Electronic Warfare Training Applications of Decision-Support Systems

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***Abstract* – Electronic warfare (EW) and the electromagnetic spectrum (EMS) as a whole are often poorly understood due to their complex nature and the number of unique aspects inherent to the field. Therefore, better training that places a greater emphasis on a visual and interactive approach rather than a purely theoretical or mathematical one is required. One way in which this can be achieved is through the use of EW decision-support systems. These can be used at a higher level to assist EW decision makers in identifying situations where better countermeasure allocations can be made, or at a lower level to help military personnel to understand the interactions inherent in the EMS. One such system is discussed along with an example scenario that demonstrates how it can be applied to these training applications.**

***Keywords* – Electronic warfare (EW), decision-support systems, electronic countermeasures (ECM).**

I. INTRODUCTION

Electronic warfare (EW) and the electromagnetic spectrum (EMS) as a whole form a complex environment with a number of unique aspects and interactions. Due to limited interaction with this environment, military personnel often lack the intuitive understanding required to effectively operate systems that function in the EMS. However, this is not limited to the operation of EW systems alone as a lack of understanding can result in inappropriate use of EMS systems that directly affects the survival of personnel. This can take the form of poor strategic choices, or something as simple as using cellular telephones in the battlefield and unintentionally giving away vital information.

Even EW operators and decision makers are not fully aware of all the effects and implications of their actions in the field through no fault of their own, but simply due to the sheer complexity of the environment. For example, if there are a number of threats facing a platform at a given point in time, which threats should receive priority for limited countermeasure resources? Is it more effective to jam a single, more dangerous threat, or a number of less dangerous ones simultaneously? This problem is not trivial as the answer depends on the characteristics of the threats being encountered, their radar modes, the countermeasure capabilities of the platform, possible interactions with other countermeasures or EM systems, as well as unintended effects such as platform illumination. Further, these factors need to be examined in the context of the mission as a whole, so that the future effects of current countermeasure actions can be taken into account. That is before even considering overall strategic goals such as balancing the competing objectives of mission cost and platform safety.

This issue is further demonstrated by how EW is handled in military doctrine, where it has previously been integrated as a type of fires [1]. This neglects the many unique characteristics of EW that are already poorly understood. These include issues such as platform illumination, countermeasure interactions, the potential of countermeasures being used to simultaneously jam multiple threats, as well as the fact that the jamming effects are temporary, rather than permanent as in the case of kinetic fires.

These issues must be overcome through better training that aims to build a more intuitive understanding of EW and the EMS as a whole. This can be achieved by placing a greater emphasis on more visual and interactive approaches, rather than purely theoretical or mathematical ones. The problem should be approached at two levels. The first is to build an innate understanding of EW interactions for personnel at all levels by demonstrating the effects of countermeasures in a visual way. This requires that all necessary information about the EMS should be gleamed at a glance: the danger presented by threats, the effects of jamming, illumination of the platform, as well the progress of threats through their engagement procedure. Secondly, training of EW operators and decision makers should help them to identify better methods of countermeasure allocation rather than simply jamming the most imminent threat at a point in time. Countermeasure allocation must take into account the future effects of jamming, as well as balance competing mission objectives such as cost, risk to platform, and levels of emissions control (EMCON). Further, trainees' strategies should be quantitatively evaluated against benchmarks so as to indicate areas of possible improvement.

Until recently, this type of EW study could only be achieved with complex low-level simulations that are simply too slow for EW strategy optimisation purposes such as SEWES, or SADM [2]. Furthermore, in these systems the user is left to sift through the data and propose better solutions without assistance from the tool. Alternatively, previous high-level simulation approaches (e.g. [3] - [7]) could have been used to develop countermeasure strategies for this purpose. Unfortunately, such systems simply allocate countermeasure resources, rather than specific techniques. More importantly, these systems also do not take into account a number of important interactions that are inherent to the EMS, producing poor solutions for this application. However, a high-level decision-support system that takes these issues into account has since been proposed [8] [9], thus opening the door to various EW training applications. These are explored in this paper with reference to a complex example scenario.

The structure of this paper is as follows. Section 2 briefly describes the operation of this decision-support system. Section 3 then describes an example scenario and presents the developed countermeasure strategy and associated results. Section 4 discusses potential training applications with

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reference to these results, before the paper is concluded in Section 5.

II. DECISION-SUPPORT SYSTEM

In order to give the reader a better understanding of the decision-support system used for this application, as well as the complexities that need to be considered in EW mission planning, a brief overview is provided. A more in-depth technical analysis appears in the publications in which it was proposed [8] [9]. Further, explanations of the jamming techniques and interactions considered are contained in a number of EW reference materials [10] [11].

The decision-support system makes use of a process of threat evaluation and countermeasure allocation (TECA). Threats are first prioritised according to the level of danger they present to the platform, before countermeasure resources are allocated so as to improve an objective function. This objective function consists of the competing goals of risk to platform, mission cost, and levels of EMCON.

A. Overall system

The system divides a mission into a number of individual time intervals, and techniques are allocated to each of the platform's countermeasure channels. In order to be representative of operational systems such as the Gripen [12] and Eurofighter Typhoon [13], these consist of two active jamming channels, a single cartridge dispensing channel, and a towed decoy. Allocations take the form of a countermeasure technique, a threat type for which it is optimised, and whether or not the towed decoy is used for an active channel. The available countermeasures are range-gate pull off (RGPO), velocity-gate pull off (VGPO), noise jamming (NJ), multiple false targets (MFT), and a cover pulse (CP), where the noise jamming is available in multiple bandwidths. Chaff can be dispensed in either a dilution (DIL) or dispersion (DIS) approach.

Threats are modelled as a number of known entities, each with its own overall probability of occurrence, where it is assumed that intelligence about the engagement area is available. The threats progress from a search radar mode or stage, through an acquisition mode, tracking and then finally a guidance stage, with artillery systems stopping at the end of the tracking stage. These radar modes are then further divided into search-type stages (search and acquisition), and tracking-type stages (tracking and guidance). Radar stages can have their lock broken if the effect of jamming exceeds a certain threshold, resulting in the radar reverting to the search stage.

B. Threat evaluation

Threat evaluation is achieved by allocating each threat a danger value for each time interval that is proportional to the level of danger it presents to the platform. This value is determined using a number of threat characteristics such as its radar mode, the time its projectile would take to reach the platform, the probability of threat occurrence (*prob.*), and the weapon accuracy (*acc.*). Each of these factors has a user-defined weight to allow for the system to be optimised to the application.

The characteristics allocated to threats also include a separate radar and weapon system range (*ran.*), a distributed radius in which they are expected to be encountered (*rad.*), the number of cartridges required to jam them (*cart.*), and a tracking system generation (*gen.*). Radar mode progression is handled using search, acquisition, and tracking times that represent the average time taken to progress through the search, acquisition, and tracking stages respectively. In comparison, IR threats, due to their passive nature, remain undetected until they enter guidance and are detected by a missile approach warner (MAW) or similar system. As such, these are allocated a reload time instead (*re.*).

C. Jamming allocation

Jamming allocation is performed using a jamming factor. This is a multiplicative factor used on the danger value of a threat to account for the effect of countermeasures on the level of danger it presents. The factor is calculated for each threat in each time interval and is a sum of the effects of each countermeasure, taking into account the relative frequencies of operation of both the threat and the countermeasures, along with the threat's radar mode, the jamming techniques used, and any interference that results.

A genetic algorithm is then used to reduce the total post-jamming danger value of all threats over the course of the mission as this minimises the risk to the platform. EMCON is improved by reducing the number of countermeasures used, whilst cost is reduced by using fewer passive countermeasures. The weights of these goals in the objective function are also user-defined to allow for a desired compromise between these characteristics.

III. EXAMPLE SCENARIO

The use of this system as a training tool is best demonstrated through the use of the example scenario depicted in Fig. 1. This scenario consists of a single aircraft entering adversary territory at the first waypoint at the bottom of the figure, engaging a target at the second waypoint, before exiting the area at the third and final waypoint. The target is protected by eight ground-based radio frequency (RF) threats depicted as crosses in the figure, as well as three infrared (IR) threats depicted as stars. Each threat is identified by two numbers. The first is the threat identity number (ID) and the second is the threat type.

It is noted that the scenario is initiated and terminated close to the target, and makes use of a coarse 10 s time interval, so as to reduce the amount of resulting data for the purpose of this paper. Also, it is noted that all waypoints and threat locations are rounded to the nearest kilometre, and the ground-based threats have zero altitude. The platform begins at the first waypoint at a height of 14 km, before descending to 8 km in order to engage the target and then ascending back to 14 km as it exits the mission area. The target is engaged 80 s into the mission, and the mission concluded after 150 s. Lastly, the cartridge capacity of the platform is set to 110.

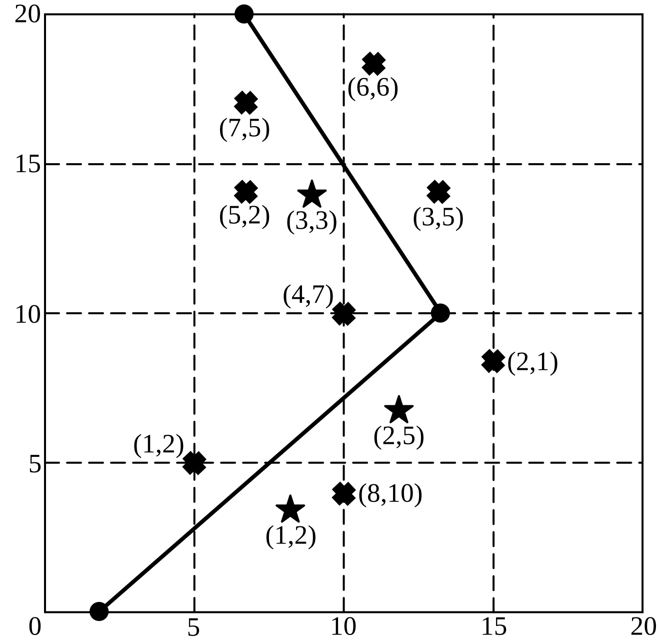

Fig. 1. Scenario threat layout (ID, Type), where axes are distance in km.

The various threat types, and their locations, have been chosen so as to create a good example in the context of this scenario, and do not represent specific real-world systems. Further, a variety of radar progression rates, and cartridge-jamming requirements have been chosen so as to increase scenario complexity and make the task of juggling threats harder to keep track of and manage. The characteristics of the IR threats appear in Table I, and those of the RF threats in Table II.

TABLE I. IR THREATS

ID	*Type*	*Acc.*	*Ran.*	*Prob.*	*Rad.*	*Re.*	*Gen.*	*Cart.*
1	2	0.95	10	0.90	1	50	2	20
2	5	0.70	6	0.80	2	30	1	10
3	3	0.85	8	0.70	1	40	2	15

Table III contains the developed jamming strategy for each time interval of the scenario, whilst Table IV shows the radar modes of the threats over the course of the mission as this is the best way to depict the interactions between the chosen countermeasure strategy and the threats. Importantly, this strategy results in the platform completing the mission unharmed. This jamming strategy was developed in a time of just 143 s in MATLAB R2011b with a genetic algorithm population size of 300, and 100 generations. This was achieved using a 2.8 GHz Intel Core i5-4200H CPU and 16 GB of RAM, demonstrating that the TECA approach is fast enough to allow large numbers of scenarios and variations on scenarios to be evaluated.

IV. TRAINING APPLICATIONS

As can be seen by the sheer amount of scenario information, the example is indeed complex. As such, developing a successful strategy – let alone an optimal one that takes multiple objectives into account – is no trivial task. There are 11 different threats with vastly different characteristics that must be juggled. These characteristics include different radar-mode progression rates, varying weapon and radar ranges, uncertain threat distributions, unique cartridge requirements, and differing accuracies.

TABLE II. RF THREATS

ID	*Type*	*W**	*Acc.*	*Weapon Range*	*Prob.*	*Rad.*	*Search Time*	*Acquisition Time*	*Tracking Time*	*Radar Range*	*Gen.*	*Cart.*
1	2	M	0.95	12	0.85	1	20	10	10	15	2	15
2	1	A	0.75	9	0.90	3	30	10	20	11	2	5
3	5	M	0.80	7	0.85	5	30	10	30	10	1	7
4	7	M	0.90	8	0.95	2	20	20	20	12	2	12
5	2	M	0.95	12	0.70	3	20	10	10	15	2	15
6	6	A	0.70	8	0.80	1	10	20	10	10	1	20
7	5	M	0.80	7	0.75	2	30	10	30	10	1	7
8	10	M	0.85	9	0.85	2	10	10	20	12	2	10

*W is the weapon column, where guided missiles have been abbreviated to M, and artillery to A.

TABLE III. DEVELOPED COUNTERMEASURE STRATEGY

Time (s)	*Coordinates (km)*			*Active Channel 1*		*Active Channel 2*		*Passive Channel 1*		*Decoy*
	x	*y*	*z*	*Technique*	*Threat*	*Technique*	*Threat*	*Technique*	*Threat*	
0	2.0	0.00	14.0	CP	2	CP	10	Flare	2	None
10	3.4	1.3	13.3	CP	10	CP	2	None	N/A	None
20	4.8	2.5	12.5	CP	7	CP	10	None	N/A	None
30	6.1	3.8	11.8	CP	2	CP	7	None	N/A	None
40	7.5	5.0	11.0	CP	2	CP	10	Flare	4	None
50	8.9	6.3	10.3	RGPO	2	RGPO	10	Flare	3	1
60	10.3	7.5	9.5	RGPO	10	RGPO	1	Flare	2	1
70	11.6	8.8	8.8	RGPO	1	CP	5	None	N/A	1
80	13.0	10.0	8.0	RGPO	7	MFT	5	Flare	5	1
90	12.1	11.4	8.9	VGPO	2	RGPO	10	None	N/A	1
100	11.3	12.9	9.7	RGPO	10	MFT	5	Flare	3	1
110	10.4	14.3	10.6	RGPO	6	CP	7	Dilution	1	1
120	9.6	15.7	11.4	NJ (MN)	3	CP	5	None	N/A	None
130	8.7	17.1	12.3	RGPO	2	NJ (MN)	6	None	N/A	None
140	7.9	18.6	13.1	CP	6	CP	2	None	N/A	None
150	7.0	20.0	14.0	NJ (MN)	6	CP	2	None	N/A	None

TABLE IV. THREAT STAGES

Time (s)	RF Threat ID*								IR Threat ID**		
	1	2	3	4	5	6	7	8	1	2	3
0	S	S	S	S	S	S	S	S	G	U	U
10	S	S	S	S	S	S	S	S	U	U	U
20	S	S	S	S	S	S	S	S	U	U	U
30	S	S	S	S	S	S	S	S	U	U	U
40	A	S	S	S	S	S	S	A	U	G	U
50	T	A	S	S	S	S	S	T	U	U	G
60	S	T	S	A	S	S	S	T	G	U	U
70	S	T	A	A	A	S	S	S	U	U	U
80	A	S	S	T	T	S	S	A	U	G	U
90	T	S	S	S	G	A	S	T	U	U	U
100	S	S	S	S	S	A	S	T	U	U	G
110	S	A	S	A	S	T	S	S	U	U	U
120	A	T	S	S	A	S	S	A	U	U	U
130	T	S	S	S	T	A	S	S	U	U	U
140	S	S	S	A	S	A	S	S	U	U	U
150	S	S	S	A	S	S	S	S	U	U	G

*S indicates the search stage, A indicates acquisition, T indicates tracking, and G indicates guidance.
**G indicates guidance, and U indicates that the IR threat is currently undetected by the platform.

An intuitive approach to strategy generation was used to seed the genetic algorithm [6]. This approach ignores all other objectives and simply consists of first allocating flares where necessary, then jamming the most and second-most significant threats in each time interval using pre-determined techniques according to the threat's type and radar stage. Finally, the remaining cartridges are allocated to chaff countermeasures for time intervals in which the third most dangerous threat presents sufficient danger. Due to the intuitive nature of this approach and its relative simplicity, it is reasonable to assume that such an approach is representative of a human strategist. Significantly, this approach was unable to determine a successful strategy for the scenario, with the platform being successfully engaged twice, hence indicating the importance of improving approaches to countermeasure allocation.

A. Superior strategy as an evaluation tool

The first application of this system to be discussed applies to EW operators and decision makers in training, where these computer-developed strategies can be used as benchmarks for rapid and quantitative evaluation. This allows for the areas of weakness in a trainee's strategies to be highlighted and improved upon. For the purposes of this example, the seed strategy discussed above will serve as a human strategy for comparison.

The metrics used for strategy evaluation appear in Table 5, and a mission-long comparison between these strategies' danger values appears in Fig. 2. Fitness is the overall fitness value of the strategy, whilst danger, EMCON and cost are the objective function values used to calculate the fitness of a strategy, totalled over the mission. Danger is the total post-jamming danger value of the strategy, and is indicative of the level of risk to the platform. EMCON is a measure of the level of use of active jamming techniques, whilst cost is indicative of the amount of cartridge use. Cartridges remaining is simply the number of cartridges remaining onboard the platform after the mission and times engaged is the number of times a threat successfully fires a projectile at the platform without being jammed. The calculation of these values is discussed in detail in the works in which this system was proposed [8] [9].

TABLE V. STRATEGY METRICS

Objective	Computer Developed	Seed ('Human')	Percentage Difference
Fitness	6.2251	12.7721	n/a
Danger	237.5379	258.6542	8.89
EMCON	0.8125	0.8542	5.13
Cost	0.6818	0.9545	40.00
Cartridges Remaining	35	5	n/a
Times Engaged	0	2	n/a

From the metrics table above, it is immediately seen that the seed approach falls short in all areas: it places the platform in greater danger, uses more cartridges, and it fairs worse at controlling emissions than the developed strategy. However, the computer-developed metrics are there to show what can be achieved using the right approaches to the mission. In this case, the seed approach is too liberal with cartridge use in particular. This not only increases mission cost and unnecessarily uses limited cartridge reserves, but can also leave the platform defenceless in instances where unexpected threats occur.

Further, these evaluations can be performed on a time-interval-by-time-interval basis as shown in Fig 2. From here it is seen that the seed strategy performed well in the early parts of the mission, but failed later on once the threats started entering tracking-type stages and requiring a greater amount of juggling. This helps the trainee determine where in their strategy they went wrong, as well as what types of scenarios need to be worked upon.

Overall, these evaluations serve to show where the strategists have gone wrong – perhaps they tend to focus too much on cost reduction, or reducing the danger presented to the platform resulting in poor emission control. Importantly, these deficiencies are shown in a quantitative way, thus indicating to what level each metric needs to be worked on, or which ones should receive priority and in what situations.

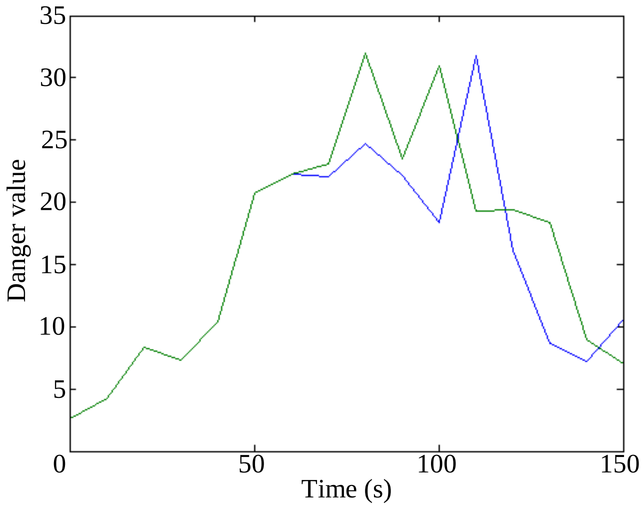

Fig. 2. Danger value comparison between the computer-developed strategy (blue) and the seed 'human' strategy (green).

B. Superior strategy as a training tool

The second application also applies to EW operators and decision makers in training. Here, the decision-support system is used to demonstrate important approaches to scenarios that otherwise would not be immediately obvious, as well as to help trainees to develop an eye for such opportunities.

For example, looking solely at RF threats in the time interval starting 80 s into the scenario, there are two threats in the tracking radar stage. These are threat IDs 4 and 5, of type 7 and 2 respectively. So, the temptation is to use techniques such as VGPO or RGPO directed at these two threat types in order to break this lock, since they are the closest to firing at the platform and hence appear as the most dangerous threats. However, due to the complex nature of this scenario, it would be foolish to simply brush off the other threats because nearby is threat ID 1, which is a type 2 threat in an acquisition stage. In the very next time interval, this threat will enter the tracking stage and require the exact same countermeasure as threat ID 5 in order to break its lock. As a result, it is more effective to hold off on jamming threat ID 5 until the next time interval, when both threats can be handled simultaneously. While this approach does have the undesirable result that threat ID 5 fires a missile and enters the guidance stage, delaying jamming is more likely to ensure the safety of the platform and pilot in this scenario. Perhaps more importantly, making a pilot aware that such outcomes are anticipated, but necessary, makes it less likely that the pilot will panic and/or make dangerous errors when a launch occurs.

A second example appears in the time interval starting 120 s into the scenario. In this time interval, threat ID 2, of type 1, is in the tracking stage and appears at first glance to be the most dangerous in comparison to the other RF threats in search-type stages. However, the platform is on the very edge of the weapon range of this threat, and will be outside of its radar range by the start of the next time interval, resulting in the threat harmlessly disengaging. As a result it would be a waste of jamming resources to focus on this threat. Instead, the system uses the combination of noise jamming and a cover pulse in order to keep all the other threats in search-type stages at bay.

C. Visual and interactive learning

The third and final training application of this decision-support system is aimed at improving the general understanding of EW and the EMS as a whole for all military personnel. This is achieved through the depiction of the EMS in a visual way that conveys all the interactions that are unique to this environment in an easy-to-digest manner. Each scenario and associated strategy can be demonstrated on a time-interval-by-time-interval basis, where each threat is depicted with a radar-mode-dependent icon. The size of these icons can then be scaled proportionally to the threat's danger value in order to indicate their priority. Next, the colour of these icons can be allocated according to a colour scale based on the jamming effect (E) resulting from the selected countermeasures. The jamming effect is defined as one minus the jamming factor [8], and the colours are allocated such that effective jamming is indicated by green ($E > 0$) and platform illumination is indicated by red ($E < 0$). This results in a graphical representation that demonstrates, at a glance, all threats, their stage of engagement, level of danger and how they are affected by the current countermeasures. One such figure from the example scenario appears in Fig. 3 for the time interval beginning 110 s into the mission.

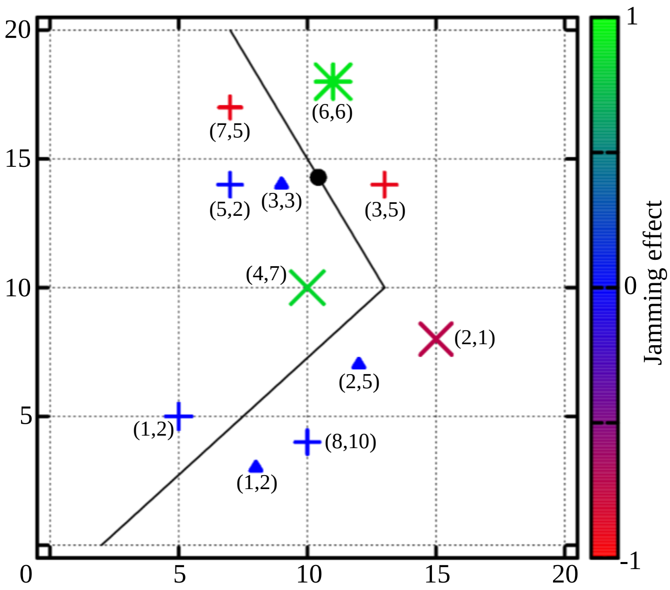

Fig. 3. Visual display for the time interval beginning 110 s into the mission with the positions being given in km and each threat being labelled with its ID and type in brackets.

From this figure it can immediately be seen that there are 3 threats that present imminent danger to the platform: threat IDs 6, 4, and 2 of types 6, 7, and 1 respectively. Threat ID 6 is in a tracking stage indicated by its '*' icon and hence is the closest to firing upon the platform, whilst IDs 4 and 2 are in an acquisition stage as indicated by the '×' icon. The remaining threats either remain undetected ('▲'), or still searching ('+') for the platform and hence present minimal danger. It is not worthwhile to jam one of the smaller threats, and it is not possible to jam all three large threats simultaneously. Therefore it is necessary to focus on two of these threats and jam them, resulting in a selection of a combination of RGPO directed at threat type 6 through the towed decoy, and a CP directed at a threat type 7. This is further combined with dilution chaff as it is complementary to both RGPO and CP techniques, hence ensuring the successful jamming of threat IDs 6 and 4. Unfortunately this illuminates the platform to threat IDs 2, 3, and 7, as indicated by the red colour of their icons. However, as discussed previously, we know that the platform will leave the radar range of threat ID2 before it is able to fire a projectile. Therefore, this combined with the fact that threat IDs 3 and 7 pose minimal danger to the platform in the time interval, means that this countermeasure selection is indeed acceptable.

Depicting the EW environment in the above manner allows for such in-depth analysis of EW strategies, which is essential in developing a strong, innate understanding of this environment. Further, this approach and the low computational cost of TECA allows for the possibility of interactive training approaches where the user can, on a time-interval-by-time-interval basis, select a countermeasure strategy and see its effects immediately. This allows trainees to see and interact with the unique characteristics of the EMS such as the fact that countermeasures can have a positive effect on a particular threat, but may illuminate the platform to others, that all signals interact with one another in the EMS in both constructive and destructive manners, and that threats are only temporarily suppressed by countermeasures.

V. CONCLUSION

While current EW simulators can be used to support EW training, they are limited by long simulation times, poor accuracy, and/or provide little or no information about possible countermeasure strategies in complex engagements. However, a recently developed EW decision-support system overcomes these limitations, and its use in EW training was proposed. This proposal was evaluated in light of a complex scenario consisting of a large number of different threat types.

Perhaps the greatest value of this approach to EW training is that computer-developed EW countermeasure strategies serve to create a benchmark against which trainees' strategies can be evaluated. Further, it demonstrates potential approaches to generating better EW strategies, as well as highlights circumstances that can be taken advantage of in order to generate these superior strategies.

An interactive and visual approach to EW strategy development that allows users to see the effects of a countermeasure strategy was also outlined. This visualisation allows a user to determine the danger threats pose to the platform, as well as threats' progression through the engagement process, at a glance. Both the jamming and illumination effects of countermeasures are also shown in an easy-to-digest manner, allowing for a user to gain a better understanding of the unique aspects of the EMS.

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