Leon F. Galle

E-mail: ***LF.Galle@MinDef.nl***
WWW.MinDef.nl

Royal Netherlands Navy Above Water Signature Management

Application o/b the new Royal Netherlands Navy
Air Defence Command Frigate – "LCF" & Future Trends

The article reflects the views of the author and not necessarily those of the Royal Netherlands Navy.

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

Leon F. Galle *was until recently Senior Ship Survivability, at the Department of Naval Architecture & Marine Engineering (**MarTech**), Directorate of Materiel of the Royal Netherlands Navy (**RNLN**). He was active for 6 years in the field of Ship Vulnerability at the Prins Maurits Laboratory of the Netherlands Organisation for Applied Scientific Research (TNO-PML). He started Survivability work (Above Water Signatures & Vulnerability) for the Royal Netherlands Navy (RNLN) in 1991. The author is national representative of NATO subgroup AC/141(NG/6)SG/7 "on Ship Combat Survivability" and manages several scientific research projects on ship RCS, IR and Vulnerability for the RNLN at TNO-FEL and TNO-PML. Since the start of 2002 the author is heading the **Bureau Future Vision & Forward Design** of the Depart Weapon, Sensor & Communication Systems **(WCS)**.*

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. Procedures will be addressed to incorporate Low Observability Requirements in a design. The LCF's Survivability has been increased by means of reduction of Susceptibility and Vulnerability. Susceptibility is decreased by the installation of the newly developed sensor-suite: a Volume Search Radar System, an Active Phased Array Radar system, a Long Range Infra Red Search and Track System and an Electronic Warfare system. The new sensor suite will, in close concert with the new Command System (SEWACO XI), manage the deployment of the Soft Kill systems (jammer & decoys) and the Hard Kill systems: Standard Missile II (SM-II), the Evolved Sea Sparrow Missile (ESSM) and the Goalkeeper system. The deployment of the Sensor Weapon Suite is supported by a low observable (RCS & IR) and stable seaway platform. The article will close with a view on future Very Low Observability (VLO) trends.

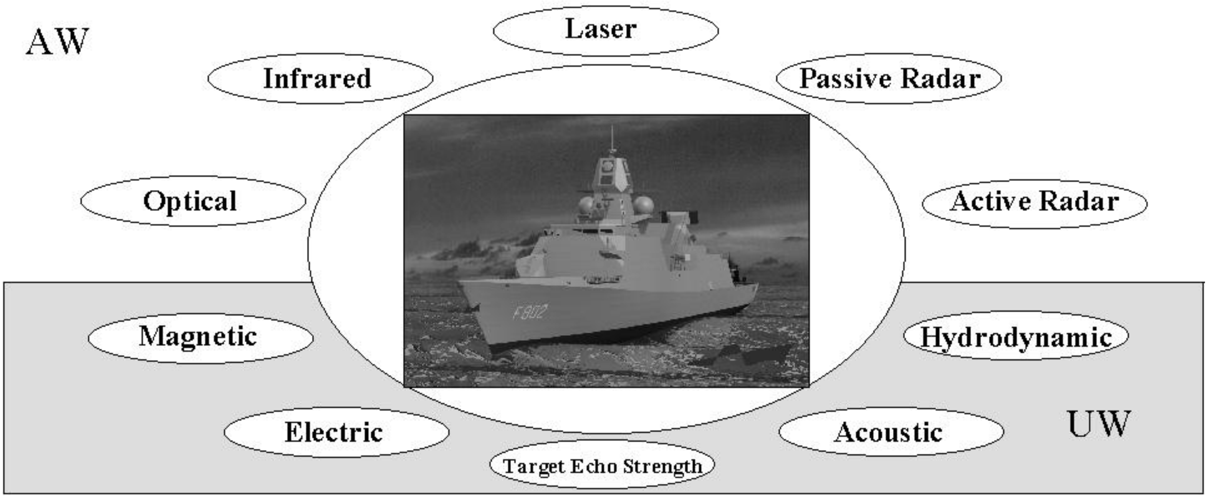


Figure 1 Relevant Warship Signatures

> ***"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. Making detection ranges equal for the different relevant signatures of the warship as quoted in the last paragraph should perform this balancing. 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] Radio Frequency

[2] People's Republic of China

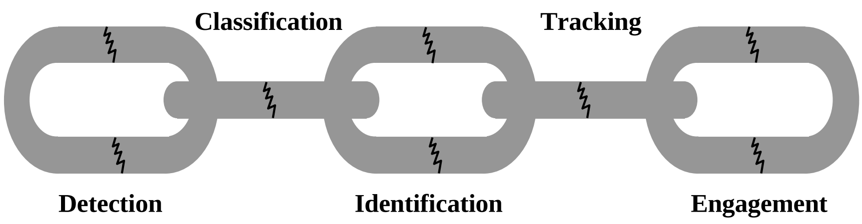


Figure 7 Low Observable Design and Tactics (= Stealth) disrupt and break the Opponent's "Kill Chain".

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.

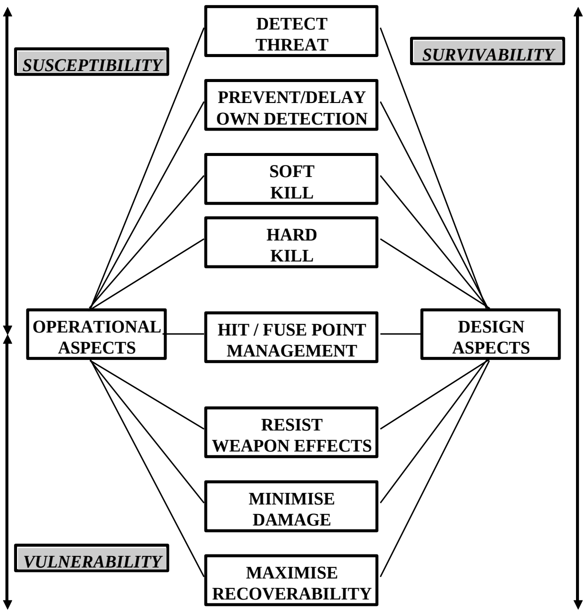


Figure 6 Generic Ship Survivability Scheme

The antagonist can be airborne, sea borne, land based and even space based 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 solutions will be addresses for supporting Survivability o/b the Air Defence Command Frigate LCF i.e. the Sensor & Weapon Suite will be introduced. 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 passive Electronic Support Measures (ESM) supports the ship. 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 its 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, σ):

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

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; σ 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 m^2			
Log RCS Reduction [dB]	Linear RCS Value [m^2]	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". Next to pure detection, signature reduction can impede the successful classification at a specific distance, see Figure 8.

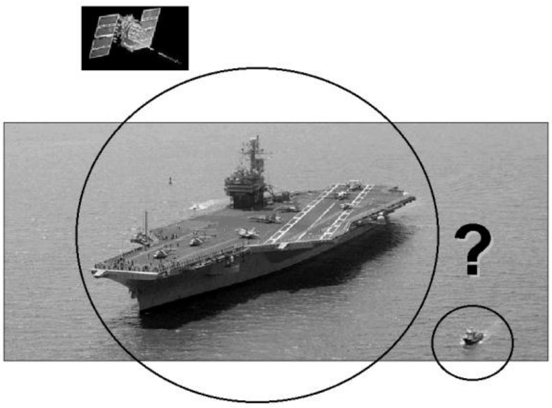


Figure 8 Signature Management can retard Classification

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}):

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

So halving the IR signature will decrease the lock-on range with $\sqrt{2}$.

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.

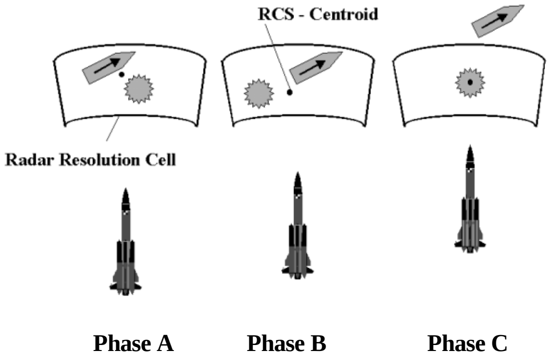
Improved Soft Kill Effectiveness

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 8 gives the principles of chaff in the seduction role.



Phase A
Lock-on
Chaff Blooming

Phase B
Ship & Chaff within Rangegate
Centroid Bias moves to Chaff

Phase C
Lock Transfer
Rangegate Separation

Figure 8 Lock Transfer Principles 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 9 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.

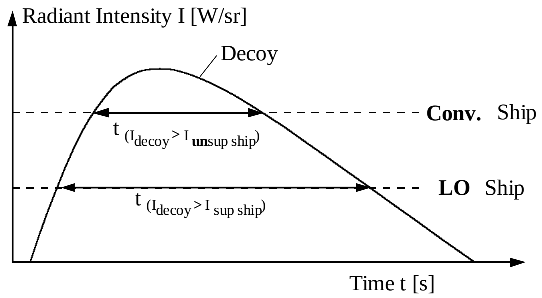


Figure 9 Generic Radiant Intensity in time for a conventional and Low Observable ship and IR seduction decoy

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, see Figure 10. 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.

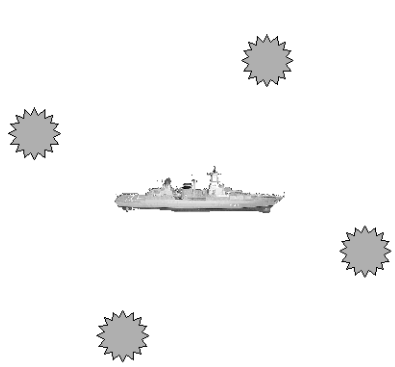


Figure 10 Chaff in the Distraction Role

Reduced Necessary Missile Flight Corridor

Missile systems, especially IR-guided, have a limited Field of View (FoV). In case the FoV is known in combination with the lock-on range for a target platform, one can construct the necessary flight corridor for a missile system to be able to make a lock-on to the ship. In Figure 11 the situation is depicted for a ship with a non-VLO i.e. conventional signature.

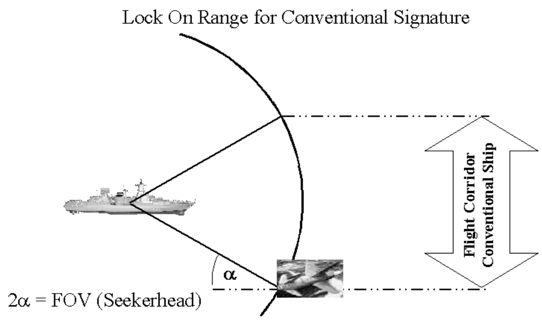


Figure 11 Necessary Flight Corridor for an IR-missile with a Platform with a "conventional" Signature.

If (V)LO technology is used on board the target platform the lock-on range can be reduced and therefore the lock-on range as well, see Figure 12. This will directly lead to a reduced necessary flight corridor for the missile system, i.e. the launching platform will need more accurate information on the position of the target platform, to be able to make a successful attack.

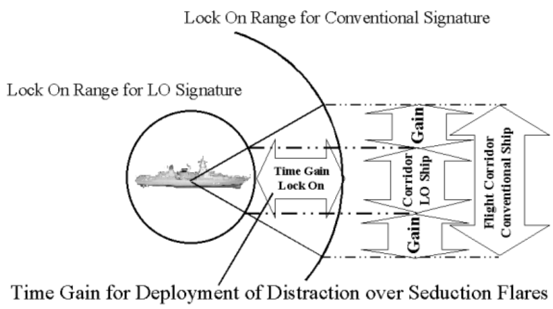


Figure 12 Reduced Flight Corridor & Time Gain for an IR-missile with a Platform with a "(V)LO" Signature.

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 (RF-case), the missile's computing power, 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 the missile has not yet achieved lock-on, see also Figure 12. 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 (two way propagation: radar → ship → radar) whereas in the jammer equation it is present to the second power (one way propagation: jammer → missile), see Figure 13.

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, see Figure 13.

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 (σ), 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 σ will improve J/S, see Table 2, and Figure 14 also taken from [Baganz & Hanses, 5].

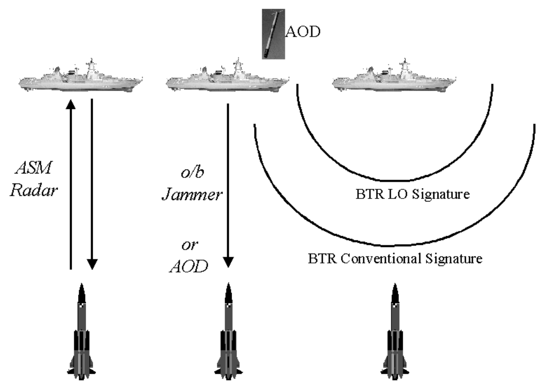


Figure 13 The Reduction in Burn Through Range for a conventional and a LO Signature

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

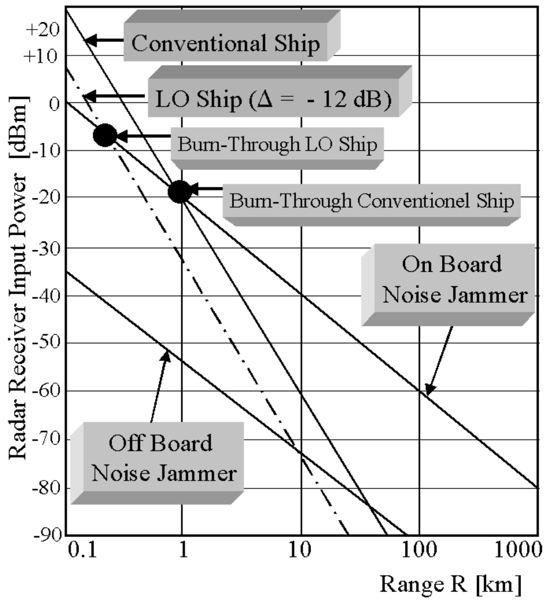


Figure 14 "Burn Through" Principle

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 steadier 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), see Figure 15.

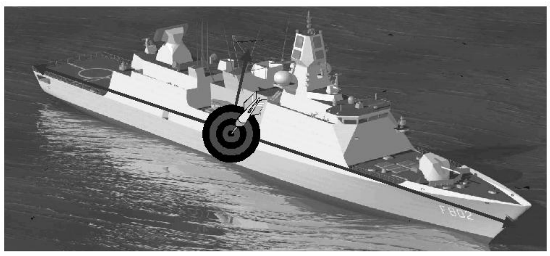


Figure 15 Signature management can influence the onboard hit point location.

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* for the new platform, if they want to incorporate these cost-effective solutions. The task for the Project Team (PT) is to meet these requirements within the budget and the time schedule. These Survivability Staff Requirements can not be generated right away for a new building program. The following procedure can be useful for this. Based on the international political situation and feasible budget, possible future war / conflict theatres and missions are to be produced by Naval Staff, from which, possible threats and targets can be created. By means of operational analysis *Performance Goals* like e.g. probabilities of survival (output) can be obtained from predefined threat scenarios (input), see Figure 16. These analyses should be performed in close co-operation with Naval Staff and Survivability (& VLO) Experts.

Figure 16 The Procedure for generating Naval Staff Performance Goals

These *Survivability (& VLO) Goals* should be an cost[3]-effective combination of on board sensor systems, Hard Kill (HK), Soft Kill (SK), Command & Control (C^2) and Ship Signatures. The analysis tool to support this balancing, will be exhaustively dealt with in the second part of this paper.
However, 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 demanded.

[3] Using first order costing approximation methods.

These *Performance Goals* have to be checked in terms of their technological and budgetary feasibility, see Figure 17. This Feasibility Analysis is to be performed in close concert with Naval Staff and the Project Team, supported by their Survivability and Costing Experts. This analyses can lead to adjustments in the budget and / or adjustments in the demanded threat level, for that project. The end results are laid down in *Naval Staff Performance Requirements*, i.e. no specific technical solutions are demanded, and only objective *Performance Levels* are ordered.

Figure 17 The Procedure for generating Naval Staff Performance Requirements

These *Performance Levels* should be objective, measurable (procedural) descriptions, applicable for a contract and during the different stages of the design, i.e. Forward/Early, Detailed, see Figure 18.
At the end of the day, i.e. during sea trials, it should be possible to measure the stated signature levels and to check if the contract specifications are met. This is especially for (Very) Low Observability / Signatures not an uncomplicated task. Different Navies and Classification Societies are working on this topic. However this challenge, i.e. the RNLN experience on this topic will not be dealt with in this paper.

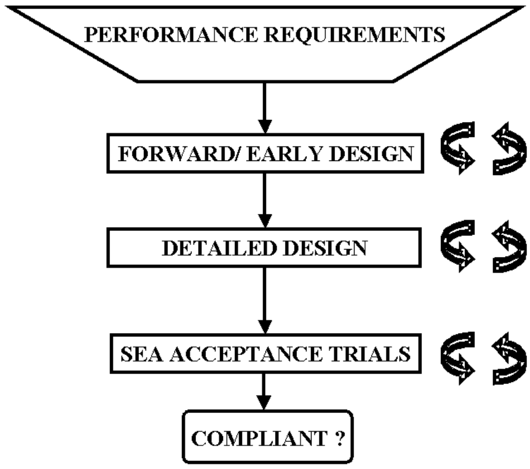


Figure 18 (V)LO Requirements should be applicable during the different phases of building project.

Predefined Threat Scenarios

The final outcome of the signature (V)LO level requirements is highly depended on the predefined threat scenarios. The definition of these scenarios is a complicated task, as well. 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.

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 19, the optimisation can not accurately be performed with a "manual" analysis methodology. Next to this a balancing between susceptibility and vulnerability reduction measures should be performed as well. 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, which can be used to engage the susceptibility problem, see Figure 19.

Next to this, it should be stressed, that in (in)ternational simulation tools so far developed, 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 in the preceding paragraphs, are not accounted for in most simulation codes. As is also the fact in the present SEAROADS version. The TNO-PML[4] Vulnerability Assessment Code RESIST[5] is deployed to tackle the Vulnerability

[4] Prins Maurits Laboratory
[5] REsilience of Ships Integrated Simulation Tool

Reduction. This RESIST code is indirectly linked to the SEAROADS code to balance to the total area of Survivability, see also Figure 19. It should be noted that both RESIST & SEAROADS do not address costing issues, so balancing for cost-effectiveness should be performed with additional costing algorithms.

LCF SURVIVABILITY FEATURES

Based on the sketched survivability approach and supported by different simulations programs & trade-offs analyses the RNLN has come to a package of advanced survivability features for the new LCF, which has been depicted in Figure 20, 21 & 22. The following paragraphs will elaborate on these and its' backgrounds. It should be noted that the list is not extensive and that next to pure survivability and financial (LCC) considerations; logistics, training and experience had a large influence on the choices.

SUSCEPTIBILITY REDUCTION LCF

Threat Detection & Hard Kill

At the end of the nineteen eighties, the Royal Netherlands Navy, participated in the development of a local area missile system called NATO Anti-Air Warfare System (NAAWS). The NAAWS-programme did not survive the budget cuts that resulted from the disbanding of the Warsaw-Pact. Lessons learned during this program are however used for the development of the air defence system for the Air Defence and Command Frigates (LCF) presently in the detailed design phase. The heart of this system is an active phased array multi-function radar. It consists of four fixed antenna plates each comprising a few thousand small transmit/receive modules. This radar called APAR, performs horizon search, limited volume search and is also used for missile support functions such as uplink and terminal illumination. APAR is depicted in Figure 20.
For local area defence the Evolved SeaSparrow Missile (ESSM) will be used. Evolved Seasparrow is a further development of the existing semi-active homing Seasparrow. Because the new frigates also have a primary task in area air defence, a long range volume radar and a medium range surface to air missile are added.
In this case the long range radar is the SMART-L[6], see Figure 20, which is a further development of the SMART-S[7] radar, used on board of the RNLN M[8]-frigates.

The medium range missile will be the Standard missile II. The basic philosophy behind the design of this AAW system is to have a smart guidance radar supporting a less intelligent missile. Time-energy budget of course is a critical factor in this system.

SIRIUS; a two colour long range infrared search and track system will be installed on board of the RNLN frigates in conjunction with the active phased array radar, see Figure 20. This system supports detection in heavy clutter and jamming and enables continuation of horizon search in periods of radar silence or heavy loading of the APAR time-energy budget.

Reduction Above Water Signatures LCF

In the following paragraphs the largest contributors to the RCS and IR signatures will be presented. RCS/IR reduction techniques will be shown, which have been applied to the design of the new Royal Netherlands Navy Air Defence Command Frigate LCF.

Reduction Radar Cross Section LCF

The Radar Cross Section (RCS) of a platform is defined by it's integral radar reflective behaviour. The metal exterior of a warship consists of hull, superstructure, supportive equipment and the payload (weapons and sensors) which all contribute to the reflective properties. Next to the platform itself, the level of RCS is determined by the aspect angle and the threat: nature of radiation (frequency, polarisation, signal shape). Superstructure parts which form orthogonal angles between two planes (dihedral) or between three planes (trihedral) are the most dominant scatter centres for contemporary conventional vessels.
Considerable (but low materiel cost) design efforts have been made to reduce the LCF radar signature. Strictly speaking the reflective energy of the LCF will not be reduced, but redirected from the threat radar i.e. the incident energy will not be absorbed by e.g. Radar Absorbent Material (RAM). RAM will only be considered for the LCF as a last resort for local scatter problems detected post-built.
Redirecting the radar energy is performed by means of (geometrical) shaping of the LCF's platform. The ship's hull only possesses, inwards and outwards inclined strakes (tumblehome and flare), this in combination with a flat (transom) stern. Vertical strakes have been avoided to prevent the hull forming dihedrals with the sea surface. The superstructure has a large fixed tumblehome angle, which allows for the rolling movement of the ship. The mast has been

[6] Active in the L-band.
[7] Active in the S-band.
[8] Multi-purpose

designed as a closed box structure, to prevent forming di- and trihedrals. The LCF lacks external gangways for a continuous junction of the superstructure with the hull. External equipment and payload has been concealed by means of bulwarks, as much as practical possible, to avoid scattering problems. This has been applied e.g. to the liferafts, gun bases, crane bases, bollards, chaff launchers and the Harpoon ASM weapon system.
Next to the deployment of TNO-FEL RCS-prediction codes, the LCF design has been verified on the basis of metalised scale model (1:75) measurements.

Reduced Infra Red Signature LCF

Thermal radiation is emitted by a body which has a temperature above zero degrees Kelvin. According to the law of Stefan-Boltzmann this radiant intensity is proportional with the 4-th power of the absolute temperature.
The contrast of the ship's radiant intensity with the environmental background is used by the missile IR-seekerhead. There are in essence two main type of contributors to the IR signature-level of the ship:

- *Warm metal hull & superstructure;*
- *Hot metal uptakes & exhaust gases.*

Substantial design activities have also been performed to reduce the LCF IR signature, in concert with the NATO Standard Code SHIPIR. The two main IR contributors have been tackled in the following manner:

Warm metal hull & superstructure

The internal of hull and superstructure has been thermally insulated to hamper heating of the external steelworks. To counter external heating by the sun an effective layout with accompanying capacities of the prewetting (ABC/NBC) system will be installed. The prewetting system will bring hull and superstructure down to near ambient temperatures under threat.

Hot metal uptakes & exhaust gases

There are commercial systems on the market that can take care of the hot metal uptake and in combination with the exhaust. These Infra Red Suppression Systems (IRSS) work in principle by mixing in cold air, either by natural or forced convection (fan-assisted). The LCF has provisions for an “Eductor/Diffuser" system. The Eductor/ Diffuser system cools the hot metal uptake and the exhaust gasses.

Next to the installation of specific hardware, first generation IR signature management Software will be installed to support the Ship’s Control Centre (SCC) to optimise it’s signature to the thermal ambient background.

Softkill LCF (RF ECM)

The LCF will be equipped with a combined ESM-receiving and jamming system. For this purpose the Sabre System is selected. The system incorporates all essential modern features like range gate pull off, coherent repeater jamming and crossed polarisation. The system will also provide a multi target capability. The ship will be provided with launchers for chaff. Next to these provisions active off-board jammers are under consideration. A final decision on this aspect has not yet been made.
As cited, TNO-FEL is closely involved in the LCF design. Among others at this moment they are developing a soft kill scheduler that should provide for automated use of the various soft kill provisions. As a next step a hard kill/soft kill scheduler is foreseen.

Soft Kill LCF (IR ECM)

IR-decoys like the Sea Gnat Mk 245 will be used on board of the LCF. The decoy contains a three-part pyrotechnic payload producing a mix of warm smoke (8-14 μm), glowing particles (3-5 μm) and gaseous products (4.1-4.5 μm) to simulate hull, stack and plume IR radiation.

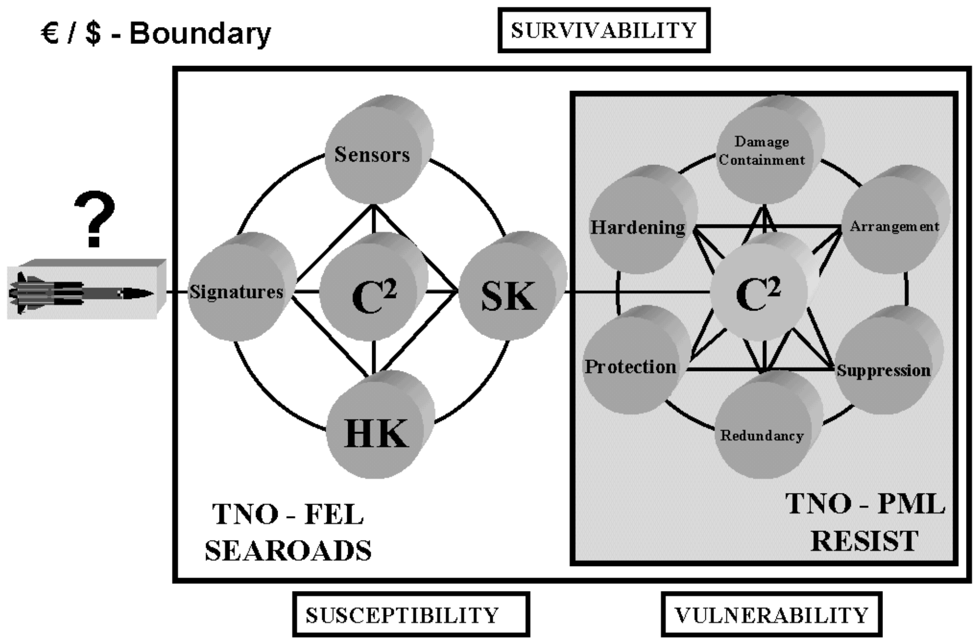


Figure 19 Balancing Susceptibility, Vulnerability & Survivability with TNO - FEL SEAROADS & TNO - PML RESIST

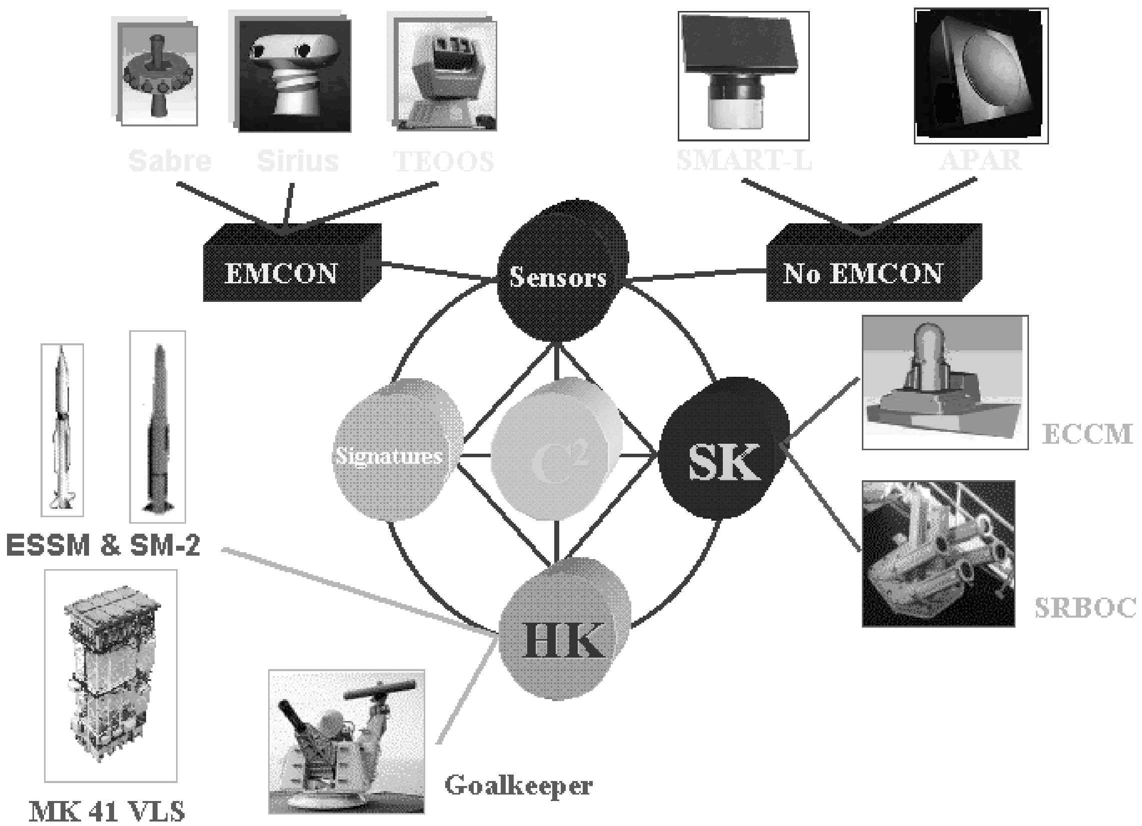


Figure 20 The Air Defence Command Frigate Cost Effective Optimised for Survivability

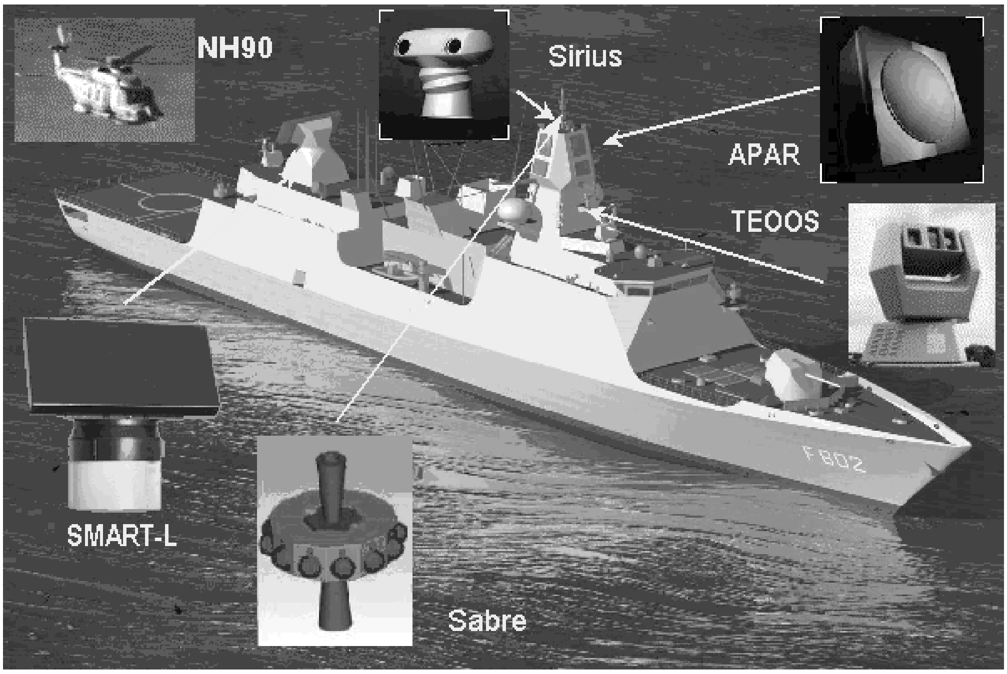


Figure 21 The Air Defence Command Frigate Main Above Water Sensor Suite (Source: Directorate of Materiel)

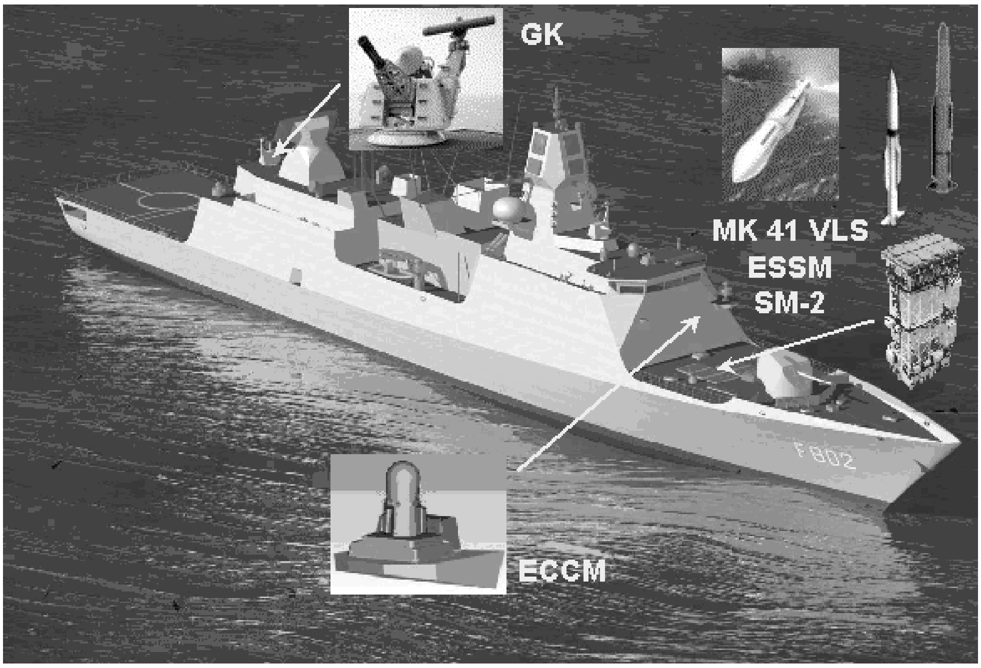


Figure 22 The Air Defence Command Frigate Main Above Water Weapon Suite (Source: Directorate of Materiel)

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 seeker might accept the ship decoys more easily. 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. A lower signature can only postpone lock-on. 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 Absorbent Materials (& Structures).
- Enclosing the external sensor systems in Frequency Selective Surfaces (FSS) and structures and further integration of systems will reduce the RF signatures of sensor and antenna systems, see Figure 25 for an overview.

- **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, 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 it 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 26 illustrates this situation, taken from [Smedberg, 13].

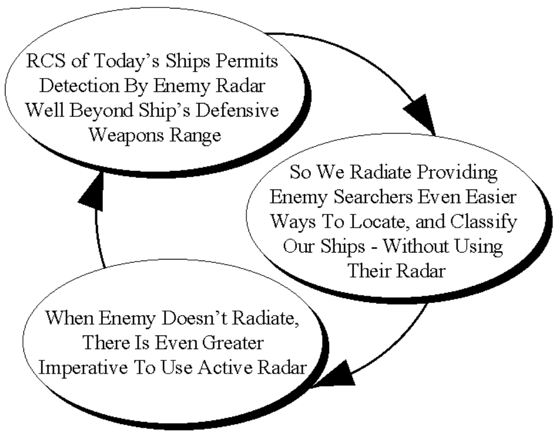


Figure 23 The Present Vicious Circle for Conventionally designed Warships

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 27, where the "Ship Shoots the Archer".

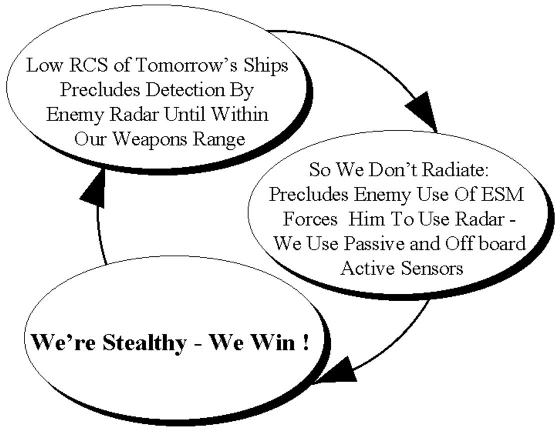


Figure 24 The Future Very Low Observability (VLO) Warship Alternative?

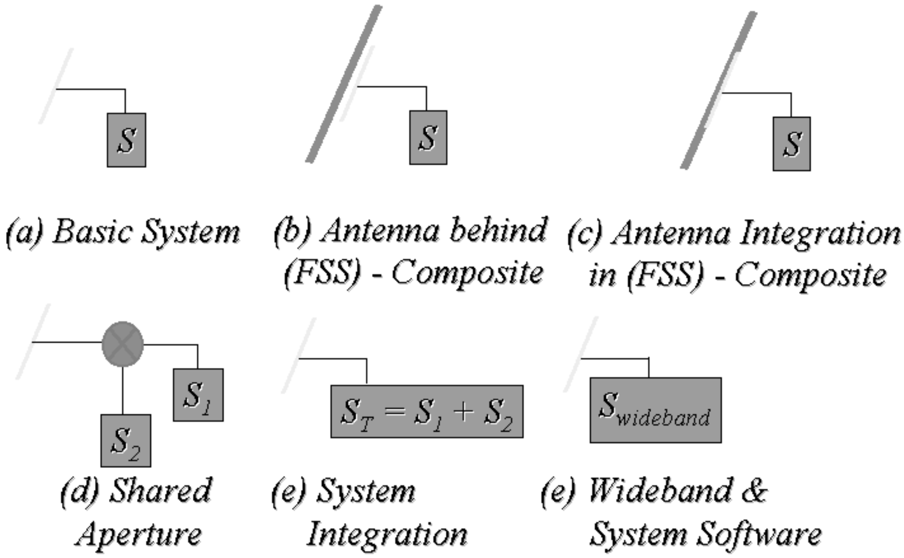


Figure 25 The Level of System Integration will influence Low Observable

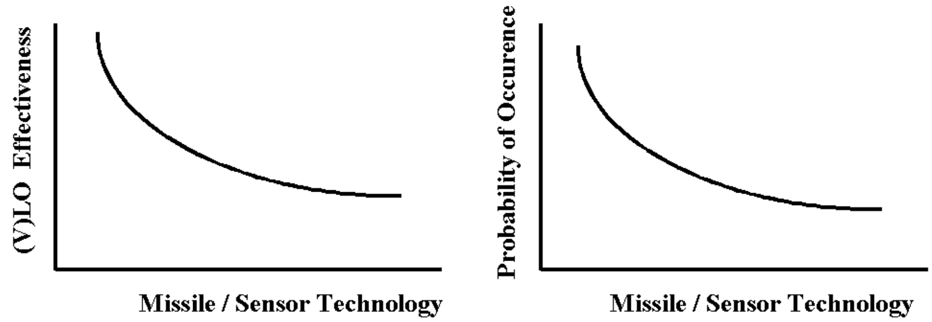
CONCLUSION / DISCUSSION

The importance of LO and VLO Ship Signature design has been demonstrated in this article. In the first part of this article the basic theoretical operational benefits of low AW-signatures has been addressed.
This significance of (V)LO is sometimes debated by stating the fact that advance in the threat (missile) side like e.g. improvements in sensor capabilities and digital signal processing technology will render V(LO) obsolete. The reply to this statement, is that in general improvements in this field will indeed reduce (V)LO effectiveness, see Figure 26a. However warships are deployed in the real world, where the most advanced threats, are not always (and luckily) encountered. The changes that the most advanced threat will be met will be lower than the ones for less sophistication, see Figure 26b. Therefore (V)LO effectiveness has to be judged with probabilistic Measure of Effectives (MoE): the combination of **Effectiveness** against a specific threat and the presumed **Probability** of encountering this threat. Next to this national simulations have shown that progress in sensor sensitivity will not always lead to significant gains in e.g. lock-on ranges, because the ambient and atmospheric conditions can be become the dominant factor.

The difficulty in stating low observable requirements has explained as well. In the second part the solutions have been addresses for supporting Survivability o/b the Air Defence Command Frigate LCF i.e. the Sensor & Weapon Suite have been introduced. The paper has been closed with views on future (V)LO trends.

ACKNOWLEDGEMENTS

The author acknowledges the Directorate of the Materiel of the Royal Netherlands Navy and the Physics and Electronics Laboratory (TNO-FEL) of the Netherlands Organisation for Applied Scientific Research for putting data and pictures at our disposal.



$$MOE = \{ Effectiveness_{(V)LO} \times Probability\ of\ Scenario\ Occurrence \}$$

Figure 26 (V)LO Effectiveness & Probability of Scenario Occurrence versus Missile Technology

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)
FoV	Field of View
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)
PC	Prime Contractor
PML	Prins Maurits Laboratory (TNO)
PO	Physical Optics
PT	Project Team
RAM	Radar Absorbent Material
RAS	Radar Absorbent Structure
RCS	Radar Cross Section
RCSR	Radar Cross Section Reduction
REA	Radar Echoing Area
RESIST	REsilience of Ships Integrated Simulation Tool
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)

REFERENCES

[1] Roodhuyzen P.J., Galle, L.F. & van Koningsbrugge, A.J.J.M.
The Survivability Frigate; The new RNLN Air Defence Command Frigate.
Presented at International Maritime EXhibition and Symposium IMDEX 1997, Greenwich, UK.

[2] Goddard, C.H., Kirkpatrick, D.G., Rainey, Dr. P.G. & Ball, J.E.
How Much Stealth ?
Naval Engineers Journal, May 1996.

[3] Galle, L.F., Heemskerk E.J. & Ewijk, L.J.
"Naval Radar Signature Management in support of Above Water Ship Survivability"
SMI Defence Conferences 1999, London.
Third Annual Stealth, LOs and Counter LOs.

[4] Galle, L. F. & Schleijpen, R.M.A.
Ship Infra Red (IR) Signatures
Ship Survivability, part II (Features of the new RNLN Air Defence Command Frigate), Marineblad, 1998.

[5] Baganz, D. & Hanses, H.D.
Stealth Technologie
Soldat und Technik 5/1993.

[6] Schleijpen, Ric M.A.
Evaluation of Infrared Signature Suppression of Ships
TNO-Physics and Electronics Laboratory
SPIE Vol 2742: Targets and backgrounds Characterization and Representation II, Orlando 1996 P245.

[7] Adamy, Dave
Basic Concepts of Electronic Warfare, EW 101
Journal of Elecronic Defense, 1997.

[8] The, Liang
Getting the act together
Hardkill - Softkill Co-ordinatiom for littoral waters
International Defense Review 8 / 1995.

[9] Krieger, D.
Naval Aviation and Stealth
Naval Institute Proceedings, 1994.

[10] Vaitekunas, David A. et al.
SHIPIR: A Naval Ship Infrared Simulator
W.R. Davis Engineering Limited,
Ottawa, Canada, July 1992.

[11] Dongen, M.P.F.M. van, Fitski, H.J., De. Thé, J.H.L.
Signature reduction: the sound of silence.
INEC 96 “Warship Design: What is so different?”
April 1996, Den Helder.

[12] Neele, Dr. F.
Prewetting Systems as an IR Signature Control Tool
SMI Defence Conferences 2000, London.
Fourth Annual Signature Management
The Pursuit of Stealth

[13] Smedberg IV, W.R.
Rear Admiral U.S. Navy (Retired)
“The Naked Fleet”, Proceedings April 1999.

BIBLIOGRAPHY

[1] Knott, E.F.
A tool for predicting the Radar Cross Section of an arbitrary trihedral corner”, IEEE South East Conference, 198 1, pp. 17-20.

[2] Gordon, W.B.
“Far field approximation to the Kirchoff-Hclmholtz representations of scattered fields”, IEEE Transactions on Antennas and Propagation, Vol.23, 1975, pp.590-592.

[3] Michaeli, A.
Equivalent edge currents for arbitrary aspects of observation”, IEEE Trans. on Ant. and Prop., Vol. AP-23, No. 3, pp. 252-258, March 1983.

[4] Ewijk, L.J. van
“Diffraction computations by means of the Method of Equivalent Currents”, TNO report FEL-94-B195, May 1994.

[5] Brand, M.G.E.& Ewijk, L.J. van
“The RAPPORT code for RCS prediction”, at PIERS conference 1995.

[6] Currie, N. C. Et al.
Radar Reflectivity Measurement Techniques & Applications
Artech House, 1989.

[7] Richardson, M.A. et al.
Surveillance & Target Acquisition Systems
Brassey’s Landwarfare,
Volume 4, 1997.

[8] Ruck,G.T. et al.
Radar Cross Section Handbook,
Volume 1 & 2.
Plenum Press, New York London 1970.

[9] Rains, Dean A.
Methods for Ship Military Effectiveness Analysis
Naval Engineers Journal, March 1994.

[10] Polk, J. & MCcants, T. & Grabarek, R.
Ship Self-Defense Performance Assessment Methodology
Naval Engineers Journal, May 1994.

[11] Davis W.R. Engineering Limited,
The Effect of IR suppression on susceptibility to IR threats
Ottawa, Canada, November 1992.

[12] Accetta J.S. & Shumaker D.L
Infrared and Electro-Optical Systems Handbook, SPIE-The International Society for Optical Engineering

[13] Davis W.R. Engineering Limited,
Onboard Signature Manager
Ottawa, Canada, December 1996.