upwind tracks compared to downwind. This difference is probably a result of the steep-faced upwind waves that result when winds are increasing and waves building. The near-complete absence of any tracks to the northwest may result from the wind setting against the southerly current and further increasing the steepness (and reflectivity) of these waves.

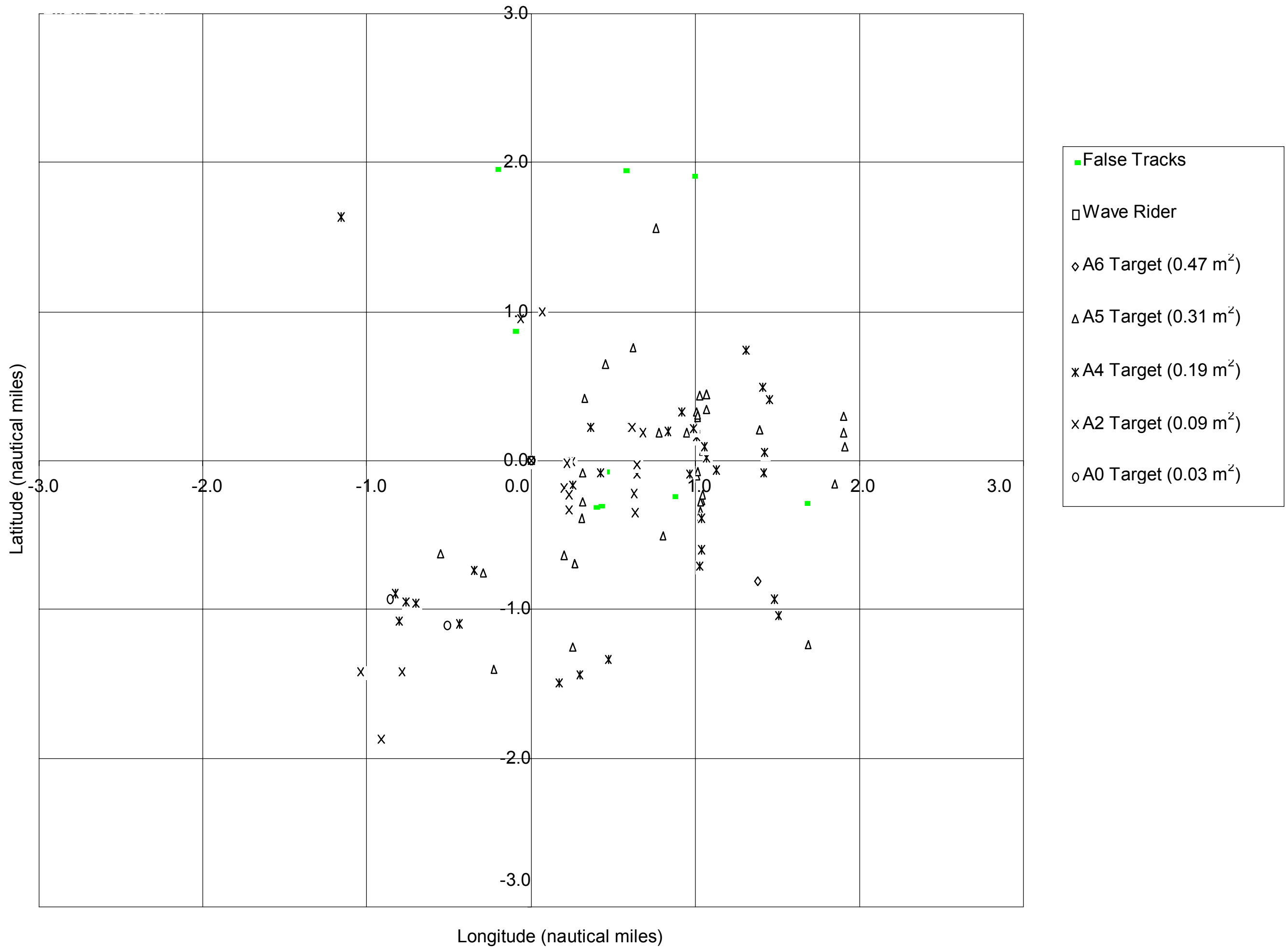

Figure 9-14 Track initiations relative to ship from two runs

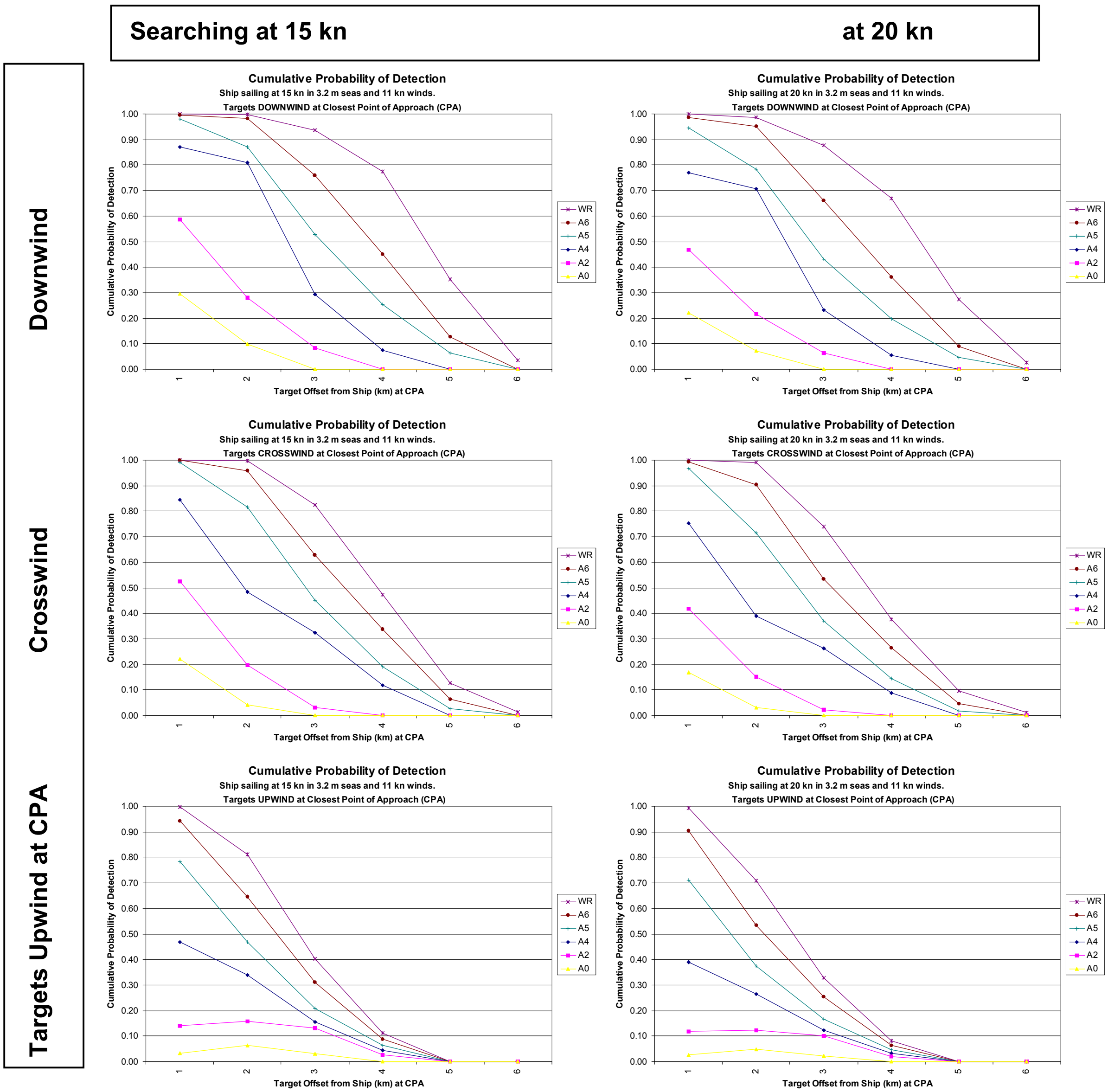

Figure 9-15 Medium pulse in Sea State 3: Pd_{cum} for 15 and 20 kn searches

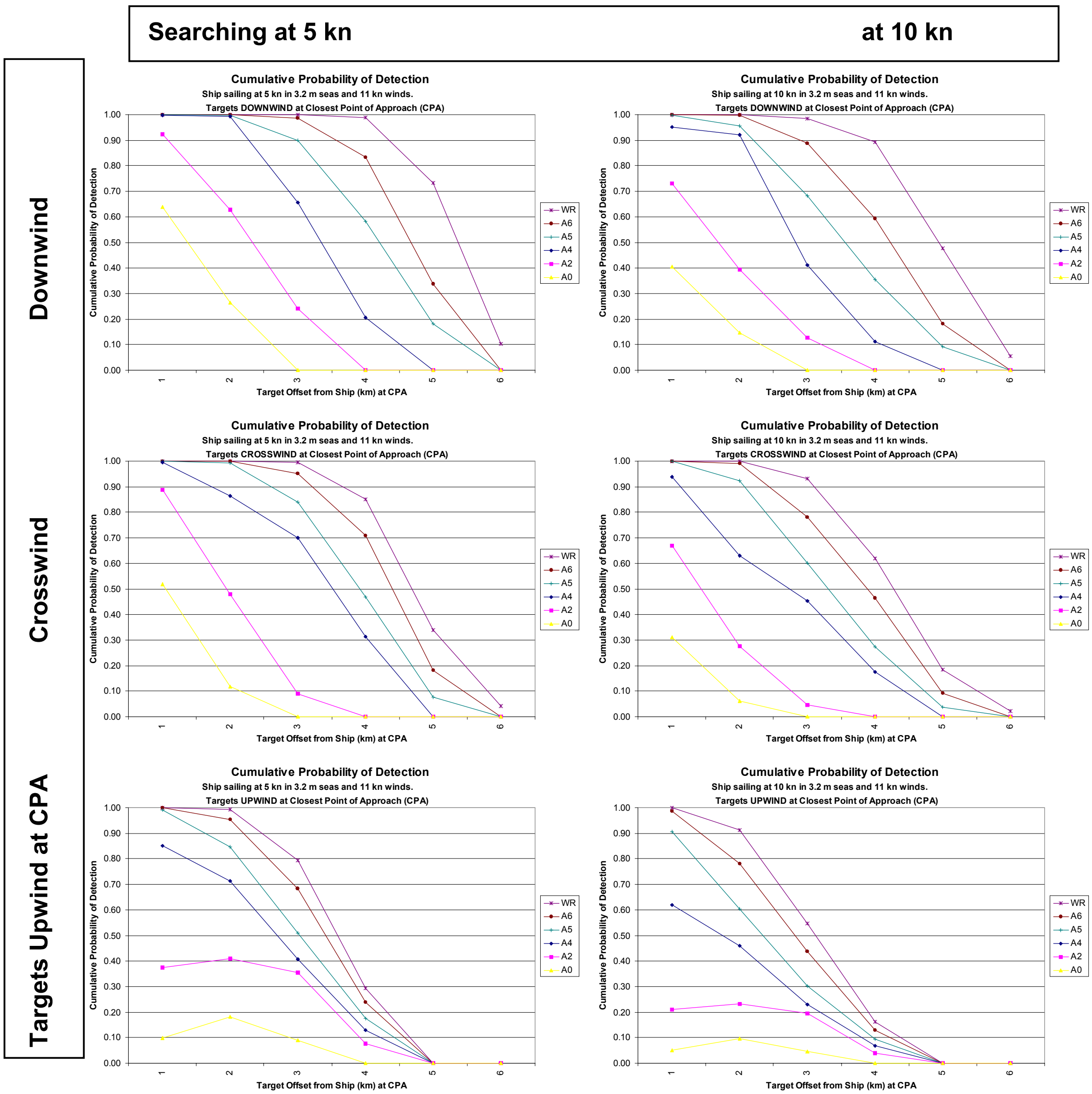

Figure 9-16 Medium pulse in Sea State 3: Pd_{cum} for 5 and 10 kn searches

9.2.2 Sea State 2 Slight Seas: 3.1 m Swell, 0.2 m Waves and 10 kn Winds

Winds are lower in this data set and falling. Compared to Sea State 3, there is much less clutter beyond 4 nmi and a marked reduction in downwind clutter intensity. The ship's wake is clearly visible and the turning knuckle is typically tracked by the SAR Tracker up to 2 nmi distant.

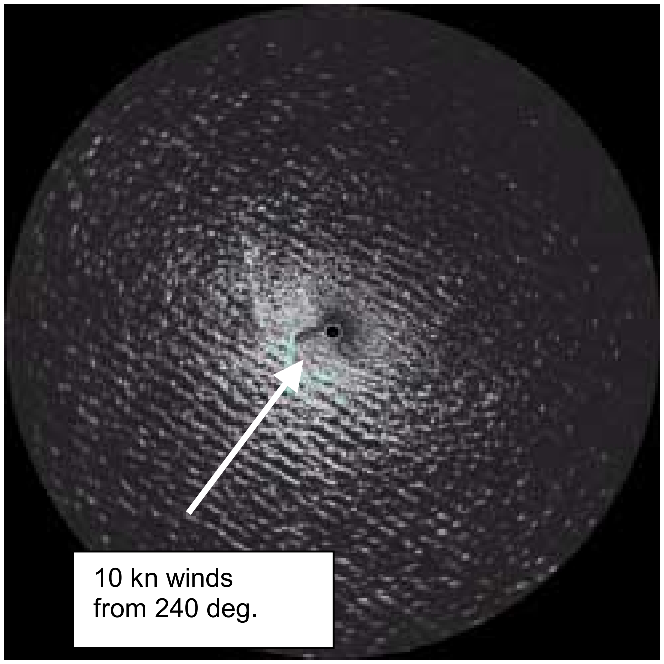

Figure 9-17 Medium pulse PPI in Sea State 2: 3.3 m combined sea (6 nmi scale)

Table 9-6 Representative SAR Tracker processing for medium pulse in Sea State 2

Sea Scan Processing Parameters											
Pfa	Integration	CFAR Window	CFAR Rank	Min Extent	Max Extent						
0.001	4	12	50	3	20						
SAR Tracker Processing Parameters											
M1	N1	M2	N2	M3	N3	V max (m/s)	Acc max (m/s^2)	R var (m^2)	Az var (rad^2)	Hypotheses	Initiation (TentCoast Confirms ConfCoast)
2	10	3	4	1	1	1.75	0.05	400	3e-4	2	4/3/0
3	20	2	2	1	1	1.5	0.05	400	3e-4	2	4/3/0

Compared to Sea State 3, the SAR Tracker confirms more tracks upwind and into the current. Maximum performance is still observed downwind.

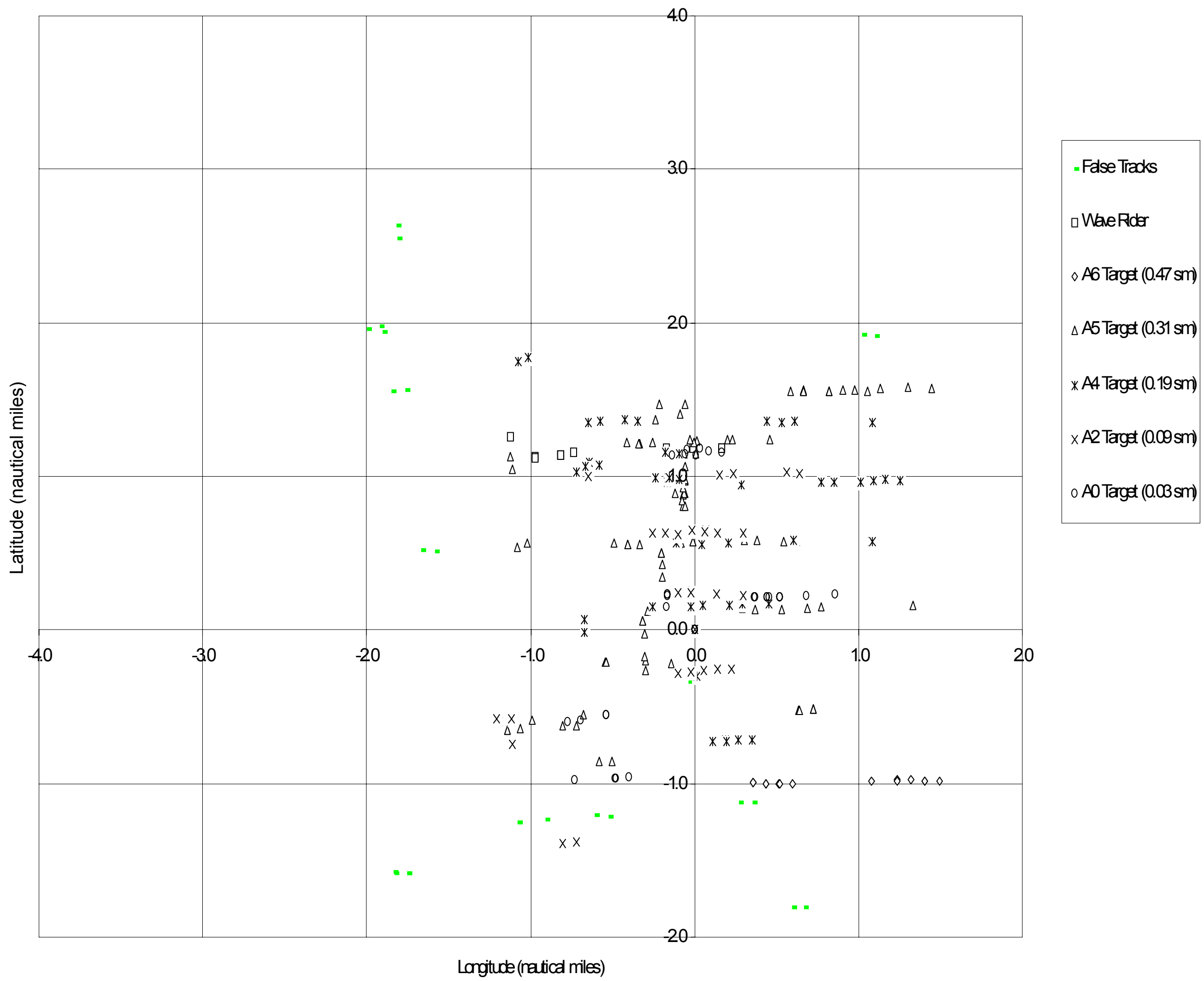

Figure 9-18 Track initiations relative to ship from two runs

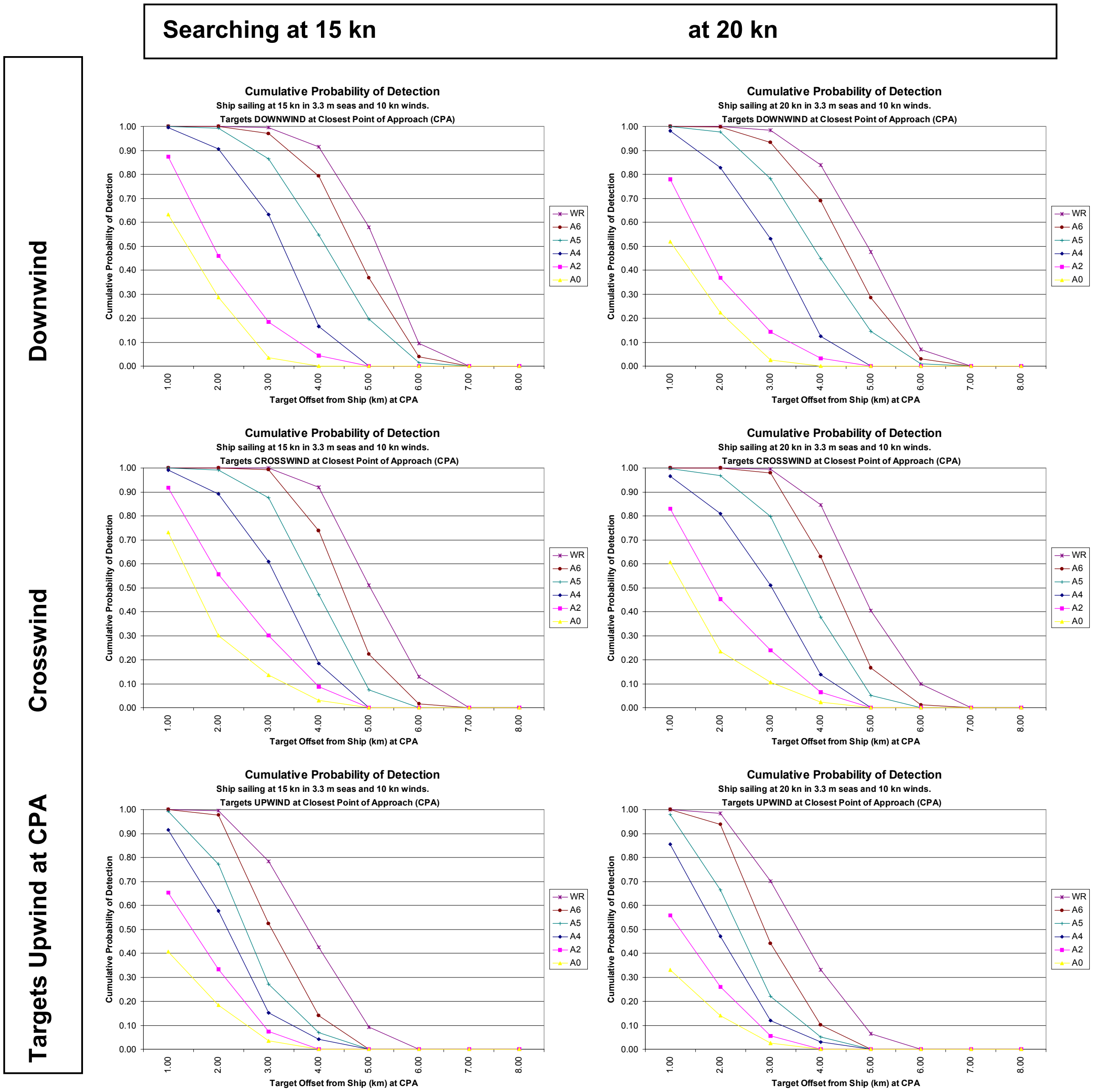

Figure 9-19 Medium pulse in Sea State 2: Pd_{cum} for 15 and 20 kn searches

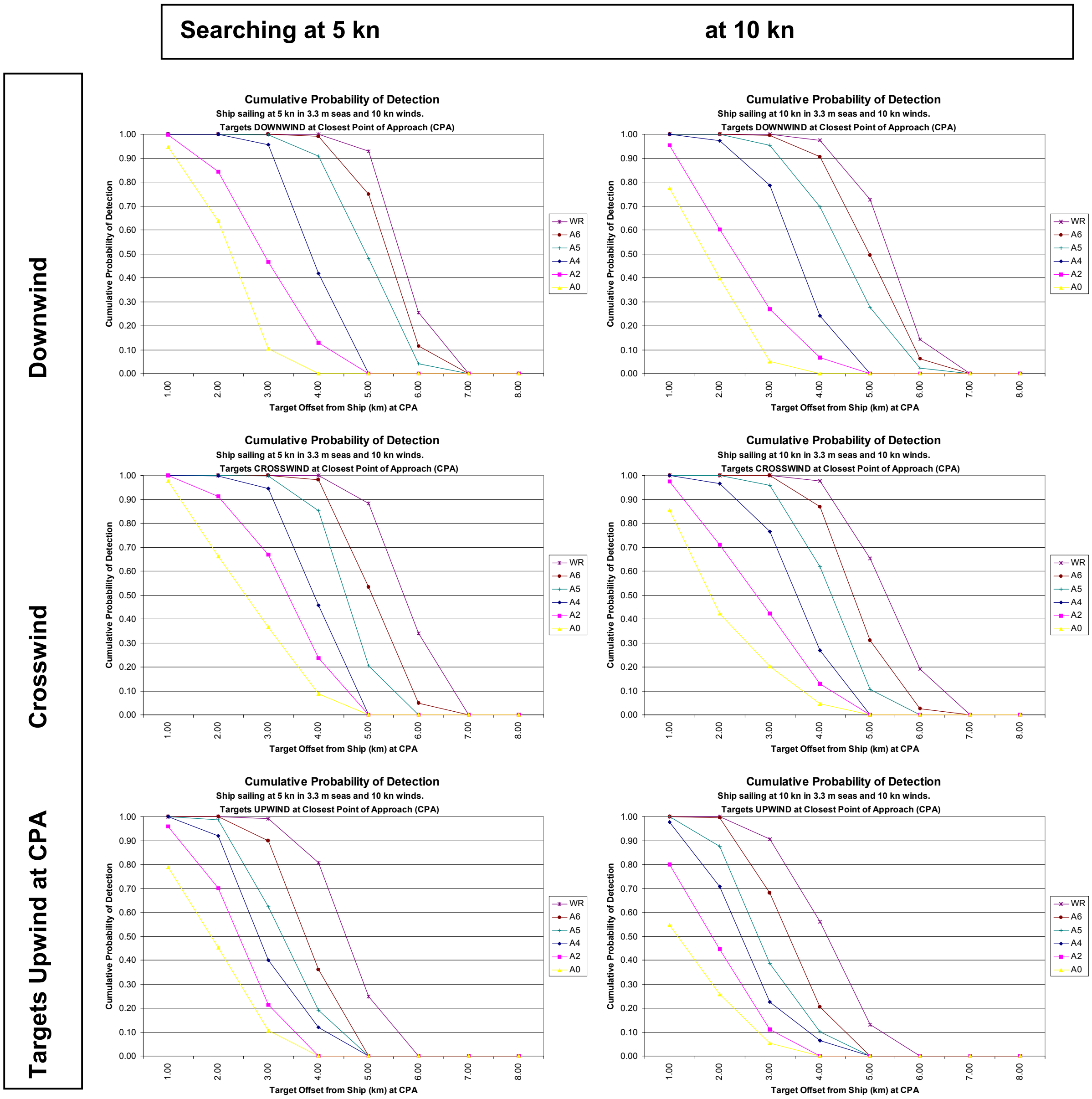

Figure 9-20 Medium pulse in Sea State 2: Pd_{cum} for 5 and 10 kn searches

9.2.3 Sea State 1 Smooth Seas: 3.8 m Swell, 0.1 m Waves and 3 to 8 kn Winds

This data set is marked by a large 3.8 m swell with small 0.1 m wind-driven waves superimposed. The sea surface is still chaotic from earlier winds and this is frequently causing waves to crest and break, which introduces bright spots on the radar display. Clutter levels are low and effectively correspond to Sea State 1.

Small regions of enhanced clutter are caused by localized rain cells roughening the sea surface. Numerous sea birds are drifting and are sometimes detected as targets when they stay drifting for more than a few minutes.

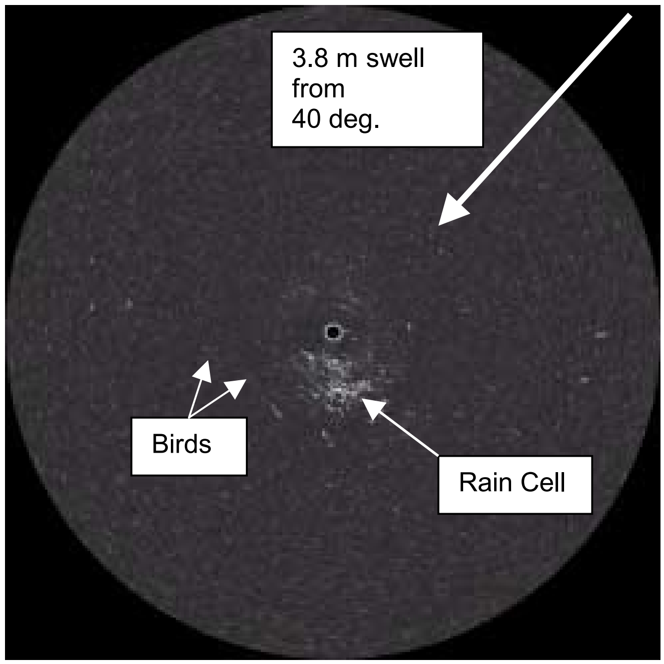

Figure 9-21 Medium pulse PPI in Sea State 1: 3.8 m swell (6 nmi scale)

Table 9-7 Representative SAR Tracker processing for medium pulse in Sea State 1

Sea Scan Processing Parameters											
Pfa	Integration	CFAR Window	CFAR Rank	Min Extent	Max Extent						
0.001	4	12	50	3	20						
SAR Tracker Processing Parameters											
M1	N1	M2	N2	M3	N3	V max (m/s)	Acc max (m/s^2)	R var (m^2)	Az var (rad^2)	Hypotheses	Initiation (TentCoast Confirms ConfCoast)
2	10	3	4	1	1	1.75	0.05	400	3e-4	2	4/3/0
3	20	2	2	1	1	1.5	0.05	400	3e-4	2	4/3/0

The data set is limited to a single east-to-west pass along the lower edge of the array. This is nonetheless sufficient because there is no discernable dependence on the swell or wind direction. Target visibility should be increased looking along the swell troughs but in 3.8 m swells this effect is apparently of limited benefit. The estimated probability of detection is therefore assumed to be independent of wind and swell direction.

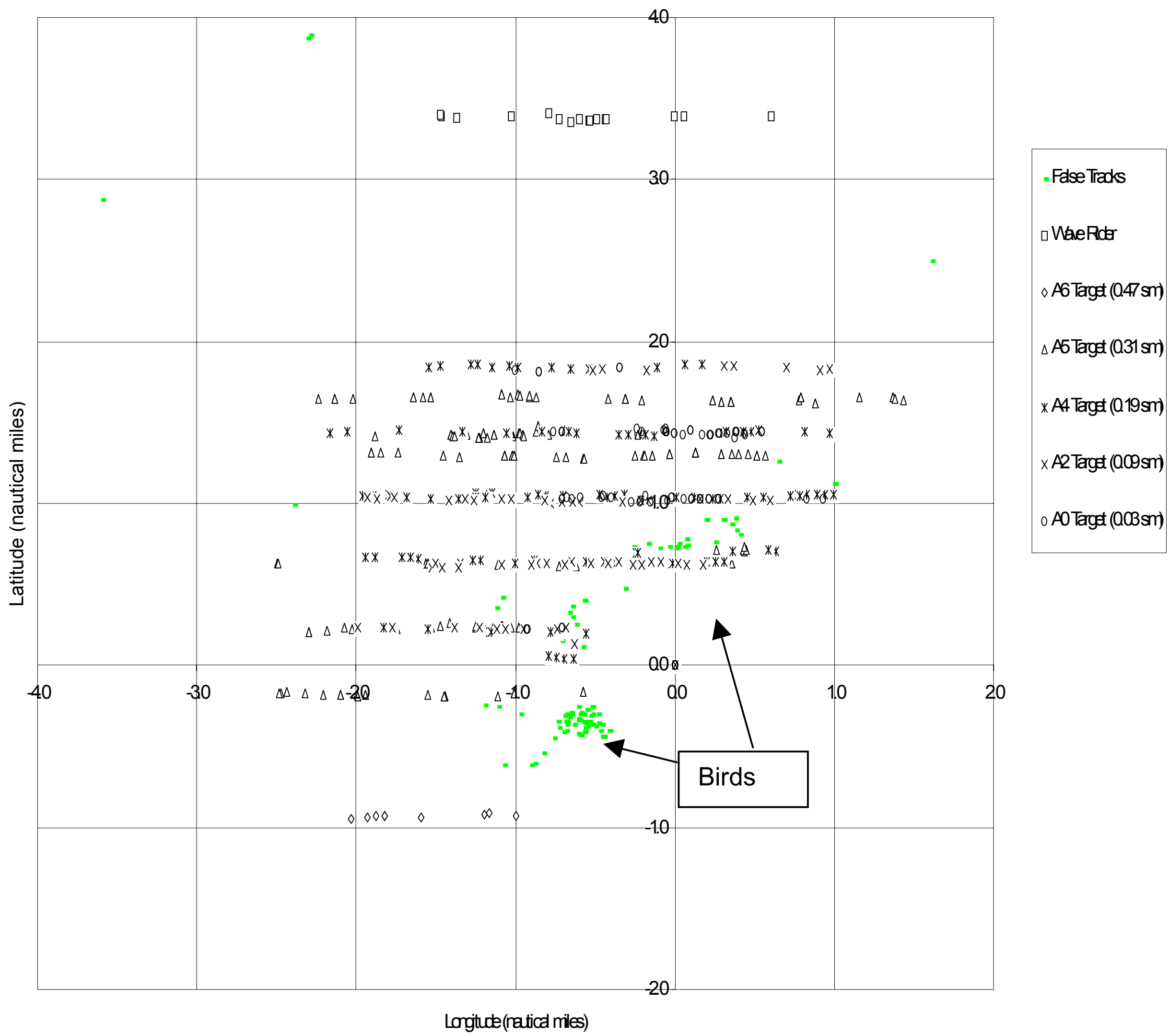

Figure 9-22 Track initiations relative to ship from two runs

Searching at 15 kn **at 20 kn**

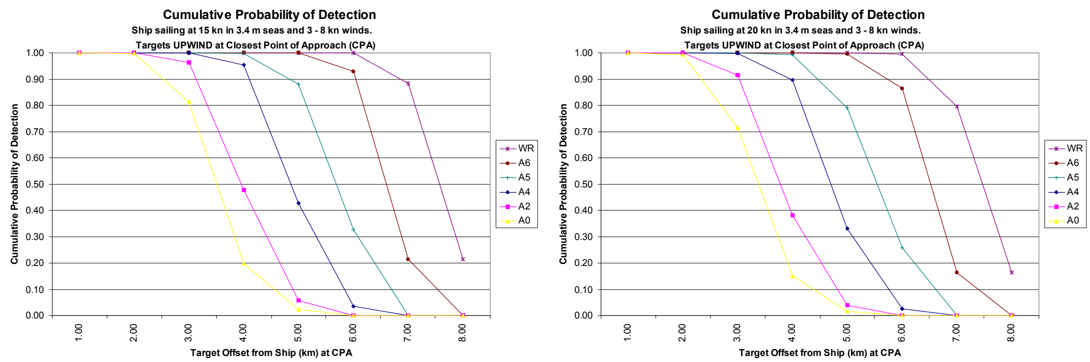

Figure 9-23 Medium pulse in Sea State 1: Pd_{cum} for 15 and 20 kn searches

Searching at 5 kn **at 10 kn**

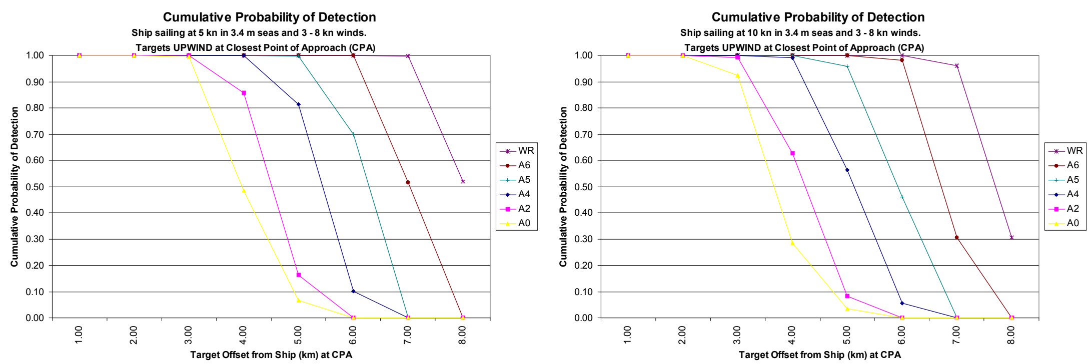

Figure 9-24 Medium pulse in Sea State 1: Pd_{cum} for 5 and 10 kn searches

10. Conclusions

The SAR Tracker has been demonstrated to reliably detect small awash 0.03 to 0.6 m^2 SAR targets in 3.2 to 3.8 m waves and Sea States up to 5. These are typical sea conditions for the North Atlantic off Newfoundland, being encountered 75 percent of the time (see Table 7-1).

10.1 Measured Detection Performance

The measured 90 percent cumulative probability of detection (Pd_{cum}) range (for a single sail-past) far exceeds that of any conventional radar or of a visual observer, even in good visibility. The smallest (0.03 m^2) targets, corresponding to a fully immersed swimmer, can be detected to between 3 and 0.8 km in Sea States 1 to 3. The largest (0.6 m^2) target, corresponding to a 4- to 6-person liferaft, could be detected to between 7.2 and 3.2 km in Sea States 1 to 5. Fewer than five false tracks per hour were observed in all cases.

Up to 40 percent longer ranges were typically attained by slowing the search rate from 10 to 5 kn, particularly at higher sea states. Moreover, the 50 percent Pd_{cum} ranges are 1 to 2 km further out and will contribute detections on about half the targets in this outer annulus. These detections are not usually considered sufficient to extend the search sweep width but do serve to usefully augment the more reliable 90 percent certain detections.

The measured detection ranges shown in Figure 10-1 and Figure 10-2 are those where the Pd_{cum} reaches 90 percent on a single sail-past at 10 kn. Equivalent curves for 5, 15 and 20 kn searches can be extracted from the detailed tables in Section 9.

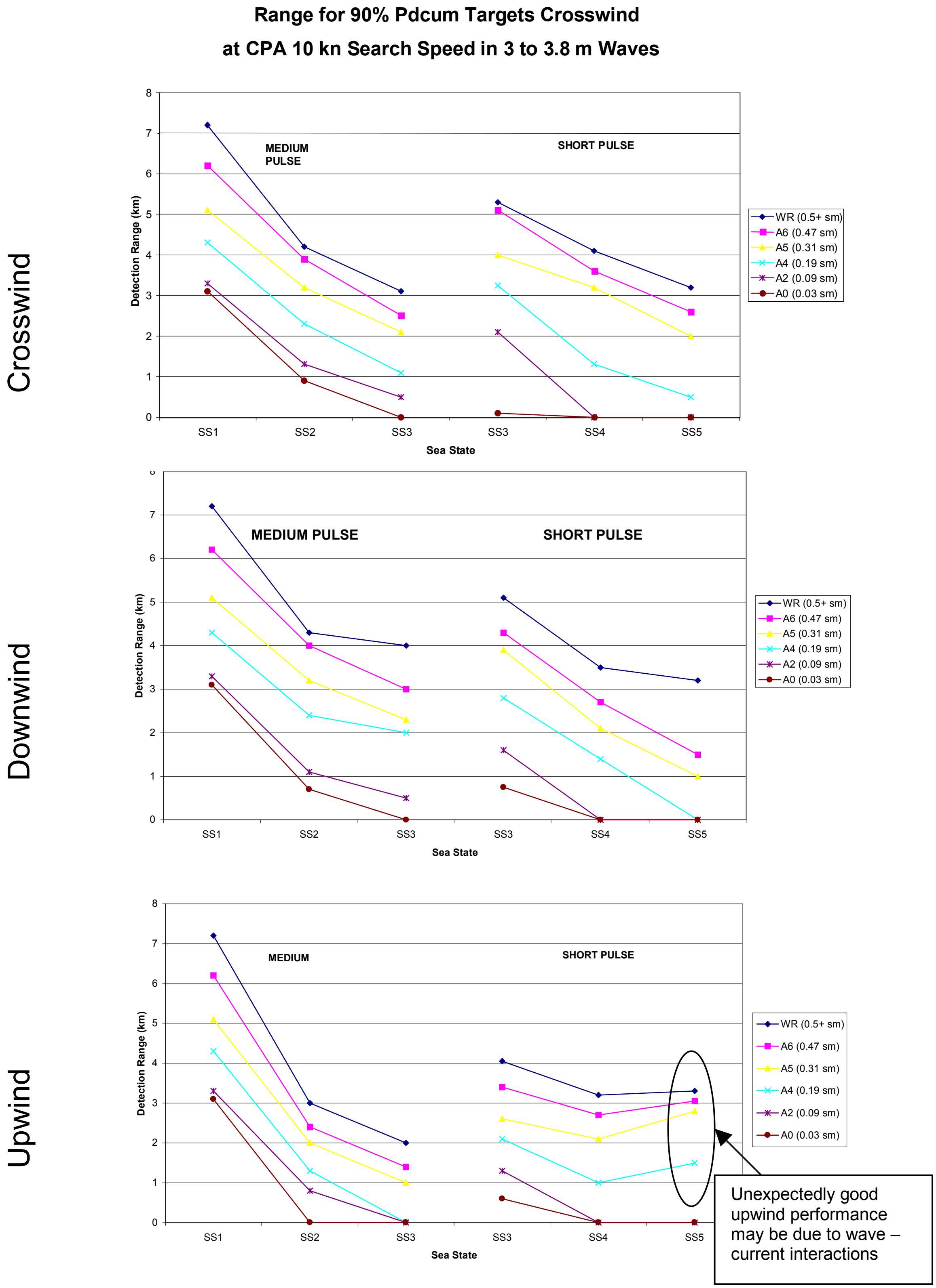

Figure 10-1 Range for 90% Pd_{cum} in 3.2 to 3.8 m waves versus sea state (10 kn search)

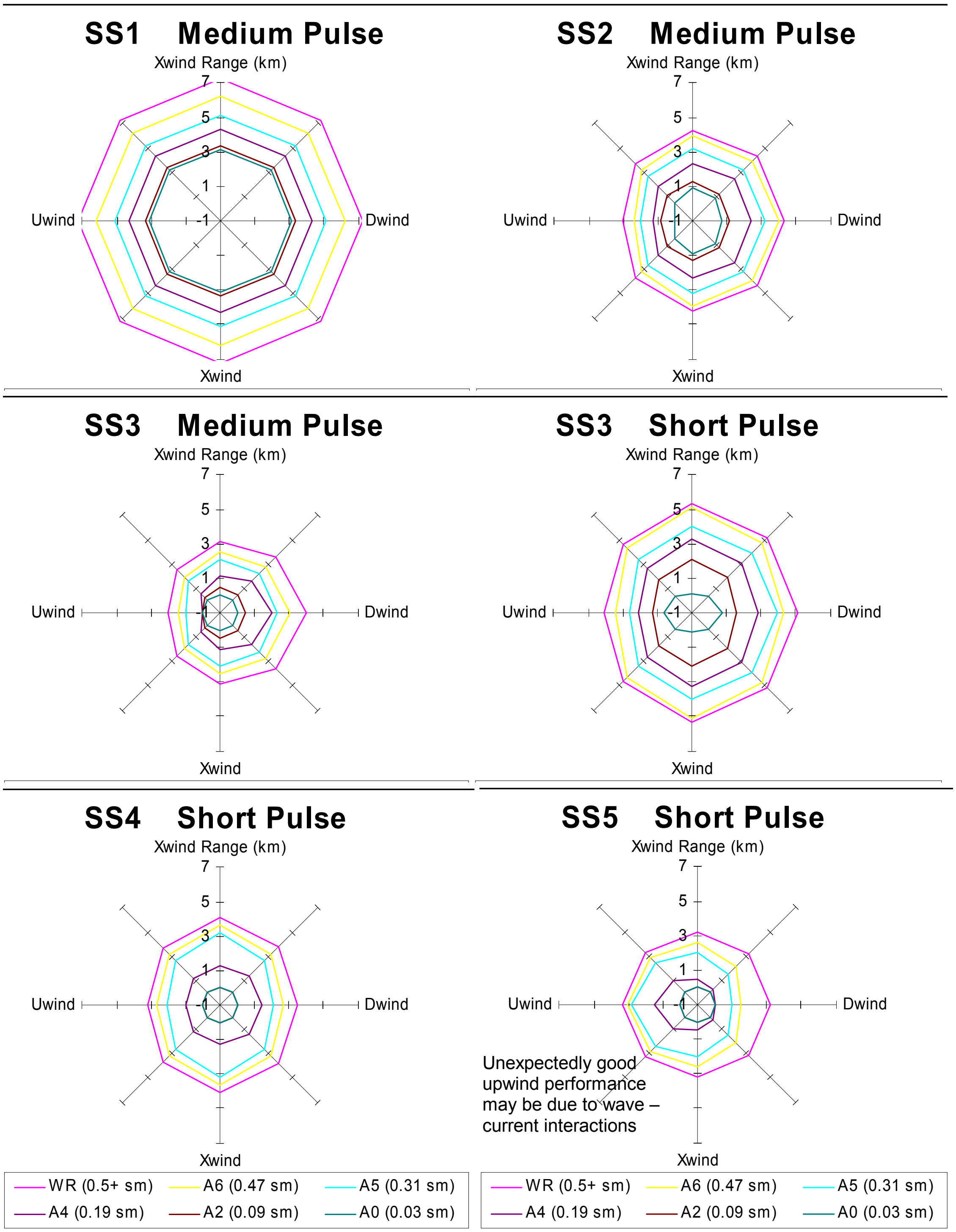

Figure 10-2 Range for 90% Pd_{cum} in 3.2 to 3.8 m waves versus wind direction (10 kn search)

The SAR Tracker performance is largely governed by the clutter and the waves.

- The percentage visibility of awash targets behind waves equally reduces the number of detections for both short and medium pulse. Smaller waves hide awash targets less frequently than larger ones. Target visibility is highest looking along the troughs (i.e., crosswind for wind-driven waves) and lowest looking into and away from the waves (i.e., upwind and downwind). In long swells, the effect is often masked by irregularities in the wave fronts.

- Medium pulse clutter (with 40 m range resolution) is four to six times stronger than short pulse clutter (6 m resolution).
- Clutter strength increases as the radar looks downwind, crosswind and upwind.

The SAR Tracker has been tested in 3.5 m waves (+/- 0.3 m) to separate the effects of pulse length, wind speed and sea state from wave height.

Medium pulse detection range is seen in Figure 10-1 to be highly dependent on the sea state and clutter strength. At Sea State 1, the clutter is negligible and so the detection range is independent of wind direction. As the winds increase to Sea State 2, the clutter rises and reduces the detection range by 30 percent for the largest (0.5 m^2) targets and by 75 percent for the smallest (0.03 m^2) ones. At Sea State 3, the detection range is reduced by a further 30 to 50 percent, depending on target size. For all targets, the maximum detection range is downwind followed closely by crosswind. Upwind range is much smaller and falls faster with sea state, particularly for the smaller targets, because the increased clutter from the steeper-faced waves in this sector force the automatic threshold control to locally increase the detection threshold. For medium pulse operation above Sea State 1, the benefits of increased crosswind visibility are therefore being increasingly outweighed by the increased crosswind clutter intensity.

Short pulse is less effected by clutter; the detection range therefore benefits from the increased crosswind visibility. At Sea State 3, the maximum detection range for all targets is crosswind followed closely by downwind and upwind. The relative crosswind advantage is steadily reduced with sea state as the increasing clutter offsets the constant improved crosswind visibility until the maximum range is observed to be downwind. The sea state at which this transition occurs is proportional to the target radar cross section. Higher sea states are expected to rapidly reduce first the upwind range and then the crosswind range as was observed with the medium pulse.

Short pulse is therefore recommended for Sea State 2 and higher searches, where clutter effectively masks the targets. Medium pulse is only superior in Sea States 0 and 1, where no appreciable clutter intrudes.

Smaller wave heights are confidently expected to increase target visibilities and therefore detection ranges, but more data is required to quantify the improvement. Higher floating targets such as 20-person liferafts and small boats are both larger and much more visible and should be detected at much longer ranges than the small awash targets used in this project.

10.2 Increased Search Sweep Widths

The exact layout of search patterns should be matched to the desired cumulative probability of detection for the expected target type. The following calibrated test targets were used to measure performance:

• Wave-Rider	0.6 m^2 estimated	Person in a small 4- to 6-person liferaft
• A6 Target	0.47 m^2	Person in a very small 4-person liferaft
• A5 Target	0.31 m^2	Person in swamped 4-person liferaft
• A4 Target	0.19 m^2	Person in water with survival suit[7]
• A2 Target	0.09 m^2	Maximum person in water (only head exposed)
• A0 Target	0.03 m^2	Minimum person in water (only head exposed)

Medium pulse is superior in Sea States 0 and 1, where clutter is negligable. Short pulse is uniformly best in Sea States 2 to 5.

[7] For calibration purposes prior to these trials, the radar cross section of a diver in a lifevest was measured as 0.14 m^2.

The detection range is only independent of wind and swell direction in Sea States 0 and 1. Higher sea states require matching the search pattern to the upwind, crosswind and downwind ranges for the expected targets. While the target RCS is well above the effective clutter reflectivity, maximum range is observed for targets that are crosswind at closest point of approach. As targets approach the crosswind clutter level, the maximum range shifts to downwind and the upwind range starts to fall more quickly than the crosswind and downwind ranges.

Search legs that cross the wind should be spaced by the sum of the upwind and downwind detection ranges since midway targets will be successively detected upwind on one leg and downwind on the other. Similarly, legs that are into or before the wind should be spaced by twice the crosswind range.

Table 10-1 and 10-2 compare the SAR Tracker sweep width at 90 percent cumulative probability of detection on a single pass to measured sweep widths for more conventional searching techniques. Unfortunately, the available SAR Tracker data is in 3.2 to 3.8 m seas while all the conventional search data is in 2 m seas or less. The targets are comparable, however, including both persons in water with survival suits (equivalent to the 0.19 m^2 A4-target) and both 4-person and 4- to 6-person liferafts (comparable to the 0.47 A6 target and the 0.6 m^2 wave-rider buoy respectively).

Table 10-1 PIW 90% Pd_{cum} sweep widths with SAR Tracker versus other techniques[8]

Wave Ht (m)	Wind (kn)	Sea State	Search Type, Platform and Speed[9]	Sweep Width (nmi) Sweep versus Wind		Sweep Width (km) Sweep versus Wind	
				XW	UW/DW	XW	UW/DW
0.19 m^2 A4 Target: Person in Water with orange survival suit							
3.8	44	5	SAR Tracker on CCGS - 5 kn	2.0	2.2	3.7	4.0
			at 10 kn	1.1	0.6	2.0	1.2
			at 15 kn	-	-	-	-
3.5	23	4	SAR Tracker on CCGS - 5 kn	2.5	2.4	4.6	4.4
			at 10 kn	0.9	1.3	1.7	2.5
			at 15 kn	0.5	1.1	1.0	2.0
			at 20 kn	0.4	0.9	0.7	1.6
3.5	10	3	SAR Tracker on CCGS - 5 kn	3.6	4.2	6.6	7.8
			at 10 kn	2.7	3.5	5	6.4
			at 15 kn	2.2	3.2	4.0	6.0
			at 20 kn	1.8	2.6	3.4	4.8
3.8	3 - 8	1	SAR Tracker on CCGS - 5 kn	5.4		10.0	
			at 10 kn	4.5		8.4	
			at 15 kn	4.3		8.0	
			at 20 kn	4.5		8.3	
1.2	17	4	Sperry 4016 radar on CCGS	0.2		0.4	
1.0	14	3?	TITAN (scan avg) on CCGS	1.2		2.2	
1.5	11	2?	Daytime Visual on MV	0.8		1.5	
with Reflective Tape							
1.8	12	2?	Night Vision Goggles on MV	-		-	
0.7	9	2?	Night Vision Goggles on UTB	0.07		0.1	
with Red Safety Lights							
0.8	9	2?	Night Vision Goggles on UTB	-		-	

[8] R.B. Fitzgerald, *Target Detection Experiment Phase III – Data Analysis*, Transport Canada Publication TP 13290E, July 1998.
[9] CCGS = Cdn Coast Guard Ship (radar at 20 m); MV = Motor Vessel "Nain Banker" (radar at 20 m); UTB = US Coast Guard (USCG) Utility Boats.

Table 10-2 4- to 6-person liferaft 90% Pd_{cum} sweep widths with SAR Tracker versus other techniques

Wave Height (m)	Wind (kn)	Sea State	Search Type, Platform and Speed[10]	Sweep Width (nmi) Sweep versus Wind		Sweep Width (km) Sweep versus Wind	
				XW	UW/DW	XW	UW/DW
0.6 m² Wave-Rider Buoy: 4- to 6- person liferaft							
3.8	44	5	SAR Tracker on CCGS - 5 kn	4.6	4.4	8.6	8.2
			at 10 kn	3.5	3.5	6.5	6.4
			at 15 kn	2.7	2.8	5.0	5.1
			at 20 kn	1.8	2.2	3.3	4.0
3.5	23	4	SAR Tracker on CCGS - 5 kn	4.6	4.6	8.6	8.6
			at 10 kn	3.6	4.4	6.7	8.2
			at 15 kn	2.9	3.9	5.4	7.3
			at 20 kn	2.5	3.5	4.7	6.5
3.5	10	3	SAR Tracker on CCGS at 5 kn	5.7	7.0	10.5	13.0
			at 10 kn	5.0	5.8	9.3	10.8
			at 15 kn	4.6	5.6	8.5	10.4
			at 20 kn	4.2	5.4	7.8	10.0
3.8	3 - 8	1	SAR Tracker on CCGS at 5 kn	7.9		14.6	
			at 10 kn	7.8		14.4	
			at 15 kn	7.4		13.8	
			at 20 kn	7.0		13.0	
In 1 to 2 m seas:							
4- to 6- person liferaft without Radar Reflectors							
1.6–1.9	19-23	5?	Visual on CCGS and USCGC	3.6-5.4		6.7-10	
with Radar Reflectors (seen from air so wave blockage is minimal)							
2.1	23	5?	APS-504(V) Airborne search	5.3		9.8	
with Canopy Lights							
1.8	18	4	NVG on CCGS	4.6		8.5	
1.8	14	4	NVG on USCGC	6.2		11.5	
4-person liferaft without Radar Reflectors							
0.9	12	2-3	Sperry 127E Radar on CCGS	0.8		1.5	
with Radar Reflectors							
1.3	14	3	Sperry 127E Radar on CCGS	2.7		5.0	

For simplicity, the SAR Tracker **average** sweep width is plotted in Figure 10-3 for 90 percent cumulative probability of detection (Pd_{cum})searches at 5, 10, 15 and 20 kn in 3.2 to 3.8 m seas. The SAR Tracker detects the 0.19 m^2 person in water with survival suit in far higher (1.5 to 3 times) seas than conventional techniques and still the SAR Tracker delivers sweep widths that are two to four times wider than the TITAN Radar Processor and three to five times wider than visual searches. Much more significant improvements would be likely if the comparisons were made at similar wave heights.

In all sea states, the SAR Tracker consistently detects the 0.6 m^2 Wave Rider buoy with 2.5 nmi wider sweep widths than it does the 0.19 m^2 person in water. Any comparison with conventional searches for 4- to 6-person liferafts is difficult since the SAR Tracker is operating in much higher waves (1.5 to 3 times higher). Despite the higher seas, the SAR Tracker detects the Wave Rider with sweep widths that are comparable to visual and radar searches against 4- to 6-person liferafts without radar reflectors or lights.

[10] USCGC = USCG Cutter.

These loose comparisons suggest that the SAR Tracker will dramatically increase the sweep widths that can be used in marine search and rescue. Moreover, the SAR Tracker detects swimmers and other awash targets smaller than 0.19 m^2 in sea states where they have hitherto been undetectable.

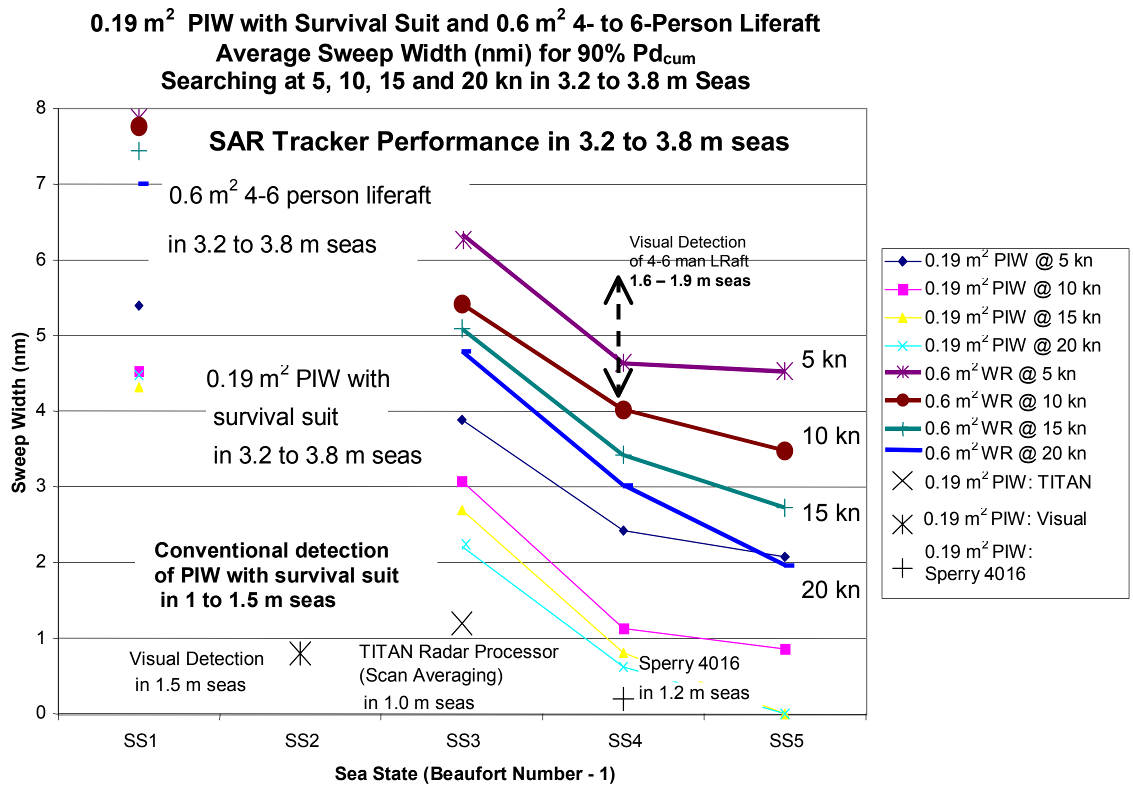

Figure 10-3 Sweep widths for 90% Pd_{cum} detection of 0.6 and 0.19 m^2 targets in 3.2 to 3.8 m seas

10.3 Inexpensive Expandable Open Architecture Implementation

The SAR Tracker uses simple and readily available PC hardware to facilitate growth and limit cost. Each parallel Correlator-Tracker requires a single dual-Pentium III PC. The SAR Tracker performance is largely defined by the available processing power and will therefore benefit from the rapid trend to higher CPU clock rates, wider bus bandwidths and less expensive multi-processor servers.

The defined performance is for two Correlator-Trackers but significant increases in detection range are expected as further Correlator-Trackers are added, up to the tentative limit of four. All inter-PC communications are over 100T Ethernet. A hub can be added should the tracks or radar data be sent to other systems.

All software is written in platform-independent, object-oriented C++ or Smalltalk that runs under Windows NT. The SAR Tracker code can therefore be loaded without modification onto whatever size computers are required for the mission. Being object-oriented, the SAR Tracker software has proven particularly simple to extend and modify in response to operator requests for different functions or displayed information.

10.4 Future Work

The SAR Tracker performance has been quantified in 3.5 m waves, in Sea States 1 to 5 and with targets from 0.03 to 0.6 m^2. Further data gathering and testing is required to measure performance in lower waves and higher sea states.

The Sea Scan radar processor works extremely well but can only process one to two million range-azimuth samples. This limits the coverage on short pulse, which is the preferred operational mode in Sea States 2 and up. An upgrade to permit 360 deg. operation to 6 or more nmi would allow the SAR Tracker to deliver its full capability.

The user interface is practical for prototyping but requires further simplifications for operational use. The graphical user interface must allow the operator to intuitively describe the following expected targets and operational constraints:

- target size and extent;
- target manoeuvrability; and
- desired false track frequency (x per hour).

The SAR Tracker must then sense the radar environment including:

- wave period and direction;
- wind strength and direction;
- clutter intensity in range and azimuth;
- clutter statistical characteristics in range and azimuth;
- ship velocity; and
- ship manoeuvres;

and then automatically set the processing parameters. Adaptation will continue as the ship manoeuvres and the radar environment changes.

Other improvements needed for field use include:

- manual track initiation and deletion; and
- operator-defined regions of greater and lesser sensitivity.

Following these improvements, the SAR Tracker should be placed in a reinforced enclosure, installed on a vessel and operators trained for field tests. This would allow SAR practitioners to explore the capabilities (and limitations) of the SAR Tracker to better define their requirements and drive the design to a final fielded product.

Airborne SAR has obvious benefits:

- Radar is looking down and is not therefore blocked by waves so the target probability of detection is higher.
- Scan rate is as high as 300 rpm so longer correlations can be processed.

The SAR Tracker incorporates high-speed differential GPS (or inertial) and motion compensation that can be easily extended with altitude information. Similarly, the ship gyrocompass heading information can be replaced with the heading data from the inertial navigation system. The Sea Scan radar processor operates on quadrants that can each be separately time stamped and marked with the radar position at that time to minimize smearing due to aircraft motion.

10.5 Faster Search Reduces Cost

The SAR Tracker has been proven to work well in the exposed North Atlantic waters off the east coast of Newfoundland. Targets the size of Persons in Water and small liferafts were detected at much longer ranges, and in waves that were at least twice as high, than possible with conventional detection methods such as visual, radar, IR and night vision goggles.

At a 10-kn search speed in 3.5 m seas, the recommended sweep widths for 90 percent certainty detection, with fewer than five false detections per hour, are summarized in Table 10-3.

Table 10-3 Average sweep widths for 90% certainty detection at 10 kn in 3.5 m seas

Target Type	Estimated Radar Cross Section (m^2)	Equivalent Target Buoy	Sweep Width (nmi) for Sea State		
			SS 1	SS 3	SS 5
4- to 6-person liferaft	0.6	Wave Rider	7.8	5.4	3.5
4- person liferaft	0.47	A6	6.7	4.8	2.6
Swamped 4- person liferaft	0.31	A5	5.4	3.9	2.1
Person in water with survival suit	0.19	A4	4.5	3.1	0.85
PIW Swimmer (max)	0.09	A2	3.5	2.3	-
PIW Swimmer (min)	0.03	A0	3.2	0.5	-

If you double the sweep width while maintaining the probability of success, then you can cover twice the area in the same time and thereby halve the cost of the search. The SAR Tracker has been demonstrated to increase the 90 percent confident sweep width by two to four times when compared to conventional visual and radar techniques. This was achieved in much larger seas than the conventional techniques and is therefore a conservative estimate of the improvement offered by the SAR Tracker.

Faster searches are particularly beneficial because they limit the enlargement of the search area due to the unknown drift of the survivors. Off Newfoundland, the Labrador Current plus the wind can easily push survivors by several nmi each hour they are adrift. Unfortunately, the direction and speed of drift are neither predictable nor constant.

The SAR Tracker has the added advantage of being completely automatic. Visual searchers will be able to focus their efforts on confirming and identifying SAR Tracker detections and on augmenting the SAR Tracker where required. Fatigue will be reduced so searchers will not need such frequent relief as at present. Alarms can be set up to automatically alert the watch-stander when a target is detected.

10.6 Faster Rescue Saves Lives

Two to four times faster searches mean that survivors will be rescued much earlier and will therefore be less exposed to the killing cold of the North Atlantic.

The number of deaths due to exposure and ensuing hypothermia should therefore be significantly reduced.

Of course, in some cases the search vessel must transit for many hours to reach the search area and it is this delay that dominates the time to rescue. The SAR Tracker could be mounted in a helicopter or aircraft to greatly reduce the transit time to the search area and further increase the search rate. The SAR Tracker already digitizes radars up to 120 rpm and computes accurate 2-D motion compensation so the changes required to digitize a high-speed airborne radar and add height to the motion compensation would be modest.

10.7 Inexpensive Operational Trials Demonstrate Benefits

With a few inexpensive improvements to make the SAR Tracker easier to use, operational trials are expected to bring immediate benefits in faster and more reliable searches. This will save lives and, at the same time, reduce SAR costs. The costs of these trials would be modest because the SAR Tracker uses off-the-shelf PC technology and could work with whatever marine radar is currently installed. Installing a 120 rpm Pathfinder II radar or gearing up the installed radar to 120 rpm would significantly improve the performance however.

10.8 Conclusion

The Search and Rescue Tracker dramatically extends the small target detection range of conventional marine radars. These radars are already used in most of the world's coast guards and navies and would not need to be replaced or modified in any way. The radar operator uses the radar as usual and needs only refer to the Search and Rescue Tracker display when looking for small targets.

The SAR Tracker reliably detects and tracks swimmers and liferafts at ranges up to 3 and 7.2 km respectively, with fewer than 5 false tracks per hour. Compared to conventional marine radars, the SAR Tracker search rate is two to four times greater for larger targets such as liferafts. The increase is even greater for the smallest targets, such as swimmers and persons in survival suits, that are not normally detectable in any wind by radar alone.

This performance improvement offers immediate benefits in faster, less expensive searches and in lives saved.