

Using A Priori Databases for Identity Estimation through Evidential Reasoning in Realistic Scenarios

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INTRODUCTION AND SCOPE

Canadian defence companies and Government Research and Development (R&D) laboratories have long ago recognized the necessity to develop comprehensive a priori databases containing all the possible attributes that can be inferred by measurements coming from a given sensor suite. In order to maintain this document at a NATO unclassified level, a small portion of an existing (consisting of more than 2200 platforms) database is presented, which nevertheless contains all the salient features needed for refining the identity (ID) of any target by the fusion of sensor information. In addition, only the information gathered from unclassified sources such as Jane's and Periscope is presented. This a priori Platform DataBase (PDB) contains all the possible naval and air targets, military or commercial, that can be encountered in realistic scenarios, and all the attributes that can be measured by any sensor belonging to any own-platform of the Canadian Forces (CF), ensuring its possible common use throughout the CF. Also presented and explained are all the attributes and all the correlations between platforms that are appropriate to Situation and Threat Assessment (STA or higher-level fusion), and which are present in the larger database. This paper focuses on only one own-platform of the CF in relevant scenarios, the maritime surveillance aircraft CP-140 Aurora (a Canadian version of the US's P3-C with S2-B avionics) in its present operational status, and also with an anticipated upgraded sensor suite. Validation and benchmarking of the chosen evidential reasoning scheme for identity estimation, is performed through several simulated scenarios that make use of DRDC-Valcartier Concept Analysis and Simulation Environment for Automatic Target Tracking and Identification (CASE-ATTI) sensor module. Two missions have received special consideration because they make full use of all the CP-140 sensors: 1) Maritime Air Area Operations (MAAO) involving a mix of commercial merchant ships and enemy line combatant ships performing exercises, and 2) Direct Fleet Support (DFS) involving fleets of Canadian and American ships on a NATO mission, that are imaged with the Aurora's imaging sensors.

1.0 ATTRIBUTE INFORMATION FROM SENSORS

The present and foreseen CP-140 sensors can be divided into three broad classes depending on the type of input they provide to the MSDF function:

- 1) *Identification* sensors, namely special-purpose "intelligent" sensors, reporting distilled ID information such as Electronic Support Measures (ESM), Identification Friend or Foe (IFF response), and datalink (Link-11 ID information)
- 2) *Imaging* sensors, namely the existing Forward Looking InfraRed (FLIR) and the upcoming Spotlight Synthetic Aperture Radar (SSAR) upgrade to the present radar. The SSAR will have

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4 modes: 2 for Land Use (the Land Spotlight and StripMap) and 2 for Ships (Sea Spotlight and Range Doppler Profiling)

- 3) *Tracking* sensors (radar when not SSAR mode, Link-11 positional information)

The set of databases needed for the identification of platforms can be decomposed into a Platform DataBase (PDB), an Emitter Name List (ENL) and a Geopolitical List (GPL):

- 1) the PDB used for identification purposes spans all possible targets that can be met in the most important Aurora missions and contains all the possible attributes for each platform
- 2) the ENL includes all emitters (navigation, targeting, etc.) corresponding to each platform of the PDB
- 3) the GPL provides the allegiance of various countries and thus can evolve as the geo-political context of missions changes.

The attributes coming from sensors that are catalogued in the PDB can be split into three groups:

- 1) Kinematical attributes
- 2) Geometrical attributes
- 3) Identification attributes

These are further detailed in the sub-sections below [1,2].

1.1 Kinematical Attributes

Kinematical attributes can be estimated through tracking in the positional estimation function of Multi-Sensor Data Fusion (MSDF), and through reports from IFF and datalink. A minimum list contains:

- maximum acceleration, both tangential (if available for aircraft, it denotes the likely presence of afterburners) and centrifugal (with higher g values likely denoting a fighter aircraft)
- maximum platform speed (the quoted value is relevant to static ambient atmosphere and must be interpreted, or fuzzified, to account for air currents, particularly when the aircraft can reach the jet stream)
- minimum platform speed, e.g. a null value for an aircraft denotes the a Short Take-Off & Vertical Landing (STOL) capability, or a helicopter.
- maximum altitude that a platform may reach can serve as a bound for altitude reported by the IFF or which can be deduced from a tracker in 3-D from sensor reports in 2-D and assumed flight characteristics. For a submarine, this corresponds to the maximum depth that can be achieved (a negative quantity).
- cruising speed

The first 4 serve as bounds to discriminate between possible target IDs, while the fourth can suggest a list of the most plausible IDs.

1.2 Geometrical Attributes

Geometrical attributes can be estimated by algorithms which post-process imaging information from sensors such as FLIR or Electro-Optics (EO) and SSAR.

Classifiers that perform such imagery post-processing can be thought of as Image Support Modules (ISM) performing much the same functionality as the ESM does for the analysis of electromagnetic signals. These ISMs need

- the three geometrical dimensions of height, width and length (for FLIR and EO), or at least their ratios if range information is not provided by the tracker that cued the imaging sensors, or if no laser ranging is possible, and
- the Radar Cross Section (RCS) of the platform seen from the front, the side and the top (for the SSAR and radiometric radar).

In addition, the distribution of relevant features may be needed for classifiers, but may be considered part of the algorithms that generate plausible IDs. Such features can be superstructure locations (for the SSAR) or hot point distribution (for the FLIR).

1.3 Identification Attributes

Identification attributes can be directly given by the ESM, or as outputs of the FLIR and SSAR ISM at various stages of their classification. The ESM requires an exhaustive list of all the emitters that are carried by each platform. In addition certain acoustic features leading to possible submarine or ship ID can be listed, such as propulsion type, number of propellers, number of blades, number of cylinders.

However the ISMs are usually designed [3] to not only attempt at providing the best single ID possible but also to estimate confidence in higher levels of an appropriate taxonomy tree, since often only general characteristics application to several platforms of a given “type” can be identified. This taxonomy tree is usually derived from some standard, either STANAG 4420 or MIL-STD 2525 (A or B), and can have many levels of branching, e.g. a “domain” includes several “types”, which include many “classes”, etc., etc., eventually reaching the leaves of the tree providing the specific platform ID or singleton.

Taxonomy trees can be implemented as an extension of the PDB. In the example shown in Figure 1 below, a number of K attributes (8 are specifically indicated) are linked to N elements (7 are specifically indicated) of the platform library including 5 elements of library taxonomy. The taxonomy is a tree of few levels where the branches are also attributes.

Often, especially for STA applications, it is enough to know the type of platform rather than its specific ID. Naval battlegroup compositions, air attack formations, and the content of convoys over land, follow general well-known patterns, and need not necessarily be detailed to the platform level to ascertain lethality and/or intent.

The usefulness of the extra taxonomy elements will be shown in the next section, in the context of a chosen evidential reasoning scheme [4].

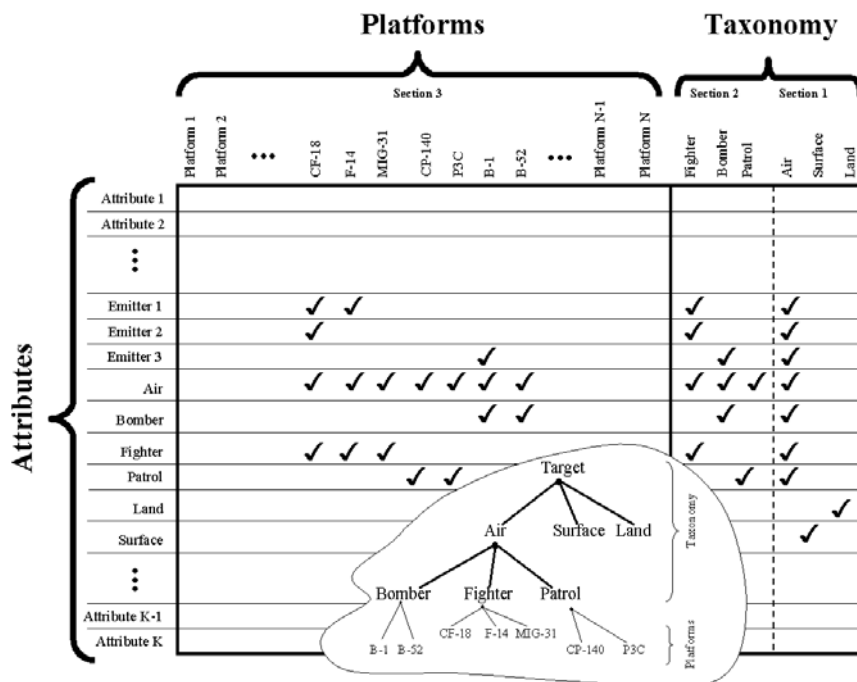


Figure 1: Example of a taxonomy tree structure for the a priori PDB.

In an alternative "transposed" description, the tabular form of the PDB can be thought of as rows being indexed by single platforms (singletons), and with columns representing measured attributes and the various levels of the taxonomy. The actual implementation is a matter of choice. Such a representation is shown in Table 1 below for a sample of Russian ships (later to be used in the MAAO scenario), with the emphasis only on the subtype taxonomy and the complete emitter list (each number in the list corresponds to a NATO designation in the ENL). It should be observed that the emitter list is exhaustive and contains many emitters common to several platforms. This immediately implies that many fusion steps of ESM reports must be performed in order to reach a proper identification to the lowest level of the taxonomy tree, namely the desired singleton.

Table 1: An example of an alphabetical list of Russian ships

#	Platform name	Type	List of emitters
242	BEREZINA AOR	TANKER	44,64,47,45,83,46,103,109
249	DUBNA AOR	TANKER	47
237	GORYA MHO	MINE SWEEPER	65,274,46,275,109
219	GRISHA I FFL	FRIGATE	44,105,103,104,47,109,106,83
220	GRISHA II FFL	FRIGATE	44,105,103,104,47,109,106
221	GRISHA IV FFL	FRIGATE	44,105,47,45,83,46,103,104,109,106
232	IVAN SUSANIN AGB	ICEBREAKER	44,56,64
234	IVAN-ROGOV-ALEKSANDR LPD	LANDING SHIP	93,89,103,101,68,46,45,65,64,62
235	IVAN-ROGOV-MITROFAN LPD	LANDING SHIP	93,89,103,101,68,46,45,65,64,105
213	KARA-AZOV CG	CRUISER	78,84,62,64,85,45,92,68,46,93,104,103
214	KARA-KERCH CG	CRUISER	78,84,62,64,47,85,45,68,46,93,104,103
215	KIROV-ADM-USHAKOV CGN	CRUISER	77,89,90,65,67,92,84,80,45,71,46,93,101,106
224	KRIVAK IB FFG	FRIGATE	63,69,67,45,68,103
225	KRIVAK II	FRIGATE	62,69,67,45,103
226	KRIVAK IIIA FF	FRIGATE	62,69,66,45,71,46,103,101
212	KUZNETSOV CV	AIRCRAFT	95,63,65,97,301,99,100,307

240	MATKA PH	PATROL BOAT	303,327,46,103,101,109
216	MOSKVA CHG	CRUISER	77,84,62,47,85,83,103,104
241	MURAVEY PH	PATROL BOAT	66,46,103,109
227	NANUCHKA I FFG	FRIGATE	128,333,83,45,104,109,334
228	NANUCHKA III FFG	FRIGATE	128,333,45,104,109,334,46
239	NATYA II MS	MINE SWEEPER	47,86,87,109,103
229	NEUSTRASHIMY FFG	FRIGATE	63,65,335,71,106
246	OSKOL AR	SUPPORT VESSEL	47
230	PARCHIM II FFL	FRIGATE	335,338,46
247	PRIMORYE AGI	SUPPORT VESSEL	64
217	UDALOY AND KULAKOV DDG	DESTROYER	69,97,65,67,91,46,71,101,106,89,93
218	UDALOY II DDG	DESTROYER	69,97,63,65,128,91,71,93,131

For convenience land targets are usually treated separately, since their taxonomy tree is much more complex.

2.0 EVIDENTIAL REASONING ON THE A PRIORI PDB

The question then arises as to which reasoning framework to use for compounding, or fusing, successive sensor declaration about a given attribute. The best choice seems to be the Dempster-Shafer (DS) formalism because it can:

- process incomplete information, implying that ignorance should be a concept defined mathematically rigorously (ignorance corresponds to the complete PDB in DS reasoning)
- not require a priori information, sometimes impossible to gather for a given mission, which rules out Bayes reasoning (Bayesian would have to split the ignorance equally across all other platforms, which can lead to large computational loads)
- handle conflicts between contact/track, implying that conflict should be defined a concept mathematically (conflict is calculated as the sum of BPAs with null set intersection in DS)
- have a real-time method, which means that DS truncation is essential (rules to that effect have been empirically determined and benchmarked)
- present the operator with the best ID, i.e. give preference to singletons, then the next best thing, i.e. doublets, then triplets, etc., or equivalently...
- have the possibility of computing beliefs in higher nodes of the tree, as sums of BPAs of the underlying branched structure
- have the possibility of providing several different functions as a decision aid, which can be, in the DS scheme, the plausibility or the expected utility interval, for example.

A sensor reporting a given attribute, then declares an ID proposition containing all the singletons having that attribute, with a Basic Probability Assignment (BPA or mass) reflecting its confidence in the attribute determination (which can be quite complex if the attributes are fuzzified).

Identity estimation is performed by the fusion of existing ID information from previous repeated fusion (therefore a long list, possibly truncated in number), with the new (possibly complicated) declaration from any of the sensors or ISMs. The DS combination method can done one of two ways

- 1) either using the original Orthogonal Sum (OS) which calculates conflict and redistributes it to the whole set of propositions [1,2],
- 2) or using a Hierarchical OS (HOS) which redistributes possible conflict by assigning the mass value to the first node of the tree that resolves the conflict [4].

The standard OS reads [1,2], for set of proposition A_i (coming from the sensor) and B_j (from previous fusion steps) yielding the set of proposition C_k

$$m(C_k) = \sum_{i,j \ni A_i \cap B_j = C_k} \frac{m(A_i)m(B_j)}{1-K} \quad K = \sum_{A_i \cap B_j = \Phi} m(A_i)m(B_j)$$

with K being the conflict arising between the sets A_i and B_j (whenever the intersection is the null set).

In the case of the HOS the algorithm is explained below [4], when each of A and B has the form of bitstreams given by Figure 1 (checkmarks being 1, otherwise entries are zero), where the operator “==” refers to the standard equality comparison operator, \cup and \cap refer to the logical OR and AND operations applied on bitstream, the \oplus symbol stands for the concatenation procedure applied on a section of bitstream, and \emptyset refers to the null set. Given two propositions described by the bitstreams A and B :

HOS : IS $A.\text{section}[3] \cap B.\text{section}[3] == \emptyset$?

No: $C = A.\text{section}[1,2,3] \cap B.\text{section}[1,2,3]$

Yes: IS $A.\text{section}[2] \cap B.\text{section}[2] == \emptyset$?

No: $C = \{(A.\text{section}[3] \cup B.\text{section}[3])\} \oplus \{A.\text{section}[1,2] \cap B.\text{section}[1,2]\}$

Yes: IS $A.\text{section}[1] \cap B.\text{section}[1] == \emptyset$?

No: $C = \{A.\text{section}[2,3] \cup B.\text{section}[2,3]\} \oplus \{A.\text{section}[1] \cap B.\text{section}[1]\}$

Yes: $C = \text{Ignorance.}$

The OS is regularly used in the MAAO and DFS scenarios to be discussed later, with an appropriate truncation scheme to keep the potentially NP-hard problem CPU-tractable. An example of such truncation rules and the related parameters is shown below [5].

- 1) All combined propositions with $BPA > MAX_BPM$ are kept
- 2) All combined propositions with $BPA < MIN_BPM$ are discarded
- 3) If the number of retained propositions in step 1 is smaller than MAX_NUM , it retains, by decreasing BPA, propositions of length 1
- 4) If the number of retained propositions in step 3 is smaller than MAX_NUM , it does the same things with propositions of length 2
- 5) Repeat a similar procedure for propositions of length 3
- 6) If the number of retained propositions is still smaller than MAX_NUM , it retains propositions by decreasing BPA regardless of length.

Typical values for the parameters are $MAX_BPM = 0.05$ and $MIN_BPM = 0.01$ for $MAX_NUM = 8$, and some simple empirical rules relating these parameters can be found, for example the following simple inversely proportional formula is suggestive of a possible simplification [5]:

$$MAX_BPM = 1 / (2.5 * MAX_NUM)$$

$$MIN_BPM = 1 / (12.5 * MAX_NUM)$$

In addition, to prevent the algorithm from being unable to recover from a series of countermeasures, a small lower limit has to be imposed for the ignorance at all times.

3.0 HIGHER LEVEL INFORMATION FOR THE A PRIORI PDB

The Levels 2 and 3 databases, i.e. the STA/RM DB should contain all the platform parameters relevant for STA as well as RM, i.e., since missiles (number and detailed properties) on enemy ships are relevant for STA, while the same information on possible own-platforms is relevant for RM. In a Network Centric Warfare (NCW) context, the lethality of enemy platforms in the red force is important for STA, and the lethality of cooperating Participating Units (PUs) is relevant for RM within the blue force. A non-exhaustive list contains elements pertaining to [6]:

- 1) Platform and Mission:
 - displacement,
 - number of operational copies of the platform,
 - list of hull numbers & names (if it can be provided for ID in harbors, air fields, etc.),
 - range of deployment,
 - platform type (with amplification),
 - role for the mission, and
 - crew (for full operation)
- 2) Armament (type and number of examples present on platform, both HW as well as humans for mission deployment):
 - Surface-to-Surface Missiles (SSMs), including submarine launched missiles
 - Surface-to-Air Missiles (SAMs), including submarine launched missiles
 - Close-In Weapon Systems (CIWSs),
 - Air-to-Surface Missiles (ASMs),
 - Air-to-Air Missiles (AAMs),
 - CIWSs,
 - conventional bombs,
 - troop complement (number of special force for assault, landing or parachuting),
 - lethality,
 - guns, and
 - torpedo tubes
- 3) Sensors (mostly passive, in order to estimate probability of own-platform detection, excluding the radar already in PDB):
 - Infra Red Search and Track (IRST),
 - sonars (e.g., Hull-Mounted Sonar, towed-array, sonobuoy, tethered sonar), and
 - imaging sensors (e.g., EO, FLIR, SAR)

- 4) Air Platforms on Deck (for surface ships):
- Number of helicopters (on any line combatant ship)
 - Number of aircraft (on aircraft carrier)

4.0 TYPICAL DS RESULTS USING THE A PRIORI PDB INFORMATION

Results from the two complex scenarios that use DRDC-Valcartier's Concept Analysis and Simulation Environment for Automatic Target Tracking and Identification (CASE-ATTI) sensor module are presented in this section [1,2]:

- 1) Maritime Air Area Operations (MAAO) involving a mix of commercial merchant ships and enemy line combatant ships performing exercises, and
- 2) Direct Fleet Support (DFS) involving fleets of Canadian and American ships on a NATO mission, that are imaged with the Aurora's imaging sensors (only the SSAR results are presented here).

For both the MAAO and DFS scenarios, the DS OS is used for the ID fusion. In both scenarios, SSAR imagery is used to attempt to help the classification. A SSAR simulator provided by DRDC-O was used to produce the imagery for the appropriate acquisition parameters. The two scenarios were intentionally built to test

- 1) the limits of the association mechanism for ESM reports (with inter-ship distances at the theoretical limit of discernability), leading to occasional miss-associations, and
- 2) the performance of the SSAR ISM, by choosing ships whose imagery can be misconstrued. This is achieved by having the scenario contain ships of unusual length for their types, which fools the Bayesian classifier, which uses length distribution to detect ship type.

The section will demonstrate that the DS scheme is robust under countermeasures (i.e. wrong ESM associations, either by deliberate spoofing, or by algorithmic error). Also this section will present a toy scenario illustrating the HOS method for the taxonomy tree previously shown in Figure 1.

4.1 OS Results for Real-Life MAAO and DFS Scenarios

At appropriate times in the MAAO scenario, several ESM contacts are received for each hostile vessel, one such contact being incorrect for one platform (chosen arbitrarily to be the Udaloy destroyer), in order to test the robustness of the DS evidential reasoning algorithm under countermeasures. This discrepancy will prompt the use of SSAR imaging of the Udaloy and members of its convoy. As soon as the operator has imaged the Udaloy, he/she will then in short order image two other ships in the Russian convoy, namely the Kara cruiser and the Mirka frigate with roughly the same acquisition parameters, since the surveillance aircraft's motion over such a short period of time is not very significant. To create the imagery of enemy ships, a simulator from DRDC-Ottawa was used with permission. The imagery thus generated is unclassified, and its interpretation by the SAR ISM is reproduced below in Figure 2 (removal of artifacts by thresholding between the top 2 rows of imagery, and centerline detection by a Hough transform are clearly visible). The category (merchant vs. line combatant) is always properly achieved by the Neural Net category classifier, and the type ID by the Bayes classifier is always correct. More information on the hierarchical SSAR classifier can be found in reference [3].

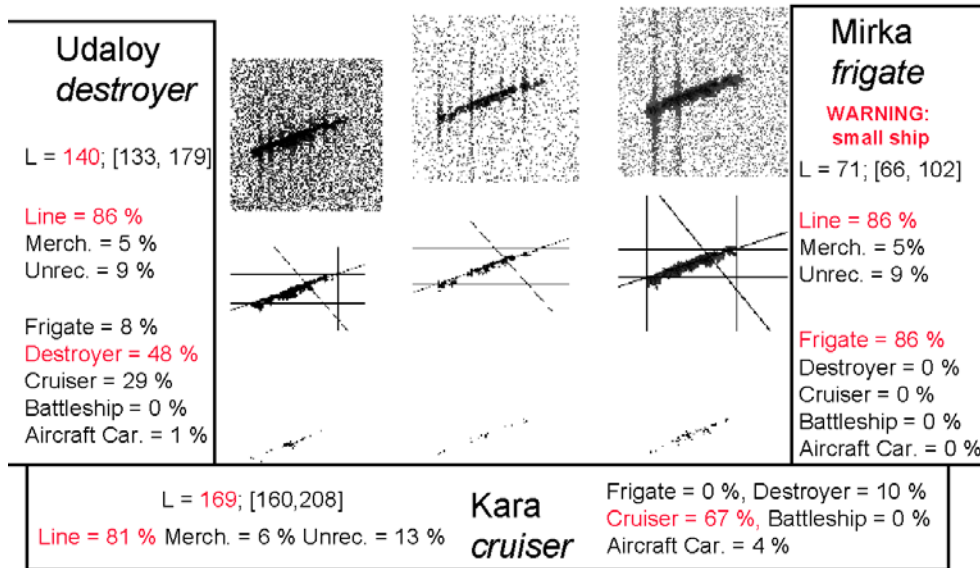


Figure 2: SAR imagery and ISM performance for Russian ships in MAAO scenario.

The PDB contains many Russian ships with emitters common to the 3 ships in the MAAO scenario, as was shown in Table 1 (not all Russian ships are in that Table, e.g. the Mirka is not listed), hence many ESM reports are necessary to achieve correct ID. The ESM reports are chosen at random amongst the possible list given in Table 1 when no countermeasures are present. The most complicated DS reasoning occurs for the Udaloy II as mentioned previously and is shown in Figure 3 below. In this Monte-Carlo case, no emitter report was detected during this time by the ESM, that could distinguish the 2 versions of the Udaloy in the PDB (triangles in blue are discriminating emitter reports and a SSAR ISM fusion confirming an Udaloy triplet of same RCS signature).

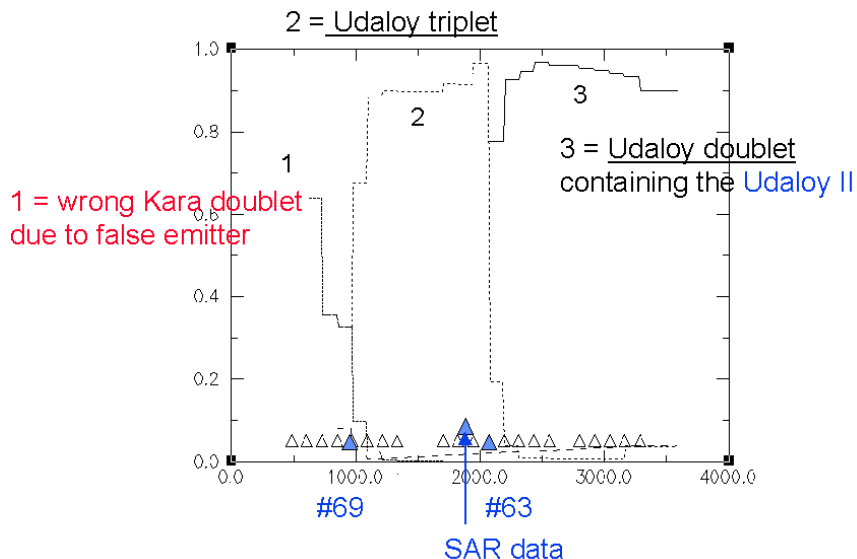


Figure 3: ID for the Udaloy II after countermeasures and with SAR ISM fusion.

If one concentrates on American ships in the DFS scenario, the resulting SAR imagery and ISM interpretation achieved is depicted in Figure 4 below.

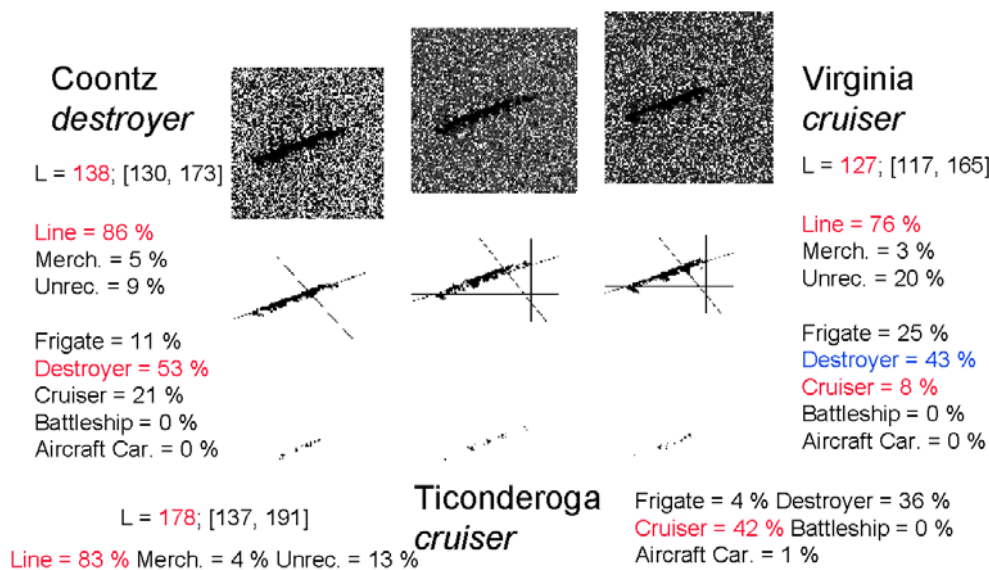


Figure 4: SAR imagery and ISM performance for American ships in DFS scenario.

In this case, it should be noted that the SAR ISM incorrectly identifies the Virginia cruiser as a destroyer because its length is small for a cruiser, (blue indicates a mistake by the SAR ISM, red a successful ID). If the imagery is done sufficiently early in the scenario, the ESM reports will eventually confirm the Virginia (rather than a destroyer such as the Spruance), otherwise it may not (depending on the Monte-Carlo run).

4.2 HOS Results for a Toy Scenario

To isolate the effect of ID fusion in the presence of a hierarchical taxonomy tree, and the functioning of the HOS, the toy scenario is much less complicated than the MAAO or DFS scenarios, and it incorporates simple trajectories, but provides conflicting ID information as time increases. Whereas the MAAO and DFS scenarios involve ships seen from a maritime surveillance aircraft, this toy scenario involves air targets seen from a Canadian Patrol Frigate of the HALIFAX (or City) class. Since the PDB contains all possible platforms, either application uses the same PDB.

In the toy scenario, we will focus on one AIR target track for which the 3 levels of taxonomy shown in Figure 1 apply. In order to provide conflict, one adds a dummy emitter which, as Figure 1 shows, is only found on bomber planes in our database. Thus the ESM will report fighter emitters most of the time, but once in a while, it will report a bomber emitter for that same plane. The other sensors simulated do not report any conflicting information (unlike the SAR in the DFS scenario).

The simulated results are as follows and are presented in Figure 5 which schematises the results of the best ID proposition, the one with the largest BPA (or mass), found for this target in the simulation case described below at critical fusion times [4]:

- 1) at time t_1 a report is received from the radar sensor reporting only kinematics. This, using a fuzzy logic test, leads to the statement Air with a BPA of 80%.
- 2) at time t_2 , a first ESM report is received. It reports one of the emitters for a fighter (with a BPA of 80%) let us call it E_1 . At this point this emitter is sufficient to correlate the information with the database and we know that this emitter is on a fighter without knowing which one.
- 3) at time t_3 another fighter emitter, E_2 , is reported giving the full identification of the CF-18 which is the only one with both emitters on board.

- 4) at time t_4 , the conflicting report is received reporting an emitter E_3 belonging to bombers only. We see that, at this point, there is identity degradation once the report is fused with the previous information but not completely.

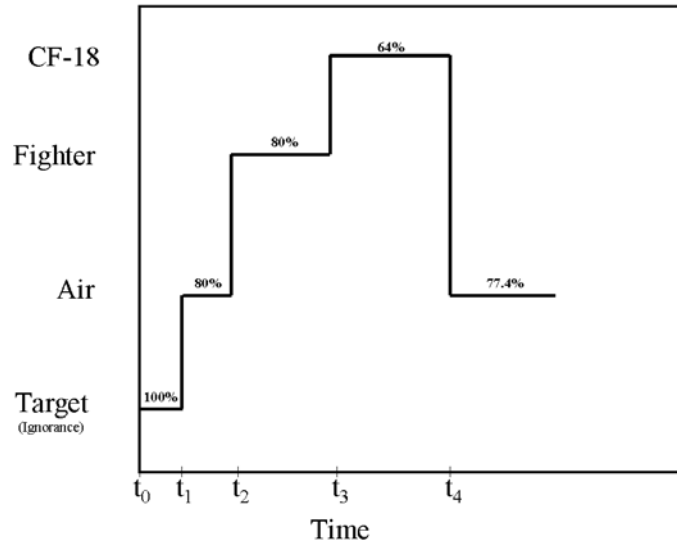


Figure 5: Taxonomy level of the target best ID proposition as a function of the time.

The following Table 2 summarises the results for all identities by showing the BPA of each proposition as a function of the time of fusion:

Table 2: Taxonomy level of the target best ID proposition as a function of the time

Proposition	t_1	t_2	t_3	t_4
CF-18	0%	0%	64%	12.8%
Air-Fighter	0%	80%	32%	6.4%
Air	80%	16%	3.2%	77.4%
Bomber	0%	0%	0%	3.2%
Ignorance	20%	4%	0.8%	0.2%

Even in the presence of conflict, the identity of the platform after the conflicting report remained partly correct. We observe that the belief in the AIR statement (sum of all BPAs of propositions that are sub-sets of air) remained after t_4 with 99.8%. This is in contrast to the OS method, which would have reduced the BPA of the Air proposition to approximately 24%. Here also the probability of the platform being a Fighter is diminished and a new Bomber statement appeared with lower confidence. The next ESM report, if not conflicting, will bring the correct identity back. This treatment of conflict, is probably more adapted to what an operator would like to see in the presence of conflicting evidence, namely assigning BPA to the first non-conflicting branch of the tree, rather than renormalizing all the fused propositions in the presence of a large conflict.

5.0 CONCLUSIONS

This paper has presented the design of a comprehensive a priori PDB for MSDF and STA applications, and examples of its successful use through the DS evidential reasoning scheme, under extreme conditions,

e.g. involving countermeasures, badly interpreted imagery, wrongful associations for large target density, etc. Several versions of the DS method and several scenarios were presented in order to present a large spectrum of realistic applications. The realism of the scenarios was provided by simulators from DRDC-V for radar (and ESM) and from DRDC-O for SSAR imagery.

Furthermore, this DS-based ID determination has been demonstrated with success in current sea trials which have been underway as part of the Command Decision Aid Technology (COMDAT) for the HALIFAX class frigates.

6.0 ACKNOWLEDGEMENTS

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7.0 REFERENCES

Only the most recent references are shown below. Earlier references (there are many before 1999) can be found within these.

- [1] Valin, P., Jouan, A., and Bossé, E. (1999), Fusion of imaging and non-imaging sensor information for airborne surveillance, Proc. SPIE Aerosense Conf. 3719 on Sensor Fusion: Architectures, Algorithms, and Application III, Orlando, 7-9 April 1999, pp. 126-138.
- [2] Jouan, A., Valin, P., and Bossé, E. (1999), Testbed for Fusion of Imaging and Non-Imaging Sensor Attributes in Airborne Surveillance Missions, FUSION 99, 6-8 July 1999, Sunnyvale, CA, Vol. 2, pp. 823-830.
- [3] Valin, P., Tessier, Y., and Jouan, A. (1999) Hierarchical Ship Classifier for Airborne Synthetic Aperture Radar (SAR) Images, Proc. 33rd Asilomar Conference on Signal, Systems and Computer, 24-27 October, Pacific Grove, pp. 1230-1234.
- [4] Simard, M.A, Valin, P., and Lesage, F. (2000), The ID box: a Multisource Attribute Data Fusion Function for Target Identification, Proc. SPIE Aerosense Conf. 4051 on Sensor Fusion: Architectures, Algorithms and Applications IV, Orlando, April 24-28 2000, pp. 180-190.
- [5] Valin, P., and Boily, D. (2000), Truncated Dempster-Shafer Optimization and Benchmarking, Proc. SPIE Aerosense Conf. 4051 on Sensor Fusion: Architectures, Algorithms and Applications IV, Orlando, April 24-28 2000, pp. 237-246.
- [6] Valin, P. (2001), Reasoning Frameworks for Fusion of Imaging and Non-imaging Sensor Information, in Proceedings of the Workshop on Estimation, Tracking and Fusion: A Tribute to Yaakov Bar-Shalom, Naval Postgraduate School, Monterey, CA, May 17 2001, pp. 269-282.

Using “a priori” Databases for Identity Estimation through Evidential Reasoning in Realistic Scenarios

NATO RTA 2003 - Prague - 20-22 October 2003



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Defense R&D Canada - Valcartier*

Attribute Information from Maritime Surveillance Sensors

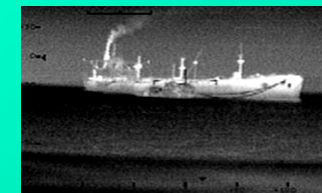


- **Identification**-based intelligent sensors
 - **Electronic Support Measures (ESM)** AN/ALR-502 providing **passive** ID information through detection of emitters cross-correlated with a realistic **a priori Platform DataBase (PDB)**
 - **Interrogation Friend or Foe (IFF)** AN-APX-502 providing **allegiance** (if in proper working condition)
 - Link-11, mainly for ID information
- **Imaging** sensors
 - **Spotlight Synthetic Aperture Radar (SSAR)** planned upgrade to AN/APS-506 radar --> design/implement cued **classifier**
 - **Forward-Looking Infra-Red (FLIR)** OR-5008/AA **passive** sensor --> design/implement different **classifiers**
- **Tracking** sensors
 - **2-D AN/APS-506 radar** providing tracks, in 3 modes
 - Link-11, mainly for positional information

CP-140 (Aurora) sensors for maritime surveillance



SSAR ↗



FLIR ↗
+ IFF
+ ESM
+ Link-11

Other Aurora sensors not considered for fusion: MAD, camera, sonobuoy information

Set of Databases needed for ID fusion



- **Platform DataBase (PDB)**, used for **Identification (ID)**
 - **all possible targets**
 - **all possible target attributes**
 - kinematical
 - geometrical
 - ID related
 - should be applicable for any (blue-force) own-platform
 - infrequent updates, pre-loaded for ID fusion
- **Emitter NameList (ENL)**
 - contains all emitters for each platform of PDB
 - provides ID # and NATO name cross-correlation
- **Geo-Political List (GPL)**
 - provides allegiance of countries
 - can change depending on mission context

Attributes in PDB :

Kinematical attributes



- can either provide **limits** for ID validation
- or provide **typical values** for fuzzified sensor declaration
 - maximum acceleration: tangential, centrifugal (g-value)
 - maximum speed: possible need for interpretation, fuzzification
 - minimum speed: useful for helos and STOL
 - maximum altitude: useful for IFF validation
 - 3-D radar tracks if available
 - negative value denotes maximal depth for subs
 - typical speed: cruise velocity, also fuzzified
 - can be obtained from tracker in fusion module

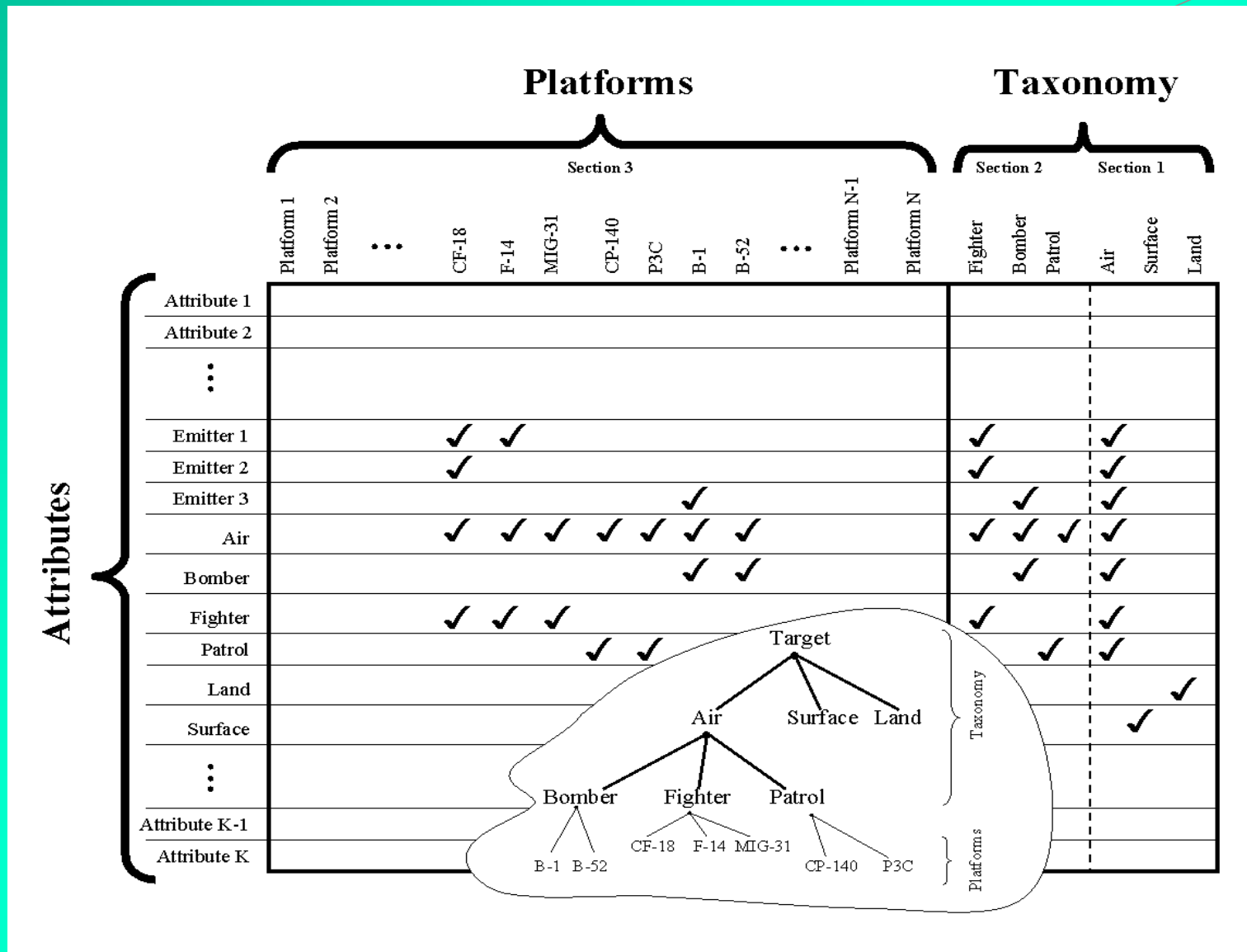
Attributes in PDB :

Geometrical and ID attributes

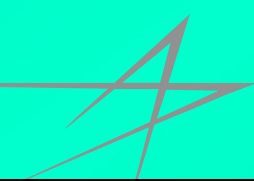


- **Geometrical**, for use with/within imaging sensor classifiers, providing Image Support Modules (ISM) similar to ESM role
 - actual size (length, width, height), for **FLIR or EO**
 - RCS values (top, side, front), for **SSAR**
- **Identification**, from “intelligent” sensors and/or operators
 - from **ISMs for FLIR and SSAR**
 - from **ESM** declaration of emitters on target platform
 - from **future acoustic ISM**: propulsion type, no. of propellers, no. of blades, cylinders, etc.
- Since ISMs often cannot report down to the exact ID (singleton), there is a need for a **taxonomy tree**

Example of a taxonomy tree



Typical ESM list in level 1 PDB



**MANY
COMMON
EMITTERS**

**within
and across**

**VARIOUS
TYPES**

**each #
corresponds
to a NATO
emitter name**

#	Platform name	Type	List of emitters
242	BEREZINA AOR	TANKER	44,64,47,45,83,46,103,109
249	DUBNA AOR	TANKER	47
237	GORYA MHO	MINE SWEEPER	65,274,46,275,109
219	GRISHA I FFL	FRIGATE	44,105,103,104,47,109,106,83
220	GRISHA II FFL	FRIGATE	44,105,103,104,47,109,106
221	GRISHA IV FFL	FRIGATE	44,105,47,45,83,46,103,104,109,106
232	IVAN SUSANIN AGB	ICEBREAKER	44,56,64
234	IVAN-ROGOV-ALEKSANDR LPD	LANDING SHIP	93,89,103,101,68,46,45,65,64,62
235	IVAN-ROGOV-MITROFAN LPD	LANDING SHIP	93,89,103,101,68,46,45,65,64,105
213	KARA-AZOV CG	CRUISER	78,84,62,64,85,45,92,68,46,93,104,103
214	KARA-KERCH CG	CRUISER	78,84,62,64,47,85,45,68,46,93,104,103
215	KIROV-ADM-USHAKOV CGN	CRUISER	77,89,90,65,67,92,84,80,45,71,46,93,101,106
224	KRIVAK IB FFG	FRIGATE	63,69,67,45,68,103
225	KRIVAK II	FRIGATE	62,69,67,45,103
226	KRIVAK IIIA FF	FRIGATE	62,69,66,45,71,46,103,101
212	KUZNETSOV CV	AIRCRAFT	95,63,65,97,301,99,100,307
240	MATKA PH	PATROL BOAT	303,327,46,103,101,109
216	MOSKVA CHG	CRUISER	77,84,62,47,85,83,103,104
241	MURAVEY PH	PATROL BOAT	66,46,103,109
227	NANUCHKA I FFG	FRIGATE	128,333,83,45,104,109,334
228	NANUCHKA III FFG	FRIGATE	128,333,45,104,109,334,46
239	NATYA II MS	MINE SWEEPER	47,86,87,109,103
229	NEUSTRASHIMY FFG	FRIGATE	63,65,335,71,106
246	OSKOL AR	SUPPORT VESSEL	47
230	PARCHIM II FFL	FRIGATE	335,338,46
247	PRIMORYE AGI	SUPPORT VESSEL	64
217	UDALOY AND KULAKOV DDG	DESTROYER	69,97,65,67,91,46,71,101,106,89,93
218	UDALOY II DDG	DESTROYER	69,97,63,65,128,91,71,93,131

Common ID fusion requirements lead to Dempster-Shafer (DS) reasoning

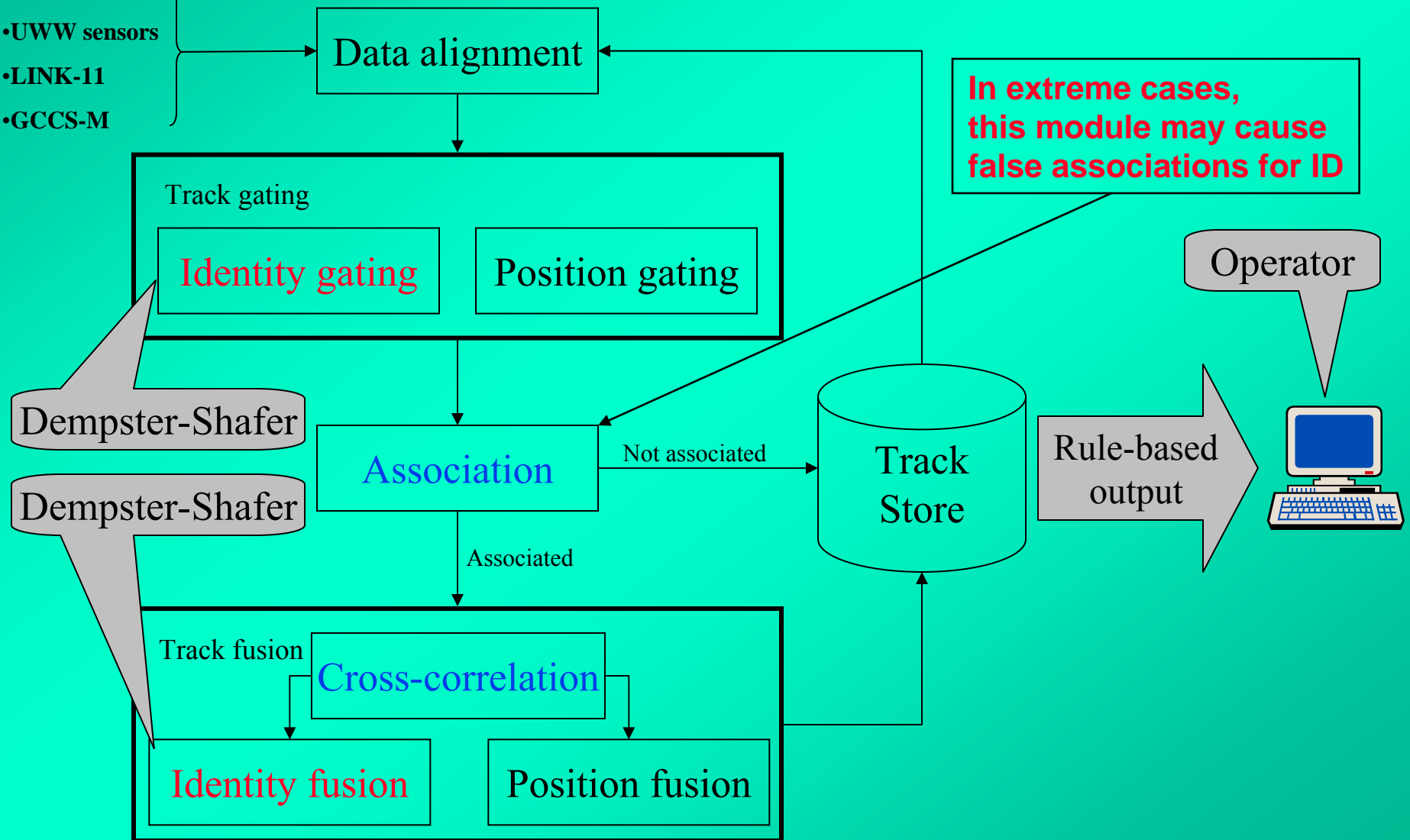
- Must process **incomplete information** ↑ **ignorance**
- Must **not require a priori information** ↑ **No Bayes**
- Must handle **conflicts** between contact/track ↑ **DS**
- Must be a **real-time** method ↑ **Truncation** is required
- Operator wants **best ID** ↑ give preference to **singleton**
- Operator wants **next best** ↑ doublet, triplet, tree, etc.
- Must be **tested** operationally ↑ **complex scenarios**
- Ordinary DS **must explode** ↑ **large complex PDB**
- Must **resist CM** ↑ contact report **conflicts with PDB**
- Must **resist false associations** ↑ ESM to wrong track

CONFLICTING, UNCERTAIN and **INCOMPLETE** information are ideally suited to **DS evidential reasoning**, while **TRUNCATION (TDS)** ensures **low CPU usage**

Where is DS used?



- AWW sensors
- UWW sensors
- LINK-11
- GCCS-M



What is DS Theory ?



- Let θ be the set of all possible propositions whose elements are
 - **exhaustive** (if not, then Smets' version of open universe)
 - **mutually exclusive** (if not, then Dezert-Smarandache version of finer granularity through non-null intersection)
- $P(\theta)$ is the set of all 2^θ subsets of θ
- Let be A an element of $P(\theta)$
- A Basic Probability Assignment (BPA or **mass**) is a function from $P(\theta)$ to $[0, 1]$ defined by
$$m : P(\theta) \rightarrow [0, 1]$$
$$A \rightarrow m(A)$$
- θ represents the **ignorance**, and can have a mass

More about DS Theory : the Orthogonal Sum (OS)



- The combined mass function of two independent mass function is **usually calculated** by using the original DS **Orthogonal Sum (OS)**:

$$m_1 \oplus m_2(A) = \frac{\sum_{B \cap C = A} m_1(B)m_2(C)}{1 - K}$$

$$K = \sum_{B \cap C = \emptyset} m_1(B)m_2(C)$$

where **K** represents the **conflict** between **B** and **C**

- The lower probability of a subset **A** of $P(\theta)$ is called the **belief** in **A**

$$Bel(A) = \sum_{i=1}^{2^{|A|}} m(A_i) \quad A_i \subseteq A$$

- The upper probability of a subset **A** of $P(\theta)$ is called the **plausibility** of **A**

$$Pls(A) = 1 - Bel(\neg A)$$

More about DS theory : Hierarchical OS (HOS)

- If contact/track fusion leads to **conflict K at level L** of a taxonomy tree
 - BPA is thrown **up taxonomy tree to first level node where no conflict exists**
 - **resolution of conflict leads to mass redistribution NOT mass renormalization**
- Algorithm for bitstream with taxonomy of ID at levels 3 and 2 (as shown previously)

Given two propositions described by the bitstreams A and B:

Add: $A.\text{section}[3] \cap B.\text{section}[3] = \emptyset$

No: $C = A.\text{section}[1,2,3] \cap B.\text{section}[1,2,3]$

Yes: $A.\text{section}[2] \cap B.\text{section}[2] = \emptyset$

No: $= \{(A.\text{section}[3] \cup B.\text{section}[3]) \oplus \{A.\text{section}[1,2] \cap B.\text{section}[1,2]\}$

Yes: $A.\text{section}[1] \cap B.\text{section}[1] = \emptyset$

No: $C = \{A.\text{section}[2,3] \cup B.\text{section}[2,3] \oplus \{A.\text{section}[1] \cap B.\text{section}[1]\}$

Yes: $C = \text{Ignorance.}$

Truncated Dempster-Shafer (TDS)

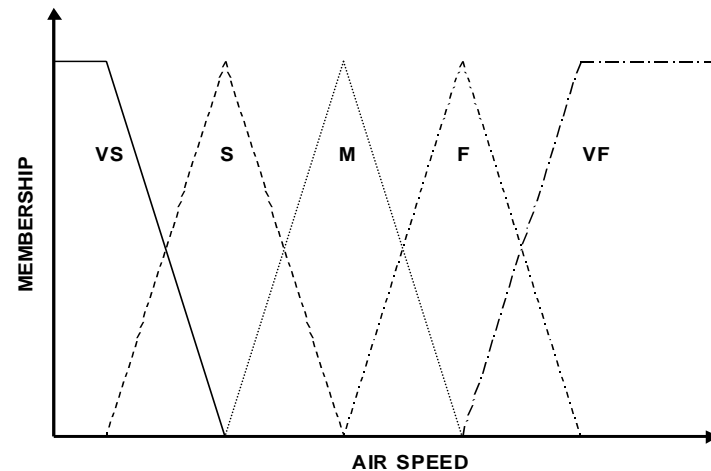


- CPU constraints handled by truncation, which can depend on task (gating, update) or importance
- Successive steps depending on BPA (mass)
 - All combined propositions with $BPA > MAX_BPM$ are kept
 - All combined propositions with $BPA < MIN_BPM$ are discarded
 - If the number of retained propositions in step 1 is smaller than MAX_NUM , it retains, by decreasing BPA, propositions of length 1
 - If the number of retained propositions in step 3 is smaller than MAX_NUM , it does the same thing with propositions of length 2
 - Repeat a similar procedure for propositions of length 3
 - If the number of retained propositions is still smaller than MAX_NUM , it retains propositions by decreasing BPA regardless of length
- Mass of truncated propositions is sent to Ignorance (which has a minimum)
- All propositions renormalized to a sum of 1 at each step
- Attribute fuzzification e.g. for speed into bins for air and sea targets independently, such that declarations can contain many propositions: 60% “very fast”, 30% “very very fast”, 10% “fast”

How and when to fuse attributes

- **How:** Fuse only fuzzified physical values, since exact values irrelevant & not easily obtained, e.g. for speed

VS = Very Slow
S = Slow
M = Medium
F = Fast
VF = Very Fast



- Fuse new sensor declarations about attribute values **only when** significantly different from history
 - pre-filtering ensures independence of successive sensor declarations, as required for efficient fusion
 - pre-filtering ensures that no single sensor dominates others, preserving complementarity

Supplemental information needed for higher level PDB



- **Levels 2, 3 databases for**
 - **Situation and Threat Assessment (STA)**
 - **Resource Management (RM)**

should contain all the platform parameters relevant for STA as well as RM, e.g. since

 - **missiles (number and detailed properties) on enemy ships are relevant for STA**
 - **missiles on possible own-platforms are relevant for RM**
- **In a Network Centric Warfare (NCW) context, the lethality**
 - **of enemy platforms in the red force is important for STA**
 - **of cooperating Participating Units (PUs) in blue force is relevant for RM**

Supplemental information needed for higher level PDB



- **Platform and Mission:**
 - displacement
 - number of operational copies of the platform
 - list of hull numbers & names (if it can be provided for ID in harbors, air fields, etc.)
 - range of deployment
 - platform type (with amplification)
 - role for the mission
 - crew (for full operation)

Supplemental information needed for higher level PDB



- **Armament:** type and number present on platform, both **HW** as well as **humans** for mission deployment
 - Surface-to-Surface Missiles (SSMs), including from subs
 - Surface-to-Air Missiles (SAMs), including from subs
 - Close-In Weapon Systems (CIWSs),
 - Air-to-Surface Missiles (ASMs),
 - Air-to-Air Missiles (AAMs),
 - CIWSs,
 - conventional bombs,
 - troop complement (number of special force for assault, landing or parachuting),
 - lethality,
 - guns, and
 - torpedo tubes

Supplemental information needed for higher level PDB



- **Sensors:** mostly passive, in order to estimate probability of own-platform detection

Note: radar emitters already in level 1 PDB for ESM

- Infra Red Search and Track (IRST)
- sonars
 - Hull-Mounted Sonar
 - towed-array
 - sonobuoy
 - tethered sonar
- imaging sensors (e.g., EO, FLIR, SAR, SSAR)
- **Air Platforms on Deck** (for surface ships):
 - Number of helicopters (on any line combatant ship)
 - Number of aircraft (on aircraft carrier)

Test scenarios



- **Maritime Air Area Operations (MAAO)**

- ID of 3 typical enemy Russian ships (also Typhoon sub)
 - Udaloy destroyer
 - Kara cruiser
 - Mirka frigate

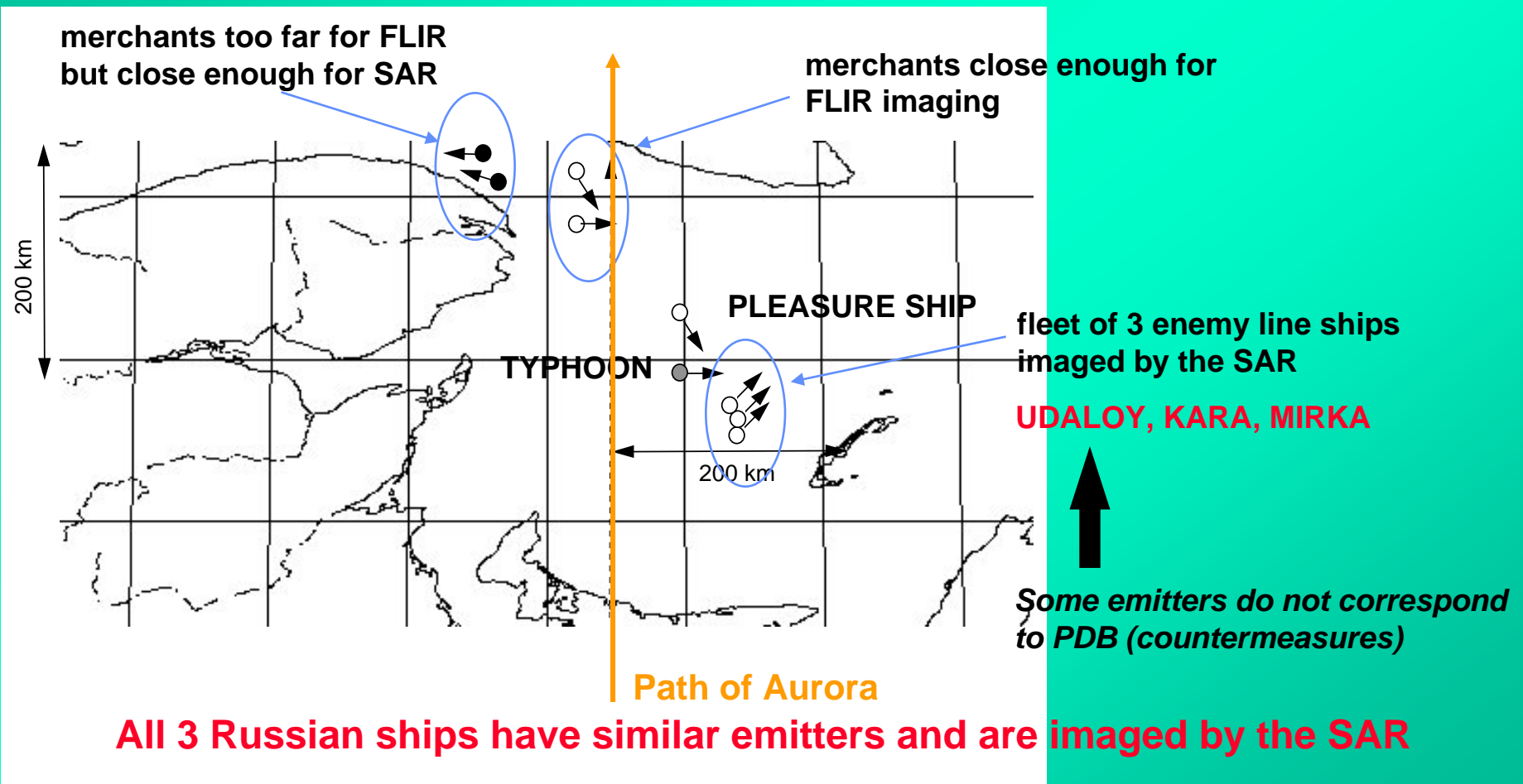
in the presence of some **ESM countermeasures** (false emitters) fusing the **SAR ISM results** since the enemy line ships are of **different types**, but typical of type

- **Direct Fleet Support (DFS)**

- ID of American ships (also Spruance, Nimitz, Sacramento)
 - Coontz destroyer
 - Ticonderoga cruiser
 - Virginia cruiser

no countermeasures, fusing **SAR ISM results**, BUT Virginia cruiser is atypically small (like a frigate)

Scenario 1 - Maritime Air Area Operations



Possibility of many other ship choices (line or merchant)

ISM results for Russian fleet



Udaloy *destroyer*

L = 140; [133, 179]

Line = 86 %

Merch. = 5 %

Unrec. = 9 %

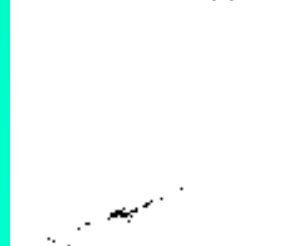
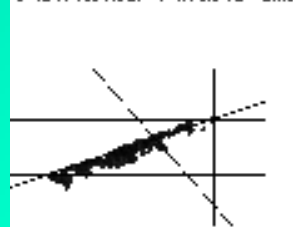
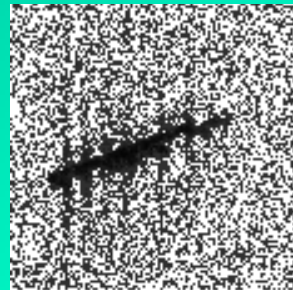
Frigate = 8 %

Destroyer = 48 %

Cruiser = 29 %

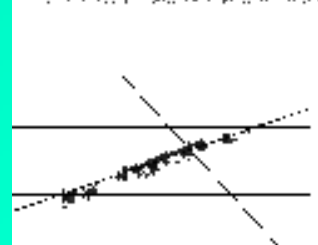
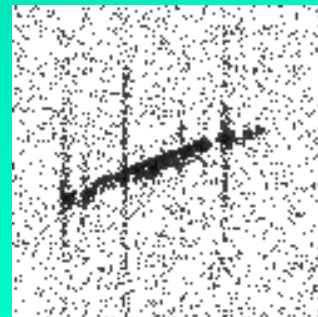
Battleship = 0 %

Aircraft Car. = 1 %

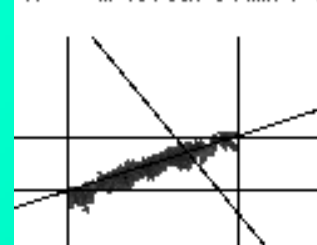
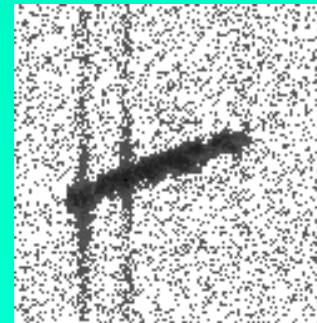


L = 169; [160,208]

Line = 81 % Merch. = 6 % Unrec. = 13 %



Kara *cruiser*



Mirka *frigate*

WARNING: small ship

L = 71; [66, 102]

Line = 86 %

Merch. = 5%

Unrec. = 9 %

Frigate = 86 %

Destroyer = 0 %

Cruiser = 0 %

Battleship = 0 %

Aircraft Car. = 0 %

Frigate = 0 %, Destroyer = 10 %

Cruiser = 67 %, Battleship = 0 %

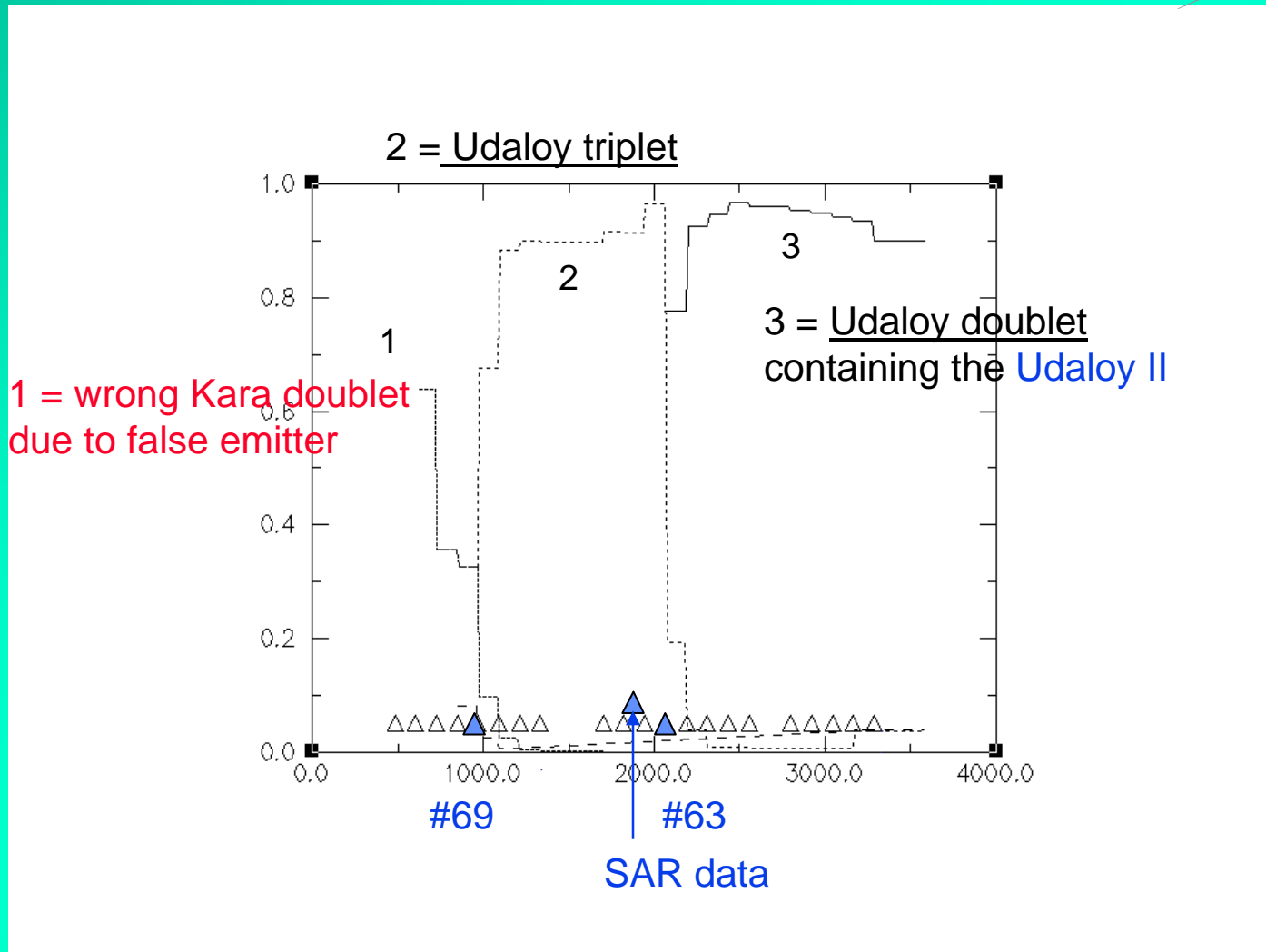
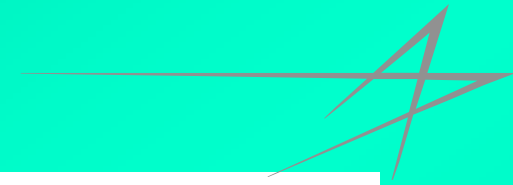
Aircraft Car. = 4 %

Naval IDs with SAR's ISM



- *As before Russian ships chosen have many common emitters reflecting incremental fleet upgrades (**emitter numbers with # in blue**)*
 - Udaloy triplet & also **countermeasures**
 - Kara quartet
 - Mirka doublet
- ***BLUE indicates correct platform ID, RED incorrect class***
- *Since ESM reports are **RANDOMLY SELECTED**, this new scenario run choose a different random set of emitters to be fused at regular intervals (also many: 30 or 60 of them)*
 - The truncated Dempster-Shafer algorithm is thus expected to **give different results**
 - The SAR reports (3 declarations) occur half-way through & are still outnumbered by ESM reports - **not easily visible**

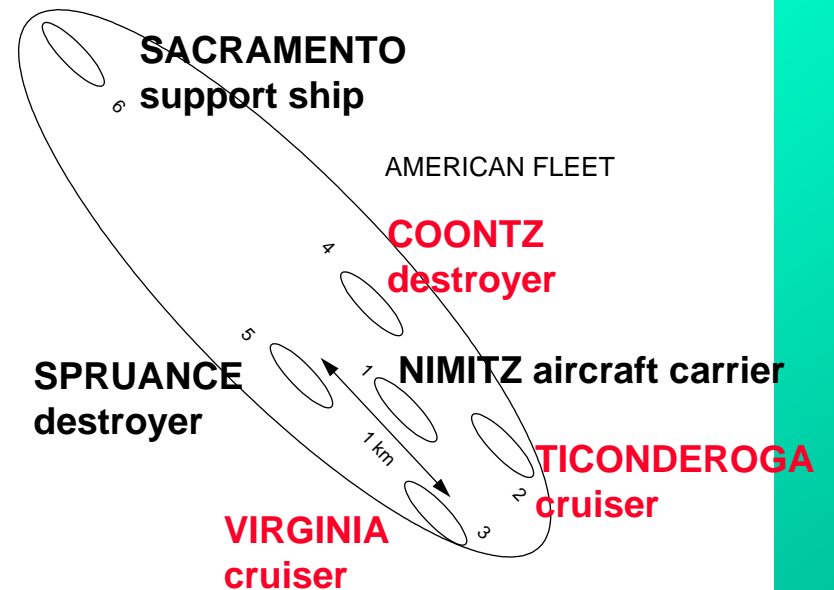
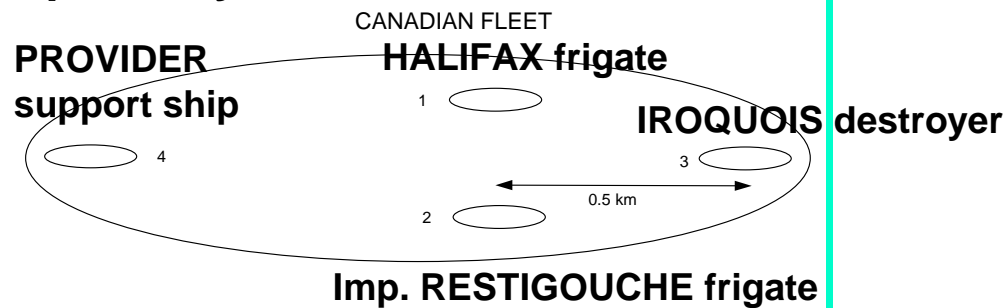
Udaloy II ID with ISM



Scenario 2 - Direct Fleet Support



Canadian contingent
too close for SAR
possibly FLIR ?



American ships in **RED** are imaged by SAR
Possibility of many other line ship choices

ISM results for American fleet



Coontz *destroyer*

L = 138; [130, 173]

Line = 86 %

Merch. = 5 %

Unrec. = 9 %

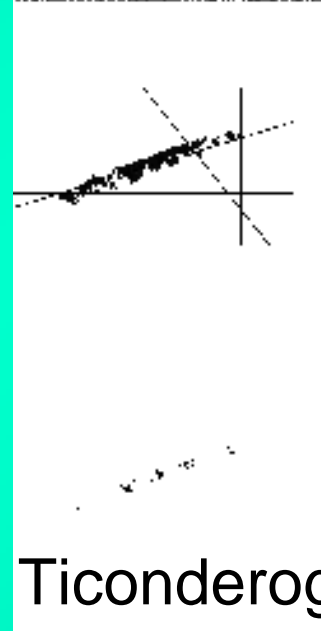
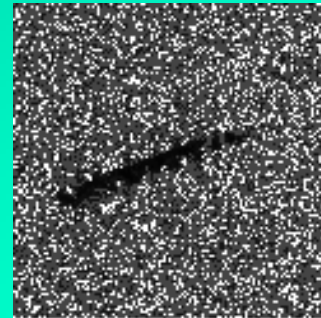
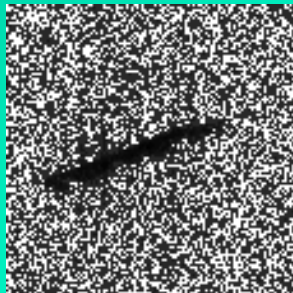
Frigate = 11 %

Destroyer = 53 %

Cruiser = 21 %

Battleship = 0 %

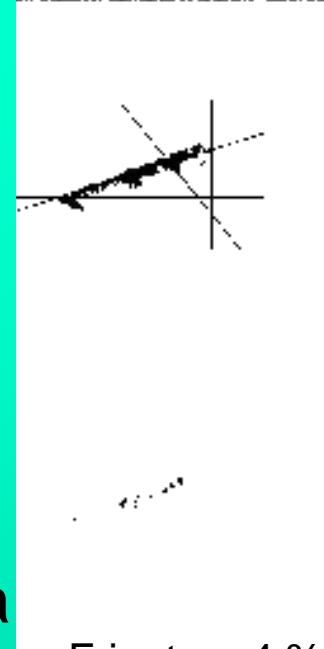
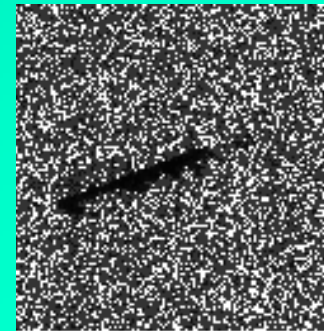
Aircraft Car. = 0 %



Ticonderoga *cruiser*

L = 178; [137, 191]

Line = 83 % Merch. = 4 % Unrec. = 13 %



Virginia *cruiser*

L = 127; [117, 165]

Line = 76 %

Merch. = 3 %

Unrec. = 20 %

Frigate = 25 %

Destroyer = 43 %

Cruiser = 8 %

Battleship = 0 %

Aircraft Car. = 0 %

Frigate = 4 % Destroyer = 36 %

Cruiser = 42 % Battleship = 0 %

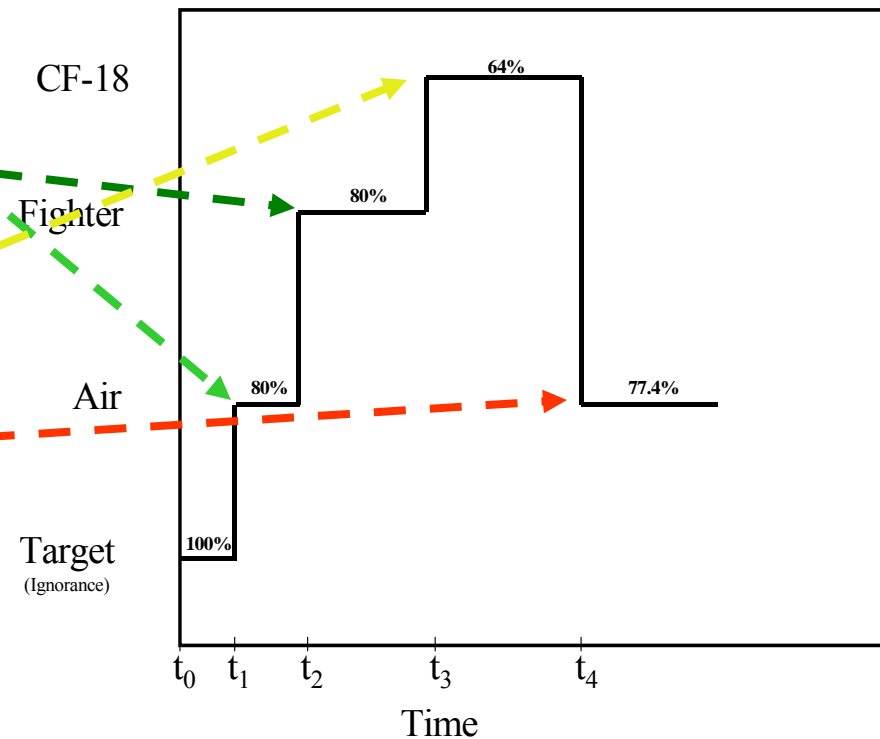
Aircraft Car. = 1 %

DS theory : HOS on a toy model

An example with conflict resolution

Proposition	t_1	t_2	t_3	t_4
CF-18	0%	0%	64%	12.8%
Air-Fighter	0%	80%	32%	6.4%
Air	80%	16%	3.2%	77.4%
Bomber	0%	0%	0%	3.2%
Ignorance	20%	4%	0.8%	0.2%

- at t_1 air declaration
 - at t_2 ESM: emitter of fighter
 - at t_3 ESM: emitter of CF-18
 - at t_4 ESM: emitter of bomber
- CONFLICT** at ID level,
at fighter level also, but
not about AIR nature



Conclusions



- ***ID fusion of imaging and non-imaging sensors done through extracted attributes listed in PDB***
- ***Comprehensive level 1 PDB exist listing all possible attributes***
 - contains attributes for SAR, tracking, geometry, etc
 - emitters often in common amongst many platforms
 - fuzzification rules for roughly measured physical quantities
- ***Higher level PDB for additional info related to platform, mission, armament, (passive) sensors, air platforms on deck***
- ***Dempster-Shafer evidential reasoning rules***
 - standard OS rule renormalizes throughout retained propositions
 - HOS rule redirects mass to first non-conflicting level of hierarchical tree
- ***Construction of many scenarios containing ESM, ISM reports***
- ***Simulated results show good ID from ESM and ISM reports***
 - TDS reasoning always correctly identifies platforms in reasonable time
 - ISM much needed when platform is nearly electromagnetically silent
 - TDS reasoning is robust under ESM countermeasures, false associations, or incorrect principal interpretation of ISM imagery