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# Operational Analysis for stating Naval Low Observability Requirements

## "The Netherlands Perspective"

The article reflects the views of the authors and not necessarily those of the Royal Netherlands Navy and/or Physics and Electronics Laboratory.

All data in this article is based on "open literature sources"

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**SYNOPSIS**

*Signature management is of paramount importance for a warship's survivability. This holds for above water as well as under water survivability. The operational benefits of low above water signatures will be explained. Cost effective signature levels can be derived by means of Operational Analysis in combination with different Low Observable Measures Trade-off analyses.*
*The Operational Analysis Simulation Code SEAROADS will be addressed. The capabilities of SEAROADS will be demonstrated with examples of Low Observability (LO) analysis. The article will close with a view on future Very Low Observability (VLO) trends.*

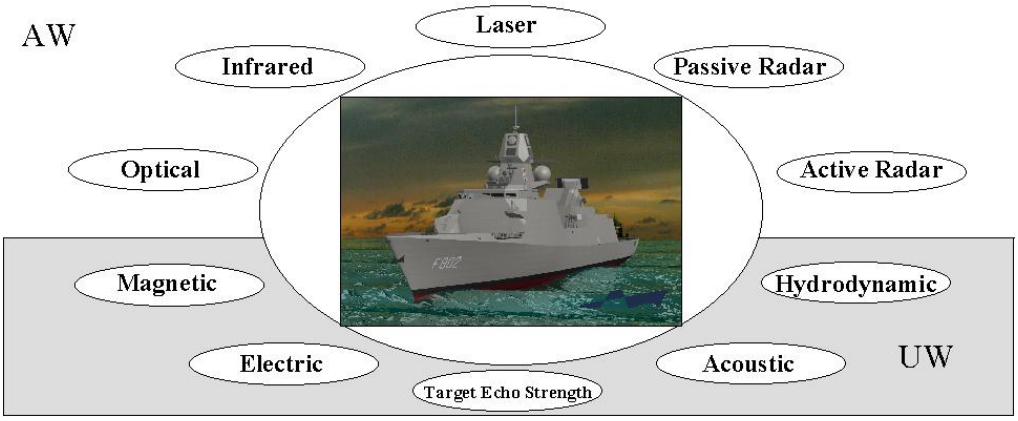


***Figure 1 Relevant Warship Signatures***

***"Future Very Low Observable (VLO) Naval Platforms, will force attackers to enter the Platform's Hard Kill Envelope……"***

## INTRODUCTION

While performing their mission, naval vessels operate in a three dimensional threat environment. The vessels are threatened at the sea surface and from the air (Above Water: AW) as well as from below the sea surface subsurface (Under Water: UW), see Figure 1.
Different threat platforms will exploit different parts of the ship signature. Figure 1 yields an overview of the most relevant signatures, that a Naval Engineer has to address for a new warship design, for UW e.g.:

- Acoustic (Broadband & Tonals);
- Target Echo Strength;
- Hydrodynamic (Wake);
- Magnetic:
  - Static;
  - Alternating;
- Electric:
  - Static;
  - Alternating.

For Above Water (AW) the following signatures are most relevant:

- Optical;
- Infrared;
- Radar Signature:
  - Passive (RCS);
  - Active (e.g. Own Radar Emissions);
- Laser.

### Balancing Signatures ?

It is often stated that a warship's signatures should be balanced; i.e. with each other. This balancing should be performed by making detection ranges equal for the different relevant signatures of the warship as quoted in the last paragraph. This seems to make sense for sensors that are located at the same platform e.g. a fighter jet, a missile for UW at the one hand and e.g. submarine and a torpedo on the other hand for AW.
Balancing signatures that are divided by the sea surface, i.e. balancing AW & UW signatures just based on detection ranges, is irrelevant. E.g. Anti Ship Missile (ASM) either uses Electro-Optic, IR or radar guidance or a combination of these. A torpedo will use the acoustic signature of the ship (passive) or use its on board sonar (Target Echo Strength; TES); it will not exploit the RF or the IR signature.

### Balancing for Mission Effectiveness & Survivability

A more valid approach is just to exploit signatures (reductions) to support the ship in performing its mission. So to optimise its Mission Effectiveness by a cost-effective combination of on board sensors, Hard Kill (HK), Soft Kill (SK), Signature Reduction (SiRe) and a Command and Control ($C^2$) system. Mission Effectiveness is in principle the relevant

Measure of Effectiveness (MoE) for this balancing operation. This mission for a ship can range from e.g. Anti Submarine Warfare (ASW), Anti Air Warfare (AAW), Anti Surface Warfare (ASuW), to Embargo and Human Relief. In most of these missions the warship will have to act under (man-made) threat conditions. This is the ***essence*** of a ***war***ship's capability. Missions can only be successfully executed, if the warship can survive such a hostile environment. Mission Effectiveness is in principle a conditional situation; i.e. under the condition that the ship survives. Figure 2 shows the essential relation between Mission Effectiveness and Survivability.

***Figure 2 The conditional relation between Mission Effectiveness & Survivability***

## Scope

This paper will elaborate on Survivability support by signatures, it will not dwell on the impact of signatures on the Mission Effectiveness. Only the Above Water component of Survivability will be addressed and its most relevant accompanying signatures i.e. the Radar and Infrared (IR) signature.
It should be noted that optimising the survivability by balancing HK, SK, SiRe, $C^2$, is also a dependent on what is technical feasible and on the costing factor; different trade-off analysis have to be performed.

## The Above Water Threat

The last decades, the threat of Anti Ship Missiles (ASMs) challenging our warships has been dramatically increased. ASMs have become more and more sophisticated in terms of velocity, agility, sensors and (digital) signal processing (DSP). This is true in the field of Infrared (IR), see Figure 3, Electro Optics (EO) guided as well as developments in the ASM Radar Guided (RF[1]) field. Examples of RF guided ASMs are the Swedish "*RBS-15"*, see Figure 4, or the US-build Harpoon, see Figure 5,

***Figure 3 IR-guided Penguin Mk 3 launched from a SH-60B Seahawk (Source: Kongsberg)***

the Russian "*Styx*" RF variant and its Chinese (PRC[2]) derivative "*Silkworm*".
RF-ASMs can either have single RF-guidance or Dual Mode i.e. initial RF combined with terminal IR guidance e.g. the Taiwanese Hsiung Feng 2. Near future systems will be able to use RF and IR simultaneously to exploit synergism (Hybrid). In an earlier paper, it was promoted to integrally take up the challenge of Survivability for ASMs [Roodhuyzen, Galle & van Koningsbrugge, 1].

***Figure 4 RBS-15 RF-guided ASM launch (source: Saab Dynamics)***

Two Survivability factors, *Susceptibility* and *Vulnerability*, were explained, see Figure 6.
Susceptibility; being the *inability to avoid* weapon effects and Vulnerability; the *inability* of the warship *to withstand* weapon effects. It will be shown that the susceptibility factor is significantly dependent on Radar as well as IR Signatures. It should be noted that the combination of Low Observable (L.O.) design and operational aspects (Tactics) is often referred to as "Stealth":

***"Stealth = L.O. + Tactics".***

[1] **R**adio **F**requency

[2] **P**eople's **R**epublic of **C**hina

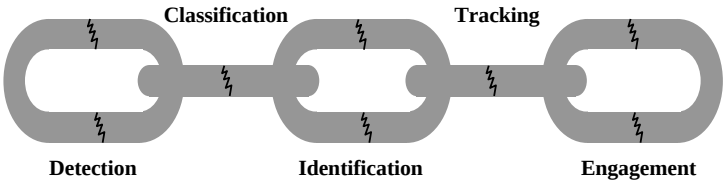


***Figure 7 Low Observable Design and Tactics ( = Stealth) disrupts and breaks the Opponent's "Kill Chain".***

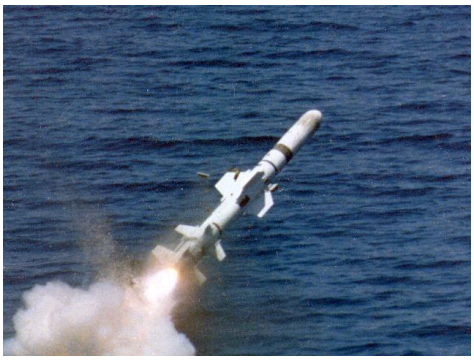

***Figure 5 RF-guided Harpoon***
***(Source: McDonnell Douglas)***

Stealth disrupts and breaks the well-known ***Opponent's*** "Kill Chain", see Figure 7, [Goddard et al., 2]. High signature levels are in principle unwanted because they will provide information to the opponent for detection, classification, identification, tracking and even homing guidance.

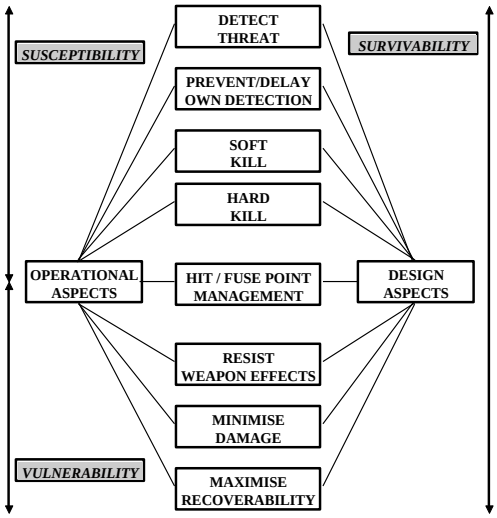


***Figure 6 Generic Ship Survivability Scheme***

The antagonist can be airborne, seaborne, landbased and even spacebased remote sensing (satellites). In the first part of this article the basic theoretical operational benefits of low AW-signatures will be addressed. Next to this, the difficulties, which accompany the production of signature requirements will be addressed. In the second part the Operational Analysis Simulation Code SEAROADS will be introduced. The capabilities of SEAROADS will be demonstrated with examples of Low Observability analysis. The paper will close with a view on future (V)LO trends.

## ABOVE WATER SIGNATURES

It is important, to be aware of the difference between the detection of ships by IR and by radar systems. Firstly, IR detection is passive. In contrast; radar detection is active; Electro Magnetic (EM) energy is transmitted to the target and its reflection is received. Secondly, IR detection will only give bearing information; a (pulsed) radar system, will give bearing and range information as well. Next to this, IR sensors possess an inherent high level of immunity to jamming techniques, this in contrast with active (RF) seekerheads.

Therefore a warship will not be able to make a positive identification of IR threat sensors e.g. IR ASMs homing in. This in contrast with the RF threat, where the ship is supported by the passive Electronic Support Measures (ESM). ESM is able to make a positive identification of active RF sensors, via its "Threat Library".
However, the incoming IR guided ASM, although not positively identified, can still be detected by radar and even under "radar silence" with IR Search and Track Systems (IRSTs). Such detection systems can become the trigger to deploy IR-decoys.

**Radar Signature**

In essence, the radar signature of a warship consists of two components [Galle et al., 3]:

- the active radar signature;
- the passive radar signature.

- The **active components** are the Electro Magnetic (EM) emissions, which are generated by the warship un- and/or -intentionally by its own radar systems i.e. surveillance, tracking and Electronic Counter Measures (ECM). These active radar components can be exploited by e.g. ESM systems of the other parties to gather information; SIGnal INTelligence (SIGINT). More severely, it can also used by Anti Radiation Missiles (ARMs); which home into these active radiation sources. The presence of ARMs in a threat area can enforce "Radar Silence"; Emission Control (EMCON) for the ship and therefore severely hamper radar operations.
Next to the exploitation of the own emissions by ARMs; Anti Ship Missiles (ASMs) can exploit the active jamming signals of the ECM system by switching on to "Home on Jam" (HoJ); i.e. by switching off its missile seekerhead transmitter and only using its receiver for homing in to the active jammer locations.

The active signature will not be dealt with under the present basic considerations, only the passive radar signature will be treated.

- The **passive component, or Radar Cross Section (RCS)**, is the part of the signature that is not generated by the ship's active emissions. The RCS is only determined by the passive reflections from the ship, "Skin Echo" or Radar Echoing Area (REA), if it is illuminated by an external radar system.

The RCS of a platform is defined by its integral radar reflective behaviour. The hull, superstructure, supportive equipment and the payload (weapons and sensors) consist of metal, glass and/or plastics. All these parts of the exterior contribute to the reflecting properties.

**Infrared Signature & Contrast**

The IR signature of a naval vessel comprises in general three components [Galle et al., 4]:

- Radiation of the warm hull (8-14 μm);
- Radiation of the exhaust stack (3-5 μm);
- Radiation of gaseous products (4.1-4.5 μm).

It is important to note that a ship's IR signature has to be evaluated against it's environment i.e. the background of sea, sky, landmass or any combination thereof. This because the threat is only able to exploit the signature difference, i.e. the contrast of ship and it's surrounding background.

## OPERATIONAL BENEFITS OF LOW RADAR CROSS SECTION

**Retardation of RF-Detection, Classification & Targeting**
It will be hard for a conventionally designed, as well as a LO frigate-sized ship, to escape detection from a Radio Frequency (RF) guided "sea skimming" ASM that "pops" over the radar horizon. However, detection, classification and targeting at long range by the "missile carrying" fighter jet can be delayed by reducing the ship's radar cross section, see Figure 6 Block 2.

The "Radar Range Equation" states that the received power ($P_r$) by the transmitting (jet)radar is proportional to the Radar Cross Section of the target (RCS, $\sigma$):

$$P_r = (P_t G_t A \sigma) / ((4\pi)^2 R^4) \qquad \text{eq.[1]}$$

with $P_t$ , $G_t$ and A being the transmitted power, transmitter antenna gain and effective aperture of the receive antenna and R the range.

*Note that; $\sigma$ is the only parameter, in the radar equation, which can influenced by the defender / target / ship.*

Long range radar systems need minimum signal levels for detection, classification and targeting: $S_{min}$. Rearranging eq. [1] yields for the maximum range:

$$R_{dct,RF} = ((P_t G A \sigma) / (4\pi)^2 S_{min})^{1/4}$$
$$= \text{constant} * \sigma^{1/4} \qquad \text{eq.[2]}$$

| *Table 1 Decrease of Detection Range by RCS Reduction* | | | |
|---|---|---|---|
| **Unreduced RCS Value σ = 10,000 m²** | | | |
| Log RCS Reduction [dB] | Linear RCS Value [m²] | Free Space Conditions [%] | Multipath Conditions [%] |
| 3 | 5000 | 16 | 6 - 8 |
| 6 | 2500 | 29 | 11 - 16 |
| 9 | 1250 | 41 | 16 - 23 |
| 10 | 1000 | 44 | 18 - 25 |
| 12 | 625 | 50 | 21 - 30 |
| 20 | 100 | 68 | 32 - 44 |

So reduction of the radar cross section of the warship will decrease the (long range) detection, classification and targeting ranges ($R_{dct}$) with the 1/4-power. Table 1 taken from [Baganz & Hanses, 5] depicts some numerical examples of changes in detection range by RCS reduction. The reduction in detection range does not seem impressive, but can still be an important operational benefit, which will be explained in the paragraph "Future Trends".

**Retardation of IR-Detection, Classification & Targeting**

In the IR-case the changes are improving for the defending platform.

If the atmospheric transmission losses are neglected, the lock-on range ($R_{l.o.}$) is in principle proportional to the square root of the IR signature of the ship ($I_{ship}$):

$$R_{l.o.} \propto \sqrt{(I_{ship})} \quad [m] \qquad eq. [3]$$

So halving the IR signature will decrease the lock-on range with √ 2.

**Ship's ESM benefit**

Next to the reduced detection advantage, reduction of the warship's RCS will force the attacker to deploy higher levels of transmitting power which increases the probability of detection by means of the passive Electronic Warfare Support Measures System (ESM) of the defending ship's Electronic Warfare (EW) system and thus increases the available reaction time; Figure 6 Block 1.

**Improved Soft Kill Effectiveness**

In essence, see Figure 6 Block 3, the active part of the warship's Electronic Warfare (EW) suite; i.e. the Electronic Counter Measures (ECM), will have two options against RF-guided missiles: an (active) jammer-system either on board or off-board (AOD) and passive RF decoys and IR-decoys. Passive RF decoys either float on the water or create a cloud of metallised glass fibres (chaff).

An IR decoy is a device which is deployed off-board the ship to act as an alternative source of IR radiation, which attracts hostile seekers. IR decoys either float on the water or create a cloud of hot particles or a combination of both.

***Chaff & IR-decoy Support***

Chaff can principally be deployed in three roles: (1) before the fighter jet (launching platform) acquires the warship (dilution chaff), (2) before the missile locks on to the target (distraction chaff) or (3) after missile lock-on i.e. to seduce (lock transfer) the missile away from the platform (seduction chaff).

***Improved Chaff-S & IR-decoy-S Effectiveness***

In the chaff seduction role (Chaff-S), the Radar Cross Section (RCS) or "skin-echo" of the warship is in direct competition with the chaff round. Figure 7 gives the principles of chaff in the seduction role.

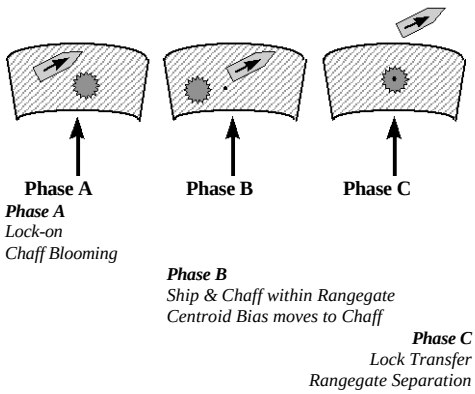


***Figure 7 Lock Transfer Principle for Chaff-S***

The same principles hold for the IR-decoy it is in direct competition with the ship's signature, so the end result is dependent on the level of the ship's signature (i.e. reduction increases survivability).
Figure 8 shows the time interval in which a generic seduction decoy is effective at two different signature levels; conventional and a low observable design. It will be clear that a decreased LO signature increases the time interval for decoy effectiveness.

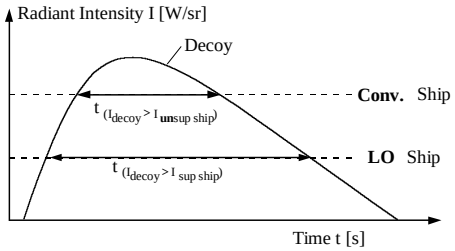


***Figure 8 Generic Radiant Intensity in time for a conventional and Low Observable ship and IR seduction decoy***

***Improved Chaff-D Effectiveness***
Dilution and distraction chaff (Chaff-D) are deployed before lock-on and so their radar reflecting properties are not in direct competition with the RCS of the ship, in case it is assumed that the missile will lock on the first target (in range) it intercepts. But a searching ASM's radar (with memory), can still opt for the largest target i.e. skin echo. Therefore, an additional advantage of RCS Reduction (RCSR) is that high-value units (HVU) can be "camouflaged" between the smaller, less valuable, platforms.

***Improved IR-Decoy-D Effectiveness***
Deployment of decoys in the dilution or distraction mode is preferred over the deployment in seduction mode. The positioning (and separation of decoy and ship) is less time critical because there is not yet a lock-on on the ship. A second reason is that if decoy and ship are both in the ASM's resolution cell, the missile's computing power, if present, may distinguish between ship and decoy.

Considerable RCS reduction (Very Low Observable Design) will help to postpone the lock-on, once the ASM breaks the horizon, and therefore extend the time frame for the decoy to be deployed in the distraction role.

In the IR-distraction role there is no competition, but distraction is only possible if lock-on has not yet been achieved by the missile. The deployment of decoys in the distraction mode is preferred over the use in seduction mode because the position of the decoy is less critical whilst the seeker is still in the search mode. IR signature reduction will help to postpone the lock-on, and therefore extend the time frame for the decoy in distraction [Schleijpen, 6].

**Improved Jammer Effectiveness**

***On Board Jammer System***
The warship's jammer system can be deployed to prevent the fighter jet and/or missile to acquire the warship by means of "masking" the ship by noise. At a certain distance the radar will be able to see through the jamming signal, due to the fact that in the radar equation range is present to the fourth power whereas in the jammer equation it is present to the second power. The range at which the received radar power equals the received jammer power is the "burn through range" from the ASM-radar's point of view or the "self screening range" from the jammer's point of view. Combining the Radar Equation and the Jammer Equation. the "masking range" or "Burn Through Range" ($R_{BT}$) can be expressed in the power ratio of the jet/missile radar and the ship's jammer system and the ship's RCS ($\sigma$), with $P_j$, $B_j$, $G_j$ and $B_m$ being the jammer power, -bandwidth -Gain and Bandwidth of the missile seekerhead radar:

$$R_{BT} = ((P_t G \sigma B_j)/(4\pi P_j G_j B_m))^{1/2} = \text{constant} * \sigma^{1/2} \qquad \text{eq. [4]}$$

The smaller the $R_{BT}$ the longer it takes for the attacker to acquire the ship and the longer for the ship to take defensive actions. After "burning through", the ASM can be forced to make a turn beyond its maximum g's turning rate, which increases the probability of missing the target. Other than noise deployed techniques by the jammer system, i.e. deceptive techniques, will be highly dependent on an adequate jamming-to-signal ratio (J/S) e.g. Cross Eye Jamming which needs 20 dB or more [Adamy, 7]. This J/S ratio can be expressed in:

$$P_j/P_r = (4\pi R^2 P_j G_j)/(P_t G \sigma) \qquad \text{eq. [5]}$$

It shows that the ratio J/S is inversely proportional with the radar cross section, so lowering $\sigma$ will improve J/S, see Table 2, and Figure 9 also taken from [Baganz & Hanses, 5].

| *Table 2 Equivalent Increase in Jammer Gain by RCS reduction* | | |
|---|---|---|
| **RCS Reduction [dB]** | **Jammer Signal [dB] Skin Echo Signal** | **Increase in Equivalent Jammer Gain [dB]** |
| 3 | S/J = X + 3.00 | 2.0 |
| 5 | S/J = X + 5.00 | 3.2 |
| 10 | S/J = X + 10.0 | 10.0 |
| 15 | S/J = X + 15.0 | 31.6 |

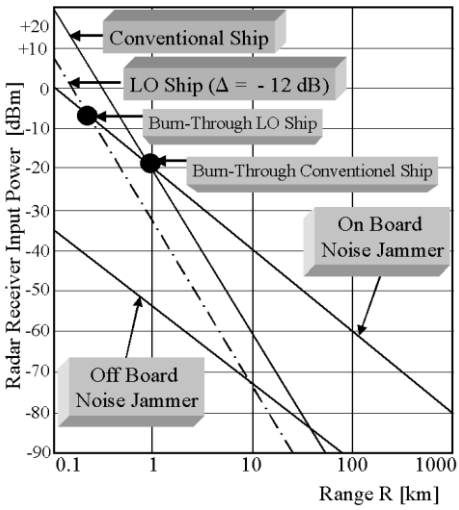


*Figure 9 "Burn Through" Principle*

**Decrease of required RF power for Active Off-board Decoy**

In case the ship's on board jammer system is deployed, the danger of a possible ASM's Home on Jam (HoJ)-mode is always present. The deployment of Active Off-board Decoys (OAD), e.g. SIREN, CARMEN and US-Australian Nulka circumvent this problem. The application of AOD's either in the noise jamming role or "repeater role" will only be possible if RF power can be made airborne technically. The required AOD RF power is, of course determined by the RCS of the ship to be protected. A low RCS will improve the AOD's (& on-board) Jammer effectiveness; Table 2, shows the ratio "Jamming Signal over Skin Echo Signal" at the ASM's seekerhead and the "Equivalent increase in Gain" to be claimed for the jammer performance if RCS reduction is applied.

**Influence on the Hard Kill component**

It is often assumed, that signature management has a small influence on the HK-performance see Figure 6 Block 4. However Hard Kill-rounds, especially Surface to Air Missile systems (SAMs), are expensive and their absolute number on board is limited. The deployment of SK-rounds (chaff and flares) is relatively inexpensive; deployment of the jammer system costs "only" electric energy and its deployment is in principle unlimited. So supporting the SK weapons by signature reduction can save HK-rounds, in this way extending defensive actions in a cost effective manner.

Next to this the ship's signature will affect the trajectory of the attacking ASM. Signature management can opt for a more "steady" RCS, in terms of reduction of glint and scintillation. This could induce a more steady ASM's trajectory, improving the effectiveness of the defending SAMs.

**Hit Point Management / Fusing Signature**

Signature management, see Figure 6 Block 5, can also be exploited in case a hit or stand-off detonation of a missile can not be avoided. Specific RCS and Infra Red signature qualities of a ship design can attract the attacking missile to less vulnerable regions of the ship. These qualities can be latent in peacetime, in order to be exploited under wartime (peace & wartime modes).

## THE DIFFICULTY OF STATING SIGNATURE REQUIREMENTS

The preceding paragraphs just gave the basic theoretical implications of signature management on Survivability.

In case a new ship project is implemented, Naval Staff has to lay down Survivability Staff Requirements. These Survivability Staff Requirements are linked to predefined threat scenarios (input) with probabilities of survival (output). The Naval Engineer has to satisfy these Survivability Requirement with a cost-effective combination of on board sensor systems, Hard Kill (HK), Soft Kill (SK), Command & Control ($C^2$) and Ship Signatures. The analyses, to come to this combination, will be exhaustively dealt with in the next part of this paper.

In recent warship building programmes of the Royal Netherlands Navy, the HK, SK and sensor suite were chosen in the early concept design stages of the project. After that, the signature requirements were

just balanced with this suite, so "full-blown" analyses were not necessary.
The final outcome of the signature level requirements is highly depended on the predefined threat scenarios.
The definition of these scenarios is a complicated task. The definitions should include information on the perceived threats and the expected environmental conditions. On the threat side the following information should be defined e.g.:

- The perceived ASM wave attack:
  - Launch distance(s);
  - Number of missiles;
  - Time between launch of missiles;

- Dynamic capabilities of the ASM-body e.g.:
  - Max. velocity;
  - Max g-turning rate;
  - Height of flight;

- Seekerhead capabilities:

  - For IR:
    - Wavelength Band (NIR, Hotspot, Imaging);
    - Field of View;
    - Sensitivity;

  - For RF:
    - Modulation Type (e.g. CW or pulsed);
    - Frequencies (e.g. I, J, K-Band);
    - Polarisation (e.g. HH, VV, HV, VH);
    - Transmitted Power Output;
    - Receiver sensitivity;
    - Illumination (full / partial).

For environmental conditions the following should be addressed e.g.:

- For IR:
  - Temperatures (Sea & Air);
  - Day / Night Conditions.
  - Cloud Cover;
  - Solar Conditions;
  - Wind (Speed & Direction);
  - Rain, snow, etc.

- For RF:
  - Sea State (Multipath - conditions);
  - Ducting Conditions.

The resulting signature requirements should be stated in a format, which enables the Naval Engineer / Design Authority to check the design variants to meet the requirements.
At the end of the day, i.e. during sea trials, the signature requirements should be part of the ship's contract with the yard. So it should also be possible to measure the stated signature levels and the check if the contract specifications are met.

## OPERATIONAL ANALYSIS

In case ship detection and the deployment of SK and HK are simplified as serial chronological and independent events the susceptibility factor of the survivability equation could be represented as:

$$P_{hit} = 1 - (P_{dect} \times (1-P_{sk}) \times (1-P_{hk})) \qquad \text{eq. [6]}$$

where:

$P_{dect}$ = Probability of being Detected;
$P_{sk}$ = Probability of successful Soft Kill (SK);
$P_{hk}$ = Probability of successful Hard Kill (HK).

In the same way the SK component ($P_{sk}$) of the susceptibility factor can be evolved into:

$$P_{sk} = 1 - (1-P_{jam}) \times (1-P_{dil}) \times (1-P_{dist}) \times (1-P_{sed}) \qquad \text{eq. [7]}$$

Where $P_{jam}$, $P_{dil}$, $P_{dist}$ and $P_{sed}$ are probabilities of successful jamming, dilution, distraction and seduction.

It has to be noted, that the presented susceptibility equation only gives a generic notion of the problem. However, this analytical approach can be convenient for a Naval Engineer who has to take the entire survivability regime into account and who has to make rough choices based on relative numbers.

However, because of the highly complicated interaction, synergistic, degraded and neutral, [The, 8] between HK, SK, C2, Ship Signatures and the perceived threat, see Figure 10, the optimisation can not accurately be performed with a "manual" analysis methodology. In order to obtain more accurate absolute figures it is advisable to use simulation codes, which approach the problem in the "time or event domain" e.g. the TNO-FEL SEAROADS-code.

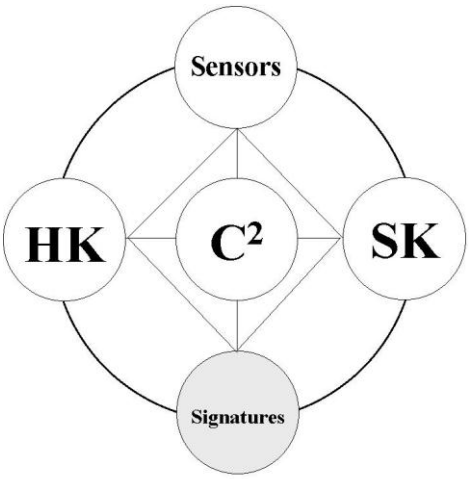


***Figure 10 HK, SK, $C^2$, Ship Signatures interaction***

Next to this, it should be stressed, that in (in)ternational simulations so far, the benefits of signature reduction have always been underestimated [Krieger, 9]. This because of the fact that many of the complex positive phenomena, like the ones addressed above, are not accounted for in most simulation codes. As is also the fact in the present SEAROADS version.

## SEAROADS

### General Description

The Maritime Operations Research (OR) Group of the TNO Physics and Electronics Laboratory (TNO-FEL) supports the Royal Netherlands Navy (RNLN) and other clients on the development, procurement and deployment of naval units. The Anti-Air Warfare section of the OR-group deploys the high-level model SEAROADS in maritime air defence studies.

SEAROADS, which is the acronym for "Simulation, Evaluation, Analysis & Research On Air Defence Systems", is a simulation model developed for maritime air defence. It is deployed to quantify and analyse the air defence capability of one or more naval vessels. The model simulates scenarios composed of an attack of Anti-Ship Missiles (ASMs) and the defence of a single ship or task group of ships against this attack. This includes simulation of the ASMs, all sensor and weapon systems of the ships, the threat evaluation and weapon assignment rules of all ships, and the possible communication and co-ordination between the defending ships.

The development of SEAROADS was initiated and has been funded by the Royal Netherlands Navy, both Directorate Materiel and Naval Staff's Operational Requirements Department. It started as a single ship model, containing only hard kill weapons. Since then, development of the model kept going on. For various studies, the model has been adapted and extended. The current version of SEAROADS includes soft kill weapons, communications, and is able to simulate multiple ships. Furthermore, it is now capable of modelling the defence of both naval and land-based units against Tactical Ballistic Missiles (TBMs).

### SEAROADS Simulation model

The model is an event driven, process oriented simulation model. It is written in Pascal (AAW modelling), C++ (simulation kernel) and C (visualisation) and runs on a SUN SPARC workstation.
It is a high-level model, in the sense that it calculates the overall air-defence performance of a ship. Performance figures of individual weapon systems (e.g. kill probabilities of a SAM against an ASM) are not calculated, but are given in input tables. Also sensor-detection probabilities depend on input tables that represent sensor and environmental characteristics, see eq. [8]. These input tables are generated by more detailed models, see Figure 11. The input tables are fed into the internal modelling and used to generate event probabilities (detection, kill, etc.) which gives the model a non-deterministic behaviour.
The model is used for various types of questions concerning AAW aspects: Evaluation of existing or new Threat Evaluation and Weapon Assignment rules (TEWAs), ships, sensor & weapon systems; effects of signature reduction, communication delays, and HK/SK co-ordination.

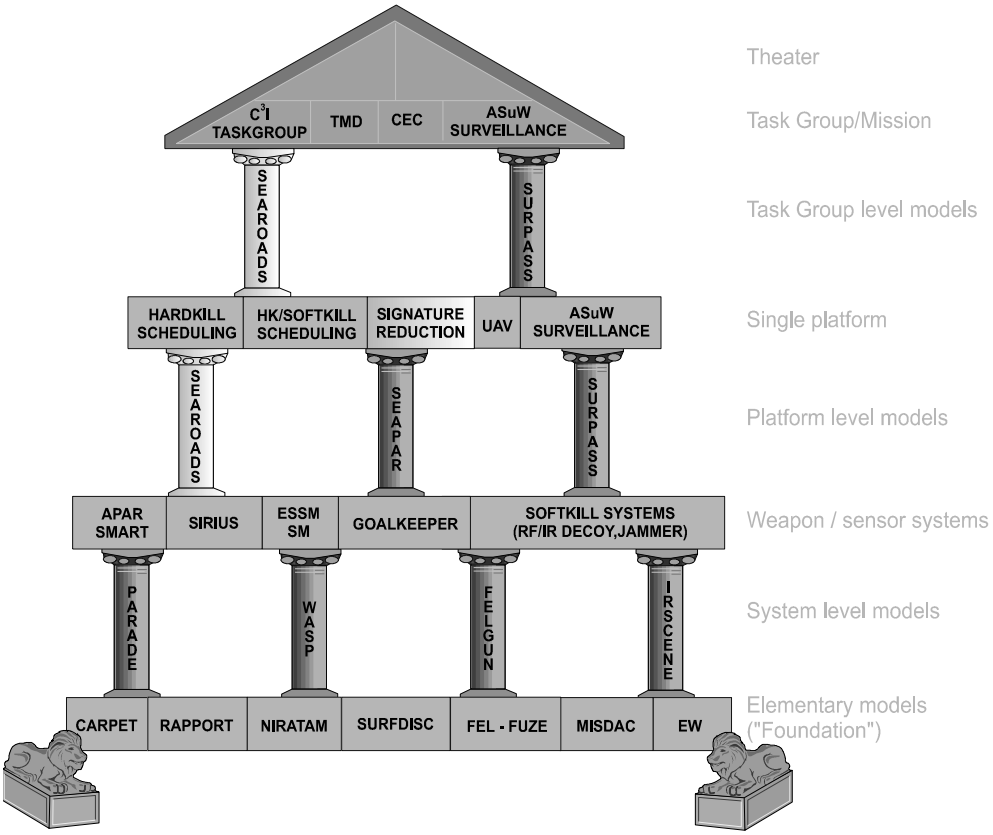


***Figure 11 The OR "Temple" of AAW***

## AAW Modelling in SEAROADS

### Environmental Conditions

The environment is defined by wind (relevant for decoys), infrared conditions (relevant for IR sensors), and IR/RF clutter. Other environmental parameters, e.g. rain, sea state, and RF propagation conditions are incorporated implicitly in the input parameters for sensors, kill tables of missiles, etc.

### Threat

Initially, only ASMs were included in SEAROADS. Later, TBMs were added as well (which will not be dealt with in this paper). More recently, a fighterjet able to launch ASMs has been included.

#### *Fighterjet*

Fighterjets have been introduced very recently. As a first approach, a fighterjet has a RF- or IR sensor (based on the ASM-seekers) and a set of ASMs. In a predefined scenario, it follows a set of way-points and activates its sensor in a predetermined time-interval. After the sensor detects a target, a short delay will be activated to model the identification of a target. Next, the ASMs will be launched one by one. The fighterjet turns around to leave the scenario, again following a set of way-points.

#### *ASM*

An ASM behaves just as a fighterjet, until the moment its sensor detects a target. It abandons the predefined path and sets course to its target (which depends on the target selection criterion e.g.: aim on the first detected target, or wait a full sweep and then aim on the one with the strongest signal return,

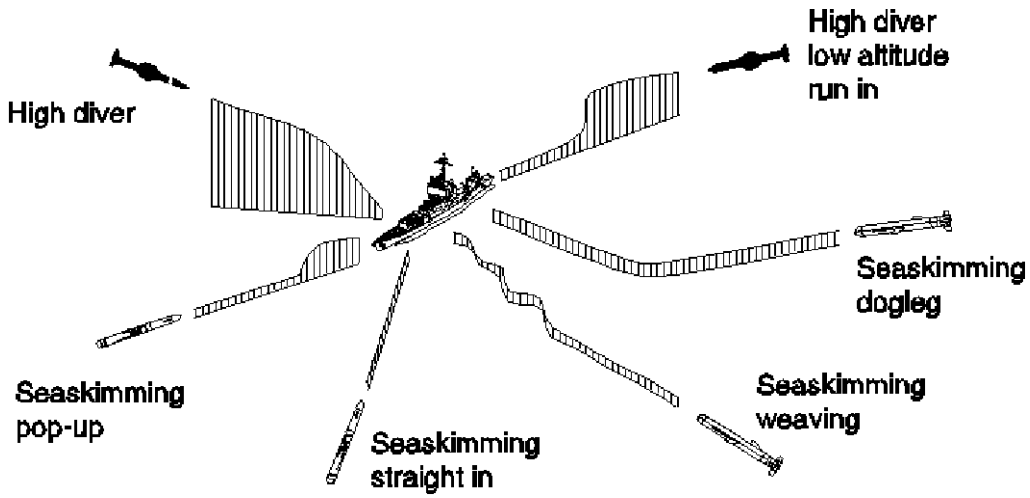


***Figure 12 Different ASM trajectories in SEAROADS.***

or the one closest to the predefined expected target location).
Some types of manoeuvres can be modelled explicitly by setting the correct way-points, such as a dive or a dogleg-manoeuvre. Other manoeuvres are modelled implicitly: a weave has effect on the velocity of the missile and the vessels HK- weapon effectiveness. Figure 12 depicts possible ASM trajectories in SEAROADS.

***Missile Seekerheads***

Two types of seekers are modelled explicitly:

- IR Hot Spot seeker
- Active RF seeker

The IR Hot Spot seeker has a narrow beam that searches in a certain pattern. It integrates the sources within the beam, and in case the received signal exceeds a threshold, the detection criterion is fulfilled. After lock-on, the seekerhead tracks the integrated centre of the IR-signature of all IR sources within the beam. IR flares with a higher signature level passing through the beam are able to seduce the seeker and pull away the lock from the ship (Lock-transfer). When a lock-on has been lost (below threshold, or the ASM is not able to turn to the target in time) it will start searching again.
A variant of this seeker is used to model an imaging seeker at a high level. The initial beam is set at a very wide angle. After lock-on, the beam narrows to the number of pixels enclosing the target. This makes it very difficult to seduce the seeker from its target.

The Active RF Seeker modelling is similar to the IR Hot Spot Seeker, the received RF signals should exceed a RF-threshold. A limited range-gate is applied. The RF Seeker can deploy an additional 'home-on-jam' mode. In case the seeker is noise-jammed, it will not detect any targets, but it will home onto the jamming signal (HoJ).

The passive RF seeker (Anti-Radiation Missile, ARM) is modelled implicitly. With this seeker, a lock-on at launch is assumed. The ASM follows its predefined trajectory (seeker lock choice is made off-line). The only way to intercept the passive RF-seeker is its destruction with hard kill weapon systems.

## *Vessel Parameters*

The defending warship ship is defined by its position, course, velocity, geometrical size, radar and IR signature, sensor systems, target evaluation and weapon assignment rules, hard kill weapons and soft kill weapons systems, communication settings, and co-ordination rules for participation in a task group.

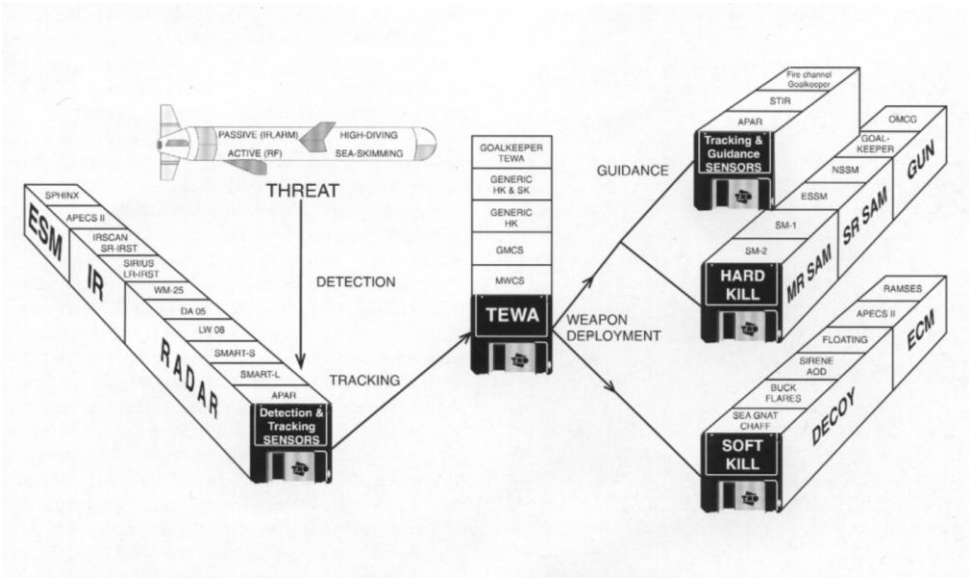


***Figure 13 Schematic overview of SEAROADS structure***

The AW signatures can be introduced from more detailed simulation models or real measurements. The IR signature can be e.g. be determined with the simulation model SHIPIR [Vaitekunas, 10]. The RCS can be e.g. be determined with the TNO-FEL model RAPPORT [Galle et al., 3].

## *Sensor Systems*

The following sensor systems are modelled to detect ASMs or fighters:

- *Rotating Search Radar*
  (e.g. LW-08, SMART-S)
  The basic formula behind the radar modelling is

  $$SNR(\sigma, d, \varepsilon, h) = \frac{\vartheta_{\varepsilon,h} \cdot \sigma}{d^4} \qquad \text{eq. [8]}$$

  with $\sigma$ the RCS, $d$ the distance, $\varepsilon$ the elevation of the target relative to the sensor, and $h$ the target height. $\vartheta_{\varepsilon,h}$ represents the radar characteristics, environmental conditions and multipath. After *n-out-of-m* detections of a threat a tracks is established, and appropriate systems can be deployed against that threat.

- *Fixed Array Multi Function Radar* MFRs
  (e.g. APAR)
  Fixed array multi function radars consist of a number of fixed faces, each covering a sector of the horizon. A multi function radar can detect and track threats, and guide different salvos of SAMs to different threats simultaneously. It is specified by parameters as coverage per face, number of faces, range and threat flight-altitude dependent propagation factors that are included in the radar detection formula, and maximum number of SAM salvos that can be guided simultaneously by a face.

- *Infra red search and track systems (IRSTs)*
  *(e.g. SIRIUS)*
  Infra red search and track system can detect a threat by its IR signature. It is specified by parameters such as rotation frequency, beam width and its noise equivalent irradiance. Both single and dual band are supported.

- *Electronic Support Measures (ESM) System*
  *(e.g. APECS, Sabre)*
  An electronic support system can detect threats that have activated their active RF seeker. It is specified by parameters such as receiver bandwidth and sensitivity.

- *Fire Control Radar* (FCRs)
  (e.g. STIR)
  After a threat is detected, a fire control radar can be deployed to track it. After that, the threat can be engaged by firing a salvo of Surface to Air Missiles (SAMs), or deploy a

CIWS gun system. In case of an SAM-engagement , the fire control radar can be used to guide the SAMs to the threat, and for kill assessment. A fire control radar is specified by parameters such as its blind angle, slew speed and threat-type dependent acquisition time.

Detailed sensor models like CARPET (Computer Aided Radar Performance and Evaluation Tool), PARADE (Phased Array Radar Analysis, Design and Evaluation), and SEAPAR (Scheduling and Evaluation of APAR, a scheduling model for multi function radars) supply input for SEAROADS on the sensor systems. For all sensors, the modelling is derived from more detailed models also present within TNO.

**Hard Kill (HK) Weapons**
The modelled hard kill systems are Surface to Air Missile (SAM) systems, including the launchers, and gun systems. These systems aim at the physical destruction of ASMs:

- *Missile launcher*
  (e.g. Mark 13, Mark 29, Mark 41, Mark 48)
  A launcher is specified by, among others, the following parameters. For each type of SAM the launcher can fire: the default salvo size, the salvo delay, the launch period between two successive missiles, and the magazine size. In case of a rotating launcher, also the blind angle and slewing speed have to be defined.

- *Surface to Air Missile system*
  (e.g. NSSM, ESSM, SM-1, SM-2)
  Each SAM system is defined by its minimum and maximum intercept slant range, cross range and height, its velocity profile (velocity as a function of time) or fly-out table (time to reach a position depending on ground range and height), and single shot kill probability as a function of the ASM type and the intercept slant, ground, and cross range.

- *Gun system*
  (e.g. OMCG, CIWS Goalkeeper)
  A gun system is specified by its firing rate, minimum and maximum salvo time, intercept slant range, cross range and height, its velocity profile, single projectile hit probability as a function of the threat type and the intercept range, and the kill probability depending on the number of projectile hits.

  The 6 degrees-of freedom (6-DoF) missile simulation model WASP (Weapon Analysis and Simulation Program) and MISVAC (Missile Vulnerability Assessment Code) provide parameter values on SAM systems. The gun model FELGUN provides parameter values on gun systems.

**Soft Kill (SK) Systems**
The soft kill systems are active and passive off-board decoys, and on-board deceptive electronic countermeasures. These systems aim at the distraction or seduction of ASMs.

The following soft kill systems are modelled:

- *Chaff*
  *(e.g. Mk 214, Mk 216)*
  A chaff cloud, reflects radar signals transmitted by the ASM. Chaff clouds are specified by parameters such as the launch distance, height and directions, bloom time, decay time, maximum RCS, radius and descend rate. It can be deployed as a distraction or as a seduction system.

- *Active off-board decoy (AOD)*
  An active off-board decoy responds to the radar signals transmitted by an ASM. It is specified by parameters such as the launch distance, height and directions, effective radiated power, size of the sector in which it is active, and descend rate. As for chaff, both distraction and seduction variants are available in SEAROADS.

- *Infrared decoys*
  *(e.g. Buck Giant)*
  An infrared flare radiates infrared signals. Flares can be launched individually, or in sequences (to establish e.g. walking off). Infrared flares are specified by parameters like e.g. the launch distance, height and direction, development time, burn time, infra red signature, and horizontal and descend rate.

- *On-board deceptive electronic counter measures*
  *(e.g. APECS, Sabre)*
- An on-board deceptive electronic system in general can be deployed in two modes; the noise jamming mode and the pulse jamming mode.
  The noise jamming mode can be used to attract active ASMs; ASMs that are still in acquisition phase as well as ASMs that have a lock on another ship (e.g. a high value unit that cannot defend itself). Noise jamming can also assist hard kill by preventing or stopping the weave of an ASM by denying the ASM distance

information. The pulse jamming mode can be used to break the lock of an ASM on the ship. A jammer is defined by parameters such as power, gain, slew speed, number of tracking channels and number of signal generators.

Parameters on chaff, active off-board decoys, and jammers are supplied by TNO-FEL's Electronic Warfare model. Parameters on IR flares are provided by the Electro-Optical groups.

**TEWAs (Intra Ship)**
Not only the weapon systems on board are of importance for the air defence capability of a ship, but also the deployment rules against threats. The deployment of sensors and weapons is controlled by so called Threat Evaluation and Weapon Assignment rules (TEWA). A number of different TEWAs are modelled in SEAROADS. This includes two TEWAs (MWCS and GMCS) as implemented on board RNLN frigates, as well as generic TEWAs for the deployment of both hard kill and soft kill systems, see Figure 13.
It is also possible that the deployment of some weapon system is not controlled by the ship's TEWA, but by a system specific TEWA. For example, the Close-In-Weapon-System (CIWS) Goalkeeper operates autonomously.

***It should be noted that TEWA's optimised for conventional designed ships (conventional related to LO) will not be optimal for LO or even VLO.***
***In order to fully appreciate signature reduction, also TEWAs optimisation cycles for (V)LO have to be performed.***

Rules that control the turning of the ship are modelled in SEAROADS. Turning a ship may be of importance for the air defence of a ship in case an ASM is in the blind angle of a fire control radar, a missile launcher or a gun, or it may be necessary for deployment of soft kill (in order to have a favourable relative wind direction). Next to this, the relative aspect angle to the threat will determine the AW- signature presented to the threat.

**Co-ordination rules (Inter Ship)**
In case a task group consists of several AAW ships, the defence between the ships may be co-ordinated to prevent that an ASM is engaged by all ships, and another ASM is not engaged at all. A number of Task Group TEWAs are modelled in SEAROADS, like sector co-ordination where each AAW ships covers a certain sector, and more complex and sophisticated TEWAs that overrule the individual ship's TEWAs. Some of these task group TEWAs have been developed in NATO working groups, such as DRG Panel 9 / RSG.11 "EW Aspects of integrated Anti-ship missile defence" that investigated hard kill and soft kill integration aspects in task groups.

**Communication**
Recently, a high order modelling of the Link 11 communication system has been incorporated in SEAROADS. The level of detail is tuned to aspects relevant for AAW, such as communication delays for sending air track information. Another system recently modelled is the Co-operative Engagement Capability (CEC), which exploits the combination of different sensor data from multiple sensors from different platforms to create a real time high quality common air picture for all connected ships. This allows for engagement of an ASM before the firing platform even detects the ASM itself. Another application of CEC is platform separation of firing and guidance of SAMs.

**Near Term Developments SEAROADS**
SEAROADS development was started in the late 80's. Many studies have been performed in which the model has been upgraded It has evolved from a single ship hard kill only model to a multi ship hard/soft kill model. The model will be fully upgraded in the next few years. It will be prepared for littoral operations and new communication concepts (e.g. Link 16, Link 22). Some aspects already present in SEAROADS will be extended, such as the radar detection process. A more detailed modelling of RF propagation will be included, including multipath, clutter and atmospheric effects. The software architecture will change from a process-oriented to an object oriented architecture. The upgraded version will be written in JAVA (hardware platform independent).

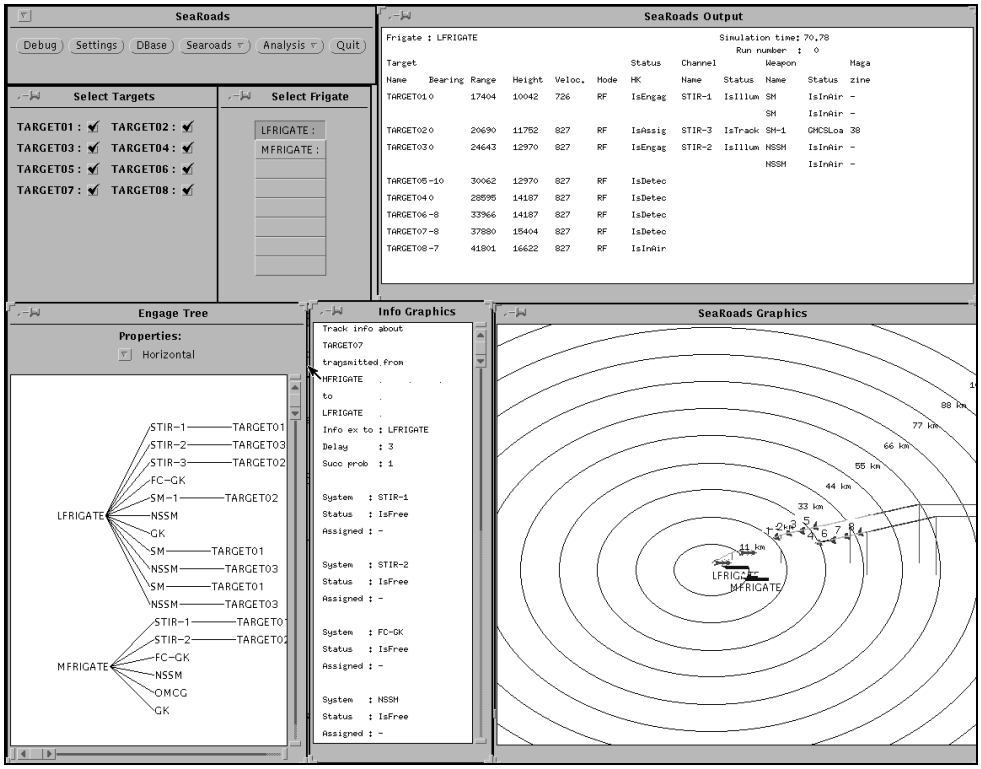


***Figure 14 SEAROADS Graphical Output during Scenario Simulation***

**Simulation of a scenario**

After a scenario has been defined by specifying the ASM attack, the ships, the environment and the co-ordination between the defending ships, the scenario can be simulated.

Several hundreds of runs are performed to obtain statistically valid results. This is important, because each single run can differ due to the incorporation of probabilities with which events take place. E.g. detection of a specific ASM at a specific moment in time by a radar occurs with a probability determined by a parameter dependent radar formula (next to the fact, that the ASM must be in the radar beam). Another example is the intercept of an ASM by a SAM. Whether or not the ASM is killed depends on the kill probability of the SAM for the ASM type and intercept geometry.

The scenario can be shown graphically on the screen during the simulation, see Figure 14. This is convenient for analysis purposes as well as for demonstrations of SEAROADS. A top view is shown, of the ship(s) being attacked by the ASMs, and the countermeasures taken against the ASMs: firing of SAMs and guns, the deployment of off-board decoys and on-board jamming. Additional information is also provided, such as range, speed and engagement status of each ASM.

**Simulation Output**

Having run a scenario a number of times, different Measures of Effectiveness (MoE) can be determined MoEs are used to quantify and analyse the air defence capability of the ship(s) against the ASM attack.

A list of the main MoEs is given below; all are averages per simulation run:

- The probability that the group of ships, or a single ship has been hit by *n* ASMs (*n* = 0, 1, 2, ....).
- Per sensor system and per ASM: detection distance.

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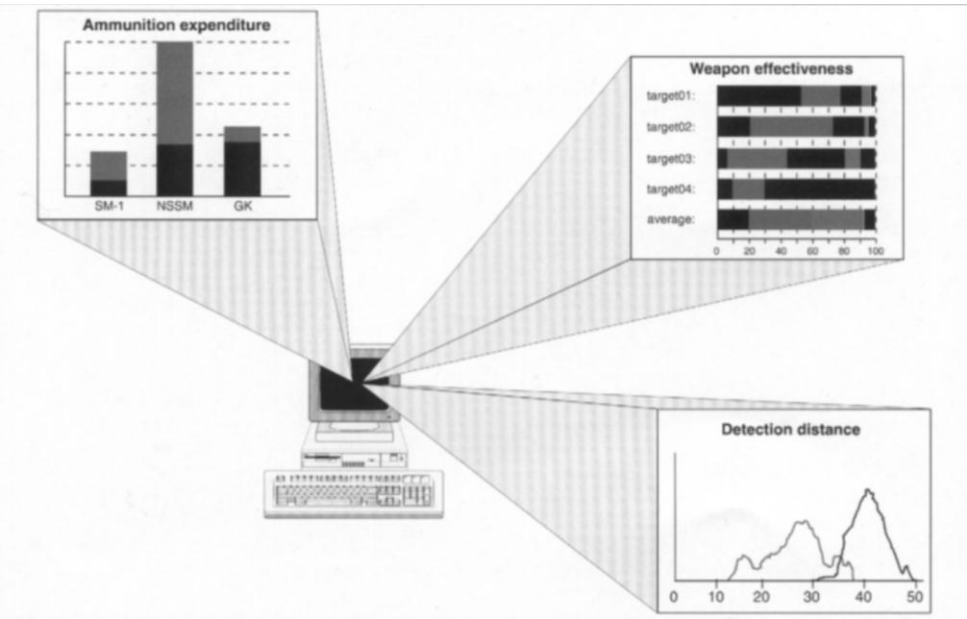


***Figure 15 Example of SEAROADS simulations MoE output.***

- Per hard kill weapon system and per ASM: number of salvos fired, number of SAMs or rounds fired, intercept range and probability that the ASM was killed by the weapon system.
- Per off-board decoy system: number of decoys deployed, and per ASM: probability that the ASM was soft killed, and range at which the decoy was effective.
- Per on-board deceptive electronic system and per ASM: number of times the ASM jammed (pulse or noise).
- Per fire control radar, missile launcher and gun: occupation as a function of time, and per ASM: the moment and number of times the system was assigned to the ASM.

The soft kill probabilities mentioned above correspond to a soft kill of the ASM, not followed by a reacquisition of a ship or a decoy, or a hard kill. However, also the occurrences of these events are output of SEAROADS.

A few examples of MoEs determined by SEAROADS, are depicted in Figure 15:

**SEAROADS Simulation Examples**

Although SEAROADS is used in many AAW areas, in this part some examples of applications in the field of signature reduction are given.

SEAROADS is used in the field of signature reduction analysis for some years. We started with analysing the effect of 'modest' (LO) signature reductions (RCS) of a ship on the soft kill effectiveness [Dongen et al., 11]. For a concept Auxiliary Oil Replenishment (AOR), ship design a trade-off was made between RCS signature reduction, and the additional placement of a CIWS. Next, the step to IR-signature reduction was made. Again, soft kill effectiveness was analysed for several levels of a ship's IR signature. More recently we included fighters. This created the capability to study very low ship signatures (very low observability, VLO) with their detoriating influence on the effectiveness of the launching platform as well.

***LO-RCS Signature reduction***

According to the SEAROADS simulation, a moderate RCS signature reduction (LO-level) will have the following effects:

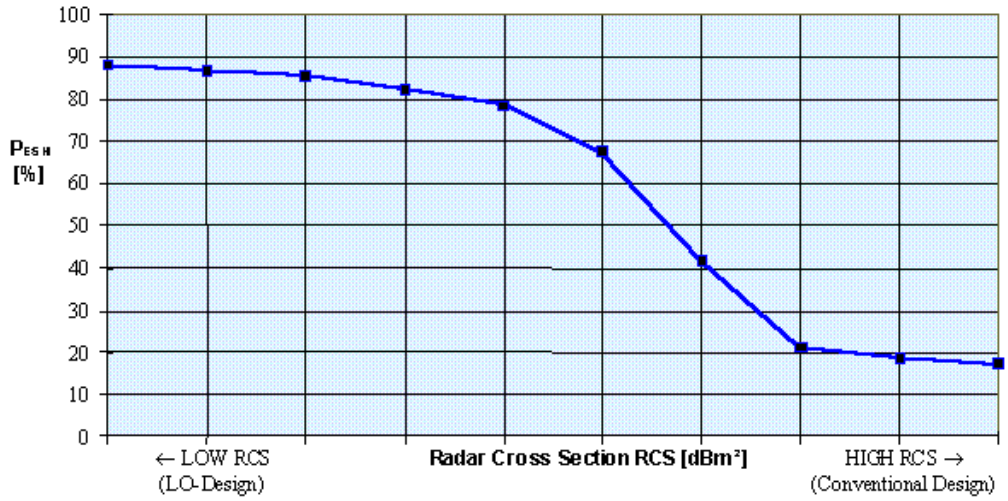


***Figure 16 Probability of Escaping a Severe Hit as a function of the ship's RCS***

- Detection of the ship by an ASM RF seeker is delayed, increasing the effectiveness of distraction decoys.
- Decoys in the seduction role will be more effective, because the ratio between decoy and ship RCS grows. The integrated centre of the ASM seeker's view will be pulled away from the ship more effective.
- The RF-ASM is at closer range to the ship when it detects its target; situations will occur where the ASM is not able to the turn to the ship in time.
- A deceptive jamming device onboard a targeted ship also has an advantage, its signal now can compete better with the RF seeker signal reflected from the ship.
- The HK ammunition expenditure (e.g. the SAMs and CIWS-rounds) is lowered.

Given a specific scenario with chaff distraction and seduction decoys, and a deceptive jamming device, the probability of a hit on the ship can be expressed as a function of the ship's RCS. Figure 16 gives a schematic view of such a function.

Figure 16 shows *that (in case only soft kill effects are considered*) it does not pay off to reduce the signature too much. Below a certain threshold the soft kill effectiveness in the given scenario will not improve.

Another aspect addressed was vulnerability, see Figure 6 Block 3 to 6. In case an ASM hits the ship, certain systems, or all systems may fail. This has effect on the defence against later in time launched missiles, and on a next attack.

***Trade-off between RCS reduction and a CIWS***

An AOR will in general not have the weapon systems comparable to frigate. Often, such a ship is escorted by warships, but this need not always be the case. Then, the AOR must be able to defend itself against an attack of ASMs. It may e.g. have a certain level of decoy capability, and a CIWS. The trade off has been analysed between RCS signature reduction and the installation of a CIWS against an attack of ASMs with active RF seekers. The RCS level was varied and the number of CIWSs (none, 1 or 2) was studied. In this way, insight was obtained in the possible benefits of designing a ship with a lower radar signature (improved soft kill performance) versus the installation of additional CIWSs.
It should be noted, there may be other reasons to install a CIWS than just engaging soft kill leakers.

***IR Signature reduction***

Modelling the IR signature is a complex procedure. It depends heavily on the environmental circumstances, as solar conditions, cloud cover, sea & air temperature, humidity, etc. On the ship, there may be hot spots (exhaust plume, stack). Transmission through the atmosphere depends on the wavelength of the IR radiation. Hot gaseous products like e.g. the exhaust gasses, radiate dominantly in the 3-5 μm band (MIR), only low levels are detected in the 8-12 μm band.

On the other hand, more cooler parts like the ship's hull have their main contribution in the 8-12 μm band.

In one of the studies the assumption was made, that is was technically possible to reduce the hot spots and the hull temperature to relative low levels. By running scenarios in different environments, insight in the effects of these reductions was obtained.
A ship was attacked by ASMs with IR seekers. The ship defended itself with IR flares only, in order to focus on soft kill effects. For the signature both a parametric and realistic signature levels were used.
The parametric signature (just a fixed figure for the Radiant Intensity Contrast of the ship, irrespective the aspect angle) gives insight in detection ranges and possible effects on Soft Kill effectiveness. The more realistic signature, aspect angle dependent and with realistic values, gives insight in the effects of removing hot spots and the effect of heating one side of the ship by the sun. It appeared that (depending on the seeker IR band and the environment) the operational effect reduction of the IR signature (i.e. the number of ASM hits on the ship) depends very much on the scenario geometry: attack direction of the ASMs and environmental conditions.

***Future developments SEAROADS***

In the past, a SEAROADS scenario started after ASMs were launched. However, when exploring very low observability (VLO), modelling the launching platform and Maritime Patrol Aircraft (MPA) will be necessary. This includes fighterjet pilot tactics: when are sensors activated, how does a pilot respond when he is detected, or illuminated by a fire control radar? The EMCON tactics of the defending side also has to be taken into account. Furthermore, it needs a more detailed modelling of human behaviour, the workload, stress, and possible errors made. Finally, the effects of a direct hit (vulnerability) and system-failure can be incorporated, so analysing "full-blown" Survivability, see Figure 6. Sensor modelling also needs to be reviewed, because sea clutter and RF propagation influence increases when working with extremely low signature levels.

## FUTURE TRENDS AW SIGNATURES

Internationally and within the Royal Netherlands Navy technologies are being explored, which will impact Ship AW Signatures in the future. "Offensive"-missile and "Defence"-warship trends will be highlighted and discussed briefly.

**Offensive"-missile Threat / Seekerhead Trends**

- Future seekerheads will act multispectrally; combinations will be formed of RF, Imaging IR, Anti Radiation (ARM), Millimetre Wave Bands (MMW) and Laser Range and Detection (LADAR) systems.
- Seekerhead sensors and signal processing will be improved per se. This statement holds for the IR as well as the RF-case. The missile system will obtain better possibilities to distinguish the ship and reject decoys. Possible (new) rejection techniques can be for IR guided missiles e.g. :
- Position comparison of ship and decoy; even if a ship manoeuvres at its maximum capabilities, decoys will move more abruptly.
- "Colour" ratio comparison: dual (MIR/FIR) or even spectral;
- Minimising the Field of View (FoV) after lock-on; this to disregard decoys;
- Comparison of intensity versus time behaviour, the decoy increases intensity faster from zero to maximum than a ship usually changes IR emission;
- Shape analysis, a ship will be a horizontal and vertical structure in basic shape analysis or an object with distinct contours in more advanced shape analysis (Imaging). E.g. the new NSM will exploit the Imaging Infrared Seeker.
- Next to this, Future Missile will exploit image processing, the information will exploited to hit at its most vulnerable spot e.g. at the waterline or at the position of the Command, Information & Control Centre (CIC).

**"Defence"-warship trends**

- Some of these missile rejection techniques can only be applied after lock-on (seduction mode). Before lock-on, the ship decoys might be accepted more easily by the seeker. Therefore decoy deployment in distraction mode is preferred over seduction mode.
- As explained earlier; distraction can only be used if no lock-on has been achieved. Lock-on can only be postponed by a lower signature. This will emphasise low IR level signature more and more and, making revolutionary ship design inevitable Onboard IR Signature Management Systems
- Sophisticated onboard IR Signature Management Systems will be developed to join the fleets. These systems will be able to assess the IR ship's signature in real time. Advice will

be generated how to adapt the signature to its environment, in terms of e.g. power setting, active plume cooling, prewetting, ship heading etc. [Neele, 12]. These systems will comprise:

- software for signature assessment and evaluation;
- Hardware for data acquisition will consist of thermocouples and meteorological instrumentation.

The system will be managed from the Ship Control Centre (SCC), but will have a close link with the Command Information Centre (CIC) where the deployment of IR-decoys will be software managed as well. Such a system will make it more feasible to deploy specific IR peace- and wartime modes.

- Shaping for RCS reduction will be applied more rigorously.
- Combinations of alternative coating systems will go to sea:
  - Infra Red Low Emissive Paints (IRLEPs);
  - Low Solar Absorbance Paints (LSAPs);
  - Radar Absorbant Materials (& Structures).

- The RF signatures of sensor and antenna systems will be reduced by enclosing the systems in Frequency Selective Surfaces (FSS) and structures.

- **The Very Low Observability Alternative**

Current conventional naval vessels have not been designed to have low signatures and can be detected by both IR and infrared sensors at long range. In this context, detection ranges should be compared with the range of the on board Hard Kill weapon systems. The (counter) detection range of current warships is typically much larger, even for LO designs like e.g. the French LaFayette, the newly built German F124 Frigate and the Royal Netherlands Navy Air Defence Command Frigate LCF, see also Figure 19, than the range of these on board weapon systems. As a result, enemy platforms can detect the ship at save ranges, deploy e.g. their ASMs and redraw. The ship is left in the negative situation to defend itself against these attacking missiles ("Ship Shoots Arrows"); the launching platform may never be detected. In an attempt to counter this situation, ships generally utilise their sensors at all times, allowing early detection of enemy platforms, but at the cost of a highly active signature. This leads to a vicious circle, in which the ship permanently is in a defensive role. Figure 17 illustrates this situation, taken from [Smedberg, 13].

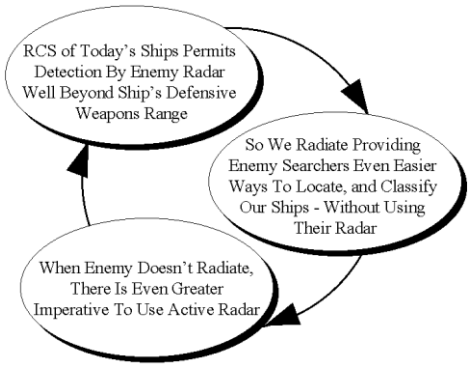


***Figure 17 The Present Viscious Circle for Conventionally designed Warships***

One way out of this situation is to reduce the signature of the ship to Very Low Observability (VLO) levels. In case a sufficient reduction is reached, enemy platform must come within the ship's weapon's range to detect , while running the risk of being attacked. To enable an early detection of the ship, enemy platforms must utilise their active sensor systems, increasing their signature and risking even earlier detection. To make full use of its Very Low Observability, the ship should rely on its passive sensor systems and minimise communications and radar emissions (emission control, EMCON). This once again leads to a vicious circle, this time however to the advantage of the warship, see also Figure 18, where the "Ship Shoots the Archer".

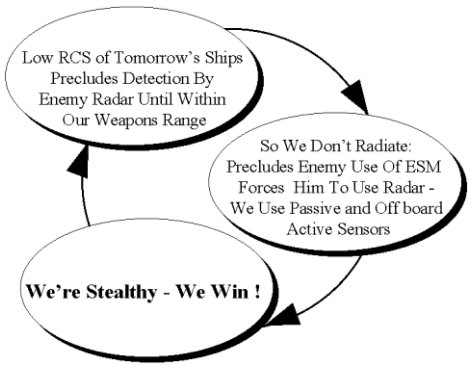


***Figure 18 The Future Very Low Observability (VLO) Warship Alternative?***

***Figure 19 The New Royal Netherlands Navy Air Defence Command Frigates; Designed for a Cost-Effective Low Observability Level. (Source: Directorate of Materiel / MarTech)***

## CONCLUSION / DISCUSSION

The importance of LO and VLO Ship Signature design has been demonstrated.
In the first part of this article the basic theoretical operational benefits of low AW-signatures has been addressed. The difficulty in stating low observable requirements has explained as well.
In the second part the paper The Operational Analysis Simulation Code SEAROADS has been introduced. The capabilities of SEAROADS has been demonstrated with examples of Low Observability analysis. The paper has been closed with views on future (V)LO trends.

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## ABBREVIATIONS

| | |
|---|---|
| **AAW** | Anti Air Warfare |
| **ADCF** | Air Defence Command Frigate (RNLN) |
| **AOD** | Active Off-board Decoy |
| **AOR** | Auxiliary Oil Replenishment |
| **APAR** | Active Phased Array Radar (Signaal) |
| **ASM** | Anti Ship Missile |
| **ARM** | Anti Radiation Missile |
| **ASW** | Anti Submarine Warfare |
| **ASuW** | Anti Surface Warfare |
| **AW** | Above Water |
| **BTR** | Burn Through Range |
| **CARPET** | Computer Aided Radar Performance and Evaluation Tool (TNO-FEL) |
| **CEC** | Co-operative Engagement Capability |
| **CHAFF-D** | Distraction Chaff |
| **CHAFF-S** | Seduction Chaff |
| **CIWS** | Close In Weapon System |
| **DSP** | Digital Signal Processing |
| **DOF** | Degree of Freedom |
| **ECM** | Electronic Counter Measures |
| **EM** | Electro Magnetic |
| **EMCON** | Emission Control |
| **EO** | Electro Optic |
| **ESM** | Electronic Support Measures |
| **ESSM** | Evolved Seasparrow Missile |
| **EW** | Electronic Warfare |
| **FEL** | Physics and Electronics Laboratory |
| **FELGUN** | FEL Gun Model (TNO-FEL) |
| **FSS** | Frequency Selective Surface |
| **GO** | Geometrical Optics |
| **HK** | Hard Kill |
| **HoJ** | Home on Jam |
| **IIR** | Imaging InfraRed |
| **IR** | InfraRed |
| **IRST** | InfraRed Search Track |
| **ISAR** | Inverse Synthetic Aperture Radar |
| **LADAR** | Laser Range and Detection |
| **LCC** | Life Cycle Costing |
| **LCF** | Luchtverdediging en Commando Fregat (RNLN) |
| **LO** | Low Observable |
| **LPI** | Low Probability of Intercept |
| **MFR** | Multi Function Radar |
| **MISVAC** | Missile Vulnerability Assessment Code (TNO-PML) |
| **MMW** | Millimetre Wave Band |
| **MoE** | Measures of Effectiveness |
| **MPA** | Maritime Patrol Aircraft |
| **NSSM** | Nato Seasparrow Missile |
| **OMCG** | Oto Melara Compact Gun |
| **OR** | Operation Research |
| **PARADE** | Phased Array Radar Analysis Design & Evaluation (TNO-FEL) |
| **PML** | Prins Maurits Laboratory (TNO) |
| **PO** | Physical Optics |
| **RAM** | Radar Absorbent Material |
| **RAS** | Radar Absorbent Structure |
| **RCS** | Radar Cross Section |
| **RCSR** | Radar Cross Section Reduction |
| **REA** | Radar Echoing Area |
| **RF** | Radio Frequency |
| **RNLN** | Royal Netherlands Navy |
| **SAM** | Surface to Air Missile |
| **SEAPAR** | Scheduling and Evaluation of APAR (TNO-FEL) |
| **SEAROADS** | Simulation, Evaluation, Analysis & Research On Air Defence Systems (TNO-FEL) |
| **SCC** | Ship's Control Centre |
| **SiRe** | Signature Reduction |
| **SK** | Soft Kill |
| **SM** | Standard Missile |
| **STIR** | Signal Track & Illumination Radar (Signaal) |
| **TBM** | Tactical Ballistic Missile |
| **TBMD** | Tactical Ballistic Missile Defence |
| **TES** | Target Echo Strength |
| **TEWA** | Threat Evaluation and Weapon Assignment rules |
| **TNO** | Netherlands Organisation for Applied Scientific Research |
| **UW** | Under Water |
| **WASP** | Weapon Analysis and Simulation Program (TNO-FEL / PML) |

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