Model-based Assessment of COMDAT I

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Abstract

The Canadian Navy has assigned a high priority to R&D projects leading to enhanced Command and Control Information Systems (C2ISs) capabilities in data fusion. In response to this requirement, the Command Decision Aid Technology (COMDAT), a major R&D project was planned for the 2000-2004 time frame to develop Technology Demonstrators which will form the basis for defining the mid-life upgrade to the HALIFAX Class frigate C2IS. The initial project, COMDAT I, concentrates on multi-source data fusion (MSDF) using the existing sensor suite for the HALIFAX Class frigate, and remote sources through tactical information systems: Link 11 and Global Command and Control System (GCCS). In this paper we discuss several extensions to the model-based-measures (MBMs) developed at Defence R&D Canada-Valcartier (DRDC Valcartier) in support of the COMDAT I project. The extended models will be used for a comparative analysis of the legacy system and the system with inserted MSDF technology under test. Results will be used to rate the new system against the legacy system in terms of Measures of Merit (MoMs) and Maritime Tactical Picture (MTP) completeness and to identify emergent properties and advantages of the inserted technology scrutinized.

1. Introduction

We present in this section a brief overview of the COMDAT project. More detailed information can be found in [McArthur et al., 1999].

The COMDAT project will develop command decision support Technology Demonstrators for the HALIFAX Class frigate that will increase Command Team battle space awareness, as well as Command decision speed and accuracy, by providing a single, integrated, Maritime Tactical Picture and by providing decision aids, for situation and threat assessment and resource management. Technology Demonstrators are installed onboard a HALIFAX Class ship and at shore-based training facilities and assessed through a program of at-sea and shore-based trials. The scope of COMDAT, while potentially very broad, was planned to be limited by focusing on decision support for the Operations Room Officer[1] (ORO) position during the tactical phase of the mission, and by addressing the needs of a single ship, rather than the needs of the Task Group or the delegated warfare Commander.

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[1] The Operations Room Officer (ORO) reports directly to the Commanding Officer (CO) and is responsible for operations of the Operations Room (OR). General duties of the ORO include directing activities of the individual teams within the OR, monitoring/compiling the tactical picture, and recommending courses of action to the CO.

The COMDAT project will be conducted in two phases, extending from 2000-2004 and from 2004-2006, respectively. Each phase of COMDAT will be conducted using an incremental development approach consisting of multiple cycles of approximately one-year duration. This will facilitate the rapid transfer of lab-based research studies into the ship-based experimental program. Each cycle involves analysis, design, implementation, and test and evaluation activities. The results of COMDAT phases one and two will both be incorporated into evolutionary upgrades to the HALIFAX Class C2IS planned for 2005-2010.

COMDAT I, the first phase of the project, concentrates on MSDF using the existing sensor suite for the HALIFAX Class frigate. The primary objective is to demonstrate a single integrated Maritime Tactical Picture through the fusion of AWW, UWW, Link-11, and Wide Area pictures. Initial work focuses on MSDF for the AWW sensor suite (short and long range radar, IFF, ESM, and Link-11), based on research studies conducted by DRDC Valcartier [Roy and Bossé, 1997], [Labbé and Proulx, 1998-1&2]. This will be followed by incorporation of UWW and then WAP pictures, based on research carried out at Defence R&D Canada-Atlantic (DRDC Atlantic) [Campbell and Roger, 1997].

The second phase of COMDAT will focus on decision aids for tasks such as: information management, including message handling; situation assessment; threat ranking and analysis; planning courses of action, taking into account rules of engagement; weapons assignment under human veto; and, navigation and ship manoeuvres. An additional objective for phase two is the enhancement of the first phase MSDF to incorporate new sensors, including the APAR phased array radar, the SIRIUS IRST radar, and the TIAPS integrated low-frequency active/passive sonar, which are planned for the HALIFAX Class mid-life upgrade. Particularly in phase two, the design and performance evaluation of COMDAT will incorporate a human-centered approach, that emphasizes that decision aids must support the information processing requirements of the human decision maker, and is based on research carried out at Defence R&D Canada-Toronto (DRDC Toronto) [McCann et al.].

2. Approach.

In previous works, several MBMs were documented by DRDC Valcartier [Labbé and Proulx, 1998-1]. MBMs were designed to improve the accuracy and sensitivity of measures by re-sampling collected data from military exercises. They provide metrics for assessing the value of inserted technology changes and hypothesized architecture changes in terms of mission-specific effectiveness. The MBMs form a subset of MoMs for C2 systems (cf. [NATO, 1999]) that encompasses the following subclasses: Measures of Force Effectiveness (MoFEs), Measures of Effectiveness (MoEs) and Measures of Performance (MoPs). Specific MBMs such as the pertinence of engagement (POE) and intended target opportunity (ITO) focus on engagement operations. They are used to evaluate the expected outcome of engaging a potential hostile target according to the information available in a commander C2IS database. Such measures belong to the higher level MoFE and MoE classes of MoMs.

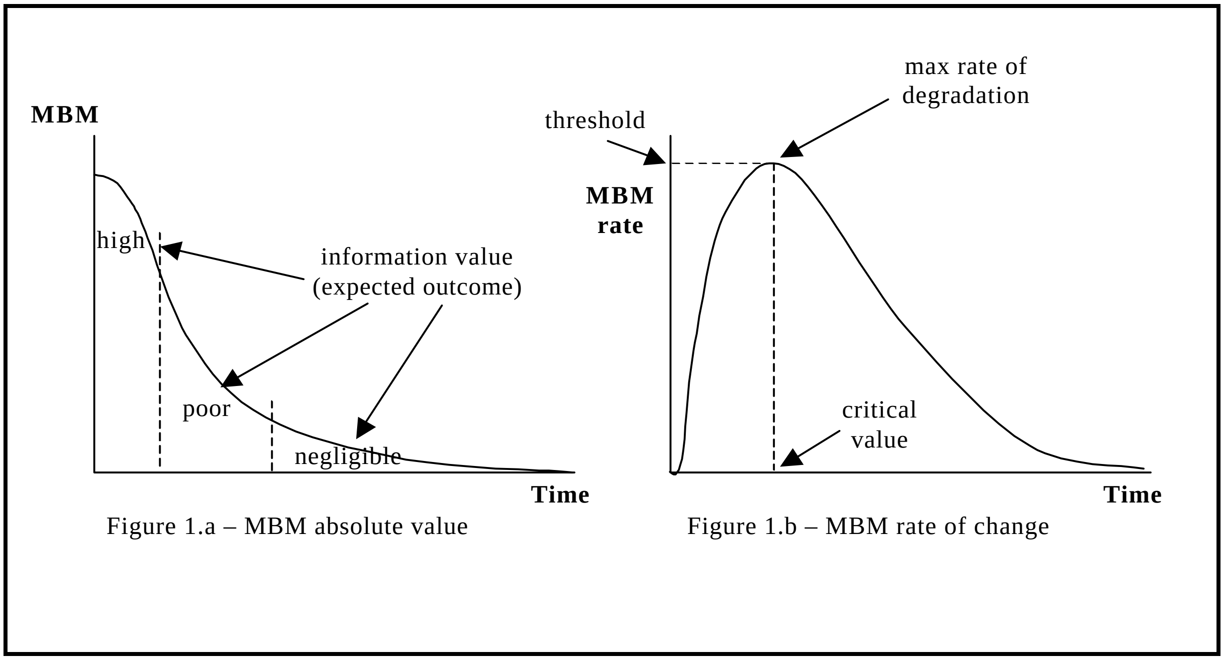

Figure 1. Typical MBM curves for engagement outcome assessment (surface picture)

Figure 1 illustrates typical curves observed for the POE measure applied over a given dataset excerpt from the surface picture information of an experiment. The time component represents the delay interval between decision to engage and the time reference of the information at the sensor baseline. The absolute value measures (Figure 1.a) require information from the ground-truth (GT) and may not be predicted in advance for a given experiment thus they are useful only in a post-exercise analysis setup. However, studying the measures rate of change (Figure 1.b) for similar experiments yields a family of curves with very similar shapes. These curves can be normalized to a standard scale and provide a sample from which characteristic curves, critical values and thresholds can be estimated in a statistically significant manner. Consequently we can infer a priori information on the rate of change of the measures even without ground-truth information. This rate of change represents the degradation effect or impact of data aging on mission effectiveness (in this case, the result of engagement decisions).

Several datasets from simulated experiments and live exercises have already been analyzed with this approach (results are documented in [Labbé and Proulx, 1998-2]). These measures will also be used to study the data provided by the COMDAT I sea and shore-based trials. However, several extensions are implemented in the MBM software to upgrade and widen its scope of application for COMDAT I. These extensions are described in the following sections.

3. Three-dimensional Battle Space

Until now, the MBM models and measures were designed and applied in the context of surface picture only. MBMs were tested for the surface segments of wide-area naval tactical picture of warships sailing within their areas of operational interest (AOIs) that report information on a variety of contacts. This information may include track, contact and sensor identification, estimated position, bearing, speed, allegiance, etc… 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 is the time at which the information was acquired by the sensor (sensor time). The report time indicates when the information was made available to its recipient’s database (WAP database time). However, the information-exchange traffic included all types of tracks (e.g., air and submarine) and other ships in the area to be controlled or monitored, over the period of time considered. Our MBMs only addressed the value of the information regarding Over-the-Horizon Targeting (OTH-T) against hostile ships. The ships of the surface tracks can be classified according to their perceived or reported allegiance as friendly, hostile, neutral or unknown. Friendly and hostile ships are military vessels of the forces in conflict. 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.

For COMDAT I the models must be extended to deal with aerial and sub-surface contacts as well. This requires extension of MBM software and utility functions to allow representation of the battle space in three dimensions. For example, areas of uncertainty for contacts (CUA) become volumes of uncertainty such as spheres and ellipsoids. Weapon footprints (WUA), trajectories and tracks are also represented in three-dimensional space. Figure 2 illustrates the various geometric shapes that are used in the extended version of the MBM software for areas of uncertainty. Each of these shapes has an associated probability distribution representing either the attraction of a given point within a WUA or the likeliness of a given point to be the actual location of the contact within a CUA. Typical distributions used include normal, triangular and uniform distributions. These are parameters that can be input in the MBM simulations through the initialization module or provided within the data input files.

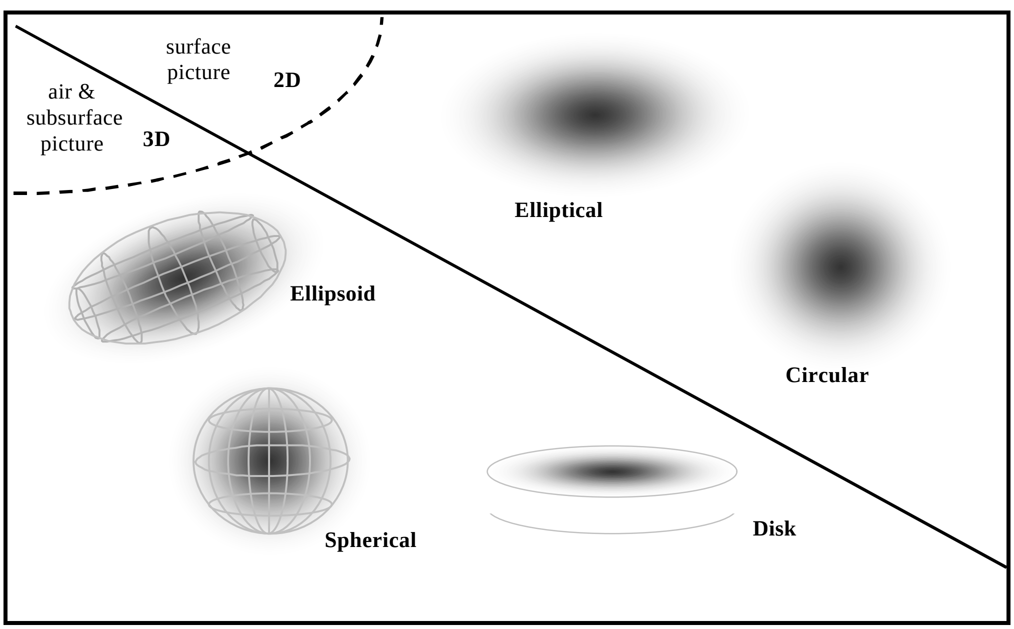

Figure 2. CUA/WUA used in MBM simulations

Analyses of previous experiments with the MBM software provided a set of characteristic curves and critical threshold values assessing the impact of surface picture quality degradation (as a function of data aging) on expected outcome of engagement decisions. Applying the extended models to the raw data collected during the sea and shore-based COMDAT I trials will provide new sets of characteristic curves and critical threshold values that will be added to the statistical database already obtained for hostile surface picture. Processing the aerial and sub-surface picture will allow the construction of similar new databases. Aerial picture analysis should yield characteristic curves that are shifted earlier in time and more compressed with smaller critical threshold values than those for the surface picture. Sub-surface picture analysis is expected to produce curves shifted later in time and more stretched with larger critical threshold values than those for the surface picture.

Implementation of the three-dimensional extension into the MBM software is straightforward and the measure computations formulation is very similar to the two-dimensional case. For instance, the extended POE measure require computations over intersections of volumes in three-dimensional metric space for which the following triple integration formula is used

$$POE = (HP * PRV) + COF$$

$$= \left(\sum_{i \in \{allegiances\}} \frac{PRV_i * T_{allegiance_i}}{\sum_{k \in \{allegiances\}} T_{allegiance_k}} \right) + COF$$

$$T_{allegiance} = \iiint_{CUA \cap WUA} \mathrm{CUA(x, y, z) * WUA(x, y, z) dxdydz}$$

$$PRV_i = pertinence \quad reward \quad value \quad for \quad allegiance \quad i;$$

$$COF = \cos t \quad of \quad firing;$$

$$\{allegiances\} = \{friend, neutral, hostile\}.$$

Calculations such as above are performed using Monte-Carlo simulation techniques. They must be performed for all engagement opportunity scrutinized and all contacts in the area of interest. When large datasets are analyzed using this simulation the processing becomes heavy on computing resources. An alternative is to actually generate specific locations for the contacts position and weapon landing points using the CUA and WUA shape, location and distribution parameters. In this way the simulation becomes more discrete and execution time greatly speeds up. On the other hand we lose much of the statistical significance induced by the previous analytical formulation and several runs must be performed to gather enough sample results data to ensure convergence of the overall results. Primary analysis of the COMDAT I data will be performed with simulations based on the analytical formulation of the measures. In another paper presented at this conference (cf. [Demers et al., 2002]) we describe the implementation and tests performed on other experimental data using the discrete version of the software.

4. Completeness.

An important extension to the MBM software is the ability to assess completeness of ground-truth and data found in a ship's Maritime Tactical Picture database for own sources, and other combination with Link 11 and Wide Area Picture Systems (WAPS) at each participant node. We discuss in this section the issues related to completeness.

4.1 Ground-Truth Completeness.

Ground-truth integrity, accuracy and completeness can be achieved only in the context of a perfectly controlled experiment (e.g., computer simulation). In live exercises such as those conducted under COMDAT I, a certain amount of uncertainty is intrinsically attached to the ground-truth information. Accuracy is usually good for friendly platforms but may be worse for non-friendly or neutral platforms so that areas of uncertainty have to be considered for the positional information found in the ground-truth. There are possible errors or biases due to the physics at play, procedures used, sensor imperfections and registration processes. Incomplete parts of the ground-truth may have to be inferred or reconstructed from various sources of information (WAPS of opposing forces, GPS logs, etc…). Measures of completeness for a live exercise GT are obtained using simple count and ratio statistics such as.

1. track density, the number of data points for each platform per selected period of time;
2. GT density, the number/proportion of platforms (or tracks) for which information exists in the GT per selected period of time;
3. proportion of "holes" in the data, holes can be "repaired" by interpolation or using WAPS of participants;
4. etc…

One must be careful when analyzing MTP exercise data with respect to reconditioned GT information. A segment of GT data that was reconstructed using the WAPS of one of the participant will obviously bias favorably the MTP quality of that participant for that period of time. The analysis process will be more objective and its conclusions more reliable if it is applied to segments where the GT completeness was optimum. Repaired or reconstructed portions of GT should be disregarded or avoided as much as possible when selecting the data segments used for the analysis. If the analysis requires lengthy segments where the GT has holes or incomplete parts then the GT reconstruction process should be designed in order to minimize any possible bias. For instance, the WAPS of each opposing force should be used to feed the GT only with the information for its own platforms. Information for neutral or extraneous parties that do not provide information on their own should be amalgamated from the available WAPS of all forces.

4.2 Tactical Picture Completeness

The completeness of the tactical picture displayed in a commander C2IS database is a concept that represents how well does the database information match the GT information for the time segment and area of interest. There are many ways to establish the MTP completeness. Here we describe the measure of MTP completeness implemented in the MBM software and used for the COMDAT I data.

While measures of completeness for GT are easy to obtain using simple count and ratio statistics it is more difficult to obtain a meaningful measure of completeness for the MTP of WAPS. MTP completeness can be considered for any independent WAPS or for multiple WAPS used to develop the MTP or a Common Operational Picture (COP). A fair measure of MTP completeness is to establish how many and how often GT tracks have been located and identified correctly in a WAPS. This requires sampling the GT database at a fixed sampling rate over time and checking how many units of a given sampled element are correctly reported in the WAPS at that time. A correct report is a contact information report with correct identification and whose CUA contains (includes) the GT unit true position at that time. Tallying these numbers over the whole sample yields a ratio statistic that is defined as the measure of completeness of the WAPS database for the period of time covered by the GT sample and geographical area considered. Completeness of a MTP involving multiple shared WAPS is established in a similar manner by checking how many units of the GT sampled elements are correctly reported simultaneously in all replicates of the tentatively shared database (obviously the completeness of the shared COP may at best match the completeness of the least complete COP participant). Defined in that way, this measure of completeness can be viewed as a MoP.

The global measure of completeness for a whole experiment can be broken down into successive measures that provide a dynamic view or history of the fluctuations of the completeness measure during the experiment. The measures of completeness are sampled at a given frequency throughout the duration of the experiment segment analyzed. This frequency should encompass many information reports successively recorded in the C2IS database. Each measure is computed over reports occurring within a specific duration interval. This duration is called the *integration time* of the measure and all completeness information acquired during that period is used to compute the measure. Integration time intervals may be arranged according to the following relations

1. integration time > sampling time, the integration time intervals overlap each other (as depicted in Figure. 3), each measure computed thus integrates a certain amount of completeness information from one or more of the previous measures, this results in a smoothing of the fitting curve through the completeness measure data points;
2. integration time = sampling time, the segment analyzed is partitioned into adjacent time intervals for which a completeness measure is output;
3. integration time < sampling time, this case is of little interest since it discards potential useful information and does not yield a history of completeness but rather selected peeks at the completeness picture.

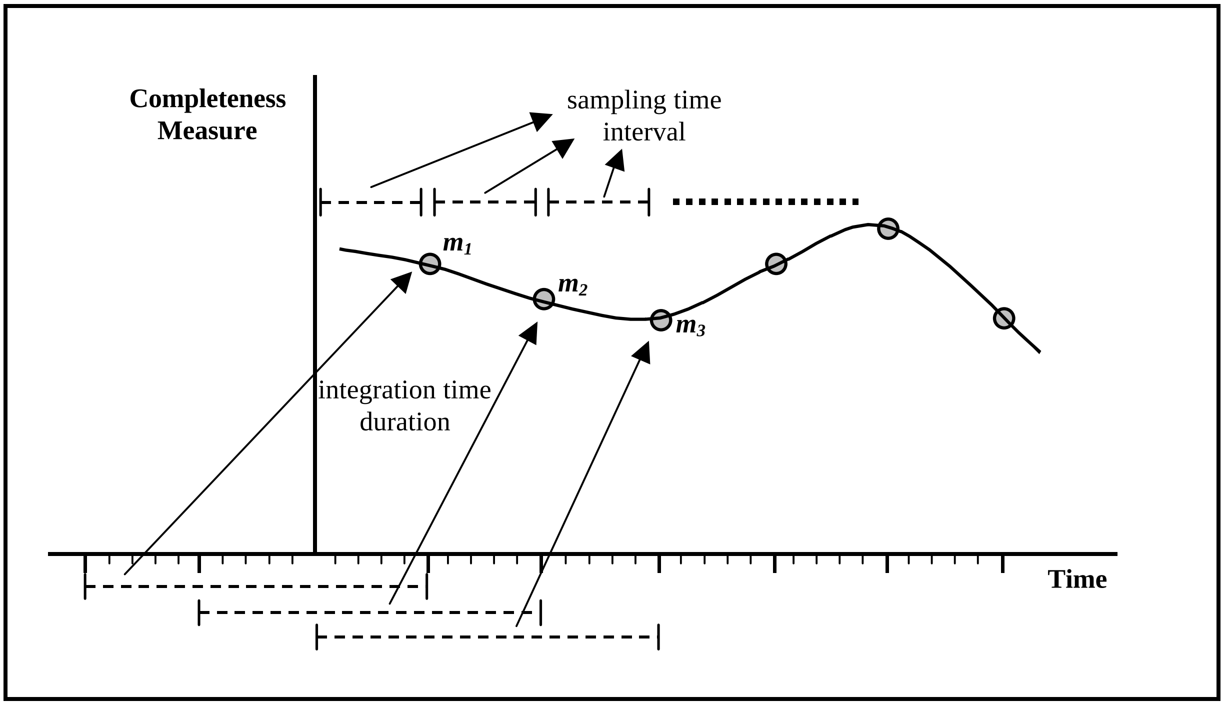

Figure 3. Completeness of MTP over time for a live exercise

Other cases must be considered such as "holes" or intervals in the data where granularity is very low, e.g., the integration time may become smaller than the time between two successive reports in the C2IS database for a certain period. In this case the count should be set to 0 as if there were only reports non-consistent with the GT for that period.

The objective is to get a comprehensive profile or history of the completeness of the MTP displayed in the C2IS for a particular experiment segment analysis and to establish meaningful relations between completeness and tactical picture quality. In doing so, we may link the tactical picture completeness, as a fused sensor coverage and information management estimator (a MOP), to higher level MoMs (MOEs and MoFEs). New sensor technology is likely to affect sensor resolution, speed of acquisition and coverage and improved sensor information fusion algorithms such as those tested in the COMDAT I trials will directly reflect on the tactical picture completeness observed. The effect of the introduction of such new technology and fusion techniques can be assessed looking at the tactical picture completeness profile in the C2IS before and after technology insertion. In addition, if we can design new MoMs that rely on completeness, mapping the completeness profile onto higher-level measures will help to evaluate its impact on mission effectiveness.

The completeness profile depends upon several parameters. Within the COMDAT I project, we will experiment various combinations of values for sampling rate, positional error, integration time and other parameters that affect the shape of the completeness curve.

4.3 Completeness and MBMs.

Completeness is an important feature for any information system. Ground-truth completeness reflects the quality of our knowledge of what the actual reality is. At the same time it imposes limits on the precision and confidence on conclusions or inferences that can be drawn from analysis results obtained using the ground-truth as a reference. The completeness of the tactical picture displayed in a C2IS is an indication of the capacity of the system to grasp information that is coherent with the ground-truth as well as the quality of the image conveyed. A high level of tactical picture completeness is surely a desirable property however it does not translate directly into mission effectiveness.

Current measures of merit (such as the POE and the ITO) obtained with the MBM software are invariant with respect to completeness. MoMs are assessed independently of surveillance-asset deployment since they do not account on MTP completeness but only on the information available to a commander in his database and on the ability of the sensors to provide correct identification and accurate position estimation. This is an advantage for comparing system efficiency independently of surveillance asset deployment and sensor capabilities. However this is a drawback of these measures in terms of MoFE since it is clear that the completeness of the MTP must have an impact on force effectiveness, and on decisions taken by commanders and consequently on the rate of success of mission operations. The current measures do not account for this aspect and are applied systematically to every engagement opportunity (an incoming information report on a presumed hostile contact). The completeness of the MTP does not affect the measures computed for any such engagement opportunity but it does affect the size and quality of the sample for which the measures are computed. Segments where completeness is high will give rise to a higher number of sample elements for the measures. Consequently, the completeness will have an impact on the overall averaged measures. This opens several paths of investigation that we want to follow.

First, the measures of completeness are implemented independently of the MBM models and the models themselves are modified to include the extension to three-dimensional battle space. In post-exercise analysis the completeness profile of the MTP is established and it is used to design a stratified sampling on the set of hostile contact information reports in the commander's database. Segments where completeness is high should be sampled at a lower rate than those where completeness is low. Applying the current MBMs on this sample and comparing the results with their application to the whole population of reports on hypothetically hostile contacts will indicate if we can restrict the analysis to a cleverly selected sample, using knowledge about the completeness, instead of the whole population (as we have done with previous experimental data). This would make the whole process less compute intensive.

Another direction is to design new sets of MoMs that would be not only dependent on the completeness of the system analyzed but would provide more sensitivity to this aspect. These measures may be incorporated in the MBM software and provide tactical picture completeness measures or estimators as complementary information used by the models. In addition, such measures would incorporate an assessment of the opportunity to take the decision to engage in a given situation without a posteriori information on the expected outcome of an engagement operation. In that case, the opportunity is not related to the expected outcome of engagement (independent of the tactical picture completeness) but on how and to what extent a commander may consider he/she has sufficient knowledge about the situation to take a decision. With a perfectly complete tactical picture the decision process is sound while it becomes a guess if the picture completeness is poor though the actual outcome of a decision to engage would be the same. However, such new measures will be useful only in post-exercise analysis where we do have the ground-truth information needed to establish the MTP completeness.

One may also consider a measure that could be computed in real time and without ground-truth information using relative “self-completeness”. Such a measure would be based only on the information available in the C2IS and might be established in a similar way as for the GT completeness by looking at the number of units currently displayed, “holes” or periods of time where a unit or track previously displayed in the C2IS was not updated, etc... Accuracy and correctness of allegiance/identity would be subjected to uncertainty and could not be matched against GT information but such a measure could be used as a real-time decision aid indicating whether or not the current “self-completeness” of the tactical picture displayed may help taking a decision. Furthermore, such computation of self-completeness would provide a means for improving information management and surveillance deployment in real time

5. Conclusion

In this paper we have presented an approach for analyzing COMDAT I sea and shore-based trial data, extending and upgrading DRDC Valcartier MBM software. The extensions to the models include new measures to assess GT and MTP completeness, processing of the aerial and sub-surface picture, new MoMs that incorporate completeness information and new sampling scheme for post-exercise analyses. In support of the COMDAT I project, the extended models will be used for a comparative analysis of the legacy system and the system with inserted MSDF technology under test. The comparative analysis will rate both systems in terms of MTP completeness, previous MBMs (POE and ITO) and new MoMs added to the MBM software.

Investigations are currently being carried out. For this paper (before using COMDAT I data), analysis of completeness is performed only for the surface picture as in previous MBM papers and involves experimentation with different means of completeness parameterization (sampling rates, integration time, positional error tolerance, etc…). Due to the classified nature of the project, analysis results for the COMDAT I data cannot be reported or discussed in an unclassified paper and forum.

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