# Impact of Systems and Information Quality on Mission Effectiveness

**Paul Labbé, P. Engineer**

Defence Scientist, IEEE Senior Member
Defence Research Establishment Valcartier/
Centre de recherches pour la défense, Valcartier
2459 Pie-XI Blvd. North
Val-Bélair (Québec), Canada G3J 1X5
Tel.: (418) 844-4000 X 4479 FAX: (418) 844-4538
paul.labbe@drev.dnd.ca

**René Proulx**

Senior System Analyst, Mathematician
Neuring Inc.
7 rue de Laval
Québec (Québec), Canada G1R 3T8
Tel./FAX: (418) 692-3878
rproulx@drev.dnd.ca
NEURING@usa.net

## Abstract

To resolve an outstanding issue in assessing the value to mission effectiveness of the insertion of information technology in command and control, the Defence Research Establishment Valcartier (DREV) has explored means and methods for linking information quality and system measures of performance (MOPs) to decision and mission measures of effectiveness (MOEs). The resulting model-based measures (MBMs) assess the capabilities of afloat-command information systems to support over-the-horizon targeting (OTH-T). Results obtained showed that the impact of system and information quality on mission success rate is non-linear but displays similar characteristic curves independent of the data set selected. Hypothesizing invariance to data for similar OTH-T parameters indicates the usefulness of such empirical curves in supporting a decision-maker. Applying this approach to large ensembles of data collected during live or man-in-the-loop simulation should allow a better understanding of invariant and variant aspects of OTH-T success rates and the choice of critical values for thresholds used to decide whether or not to engage a target at a given time and shooter location. Other results focus on the dependence of MBM metrics on model parameters such as weapon and contact uncertainty areas. These results should be useful in assessing the validity of MBM metrics for various engagements.

## 1. Introduction

Parameters such as entropy can be used to characterize computing information quantity, others such as expected-positional-error to reflect its quality or accuracy, throughput to measure systems performance, and level of success in achieving a particular operational objective to assess mission effectiveness. But the global optimization needed to ensure effective battle force operations requires that these parameters be computed in terms of value toward desired end results. Such optimization cannot be done from a local point of view unless an appropriate “looking glass” is used to transform local information into global metrics and as long as the end results are reliably reflected in information available locally.

The effect of communications, command, control and information system (C3IS) improvements or changes on military operations or on mission effectiveness can be evaluated through characterizations of system performance and of information quality known as MOPs. Such results, however, fall short of demonstrating the impact of C3IS improvements or changes on the actual capability to conduct successful operations or on mission effectiveness, defined here as

MOEs. Only by relating information quality and system MOPs to decision and mission MOEs in a causal manner can one establish the value of the static and dynamic information a commander uses to plan operations and to make decisions. This relationship fulfills an essential analysis requirement for comparing the effects of changes in wide-area picture (WAP) systems and procedures on mission effectiveness and can also contribute to cost-effective planning of both system development and military operations [1-6].

This paper presents a simplified version of this encompassing objective using a measure of mission effectiveness that can be approximated by assessing the outcomes of hypothetical target engagements. MBMs were developed to compute the value of information used by a commander when deciding to intercept a target at a given time (including the people, procedures, systems and sensors involved in the generation and sharing of this data). Consequently, these MBMs link information quality and systems MOPs to a MOE. Computation of the measures is performed in a simulation setting in which commanders use current information for OTH-T. Models were designed to account for errors in the reported information of track data, for weapon footprints and for contact uncertainty parameters. Different probability distributions, utility functions and decision models are used to compute the expected outcome of engagements, yielding two similar measures: pertinence-of-engagement (POE) and intended-target-opportunity (ITO).

Some geopolitical conflicts call for drastic changes in normal rules-of-engagement (ROEs). When engaging potential targets, it is crucially important to predict and evaluate the aggregate impact of an offensive action such as the launch of a missile. This impact may be estimated in various ways and from different points of view. It may include the cost and effort of conducting an offensive action, expected enemy damage as a result of such action, tactical consequences, geopolitical changes and many other factors. It is unlikely that a simple measure of impact could apply to all cases of interest, but any such measure should capture an essential component of the impact, by establishing some quantification of the outcomes of an offensive action.

In the context examined, the POE assesses the general outcome of launching a weapon at a target, an identified hostile contact in the decision-maker database. This measure relies on a utility function that considers the cost of firing weapons, hit probabilities of objects in the footprints of available weapons and the pertinence-reward value that combines allegiances of these objects (ships, in this case). The ITO assesses the outcome in a similar manner but it is more specific. Its target-reward-value, which combines allegiances of objects in weapons' footprints, gives lower weights to hostile ships other than the intended target. Thus, the ITO provides a more accurate estimate of the impact of a system in terms of mission effectiveness when certain targets have a determinant role in courses of action crucial to mission success.

This work is an extension of the study performed by an AUS-CAN-NZ-UK-US[1] working group for the Command and Control Board. It focuses on information management, defined here as a collection of effective processes needed to produce, store, retrieve and share information in any format, on any medium and via any means of exchange to support operations and missions. The study found that mission effectiveness is increased by such architectural changes as modifying broadcast procedures at the track coordinator, basing transmission priority on the value of track information to the mission and on the fusion of local to global information.

[1] Australia, Canada, New Zealand, United Kingdom and United States committees for operations interoperability.

Results also showed that by using appropriate MBMs and experimental data from operational or experimental systems, one could project the impact of architectural changes on mission effectiveness. Accumulated results gathered from applying MBMs to various experimental data collected from simulated and live military exercises allowed us to build an empirical model of data aging for OTH-T. Typical curves of data aging and timeliness pace have been obtained. It is likely that typical critical times and formulas (inequalities) for engagements could be deduced from these results. Once these critical times and formulas are established, ground-truth (GT) data will not be necessary to apply them in real-time applications. Consequently, if results are coherent across various military exercises it is expected that one would be able to use these timeliness models of the impact of information on mission effectiveness to predict, in real-time situations, the probability of success of an OTH-T engagement. This probability excludes damage assessment and the kill probability of the weapon used. Our MBM probability of success indicates the value of the information to the decision whether or not to engage a specific target. The transformation of these probabilities into kill probabilities and damage levels requires several refinements that may use classified information: specifics of each target, including its status and environment, and specifics of each weapon used against a target, including countermeasures, environmental, geographical and relative-geometry factors.

This paper defines various parameters and aspects of MBMs. Sensitivity of the measures to variations in certain parameters is examined. Non-linearity of data aging and its rate are studied and modeled. A targeting predictive model is provided. Impacts on mission effectiveness of reported potential architecture changes are summarized.

## 2. Background

To study WAP systems (WAPSs), the AUS-CAN-NZ-UK-US C3 (command, control and communications) defined a work program and set up an ad-hoc working group to investigate the management of organic and non-organic information in a maritime environment (MONIME). MONIME was mandated to conduct a series of experiments to collect sufficient data for WAP systems analyses, characterization and requirements definition [7]. Experimental data include the 1993 Tactical Information Management Simulation (TIMSIM ’93) [8], the Rim of the Pacific live exercises 1994 and 1996 (RIMPAC ’94 and RIMPAC ’96 [9, 10]) and the second 1995 Maritime Command Operational Training Exercise held along the Pacific Coast (MARCOT ’95-2) data [11]. Results and recommendations from this series of experiments form the basis of the AUS-CAN-NZ-UK-US C3 Organization’s “Handbook 5 (HB5), Guidelines for Maritime Information Management”: guidelines to be used in the procurement of national C3I WAP-based systems for the compilation and sharing of accurate WAPs [1].

### *2.1 Architecture and Information Flow Used in Experiments*

The architecture and information flow used in the sampled TIMSIM and RIMPAC exercises are based on a central node that processes data from local and remote sources or sensors (including space-based assets). The Force Over-the-horizon Track Coordinator (FOTC) requires several Global Command and Control Systems (GCCSs) and is a man-intensive information processing and management function usually assigned to a suitably equipped ship, e.g., a carrier vehicle (CV). The FOTC fuses and compiles the tactical picture. Procedures allow the data—mainly

track information—to be broadcast periodically[2] by satellite or radio, using the Allied Command Information Exchange System (ACIXS)[3], for example. High-interest tracks can be sent over narrow-bandwidth radio channels to participating units not on ACIXS. Participating units use GCCS in conjunction with their C3IS for planning and operations. TIMSIM includes data for the Tomahawk Weapons Control System (TWCS). In Figure 1, track coordination occurs at the FOTC node and information arriving to the FOTC is similar to that fed to a TWCS, although information-management procedures are slightly different since the two systems serve different purposes.

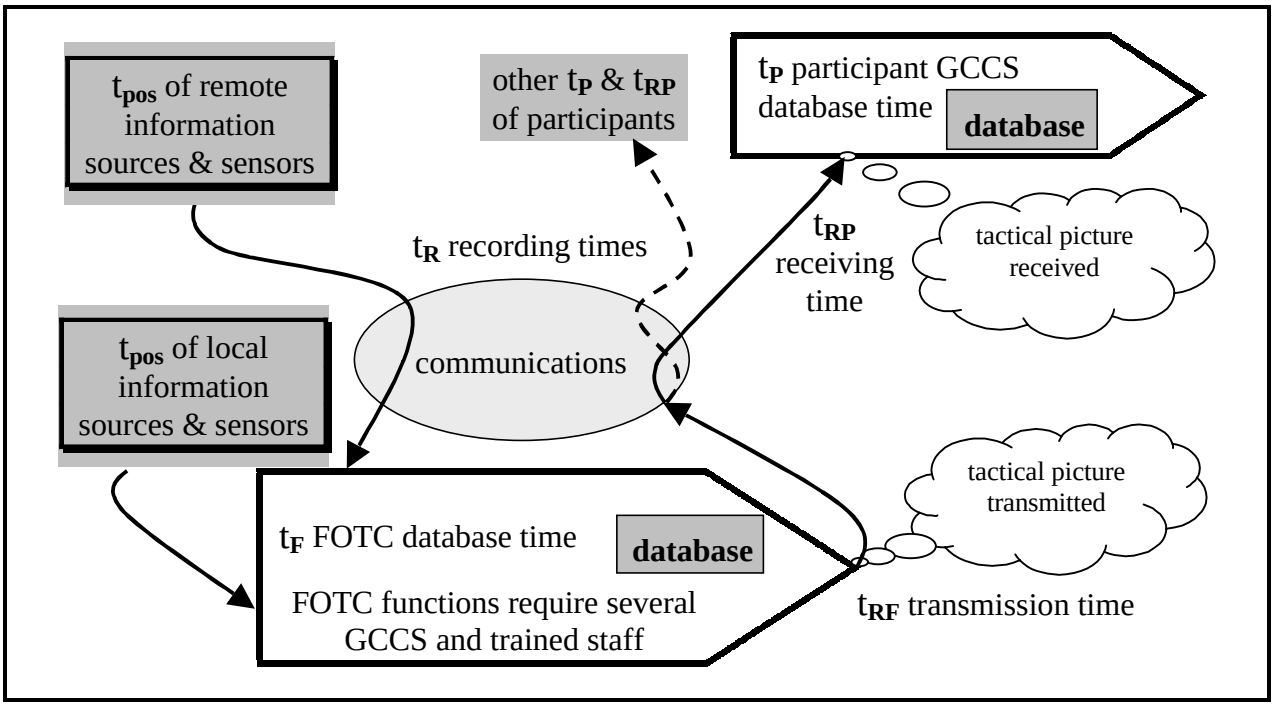


Figure 1. Information flow of the wide-area systems used in the experiments

### *2.2 Tactical Information Segment Used for the Tests*

OTH-T MBMs were tested for the surface segment of a wide-area naval tactical picture of warships sailing within their areas of operational interest (AOIs) that report on a variety of contacts. However, the information-exchange traffic included all types of tracks (e.g., air and submarine) and other systems and operations information required, but our MBMs only addressed the value of the information regarding OTH-T against hostile ships. The ships of the surface tracks can be classified according to their perceived or reported allegiance as friendly (F), hostile (H), neutral (N) or unknown (U), a subset of NATO-defined allegiances. Friendly and hostile ships are military vessels of the forces in conflict. Usually we refer to friendly ships as the “blue” force and to hostile ones as the “orange” or “red” force. Neutral contacts are

[2] Periodic update times observed in our data include 20, 15 and 10 min.

[3] The OTCIXS, Officer in Tactical Command Information Exchange System, or ACIXS, is a communications system that uses satellite technologies at data rates ranging from 2 400 to 9 400 kb/s. TADIXS, Tactical Data Information Exchange System, is the real system (UHF SATCOM data link) and OTCIXS or ACIXS is a concept.

generally merchant ships, liners or other vessels extraneous to the conflict. The unknown allegiance category indicates a lack of information about a contact. A perfect reporting system with all the appropriate information would not need this category.

#### 2.2.1 Ground Truth

Different ships or groups of ships may and usually will have different tactical pictures of a given area at any given time, despite the ultimate goal of sharing the same picture at all times by all units of a battle force. With current systems, the tactical picture available to commanders may be incomplete, erroneous and cluttered with duplicate information. There is, of course, only one real wide-area naval situation at any given time. We refer to this situation as the GT. GT information consists of the identification, allegiance and location at any given time[4] of every ship in the area to be controlled, over the period of time considered. In post exercise analyses we use GT, although our knowledge of it may not be perfect. The only GT allegiances used are F, H and N. In TIMSIM, GT is generated by the simulator under the control of a game umpire. In RIMPAC, GT is reconstructed from all available sources recorded; it is not as complete and accurate as in TIMSIM since RIMPAC is not a fully controlled experiment and has to deal with unpredictable and unrecorded information, e.g., environmental conditions, fishing boats and merchant ships.

### *2.3 Operations*

For the purposes of our MBM study, an OTH-T engagement situation occurs every time an armed ship from the blue force has knowledge of the presence of an enemy ship (orange force) within range of the ship's weapons. This knowledge is acquired through surveillance operations whose sources can be within (organic information) or outside (non-organic) a blue force commander's assets and organization. Information may also be based on intelligence reports. We assume that the commander follows appropriate procedures, that the target is located within the physical limits of the systems (mainly the weapons) and that it can be engaged according to the applicable ROEs. Under these conditions an engagement situation occurs each time a blue force C3IS receives an information report on a presumably hostile contact. For MBMs, hostility depends on the identification/allegiance indicated in the information report.

### *2.4 Experimental Setup*

The report time $t_r$ must be estimated, since available instrumentation captures only the time at which the report is observed leaving the compilation node (e.g., the FOTC) or entering a recipient node (the recording time of Figure 1, $t_{\mathbf{R}}$). Except for the current time, the information in a report does not change until a new report for a given track or contact has been correctly[5] received and has been inserted into a C3IS database, or more specifically a GCCS[6] database: R(t)

[4] In practice, the GT data are listed according to a discrete time variable with short steps (set to 1 min in our tests).

[5] Correctly received report: A report processed by the C3IS node and added to the database for this track. Reports that should have been correctly received but did not appear in the database are not considered: MBMs are limited to what the commander can see.

[6] GCCS-M or JMCIS, Joint Maritime Command Information System and/or Strategy (US); it includes NTCS-A and interfaces.

= constant for $t \in [t_{pos}$ , time of a new report for that track[[7]. Only the associated time and identification (i.e., the unit identifier) of the database change.

Assuming no processing or transmission delays, at time $t_{pos}$ we assess the goodness of the sensor data for a decision (sensor baseline). After a delay ($t_r - t_{pos}$), i.e., at time $t_r$, we assess another MBM as soon as a report enters a GCCS database. A report $R(t_r)$ tells us where to apply the MBM and time $t_r$ tells us when in the GT file. For the results presented in this paper we considered decision times occurring from 0 to 64 min after the position time, in order to assess success rate non-linearity as a function of information age ($t_r - t_{pos}$).

The FOTC is at the compilation node, and the time $t_{\mathbf{F}}$ of Figure 1 is the FOTC time estimated from the transmission time $t_{\mathbf{RF}}$ ($t_{\mathbf{RF}} > t_{\mathbf{F}}$). An information item is stored in the database as soon as it has been processed by the FOTC staff and GCCSs. Then it is queued to outgoing message lists—the FOTC broadcast or another information service—until the next transmission opportunity. The time when a report is received from another participating GCCS unit is referred to as the participant time[8] or $t_{\mathbf{P}}$ in Figure 1. All this happens in real time, while sampling the process of developing and sharing a common WAP.

In practice, the information reports received by a ship are entered manually or automatically into an input queue, not directly into the database, and the report time thus represents the time at which this operation was performed, without regard for delays due to instrumentation. So there are two recording times, $t_{\mathbf{RF}}$ and $t_{\mathbf{RP}}$: $t_{\mathbf{RF}}$ for the FOTC and $t_{\mathbf{RP}}$ for the participant receiving time, with $t_{\mathbf{F}} < t_{\mathbf{RF}} < t_{\mathbf{RP}} < t_{\mathbf{P}}$. For our purposes, we consider that the commander of a ship has knowledge of an incoming contact information report at $t_r$ , which we approximate with $t_{\mathbf{RF}}$ and $t_{\mathbf{RP}}$ depending on the measure required.

### *2.5 Areas of Uncertainty*

The positional information in WAP systems is uncertain for several reasons. For example, any sensor that estimates the location and identification of an object it has detected does so with finite resolution. One aspect of its resolution, the positional accuracy, leads to an area-of-uncertainty (AOU) around the estimated location. In some systems this contact AOU is provided by the source of data, but since AOUs are not yet systematically provided for in all the contact reports subjected to our analysis we impose an alternative in our model that is described later. There are also other types of AOUs that naturally arise in physical systems.

### *2.6 Time of Engagement Opportunity*

An engagement situation occurs whenever the commander of an armed blue ship receives an information report on a presumed hostile contact. This report holds a position time $t_{pos}$ and a report time $t_r$, with $t_{pos} < t_r$. The models may use either of these two values as the actual time of engagement opportunity, i.e., the time at which an engagement may take place (or might have occurred). Of course, in reality an engagement decision cannot be taken before the existence of

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[7] Brackets opened toward the outside mean that the exact value is excluded of the range of the variable, e.g., $t \in [t_{pos}$ , time of a new report for that track[ includes $t_0$ but excludes the new report time. Otherwise double accounting of data would occur.

[8] Note that $t_{\mathbf{P}}$ for the participating GCCS unit time is larger than $t_{pos}$ , the "position time" from the sensor, and larger than $t_{\mathbf{F}}$ due to the delays required to process and transmit the information.

the information report is known. However, allowing the selection of different times of engagement in the models yields essential measures for estimating the impact of system changes on mission effectiveness.

The baseline assessment models used may be viewed as "optimal" since they are equivalent to assuming that information reports are available instantaneously, when they are generated by sensors/sources (i.e., position time = report time = time of engagement opportunity). These models represent the maximum usefulness value of the available information that can be provided to a commander. This value is the source or sensor baseline, which can be used to evaluate the impact of systems architecture changes on mission effectiveness.

The delay models are "time degraded" models where the target information has not been updated since position time (i.e., position time < report time = time of engagement opportunity)[9]. Time degradation of the information represents system limitations that are assumed to be sub-optimal. In previous studies [4] we have shown that assuming dead-reckoning of the intended target during the time of delay actually yields a worse engagement outcome than assuming a static position, so the results presented here were obtained using delay models with no target location prediction. The precise definition and parameters of the MBM simulation models and scenarios are given in [12-14].

Actual engagement decisions are few in live or realistic exercises, so the conclusions drawn from their outcomes have very little, if any, statistical significance. In contrast, applying the models as we did over the experimental data yields samples approximately a hundredfold larger, which reinforces the statistical soundness of inferences made.

## 3. Some Definitions

An encompassing definition of a MBM follows:

1. A MBM is a measure in which a particular decision-maker (DM) has been removed from the command and control loop in order to assess the value of a set of MOPs for certain MOEs, systematically by simulation. Since several DMs may influence a function, they are removed individually, one at a time.
2. MBMs replace the complex, man-in-the-loop decision process with simplified models.
3. All staff other than the decision-maker for the function under study is included in the system assessment.
4. The simulation models link MOPs to MOEs by evaluating the results of actions, based on GT.

Specifically, the reported MBMs are defined for OTH-T. Such MBMs assess the value of the information made available to a commander by examining each tactical report of track data that meets a particular set of engagement conditions. Location, systems and temporal data are used to establish the engagement parameters and scenarios. Outcomes subsequent to decisions are assessed using both decision-process model definitions and algorithms that include hit-probability calculations, as well as GT information about actual target locations (possible because this is a post-exercise analysis). AOUs are used to represent the intrinsic level of

[9] The position time or sensor detection time is earlier than the report time. We set the time of an engagement to the report time so as to measure the effect of data aging on the result of the engagement.

uncertainty of missile-interception areas, of GT data and of the information presented by C3ISs to commanders. The measures assign reward values that take into account the allegiances of contacts in the interception area and a utility cost for firing a missile.

Using MBMs as a yardstick based on OTH-T effectiveness, various potential changes to the architecture used in Coalition exercises that might improve the timeliness and accuracy of the information made available to decision makers at time of decision (a MOP) are assessed in terms of their impact on OTH-T potential success rates (a MOE). In this paper, information processing includes sensor data processing, data fusion, situation assessment, weapon pairing, action planning and other deliberative processes that take place before sending the engagement data to the shooter. The information exchange concerns the geographical distribution of the required engagement data from an information-processing node to a shooter. Updated information is used during weapon deployment until final interception or success is confirmed. Resource optimization would benefit from decision support based on OTH-T MBM characteristic curves and the critical age of information required for a given mission success rate.

### *3.1 Scenario*

In Figure 2 we assume that the WAP compilation and CWC (composite warfare commander) are both on Platform 1. At time $t_1$ a wide-area sensor and various other sources provide the WAP in the area delimited by the circle A. At time $t_1$ Ship 2 of a SAG (surface action group) is identified as the candidate to investigate an area reported by intelligence as of interest. The tactical sensors of Ship 2 are limited to the area of circle C. According to an intelligence report and encyclopedic data, the suspected hostile target may have weapon area coverage capabilities that are represented by circle D. The elliptical area labeled D represents the capability of an appropriate Ship 2 weapon to maneuver around the aim position once it is in its “lock-on some target” phase. This missile footprint can be deduced from the engagement geometry, scenario parameters and missile characteristics, but to keep our model simple and unclassified we selected typical characteristics described and used in previous MBM definitions [4].

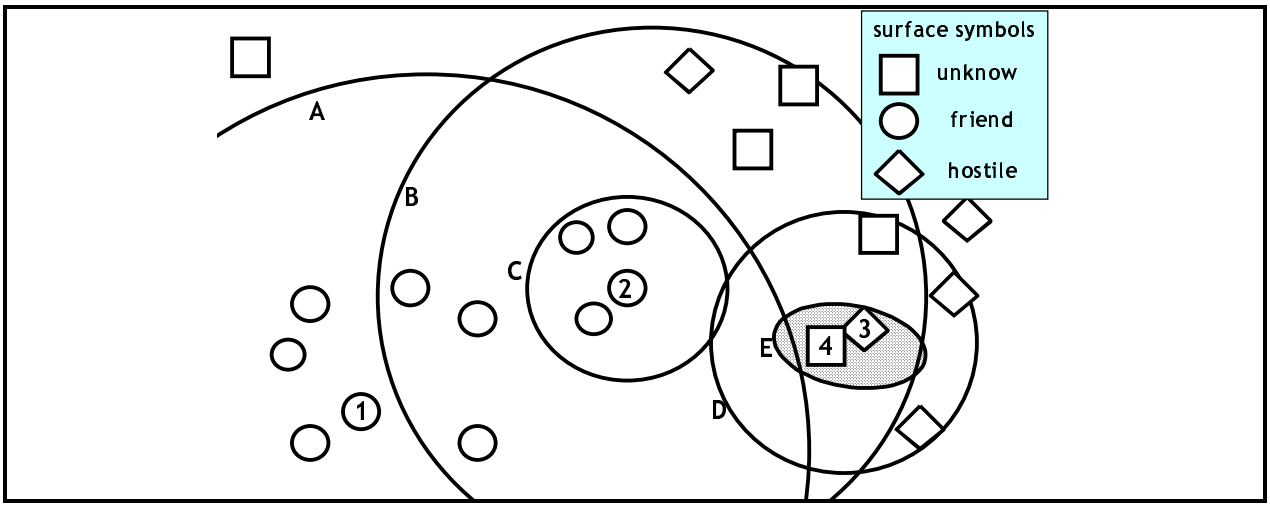


Figure 2. OTH-T scenario for surface contacts excluding neutral: Composite warfare command and force over-the-horizon functions are effected by Ship 1, wide area sensor coverage at time $\mathbf{t_1}$ is limited to circular area A, cued sensor coverage at time $\mathbf{t_2}$ is indicated by circular area B, designated surface action resource for this potential engagement is Ship 2 with own sensor range limited to circular area C, Ship 3 is the potential target with an expected weapon range limited to circular area D, circular area E indicates Ship 2 weapon footprint and Ship 4 is an unknown at time $\mathbf{t_1}$.

The platform labeled 4 is assumed to be undetected or unidentified at time $t_1$. But once the cued sensor reports a more accurate picture for the AOI for the prosecution of the possible hostile 3, it can be declared unknown, neutral or friendly, and its relative distance to the potential hostile reported more accurately at the WAP compilation node (CWC's Ship 1). We assume that at time $t_2$ Ship 2 receives the information that Platform 3 is hostile and Platform 4 is merchant (friendly). Ship 1 must wait until the probability of hitting the hostile target is large enough and the probability of hitting the merchant ship is low enough before engaging. More sensor cueing may be required for this type of targeting.

Assuming that the ROEs for Ship 2 are compatible with our hypothetical case, a sequence of assumptions and a course of events and actions that are consistent with appropriate command and control cybernetic models might be:

1. The WAPS provides the initial data for Ship 2 for action related to the investigation of a potential hostile target in an area defined by an intelligence report.
2. The contact is identified as hostile via the WAPS or electronic support measures, but better position information is required before engagement. A more detailed picture is also required because the area is known to be a merchant-ship route.
3. Ship 2 requests the necessary support, uses the WAPS and interacts with the CWC to get it (sensor cueing, in this instance).
4. Non-organic sensors search the area of interest and report via the WAPS.
5. The decision-maker on Ship 2 (DM2) reaches the following state of awareness: DM2 has enough confidence in the nature of the target to proceed with an attack. At the same time DM2 finds that, according to the current position and Ship 2 missile-footprint data, a merchant ship is too close to the hostile target.

6. As time passes, new data show that the hit probability for the hostile target is high enough and unintended hit probability is low enough to allow the target to be engaged, using a missile of a certain type from Ship 2. Ship 2 may use more organic or non-organic sensor support for this targeting.
7. Ship 2 monitors the progress of action and continues its mission. Based on newly acquired information or on a damage report, some of the previous actions may be repeated.

The decisions made by this model result in a random variable described by the outcomes, i.e., the consequences of action, so the above assumptions and courses of events are part of the model to which we apply statistical tests. The results of these tests indicate if the hypothesis is acceptable at the significance level of the tests. This is a multiple-step approach, since statistical evidence must also be found for the quality of the data used and which set or sets are to be used.

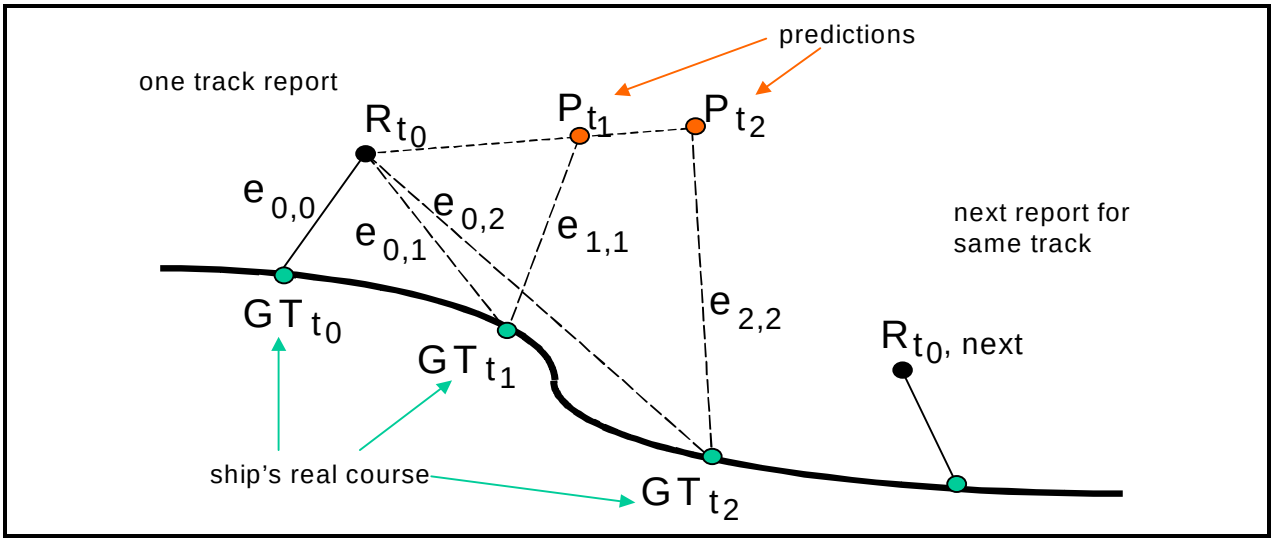


Figure 3. Track-report positional errors $e_{i,j}$ with and without predictions for various assessment times

### *3.2 Contact Information Reports*

The tactical information about a ship forwarded to a commander through different information channels and means contains the identification (class-name) of the ship, its position and, eventually, other information such as course, speed and allegiance. Each occurrence of such combined data is referred to as an information report on a contact. The "position time" $t_{pos}$ indicates the time at which the information was acquired (sensor time). The "report time" $t_r$ is the time when the information report was made available to its recipient's database. In a real situation another time may be necessary: the commander's decision time, which occurs after $t_1$. Figure 3 shows a first-order position prediction algorithm such as dead reckoning (DR), with the reported position at $t_0$, the predicted positions at $t_1$ and $t_2$, and the GT positions at $t_0$, $t_1$ and $t_2$. With respect to the preceding definition of contact reports, we can consider that an engagement situation occurs each time the commander of an armed ship from the blue force receives an information report on a presumably hostile contact. For the MBMs, hostility depends on class-name identification or allegiance as indicated in the information report. For assessment purposes the hypothesized decision time can be anytime after $t_0$.

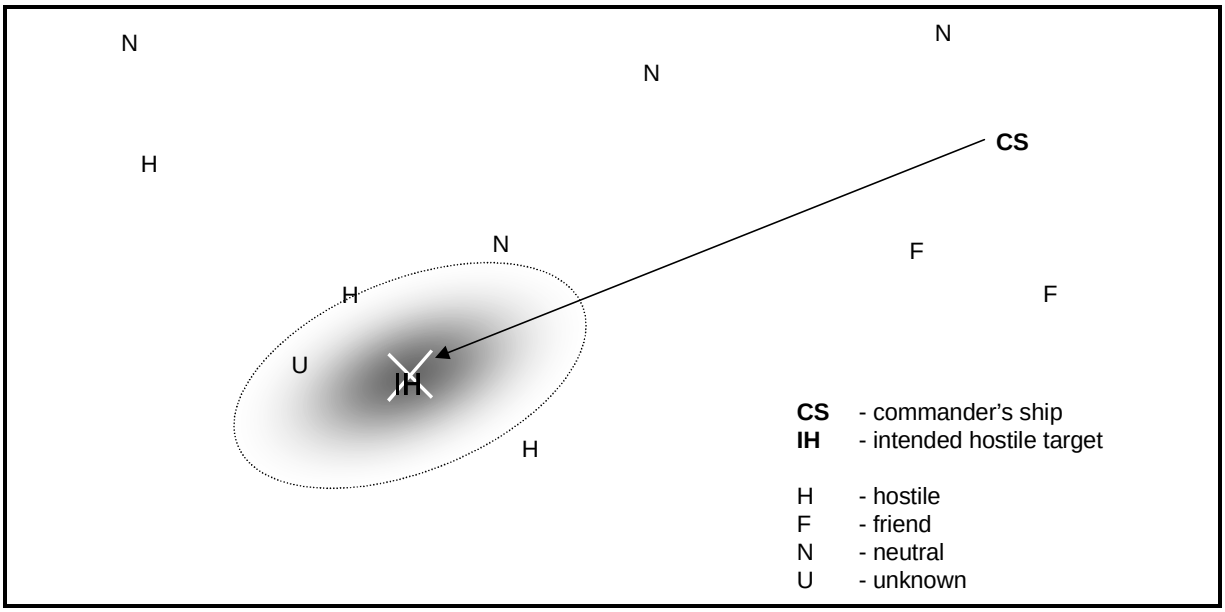


Figure 4. A typical engagement situation with a weapon aiming vector and a weapon-uncertainty area centered at the intended hostile (IH)'s position

#### 3.2.1 Positional Uncertainty

The positional information in WAPS is uncertain for a number of reasons. This lack of precision is expressed by an AOU: there is a probability $p_i$ that the object lies anywhere within this area and a probability $p_o = 1 - p_i$ that it lies outside. Typically, a system may use a confidence level of 95%; that is, the probability of the object being outside by ***chance only*** is 0.05. In some systems the contact AOU is provided by the source of data, but since this information is not available for all the contact reports used in our analysis, we have simplified the computation by assuming that $p_o$ is null or negligible (i.e., $p_i = 1$).

### *3.3 Weapon-uncertainty Area*

In DREV MBMs the weapon-uncertainty area (WUA), also called the weapon footprint, is modeled as an ellipse centered on the location at which the weapon is aimed. Its orientation, i.e., its major axis, lies along a straight line connecting the weapon-launching ship to the presumed location of the intended target (see Figure 4). The WUA is specified by three parameters:

1. the half-length of the minor axis of the ellipse;
2. the half-length of the major axis of the ellipse; and
3. a weight function defined over the area of the ellipse.

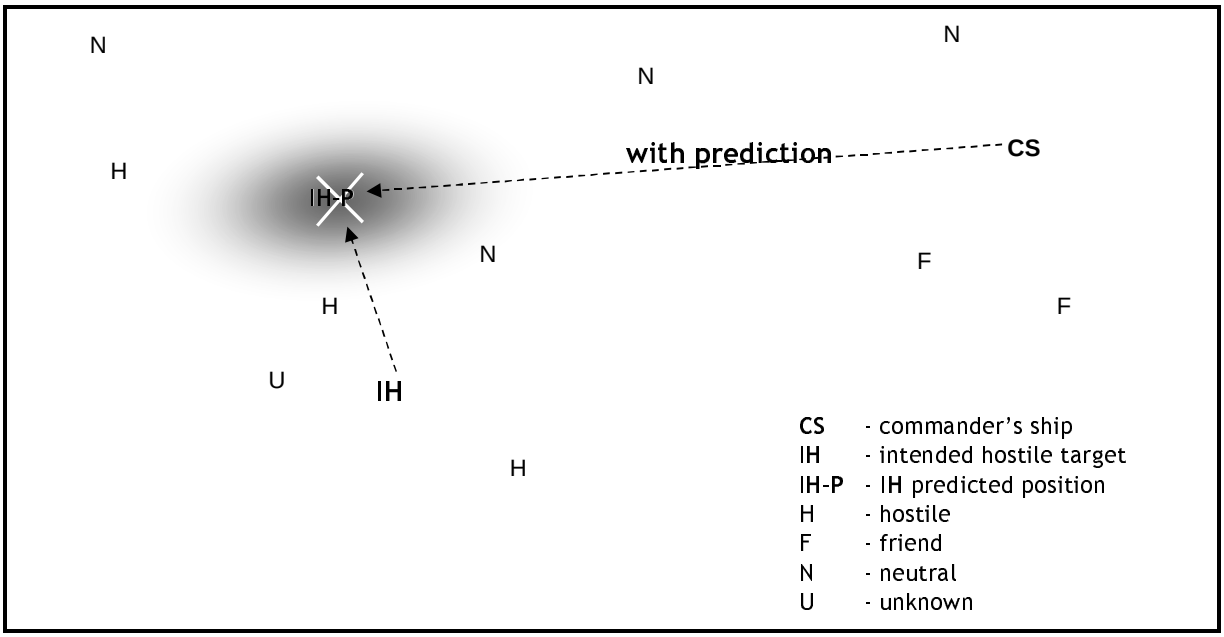


Figure 5. An engagement situation with a weapon-uncertainty area centered at the IH-P's position

The weight function, defined over all points within the elliptic area (Figure 4), assigns to each such point a weight indicating the likelihood of that point's being hit by the weapon if it is launched. Although any suitable function can be used for this weapon parameter, we use uniform and triangular functions as a starting point. These functions can be described as follows:

$$\text{uniform}\, W(x,y) = \begin{cases} 1, \text{ for all points } (x,y) \text{ in the WUA} \\ 0, \text{ elsewhere} \end{cases}$$

$$\text{triangular}\, W(x,y) = \begin{cases} \dfrac{R(x,y) - \sqrt{(x-cx)^2 + (y-cy)^2}}{R(x,y)}, \text{ for all points } (x,y) \text{ in the WUA} \\ 0, \text{ elsewhere} \end{cases}$$

The scenario of Figure 4 can be modified if it is assumed that the commander uses predicted positions, which may be calculated by his information systems. Then at $t_1$ instead of using the report at time $t_1$ ($R_{t_1}$) of Figure 3, he uses the predicted position at time $t_1$ ($P_{t_1}$). This new scenario with the predicted position of the intended hostile (IH-P) is shown in Figure 5.

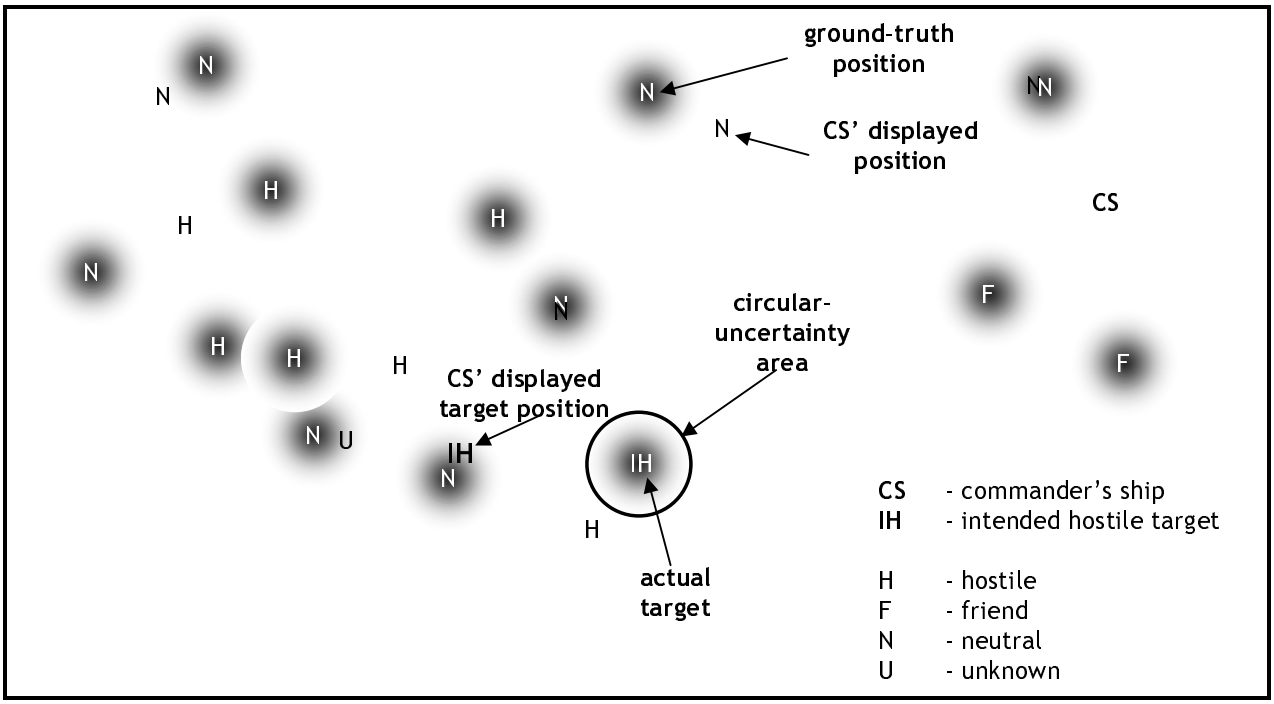


Figure 6. A CUA is applied to each GT position, except for the reference ship

### *3.4 Circular-uncertainty Area*

A circular-uncertainty area (CUA) represents a possible positional error in a contact information report from a given WAPS. The CUA, which is equivalent to the AOU of the specified contact information report, must be applied to all the GT positional reports used to assess a given measure at decision time. Figure 6 shows a CUA for each GT position at a given time—except for the commander's ship, which is used as a reference. The CS displayed information may not contain any data for a given GT position or it may display "phantom" ships. The displayed data may also contain other errors—in type of contact or allegiance, for example.

Within the models, a CUA is specified by two parameters:

1. a circle radius; and
2. a probability density function (pdf) over the circular area.

The pdf parameter is a probability density function defined over all points within the circle. It assigns to each point a probability that the ship (if there is one) corresponding to the contact information report is at that point at the position time indicated in the report (or at a later time, to include the effect of delay on this probability). Although any bidimensional or bivariate pdf (b-pdf) can be used for this parameter, we use uniform, Gaussian and triangular bivariate distributions as starting points, as described in the next subsection. The Gaussian bivariate pdf is defined over the entire plane, so a truncated version—one with a zero value outside the CUA—is used to reduce the computation load[10]. Figure 7 illustrates this for a univariate Gaussian

[10] Assuming that a continuous bivariate pdf like the Gaussian extends over the entire plane would have required an infinite number of computations per engagement assessment.

distribution and Table 1 summarizes the characteristics of the truncated bivariate pdfs used in our analyses.

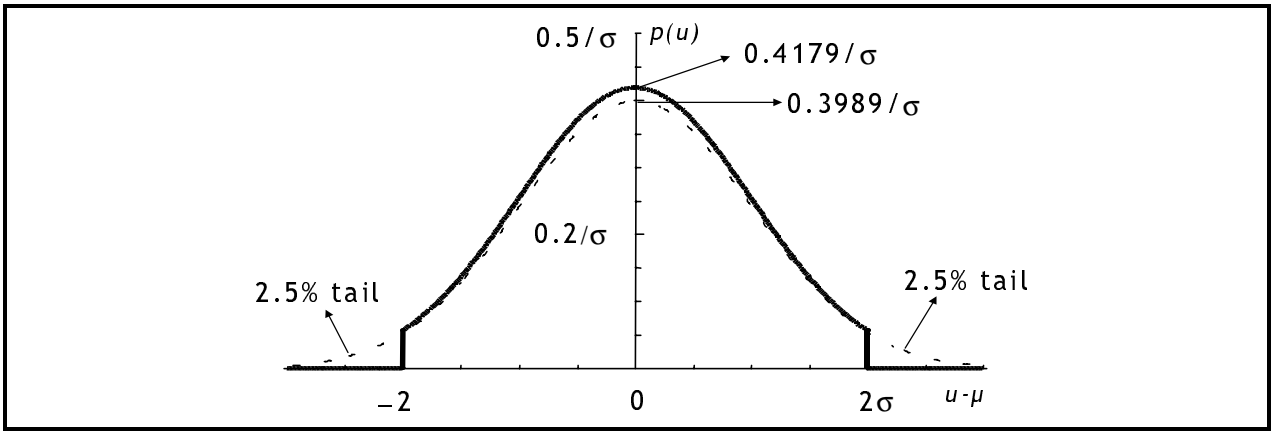


Figure 7. Superposition of a normal pdf and a 95%-truncated-normal pdf of mean μ and standard deviation σ

A CUA can be assigned to any contact, but in the particular case of a presumed hostile contact we call it a target-uncertainty area[11] (TUA), since we are primarily concerned with the impact and outcome of engagement decisions concerning contacts of this type.

Table 1. Comparing b-pdf values at the center and edge of a CUA of radius a = 1

| pdf | at the center of the CUA | at the edge of the CUA | pm outside the CUA |
|---|---|---|---|
| truncated-normal with a/□ = 2.45 (95%) | 1.00 | 0.008 | 0 |
| triangular | 0.955 | 0 | 0 |
| truncated-normal with a/□ = 2 (86%) | 0.736 | 0.025 | 0 |
| normal with a/□ = 2 | 0.637 | 0.022 | 0.14 |
| uniform | 0.318 | 0.318 | 0 |

The CUA represents not only the expected errors found in operational systems but also errors in GT position reports. It has been observed [9-11] that even in controlled experiments proper GT data files may have to be reconstructed from partial information: holes in the GT data may have been filled by interpolation that introduces positional imprecision. In some cases, parts of the GT files may even be reconstructed using contact information reports from a commander's database. In addition, it cannot be assumed that all positions in WAP contact information reports are matched by equivalent GT position reports at the exact same times. In such cases we have to interpolate between two GT position reports to get the equivalent GT position at a particular time. All these considerations can be combined in the view that a CUA around any GT position

[11] In [15], we do not use the TUA acronym and refer only to the more general CUA.

report represents a combination of all the errors in both the CS contact information and GT position reports. This simplification reduces the computation required for each MBM.

Finally, we will later show that considering CUAs around GT positions accounts for all possible WUA center-position alignments within a given TUA (the CUA of a target). The uncertainty of the TUA is therefore transferred and blended into an equivalent positional uncertainty around the GT location values in the vicinity of the WUA. This allows computations in the models to use a single WUA for a given target and still accounts for all the uncertainty involved (Figure 8).

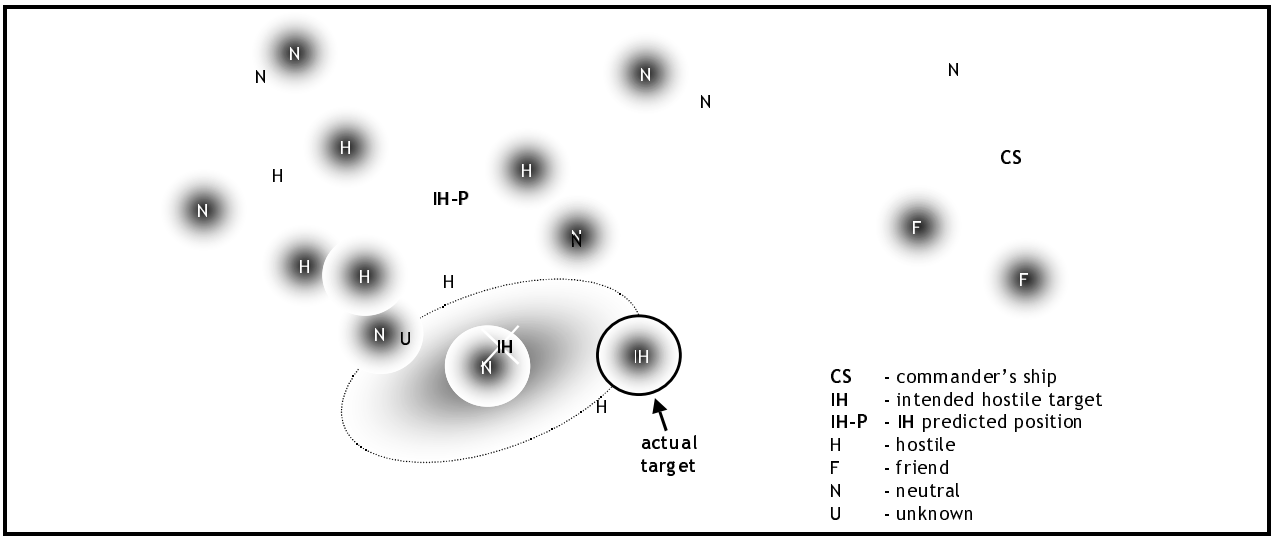


Figure 8. Intersections of three CUAs with the WUA: surface overlaps

### *3.5 Measures of Engagement Opportunities*

In geopolitical conflicts where engagement situations may arise, it is of crucial importance to evaluate the impact of an offensive action such as the launch of a weapon. This impact may be evaluated according to many parameters and from many different points of view: for example, the cost and effort of conducting an offensive action, expected enemy damage as a result of such action, tactical consequences, and geopolitical and other aspects. Obviously, the impact is not necessarily the same for the personnel aboard a ship under threat in a short-range encounter as it is for the fleet commander or the government of the nation under whose flag the ship sails. It is thus unreasonable to hope to identify a simple measure of impact that would apply to all cases of interest, but it is surely possible to capture an essential component of that impact by establishing some quantification of the outcome of an offensive action. Two measures are proposed here for this purpose: the "pertinence-of-engagement" and the "intended-target-opportunity." Their descriptions follow.

#### 3.5.1 Pertinence-of-engagement Measure

The POE measure is a means to assess the general outcome of launching a weapon at a target in an engagement situation. It can be viewed as a measure of the pertinence of the decision to engage. It involves three aspects:

1. The cost[12]-of-firing (COF) the weapon: a negative quantity expressing the expense (economic, material and personnel) associated with the launch of the weapon.
2. The hit probability[13] (HP): the probability that the weapon will hit something (a ship) within its WUA. It is computed by looking at the joint probability distribution of all the ships whose CUA intersects the WUA at the time of engagement opportunity (see [12, 15] for precise mathematical formulations and computing algorithms).
3. The pertinence-reward-value[14] (PRV), which combines the allegiances of the potential target ships with their probability of actually being hit should the weapon be fired, for all ships within the WUA at the time of the engagement.

$$\mathbf{POE} = (\mathbf{HP} * \mathbf{PRV}) + \mathbf{COF}$$

$$= \boxed{\sum_{i \in \{\text{allegiances}\}} \frac{\mathbf{PRV}(i) * T_{\text{allegiance}(i)}}{\sum_{k \in \{\text{allegiances}\}} T_{\text{allegiance}(k)}} + \mathbf{COF}}$$

$$T_{\text{allegiance}} = \iint_{\text{CUA} \cap \text{WUA}} \text{CUA}(x, y) * \text{MBA}(x, y)\, dxdy$$

$\mathbf{PRV}(i)$ = **reward value for allegiance i**

$\mathbf{COF}$ = **cost of firing**

{allegiances} = {friend, hostile, neutral}

Figure 8 shows the CS aiming at the last reported position of the intended hostile (IH) target. Black text symbols represent what is shown on the CS tactical display and white text symbols, with their surrounding CUAs, represent the actual GT positions of ships superimposed over the CS tactical display area at the same time. A MBM hit probability is defined by the joint probability distribution of all ships whose CUA intersects the WUA; e.g., the surface overlaps of two N GT and the IH GT CUAs in the snapshot shown in Figure 8.

#### 3.5.2 Intended-target-opportunity Measure

Though quite similar to the POE measure, the ITO measure is more specific because it focuses on the outcome of launching the weapon with respect to the intended target in the engagement situation. It involves:

1. the COF (as defined previously),
2. the HP (as defined previously) and
3. the target-reward-value[15] (TRV), which combines the allegiances of ships with their probability of actually being hit, should the weapon be fired, for all the ships within the WUA at the time of the engagement opportunity. It is similar to the PRV, except that it gives lower weight to hostile ships other than the intended target.

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[12] In this context the cost is taken in its mathematical sense, i.e., a utility function/value, as is commonly used in mathematical models.

[13] In [15] two different hit probabilities are defined: the General Hit Probability (GHP) and the Specific Hit Probability (SHP). It has been observed that this technique can lead to unrealistic assessments of outcomes in some cases, i.e., when the CUA of the intended target does not intersect the WUA, and hence its SHP is 0, while the CUAs of a number of friendly or neutral ships *do* intersect it. The models now consider only the GHP (called simply HP). The probability of hitting a specific ship is still computed and available within the models, but it is integrated in the reward-value terms of the equations to avoid the absorbing effect of multiplying by a zero value, thus preserving the continuity of the measures.

[14] The PRV is equivalent to the General Reward Value (GRV) in [15].

[15] The TRV is equivalent to the Specific Reward value (SRV) in [15].

$$ITO = (HP * TRV) + COF$$

$$= \boxed{\sum_{i \in \{allegiances\}} \frac{TRV(i) * T_{allegiance(i)}}{\sum_{k \in \{allegiances\}} T_{allegiance(k)}} + COF}$$

$$T_{allegiance} = \int_{cva} \int_{wva} CVA(x, y) + WVA(x, y)\, dxdy$$

TRV (i) = reward value for allegiance i

COF = cost of firing

{allegiances} = {friend, hostile, neutral}

## 4. Data Aging Non-linearity of Reported Hostile Contacts

The assessment, based on MBMs, of the value of available GCCS tactical information for surface hostile contacts for several naval exercises typically shows non-linear data aging, illustrated in Figure 9. For fresh surface contacts—up to 20 min— a first-order approximation of the rate of aging is linear. If we assume that this approximation starts from the maximum available value of 100% at no delay and reaches the minimum value after 20 minutes, then the value of the information for OTH-T hostile surface contacts degrades by about 5% of its original value per minute, during its most useful life. Next we will further examine this behavior to determine a predictive model[16].

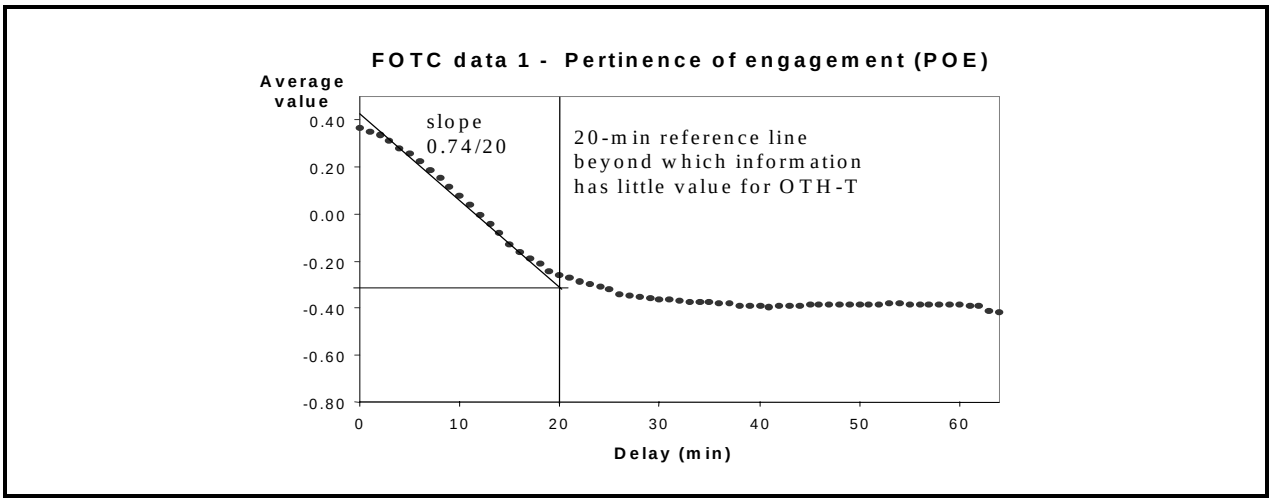


Figure 9. Typical FOTC POE value as function of time for a data set

### *4.1 Fitting Models and Characteristic Curves*

OTH-T MBMs for various scenarios and parameters indicate the expected outcome of possible engagement actions. Notwithstanding the scaling aspects of the measures (a topic discussed in [14]), higher values mean more favorable engagement outcomes. However, the absolute values of the MBMs can be used to compare data sets extracted from different experiments only in a post-exercise context; we need the GT data to compute the MBMs. New scenario parameters and/or improved communications hardware and equipment have an impact on the output values. Systems evolution and use of new technologies cannot be known in advance but their effects

[16] Note that the linear model or first order approximation is based on the MBM values as a function of time, while the fitting models fit the **rate of change** of MBM values as a function of time.

may need to be predicted. Thus it is difficult to draw useful conclusions for future experiments or real-world engagement situations based on the raw measures themselves.

On the other hand, the behavior of the measures with respect to architectural changes in C3IS systems can be investigated for invariant patterns and critical values. One possible such behavioral indicator is the proportional rate of degradation of the measures. The basic assumption is that information is most useful when there is no more than a small delay between information acquisition and the time at which engagement can be decided. As delay increases, information becomes less and less useful and ultimately has no impact on the actual outcome (causality fades as delay and distance between fact/entities increase). Between these two extremes, the usefulness of information degrades at a rate expressed by some relation. It is hypothesized that the envelope of this aging degradation function can be approximated by a fitting model that incorporates certain invariant or typical parameters and that critical values for given degradation rates may be estimated that are independent of the particular experiment or real-world engagement situations involved.

The information degradation is estimated by the proportional rate of change of the MBM measures. First, the absolute pointwise rates of change are computed from the raw MBM measures. Then a prediction model is fitted by nonlinear regression. The maximum rate of change deduced from that model is used as a normalization factor to yield a proportional characteristic degradation curve over an independent uniform scale. This curve can be used to compare information degradation among different experiments, since it does not predict the actual raw values of the measures or their absolute rate of degradation, but only the extent to which information usefulness degrades for given delays. Our investigation focuses on invariant patterns and critical values that could be used to support decision-makers in future real-time circumstances where GT is unknown; i.e., decision-support situations.

We tested three different model families over several data sets, the Rayleigh, Weibull and log-normal models[17], selected for their close resemblance[18] to the actual data plots of the MBM measure rates of change. These envelope-fitting models are shown in Figure 10.

.[17] The Rayleigh model was initially tested only because it involves one fewer parameter than the Weibull model, of which it is a special case. Although it cannot yield a better fit than the Weibull we wanted to see how large was the difference in the fit. In some cases the resulting sum of squared errors was almost twice that of the Weibull, so we discarded the model.

[18] The actual models fitted use a supplementary scale parameter that is multiplied by the model's standard function to account for the fact that the data fitted is not a histogram or a pointwise estimator for a density function. Thus this parameter represents the actual value of the integral under the curve.

**Model 1:** □ * lognormal(□, □) $$F(\theta,\mu,\sigma,x)=\frac{E^{-\frac{(-\mu+\log[x])^2}{2\sigma^2}}\theta}{\sqrt{2\pi}x\sigma}$$

**Model 2:** □ * Weibull(□, □) $$F(\theta,\alpha,\beta,x)=E^{-(\frac{x}{\beta})^{\alpha}}x^{-1+\alpha}\alpha\beta^{-\alpha}\theta$$

**Model 3:** □ * Rayleigh(□) $$F(\theta,\sigma,x)=\frac{E^{-\frac{x^2}{2\sigma^2}}x\theta}{\sigma^2}$$

Figure 10. The models used for fitting the envelope of the rate of aging of early life OTH-T information

Figure 11 shows the rates of change of the OTH-T MBM results presented in Figure 9, and Figure 12 shows the three models fitted with nonlinear regression over the rate values. For each data set, the best model was selected and the resulting characteristic curves for the proportional rates are given in Figure 11. Figure 12 indicates how these models resemble each other and their agreement with a single data set. For this particular case the Weibull model outperforms the log-normal model, although the latter demonstrated the best fit over the data sets tested previously. Note that the Rayleigh model performs well too.

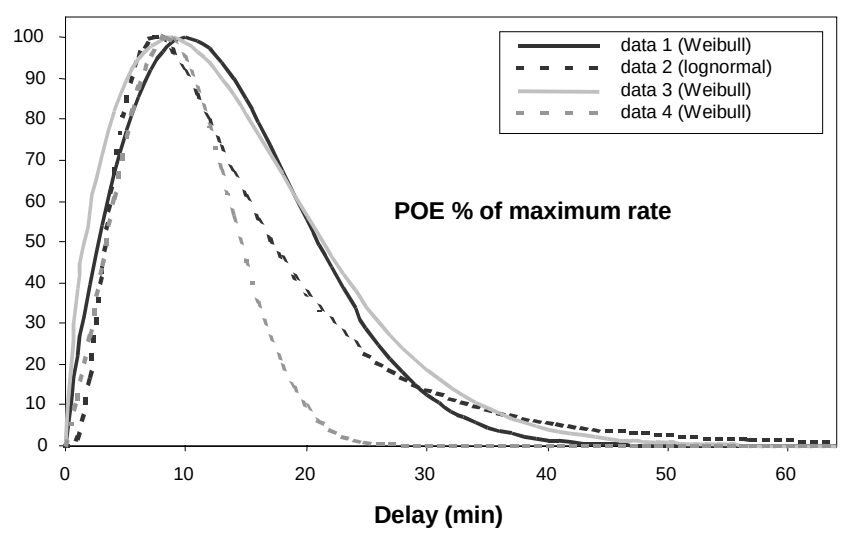


Figure 11. Best envelope fittings of normalized FOTC POE degradation rates as function of time for four data sets

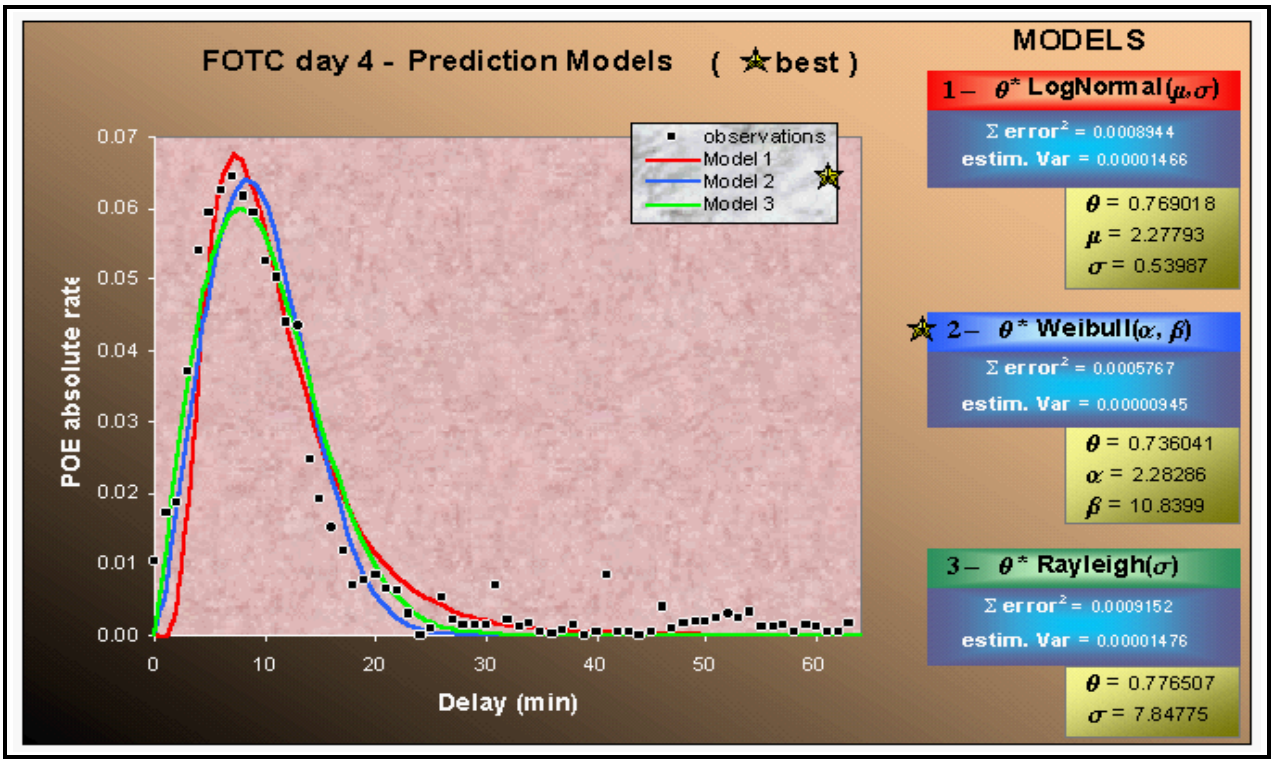


Figure 12. Fitting one data set with similar models

Table 2. Information age at 25, 50, 75 and 100 % of maximum
FOTC POE degradation rate of impact on OTH-T for four data sets

| **FOTC data set** | **critical age (min) at a proportion of each maximum** | | | |
|---|---|---|---|---|
| | proportion in % of a maximum rate of degradation | | | |
| | **25** | **50** | **75** | **100** |
| 1 | 1.14 | 2.70 | 4.76 | 10.04 |
| 2 | 2.34 | 3.28 | 4.40 | 7.48 |
| 3 | 0.49 | 1.56 | 3.32 | 8.64 |
| 4 | 1.87 | 3.34 | 4.95 | 8.42 |
| **overall average** | **1.46** | **2.72** | **4.36** | **8.65** |

Similar curves were obtained for different source-data sets. From them we can establish a set of thresholds or critical delay values for which the information usefulness degradation reaches given proportional rates of degradation. Table 2 shows critical delay values for proportions of 25%, 50%, 75% and 100%. In this context, 50% means that the current rate of degradation is half the maximum rate and 100% indicates the point at which information usefulness degrades the

most rapidly. After that point the degradation rate falls as the usefulness of the information becomes negligible. Consequently, one must focus on the segment where the slope is positive, i.e., the leftmost part up to 100%, since success rates are higher in this segment.

Average delays such as those given in Table 2 may serve as threshold values to help a decision-maker decide at what time taking an action becomes urgent or when further delay would be particularly hazardous. It can also indicate when information becomes obsolete and should be discarded, refreshed or updated by redeploying new information-gathering assets. The proportions can be different from those illustrated and any particular proportion value could be used to define a new threshold.

### *4.2 Dependency of Model Parameters*

An important aspect of the MBMs is the sensitivity of the output measures to model parameters or their susceptibility to parameter variations (analysis of variations). We need to investigate how the measures are affected when models and scenarios used are given different parameterizations and configurations. Among the most important model parameters are those concerning the uncertainty areas for weapons and contacts. Within the MBM software a weapon footprint is typically modeled as an elliptical area over which a weight function is defined. A contact uncertainty area is a circular area with a distribution function indicating the probability that the contact actually lies at any given point within it. We performed comparative analysis using different values for some of these parameters: e.g., the radius of uncertainty for contacts and the major/minor axis length for weapon footprints. Figure 13 shows some typical results obtained for the average MBM measures applied over the same source data using different parameter values for uncertainty areas.

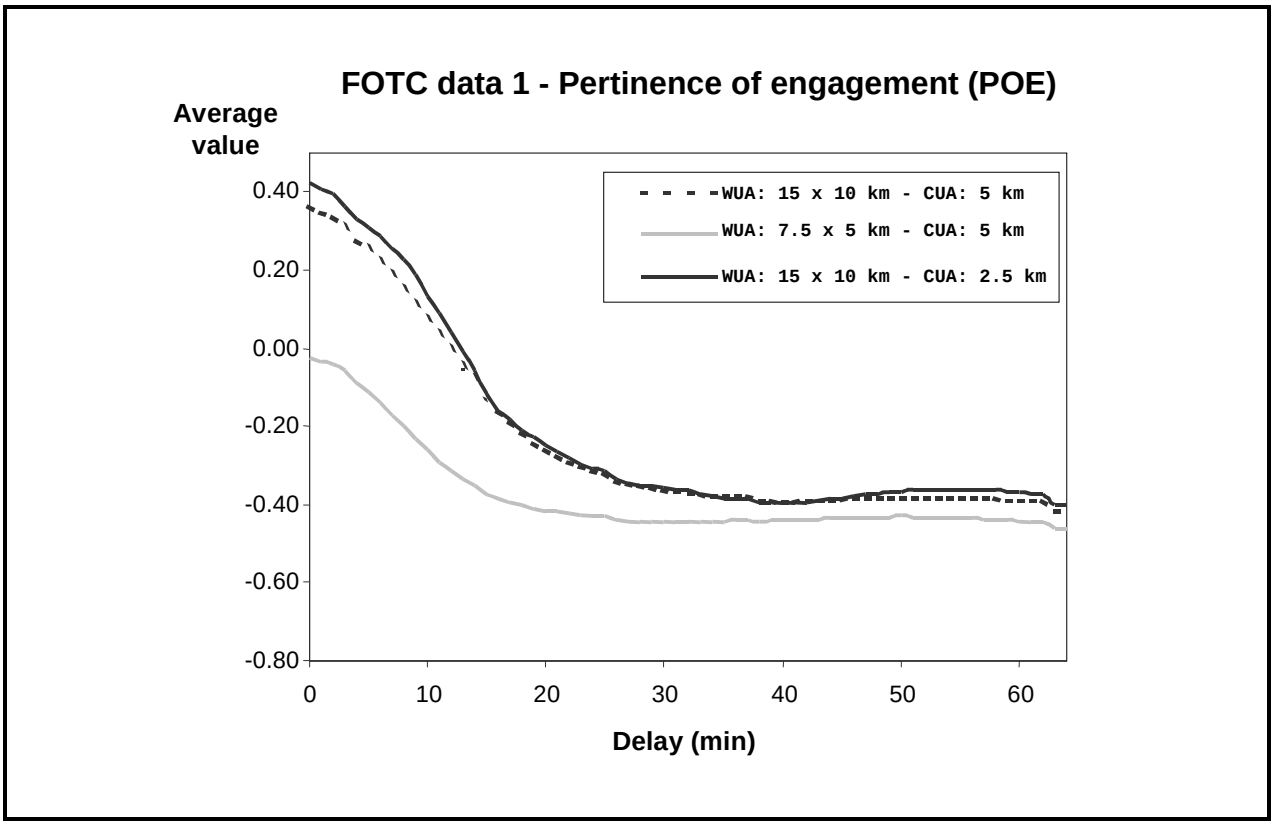


Figure 13. FOTC POE results as function of time for three sets of MBM uncertainty area parameters

Table 3. Information age at 25, 50, 75 and 100 % of maximum
FOTC POE degradation rate of impact on OTH-T for three MBM parameter sets

| **parameters (km)** | | **critical age (min) at a proportion of each maximum** | | | |
|---|---|---|---|---|---|
| | | proportion in % of a maximum rate of degradation | | | |
| **WUA** | **CUA** | **25** | **50** | **75** | **100** |
| 15 x 10 | 5 | 1.46 | 2.72 | 4.36 | 8.65 |
| 7.5 x 5 | 5 | 1.28 | 2.19 | 3.29 | 6.07 |
| 15 x 10 | 2.5 | 2.42 | 3.61 | 5.01 | 8.59 |
| **overall average** | | **1.72** | **2.84** | **4.22** | **7.77** |

The curves in Figure 13 indicate that reducing the radius of the contact uncertainty area yields a slightly better measure output. This is to be expected since a weapon footprint centered at the contact reported location is more likely to cover all or a greater part the contact uncertainty area when its radius is smaller: the actual location of the contact is more likely to lie within the weapon footprint and a successful action result is more probable. On the other hand, if the weapon has a smaller footprint it may not overlap as many CUAs and as much of their areas,

leading to more misses. Unsurprisingly, the discriminating effect of these parameter variations vanishes when delay increases. MBM parameter dependency is most acute in the range of critical delays where information still has some value. This effect needs investigation in more detail: e.g., what are the limits of this observed trend and what is the best weapon-to-contact ratio with respect to the parameters used to describe uncertainty areas?

Constructing the characteristic curves as described in the previous section for different parameter values yield the corresponding threshold critical delay values for the same proportional rates of degradation. Table 3 shows the comparative critical values for average delays according to different uncertainty-area parameters.

It is not yet known if the overall averages can be considered to be robust estimators for any particular set of parameters. More analysis results for different sets of such parameters must be processed to reach a conclusion. It could be that invariance holds for different source data sets only if the uncertainty area parameters are constant, or that it holds regardless of these parameters. This is one aspect that we wish to investigate more closely in future work. We also want to study sensitivity with respect to other parameters.

### *4.3 Fitting Results of a Live Exercise*

Initial fitting results from the RIMPAC ’96 live exercise data confirm the non-linearity of OTH-T MBM values as a function of time. For the two periods selected we obtain the results of Figure 14. We observe a second mode in information aging that was not noticeable in the TIMSIM data. Since we are interested in the fit to the early life of the information used in OTH-T another set of fittings was prepared for results limited to a 40-min delay, Figure 15. It is worth noting that for the most current information sets the fits display a closer match to the fits obtained for the simulated results. Furthermore, if we focus on the most important parts of the results—those corresponding to the positive slope of these bell-shape curves—we observe that their maxima occur at delays larger than for the TIMSIM results, i.e., at about 15 and 10 min for period 1 and 2 respectively, compared with an average of 8.65 min for TIMSIM.

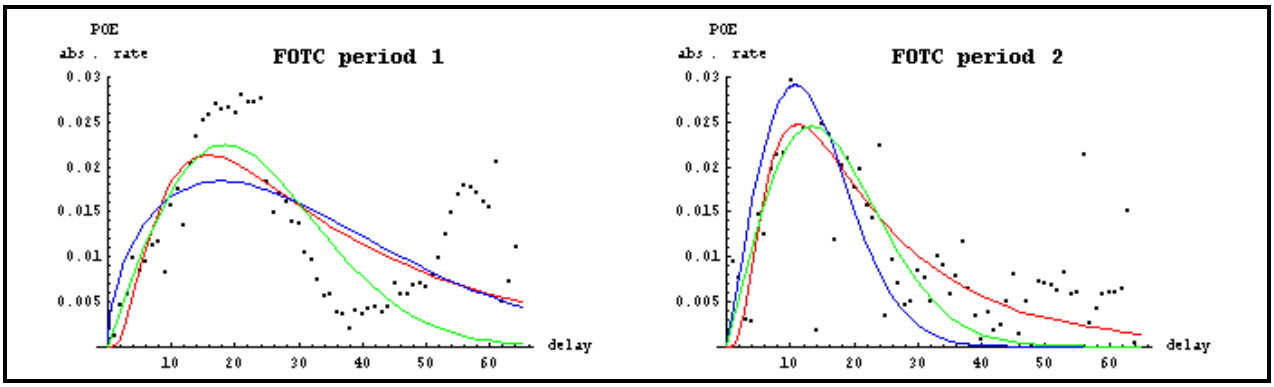


Figure 14. FOTC POE results as function of delay in min for three sets of MBM uncertainty-area parameters (fits for younger than 60-min old data , Rayleigh in green, Weibull in blue and lognormal in red)

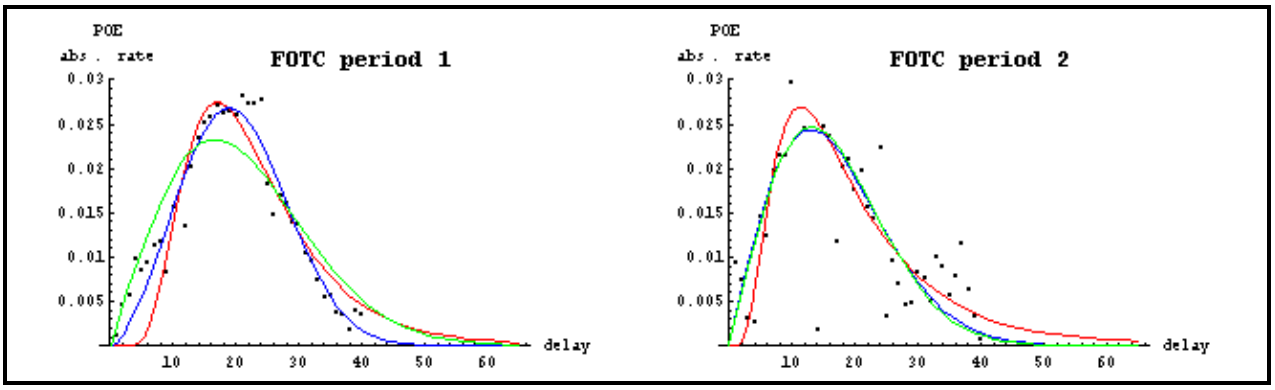


Figure 15. FOTC POE fitting results as function of delay in min for two periods of RIMPAC '96 (fits for younger than 40-min old data, Rayleigh in green, Weibull in blue and lognormal in red)

## 5. Measuring the Value of Certain Architectural Changes Using MBMs

In this section we summarize results reported previously on the impact of various architectural changes that affect cooperative engagement or OTH-T. One of the authors has reported [16] recently on an agent-based architecture framework to implement the proposed changes and to support a Canadian Technology Demonstration that would allow further investigation of the reported improvements.

### *5.1 Possible GCCS Tests for Assessing Improvement to Information Sharing*

A short examination of the GCCS transmission-queue management abilities (outgoing messages) for broadcast in the FOTC function and other information forwarding functions reveals a variety of information management (IM) possibilities. Here are several that may improve the value of the shared information for missions.

Outgoing messages may be selected for a given geographical area that matches the operational AOIs of the deployed units. Different transmitting strategies may be defined, each with its own outgoing message queue. During RIMPAC exercises, ACIXS and HIT[19] broadcasts were used. It is also possible to use the time currency of reports to select data older or younger than a certain value, allowing use of a first-in/first-out (FIFO) or a last-in/first-out (LIFO) strategy.

Some information management heuristics that improve tactical information sharing may be defined from the results of HB5 and the exploitation of the GCCS IM transmission abilities. However, schemes or information-management heuristics that prioritize data to be sent based on its information value to a task or a mission cannot currently be implemented easily within the GCCS software. For more complicated schemes that identify data to be sent based on the significance of changes relative to thresholds defined for tasks and missions (e.g., attribute changes such as an allegiance shift of "unknown" to "hostile," or a new position more than 2 nmi[20] from the last reported position), software improvements are needed. Some of the required modifications are appropriate to the application software of the information node, while

[19] High interest track.

[20] Nautical mile.

others are more related to the middleware arena. Should the middleware use an independent version of the sharable database to interact with other units and with the local information databases of its unit, or not?

### *5.2 Priority Based on Information Value to Missions*

In Coalition operations a large variety of information needs to be exchanged at many different levels of quality of service. If one assumes that the radio-communications asset to be used can be exploited via some kind of priority scheme (exploiting the NATO Communication System Network Interoperability (CSNI) project results), there is a need to assess the value and timeliness of the data to be exchanged as a function of the requirements for the successful accomplishment of the tasks of each addressee.

Assigning priority to messages, packets or cells in terms of task or mission effectiveness requires the extraction of the information they contain; that is, to find what each piece of data means for its end user. Then using knowledge about the missions and tasks to be accomplished and from established time and location value attributes for information per task, the value of the data and related time-line requirements can be assessed. Then through an appropriate combination of factors in a utility function, the current priority of the data can be computed from the time-dependent value of the information contained. The value of some data may depend on a combination of information from other data to be sent simultaneously; the value is conditional on the possibility of sending both sets of data within a given time interval. For this and related reasons, the priority of all time-dependent pieces of information stacked in such queues must be reassessed just prior to each transmission opportunity.

For example, a 1-hour moving time window for a complete database update combined with a 1-min partial synchronization for priority information ("improved timeliness" rather than "real-time") may impact OTH-T for surface warfare and significantly increase the probability of success for the mission. To update the distributed databases and improve partial synchronization, new information is sent as soon as possible using a priority scheme based on the value of the new information relative to that of the backlog information. The backlog information is required for the 1-h database coherence imposed by certain mission effectiveness criteria. A scheme of this nature trades the bandwidth, manpower and system resources needed to share high-value timely information essential for higher mission effectiveness against a small decrease in database synchronization and coherence. Delaying the exchange of data with less information value does not substantially decrease the success of the overall combination of tasks and missions to be conducted over the various AOIs. The result is not true optimization but is a solution that can be computed in a finite time with only the local and current information and knowledge available to a unit, aided by information accessible over the network.

### *5.3 A Simple Information Management Heuristic*

A simple yet efficient heuristic to improve the value of shared information might be to use two transmitting queues for the FOTC broadcast. One would be defined for outgoing messages that are the most current, say no older than 1 min. Few reports fall in this category, so frequent short broadcasts at every minute would be possible, whenever information is ready to be sent at a transmission opportunity. This should help increase database synchronization responsiveness and

timeliness. A second queue for outgoing messages older than 60 min would be used to maintain the coherence of the database and to resynchronize when a new participant joins the net. Its transmission might be spread over a moving time window to avoid transmitting the same data more than once every hour, since the potential quantity of data is large enough to saturate ACIXS. And limiting the geographical area of the reports to be sent would help further, without adversely affecting most missions. Using such an information management heuristic (IMH) would allow a unit moving from one FOTC area to another to adapt its database progressively, impoverishing its database coherence with the former FOTC and enriching the coherence and synchronization with its new FOTC. The unit would then be more quickly ready for new assignments.

Our short review of GCCS documentation suggests that the current version used by the Canadian Navy, JMCIS TAC4, cannot easily implement an IMH with transmission priority based on the value of the messages to a mission, as computed by the utility function described in [13]. However, the just-proposed simple IMH can easily be implemented with the current GCCS software and hardware, since it does not require the computation of the information value (a utility function to do so is not yet available).

### *5.4 Qualifying Track Information in Lieu of Coding*

Statistics may provide insightful information about a set of observations without requiring that an end user examine all the data. Statistics, confidence levels, degrees of belief and the value and quality of attributes are candidates for decreasing the amount of information that must be examined before one reaches a conclusion or decides to act. It seems logical that they can also be used to de-clutter WAPs. Currently there are standards that define such quality factors for tactical information: an AOU for a position attribute, a track quality number for a Link 11[21] track report, for example. Schemes for assigning these values were designed with sufficient care and understanding of operations and of the physical phenomena at play to offer a clear benefit to users who want to share the best tactical information while exchanging the least amount of data and using the minimum radio channel capacity. Since such schemes improve the amount of useful information correctly exchanged, one may consider them a form of coding based on the value of information, rather than on the quantity of information bits exchanged, as defined by Shannon. Unfortunately, adherence to these standards and schemes is not mandatory, so end users are often deprived of their potential benefits.

To conserve channel capacity, unneeded information redundancy should be removed; e.g., if new information concerning a track becomes available before a transmission opportunity, the old piece of information should be preempted (in 1-min and 1-h broadcasts). A statistical process can take into account the multiple versions available and summarize the information to be sent to the end user.

[21] NATO tactical data radio system.

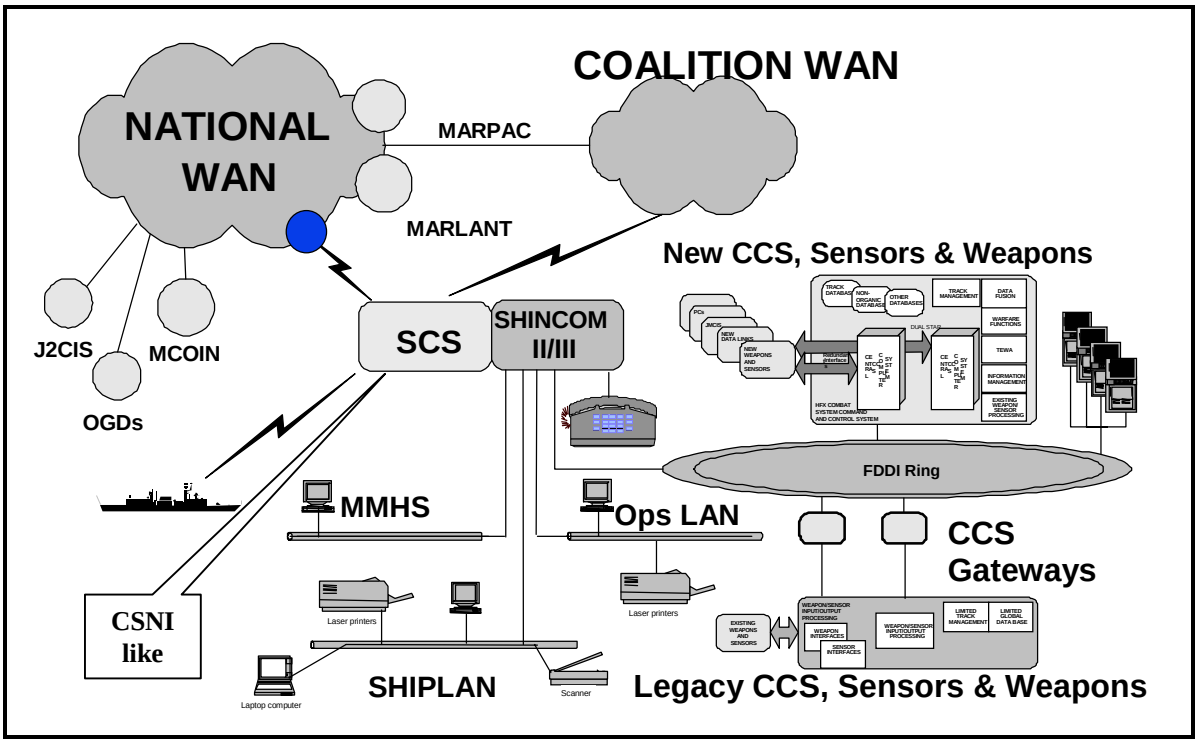


Figure 16. Planned ship communications system[22]

In the case of the proposed IMH, it might be argued that a 1-h broadcast interval is too long to support database coherence. On the other hand, if better adherence is imposed to schemes that assign quality factors to tactical information or track attributes, the global value of the part of the information common to all the participating databases in a geographical area will increase. Furthermore, the ability to send short broadcasts of timely information every minute by using the channel capacity saved by exchanging less data during global broadcasts with the 1-h broadcast should greatly improve database coherence and synchronization.

### *5.5 IMHs Expected Effectiveness Gain*

The total loss in OTH-T mission effectiveness due to data aging between the sensor and the FOTC broadcast was found to be 63% with the MBMs [15]. Consequently, 63% is the maximum achievable MBM improvement of WAPs and procedures, assuming instantaneous track management and information exchange. For this particular result the average time delay was around 20 min for the hostile tracks.

Track data updates at the FOTC databases occur as they are produced by their respective track managers. Their frequency depends on a large variety of factors, including conflict status and tempo, current operations, surveillance-asset deployment, staff load, stress and training, and

[22] Adapted from The Naval Strategic Capital Program presented at the Canadian 1998 Information Management Seminar, slide title: "Ship Integrated Information Management System (SIIMS)". CCS, combat control system; MMHS, maritime message handling system; SCS, ship communication system; MARLANT/MARPAC; maritime command Atlantic and Pacific respectively; SHINCOM, shipboard integrated communication system; OGDs, other government departments; MCOIN, maritime command operational information network; J2CIS, Joint C2 and Intelligence System;

FOTC operations orders. Nevertheless, it is reasonable to assume that the staff cannot manually update all tracks at the same time, only over a period of time. If we assume a periodic broadcast from the FOTC at every 15 min and track data updates occurring uniformly during this 15-min period, then some updates may have occurred just at the beginning of this period and others just before its end. Over several broadcasts the mean delay should be around half the broadcast period, 7.5 min for this case.

The proposed naïve IMH imposes a 1-min short broadcast, or a mean delay of 0.5 min. Based on the estimated data aging imposed by a 15-min FOTC broadcast procedure of 7.5 min, the time currency gain of this IMH should be approximately 7 min. Though the effect of data aging on MBM might not be linear, a first approximation is to assume linearity. In such a case, the IMHs expected effectiveness gain would be (7/20)•63%, or **22%**. This result applies to the impact on OTH-T effectiveness based on the experimental data analyzed for hostile surface contacts reported by the FOTC.

### *5.6 Sensors-to-shooter Improvement and Cooperative Engagement*

It is desirable to use remote sensor information for targeting in certain scenarios in which weapons are available with effective ranges much in excess of the ranges of the sensors on the ship. Some missiles possess substantial target tracking and homing capabilities, and in scenarios where the target can easily be identified by the missile seeker, such as a ship in open-ocean area, precise targeting is not essential. However, a timely tactical picture is necessary to provide sufficient lead-time for high probability of mission success. On the other hand, some targets may be more difficult to seek against their backgrounds. In such cases it may be necessary to use alternate final homing of a missile that relies more on accurate inertial and navigation and accurate geodetic position estimated by intelligence and surveillance. If the target is mobile, continuous updates of the target position must be provided during the flight of the missile. Other engagements may require intermediate target positional accuracy and rely on the seeker for the final intercept phase. In dynamic cases, improved sensor-to-shooter timeliness is needed to maintain a sufficiently high kill probability to make the engagement cost-effective.

In light of these considerations, the Canadian Navy plans to improve information connectivity for national and coalition operations (Figure 16). Initially, exploiting the NATO Communication System Network Interoperability (CSNI) project results would provide the connectivity required, but the cooperative engagement capability (CEC) concept must be implemented and integrated. Canadian research and development toward the Ship Integrated Information Management System (SIIMS), planned for 2010, should address these important issues. This system should encompass the integration of middleware strategies and the cooperative engagement concept as well as the optimization of information sharing as described in HB5, where information value is used to prioritize information exchange.

### *5.7 Reported Time Lines for the Joint Attack Command and Control System*

Reported Time Lines for the Joint Attack Command and Control System (JACCS) in the 1999 Joint Warrior Interoperability Demonstrations (JWID ’99) plan (JW002) (based on JWID ’98 results) can be used as time references for improved C3IS timeliness. Values provided in seconds are converted to min: $t_a$ acquisition and transmission delay, 1.5 min; $t_c$ compilation, 1.3 min; $t_J$

pairing (JACCS), 0.2 min and $t_w$ weapon control, 0.5 min; for a $t_t$ total from sensor to shooter of 3.5 min for the updates. For complex imagery to be interpreted by trained operators and transformed into information and knowledge before devising a plan it is likely that the mean total delay would be around 7 min, but the 3.5 min mean delay figure might hold for updates.

### *5.8 Remote Sensing*

A remote-sensing asset such as Canada RADARSAT has demonstrated its ability to provide synthetic-aperture radar imagery of surface and subsurface structures that intelligence staff could use to identify potential targets. Other imagery, geological and geolocational information are then used to enhance the understanding of the sensed image and to describe a potential target for a mission accurately. Precision OTH-T is required for some missions. Missiles used in these missions may rely heavily on precise inertial navigation, with assistance possible from other systems such as GPS.

Some remote sensing assets offer only limited time-window opportunities for a given geographical area. The opportunity is periodic and depends on the elliptic orbit of the satellite relative to the area to be observed. Furthermore, specific antenna and processing patterns combined with the competition for services in response to other customer's requests further limit the availability, accuracy (since it depends on observation time and amount of processing done) and response time of remote sensing systems. However, for the intelligence purposes of better identifying and precisely locating underground structures such delays are acceptable: the potential target is not likely to move during the process. In fact such steps can often be taken well before the force asset is moved into weapon range of the potential target. Updates are more or less related to changes occurring in the vicinity of the area of interest and can be sensed with alternate means (tactical sensors and visual contacts).

### *5.9 Adapting Model-based Measures to Precision Targeting*

Precision targeting is not immune to error. Errors may be induced during the sensing and identification process, the interpretation and understanding of the situation, the plan definition (including weapon-target pairing) and execution, or may be due to environment changes that affect the probability of success or even the validity of the mission (a target found to be of no value during the missile flight). For these reasons the statistical models used in MBMs may be adapted to precision targeting. Although in this paper we did not do so, we assume that the results still have sufficient significance for our initial assessment of the value of the improved sensor-to-shooter architecture in terms of mission effectiveness, primarily because of the large potential impact observed.

Current MBM implementations assume missiles with no partiality other than the statistical distribution defined over the weapon footprint uncertainty area. Though targets are assumed to be in the open ocean, the uncertainty areas employed are useable in other environments, as long as the assumed missile still responds as described for the implemented MBMs. Future MBM studies will report on the effects of varying the uncertainty parameters. Also it is assumed that the target does not move significantly from the time the missile is fired to the interception time $t_i$. In fact we have set the flight time to zero. MBMs can be computed for the effective interception time applicable to more maneuverable targets or large $t_i$ delay values.

### *5.10 Sensors-to-shooter Improvement in Terms of Expected OTH-T Effectiveness Gain*

According to previous analyses and as reported here, it seems that the information processing time from the sensors to the FOTC database (after the situation assessment process) for the collected data is the remainder of the 20 min from the 7.5 min required for the broadcast: 12.5 min. As indicated above, for new contacts we may assume a delay of 7 min; that is, a timeliness improvement of 5.5/12.5. The potential gain due to this MOP improvement can be associated with the remainder of the maximum total gain available, (12.5/20)•63%, or 39%. The potential gain for this MOP improvement is (5.5/12.5)•39%, or 17%. For the 3-min updates the MOP improvement is 9/12.5 and the potential mission gain is 28%. In both cases we assume the current FOTC broadcast delay or an alternate architecture for managing, processing and distributing the data from the sensors to the shooter that adds a mean delay of 7.5 min.

If we assume that the information concept of the FOTC is modified as described above, then these potential gains are slightly lower than optimum. First we have 7 min plus 0.5 min or an improvement of (12.5/20)•63%; that is, 39%. Second, we have 3 min plus 0.5 min or a gain of (16.5/20)•63%, or 52%.

If we assume that the information concept is as described for JWID, these potential gains are slightly higher than with the integrated information concept with the FOTC. First we have 7 min or an improvement of (13/20)•63%, or 41%. Second, we have 3 min or a gain of (17/20)•63%; that is, 54%.

## 6. Architecture Changes

This section summarizes the differences in potential results offered by the architectures assessed in this paper.

### *6.1 Architecture Zero*

This is the reference architecture (Figure 1) for which experimental data were collected as described at the beginning of this paper. The maximum available improvement to information processing and sharing, in terms of the impact on OTH-T mission effectiveness for the hostile surface tactical picture, from this architecture to a hypothetical perfect information system was found to be 63%.

### *6.2 Architecture One*

Architecture One represents the procedure change proposed in a paper in preparation for MILCOM ’99 that addresses the impact on mission effectiveness of improving the FOTC broadcast timeliness MOP. Information processing in this architecture is as in Architecture Zero. Results for Architecture Zero are used to show the relative value of timeliness improvements in terms of the impact on OTH-T mission effectiveness for the hostile surface tactical picture. The maximum relative impact on OTH-T was found to be 22%.

### *6.3 Architecture Two*

Architecture Two (Figure 1 but with improved FOTC information processing or separate hardware and software, as for JWID) represents changes to information processing alone, without changing the information-sharing procedures, which remain as in Architecture Zero: that is, the mean delay for the FOTC broadcast information exchange is 7.5 min. Results for Architecture Zero are used to show the relative value of such improvement in terms of the impact

on OTH-T mission effectiveness for the hostile surface tactical picture. The maximum relative impact on OTH-T of this MOP improvement to information processing was found to be 17% for a 7-min initial mean delay and 28% for 3-min updates (information generation time).

### *6.4 Architecture Three*

Architecture Three (with an improved FOTC broadcast and information processing, and GCCS integrated into the ship command and control system) represents changes to both information-processing and information-sharing procedures. Information sharing in this architecture is similar to that in Architecture Zero but the mean delay for the FOTC broadcast information exchange is 0.5 min. Results for Architecture Zero are used to show the relative value of such improvement in terms of the impact on OTH-T mission effectiveness for the hostile surface tactical picture. The maximum relative impact on OTH-T of this MOP improvement to information processing and sharing was found to be 39% for a 7-min initial mean delay and 52% for 3-min updates (information generation time and delivery to the shooter).

### *6.5 Architecture Four*

Architecture Four (hardware and software in addition to that required for the FOTC/GCCS/ACIXS integrated concept) represents changes to information processing alone, without changing information-sharing procedures of the FOTC but using additional assets. Information processing and sharing in this architecture uses supplementary hardware, functions and staff. We found an initial delay of 7 min and with updates at every 3 min. Results for Architecture Zero are used to show the relative value of this improvement in terms of the impact on OTH-T mission effectiveness for the hostile surface tactical picture. The maximum relative impact on OTH-T of this MOP improvement to information processing and sharing was found to be 41% for a 7-min initial mean delay and 54% for 3-min updates (information generation time and delivery to the shooter).

## 7. Conclusions and Recommendations

Despite the complexity of the systems evaluated, the new measures were able to recognize changes and variations in the systems and in the opposing forces that classic measures did not detect or identify.

***The reported method thus offer better discrimination among system options and reduce development risk by accurately estimating the impact that changes in procedures, systems and information have on mission effectiveness.***

Results from the version of DREV MBMs presented in [17] lead to the following conclusions:

1. improvements in WAPS capabilities versus hostile ships that can be obtained by optimizing sensor suites appear to be limited to about 9%, and that gain is possible only if the WAPS themselves are optimized first;
2. changes in WAP systems and procedures can improve performance in excess of 63% for the ITO, from the reference value at sensor time at the FOTC node (assuming instantaneous track management and information exchange);

3. improvements exceed 77% at the Surface Action Group 1 (SAG1) nodes under the same conditions, providing that communications improvements from the FOTC to the SAGs are made (i.e., including the assumptions from 2); and finally,
4. communications impact the distributed picture by only 14% all cases at SAG1, about 1.5 times as much as sensors.

***Consequently, the most important step to improve overall performance is better exploitation of already available sensor and source data by improving WAP systems, concepts and procedures at the tactical information management node or in a distributed version of it, the FOTC.***

Based on the results obtained for hostile surface contacts and for the surveillance deployment used during the TIMSIM exercise, an improvement of 4% in sensor performance alone, without improving the WAP systems and communications, would provide less than 1.3% (was 1.6%) improvement in the shared picture. This apparent loss in exploiting available information may be of concern to users and to experts such as the members of the Copernicus Requirements Working Group (CRWG), who are developing improved GCCS, related architectures and procedures.

If we assume that the initial information value for hostile surface OTH-T is 100% at sensor time (it should be less than 100% since it normally contains a certain level of uncertainty and inaccuracy, see [18]) and if we accept the first order approximation presented in this paper, then the rate of degradation of the value of information is about 5% a minute during its most useful life for OTH-T hostile surface contacts.

Better transfer of sensor, intelligence and Link 11 data is required to improve the assistance that WAPS provides for commander decisions. We recommend that operators and commanders afloat be provided with more efficient data management aids, including some automation in the selection, exploitation, fusion and integration of Link 11 data.

MBMs demonstrate the feasibility of statistically estimating the impact of information and systems quality on decision outcomes and mission effectiveness. Generally speaking, raw data that directly relates the quality of command information systems to measures of effectiveness are sparse and expensive to obtain, so it is very difficult to demonstrate information and systems qualities and their impacts on decision outcomes and mission effectiveness. DREV MBMs address this difficult problem. They improve estimation accuracy using the same raw data currently available from instrumented military exercises. Results from both versions of MBMs [8-11, 19-26] provide insights that were not available with the measures currently applied to such data.

For the hostile-ship picture found in a commander's database, we have defined two MBMs to capture the essential components of the impact of the information used in engagement decisions: the POE for the pertinence of engagements and the ITO for the intended target opportunity. The ITO measure amplifies the POE's significance by assigning a smaller reward if the hostile target that is intercepted is not the intended one. Both measures use a fixed cost for launching a missile and both compute interception probabilities and reward values. In both cases, hypothetical blue-on-blue engagements are assigned large negative values to indicate the counter-productivity of such actions. Over a large number of engagements these measures provide a fair evaluation of the goodness of the picture used in the decision process.

Our approach to measure the impact of MOPs (measures of performance of functions or systems) causally on MOEs (measures of effectiveness for mission goals) suggests the following analogy: if the results (MOEs) of decisions and missions are identified as the effects, and the picture and system qualities (MOPs) as causes, then one can say that we causally measure the value, usefulness or goodness of a tactical picture and a C3IS to commanders' decisions and missions.

For example, the proposed models accurately measure the relative improvements due to changes, but since we do not have a well-established level of picture quality needed for a particular mission, the measures cannot deliver an absolute measure of goodness. In addition, they do not assess the damage inflicted to hostile ships. On the other hand, from the application of these measures to a set of several exercises (at least four), it would be possible to infer the minimum information quality and systems performance required for that specific type of decision or mission. This minimum requirement could be expressed in terms of action/mission success rates or risks of failure, giving a probabilistic indication that at this information quality level, for a given class of mission scenarios, mission success is in excess of a given percentage, say 80%.

A MBM for the WAP completeness measure has been proposed [17] and a clear distinction shown between the proposed measures and traditional ones: the new measures are intended to evaluate the effectiveness of a WAPS for a specific mission, rather than to investigate some particular system performance parameter such as communication delay. Further studies are needed to explore MBMs for other mission goals such as drug interdiction or area control.

The data collected and analyses presented in [27, 28] support the following conclusions for the hostile surface tactical naval picture used for OTH-T and CEC:

1. of the 63% of potential improvement in the observed experiments, more than half is related to transforming sensor data into information and knowledge,
2. the remainder seems to be associated with FOTC broadcast procedures,
3. changes to improve FOTC broadcast procedures alone impact OTH-T by 22%,
4. changes to improve knowledge generation with 3-min updates alone impact OTH-T by 28%,
5. changes to improve both in a unified concept (GCCS/FOTC) impact OTH-T by 52%, and
6. changes to improve both but with the addition of staff and hardware impact OTH-T by 54%.

Due to the complexity and intricacies of C3IS and the fact that their impact on mission effectiveness cannot be measured as directly as that of most weapon systems can be, further studies are required to explore the avenues indicated in this document. Nevertheless, the data used showed that the potential gain in OTH-T is relatively independent of the specific systems changes in terms of the implementation but depends strongly on the performance of a change in terms of delivering more timely and precise appropriate information to the shooter. Changes relying on independent dedicated asset and systems as in one of the JWID planned for 1999 displayed the highest mission effectiveness gain. However, such proliferation of distinct hardware and un-integrated concepts are not cost effective in long run. A more promising approach might rely on the integration of the concept within the framework of the Force Over-the-horizon Track Coordinator (FOTC) and the GCCS, using a modified standard operating procedure (SOP) and appropriate middleware. We have shown that both possible implementation

strategies could offer information with similar quality to the end user and consequently improve mission effectiveness by essentially the same amount[23].

Since the effect of data aging for hostile surface tracks is almost linear in its early age (less than 15 min) as shown in this paper, the results presented here and previously are accurate enough for comparison purposes. They provide sufficient evidence to justify further investigation of the problems and to explore GCCS/FOTC changes. More complicity between the information sources, the communication networks, the systems used by the staff and the software agents representing the information requirements of the end users may prove to be very cost-effective in the long run. Since assuming infinite communications bandwidth, computing and staff asset has already proven to be disastrous in certain military operations, searching for efficient or smart exploitation of these critical resources must be made a high priority.

Results presented in this paper support the Canadian Navy plan for a CEC for national and coalition operations. It seems from these results that for some of the missions requiring such capability the Canadian architecture evolutionary plan for improved information management and direct sensors to weapon information flow would improve effectiveness by large factors: in excess of 20% and up to 50%, depending on specific targeting missions and change implementation.

In [14] we hypothesized that the maximum rate of degradation of information usefulness would occur when the age of information is close to 9 min for the MBM parameter set used. An actual average value of 8.65 min was found for the FOTC analyses presented here. This average drops to 7.77 min if we add results computed with different sets of MBM uncertainty area parameters. However, it is larger (about 15 and 10 min) for the two data sets from a live exercise analyzed.

More experimental source data sets need to be analyzed to obtain larger samples of critical values for given thresholds in order to establish reliable distribution estimators with acceptable confidence intervals. We will pursue analyzing other data sets extracted from live exercises and results will be compared and aggregated with the results we have so far.

Supplementary analyses need to be performed with rounds of simulation using the same source data sets but different parameter values. More important, **new sources of experimental data from military exercises are needed** and agreements with other organizations and countries on the collection of such data must be arranged, bilateral, AUS-CAN-NZ-UK-US or NATO. Purposes and mutual benefits include risk reduction in the design of future systems and improved support to commanders, resulting in cost-effective increases in mission effectiveness.

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