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Networked Underwater Warfare Metrics

Definitions for Operational Requirements

Mark A. Gammon

Defence R&D Canada – Atlantic

Technical Memorandum

DRDC Atlantic TM 2005-268

July 2006

Canada

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Abstract

The Networked Underwater Warfare (NUW) Technology Demonstration Project (TDP) requires the development of metrics for the evaluation of the NUW TDP Trial to be held in March of 2007. An opportunity exists to implement some of these metrics into the network so as to provide at-sea real-time analysis of system performance while the trial is underway. A review of ASW Measures of Performance is provided with a description of typical metrics associated with ASW from a detection, classification and localization perspective. An additional review of metrics associated with Intelligence, Surveillance and Reconnaissance is given with particular emphasis on fusion performance. From these, metrics for the NUW TDP are developed for at-sea analyses that are separated into operator and observer metrics. In addition, other metrics that can be used for post-trial analysis are provided.

Résumé

Le projet de démonstration technologique (PDT) de guerre sous-marine en réseau (GSMR) exige la définition de paramètres pour évaluer l'essai PDT NUW prévu en mars 2007. Une occasion est offerte de mettre en oeuvre certains de ces paramètres dans le réseau afin d'analyser en mer en temps réel les performances du système en cours d'essai. Un examen de mesures de performances GASM est présenté avec une description de paramètres typiques associés à la GASM à des fins de détection, de classification et de localisation. Un examen de paramètres associés au RSR (renseignement, surveillance, reconnaissance) est également présenté, visant particulièrement les performances de fusion. Sur cette base, des paramètres pour le PDT GSMR sont définis pour des analyses en mer et séparés en paramètres opérateur et paramètres observateur. D'autres paramètres sont présentés pour des analyses postérieures à l'essai.

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Executive summary

Introduction

The Networked Underwater Warfare (NUW) Technology Demonstration Project (TDP) will be conducting a trial in March 2007 to demonstrate the effectiveness of a network of sensors and platforms to detect, classify and localize underwater targets. In order to demonstrate the effectiveness of the network, the NUW TDP requires the development of metrics that can be used to measure the improvements in effectiveness. In addition, an opportunity exists to build some of these metrics into the network so as to be able to measure the system performance in real-time. The specification of these and their presentation to the observer at-sea is required prior to completion of the system design.

Results

A review of some standard ASW Measures of Performance (MOP) was made to determine if any could be used for the system metrics. These are separated into metrics for the operator and metrics for the observer. The variability in the environment makes this a challenging task. In addition, a review of metrics from Intelligence, Surveillance and Reconnaissance (ISR) was conducted as these pertain to the fusion of data from the different platforms and sensors into a common operating picture. A number of metrics were devised for the operator and observer at-sea. In addition, other metrics were defined for use in post-trial analysis as these will provide a greater statistical sample over the period of the entire trial.

Significance

The use of at-sea real-time metrics provides a unique opportunity to incorporate metrics directly into the trial system. These may in turn lead to operator decision aids or observer aids in determining how a trial is being performed and whether changes are required in real-time.

Future plans

The metrics proposed here are a guide only and require revision as necessary. Issues may arise particularly in the input of the ground truth data that is a necessary requirement for observer metrics. Once these are built into the system, post-trial analysis on the metrics themselves should be conducted to determine which ones provide the most utility and which metrics should be revised given the trial experience. Prior to the system design the metrics that will be incorporated need to be selected through discussion with the scientific observers, system contractors and operators.

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Sommaire

Introduction

Un essai aura lieu en mars 2007 dans le cadre du projet de démonstration technologique (PDT) de guerre sous-marine en réseau (GSMR) afin de démontrer l'efficacité d'un réseau de capteurs et de plates-formes pour la détection, la classification et la localisation de cibles sous-marines. Il faudra à cette fin définir des paramètres pour mesurer les gains en efficacité. Une occasion est offerte d'intégrer certains de ces paramètres au réseau pour mesurer les performances du système en temps réel. Il faudra aussi spécifier ces derniers et les présenter à l'observateur en mer avant d'achever la conception du système.

Résultats

Un examen de mesures de performances GASM standard normalisées a été fait afin de déterminer celles qui pourraient servir pour les paramètres du système, séparés ici en paramètres opérateur et paramètres observateur. La variabilité du milieu rend la tâche difficile. Un examen de paramètres RSR (renseignement, surveillance, reconnaissance) a également été fait en ce qui concerne la fusion de données de différents capteurs et plates-formes en une image commune de la situation opérationnelle. Un certain nombre de paramètres ont été définis pour l'opérateur et l'observateur en mer. D'autres paramètres ont aussi été définis pour les analyses postérieures à l'essai afin d'élargir l'échantillonnage statistique pour l'ensemble de la période d'essai.

Portée

L'utilisation de paramètres de mesure en mer en temps réel offre une occasion unique de d'intégrer des paramètres directement dans le système d'essai. Ceux-ci pourraient être ultérieurement intégrés à des outils de décision opérateur et d'observation pour le suivi et la modification d'essais en temps réel.

Recherches futures

Les paramètres proposés ici sont fournis à titre de guides seulement et seront révisés au besoin. Des difficultés pourront se poser en particulier quant à l'entrée des données de terrain nécessaires pour les paramètres observateur. Après intégration au système et à la fin de l'essai, ces paramètres devraient être analysés afin de déterminer les plus utiles et ceux qui devraient être révisés selon les résultats de l'essai. Avant de concevoir le système, il faudra sélectionner les paramètres à intégrer en discutant avec les observateurs scientifiques, les entrepreneurs responsables et les opérateurs.

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Acknowledgements

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1. Introduction

Networked Underwater Warfare (NUW) offers the potential for a significant enhancement in the manner that detection, classification, localization and tracking of acoustic contacts may be undertaken using a diverse range of underwater sensors and platforms. The underlying principle is that information would be shared between units using a system connecting the platforms by an Internet Protocol or IP network. The sharing of information at this level would provide for a Common Operating Picture (COP) across the platforms. Currently an NUW Technology Demonstration Project (TDP) is being undertaken at Defence R&D Canada - Atlantic to demonstrate the ability of a number of networked platforms to detect and track an underwater target.

From an operational point of view, the use of a networked system can offer significant advantages. Besides the ability to transmit different types of data as outlined in [1], there is the potential to capitalize on different platform positions, sensor characteristics and availability to enhance the synergistic effectiveness of the complete system. This may yield significantly higher probabilities for detection, classification and localization than would be possible by a single platform or stand-alone systems used in a Task Group.

Capturing the effectiveness of system is challenging given the underwater environment. Despite the advances in sonar performance prediction and environmental assessment, the variability in the environment, clutter and false contacts continue to make direct measurement of performance a difficult task. While the metrics presented in this report can be implemented for post-exercise analysis, the goal is to utilize the various measures of performance incorporated into the NUW system and provide near real-time measurements. These may be also developed into decision aids for the operator.

The NUW TDP will demonstrate a system that shares information and generates a COP. As shown in Figure 1, the principal platforms in the TDP will include a Maritime Patrol Aircraft (MPA) equipped with sonobouys and a surface ship, the Canadian Forces Auxiliary Vessel (CFAV) QUEST, fitted with a towed array; a supporting VICTORIA class submarine, HMCS CORNER BROOK; and a KINGSTON class ship. The submarine will only have periodic availability to the networked system but can enhance the overall underwater picture by a measurable amount through the inclusion of contact information as well as increase the submarine's situation awareness by receiving the other nodes contacts. Further, the addition of the submarine in the COP may change the concept of operations for the submarine given that it will have access to a range of sensors through a network that would have been unavailable in a stand-alone system. A depiction of the network is shown in Figure 1.

There are a number of different types of information that could possibly be exchanged as described in [1]. These include a range of information types from environmental to sonar ping data to contact and track data and other tactical information. The data could exceed the bandwidth of the NUW proposed system, however, if the information is managed, there is sufficient bandwidth to pass the right information at the appropriate times. The availability of a larger range of data than that used in current systems is one of the key features of the proposed system. It also poses challenges as to the selection of the most appropriate data to transmit at the right time.

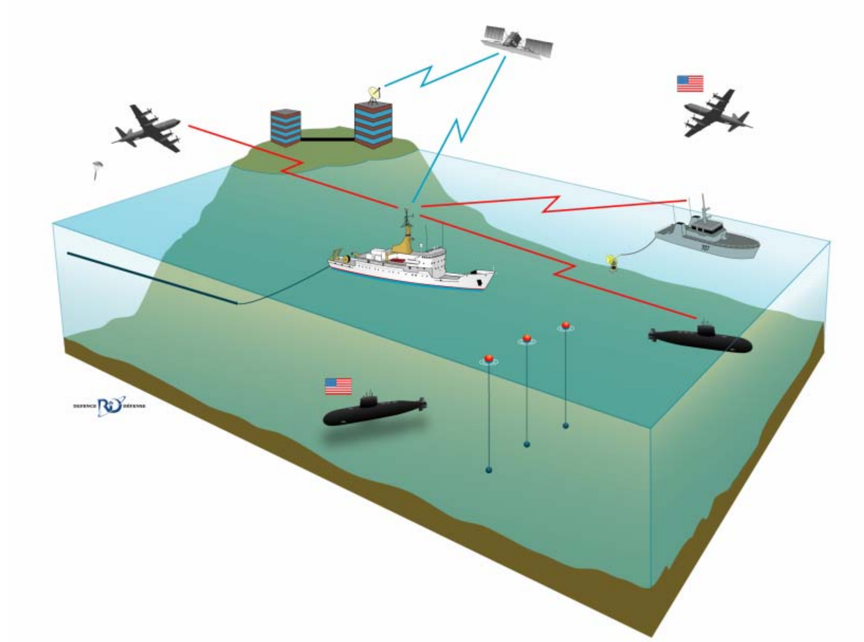

Figure 1. Networked Underwater Warfare Platform Nodes

Development of Measures of Performance (MOPs) and Measures of Effectiveness (MOEs) in the form of NUW metrics is required both to define the methodology for the trial evaluation as well as to provide the expected means for validation of the system. In addition, metrics may be incorporated into the system such that a real-time analysis capability can be built. The use of some of these metrics, particularly those that are ground-truth independent, may lead to the development of operator utilities. The current requirement is to develop metrics that can demonstrate the effectiveness of the NUW system.

1.1 Purpose

The purpose of the study is to examine different metrics for the analysis of the trial that will be conducted for the NUW TDP. The metrics are examined from a number of different perspectives; from a traditional Anti-Submarine Warfare (ASW) utility, from a data fusion and Intelligence Surveillance and Reconnaissance (ISR) perspective, and from operator and trial observer perspectives. Each of these poses challenges and opportunities. The purpose is to develop metrics for post-trial analysis as well as metrics that can be used in near real-time analysis by building these into the NUW system.

1.2 Outline

The report is structured as follows; section 2 describes some background on the NUW TDP trial and some of the issues for net-enabled maritime operations. Section 3 reviews traditional ASW MOP and MOE and highlights issues regarding their utility. Section 4 examines ISR metrics and their utility for evaluating data fusion in particular. Section 5 proposes a number of metrics for use in the NUW TDP. Section 6 provides a summary.

2. Networked Underwater Warfare Operational Issues

The use of a networked system for underwater warfare is expected to yield a gain in effectiveness over the use of a system of stand-alone sensors and platforms. There are a number of issues arising from the use of a network that concern this increase in effectiveness and the relationship between the nodes in the network. From an operational perspective these issues mean that the network performance may not be a simple sum of the performance of different sensors. The focus for the NUW TDP is to demonstrate the use, utility and benefits of a networked system by developing and testing a system to show the significant benefit from actual results. The challenge when using actual results from underwater sensor trials is that only in limited instances can a single trial provide statistical validation of performance.

2.1 Network Nodes

In Figure 2 some detail of the NUW trial network is shown with radio symbols to indicate the UHF SubNet Relay links between the antennas from each platform. The connectivity of these nodes depends on a number of engineering and physical factors. For example, the submarine will be part of the network when it comes to periscope depth or PD. The addition of the submarine as a blue force operative is unique as the information that can be passed to and obtained from the submarine is potentially high. The submarine as an ASW platform is obviously a predominant sensor platform. The use of the submarine as a node in the network presents a significant opportunity. Having the submarine as part of the network will allow the submarine to utilize the other nodes in the network to refine its own underwater picture. Equally, other platforms will be able to "see" what the submarine has for a surface picture if the submarine's contacts can be promulgated, which will give the ships a counter-detection range for their own vulnerability assessments.

Since the information for the submarine is only available as the submarine comes to periscope depth and is able to broadcast and review information, the manner in which the submarine behaves may be significantly altered. The employment of the submarine as a blue force asset may be tactically quite differently from the Concept of Operations (ConOps) where a submarine is given an area to patrol quite apart from the main Task Group.

The indiscretion rate and the submarine operation during the trial must be determined "a priori" because of the absence of communication while the submarine is submerged. Complicating the use of the submarine as a blue force asset is the requirement for the submarine to remain covert. This in turn impacts the ability of the submarine to be part of the network. The indiscretion rate or the rate at which the submarine comes to periscope depth to obtain the networked COP will vary by the risk that that the submarine will tolerate. A greater indiscretion rate will increase the counter-detection risk for the submarine but will enhance the submarine's situational awareness and COP. For the trial, the indiscretion rate will be planned which will introduce some artificiality. Free-play trial runs will allow the submarine to choose how often it comes PD to join local ad-hoc tactical networks.

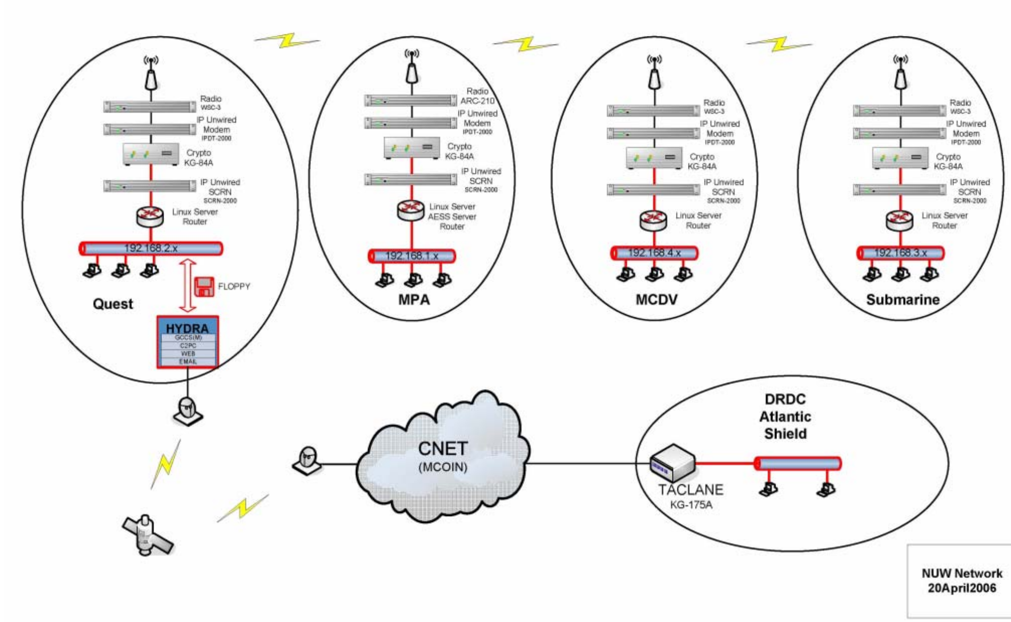

Figure 2. NUW Trial Network

As well as the submarine, a Maritime Patrol aircraft (MPA) will be processing a sonobouy field. As the life of the sonobouy field is limited in duration and the MPA has a limited Time on Station (TOS) and availability, the connectivity will be subject to these time limitations when on station. The link between the CFAV QUEST and the KINGSTON class ship should be nearly continuous communication between the ship platforms while they are in range.

A HALIFAX class ship is not available for the trial; both engineering limitations and availability exclude this platform from the trial. The QUEST is being used to illustrate the potential use of the system. Currently the only ship participating in the trial with a towed array is the QUEST. The array will be able to handle both passive and active data. In addition to the QUEST, there will be a KINGSTON class ship towing an acoustic source. The MPA is also equipped to handle, as part of a multi-static sonar project, a multi static return from the active source. The active source generated by the KINGSTON class ship will be processed from both the QUEST and the MPA.

The reach back cell that is shown in Figure 2 at DRDC Atlantic may be set up instead at the Canadian Forces Maritime Warfare Centre (CFMWC) if resources allow. The current proposal is to use the CFMWC synthetic battle lab as an experimental joint Maritime Operations Centre (MOC). The use of a reach back cell offers the opportunity to monitor the sensor contacts from the system in near real-time. The reach back cell could additionally have more processing capability than is available on any individual platform; thus it may provide more input to the network. The NUW Force Commander will operate at the joint MOC with support staff from each of the platform shore commands. The inclusion of a reach back cell will be through the Maritime Command Operational Information Network (MCOIN) that will provide information available to MCOIN users. In addition to command and control, a reach back cell will be tested at the Meteorological and Oceanographic Centre (METOC). METOC will provide environmental and acoustic assessments from their facilities.

2.2 Networked Effectiveness

The main purpose of the networked system is to allow greater information sharing and the hypothesis is that the increasing information sharing will allow a higher degree of effectiveness in the system for detecting and tracking acoustic contacts. While this is the expected result, in practice there may be a number of reasons why this could be difficult to demonstrate, even if perfect connectivity between the different nodes of the system can be maintained.

In the system currently in use aboard a HALIFAX class ship, namely LINK 11, each ship is connected to a linked display that allows ships to promote contacts and the tactical picture on a common display that can be viewed by other ships and aircraft having the same linked system. For sonar contacts, this means that the sonar operators first detect the sonar contacts and these are reported to the operations room for processing. The operations room then puts these on the link system. By entering the data on the system, ships in a Task Group are able to “see” each other’s contact information.

Because of this gap each ship does not have direct access to each other’s contact information and sonar operators. Nevertheless, given the time available for processing of acoustic contacts, the time lag associated with putting contacts onto the link is negligible in comparison to the actual process of prosecuting the contact. In general the actual feature information for the contact is not available for processing by another platform. However there is some increase in operator awareness due to the sharing of the link system information.

Network Quality of Service (QOS) refers to the ability of the network to transmit information and process it. Networked effectiveness is slightly different; it refers to the ability of the system to increase the overall effectiveness of the task group or network of platforms to detect, classify, and localize acoustic contacts. There is one scenario where these are co-incident; during a torpedo attack. The ability of a ship to detect and evade a torpedo attack is not wholly dependent on organic assets and an alert by other members of a Task Group can be significant in the probability of success of evading a torpedo. In this case, the efficiency of a networked system has direct bearing on the effectiveness of the network. In practice, ships use the more rapid method of torpedo alert by calling a torpedo attack as an urgent radio call. While this has proven effective in alerting ships to the possibility of a torpedo attack, it does not provide a great deal of information as to the bearing or location of the torpedo and the estimated torpedo heading and track. A networked system would be better able to exploit this information more explicitly as part of integrated torpedo detection and warning systems.

The effectiveness of the networked system can be measured using a number of MOEs indicating the overall effectiveness in terms of the track quality, or other data fusion MOPs, and by the probability of detection, classification, and localization. But the underwater environment hampers the analysis of these probabilities. The variability in the underwater environment means that it is difficult to pinpoint what acoustic variables are significant and thus what conditions affected sonar performance during a particular time segment in a trial. Despite these challenges, there are various MOPs and MOEs that can be used to indicate the sensor performance and system effectiveness and these are examined in the following sections.

3. ASW MOP and MOE

3.1 Passive Sonar (Towed Arrays)

Analysis of sonar effectiveness has been carried out by OR in support of CFMWC for Towed Proficiency Training (TPT) exercises [2] and during Maritime Command Training (MARCOT) exercises [3]. The analyses were conducted to measure sonar performance using ASW MOPs that had been developed over the course of some years between 1993 and 1997. The results from some of these trials and a description of the ASW MOPs were reported in [4].

As mentioned in section 2, the variability of the environment makes it difficult to forecast sonar performance deterministically. MOPs often require revision and refinement. However, standardized MOPs provide for some continuity between different trials.

Some of the early MOPs that have been used are as follows:

- Contact validity and accuracy;
- Average contact times;
- Average detection range and comparisons with predicted ranges; and
- Time history plots of the target from the sensor.

The latter can be plotted with other types of information or events that occur. Later MOPs that were standardized were separated into categories that included detection, classification, tracking, localization, engagement and vulnerability. For detection these included:

- Initial detection ranges and distribution parameters;
- Initial detection bearing and range errors and distribution;
- Percentage of contacts as a function of range;
- Probability of detection as a function of range (P_d); and
- Cumulative probability of detection as a function of range (CP_d).

In some cases these were compared to the predicted range Figure of Merit (FOM) for a particular sonar, which in turn, required accurate water temperature profiling and ambient noise measurements. The commander at sea is provided with a minimum, maximum and average or mean contact range. For the P_d calculations, the signal excess must be solved at each time interval for a particular sensor.

For classification, the probability of correct classifications and the false alert rates are obtained from the classification matrix of the number of occurrences of a classification given as either Poss-sub or Non-sub when the target is either present or absent. The time and the distribution from detection to classification can also be determined from logs and reports. The range at classification is also an observable MOP.

For tracking, the plots of Time in Contact (TIC) versus target range give an overview of the time that the track was maintained. The MOPs are the TIC versus sonar operational time, TIC versus sonar tracking opportunity, and tracking errors. Tracking opportunity requires that a calculation be made of the opportunity to detect (and track) the target.

The definition for localization is given as when attack criteria are met, and MOPs are the probability of successful localization given a valid contact, the time from classification to localization, probability of localization as a function of range, and cumulative probability of localization as a function range.

Engagement MOPs are not considered in this report, but are part of the overall ASW engagement. Similarly, vulnerability issues refer to the ability of the platform to evade a torpedo threat and are also not referred to here. It should be noted that these and the previous ASW MOPs just described were used for towed array analysis and may not be fully applicable to other types of sensors.

As an example of a commonly used ASW MOP, Figure 3 shows the TIC by range of a ship versus a submarine. The example shows that the contact was gained at a relatively short range of around 3 (units) and lost after a certain period of time when the target began closing. It regained contact as the target opened and lost it once again as the target began closing. The point is that the gain/loss of contact is not, for this particular example, a direct function of the range to target. In this example the gain or loss of a contact may be more directly associated with the aspect to the target, such that once the target changes bearing and aspect, the contact is gained or lost.

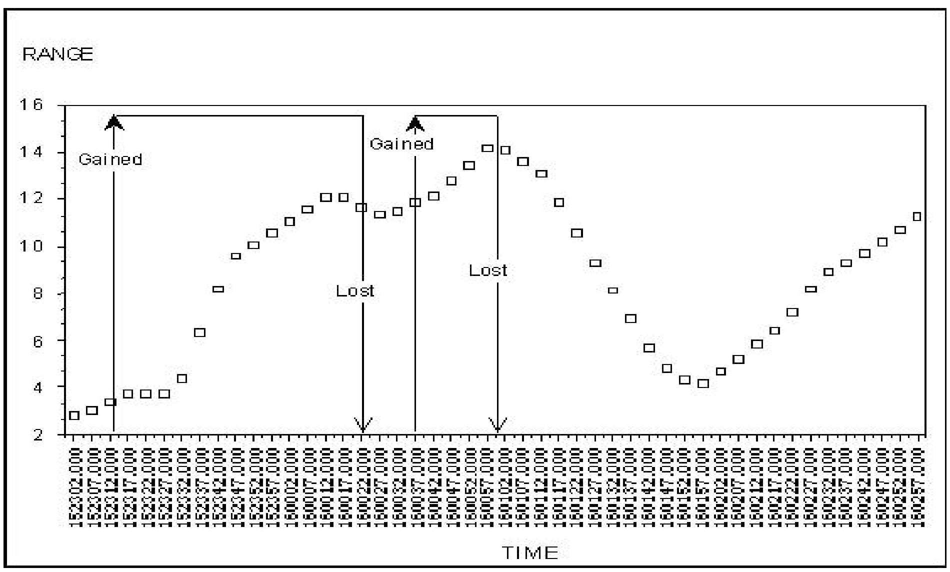

Figure 3. Example Time in Contact of a Ship versus a Submarine

3.2 Active Sonar

Active sonar and multi-static sonar have alternative but similar MOPs. Results of a Low Frequency Active (LFA) sonar trial were reported in [5]. One of the distinctions that must be made is in the type of contacts, whether they are valid or invalid as compared to all of the reported contacts. A contact was considered if it was in a sector defined in +/- 45-degree arcs from the submarine, although the rationale for this definition is somewhat vague. For typical sonar systems a +/-10 degree error is tolerated for a valid contact but with LFA this was extended to +/-20 degrees. An error of 10 kiloyards for range was used for a valid contact.

An average contact range, an average actual range to the target and an average calculated offset distance between the actual range and the contact range provide some measures of the range and error in contacts. These determined the average range and bearing errors. Valid in-contact times were also used for TIC. The TIC out of the sonar operation periods or availability gave an approximate percentage for TIC.

3.3 Different Sonar Types

In addition to low frequency active sonar and passive towed arrays, there are additional types of sonar that have been considered. These include sonobouys, passive and DIFAR, hull mounted active sonar, and submarine passive (towed and passive flank arrays) and active sonar. Each of these has different characteristics for which the particular MOPs for a specific trial or exercise have been designed. For the NUW TDP trials, other MOPs that are sensor specific are not covered. Generic MOPs that refer to active or passive sonar as described previously are sufficient to describe the ASW performance of the sensors from a diverse range of platforms and sensors. However as trial plans are formulated, other specific MOPs could arise and the opportunity to revise, add, or modify MOPs is possible.

As the previous section describes, some definitions are required for measures that are based on contact validity. As the sensors themselves may have different tolerances or operational standards, the definitions may be restricted to a single sensor and require that different definitions be used for different sensors. This leads naturally to the issue of what is valid information when trying to compile the COP as one sensor's contact may be declared invalid while another contact by the same criteria is considered valid. The simplest way to avoid this issue is to set one criteria for all sensors. However, this goes against the previous argument that the criteria for a valid contact will differ by sensor. The resolution of this issue may not be trivial.

4. Data Fusion Metrics and Utility

Data fusion encompasses a broad field; likewise, metrics for data fusion are also profuse. This section will review some of the metrics as given in [6] for Intelligence, Surveillance and Reconnaissance (ISR). The objective is to determine which of these would be applicable for the NUW TDP.

ISR metrics are grouped into five different categories; Measures of Sensor Performance (Sensor MOPs), Measures of Fusion Performance (Fusion MOPs), Measures of Recognized Picture Quality, Measures of ISR Effectiveness (ISR MOEs), and finally Measures of Force Effectiveness (MOFEs). These metrics have a hierarchy of value to the commander, for which sensor MOPs are arguably the least and MOFEs have the most utility for decisions. As a note, instead of using the terms measures of performance and measures of effectiveness as in the previous section, the following refers interchangeably to the use of metrics as a basic terminology for measures.

4.1 Sensor Performance Metrics

The lower level metrics pertain to sensor performance. These are listed as follows:

- Range;
- Coverage;
- Persistence;
- Revisit Time;
- Reporting Timeliness;
- Tasking Timeliness;
- Report Accuracy;
- Number of reports;
- Report Frequency;
- Uniqueness;
- Availability;
- Reliability;
- Vulnerability;
- False alarm rate; and
- Resolution.

Each of these has a definition, utility and challenge for implementation. Some of these overlap the definitions from the section on ASW MOPs. *Range* is a basic parameter that is better defined in terms of sensor parameters reflecting the environment. *Coverage* pertains to an area (or volume) in which the sensor can "make reports". ISR characterizes sensors by their ability to report, as this is a key aspect of the contribution that a sensor makes in a surveillance system. *Persistence* refers to the amount of time during which a sensor can continuously maintain coverage. *Revisit time* is the frequency that a sensor observes a given location. These metrics can all be applied to a single senor.

The next metric, *reporting timeliness*, is defined by the distribution of time intervals between the initiation of a contact report and the receipt of the report at some specific node in the system. This would be the first metric that would pertain to a networked system of information nodes. Similarly *tasking timeliness* refers to the distribution of time intervals between a request for a sensor report and the receipt of a report from a specific node in the system. These metrics are useful in determining the contribution that each sensor makes in maintaining a current picture.

Report accuracy is captured in a number of ways in ASW MOPs by bearing and range accuracy. The *number of reports* and the *report frequency* are measured over a given time period and again refer to reports from a sensor (platform) into the surveillance system. *Uniqueness* refers to the percentage of valid contacts reported by the sensor.

Availability is defined as the ratio of time the sensor is available to the amount of time the data is required. *Reliability* refers to the mean time between failures. *Vulnerability* refers to the probability of losing the sensor from enemy action.

The *false alarm rate* is given by the number of false reports calculated over a period of time. *Resolution* refers to the size of the object that can be resolved on an image. In terms of applicability, the latter is not part of the acoustic environment and can be re-defined by the level of sound that can be perceived at a particular range. This sensor performance measure is better referred to as a figure of merit for the sonar system. However resolution in sonar terms is a system characteristic referring to the bearing accuracy for a sonar beam and also to bearing resolution, or the ability to tell which side of a sonar array that the contact is placed relative to the array.

These fusion metrics are not all easily applicable to the NUW TDP. Range has previously been listed as one of the parameters for sensor performance. The average contact range and the distribution for a particular sensor better describes the sonar performance. By itself the range of one sensor may not be the critical or significant parameter in a networked system, as the number and distribution of the sensors impacts the ability of the system as a whole to track targets.

Coverage is a convenient way of looking at surveillance capability but coverage in the acoustic sense refers back to range and the problems associated with this definition. Thus coverage may not be a requirement for a fusion metric. The area that the sensor can cover is better related to the environment and the predicted range of the sensor. This goes back to the requirement for a predicted sensor performance and that requires accurate knowledge of the parameters in the sonar equations.

Persistence can possibly be used if the sensor opportunities can be quantified. Revisit time for an individual sensor may not be as applicable in the sonar case as the sensor is either in contact or not and a repeating sensor “sweep” is not typical of sonar operations. However this may be more applicable in the case of sonobouy fields that are ‘visited’ by the MPA.

Reporting and tasking timeliness need to be assimilated into the NUW TDP as these do refer to a networked system though the form of the measures may be quite different. In particular, reports can be assumed to be contact reports and these can be promulgated through the system. Similarly, the accuracy, number and frequency of the reports are possible measures of the network capabilities.

Uniqueness is not a measure of sensor fusion but of single sensor performance. This may define the utility of the individual sensors in the network. Among the remaining measures, the false alarm rate has the most applicability to the acoustic sensor networking system. Specifically, it should be noted how long a false contact is promulgated through the system before it is determined to be an invalid contact.

4.2 Fusion Metrics

There are a number of fusion metrics related to the ability of the system to fuse data from different sensors into individual contact tracks. As there may be more than one contact or at least the possibility of false contacts, these metrics are mostly applicable to the NUW TDP. For this reason, they are described in more detail.

4.2.1 Track Purity

Track purity refers the percentage of information items that are used to build a track that actually originate from the track. As different sensors provide data that are merged into a single track, different targets may be assumed to be one target when they are in fact more than one. Note that this is not the same as the number of data items that refer to the actual target versus data items that refer to other false targets or clutter. However in the acoustic case this may be more frequent than the problem of two actual contacts being merged unless the contacts being considered are surface contacts. For the NUW TDP, only sub-surface contacts are being considered, though surface targets of opportunity will occur and may add some complexity to formation of the COP.

4.2.2 Association Performance

This refers to the percentage of information items that are fused to the right tracks. In other words, if the contacts received are associated with the wrong tracks, then their capability to produce the right tracks is reduced. As in the previous case, track association is one area where surface contacts may be a more difficult case. For subsurface contacts, track association would be more a question of the capability of the sensors to provide information leading to building a track among, for example, a high clutter environment for the active sonar case.

4.2.3 Track Accuracy

Track accuracy is defined by the attributes that are used for the track, which could be quantities as defined by the differences in course, speed, and position at each time stamp of the track compared to the target ground truth. Other attributes for classification are given in [6] as the percentage of time that these are correctly identified. For the acoustic case, track accuracy can also be distinguished by the area of probability (AOP) in which the time that the target is within the area of defined probability versus the time that it is outside the AOP is given as a percentage. Further in the acoustic case, the classification is reported as in the ASW MOPs as the number of correct classifications versus invalid ones rather than by time. For the NUW TDP, the consideration of using different sensors form different platforms means that one generic definition will be required for track attributes. For the current case, it is recommended that a kinematic comparison using the error in track versus actual position be used and this be based on a fixed time interval.

4.2.4 Track Stability

Track stability is derived from the previous measure as the variance in track accuracy over the lifetime of the track. The definition of the lifetime of a track is not clear as the track can be dropped; a new contact could be the same target and consequently the same track. However the track may be defined as the period in which the contact is held even intermittently over a period of time.

4.2.5 Track Continuity

Continuing the previous statement, track continuity refers to the inverse of the number of discrete segments of a track for a particular target. This provides some measure of the ability of the system to minimize track segmentation; a continuous track would have a value of one, while two segments would have a value of 0.5 and so forth. A better measure at least for the acoustic case may be to examine the time the contact was held over each track segment.

4.2.6 Mean Track Life

This is defined as the average lifetime for the tracks. It is noted in [6] that this value would be better compared to the true track lifetime. The true track lifetime is determined by the notion that the contact is within sensor range. Acoustic contacts are harder to quantify in this manner but some measure of the track life can be used based on the Time in Contact (TIC) form the ASW MOPs. These could be averaged to produce a mean track life.

4.2.7 Number of Sources

The number of independent sources used to build a track is a measure of robustness rather than redundancy. The robustness of a track is assumed to increase with the number of sources. In the acoustic environment this may not always be the case as the different sources may provide different contacts and a measure of confusion may result. However in general a larger number of sonar sensors should enable a better COP and the correct fusion of the contacts is both the advantage and the challenge facing networked underwater sensors.

4.2.8 Fusion Timeliness

This is defined as the average time taken between the receipt of an information item and the completed fusion into the recognized maritime picture. This indicates how much latency there is in the fusion system. In the case of the NUW TDP, a comparison of fusion timeliness from the networked system to a stand-alone manual reporting system would provide an indication of the increase in performance of the networked system.

4.2.9 Capacity

The number of information items that can be handled by the system defines the capacity over a period of time. The capacity of the system may be limited by bandwidth, or by the number of reports that can be managed and is a quantity more related to the network performance as a specification rather than an indication of fusion performance, but it can also provide an indication of the limits are for fusion performance in terms of bottlenecks.

4.2.10 Fusion Opportunities Taken

Fusion opportunities are those that make use of information items that are available to add to the fused picture. The percentage of the information items used compared to the total number of information items on the system provides an indication of how well the system used information. As most of the items used in the NUW TDP will refer to contact reports, the measure of which contact reports are used compared to the total number may provide a system fusion performance measure, as long as some distinguishing characteristics can be used to determine when an information item is used and when it is not part of the fusion process.

4.3 Recognized Maritime Picture (RMP) Metrics

There are a number of metrics associated with the quality of the RMP. These include completeness, correctness, currency, clarity, consistency, prediction performance and extent of information. Completeness refers to the proportion of targets detected versus the number of targets within the networked sensor range. As in the previous discussions, the difficulty will be in assessing what the individual sensor range or coverage will be for a given area and time. For the current scenario, the trial may have only one sub-surface contact that is either detected or not. In this case, a metric for completeness that determines how much ground truth is represented in the recognized maritime picture may not be very useful.

Correctness refers to the proportion of targets in the RMP that have correct target attributes. Again, if there is only one subsurface target, this measure may be of limited utility. Currency is the age of a track defined as the time elapsed between the last track update and a cut-off time at which the data is deemed to be too old to be useful. A cut-off time could be defined by the time for a target to evade outside of an area for localization for a given target speed, for example.

Clarity can be defined as the ratio of actual contacts versus the total number of contacts in the RMP. This may be useful for measurement of the amount of clutter in the RMP and as well as a measurement of the difficulty of finding the actual contact or track. Tracking algorithms may be used to filter the clutter and this measurement may indicate how useful the tracking algorithm is in a high clutter environment.

Consistency refers to the ratio of the number of targets in the picture of an individual platform to the number of targets compiled by a coordinator. This measures the difference between each platform and overall to provide the quality of the tactical picture. This may not have as much merit in the NUW TDP as the contacts are communicated in near-real time and each platform should have a networked picture- however in some cases this might not be the case at all times (especially in the case of the submarine). It may also prove to be an interesting metric of the difference between the networked user and the stand-alone user.

Prediction performance is an average radial distance between a projected track at a given time and the actual track. For the sub-surface intermittent contact, for given projected lead times, the actual track versus the projected track can provide a measure of the ability of the sensors' tracking algorithms. This measures the performance of each tracking algorithm used on-board as well as the performance of the overall tracking ability of the network.

Extent of information is a measure of the average number of known attributes associated with each track over a period of time. It is used to indicate the depth of knowledge in the RMP. It may be useful to discriminate between normal target attributes of speed course and position with extra information such as classification and identity of the target. In terms of the NUW TDP, this metric could be associated more with the types of information being transmitted from each sensor. The types of information are discussed in depth in [1].

4.4 ISR and Force Effectiveness Metrics

In reference [6] from which this summary is derived, the statement is made that an ISR system can perform very well according to the previous generalized system metrics while not being effective. Reference [6] also offers a guideline to establishing ISR Metrics, including the requirement to define actions associated with ISR tasks, including the types of information of interest, defining the spatial extent of an area, the temporal extent of interest, and any other additional constraints such as tracking is required to be covert.

Typically, a maritime vignette is required to determine the force effectiveness. The command decisions that are necessary to conduct the vignette would be examined to determine the effectiveness of the ISR system to support the decision-making process. For the NUW TDP, the process is basically one of search and detection, followed by localization and classification of the target. Although prosecution and post execution of the target is examined in terms of the information requirements, these elements would not be part of the NUW TDP unless some element of this phase could be included in the demonstration. For example, in order for the MPA to prosecute, the target must be localized to within a firing criteria; the number of times that this is achieved could be one ASW metric. However, for the NUW TDP, an actual military exercise is not envisioned at this time and hence the effectiveness of the system in an ASW scenario is not evaluated.

As an indirect method, once the trial has been conducted and some measure of the performances of the individual systems have been derived, it may be of substantial benefit to conduct some simulation and modelling of the networked system inside of hypothetical ASW scenarios in order to indirectly measure the probably outcome of having a networked system. This type of analysis as well as analysis of the network using queuing theory can be conducted once some statistics on the networked elements has been collected.

5. NUW TDP Metrics

For the NUW project, metrics from the previous sections are selected for two different groups, the operators and the observers. From the operator perspective the metrics that will be useful relate to whether a target is found and what metrics that can be made available to the operator that *do not rely on ground truth of the target*. For the observers, the ground truth will be known or estimated from the trial plan and periodically updated with actual ground truth data, hence metrics available to the observers can incorporate ground-truth. The availability of ground truth is one of the underlying factors in deciding which metrics may be used.

5.1 Operator Metrics

The following are metrics from the ASW MOP section that do not use ground truth of the target. These could be made available to operators that are using passive sonar.

- Average contact time;
- Actual Time in Contact; and
- Time from Classification to (apparent) localization (apparent based on whether the contact is later determined to be valid or invalid).

If the FOM or predicted range of the sensor is available to the operator, these can be used for a comparison to be made between the predicted range and the contact range once a track is established using a Target Motion Analysis (TMA) algorithm.

For operators using active sonar, both range and bearing are available and an additional metric is;

- Average contact range.

Further network metrics are unavailable to the operator as they involve more than one platform whereas the operator is limited to own-ship data. The aim of having an at-sea real-time metric is to provide a built-in measure that can be used to compare the stand-alone system to the networked system. For that purpose, the effectiveness of the individual sensor systems are not the primary focus of the networked metrics.

Because range data is not always available and is specific to the individual sensor, this parameter is excluded in the development of an at-sea real-time metric. However, coverage is a significant operational parameter. The contact time can be used as a measure in the form of a temporal coverage metric. The performance of the metric is related to an accumulated time in contact where each additional time increment in contact can be transformed into a scale.

The scale is a function of the average expected threat speed and radius from a datum in which localization is deemed to become difficult on an expanding circle as shown in Figure 4. That radius is arbitrary and hence the calculation of the time governing the loss of contact is also arbitrary. Operational requirements may specify what tactics could be employed given the time lateness of a particular datum.

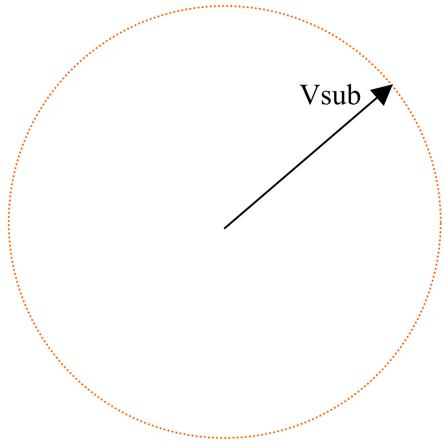

Figure 4. Expanding Range Circle for a given Lag time.

For example assume an underwater target is estimated to be operating at a maximum of 5 knots. For a 30-minute time window, the radius would be 2.5 nautical miles from the datum point of the last known contact position (or bearing for passive sensors). If a 30-minute time period is assumed as a time period for normalization then a scale can be constructed for the event. The colour scale could be an indicator to provide a visual operator aid (where blue represents a "cool" or no contact and red presupposes a "hot" contact.

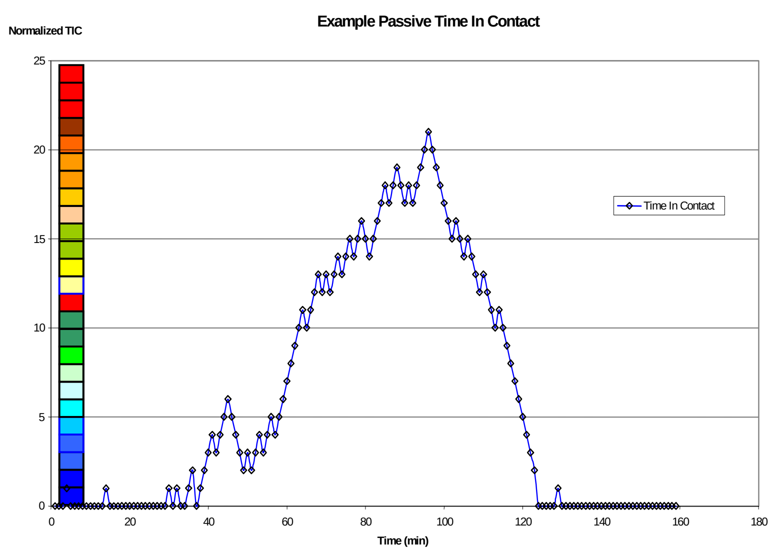

Figure 5. Normalized Time In Contact

5.2 Observer Metrics

In addition to the individual operators, there will be trial observers that will require additional metrics for observation in near –real time analysis of the conduct of the trial. For these it is assumed that ground truth is readily available. It should be noted however that for ground truth to be accurately obtained either an underwater tracking range should be used or some other similar means of tracking the target is required. This may not be the case during the trial. The targets ground truth is then subject to errors or differences between the actual target track and the track prescribed for a given period during the trial.

Assuming that ground truth is available in some form, then range or more accurately position of the target becomes a useful factor in devising metrics. As the submarine will periodically report its position, it should be possible to determine how close the submarine is to the planned track. A measure of errors between the planned track and actual position of the submarine would provide an indication of how well the submarine can follow a given course. It would also indicate how significant this factor impacts on trial plans.

The following represents a number of metrics that could be used during the trial by observers.

5.2.1 Contact Validity

Contact Validity- for this metric a definition of the valid versus non-valid contacts has to be used. For passive contacts this means using a bearing error to discern if the contact is within the feasible error of the system being considered. For a towed array the bearing error varies with beam and these must be considered when establishing the error criteria. Contact validity can be used in post-trial analysis for determination of the number and percentage of false contacts. As well, during the trial a running total of the number of false contacts can be used as an indication of sensor/platform performance. This requires either a manual or automatic processing of the errors associated with each contact and a database of the false contact ratios for each sensor.

5.2.2 Detection Range

For a given contact whether active or passive, the use of ground truth establishes if the contact is valid; if the contact is valid then the range of the detection is used to establish the operational performance characteristics of the particular sensor. The range from initial detection until the contact is lost provides the detection range. These can be plotted by incident for the sensor.

5.2.3 Time History Plot

Given both the detection range and the temporal coverage of when the sensor is in contact, Figure 6 shows how a running plot of the event can be produced that shows where the target is relative to the sensor and the time in contact. As the submarine closes with the sensor, the incidence of when the sensor is in contact increases. The plot was generated using signal excess and a detection threshold in which variability is applied to the detection threshold to simulate the variance in the system.

5.2.4 Probability of Detection and Cumulative Probability of Detection

Given the range to the target, the distribution of the range versus the number of samples (for example in minutes), the probability of detection of the target as a function of range and the cumulative probability of detection as a function or range can be plotted as shown in Figure 7. There is a question of whether each time in contact is used as a detection possibility or as a distribution of contacts, but the methodology is the same.

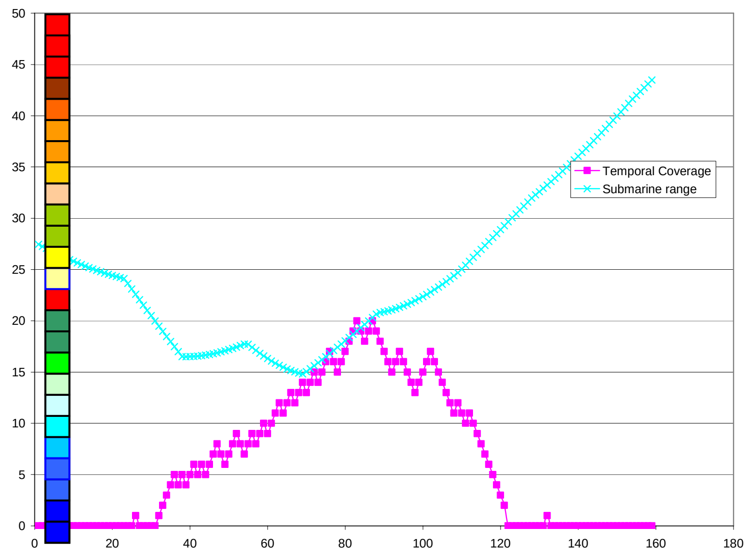

Figure 6. Plot of an Example Submarine and Temporal Coverage Metric

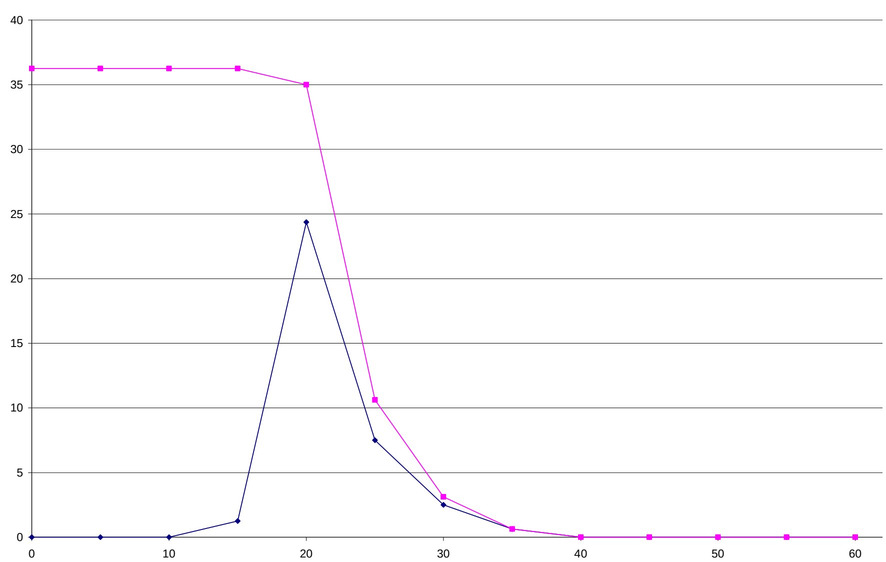

Figure 7. Probability of Detection as a function of Range

It should be noted that these distributions are changing with time and are not stationary. In that case the probabilities are really only valid at the end of the trial segment. However they can be portrayed periodically as shown in Figure 8 for the probability of detection and in Figure 9 as the cumulative probability of detection. These could be calculated as a running series with time as they accumulate over the trial segment.

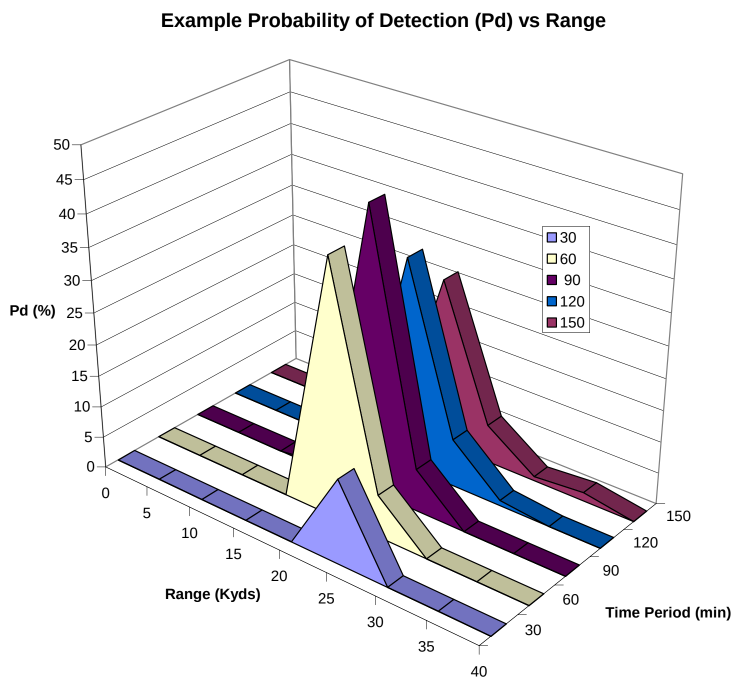

Figure 8. Example Probability of Detection over Increasing Time Periods

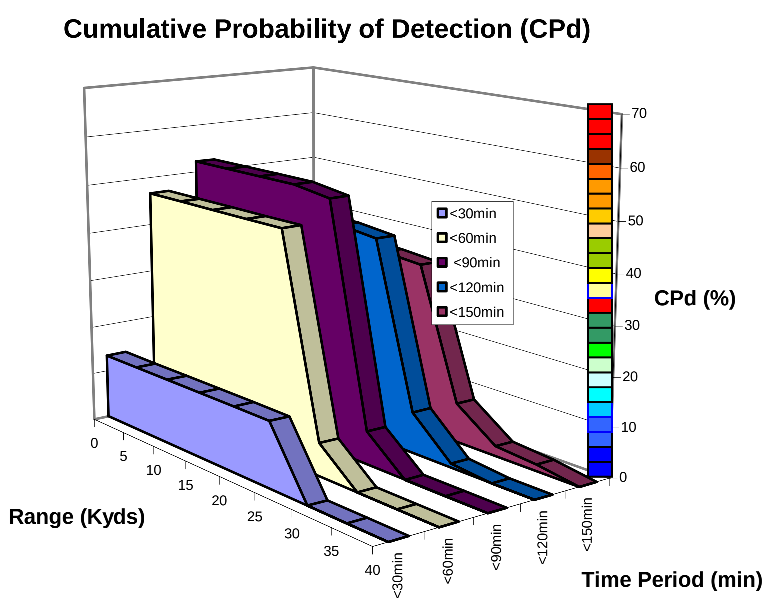

Figure 9. Example Cumulative Probability of Detection over Increasing Time Periods

5.2.5 Graduated Time History Plot of P_d

To use these metrics in *real-time* on board the ship by the observers, a method of portraying the Pd for observer use during at-sea analysis using a similar graduated scale as used for the normalized cumulative time in contact can be used for the cumulative probability of detection. In this case the probability of detection as accumulated over a given time period can be portrayed in a bar graduated colour scale. This is represented in Figure 9.

5.2.6 Coverage; Target Range Circles

Once the sensor metrics are determined then the analysis of the network can commence. In the guide for ISR Metrics in [6] the sensor performance is limited to the coverage and range of a sensor. Coverage is not pre-determined for the case of sonar and is further subject to the target parameters. In the simulation used for the previous passive sonar data, the range circles represented by each target as shown in Figure 10 are the ranges that the target is vulnerable to detection by the receiver, rather than a detection range of the sensor for a generic target. This difference means that a range circle cannot describe each sensor, but each target can.

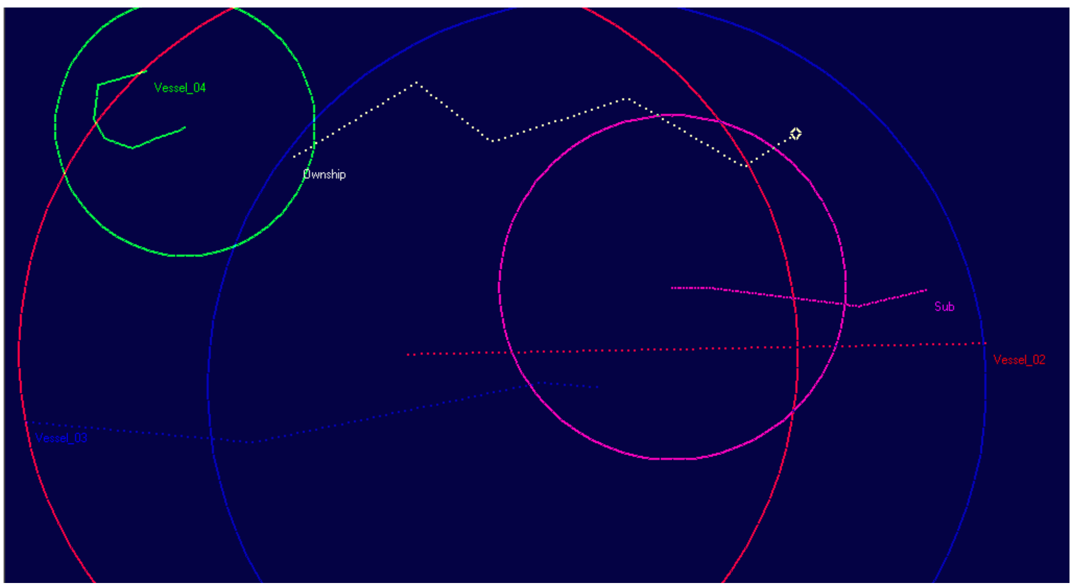

Figure 10. Target Range Circles for a Single Passive Sensor

For the observer, the ability to know *a priori* the location of the target as well as the sensors means that given some description of the environment, an overlay of range circles on each target can be portrayed. The situation becomes more complex when there are a number of sensors and multiple targets. For the time being, only one target is assumed as shown in Figure 11. In that case from one sensor a range circle can be either put on the target or the sensor. As there are multiple sensors, each sensor (for one given target) can have the sensor range for that specific target placed on the sensor. Coverage can then be indicated by the range circles as an area coverage or “cookie cutter”.

Once coverage has been determined, pertaining to both individual sensors and the network as a whole, the idea of persistence can be measured as a temporal rather than a spatial measurement of the ability of each sensor and the network of sensors to hold contact. The time that a sensor can continuously maintain contact once detection is made is subject to some variability and the measurement becomes stochastic. These can be compared between sensors and between stand-alone systems and the network.

5.2.7 Revisit Time

The revisit time is only applicable to sensors that can leave the area of operation and return. This may be the case if a platform cannot remain on station for the entire duration of the operation. This is the case particularly for aircraft but not usually applicable for ships or submarines. In that case, the revisit time is calculated for the aircraft and is assumed to be 100 percent for the other types that remain on station. While on station the spatial coverage of the sensor may cover the same area over numerous occasions. If the area of operation is divided into sub-areas, the number of times that an area is revisited by one sensor, and by the network of sensors can be calculated and displayed as a grid. These can be calculated for each period of the operation, as for example a four hour time period during the trial. If the re-visit time is nil for a time period that may be too short to allow a platform to go over an area again then the accumulated number of occasion over a number of time periods could be used as an indication of the ability of the platforms to look at one area.

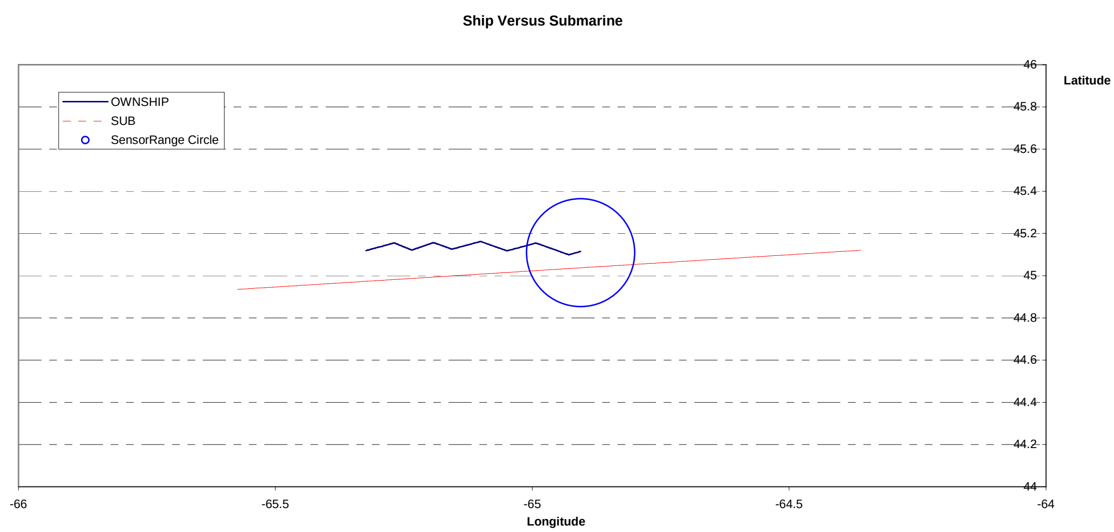

Figure 11. Sensor Range Circles for a Single Target

5.2.8 Reporting Timeliness

In terms of the network, the reporting timeliness can be measured by the distribution of time intervals between initiation of a contact report by and individual sensor and the receipt of the information at another node. The measurement requires the time stamp of the sensor sending the report and the time stamp of the node/sensor receiving the report. A statistical distribution of these reports at each node can lead to an understanding of the time delays associated with the network at each node. These could also be applied to further division by the type of information transmitted between nodes.

If requests are sent through the network for a sensor report from one node to another, these could be considered as tasking and the timeliness of receiving the tasking and sending the required information (along with the time taken to send the information) can be used for a measure of the tasking timeliness. For the metrics associated with persistence, revisit time, tasking timeliness and reporting timeliness, the use of these during the trial in a real-time sense would require the analysis of a running database. Under normal circumstances these would be analyzed for a given time period and summed up over the period of the entire trial. These are calculated in post-trial analysis. The challenge here is to modify these so as to be useful during the trial. However this may not be possible unless the data can be automatically updated while the trial is ongoing.

5.3 Post-Trial Analysis Metrics

The requirement for trial metrics for the NUW TDP also includes those metrics that can be applied during the post-trial analysis phase. There are numerous metrics that could be applied at sea during the trial that could also be used after the trial is conducted. These relate in particular to those metrics that require operator reports, or post action style reports that are only obtainable once the trial is concluded. Other metrics are used subsequent to the trial so as to increase the number of samples from different trial periods and provide an overview of the trial.

The following table looks at the different sensor performance metrics and provides short notes on whether they can be applied during the trial, for post-trial analysis, or possibly both. It should be noted that with all these metrics, actual use would be determined once the system is built and further, actual trial experience will show how well different metrics can be implemented. As such, the following list is tentative and subject to revision but provides a guide to consider metrics for the trial.

With regard to fusion metrics, while it is possible to implement some of the metrics pertaining to the time of reported contacts, number of reports and the timeliness of the contact, these may be better suited for post trial analysis. However, one of the metrics that could be implement concerns the number of report per sensor. These would reflect the number of contacts from each sensor/platform, and the total number as available to the network. The percentage of correct contacts reflects the performance of each sensor and of the network as a whole. Other metrics such as track accuracy can also be implemented for the observer. More importantly would be to look at the accuracy of individual contacts based on the errors in bearing and range, versus the error in the estimated position for the fused network.

These metrics can also be implemented and examined for their utility in post-trial analysis. The problem with implementing the fusion metrics for at-sea analysis stems from the time duration of each segment. During the post-trial analysis, an accurate picture of how the trial progressed and the accuracy of each of the systems compared to the network can be determined. During the trial, the period available for analysis will be limited to either a trial segment or limited to the duration of the trial up to the point in real time. These may not make much sense until the trial (or trial segment) is completed. Further, the number of reports during any particular trial segment may be very low, and the results will be misleading. One of the goals from the analysis of the entire trial will be to obtain enough samples to provide realistic statistics.

Table 1. NUW TDP At-Sea and Post-Trial Sensor Metrics

Metric	At-Sea Analysis		Post-Trial Analysis
	Operator Metrics (per sensor)	Observer Metrics (for each sensor/platform and for Network per Trial Segment	For Entire Trial Duration
1. Contact Validity	No contact info available to operator	Requires ground truth – needs validity definitions	Yes- can be re-assessed to determine if definitions were valid/invalid
2. Time in Contact	Yes- can use normalized or actual TIC	Yes- can be implemented for each system and for whole network	Yes – can be implemented for each trial segment but also for entire trial.
3. Detection Range	No- needs ground truth	Yes- if ground truth available- for each trial segment	Yes- an average detection range for entire trial
4. Probability of Detection as a function of Lateral Range	No ground truth	Post- trial segment – Can use a running metric as a possible metric for at-sea analysis	Post trial
5. Cumulative PD	No ground truth	Post- trial segment – Can use a running metric as a possible metric for at-sea analysis	Post trial
6. Initial detection range & Distribution	No- No Ground Truth- but can plot reported ranges	Yes- if ground truth is available. Distribution limited to time segments	Yes – distribution covers entire trial
7. Time History Plots	Yes- TIC with normalized metric	Yes- TIC plots for each sensor in network and for entire network	Useful for full trial, can be plotted for each trial segment and compared to other parameters.
8. Percentage of Contacts with range	No- unless using only contact reports	Yes- with Ground truth	Yes- for whole trial
9. Cumulative Pd with Range	No	Yes- per trial segment	Yes- for entire trial
10. Average Contact range	Yes- for active sonar contacts- reported range only	Yes- actual range	Yes- for entire trial
11. Coverage	Yes- Temporal given by TIC; Spatial given reported Ranges	Yes- temporal and spatial for trial segment per sensor and network	Yes- for entire trial
12. Contact validity	Yes- for reporting false contacts	Yes- for reporting actual contacts	Yes- total from trial
13. Percentage of False Contacts	No	Yes	Yes

6. Summary and Conclusions

Metrics associated with analysis of underwater detection and classification of contacts is presented detailing their use with respect to the NUW TDP. One of the goals in the development of metrics for the trial is to provide at-sea metrics that can be used while the trial is underway. These represent an opportunity to build the metrics into the system for automatic data collection and analysis as well as provide instantaneous feedback to the operators and trial observers on the performance of the trial.

The division of the metrics into operator use and observer stem from the limited information available to the operator. The operator will not have access to trial plans showing target ground truth. The observers on the other hand should at a minimum have the ground truth available. How the ground truth can be entered into the system to be used for metrics requiring ground truth in the calculation may be a challenge. The submarine will have intermittent reports on position to update their actual track versus their planned track and it may be that little difference will exist between the planned submarine track and the actual track.

Besides the at-sea metrics, the trial will be analyzed in post-trial analysis to determine how well the trial objectives were met overall. Observer metrics using the ground truth are calculated for each trial segment, but probably will be reset for each trial segment. Therefore the observer will have only written records of the trial performance while at sea. Post trial analysis includes statistics of the probability of detection for each sensor and platform versus the network. The overall goal of the trial is to demonstrate the effectiveness of a networked group of underwater sensors. The post-trial analysis should reflect this aspect.

One of the problems associated with any acoustic trial is due to the variability of the acoustic environment. It is important to be able to obtain enough samples for initial detections, for example, to be able to draw some statistically relevant conclusions with regard to the overall performance of the system. Given the variability of the environment, the effectiveness of the system may not be wholly apparent even after a successful trial, given that the environment changes by geographic and seasonal variations. By having a sufficient number of metrics, different perspectives on the performance of the system can be obtained which hopefully will enable the evaluation of the networked effectives of the TDP.

Finally, it should be noted that the metrics described in this report are only a guide that will require revision. Metrics may not be fully applicable, and as just stated, a paucity of data may make some metrics quite useless. Other issues, such as the implementation of the metrics into the system for at-sea analysis, particularly in the capturing of the ground truth target data, may also require that metrics be revised accordingly. Only during post-trial analysis will the complete use of the metrics for the trial be determined, and the lessons learned should be captured for future use as networked systems will continue to be tested given their potential for enhancing the detection, classification and localization of underwater and surface contacts.

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The Networked Underwater Warfare (NUW) Technology Demonstration Project (TDP) requires the development of metrics for the evaluation of the NUW TDP Trial to be held in March of 2007. An opportunity exists to implement some of these metrics into the network so as to provide at-sea real-time analysis of system performance while the trial is underway. A review of ASW Measures of Performance is provided with a description of typical metrics associated with ASW from a detection, classification and localization perspective. An additional review of metrics associated with Intelligence, Surveillance and Reconnaissance is given with particular emphasis on fusion performance. From these, metrics for the NUW TDP are developed for at-sea analyses that are separated into operator and observer metrics. In addition, other metrics that can be used for post-trial analysis are provided.

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Net-Centric Warfare
ASW Measures of Performance
Metrics
Networked Underwater Warfare