Timeliness Characteristic Curves and Critical Values for Over-the-horizon Targeting

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Abstract

Obtaining sets of timeliness characteristic curves and critical values for various missions would provide critical knowledge to support decision-makers in predicting the potential success of an intended or planned action. Empirically deduced knowledge will indicate a mission success rate for given information and scenario conditions. In previous studies we reported on model-based-measures (MBMs) designed to assess the capabilities of afloat-command information systems to support over-the-horizon targeting (OTH-T). Results showed that the impact of system and information quality on mission success rate is not linear but exhibits similar characteristic curves independently of the data selected. Hypothesizing invariance to data for similar OTH-T parameters indicates the usefulness of such empirical curves in supporting a decision-maker. We expect that applying this approach to large sets of data collected during live exercises or man-in-the-loop simulations would allow better understanding of invariant and variant aspects of OTH-T success rates. Then critical values would be established as thresholds in deciding or not to engage a target at a given time and warship 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

The evaluation of effect of communications, command, control and information system (C3IS) improvements or changes on military operations or on mission effectiveness can be conducted through characterizations of system performance and information quality known as measures of performance (MOPs). These results 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 measures of effectiveness (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 wide-area tactical information a commander uses to plan operations and make decisions. This relationship fulfils an essential analysis requirement for comparing the effects of changes in wide-area picture (WAP) systems and procedures on mission effectiveness and can also lead to cost-effective planning of both system development and military operations [1-3].

Findings based on simulated and live military exercises using model-based measures (MBMs) open new avenues in assessing the value of systems changes to improve mission effectiveness. Defence Research Establishment Valcartier (DREV) has developed specific MBMs to determine the effect of information quality and system performance on mission effectiveness.

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 with simplified models the complex man-in-the-loop decision process that has been removed.
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 ground truth.

For this paper, MBMs are defined for over-the-horizon targeting (OTH-T). Such MBMs assess the value of the information made available to a commander by examining each tactical report of track data that satisfies 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 ground-truth information about actual target locations (possible because this is a post-exercise analysis). Areas-of-uncertainty (AOUs) are used to represent the intrinsic level of uncertainty of missile-interception areas, of ground-truth 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 yardsticks based on OTH-T effectiveness, various potential changes to the architecture used in Coalition exercises to improve timeliness and accuracy of the information made available to the 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 the engagement data is sent to the launching unit. The information exchange concerns the geographical distribution of the required engagement data from an information-processing node to a launcher. Eventually, updated information is used during weapon deployment until final interception or success confirmation. Resource optimization would benefit from decision support based on OTH-T MBM characteristic curves and the critical age of required information at a given mission success rate.

2. Background

To study WAP systems, the AUS-CAN-NZ-UK-US[1] 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 [1]. Experimental data include the 1993 Tactical Information Management Simulation (TIMSIM ’93) [4], the Rim of the Pacific live exercises 1994 and 1996 (RIMPAC ’94 and RIMPAC ’96 [5]) and the second 1995 Maritime Command Operational Training Exercise held along the Pacific Coast (MARCOT ’95-2) data. 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].

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

2.1 Architecture and Information Flow Used in Experiments

The architecture and information flow used in the TIMSIM and RIMPAC exercises that we sampled 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 radio or satellite links, for example, the Allied Command Information Exchange System (ACIXS)[3]. High-interest tracks can be sent over narrow bandwidth radio channels for 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 at the FOTC is similar to what is sent to a TWCS though information management is slightly different since they are designed for different purposes.

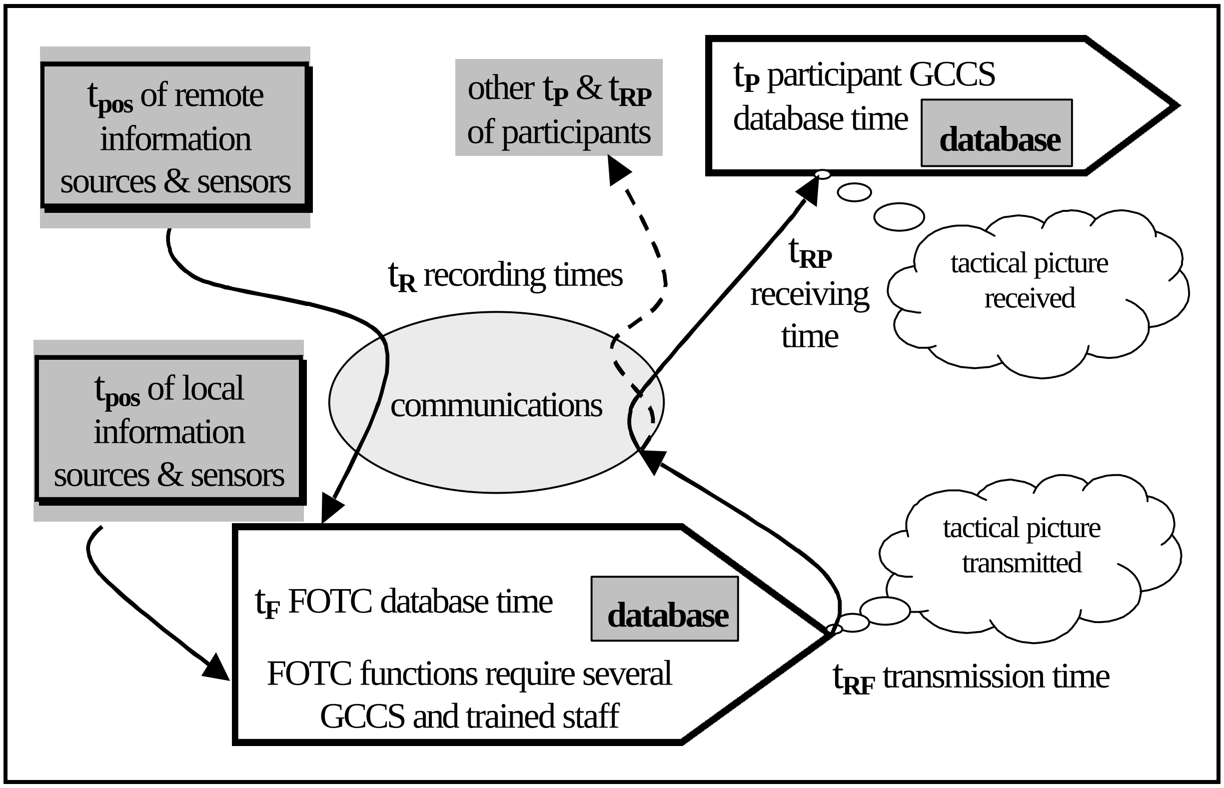

Figure 1. Development of a common operational picture

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[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.

2.2 Tactical Information Segment Used for the Tests

OTH-T MBMs were computed for the surface segment of a wide-area naval tactical picture of warships patrolling within their areas of operational interest (AOIs) and reporting 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 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 duplicated information. There is, of course, only one real wide-area naval situation at any given time. We refer to this situation as the ground truth (GT). GT information consists of the identification, allegiance and location at any given time[4] of every ship in the controlled area, over the period of time considered. In post-exercise analyses we use GT, though 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 as stimulation files. 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 events, fishing boats and merchant ships.

2.3 Operations

For our MBM purposes, 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 and 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 rules of engagement (ROEs). Then 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.

Tactical information about a ship contains its identification (class-name), its position and, at least eventually, other information such as course, speed and allegiance. Each occurrence of such a data combination is referred to as an information report on a contact. Each such report recorded during an experiment (an exercise or a simulation) also holds two time values: the "position time" and the "report time." The position time t_{pos} is the time at which the information was acquired by the sensor (sensor time). The report time t_r indicates when the information was made available to its recipient's database (WAP database time).

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

2.4 *Experimental Setup*

The report time t_r must be estimated, since available instrumentation captures only the time (the recording time of Figure 1, $t_{\mathbf{R}}$) at which the report is observed during its transition out of the compilation node (e.g., the FOTC) or into a recipient node. The information in a report does not change (except for the current time) 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: $R(t) = \text{constant for } t \in [t_{pos}$, 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 $R(t_r)$ identifies a potential engagement opportunity for which an MBM can be computed and the time t_r tells us where to look in the GT file. For the results presented in this paper we considered decision times occurring at delays varying from 0 to 64 min after position time for the purpose of assessing success rate non-linearity as 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 by the transmission time $t_{\mathbf{RF}}$ $(t_{\mathbf{RF}} > t_{\mathbf{F}})$. As soon as an information item has been processed by the FOTC staff and GCCSs, it is stored in the database. Then it is queued to outgoing message lists as for a FOTC broadcast or other 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 manually or automatically entered 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 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 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 arise naturally in physical systems.

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[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.

[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.

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 time 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 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 systems 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 deliver the maximum usefulness value of the available information that can be provided to a commander. This value is the source or sensor baseline that can be used as a reference 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 [6], we have shown that assuming dead-reckoning of the intended target during the time of delay actually yields a worse engagement outcome than assuming 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 [3, 6, 7].

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 to the experimental data yields samples of sizes approximately a hundredfold larger, which reinforces the statistical soundness of inferences made.

3. Fitting Models and Characteristic Curves

OTH-T MBM measures indicate for various scenarios and parameters the expected outcome of potential engagement actions. Notwithstanding the scaling aspects of the measures (this topic is discussed in [7]), higher values mean more favorable engagement outcomes. However, the absolute values of the MBMs can be useful for comparison purposes between data sets extracted from different experiments only in a post-exercise context. This is because 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 one may have to predict them. 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 C3I 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 here is that information is most useful when delays are negligible between information acquisition and the time at which engagement can be decided. If delays increase then information becomes less and less useful and ultimately has no impact on the actual outcome (causality fades away as delay and distance between fact and entities increase). Between these two extremes, the usefulness of information degrades at a certain rate according to some relation.

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[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.

It is hypothesized that the envelope of this aging degradation can be approximated by an appropriate model with some invariant or typical parameters. Critical values for given degradation rates may be estimated regardless 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 using nonlinear regression. The maximum rate of change is deduced from that model and is used as a normalization factor to yield a proportional characteristic degradation curve over an independent uniform scale. This curve can still be used to compare information degradation among different experiments. It cannot predict the actual raw values of the measures or their absolute rate of degradation but only the proportional speed at which information usefulness degrades for given delays. This is where we focused our investigation for invariant patterns and critical values that could be used to support decision-makers in future situations (real-time without ground-truth as it should be for decision support).

We tested three different model families over several data sets, the Rayleigh, Weibull and lognormal models[10]. The models were selected due to their close resemblance[11] with the actual data plots of the MBM measure rates of change. Figure 2 shows a typical MBM measures data plot for a given data set, Figure 3 shows the corresponding rates of change data plot and Figure 4 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 illustrated in Figure 5 .

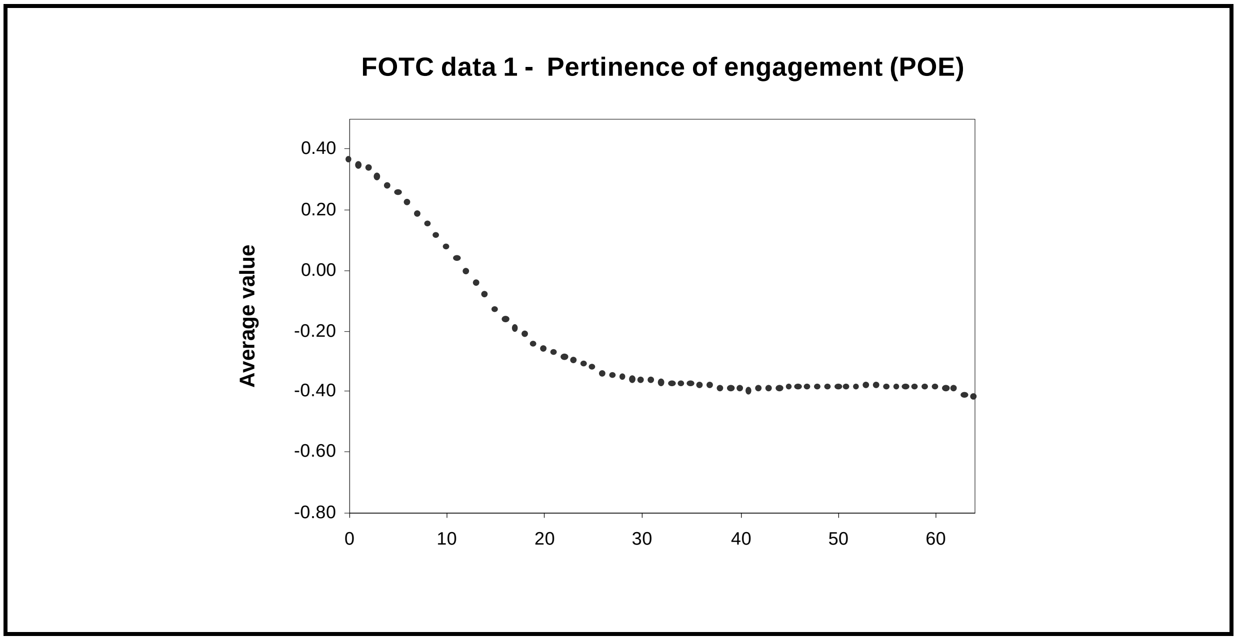

Figure 2 Typical FOTC POE value as function of time for a data set

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

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

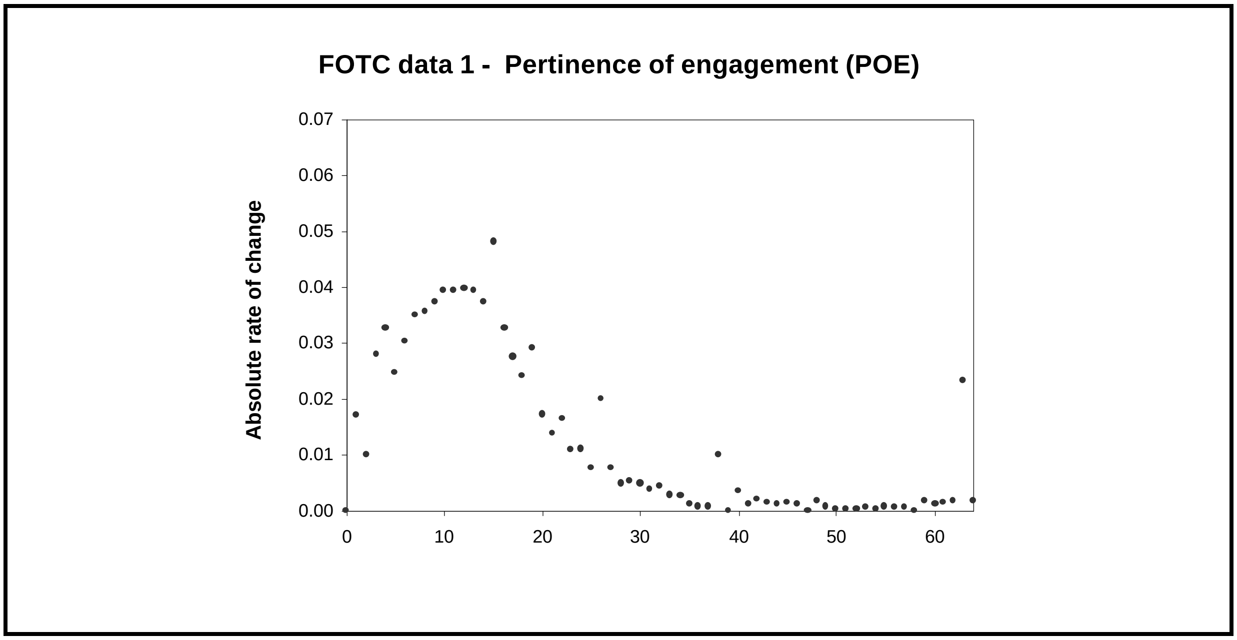

Figure 3 Typical FOTC POE degradation rate as function of time for a data set

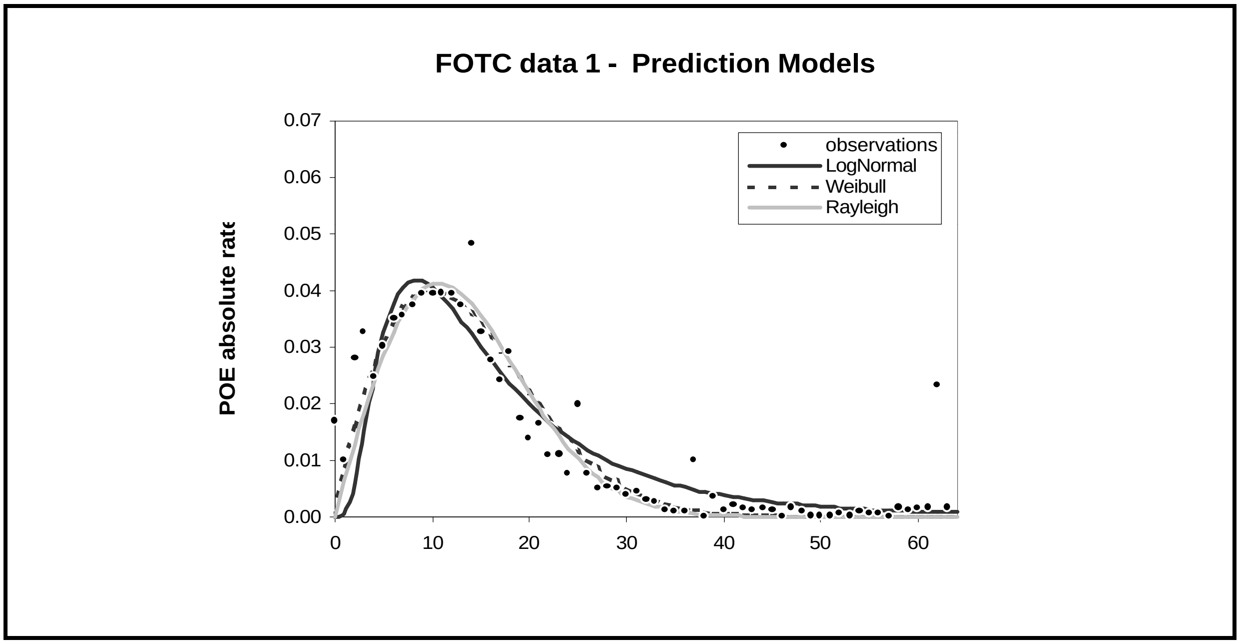

Figure 4. Three-envelope fitting models of normalized FOTC POE degradation rates as function of time for a data set; to be used in prediction models to support or improve engagement risk management

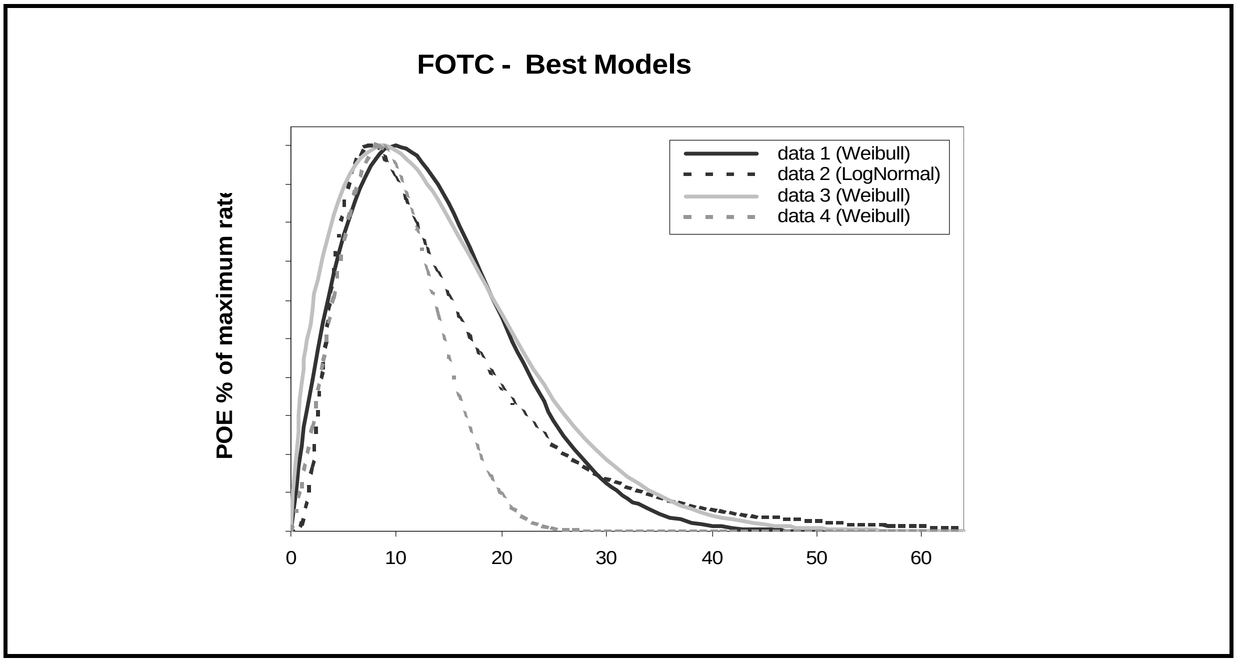

Figure 5. Best envelope fittings of normalized FOTC POE degradation rates as function of time for four data sets

Similar curves were obtained for different source-data sets and from these we can establish a set of thresholds or critical delay values for which the information usefulness degradation reaches given proportional rates of degradation. Table 1 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, degradation rate lowers down, as information usefulness 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.

TABLE 1
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**

Average delays such as those given in Table 1 may serve as threshold values to help a decision-maker in figuring out at what time taking an action might become urgent or hazardous if delayed furthermore. It can also indicate when information becomes obsolete and should be discarded, refreshed or updated by deploying or activating 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. Dependency of Model Parameters

An important aspect of the MBMs is the sensitivity of the output measures with respect 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 weapon and contact uncertainty areas. 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 probability distribution giving the probability that the contact actually lies at any given point within that area. We performed comparative analysis using different values for some of these parameters, e.g., radius of uncertainty area for contacts and major/minor axis length for weapon footprint. Figure 6 shows some typical results obtained for the average MBM measures applied over the same source data with different parameter values for uncertainty areas.

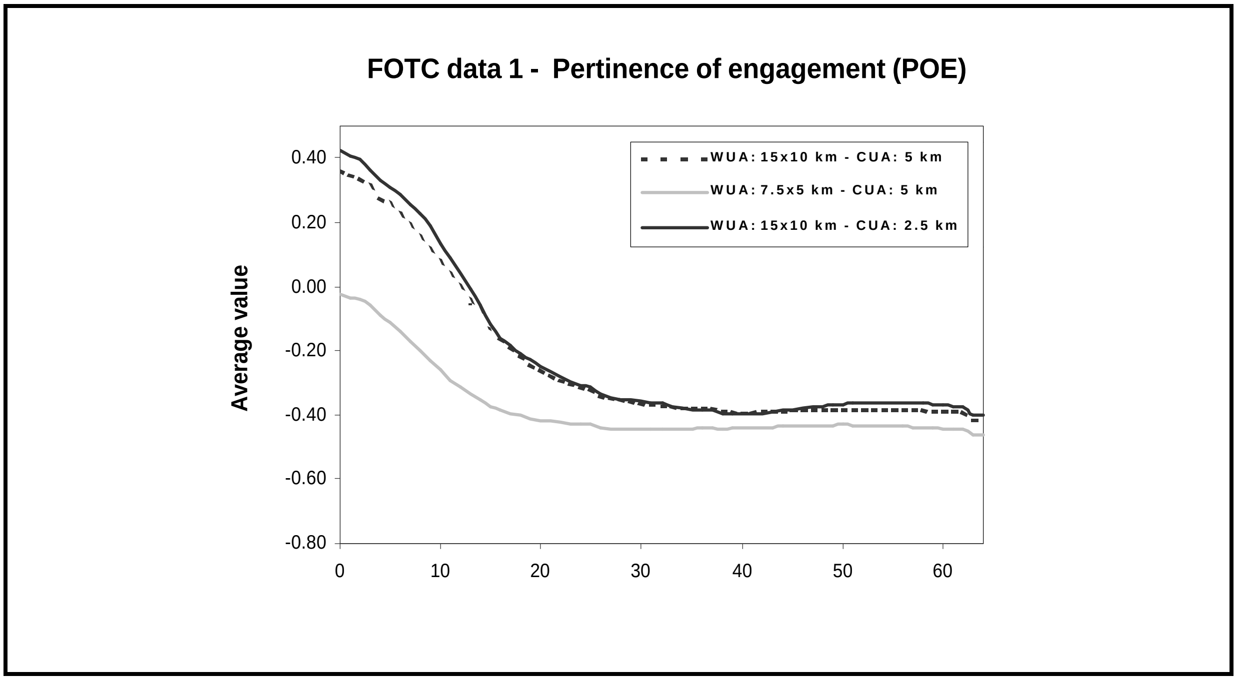

Figure 6. FOTC POE results as function of time for three sets of MBM uncertainty area parameters

The curves illustrated in Figure 6 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 than when the radius of this area is smaller. Consequently, 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 more reduced footprint area it may not overlap as many CUAs and much of their surface. Thus it may allow more missed hits. Unsurprisingly, the discriminating effect of those parameter variations vanishes when delay increases. MBM parameter dependency is most acute in the range of critical delays where information still have some value. It is yet to be investigated in more details, i.e., what are the limits of this trend that we observed and what is the best weapon to contact ratio as far as uncertainty area parameters are concerned.

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 2 shows the comparative critical values for average delays according to different uncertainty area parameters.

TABLE 2
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**

It is not yet known if the overall averages can be considered as robust estimators for any particular set of parameters. More samples of analysis results for different sets of such parameters need to be processed to reach a conclusion. It could be the case 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 sensibility with respect to other parameters as well.

5. Conclusions and Recommendations

In [8] 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 OTH-T 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.

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 are currently analyzing other data sets extracted from live exercises and results will be compared and aggregated with the results we have so far. Advanced results will be reported at the Fifth Command and Control Research and Technology Symposium later this year.

Supplementary analyses need to be performed with rounds of simulation using the same source data sets but different parameter values.

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