Quantifying the Effects of Chaff Screening on Hardkill and Softkill Coordination

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ABSTRACT
For the Navy, Anti-ship Missile Defence (ASMD) is a priority due to the obvious mismatch between a missile threat’s speed and maneuverability compared to a warship. Chaff is an off-board, passive technique that can be combined with a ship maneuver to create an effective tactic for ASMD. The effectiveness of chaff tactics is fundamentally dependent on the chaff radar cross section (RCS) as well as environmental factors including multi-path, sea state and wind conditions; engagement geometry such as threat bearing and ship maneuvers; target and threat properties like ship RCS and sophistication of electronic counter countermeasure (ECCM) features of the threat missile. In the future, hardkill and softkill coordination of maritime platforms is viewed as a force multiplier that will also improve the survivability of the task group. Therefore, the deployment of chaff must be made with consideration to many variables and the resulting optimization problem of developing robust tactics is complex. In this work, we present an application of a chaff modelling tool that can be used to aid in the design and analysis of optimal chaff countermeasures for ASMD. In particular, the effects of chaff screening and interference on the detection and engagement of missile threats for different task group geometries (scenarios) is studied. Our chaff design tool can be used to study the frequency and angular dependence of chaff RCS as a function of time and range for spherical and ellipsoidal chaff clouds. Our model accounts for the limitations of a radar’s tracking cell and can predict both monostatic and bistatic RCS behaviour. The results of such studies can then be used to help design effective deployment and engagement strategies.

INTRODUCTION
Anti-ship missile defence (ASMD) has been identified as a priority for many Navies due to advances in missile technology and the increased scope of Maritime activities. Changes in threat technology and the types of threats, in addition to the expanded scope of operations, will call for an evolution in naval operations, ship technology and tactics. Supersonic and highly maneuverable threats with low visibility will require a ship’s defensive systems to be automated due to reduced reaction time. This will demand increased integration among different systems, particularly sensors and weapons, in order to win back as much reaction time as possible. Also, cooperative engagement capability (CEC) and co-coordinated hard kill-soft kill will be requirements for warships working within close proximity of other platforms, in a network centric defensive formation and will necessitate information sharing among the platforms. Ultimately, these will lead to new ship systems and architecture.

The continuing evolution in threat systems technology includes increased threat speed and maneuverability, where there is a trend towards the development of supersonic and “high-g”/weaving anti-ship missiles capable of sea-skimming, i.e. travelling just above the sea surface. These new threats will be much more stealthy, possessing smaller radar cross section (RCS) and consequently more difficult to detect at longer ranges. Furthermore, advances in guidance and tracking technologies will see the emergence of multi-spectral threats with a combination of EO/IR sensors and/or radar capability. Variations will include systems with combinations of active and passive homing. These combined advances will lead to a significant reduction in the available reaction time for the ship’s defence systems, as these new threats will close much more rapidly and have the ability to “turn on” or unmask late into the engagement, and will render traditional countermeasures and tactics less effective.

The scope of maritime activities has also expanded since the end of the cold war. In particular, today’s naval operations include deployments in littoral or gray water environments. This is significantly different from the open sea or blue water operations of the past. Operation in littorals will increase the “density” of the deployed forces leaving them more prone to attack and also more difficult to defend due to increased risk of fratricide. Therefore, force deployments will necessarily be required to work in a more a network centric framework, relying on the combined defenses of the individual ships in order to establish a layered defensive posture. In addition, littoral operations expose Naval forces to new threats including shore-based, shoulder launched, short-range rockets (with/without imaging seekers) and the increased threat of mining.

Computer based modelling and simulation is recognized as an effective tool for development and testing of new technologies as well as procurement. Among other benefits, simulation is generally considered as a cost effective approach for evaluating very complex systems that must operate under different and often extreme environmental conditions and which are sensitive to numerous parameters. Anti-ship missile defence (ASMD) has been identified by the Canadian Navy as one area that could benefit from advanced modelling and simulation efforts due to the complexity of any particular engagement scenario. The complexity arises due to geometry of the engagement, threat and environmental dependencies and is further complicated by the stochastic nature of many of the variables. Continuing developments in threat systems technology and the increased scope of maritime activities into littoral regions require an evolution in tactics, naval operations and ship technology to address issues such as reduced reaction times, integration between sensors and weapons and automated responses. Computer based simulation offers a viable means to explore these concerns.

The Electronic countermeasures (ECM) section at Defence R&D Canada – Ottawa (DRDC-Ottawa) is developing a software test bed to model and simulate the terminal phase of an electronic warfare (EW) engagement for ASMD (Manji 2001a). The scope of this project is to develop a system:

1) To test current doctrine for ASMD
2) To propose and develop new tactics and measure their effectiveness
3) To develop and test Naval EW control concepts

Our current work focuses on the development of decision aids for automated decoy deployment, in particular using chaff as a tactic of choice. Future work includes evaluation of different tactics and techniques and exploring hard kill and soft kill coordination.

**CHAFF ANALYSIS TOOL**

Our initial objective was to develop a computer program to calculate the RCS of a chaff cloud as a function of time (bloom) over a number of parameters including a mixture of chaff lengths, frequencies, range to radar...
and monostatic and bistatic reflection. The aim was to develop a graphical tool to study, in detail, chaff cloud RCS characteristics to assist in the design of chaff countermeasures to be used in our chaff effectiveness simulator for naval EW engagement simulations and ASMD.

The graphical user interface (GUI) and computational engine were both programmed in MATLAB. The computational engine is based on a new chaff RCS model developed from first principles by Kashyap and Louie (2001). This work is also described briefly by Manji et al 2002. The GUI was developed using MATLAB user interface (UI) control functions.

Figure 1 shows the main interface in which users can set and initialize parameters relevant to their studies. Parameters specific to the chaff cloud include:

1) The number of chaff cuts to be used
2) The lengths of the individual cuts
3) The number of particles for each cut
4) Chaff cloud model (spherical or elliptical)

![Figure 1: GUI Interface for the Chaff Evaluation Tool. The main interface enables users to set all relevant parameters.](image-url)

Parameters specific to the radar include:

1) Radar geometry (monostatic/bistatic reflection)
2) Frequency range over which the RCS is to be calculated
3) Tracking cell parameters which include the pulse width, beam width and range to cloud

Once all the parameters are initialized, the calculations are performed and the appropriate graphs are generated.
For the case presented in Figure 1, the following parameters were used in the study:

- Number of chaff cuts: 3
- Lengths of chaff cuts: 0.01764 m, 0.01526 m, and 0.00972 m
- Number of dipoles for each cut: 108M, 108M and 228M respectively
- Chaff cloud model: elliptical
- Radar Geometry: bistatic
- Bistatic angle: 27 degrees
- Frequencies of interest: 8.5 GHz and 12 GHz
- Pulse width: 0.3 µsec
- Beam width: 4.5 degrees
- Range to radar: 0.9 km

**POLAR RCS DISPLAY**

There are two displays of interest. The first is a polar RCS display that shows the particular geometry defined by the user. It also plots the maximum RCS as a function of reflection angle and frequency. Figure 2 shows this display for the parameters listed in the previous section. In this example, an ellipsoid model was used and is shown in red. The monostatic and bistatic reflection angles are also shown along with the tracking cell. The circular rings that appear in colour give the RCS values for all aspect angles as a function of frequency. This includes the maximum RCS as well as the RCS response of the tracking cell.

![Polar RCS Display](image)

**Figure 2: RCS Display in Polar Coordinates.**

**RCS PLOT VS. BLOOM TIME AND CLOUD RADIUS**

The second display plots the RCS of the chaff cloud as a function of radius and bloom time. This is shown in Figure 3. The plots also show RCS curves limited by the tracking cell. It should be noted that the RCS time and radius plots are correlated and therefore have similar shapes; both are shown for the convenience of the user.
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Of particular interest to both chaff designers and tacticians is the time behaviour of the RCS and tracking cell effects due to radar beam width and pulse width limitations. Interesting features that appear on these plots is the time (or radius of the cloud) at which tracking cell limitations effect the RCS and therefore ultimately the received power in the radar. These curves are plotted for particular bistatic angle of interest. These angles are adjustable after the initial calculations are complete using the parameter interface GUI. The plots are automatically updated.

In the above case, for a frequency of 8.5 GHz, the maximum RCS is approximately 37.5 dB and range cell limitations occur at a radius of 30 m (or a bloom time of 30 sec). For a frequency of 12 GHz, the maximum RCS is 32 dB with range cell limitations occurring at a radius of 35 m (or a bloom time of 40 sec), which is not unexpected.

EXPANDED FUNCTIONALITY

In an effort to expand the utility and functionality of the tool, two initiatives were undertaken. The first was to add 3D plotting of the scenario which clearly shows the geometry of interest. The second initiative was to create a “data slicer” type toolset in order to present the results in a variety of ways which would allow better analysis.

Figure 4 shows a selection of 3D plots available when the 3D option is turned on. The sliders on the graph allow one to choose the incident, reflected or bistatic angle. Note that only two of the three angles need to be defined and the other is computed automatically. The difference between the bistatic and reflected angle is that the reflected angle is referenced the same plane as the incident angle. This is better demonstrated in Figure 4b. The choice of which convention to use is left to the user an option.
Figure 4: 3D plots that are available when the 3D plotting feature is turned on (a) 3D plot with the chaff cloud shown in black, tracking cell in blue and incident angle (red) and bistatic angle (blue) (b) 3D plot using polar map option, here the incident and reflected angles are shown.

The utility of the “data slicer” is best demonstrated using another case study. The following parameters used in the next example.

- Number of Chaff cuts: 3
- Length of Chaff cuts: 0.01764 m, 0.01526 m, 0.00972
- Number of dipoles in each cut: 108M, 108M, 228M
- Chaff cloud model: elliptical
- Radar geometry: bistatic
- Bistatic angle: 27 degrees
- Reflected angle (projection on plane, phi component): 36
- Incident angle (projection on plane, phi component): 18
- Frequencies studied: 8 GHz, 14 GHz
- Pulse Width: 0.3 \( \mu \)sec
- Beam Width: 1.0 degrees
- Range to radar: 1.6 km

In the above case, our program calculates the RCS vs. time and radius as before. These plots are shown in Figure 5.
In this particular case, the chaff is more effective at lower frequencies with a nominal 5dBsm difference at full bloom. In order to better understand the chaff behaviour over a variety of conditions it is now possible to invoke the “data slicer” in order to perform a detailed analysis. Figure 6 shows the two optional control windows for the “data slicer”.

Figure 6: Optional control windows for the “data slicer”. The left hand window is useful for detailed analysis with respect to bloom time and angle and the right hand window is useful for studies on frequency and range dependence.

Depending on the parameters of interest, the data can be sliced and presented in a variety of combinations. First, using the left hand control window, one can view a plot of the growth of the RCS over reflected angle (0-360 degrees) at the time points indicated.

Using the right hand control window shown in Figure 6, even more display combinations are possible. Examples are given Figures 7 through 10. The header at the top of the window gives the type of graph and the conditions used to generate the curves.
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Figure 7: RCS vs. Frequency for Range 0.10 to 20 km (Coloured Lines), Step 0.10 km.

Figure 8: RCS vs. Range for Conditions Specified in the Window Header.

Figure 9: RCS vs. Time for Frequencies 8 GHz to 14 GHz (Coloured Lines), Step 0.50 GHz.

Figure 10: RCS vs. Time for Range 0.10 to 20 km (Coloured Lines), Step 0.10 km.

The above examples are useful in evaluating the sensitivities of chaff RCS over a number of variables and the interface is sufficiently flexible to allow the user to choose a primary variable (horizontal axis) and a secondary variable (coloured lines).
Of particular interest to chaff designers is the bloom characteristics (Figures 5, 9, 10) and frequency coverage (Figures 5, 7, 9) over which the chaff will be effective. The particular parameters are important in evaluating chaff cloud performance of seduction chaff against supersonic, multi-spectral and frequency agile threats. Furthermore, for non-spherical chaff clouds the RCS will also be dependent on incident angle (Figure 5) i.e. the relative angle between the missile and chaff cloud.

The results presented on Figure 7 and 10 are preliminary and may need to be improved for near field conditions.

**CHAFF SCREENING AND INTERFERENCE**

Chaff is used as a self-protective measure for both aircraft and naval vessels against active RF threats. In the naval environment, chaff can be used in a variety of modes including distraction, confusion and seduction. The principal difference among these various deployments is engagement status and range (and height) at which the chaff is dispensed. *Confusion* chaff is typically deployed at longer ranges while the enemy is in the process of compiling a tactical picture and prior to combat. Often the target ship is below the radar horizon of the enemy and the purposes of deploying chaff is to confuse the enemy’s tactical picture, by presenting what appears to be other legitimate targets and perhaps force him to attack decoys. *Distraction* chaff is used when the enemy has already engaged the ship by launching missiles. Chaff is dispensed at a medium range while the missile is in search mode. The chaff is used to create realistic targets that appear to the missile as legitimate targets to which it will lock, thereby protecting the ship. *Seduction* chaff is used at short range, in the terminal phase of an engagement when the missile has a radar lock on the ship. The purpose of the chaff is to draw the centroid of missile seeker’s tracking cell off the ship by presenting a sufficient and realistic return within the seekers tracking gate.

The use of chaff as an effective decoy for ASMD has been debated. Some would argue that modern seekers, equipped with advanced electronic counter-countermeasures (ECCM) can readily discriminate between a ship’s RF signature and that of a chaff cloud. With the development of imaging seekers and dual mode (RF and imaging) seekers, they would further point out that chaff based countermeasures are even less effective. Others contend that if used properly, chaff can provide an adequate defence under certain conditions and therefore could play a role in a layered defence strategy. A layered defence would include ECM (soft kill) at long range, surface to air missiles (SAMs) at medium range and a close in weapon system (CIWS) at short range. The later two represent a ship’s hard kill assets. The options for ECM include: chaff as a passive, off board decoy, an active off board decoy such as NULKA and/or an onboard jammer. Typically, off board, active decoys are expensive and limited in supply. Further, since an on board jammer could effectively act as a beacon, many perceive chaff as the preferred option when given a choice between the two countermeasures. Our research also involves determining the best use of chaff as one type of ECM either independently or in coordination with other soft kill techniques and hard kill assets.

Realistic simulations using chaff as a tactic require a distributed (or volume) chaff radar cross section (RCS) model, which is positioned using a realistic chaff rocket model (Manji 2001b). The chaff rocket model takes into account the effects of wind, movement of the launch platform and rocket parameters such as fuse time, aerodynamic drag, gravity and fuel burn. The volume model for the chaff cloud should account for the portion of chaff in the missile seeker’s radar resolution cell which is dependent on the beam width, range and pulse width of the seeker. The RCS of the cloud will depend on a number of physical parameters including the size and number of particles, reflection angle and bloom characteristics. The success of seduction tactics in the terminal phase of an engagement will critically depend on both the proper RCS value (relative to the ship RCS) and how quickly the cloud blooms (and therefore reaches maximum RCS).
We previously presented a graphical, computer based tool that can be used to study both monostatic and bistatic chaff cloud RCS behaviour (Manji et al 2002). This tool can be used to define parameters used in testing chaff deployments in our chaff effectiveness simulator as well as provide a better understanding as to the efficacy of a particular deployment. The bistatic option is useful for studying self-interference (or net-centric interference) once chaff is deployed. This tool is based on a new mathematical model for computing the RCS of a chaff cloud. Both spherical and elliptical clouds can be studied and limitations due to the radar’s tracking cell are also accounted for. The display gives curves of the behaviour of the RCS over time (and radius), frequency and angular dependence of the RCS for monostatic and bistatic tracking of the cloud. In this work, we present an enhancement and application of our graphical modelling tool.

CASE STUDY

Let’s consider a scenario that chaff is illuminated in order to jam a guided missile seeker. Figure 11 shows the engagement geometry. Lets assume that the seeker is activated at a range of 7 km. The following parameters are used in the scenario. Lets try to find the time to launch the chaff, if 30 dB RCS is required to seduce the missile seeker when the seeker radar is activated.

- Number of Chaff cuts: 3
- Length of Chaff cuts: 0.01764 m, 0.01526 m, 0.00972 m
- Number of dipoles in each cut: 108M, 108M, 228M
- Chaff cloud model: elliptical
- Radar geometry: bistatic
- Bistatic angle: 90 degrees
- Frequencies studied: 8.5 GHz
- Pulse Width: 0.1 µsec
- Beam Width: 1.0 degrees
- Range to radar: 7 km
- Speed of missile: 1 Mach

![Figure 11: The Engagement Geometry of a Scenario that Chaff is Illuminated in Order to Jam a Guided Missile. (Bistatic Angle = 90 Degrees).]
Figure 13a shows the bistatic angle between illumination signal and reflected signal is 90 degrees. The chaff analysis tool can calculate the RCS of the chaff cloud including the tracking gate limitations and the bistatic angle. The results for both the entire cloud and the tracking gate RCS are plotted in Figure 12. For both cases, the required RCS is reached at earliest in 23 seconds after the chaff is launched. This result dictates that the chaff must be launched 23 seconds before the seeker is activated. Since the speed of missile is 1 mach, the chaff should be launched at the latest when the missile is 14.82 km (7km+7.82km) away from the ship.

The launching range and time can be different for the other engagement geometries. Figure 13b shows a slightly different engagement with a wider bistatic angle.
In case the bistatic angle is 150 degrees, the required RCS is reached at earliest in 40 seconds after the chaff is launched. This result dictates that the chaff must be launched 40 seconds before the seeker is activated. Since the speed of missile is 1 mach, the chaff should be launched at the latest when the missile is 20.6 km (7km+13.6km) away from the ship.

As it can be seen from the results for both engagement geometries, the chaff launching time is dependent on tracking gate limitations and bistatic angle.

CONCLUSIONS

This recently enhanced tool allows us to characterize both monostatic and bistatic chaff cloud behaviors and therefore better understand the effectiveness of chaff countermeasures that are simulated in our ASMD simulator. Conversely, this tool would also prove useful in the design of chaff to meet specific performance criteria.

We plan to integrate the RCS calculation tool into our ASMD software to improve the fidelity of our simulations. The results of these simulations can be used to help design effective deployment and engagement strategies.

REFERENCES


**AUTHORS**

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