Virtual Battle Experiments to Investigate Coalition Data Sharing

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Abstract

There is a supposition in net-centric warfare that the effectiveness of a coalition will increase with the amount of shared data. This supposition presumes that the shared data contributes positively to the situational awareness and effectiveness of the recipient platform. In the limiting cases, the resource cost to the recipient platform may exceed the potential value of the contributed information. In the ideal situation, shared data at appropriate levels of refinement improves the effectiveness of the entire command team.

A series of Virtual Battle Experiments (VBEs) has been initiated with which to investigate the influence of sharing broadband passive sonar data and how this influence changes with the level at which the data is shared. The experiments use different operators in multiple sessions to make statistically relevant measurements. In the baseline experiment, VBE CA-1, the shared data was provided in a purely visual format. Operator effectiveness was evaluated by analyzing the speed and accuracy with which sonar track segments were manually associated. Also of interest in this experiment was the decision rationale that was used by the operators to associate or disassociate track segments. This paper summarizes the results of this trial and outlines our plans for extending these experiments.

1. **Introduction**

1.1 ***Coalition Data Sharing***

There is a supposition in net-centric warfare that the effectiveness of a coalition will increase with the amount of shared data [1]. This supposition presumes that the shared data contributes positively to the situational awareness and effectiveness of the recipient platform. Logically, however, the marginal utility of additional data diminishes since the most valuable data would typically be chosen to be exchanged first. Further, there is a cost to processing the received data that typically increases with the decreasing information content of the additional received data. There is, therefore, little benefit to exchanging low-level data if the data does not contribute to an improvement in situational awareness or if the recipient platform lacks the capability to further process the data. There may be significant benefit, however, if the recipient platform is able to jointly process the received data with organic data to produce a more accurate or complete operational picture. The issue then becomes a trade-off between the cost of exchanging and processing the data and the relative improvement in the operational picture.

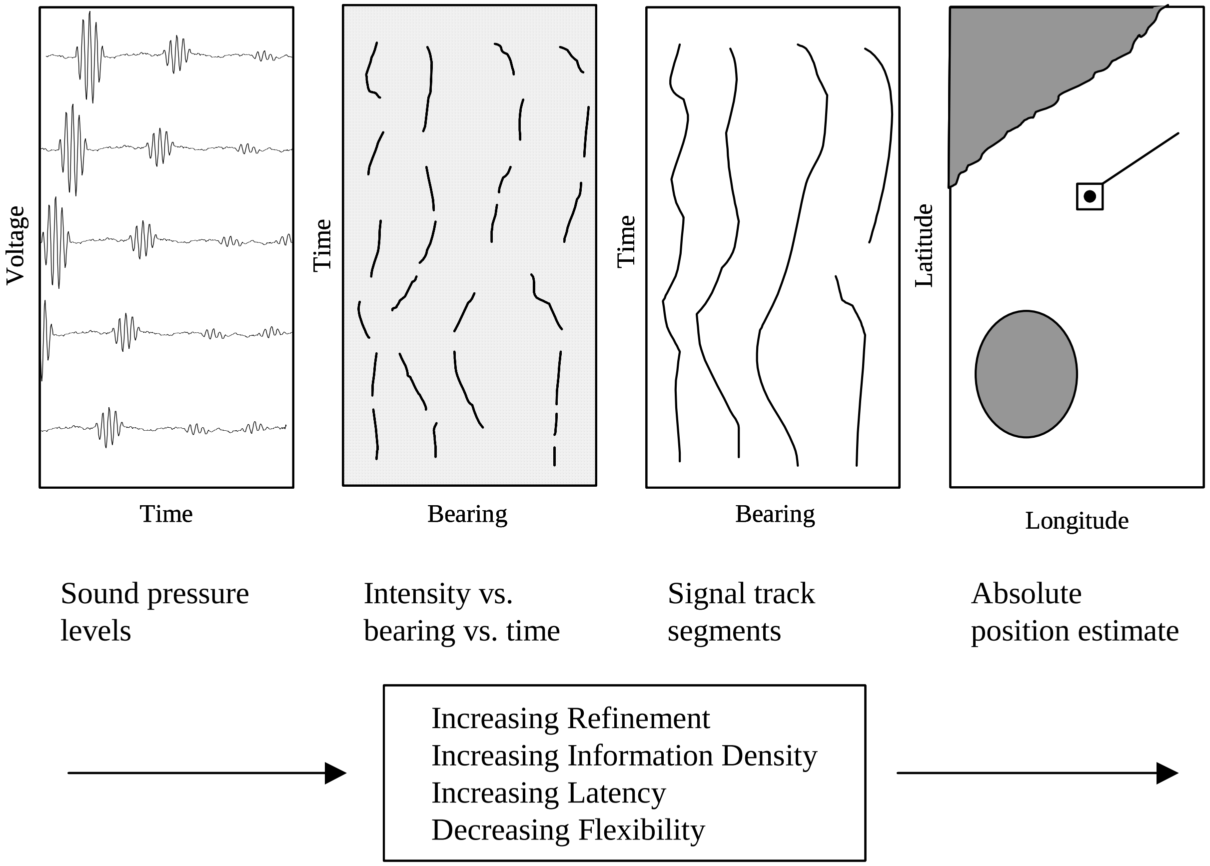

Figure 1. The sonar data refinement process requires some trade-offs. The information density of the target data increases as the data is processed while information that is not considered to be relevant or useful in subsequent stages is discarded.

In order to investigate the potential benefits of coalition data exchange it is useful to examine the results of a number of scenarios in which data at differing levels of processing are shared, and evaluate the relative value of the shared data. By focussing on relative comparisons between specific scenarios, statistically meaningful measurements can be made that predict the potential value of additional shared data in similar circumstances. The goal of this investigation is to provide some criteria by which to evaluate a suitable balance.

1.2 ***Sonar Data Development***

Passive sonar can be used in the underwater environment to covertly detect and track vessels by their own acoustic emissions [2]. As shown in Figure 1, there are several steps in the process of refining passive sonar data from a towed array receiver into estimates of target position, course and speed [3]. Data is initially available from the array as a time series of acoustic pressures from each hydrophone in the array. Onboard the towing vessel, the measured pressures are processed into time series of received power versus bearing, which are then presented to a sonar operator. To an operator observing a time-bearing display, the acoustic emissions of a target vessel will appear as an intensity peak changing slowly, if at all, in bearing over time. The series of intensity peaks can be assembled into a track by a signal following algorithm and future values predicted, assuming that there are no rapid changes in the operation of the target vessel. Should a signal follower be unable to maintain lock on a track, the track is terminated and a new track segment initiated when the series of intensity peaks reappears.

Although the passive sonar system does not provide target range, course or speed information directly, the sonar operator can estimate this information by using tools such as Target Motion Analysis (TMA) to analyse the target's track history. The accuracy of TMA is improved by the increased duration of the available target track. In order to increase the duration of available track history, the sonar operator may associate multiple sonar track segments that are believed to have originated from the same target into a longer, fused track. This task, however, can be especially challenging given the complexities of acoustic propagation in the underwater environment. In each of the above stages of data refinement, the information density of the target data increases as the data is processed. Information that is not considered to be relevant or useful to subsequent stages is discarded. This results in reduced opportunities to pursue alternate tactical picture development paths.

Data sharing can occur at any stage in the sonar processing sequence described above. However, the TMA results are the most concise and, to a recipient lacking tools, staffing or expertise or for whom urgency is not an issue, probably the most useful. But suppose that the recipient had some additional resources and an interest in pursuing an alternate development path, possibly involving triangulation or cross-correlation of data between platforms? Would it not be worthwhile to exchange sonar data at a level at which the additional processing would still be feasible? The answer would depend on the availability of sufficient communication bandwidth and processing capability to deal with the data and the value of the expected result. In order to investigate the value of coalition sonar track sharing, it is useful to consider the influence of shared sonar track data, and how the value of that shared data changes with the level of refinement of that data and the tools and training available to the sonar operator.

1.3 *Virtual Battle Experiments*

Under its mandate to investigate common areas of research regarding maritime command, control and information management, Maritime Systems Group Technical Panel 1 of The Technical Cooperation Panel (TTCP MAR TP-1) has been conducting Virtual Battle Experiments (VBEs) using a simulated maritime environment to investigate the benefits of Network Enabled Capability (NEC) [4]. The simulations have been constructed by assembling Virtual Maritime Systems Architecture[1] (VMSA) based federates into a High Level Architecture (HLA) compliant federation [5]. Each federate provides component or subsystem capabilities of varying scope, allowing the simulations to be tailored to the needs of the experiment.

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[1] VMSA was developed by the Australian Defence Science and Technology Organization. The architecture and many simulation components, called federates, were made available to DRDC Atlantic through a Memorandum of Understanding between Canada and Australia, Subsidiary Arrangement 18.

VMSA-based simulations are time managed, allowing them to be well controlled and repeatable. By taking advantage of this feature, the results of multiple independent runs of an experiment using different human operators can be analyzed to compile statistically relevant answers to the experimental objective. The distributed and synchronous nature of this architecture is also well suited to the logging and subsequent analysis of experimental data.

2. Coalition Sonar Track Sharing

The Coalition Sonar Track Sharing (CoaSTS) program is a series of controlled, repeatable, human-in-the-loop experimentations to investigate the influence of shared sonar track data at various levels of development. The program uses a VMSA-based maritime simulation in which a sonar operator is tasked to use organic, and in some cases nonorganic, broadband passive sonar tracks to monitor local vessel traffic. The quality of the local operating picture is determined by the degree to which the operator has successfully identified and associated the multiple, temporally distinct sonar track segments originating from each target vessel. Multiple independent sessions of each configuration are run using different operators and a limited number of traffic scenarios. Statistically relevant comparisons can then be made between the results of various configurations.

The program uses the experimental infrastructure shown in Figure 2 to address the following question:

What is the influence of shared sonar track data, and how does the value of that shared data change with the level of refinement of that data and the tools and training available to the sonar operator?

Measurements using the following 6 configurations are sufficient to make the most relevant comparisons.

1. **Basic organic**. The basic configuration of the passive sonar system contains only ownship track and chart displays. The organic passive sonar produces sonar track segments that appear on the track display. The operator is tasked to develop a local operating picture by fusing the track segments into longer, master tracks. The position of the operator's vessel, ownship, is shown on a chart display. (White portions of Figure 2)

2. **Basic organic and nonorganic**. Sonar data from a similarly equipped allied ship are also available on a separate display. The sonar operator can associate the organic or nonorganic sonar track segments into master tracks but cannot intermix, other than cognitively, the organic and nonorganic data. The positions of both ships are shown on the chart display. (White and green portions of Figure 2)

3. **Basic organic and nonorganic with triangulation**. The sonar operator has access to both organic and nonorganic sonar data and a triangulation tool with which to evaluate associations between the two. The operator continues to be responsible for developing the local operating picture by associating sonar track segments but now has a tool with

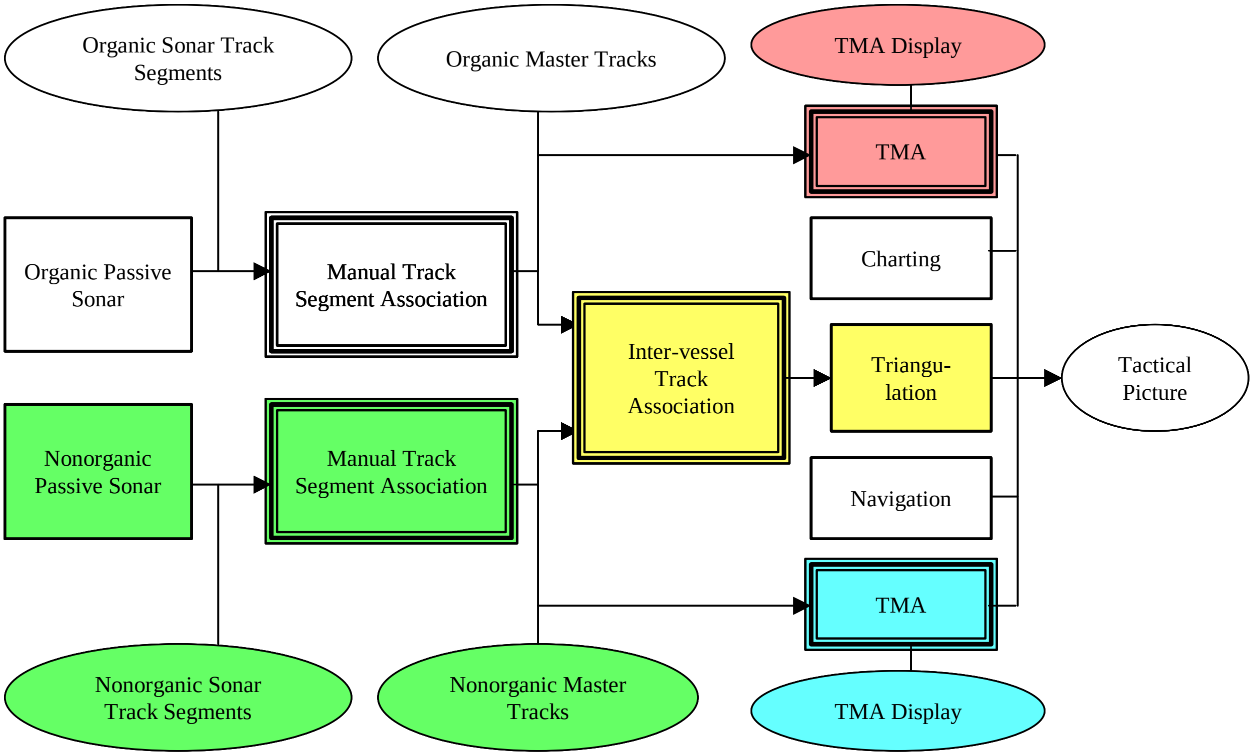


Figure 2. The CoaSTS experimentation infrastructure. The basic organic components are white. The basic nonorganic components are green, the triangulation components are yellow, the organic TMA components are pink, and the nonorganic TMA components are blue. Those components that have a highlighted border require operator interaction.

which to evaluate the relationship between organic and nonorganic tracks. (White, green and yellow portions of Figure 2)

4. **Basic organic and nonorganic with triangulation and organic TMA**. The sonar operator has a TMA tool with which to convert the bearings-only master tracks shown on the ownship track display into latitude-longitude target vessel position estimates on the chart display. The triangulation tool continues to be available, and the operator continues to be responsible for developing the local operating picture by associating sonar track segments. (White, green, yellow and pink portions of Figure 2)

5. **Basic organic and nonorganic with triangulation and dual TMA**. A triangulation tool and TMA tools are available for use with both organic and nonorganic sonar tracks. The operator continues to be responsible for developing the local operating picture by associating sonar track segments. (All of Figure 2)

6. **Basic organic and nonorganic with dual TMA**. TMA tools are available for use with both organic and nonorganic sonar tracks but the triangulation tool is not available. The

operator continues to be responsible for developing the local operating picture by associating sonar track segments. (White, green and blue portions of Figure 2)

Since configuration 2 is the first level at which nonorganic data is available, it represents the lowest level at which sonar data might be shared in this experimental program. Comparisons of configurations 1 and 2 provide a baseline for the following experiments by identifying the minimum configuration in which the sharing of sonar data could provide some level of benefit. The degree of benefit was determined by experiment, although the lack of tools beyond the operator's cognition is a severe constraint.

The operator can use the triangulation tool in scenario 3 to translate pairs of bearings-only tracks into estimates of target vessel position tracks on the display chart. This could be used to evaluate the likelihood that a pair of organic and nonorganic sonar tracks shares a common origin. Track segment association continues to be relevant since the duration of the shortest bearings-only track would determine the duration of the position tracks. Although gaps in a bearings-only track would produce gaps in the corresponding position track, apparent track continuity across both gaps would strongly suggest that the tracks share a common origin.

The availability of organic TMA in scenario 4 allows the operator to compare position information developed from an organic bearings-only track with that developed from triangulation of that track with a nonorganic bearings-only track. This provides a second venue for evaluating whether the pair of tracks shares a common origin. Track segment association continues to be relevant since the duration of the organic track has the potential to influence the TMA results. In scenario 5, this ability to compare TMA and triangulation solutions is extended as nonorganic TMA becomes available. In scenario 6, the triangulation tool is not available but, by making use of the dual TMA tools, the operator can continue to compare pairs of organic and nonorganic bearings-only tracks on the chart display.

In each of the above cases, the abilities of the sonar operator are varied through the incremental changes in the available processing tools. Meaningful comparisons can therefore be made between configurations to determine the relative influence of the tools on the effectiveness of the operator. Comparisons can also be made among multiple implementations of each tool.

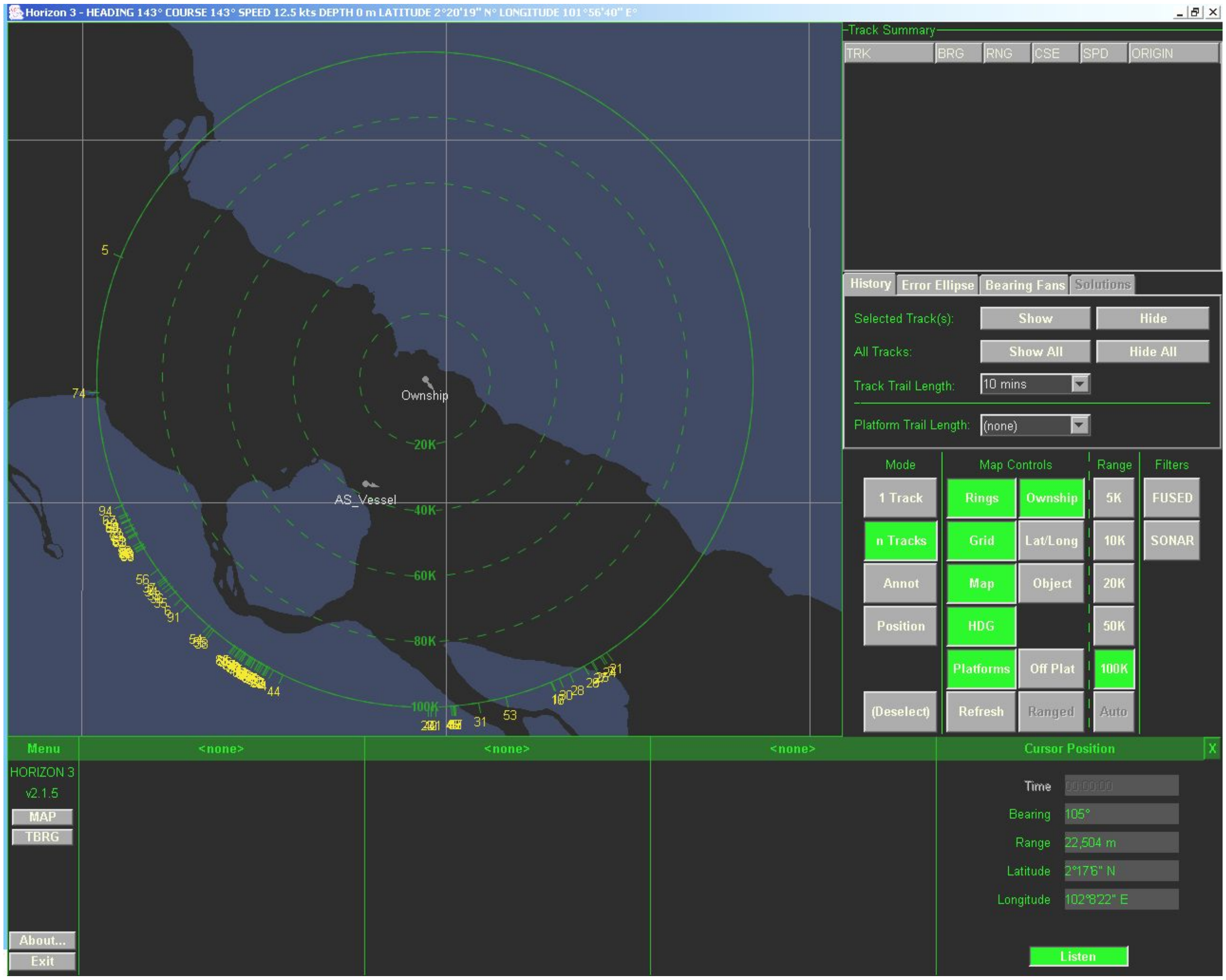
3. Virtual Battle Experiment CA-1

3.1 *Objectives*

VBE CA-1 was an implementation of the first two CoaSTS configurations and was intended to provide a baseline for future data sharing experiments. The experiment was also motivated by an interest in the types of algorithms used to associate passive sonar tracks [6,7,8]. The objectives of this experiment were a hypothesis test and a discovery exercise:

1. *Sonar track sharing between coalition partners is beneficial even when the data can only be shared as an independent display.*

2. *What is the rationale used by a sonar operator to make association and disassociation decisions?*



Horizon 3 - HEADING 143° COURSE 143° SPEED 12.5 kts DEPTH 0 m LATITUDE 2°20'19" N° LONGITUDE 101°56'40" E°

Track Trail Length: 10 mins

Platform Trail Length: (none)

Cursor Position

Time 00:00:00

Bearing 105°

Range 22,504 m

Latitude 2°17'6" N

Longitude 102°8'22" E

Figure 3. The Horizon chart display showed the navigable waters of the strait and the locations of the ownship and the allied ship.

The hypothesis test was to be addressed by comparing quantitative metrics describing the outcome of the two experimental configurations while the discovery exercise was to be addressed by cataloguing and summarizing operator responses.

3.2 *Design and Implementation*

In the baseline scenario the ownship was a frigate using a towed array sonar to monitor vessel traffic in a narrow strait. A similarly equipped allied ship patrolled the other side of the strait. The sonar operator was provided with a chart display, shown in Figure 3, showing the position of the ownship and the allied ship in the strait and a track display, shown in Figure 4, showing the sonar track segments produced by the ownship sonar. When shared data was available, sonar track segments from the allied ship were provided on a separate and independent display. The sonar tracks provided bearing information only and were broken up in time due to the effects of the local environment and interference between the acoustic emissions of the target vessels. The

Horizon 3 - HEADING 143° COURSE 143° SPEED 13.8 kts DEPTH 0 m LATITUDE 2°20'53" N° LONGITUDE 101°56'14" E°

Platform: Ownship

HORIZON 3 v2.1.5

Selected Tracks: CA_Sonar:38, CA_Sonar:2

Associate Using: Combine All Tracks

Annotation Text:

Age (seconds): 0

Associated Track: <none>

Bearing (min, max): 180.0 180.0

☐ Bearing Valid

☐ Periscope Image

Annotation: HLA: Sim started

Text: HLA: Sim started

Bearing: 0 0 ☐ Valid

Track: <none>

Time: 2:00:05 PM

Bearing: 022°

Range: 9,610 m

Latitude: 2°34'22" N

Longitude: 101°42'11" E

Figure 4. The Horizon time-bearing display showed sonar track segments produced by the ownship sonar.

acoustic signals were not scattered, reflected or refracted, so each vessel in the strait produced no more than one track at any time. Each sonar provided full coverage of the travelled portion of the strait. The task of the sonar operator was to develop as complete an operational picture as possible by associating the sonar track segments into longer, fused tracks.

The core of the experimentation infrastructure was the VMSA federation running the simulation. The federation was made up of a minimum number of federates, or software modules, each representing components of a shipboard system. Gameboard, an automated helm federate that executed script files produced by Scenario Generator [9], controlled the movement of the vessels in the strait. The helm commands were translated into position, course and speed by the motion federate while a sonar federate of our own design observed the positions and types of the vessels in the strait and produced sonar track segments for display to the sonar operator. The sonar federate also produced a log file recording relevant characteristics of the tracks that it produced. Five instances of Horizon, a track data hosting and management system, were used to construct

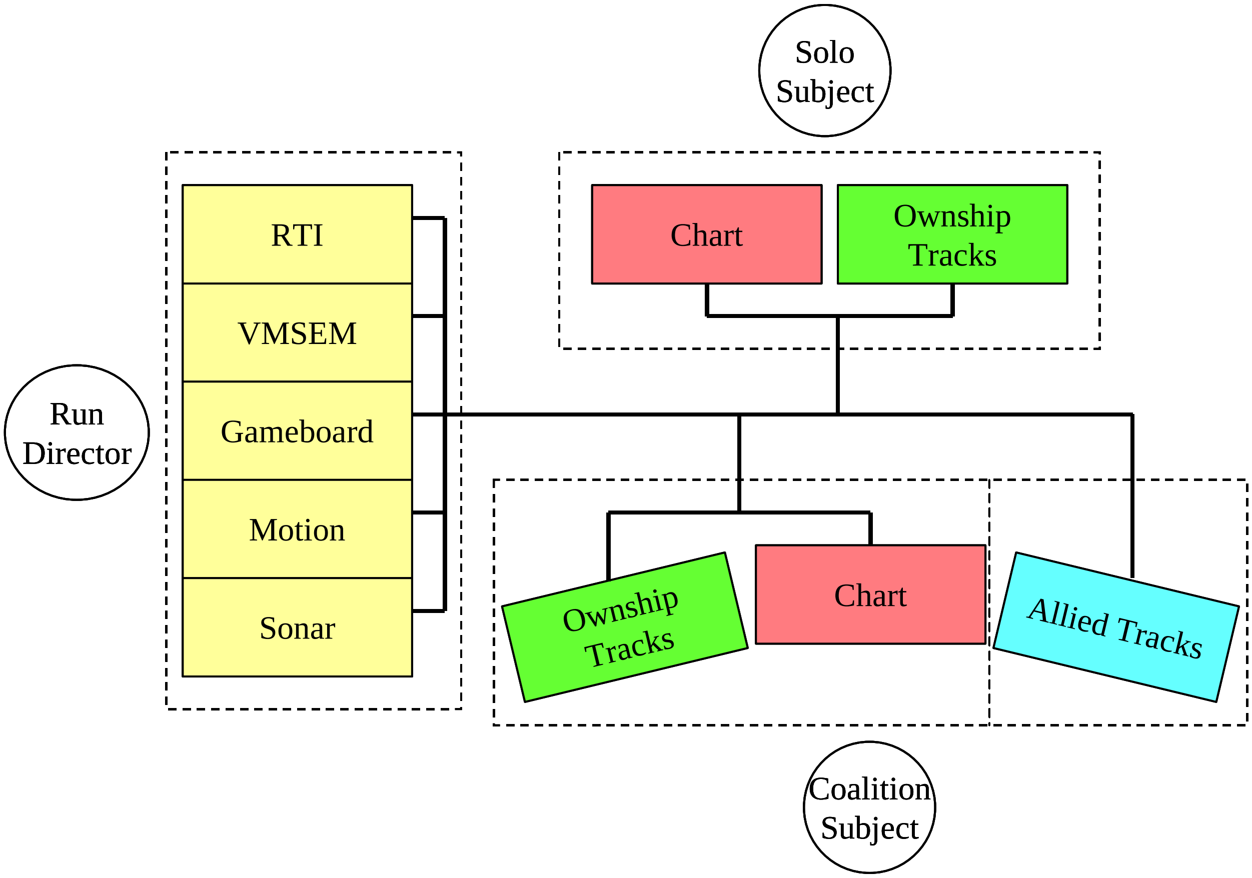
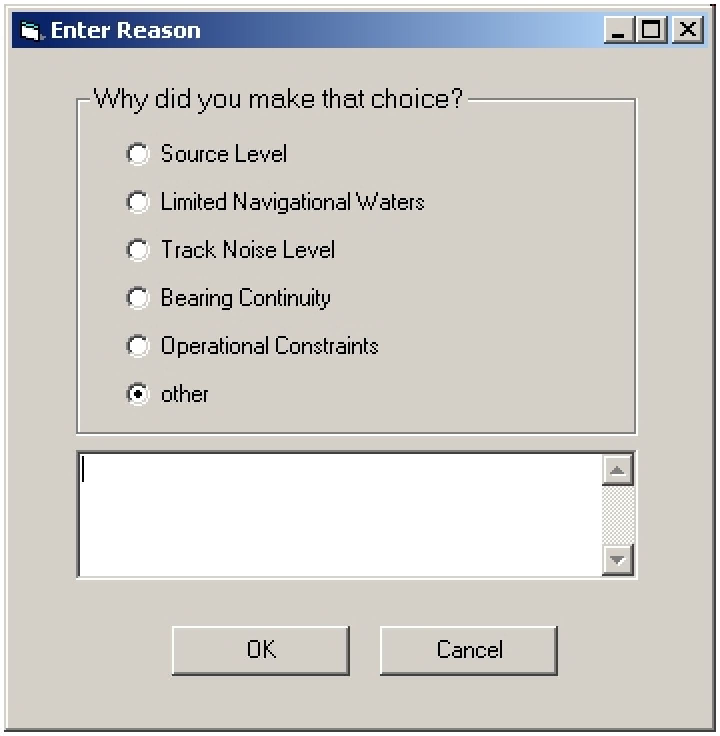


Figure 5. Physical layout and distribution of the experimentation infrastructure. Each dashed box represents a single computer. All subject displays are individual instances of Horizon.

two operator positions as shown in Figure 5, one with two displays for the solo case and another with three displays for the coalition case. This permitted two operators to interact with a given scenario simultaneously and independently. Horizon also produced its own text and binary log files.

The ownship heading was shown in the Horizon track display in Figure 4 as a series of filled grey circles. Sonar track segments were shown as a series of open yellow circles terminated by a question mark. The Active Fusion tool in the lower left corner could be used to associate one or more sonar track segments and/or fused tracks into a fused track by selecting the tracks to be associated and then clicking on the green checkmark. Tracks that had been fused would then be removed from the display and replaced by a series of lightning bolt symbols indicating the new fused track. The Active Fusion tool could also be used to disassociate a fused track back into its component track segments.

An ideal time to query an operator as to the rationale for making an association or disassociation was immediately after the decision had been made. This was done using a program called EnterReason to detect mouse clicks in a predefined region of the screen and then present a list of


Enter Reason

Why did you make that choice?

○ Source Level
○ Limited Navigational Waters
○ Track Noise Level
○ Bearing Continuity
○ Operational Constraints
● other

Figure 6. The EnterReason popup would appear whenever an association or disassociation was made.

possible reasons as a popup query on the screen. The list, shown in Figure 6, included an 'other' option which would open a text box to accept a freeform response. The time and nature of the decision and operator's response were logged to a file.

A set of quantitative metrics was used to make clear and unambiguous comparisons between the coalition case, which included shared sonar data from the allied ship, and the solo case, which did not include shared data. The metrics included Picture Clarity, Track Continuity, Association Continuity, Association Completeness, Association Correctness and Association Delay. In spite of multiple prior test runs, a misunderstanding with respect to the Horizon text logging meant that only a partial set of association information was available for analysis[2]. The full set of information was recorded in the Horizon binary log file; this data will be analyzed in the future. The only metrics suitable for use with the reduced data set were the Association Correctness, a ratio of the number of correct associations to the total number of associations, and the Association Delay, a measure of the time lag between an association decision and the latest initiation time of the component tracks.

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[2] The Horizon text log was a periodic system state log that recorded the status of all active tracks every 15 seconds. In testing, this was adequate for the complete recording of the operator's actions. In practice, decisions were made more rapidly than anticipated, and some associations were made involving only track segments that were no longer being actively updated. Event-based logging would have provided a better record in this case.

3.3 ***Execution***

Although much of the work of this experiment centred on the development of a maritime simulation, it is the interaction of the human subject with the simulation that is of primary interest. The simulation is a tool, a stand-in for the real world. The ideal candidates for these naval sonar experiments are, ideally, experienced naval sonar operators. A statistically relevant experiment, however, requires a significant number of operators and there are several challenges inherent in their recruitment. In order to limit the complexity of this experiment, it was decided to use technically competent in-house personnel in this experiment and, based on those results, recruit an appropriately sized pool of naval sonar operators for later experiments.

Eight volunteers participated in the experimentation sessions, each subject taking the positions of solo operator and coalition operator once and seeing a different scenario each time. A typical experimentation day included 45 minutes of training followed by a break, then a 2 hour experimentation session. A second 2 hour experimentation session was held after lunch, followed by a break. The day ended with a 45 minute exit interview, which provided an opportunity for the subjects to describe their previous experience with sonar and provide feedback on the experimentation sessions. The scenario used for training was never used in an experimentation session.

3.4 ***Analysis***

Automated analysis software was developed to use the metrics described above to produce performance summaries for each of the subjects and the experimental sessions. The analysis was done in several steps, each of which produced a log file for verification and potential later analysis. A summary of all of the sessions was also produced. The summary file was further analyzed to produce the overall results.

In the 16 experimentation sessions, each sonar produced an average of 157 track segments from the 9 observable vessels. The Horizon text log file did not record all of the track associations made by an operator, rather, it recorded only those that were later updated with new track data. 76% of the track associations could be recovered, but only 67% had sufficient information to be analyzable.

In both the solo and coalition cases, the mean Association Correctness for track segments originating from an individual vessel was 78% for solo tracks and 96% for joint tracks. Solo tracks are segments that originated from a single distinct target vessel, while joint tracks represent multiple vessels that were indistinguishably close in bearing. The higher score in the joint track case is not surprising since each of the associated sets needed only a single common target to be correct and each joint track identified several targets. The mean Association Correctness scores in the coalition case were 4% and 5% better than in the solo case, for the solo track and joint track cases respectively.

The association-weighted mean Association Delay was 804 seconds in the coalition case and 908 in the solo case, with respective standard deviations of 54.3 and 60.9 seconds for the means and 963 and 1192 seconds for single observations. Although the mean association delay was 11%

lower in the coalition case, the level of significance was only 90% [10]. If the full set of fusions had been available, the level of significance would rise to 93%, which is still not sufficient for a conclusive result. Based on these statistics, 6 additional subjects would have been needed to reach at least a 95% level of significance.

The popup query did not appear to be a very effective method of obtaining the decision rationale information that we were looking for, possibly because the operators saw the query as a multiple choice question in which at least one of the presented answers is correct, possibly because the freeform nature of the 'other' choice left the responses too open, or possibly because of the limited expertise of the operators. The most frequently cited option was 'Bearing Continuity'. The most insightful freeform responses were 'Bearing Rate', 'Track Continuity' and 'Chart Position'.

In the exit interviews, most subjects indicated low to medium-high satisfaction with their development of the local operating picture and appeared to be comfortable with, but not confident in, the results. The challenge of having to think in bearing-space instead of the more familiar 2-dimensional distance space was cited as a significant difficulty. The most frequent request was for a tool with which to triangulate pairs of organic and nonorganic bearings-only sonar tracks into positional tracks.

4. Concluding Remarks

Based on the particular scenarios considered in this experiment, the results of the quantitative analysis provided slight but not conclusive evidence of an improvement in operator performance due to the presence of shared data. The association decision rationales indicated by the operators were interesting, but not as insightful as had been hoped.

In the follow-on experiment it would be useful to provide the same level of passive sonar data in conjunction with a triangulation tool, so that the recipient could triangulate passive sonar tracks from both vessels to estimate the positional tracks of the target vessels. In this experiment each coalition vessel had full coverage of the travelled portion of the strait but from differing perspectives. In future experiments this might be reduced to variable degrees of partial coverage. The results of this experiment provide a baseline for these and other follow-on experiments.

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