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Methods for evaluation of Air-Defence systems on Surface ships

Lars Höstbeck, M Sc
Defence Research Establishment, Division of Defence Analysis
SE-172 90 Stockholm, Sweden

Since the late sixties the main threat against surface ships has been Surface-to-Surface (SS) and Air-to-Surface (AS) Missiles. The Air-Defence systems on surface combatants are crucial for the survivability of the ship and a wide range of defence systems has been developed, both soft kill systems (EW-systems and countermeasures) and Hard-Kill systems (guns and Surface to Air Missiles).

When evaluating the effectiveness of Air-Defence systems a number of issues have to be considered. Besides the accuracy of gunfire and the reliability of missiles there are the algorithms of fire control and guidance systems as well as the performance of the threat.

Available computer models are often too specific and therefore not possible to adapt neither to new tactics and environment nor to the performance of new systems. The evaluation of effectiveness in future threat scenarios, such as peacekeeping operations and operations other than war, can not be made with old models.

In this work we argue the case for the use of methods built on manual calculations aided by computerised tools rather than complete computer models. The point is exemplified by a simple method for calculating the probability of survival for a ship that is attacked by multiple missiles with different characteristics.

In 1997 the operations analysis group with the Swedish Naval Staff was asked to participate in a study of maritime air-defence systems. The aim of the study was to develop a plan for the enhancement of the air-defence systems within the Swedish Navy and the Coastal Artillery. The study itself is not finished yet. This paper describes the work with methods for evaluation of air-defences systems on the surface ships.

The Swedish Navy consists of rather small ships, corvettes of about 400 tons, fast attack crafts of about 200 ton and fast patrolboats of about 150 tons. These ships can not carry a multitude of different air-defence system and today they are depending on 40 mm and 57 mm guns and chaff. There are no CIWS, such as the Goalkeeper.

One question that is supposed to be answered in the study is whether or not to equip the corvettes with Surface to Air Missiles (SAMs). Due to the space available the only real option for the current, Göteborg-class, corvettes are short-range missiles. For the forthcoming Visby-class corvettes, that will be slightly bigger, the freedom to choose is bigger, but the cost for support and maintenance of two different systems has to be considered.

Clearly the study needed methods for the evaluation of different combinations of radars, Infrared Search and Track (IRST), guns, missiles and chaff. Furthermore, the costs of the different combinations have to be considered. We need to be able to model the air-defence of a ship in order to evaluate the different combinations air-defence systems. This, of course, is not a new problem. What is new since the last time it was done on such a scale in Sweden is the large number of PCs and the number of computer models for evaluation.

I want to emphasise the point that a model is not necessarily a computer model, and that all computer model starts as a model drawn with a pencil on a paper. The timeframe of the study, initially March to December 1997 and later prolonged until December 1998, does not allow for the development of a computer model of any size or complexity.

A traditional measure in this case would be the air-defence systems capability to destroy an incoming threat. We decided against this on the grounds that we had to evaluate the effectiveness of both soft-kill and hard-kill systems within the same scenario, and a soft-kill system can not really destroy the threat. The measure we finally chose was the ship's survivability. We chose to present the survivability as a function of the number of threats within 20 seconds. The threats could for example be laser-guided bombs or sea-skimming missiles.

Next to be decided was what we needed to model in order to be able to determine the ship's survivability. The conclusion was that we needed to model the guns and the air-defence missiles in some detail but the Radar and IRST could be modelled as a distance of detection. The link between the detection and the destruction of the threat, the Command and Control (C^2) system had to be modelled in some way. This included not only the technical aspects of the C^2 system but the tactics and human factors as well.

A search through the organisation revealed a number of models on a technical level that could be used in different parts of the work. There was one model on a tactical level, Rogov, which combined guns and missiles with detection range on a ship to calculate the survivability of missiles that are fired against the ship, or a convoy of ships. This model looked promising at first, but since it was developed to make assessment during wargaming it was really not suitable for evaluation of air-defences.

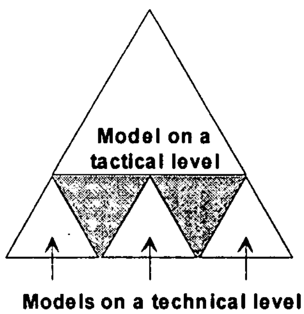

Figure 1. A hierarchy of models where the output of the models on the lower level is used as input on the higher level.

As a decision was made not to use Rogov, an alternative model had to be developed. This new model had to be able to handle the following :

- Time and distance of detection of a threat
- Reaction time within the C^2 system
- Time of firing (missile or gun)
- Time to reload
- Time of flight to target
- Tactics
- Combinations of guns, missiles and chaff
- Multiple threats at random spacing in time and angle

A typical scenario is a single ship attacked by a single surface-to-surface missile (Fig. 2). Some distance away radar or IRST detects the missile. The missile has to be identified as a threat and tracked by the system. After a short period of time there is a first possibility to fire at the missile. The first weapon to be deployed is probably a surface-to-air missile. If the missile needs to be guided towards the target, this system can not fire a second time until the first missile has reached the target.

The incoming missile has to be destroyed a sufficient distance away from the ship as the debris from the missile otherwise would damage the ship. This leads to the concept of a last possible time to fire if we wish to hit the incoming missile at a safe distance. If our efforts fail the incoming missile will hit the ship a few seconds later.

The time that the first threat is detected is set to be $t_{01}=0$. Subsequently the first possible time to fire against this first threat is called t_{11}, the last possible time to fire if we wish to avoid the debris is called t_{21} and the predicted time of impact in the ship is called t_{31}.

A specific combination of threat, C^2-system and surveillance system is now described by the four-tuple

$$T_1 = (t_{01}, t_{11}, t_{21}, t_{31}) \qquad (1)$$

(Actually, t_{31} also depends on the weapon system of the ship. To simplify the calculations the same time is used in every case.)

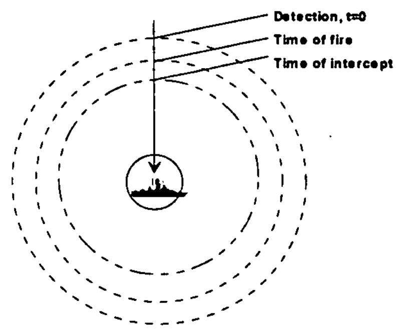

Figure 2. A simple scenario with a single ship attacked by a single surface-to-surface missile.

To add a second threat of the same kind is now very simple. Under the assumption that the missile is detected at the same distance a second threat can be described as

$$T_2 = (t_{02}, t_{12}, t_{22}, t_{32}) \qquad (2)$$

$$t_{n2} = t_{n1} + s \qquad (3)$$

s is the time between the detection of the first and the second missile. As the number of incoming missiles grows there will be a large number of times to keep track of. The easiest way to handle this was to use a graphical method (Fig. 3).

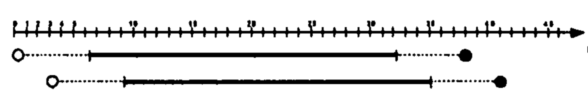

Figure 3. A scenario with three incoming missiles.

Weapons are introduced into the models as crosses (for missiles) and bars (for gunfire). First we consider only a surface-to-air missile system. The first possible time to fire is defined by t_{11}. If the missile needs to be guided to the target, such as the proposed Swedish RBS23, the second possible time of fire is when the first missile has reached its target and the system is tracking a new target. This time has to be calculated specifically for every situation.

When the system is ready to fire a second time, a decision has to be made what target to fire upon. The target chosen and the time the SAM is fired is marked in the chart with a cross.

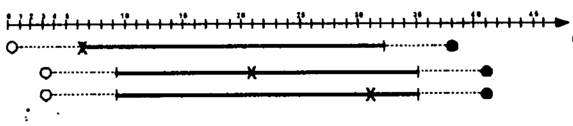

Figure 4. A scenario with tree incoming missiles and a SAM system that has fired tree times. The times of firing are marked with crosses.

When all possible SAMs has been fired the lines representing the missiles has a number of crosses. Each cross represents a SAM fired at that incoming missile. The more detailed model of the surface-to-air missile provides us with the probability that the SAM will kill the incoming missile, P_{kill}. The possibility that a missile survives the SAMs is calculated as

$$P_{sur} = (1-P_{kill})^n \qquad (4)$$

n is the number of SAMs fired at this missile, i e the number of crosses on one line in the chart. This calculation is done for every missile in the scenario.

A gun is now added in a similar way. As the accuracy of a gun is depending on the distance to the target two volleys of gunfire will differ in length as well as in P_{kill}. In the chart a volley of gunfire can not be marked with just a cross. The length of the volley has to be taken into account. The equation (4) must be modified to

$$P_{sur} = \prod_n (1 - P_{kill(n)}) \qquad (5)$$

n is the different volleys and $P_{kill(n)}$ is the probability that volley n destroys the incoming missile.

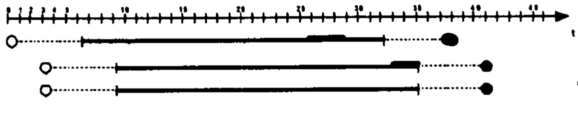

Figure 5. A scenario with three incoming missiles and a gun that has fired two volleys. The volleys are marked with bars.

When the calculation has been made for all weapon systems, it is possible to calculate the possibility of survival for each incoming missile in the scenario. Under the assumption that a surviving missile will strike the ship the probability of survival of the ship is calculated from the probabilities of survival of the missiles.

Electronic warfare components have to be included in the model, as EW today is essential in the air-defence of a ship. This can be done in two ways. Both ways depend on some assessment of the effectiveness of the EW system, a P_{kill} for the EW system. We settled for a definition of effectiveness as "the probability that a missile never acquire a lock on the ship and that a missile that has acquired a lock on the ship looses the lock and do not reacquire it".

The first way to include EW components is to regard the incoming missile as an entity that is reduced by EW. If there are four incoming missiles and the EW has a P_{kill} of 0,5 two of the missiles are taken out of the scenario. This model works only if the EW reaches farther out than the guns or missiles, and that the ship has equipment that can determine whether or not a missile that is detected is a threat.

The second way is to treat every missile independently. Once the possibility of the missile surviving the hard-kill systems has been calculated this probability is reduced by a factor corresponding to the effectiveness of the EW systems. If a detailed model of the ship and the EW system is used it is possible to determine the ships probability of survival as a function if the angle from which the missile comes.

The model described in this paper was developed for a very specific purpose and in a short period of time. It was born out of the necessity to develop a model on a tactical level that satisfied the needs of the analyst.

The study required a versatile model that was easy to adapt to different situations, and I believe that this model meets the requirements. The problem is that the model demands a "hands on" approach from the analyst. Every step of the way the analyst has to keep an eye on a large number of parameters and decide which to take in to account. The model can not run on it's own and leave the analyst to evaluate the results.

Since the input to the model could be output from *any* model on a lower level, the analyst is free to choose what parameters should influence the result, and in doing so also determine the accuracy of the output from the lower level model. Since the higher level model depends on the output from a number of lower level models, some caution is recommended. The models used on the lower level should have the same level of coarse-graining as the result otherwise could be misleading.

The model and the method described above was tried in the study mentioned above. The fact that it was not a computer model made it easier to trace the results back to the data put in to the lower level models. The disadvantage was that the result from the model lacked the reliability that is associated with a computer model.

The fact that we stayed with pen and paper and did not take the step to a computer model had the advantage that all the time spent working with the model was spent producing results. In the time available for the study, a computer model would have tied up our resources with the problem of how to convert the scenarios to codes. A conclusion from our part is that the step from model to computer model is not always justifiable. I would not completely rule out that this model, some day in the future, is going to run on a PC, but I believe it is very unlikely that it has graphics including miniature ships and symbols for missiles moving across the screen.