# Evaluation Tools for the Effectiveness of Infrared Countermeasures and Signature Reduction for Ships

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## ABSTRACT

The protection of ships against infrared guided missiles is a concern for modern naval forces. The vulnerability of ships can be reduced by applying countermeasures such as infrared decoys and infrared signature reduction. This paper will present a set of simulation tools which can be used for assessing the effectiveness of these measures. The toolset consists of a chain of models which calculate the infrared signature of a ship (EOSM), generate an infrared image of the ship combined with a realistic sea foreground and sky background (EOSTAR) and determine the behaviour of an infrared missile seeker against these images and simulate the complete missile fly-in including countermeasure deployment (EWM). Tools will be discussed and typical simulation runs will be shown for hit point analysis studies and countermeasure effectiveness.

## 1. INTRODUCTION

The operational effectiveness is one of the main drivers in the design phase of a ship. This operational effectiveness is a measure for the ability of a ship to perform its tasks in a conflict situation. One important aspect of the operational effectiveness is the survivability. The survivability is determined by:

- Susceptibility: the process of the detection of a platform up to the probability that the platform will be hit by an enemy weapon.
- Vulnerability: the level of reduction of operational capabilities of the platform after a hit.
- Sustainability: the level of availability of the essential systems on board of a platform during a full operation.

At a sublevel of the vulnerability the actual point of impact or “hit point” in a missile attack is a key element. Current benchmarking studies aim for a better understanding of the aim point selection in missile seekers and aim for improved models to simulate the final approach of a missile to a ship. The main goal in this paper is to verify the availability and quality of the necessary modelling tools, needed for analysing the hit point location for various attack conditions with infrared guided missiles. The results of the hit point analysis should help to avoid positions on the ship, which are unintentionally preferred by missile seekers as hit points. Also countermeasures against incoming infrared missiles by means of flare deployment from trainable launcher systems get attention in this respect. Flare deployment are currently being performed for better insight in the protection of vulnerable ships.

The TNO tools referred to in this study are Electro-Optical System for Transmission and Ranging (EOSTAR), the Electro-Optical Signature Model (EOSM), and the Electronic Warfare Model (EWM).

First a short description of the toolsets used is presented in Section 2. In Section 3 modelling applications are given in more detail for typical hit point analyses. A countermeasure example is given as well. A selection of results from simulation runs are presented in Section 4. Summarised findings and conclusive remarks are given in Section 5.

## 2. TOOLSETS

The applications discussed in Section 3 are based on infrared image sequences generated with the EOSTAR model. EOSTAR is a flexible tool to assess the performance of electro-optical sensors in the maritime environment. This includes detection range calculations against specific targets. EOSTAR provides a toolbox with modules to evaluate the main atmospheric processes, such as transmission, refraction and turbulence. Background and signature models allow the generation of synthetic camera images for a scenario of interest and calculation of the thermal radiance properties of the scene elements in these images. A sensor module, including signal processing algorithms, generates the synthetic image as seen by an operator or the sensor. These synthetic images consist of a ship placed in a sea foreground and against a sky background with clouds.

EOSM (Electro-Optical Signature Model) is a tool for calculating infrared signatures of military platforms by solving detailed heat balance equations. In an international comparison of infrared ship signature prediction models based on data from a

NATO trial, EOSM performed very well and comparable to the SHIP-IR model [2]. It is well known that the signature of a ship can strongly change with the environment. See Fig. 1 for an example of an infrared signature of the frigate that was generated with EOSM.

*Figure 1. Typical images generated with the EOSTAR EOSM tools. Top panel: LWIR. Bottom panel: MWIR.*

The Electronic Warfare Model EWM is a system that is capable of performing closed-loop simulations regarding the engagement of missiles against ships. EWM includes detailed seeker models both for infrared and radar guided missiles. These seeker models simulate the details of the interaction of the seeker and targets. The missile flight dynamics are also simulated in a detailed manner. Up to now the EWM was used as developed for the countermeasure evaluation studies and although the limitations are known, EWM was not adapted to end guidance simulations for the current study. On the other hand the current studies have provided a lot of lessons learned to be taken into account when a final homing mode is implemented eventually. A more detailed description of EWM is given in [1].

## 3. APPLICATIONS

The models introduce above were used for hit point analysis and countermeasure effectiveness studies. Four different infrared imaging seeker models were implemented (Table 1). It is expected that imaging seekers will have the best capabilities to select a specific aim point on the target. The current implementations of the imaging seeker models are the best available at this time.

*Table 1. Infrared seekers used in the hit point analysis.*

| | | | |
|---|---|---|---|
| Seeker 1 | Imaging: Correlation tracking | Open loop simulation | Ref. 3 |
| Seeker 2 | Imaging: Centroid tracking | Open loop simulation | |
| Seeker 3 | Imaging: Track gate | Closed loop simulation with EWM | Ref. 1 |
| Seeker 4 | Hot spot | Closed loop simulation with EWM | Ref. 1 |

The various seeker models allow gaining a good understanding of the effects of the various tracking algorithms on the aim point selected by the seeker. For imaging seekers it has to be noted that image processing should be able to select a specific part or section of the ship as the aim point. However, most often this type of processing requires quite some a priori knowledge like the aspect angle under which the approach will take place. This has consequences for the robustness of the tracking algorithm. Therefore we assume that this type of processing will possibly be implemented in future seekers, but is not yet implemented in the current generation of seekers.

All seekers have been developed in the past for other simulations. For none of the seekers a special final homing algorithm was implemented. Seeker models 1 and 2 represent seekers with more advanced image processing than the imaging seeker 3. The seeker with correlation tracker is described in [3]. The hotspot seeker was used as a reference. Both seekers 3 and 4 are described in [1]. Seeker models 1 and 2 were developed to be used in combination with high quality image sequences of a tank in a land background, while seeker models 3 and 4 were developed for use in the EWM in combination with a very rough representation of the ship. For the countermeasure effectiveness studies this is justified, because the outcome is more determined by the position of the decoys with respect to the ship than by the details in the signature at the range where the decision is taken to track either the decoy or the ship. None of the seekers was specifically tuned for the ship image sequences. A good tuning of the seekers to the quality of the new image sequences requires quite some effort. A real seeker algorithm has to be robust over a wide range of circumstances covering low contrast and high contrast targets, targets with and without countermeasure deployment and

all aspect angles.
It was decided to limit the number of scenarios to two weather conditions, clear sky and full overcast at a mid-latitude position. Full overcast gives a condition where the surface temperature of the ship is mainly determined by the ambient air temperature. In the clear sky condition the solar heating of the ship has to be taken into account. Maximum and minimum contrast is than expected for the sun and shadow side of the ship respectively. The sky background and the sea foreground models in EOSTAR are derived from models for IRST (Infrared Search and Track) system evaluation. Because an IRST system on board generally does not move very fast over the water surface, the effects of fast movement over the sea surface are not included in the foreground model. This makes the foreground in the image sequences look somewhat unrealistic. However, this does not affect the seeker behaviour, and for the hit point analysis we considered it not necessary to improve this part of the scene generation.

The intensity of the plume from the smokestack has a strong effect on the ship signature especially in the MWIR (3-5 µm) band. For this band, infrared images for three different power settings were calculated resulting in three different plume conditions, i.e. a large plume from the gas turbine engine, a medium size plume for the diesel engine and no plume at all. In the LWIR band the effect of the plume is much less dominant and therefore the LWIR images are calculated without plume. These combinations of weather conditions and plumes result in the twelve image sequences or scenarios as listed in Table 2.

For the hit point simulations the image sequences of a frigate (see also Fig. 1) were derived by converting the radiance map directly to grey levels in the images. In reality the optics and the detector sensitivity of the camera or the missile seeker have to be included as well. Currently this can be done as a part of EOSTAR as well. The new approach may result in some differences in the grey levels, but this will not influence the conclusions for the hit point analysis.

It was decided to use the models without modifications. The seekers 1 and 2 were used in an open loop simulation, where an image sequence was generated in advance with the target always positioned in the centre of the field of view. The anti-ship seekers on the other hand were used as a part of the EWM model that allows for closed loop simulations. Based on the seeker tracking output, EWM calculates the new line of sight direction for the missile seeker and provides this as an input for EOSTAR.

For the countermeasure methodology a logistic vessel – a landing platform dock (LPD) – of the RNLN was used in the EWM model. Large logistic vessels are vulnerable for missile threats, mainly due tot their size. The LPDs and successors are therefore to be equipped with a flare decoy launcher system against imaging seeker missiles. The goal is to find an efficient decoy system setup that satisfies the safety of large logistic vessels during a missile threat. Therefore the functionality of new launcher systems, like trainable systems, has been explored. One scenario is given here and in Section 4 one example is presented.

The overall countermeasure setting is as follows. The ship, positioned at the origin, is threatened by a missile fired from an adversary naval vessel 15 km eastwards. The IR seeking missile will reach the ship in approx. 50 seconds so that there is ample time for pre and post launch manoeuvres. The LPD can manoeuvre twice and change its speed twice in each scenario. There is an adjustable blowing wind that affects the movement of the decoy screen. The ship’s speed, wind speed, manoeuvre angles are important parameters as are the quality factor parameters that are required for a proper missile/target interaction. Note that the decoy screen is deployed according to very specific settings of each round in the launcher system; to name the most important ones: maximum intensity, fall speed, flight time, lifetime, diameter, altitude, range. The values for fall speed, diameter, lifetime, and maximum intensity are constant for all rounds fired for all scenes tested. The flight time, altitude, and the range are required for positioning each round in the air. These values are different for each round. Changing these key parameters is an elaborate process due to a large parameter space, though some insight can narrow down certain settings for proper scenario testing.

Decoys are not yet implemented in EOSTAR and therefore a very crude model for the ship and the decoys has been used. Also, as said before, the outcome is more determined by the position of the decoys with respect to ship than by details of the ship.

## 4. SIMULATION RESULTS

For the open loop simulations 12 typical scenarios have been used, for the closed loop only a subset has been used, not using the overcast sequences. All simulations are done for broad side (port side or starboard side) approach of the seeker to the ship. For this paper a selection of the results for the open loop simulations with the anti-tank seekers is shown in Fig. 2a – 2d.

*Table 2. Scenarios for image sequence calculations. The grey-scaled boxes have been selected for the results (see also Table 3 for corresponding scenarios).*

| | Clear sky Solar heated | Clear sky Shadow side | Over-cast |
|---|---|---|---|
| MWIR / No plume | 1 | 2 | 3 |
| MWIR / Medium plume | 4 | 5 | 6 |
| MWIR / Large plume | 7 | 8 | 9 |
| LWIR / No plume | 10 | 11 | 12 |

The figures show the final image in each simulation sequence where a purple marker indicates the aim point selected by the seeker. The green marker indicates the centre of the field of view.

### 4.1. Open loop correlation tracker

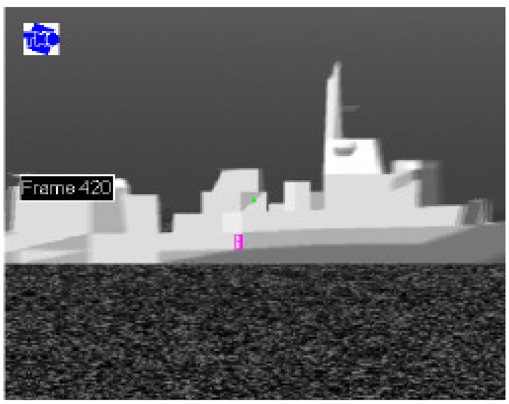


*Figure 2a. Stable track. Final aim point on the hull.*

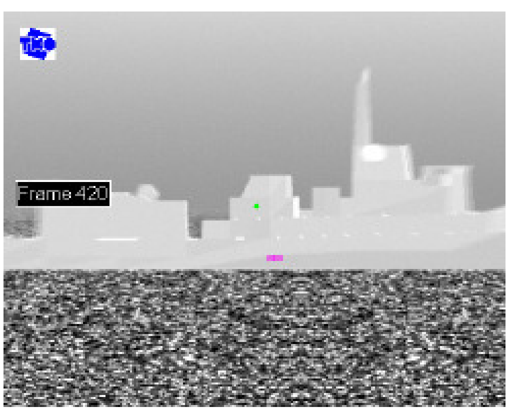


*Figure 2b. Less stable track, due to the lower contrast on the shadow side.*

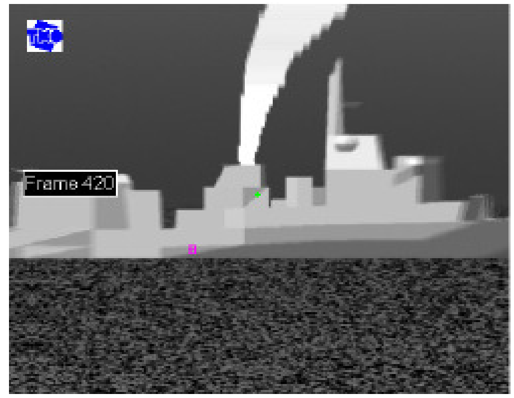


*Figure 2c. Plume seems to be ignored by the correlation tracker. Similar result as in scenario 1.*

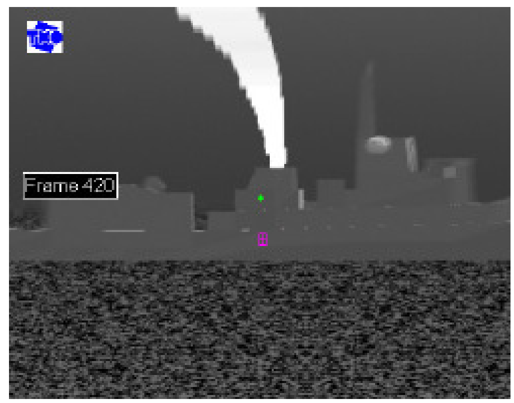


*Figure 2d. Plume seems to be ignored by the tracker. The hot plume has effect on the dynamic range, which compresses the contrast on the ship itself. Note that the wind direction has reversed.*

### 4.2. Closed loop imaging seeker

A list of typical scenarios for the closed loop simulations with their numbers are given in Table 3. No simulations were conducted for the cloudy conditions, because the clear sky conditions provide both the maximum and minimum contrast scenarios. For each scenario typically 10 runs were performed. The difference between the runs is caused by the noise which is added to the seeker pointing commands. The seeker pointing command is derived from the tracking algorithm, to simulate noise effects such as mechanical noise in the seeker gimbal or turbulence in the atmosphere, noise is added to the pointing direction for the seeker, which causes that line of sight for the new image to be processed is not exactly aligned with the pointing position determined by the tracker form the previous image. The grey scaled boxes in this table are simulations that have been conducted for the same scenarios as the open loop simulations listed in Table 1.

*Table 3. The sixteen frames of operation for the IR imaging seeker as well as for the IR hotspot seeker threat analysis. It is assumed that differences between MWIR and LWIR are only significant in the "no plume" situation, the small and big plume scenes have not been explored for LWIR. Scenarios 1-4 have been selected for the results in this paper.*

| IR imaging seeker scenario number | IR hotspot seeker scenario no. | 3-5 µm | 8-12 µm | No plume | Small plume | Big plume | Sun side | Shadow side | Corresponding scenario Table 1 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 9 | ✓ | | ✓ | | | ✓ | | 1 |
| 2 | 10 | ✓ | | ✓ | | | | ✓ | 2 |
| 3 | 11 | ✓ | | | ✓ | | ✓ | | 4 |
| 4 | 12 | ✓ | | | ✓ | | | ✓ | 5 |
| 5 | 13 | ✓ | | | | ✓ | ✓ | | 7 |
| 6 | 14 | ✓ | | | | ✓ | | ✓ | 8 |
| 7 | 15 | | ✓ | ✓ | | | ✓ | | 10 |
| 8 | 16 | | ✓ | ✓ | | | | ✓ | 11 |

As for the open loop simulations the seeker parameters have not been optimised for the simulations. The size of the hot spot detector area was simple copied from previous simulations which might have had a different spatial resolution in the image, resulting in a different instantaneous field of view for the seeker. This then may influence the size of the hot spots as "seen" by the missile seeker.

The imaging seeker sets a track window around the selected target. Initially this is the whole ship but when the ship starts to grow in the field of view the imaging window selects a subpart of the target according to predefined criteria. Despite the fact that the seeker parameters have not been tuned for these specific image sequences, the settings used are still considered to be representative for a realistic seeker. Visual inspection of the results indicate that when the seeker had been tuned better, a lock-on might have been possible in some cases where no lock on could be achieved for the current settings.

A selection of results for the closed loop simulations with the imaging seeker are shown in Figures 3a – 3d. For each scenario the horizontal position of the hit points of the ten simulation runs are indicated by a yellow bar against a generic background picture of the ship, in the top part of the figure. This background image is for visualisation only and clarifies the dimensions of the hit point in reference to the ship. The middle part shows the typical hit point for a single run with enlarged pictures showing the detailed aim point. In the pictures a yellow vertical line represents the centre of the ship from a lateral point of view. A vertical dashed white line is the average hit point. Its uncertainty is marked by two short vertical red lines (sometimes with an arrow in it). Extra hit point sections are marked by vertical dotted lines. The spread for such sections are marked by a different colour. The small hollow red square is a hit point for one run.

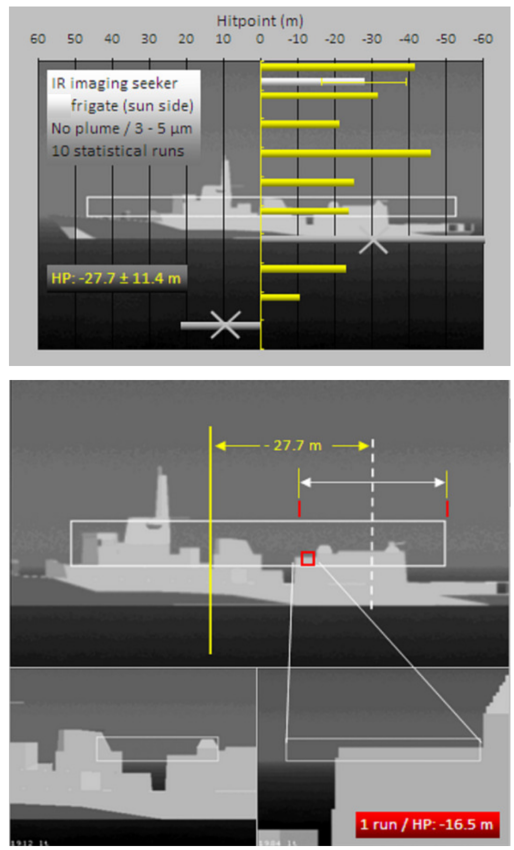


*Figure 3a. Hit point results for scenario 1. Eight successful runs show the average hit point in the back of the ship at approx. -28 meter from the centre (top panel. Two outliers have been left out. Lower panel: a single run hit point - the open red square in the lower panel - lies within the uncertainty of the eight runs. The scenario hit point (all-run average) which is more to the back of the ship is represented by a white dashed vertical line and a standard deviation given as two red short vertical lines.*

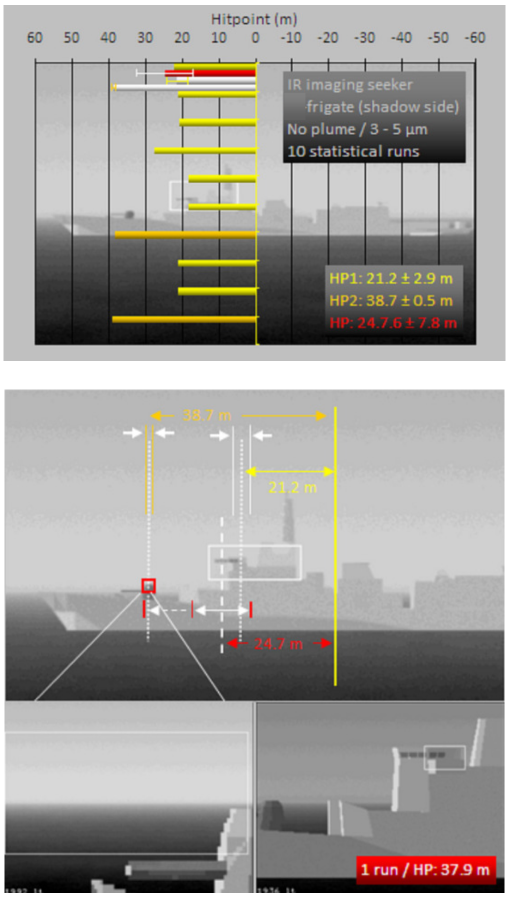


*Figure 3b. Shown are two hit point preferences, marked by a different colour, for scenario 2. Two runs have a preference to hit the ship way up front (approx. 39 m from the centre). The other eight runs converge at approx. 21 m from the centre in the bridge area (with a small standard deviation). The red bar designates the overall average and standard deviation. Lower panel: a single run hit point, showing a preference for one of the two hit point areas (see above). The preferred target seems to be the front cannon. Note the two zoom views: earlier in the flight the missile aims at the bridge (right zoom) while it hits the front side of the cannon in the end stage (left zoom).*

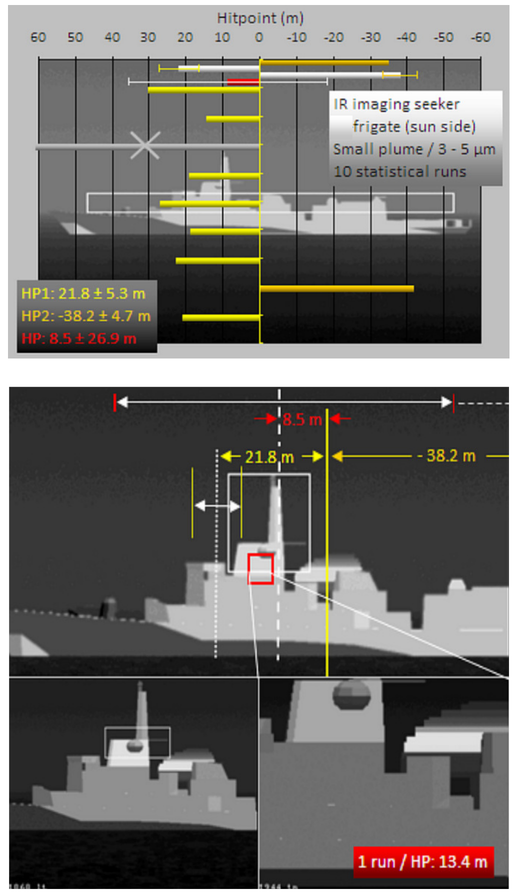


*Figure 3c. Two preferred hit point areas are identified for scenario 3. One in the aft section of the ship and one in the bridge section. One run is assumed invalid. Note that the background picture in this top panel is for illustration only and does not include a plume. The size of the plume in the bottom panel can be clearly seen. Lower panel: a single run hit point lies just behind the bridge in the mast section. The average of all nine successful runs is at 8.5 m from the centre of the ship. The standard deviation for all measurements is large (26.5 m) (due to the hit point aft section at -38.2 m just outside the picture frame).*

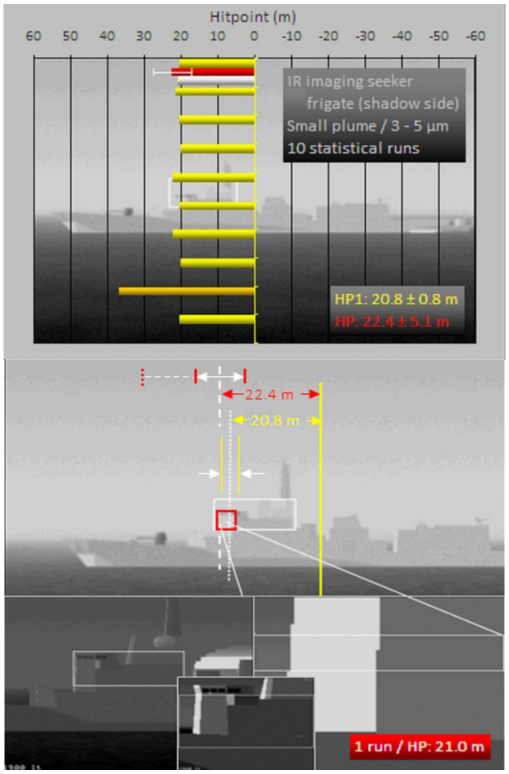


*Figure 3d. Hit point results for scenario 4 showing a clear preference for the bridge section of the frigate, despite the plume present. Lower panel: single run hit point result for which it is clear that the hit point is caused by the bright lit forward section of the bridge (see frame inset for details).*

### 4.3. Countermeasure methodology

One example for a countermeasure scenario is given here. An LPD vessel sails with ship speed of 10 m/s. The wind direction is 200º and the wind speed is 0.5 m/s. The (initial) heading of the ship is 150º. Fig. 4a shows the final stage for a typical countermeasure scenario.

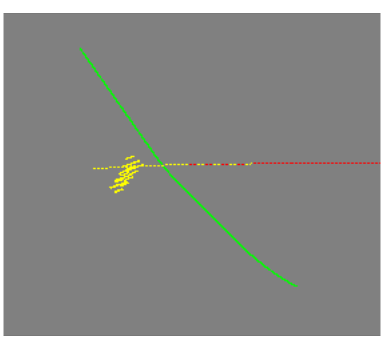

*Figure 4a. Bird's eye view of the end stage. The green line is an LPD sailing, after two manoeuvres, to the upper left corner. The missile, coming from the right in red (and then yellow), hits the decoy screen in yellow. The wind causes a drifted decoy screen. 0º is to the right.*

The images from a seeker's point of view are shown in Fig. 4b where a selection of images in sequence is presented. The example shows a successful countermeasure for a seeker looking in the 3 – 5 µm wavelength range. The vessel model consists of three blocks – a very simple representation indeed – with the hot smokestack clearly visible from great distance. This hot spot clearly is a definite target for the missile if no countermeasures were initiated.

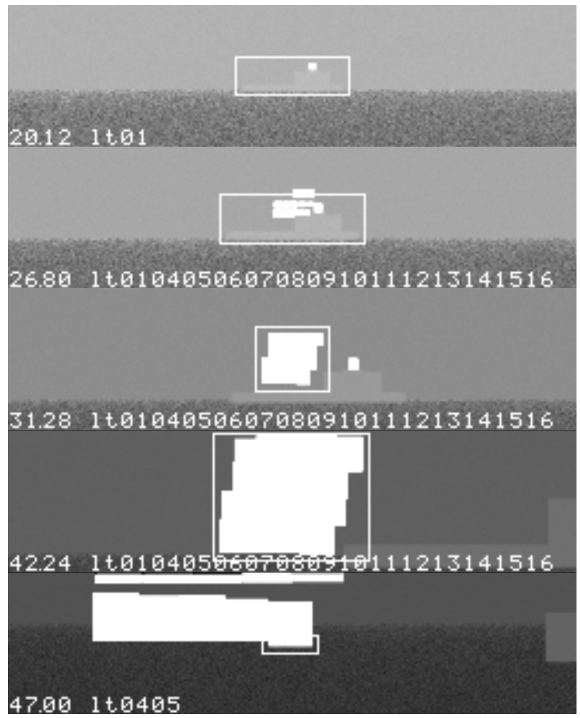


*Figure 4b. A successful countermeasure. The missile picks flare number 5 after almost 50 seconds. The closest point of approach (CPA) is 183 m.*

The results shown in Figure 4a and 4b are for one specific combination of wind speed, ship speed, wind direction, and ship direction. The two directional parameters however can be varied for appropriate user resolution specifications. High resolutions cost a lot of processing time, hence for current countermeasure studies a moderate resolution has been used with a wind direction that varies from 90º – 270º (symmetrical plane) with steps of 9º and with a variation in the ship direction of 0º – 360º with steps of 5º, totalling 1349 combinations for all wind and (initial) ship directions. This is for one selected speed of the ship and for one wind speed.

## 5. SUMMARY AND CONCLUSIVE REMARKS

In this paper the tools for hit point analyses and countermeasure studies have been demonstrated for a selected number of scenarios.

The coupling between the TNO models EOSTAR, EOSM, and EWM, for IR simulations, was already available from previous studies and has now been used for the first time. A number of problem issues have been detected and have been solved. For the infrared seekers no preferred aim point is found consistently over all scenarios. Even when the aim point within a certain scenario seems to be very consistent, it has to be noted that this is related to a very specific detail in the ship superstructure often only visible for a limited range of aspect angles.

The main conclusion for the closed loop imaging seeker is the same as for the open loop imaging seekers simulation. No single aim point can be declared which is consistently the same for all ship signature conditions and for all exhaust plume conditions. For subsets of scenarios with similar signature conditions or similar plume conditions the hit points can be clustered in certain preferred areas. Depending on the scenario these preferred areas can cluster for example around the plume, the bridge etc.

When there is a relatively small contrast, in case of the shadow side of the ship without plume, the seeker is unable to lock on the ship. The fact that a seeker cannot lock on to a low contrast target is not necessarily a simulation artefact, because this has been observed in trials as well. In the absence of a plume the seeker selects a part of the ship consistently. For all scenarios with an exhaust plume the seeker selects the plume, even the small diesel plume which was often ignored by the imaging seeker. For hotspot seekers in general, as for the imaging seekers, no single aim point can be declared which is consistently the same for all ship signature conditions and for all exhaust plume conditions.

For a full hit point analysis more scenarios should be used. Full analysis requires a full matrix with, for instance, attack direction, wind speed, and ship speed. To increase the selection of seekers in the EWM environment, implementation of the correlation tracker and the centroid tracker as used in the seeker models 1 and 2 could be considered. The tuning of the seeker parameters for improved results in the final approach towards the target should be part of a further study. Even more important, the implementation of a specific tracking algorithm for the final homing section, including the decision logic for the transition from midcourse guidance to the final homing guidance will require a significant effort.

The results presented here and for the other scenarios have been analysed manually. For more extensive studies with multiple runs over multiple aspect angles for multiple scenarios it will become useful to develop tools to set up the simulations automatically. Also tools for automatic analysis of the results could be useful. Another issue is the run time for the simulations. Especially for the imaging seekers it could be useful to try to reduce the run time of the simulations.

The countermeasure studies only reveal one example of an EWM application in this paper. The successful LPD scenario showed a very crude ship and decoy screen. This is justified to certain extend because for the countermeasure effectiveness the outcome is more determined by the position of the decoys with respect to the ship than by the details in the signature. This certainly applies to the range where the decision is taken to track either the decoy or the ship. However, it is expected though that the EOSTAR image sequences for ships and decoy screens, which are currently being implemented for newly built vessels, result in a more realistic and certainly synergistic system of models.

Further countermeasure developments refer to screen deployment. The example shown in Section 4 is a straight line of flight deployment of the flares. Current implementations are dealing with a (trainable) rotation of the deployed decoy screen. This will ultimately result in ‘one-manoeuvre’ scenarios with similar effectiveness compared to ‘two-manoeuvre’ scenarios.

In conclusion: a powerful toolset to assess the survivability of ships against infrared guided missiles has been set up by linking the three TNO models suites EOSTAR, EOSM, and EWM. The application of the toolset for hit point analysis and for countermeasure effectiveness has been demonstrated.

## 6. ACKNOWLEDGEMENTS

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