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Ship Infrared (IR) Signatures

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SHIP INFRARED (IR) SIGNATURES
(SHIP SURVIVABILITY PART II)

(Platform Features of the new Air Defence Command Frigate "LCF[1]")

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

The English language has been used for this article, since an edited version will be submitted to the ASNE[2] "*Naval Engineers Journal*" for publication.

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[1] "**L**uchtverdedigings **C**ommando **F**regat"
[2] **A**merican **S**ociety of **N**aval **E**ngineers

Figure 1 CATIA/CAD impression of the new RNLN Air Defence Command Frigate "LCF" (Source: MarTech)

"Facile est inventis addere"

SYNOPSIS

A low Infrared (IR) signature is of paramount importance for a warship's survivability. In this paper, basic IR theory will be addressed, next to the simulation of IR Signatures, to give insight to IR signature management. Possible IR Signature Suppression techniques will be presented and elaborated upon. A general overview will be given of the Infrared Signature Suppression Features which have been installed in the design of the new RNLN Air Defence Command Frigate "LCF", see Figure 1. The article will close with views on future trends.

Figure 2 Penguin IR-guided ASM (source: Kongsberg Aerospace)

INTRODUCTION

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 signal processing. Next to developments in the ASM Radar Guided (RF[3]) field, this is especially the case in the field of Infrared (IR) Electro Optics (EO). Examples of IR guided ASMs are the Norwegian "*Penguin*", see Figure 2, the Russian "*Styx*" IR variant (P22/Snegir) and its Chinese (PRC[4]) derivative "*Silkworm*"; the Hai-Ying 2 (HY-2). IR ASMs can either have single IR-guidance or Dual Mode i.e. initial RF combined with terminal IR guidance e.g. the Taiwanese Hsuing Feng 2. Future systems will be able to use RF and IR simultaneously to exploit synergism (Hybrid).

A preceding article, i.e. "Ship Survivability (Part I)" [Galle, 1], promoted to integrally take up the challenge of Survivability for ASMs. Two Survivability factors, *Susceptibility* and *Vulnerability*, have been introduced.

Susceptibility, being the *inability to avoid* weapon effects and Vulnerability, the *inability* of the warship *to withstand* weapon effects.

It was shown that the susceptibility factor was significantly dependent on Radar as well as IR Signature. High signature levels are in principal unwanted because they will provide information to the opponent for detection, classification, identification, tracking and even homing guidance. The antagonist can be airborne, (sub)seaborne (e.g. periscopes), landbased and even spacebased (satellites).

This article will elaborate on *IR Signature* phenomena. An overview will be given of possible technologies to diminish and manage it. Suppression features which have been installed in the design of the new RNLN Air Defence Command Frigate "LCF" will be discussed.

A succeeding article will address the *Radar Signature*; i.e. Ship Radar Signatures (Ship Survivability Part III). Part IV will focus on *Ship Vulnerability*.

OPERATIONAL IMPORTANCE OF IR SIGNATURES

It is important, to be aware of the difference between the detection of

[3] **R**adio **F**requency

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

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 reflection can be 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 comparison 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); like the long range SIRIUS system to be installed on the LCF. These detection systems can be the trigger to deploy IR-decoys.

Decoys
An IR decoy is a device which is deployed off-board from the ship to act as an alternative source of IR radiation, which attracts hostile seekers. In general IR ship decoys are fired from launchers on the ship, see Figure 3. IR decoys either float on the water or create a cloud of hot particles or a combination of both. The LCF will be equipped with German Buck Giant decoys. The "Giant" 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, which will be explained later on.

Figure 3 Plume suppressed frigate with an IR-decoy in seduction (Source: Royal Canadian Navy)

Decoys can be deployed in two roles: before the missile locks on to the target (distraction) or after missile lock-on i.e. to lure (lock-transfer) the missile away from the platform (seduction).
In the seduction role, the decoy 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).
Figure 4 shows the time interval in which a generic seduction decoy is effective at two different signature levels; suppressed and unsuppressed. A decreased signature increases the time interval for effectiveness.

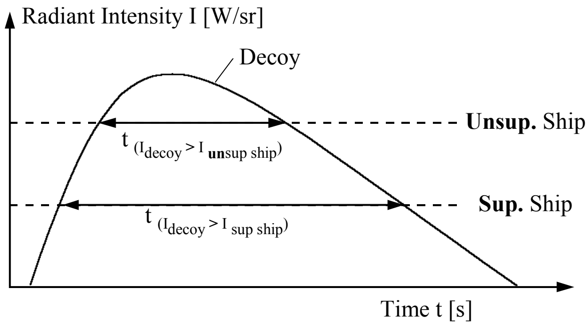

Figure 4 Generic Radiant Intensity in time of unsuppressed and suppressed ship and IR seduction decoy.

In the distraction role there is no competition, but distraction in itself is only possible, if lock-on has not yet been achieved by the missile. The use of decoys in the distraction mode is preferred over the use in seduction mode because the position of the decoy is less critical while 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, 2]. In case atmospheric transmission losses are neglected, the lock-on range ($R_{l.o.}$) is in principal proportional with the square root of the IR signature of the ship (I_{ship}):

$R_{l.o.} \propto \sqrt{(I_{ship})}$ [m]   eq. (1)

So halving the IR signature will decrease the lock-on range with $\sqrt{2}$.
Based on the preceding considerations and by ship/threat scenario simulation and analysis, it is possible for Naval Staff to establish IR Ship Signature "*Staff Requirements*". It is the task for the naval engineer to meet this requirements in a cost effective manner.

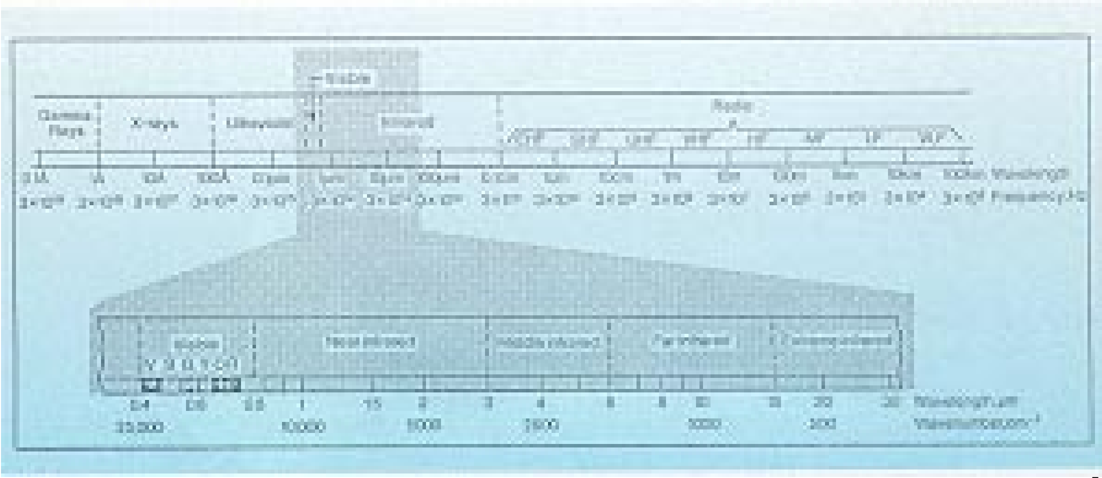

Figure 5 Infrared in the Electromagnetic Spectrum

SOME BASIC INFRARED THEORY

IR in the EM Spectrum
The wavelengths of the Electro Magnetic (EM) spectrum range from hundreds of kilometres (Very Low Frequency; VHF) down to only nanometers of Gamma-rays (10^{-9} m), see Figure 5. In this huge EM-spectrum the human eye is only sensitive to a very small range; from 0.4 µm to 0.7 µm (10^{-6} m). Wavelengths larger than red i.e. from 0.75 µm up to 1000 µm (1 mm) are denoted *Infrared* wavelengths. The Infrared Realm is divided in 4 regions, Near IR (NIR), Middle IR (MIR)or Mid wave Infrared (MWIR), Far IR (FIR) or Long wave IR (LWIR) and Extreme IR (XIR). The names relate to their position relative to the visible realm. The XIR has wavelengths up to 1 mm and comes close to the radar spectrum. It will be explained later on, that the ***MIR*** and ***FIR*** bands are the most important for a naval scenario.

Stefan-Boltzmann's Law
Thermal radiation is emitted by an object which has a temperature above zero degrees Kelvin (K). According to *Stefan-Boltzmann's Law*, Radiant Intensity, which is power per solid angle[5], is proportional to the 4-th power of the absolute temperature. The hotter the source, the more energy it will emit. Defining T, A, k as (absolute) temperature, (presented) area and Boltzmann's constant respectively, the total Radiant Intensity (I), is determined by:

$I(T) = k.A.T^4/\pi$ [W/sr]   eq. (2)

It is noted that eq. (2) is true for a black body with perfect emissivity; $\varepsilon = 1$. In general ε is less than 1 and the emitted energy is given by $I = \varepsilon.I(T)$. From this equation it is clear that surfaces with equal temperature can show different radiant intensities if their emissivity is different. In

[5] steradian [sr].

practice, unity for ε, is most perfectly realised by a cavity; internal shipboard construction e.g. funnels can therefore be efficient black bodies.

Planck's Law

Stefan-Boltzmann eq. (2) yields the total Radiant Intensity. Radiant energy is not homogeneously distributed over all wavelengths (λ). *Planck's Radiation Law* gives this distribution, see Figure 6. The total (integrated) area under Planck's curve gives the total "Stefan-Boltzmann" energy.

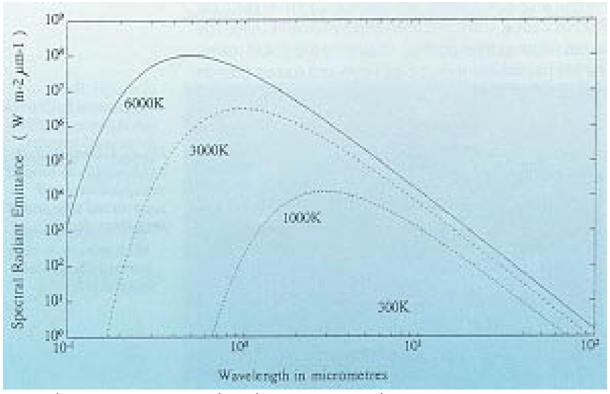

Figure 6 IR emission according to Planck (Source: Brassey's)

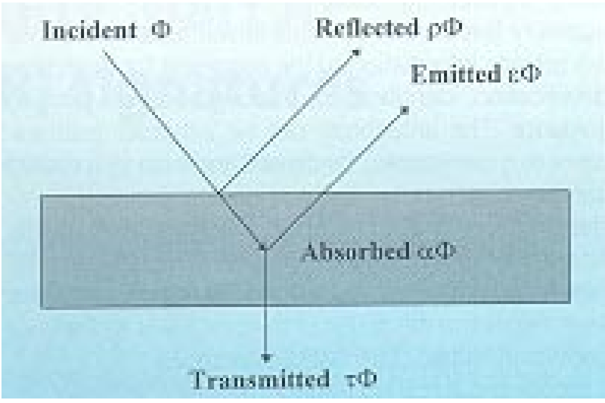

Figure 7 Total Infrared Power Law

Wien's Displacement Law

Studying Figure 6, one notices, that the wavelength, were the radiation is at maximum, shifts reciprocal with temperature. The higher the temperature, the more the maximum shifts to the shorter wavelengths. This phenomenon has been described by *Wien* in his *Displacement Law*, with λ_{max} in [µm] and T in absolute temperature[6] [K]:

$\lambda_{max}.T = 2898$ [µmK] eq.(3)

Wien's Displacement Law shows that objects at room temperature 300 K (27 °C) radiate with a maximum at about 10 µm and a black body at 1000 K (727 °C) at about 3 µm, while being emitting about 100 times more energy (Stefan-Boltzmann), see also Table 1.

Total Power Law

[6] Note: 0 °C = 273 K.

Emissivity ε will be smaller than unity ($\varepsilon < 1$) for practical solid materials, so called "*grey bodies*[7]". For bare polished metals ε can even go down to 0.02, for the most engineering materials ε will be between 0.80 and 0.95, as for standard paint finishes. For non transparent (opaque) materials, emissivity is ***only*** determined by the properties of the external surface e.g. paints and coatings. The emissivity of a surface, and therefore the emitted IR energy see eq.(2), can e.g. be lowered by special paints, but reflectivity will be raised. This can be proven by the following considerations, see Figure 7.

The summation of absorbed, reflected and transmitted radiant power must equal incident power:

$\Phi_{abs} + \Phi_{ref} + \Phi_{tr} = \Phi_{in}$ [W] eq.(4)

Equation eq.(4) can be made non-dimensional, by defining absorptivity α, reflectivity ρ and transmissivity τ as ratios of $\Phi_{incident}$:

$\alpha + \rho + \tau = 1$ [-] eq.(5)

For non transparent (opaque) materials, $\tau = 0$, eq.(5) can be reduced to:

$\alpha + \rho = 1$ [-] eq.(6)

Kirchhoff's Law

Next by substituting *Kirchhoff's Law*, which states that the absorptivity α of a body must be equal to its emissivity ε; ($\alpha = \varepsilon$):

$\varepsilon + \rho = 1$ [-] eq.(7)

[7] ε, for grey bodies, being independent of wavelength is an idealisation of real physics.

Table 1 IR wavebands		
Name of Waveband	**Max. Wavelength [μm]**	**Source Temperature [°C]**
Near IR (NIR)	0.75 - 3.00	3600 - 700
Middle IR (MIR)	3.00 - 6.00	700 - 200
Far IR (FIR)	6.00 - 15.00	200 - minus 100
Extreme IR (XIR)	15.00 - 1000.00	-100 - minus 270

Which proves the statement that low emissive paints will have high reflective properties.

This reflective property is of high importance when we consider the infrared radiation from surfaces of the hull or the superstructure of the ship. A sensor will not only see radiation emitted by the ship's surface, but also radiation from the environment reflected by the surface. The emitted part is governed by the surface temperature T_{surf} and the emissivity. The radiation from the environment is characterised by a weighted average temperature of the environment T_{env} and the reflectivity ρ. The total radiant intensity of a surface is then given by:

$$I = \varepsilon I(T_{surf}) + \rho I(T_{env}) \quad [W/sr]$$

$$= \varepsilon I(T_{surf}) + (1-\varepsilon) I(T_{env}) \quad \text{eq. (8)}$$

GASEOUS PRODUCTS

Solids behave like "*Planckian*" broadband continuous radiators. For most solids, the approximation of ε as constant over wavelength is satisfactory for simple analysis. However this is not the case for the selective (in wavelength) emissions of gases products or special IR coatings. Gases (e.g. exhaust gases) will radiate selectively at characteristic wavelength regions in so-called emission bands. This is because their emission is based on alterations of oscillation and rotation states of the molecules; according to the quantum theory they will only adapt certain energy

levels and they can only perform allowed transitions (quantum jumps).

Atmospheric attenuation

Atmospheric attenuation will diminish the amount of radiation available to the observer/threat. In a naval scenario IR radiation will be absorbed by two main mechanisms in the atmosphere. On the one hand scattering of energy by small dust particles and small water droplets and on the other hand absorption by molecules of atmospheric gases (e.g. CO_2, H_2O and O_3). Figure 8 yields the results of this attenuation, close to the sea surface over a range of 2 km.

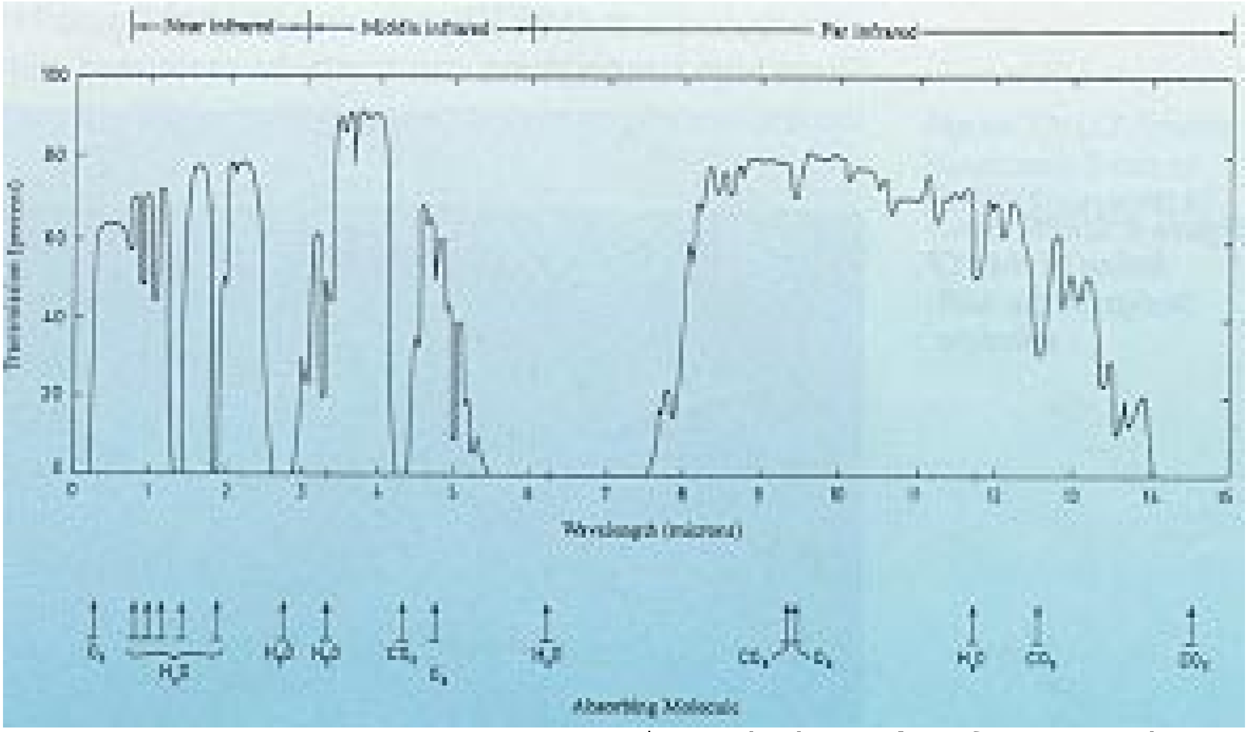

Figure 8 IR Transmission in the atmosphere at sea level over 2 km (Source: Brassey's)

Studying this graph, two distinct transmission bands or windows come out as relevant for Ship Signatures; they are transparent for IR radiation: the **3-5 µm** (**MIR**) and **8-14 µm** (**FIR**) waveband.
Wien's law shows that the MIR band coincides with the maximum radiation for objects at temperatures of 600 to 1000 K such as the hot metal parts of the funnel and exhaust gases. Objects at ambient temperatures (about 300 K ≈ 25°C) such as the hull or the superstructure of the ship have their maximum radiant intensity in the FIR band.
The MIR window is often used for missile seekerheads, mainly because of the availability of simple MIR detectors for hot spot detection/tracking e.g. reticle types. In the MIR band however, reflections of solar radiation at the sea surface (or at the ship's hull or superstructure !) can easily be mistaken for a hot spot target. For detection of cooler parts the FIR band is preferred.

Contrast
It is important to notice that a ship's IR signature has to be evaluated against it's environment i.e. background of sea, sky, landmass or any combination thereof[8]. This because the threat will only be able to exploit the signature difference[9], i.e. the contrast of ship and it's surrounding background.

IR SIMULATION

The above presented basic theory, gives just a flavour of the physical laws to be implemented (mathematically) in IR simulation codes. Simulation has become indispensable, because IR signature management with it's highly (environmental) interactive character, has become too complex to be analysed by "hand". Manual analysis is only feasible for a qualitative comprehension of the problem.

Simulation versus "*live Trials*"
To determine the IR signature and/or the influence of the introduction of new signature reduction techniques, "*Live Trials*" are to be preferred over simulation, because all important phenomena are taken care of, of

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[8] Depending of the expected aspect angle of the threat (Azimuth & Elevation).
[9] In theory, will it be impossible for a sensor, to detect a target with the same Radiant Intensity (per unit area) as its background (i.e. No Contrast).

itself. Next to this at present, IR simulation codes are still in development and far from "perfect".

However, Live (Sea) Trials are expensive and dependent on the availability of high value units. Next to this, it is nearly impossible to evaluate different candidate configurations under the same ambient conditions. Additionally, IR simulations allow more flexibility than "Live-trials". For example the weather conditions can easily be changed in the model whereas in a live-trial, one has to accept the given conditions.

Aware of its limitations, simulation codes have become an indispensable tool for naval engineers. Especially in the design phase (e.g. LCF), where no ship is even available to evaluate. Still the naval engineer must be able to make trade-offs to optimise the Ship IR Signature cost-effectively. However, it should be kept in mind, that simulation is only a tool, which can decrease the number of trials. It can not replace the ultimate "Live Trial".

Interaction Ship & Environment

As stated above, a ship's IR signature has to be evaluated and therefore simulated against (contrast!) and in it's environment. Recalling eq.(8); the first emissive radiant intensity term $\varepsilon I(T_{surf})$ of a ship's surface element, is dependent on its temperature. This temperature is determined by the thermal interaction of the ship with its environment. The second reflective radiant intensity term $\rho I(T_{env})$ of a ship's surface element is dependent on the reflection of again its environment.

A ship's internal configuration and external surface is complex and non-homogeneous; external surfaces elements will have different equilibria for temperature. The different ship's surface element temperatures will be determined by the incident Radiant Intensity (e.g. sun, clear sky, partial cloudy or overcast), reflectivity, absorptivity, the thermal conductivity, heat capacity (thermal inertia) and of course the ship's internal heat sources and insulation system.

Other factors that play a role are: the wind- (heating or cooling), ship- speed & direction, rain and impingement of the exhaust gases on the ship's structure.

This leaves the IR simulation code with a large interaction problem between ship and environment to be solved.

SHIPIR

Within the NATO research community[10] a ship IR simulation code evaluation has been performed during the past few years. National codes were compared and evaluated. The Canadian developed code acronymed "***SHIPIR***[11]" was adopted within the NATO community as a standard Naval Ship Infrared Simulator code. SHIPIR has also been adopted by the RNLN and TNO-FEL for ship IR simulation.

SHIPIR is able to assess and analyse IR signatures of current naval ship designs as well as to evaluate future ship designs with Infrared suppression techniques [Vaitekunas, 3]. The model is capable of handling a wide range of operational, atmospheric, observer and spectral conditions. Figure 9 shows a SHIPIR simulation of the new LCF design in the MIR-window. SHIPIR has a coupling with the NAME[12] (MarTech) **C**omputer **A**ided **D**esign CAD-Software CATIA.

[10] AC/243 (Panel 4/RSG.5) on "Maritime IR Target and Background Signatures, Measurement and Characterisation"
[11] SHIPIR has been developed by W.R Davis Engineering Limited.
[12] Design of Department of **N**aval **A**rchitecture and **M**arine **E**ngineering (MarTech)

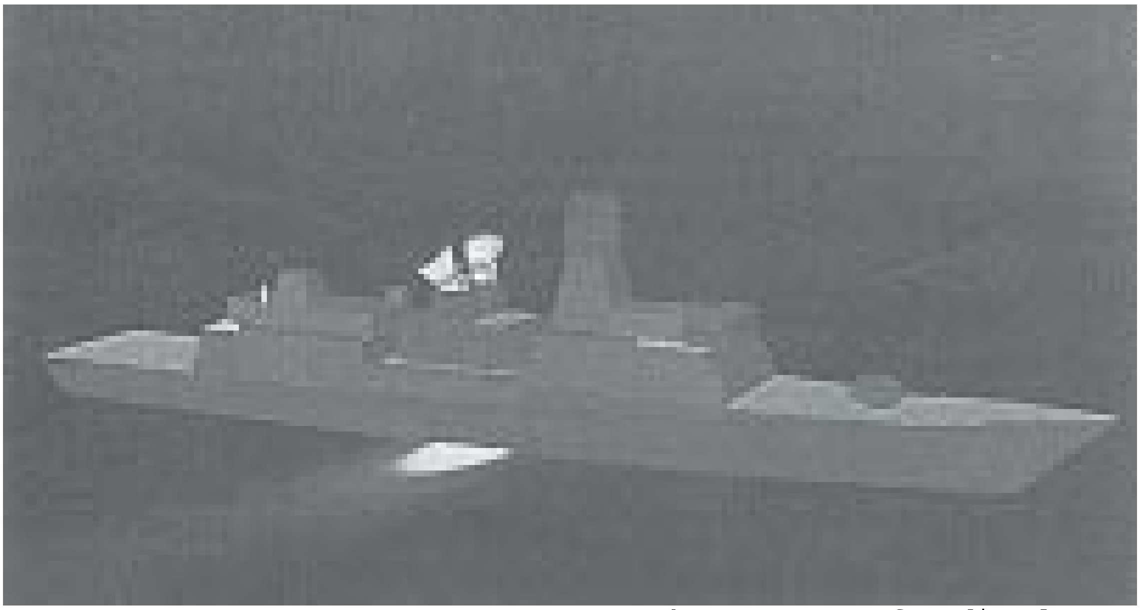

Figure 9 SHIPIR simulation of the LCF Design in the MIR-window

IR SIGNATURE CONTRIBUTORS

MIR SIGNATURE

High temperature objects (hot spots) will be the main contributors in the MIR 3-5 µm waveband, see Figure 11. These high temperatures can mostly be associated with the ship's prime movers of the propulsion and the power generator systems. The exhaust gases of the diesel engines (propulsion and diesel generators) can have temperatures from 250 up to 600 °C. For gas turbines the exhaust gas temperatures are in the range of 500 to 600 °C. The high temperature exhaust gases will in general generate two sources for the MIR band; the exhaust gas itself and the metal parts of the stack heated by the hot gases.

Plume Radiation
Firstly, the exhaust plume itself will, at maximum speed, be visible in a deformed conical shape to a height above the stack of about five times the diameter of the exhaust duct at full power. The amount of radiation produced by the plume is dependent on: plume temperature, power setting, chemical content and ability of the system to completely "burn" the fuel.

Exhaust gases, for diesel as well as gas turbines, comprise of three main IR sources: Carbon Dioxide (CO_2), Carbon particles (soot) and unburned fuel. The soot as well as unburned fuel particles behave both as efficient black body radiators; they radiate according to "Planck". In contrast, hot Carbon Dioxide gas only radiates strongly in the 4.2 - 4.8 µm region.

Figure 10 Visual image of a RNLN Standard Frigate (Moderate Speed)

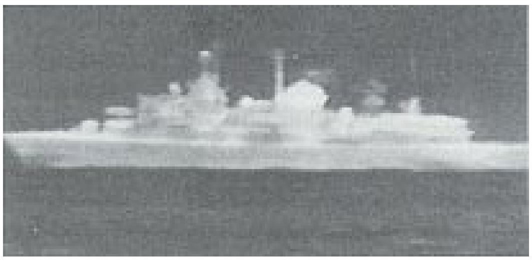

Figure 11 MIR image of a RNLN Standard Frigate (Moderate Speed)

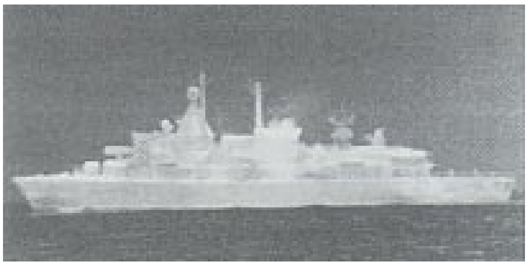

Figure 12 FIR image of a RNLN Standard Frigate (Moderate Speed)

Stack/Duct Radiation
The second MIR radiator is the stack which will be heated by the carriage of the hot exhaust gases. The top of the duct can be a major problem because it can be visible at near horizontal aspects, especially if the ship rolls.

Visible stack surfaces and exhaust plumes will typically occupy less than 2 percent of the projected area of a ship's hull and superstructure, but can contribute up to 99 percent of the total ship signature in the MIR window and 46 percent in the FIR window [Simpson, 4].

High specular returns (Glint) from sun reflections can also be major contributors to MIR signature.

FIR SIGNATURE

In case a ship has hot spots in the MIR band they will also be observable in the FIR band. However their Radiant Intensity will be more matched with warm bodies, see Figure 12.

Next to the already mentioned "hot spots", the most important contributor to the FIR signature is the "warm" metal hull and superstructure of the ship. External hull/superstructure plating of machinery compartments will internally be heated by the machinery and/or Heating, Ventilation Air Conditioning (HVAC) systems. Externally they will be heated by the radiation of the sun. Other contributors can be e.g. heated bridge windows, weapon heaters and ventilation exhausts systems.

An important factor in FIR can be the impingement of hot exhaust gases at structures and equipment ("down wash"), which will be significantly heated above ambient temperatures.

More structural details can be observed in Figure 12, because, as explained earlier, FIR is sensitive to emission from objects at ambient temperature. This property of the FIR waveband is especially useful for target classification.

IR SUPPRESSION

IR DESIGN DISCIPLINE

The naval engineer can already gain a great deal of IR reduction by shear design. Simple inexpensive design techniques have to be explored, before going into special IR reduction techniques. An example of such a simple design technique is "*Optical Blockage*". As IR is an Electro-Optical signature it is sufficient to get warm/hot sources out of the Line of Sight (L.o.S) of the expected threat view aspect. For "*Sea Skimming*" missiles this will be horizontal aspect. E.g. raked funnels are a potential hot spot problem, because the hot funnel top will be visible. "Flared" funnels are not a problem as long as the orientation of the top is correct i.e. horizontal, like the bifurcated funnels on the LCF. Another simple technique is the installation of appropriate thermal insulation in internal hot areas to lower external surface temperature, especially in machinery spaces and funnel areas.

A test method, in the design procedure, which has been used for years (e.g. Standard, Air Defence and Multi Purpose frigate) in the Royal Netherlands Navy, is the employment of "*Smoke Hindrance Trials*".
These trials[13] use a scale model (1:75) of a design option positioned in a wind tunnel. The flowfield of the plume is observed by means of smoke, see Figure 13. This technique is not only useful for safe helicopter operation, but

[13] Model agreement in flow dispersion is satisfied by a constant momentum density ratio between exhaust and ambient flow, see also bibliography [Baham, 4].

good design can also avoid impingement on superstructure and sensors. In turn, this will not only avoid fouling of systems, but also warming up and so prevent the formation of additional warm bodies.

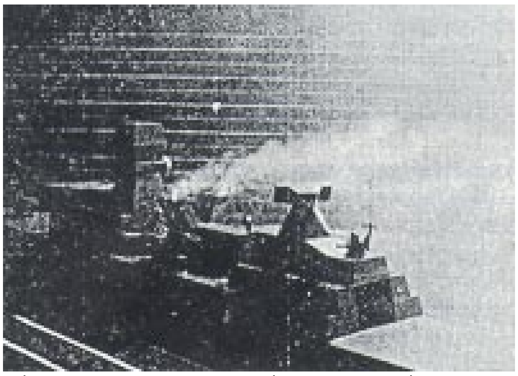

Figure 13 LCF Smoke Hindrance Trials at NLR[14]
(Source: NLR)

PAINT SYSTEMS/COATINGS

As was stated earlier, absorptivity, reflectivity and emissivity are properties of the external surface/finish. So there is a lot to be gained to pay attention to the external surface of the ship.

One of the possibilities is the application of IR Low Emissive Paints (IRLEPs). IRLEP has a low emissivity and will therefore reduce the thermal emission of a surface compared to the same surface covered with regular paint finish, see also eq. (2). Next to this, IRLEP treated surfaces will be less warmed up by the sun; according *to Kirchhoff's Law* the absorptivity equals the emissivity. So IRLEP reduces not only the energy to be radiated at the same temperature, but also diminishes the temperature itself, by reduction of solar absorption.

However, connected with the low emissivity is a high reflectivity, see eq. (7). Due to the higher reflectivity, the signature of the ship will be more dependent on its environment, see also eq. (8). This is a factor which has to be carefully monitored in the application of IRLEPs.

In principle the emissivity can be made wavelength dependent. Ideally one would like to have a high reflectivity in the spectral range with maximum solar radiation and a moderate reflectivity in the MIR and FIR bands, keeping into account the environment effects mentioned above; Low Solar Absorbance Paints (LSAPs).

[14] **N**ationaal **L**ucht en **R**uimtevaart laboratorium = The Netherlands National Aerospace Laboratory

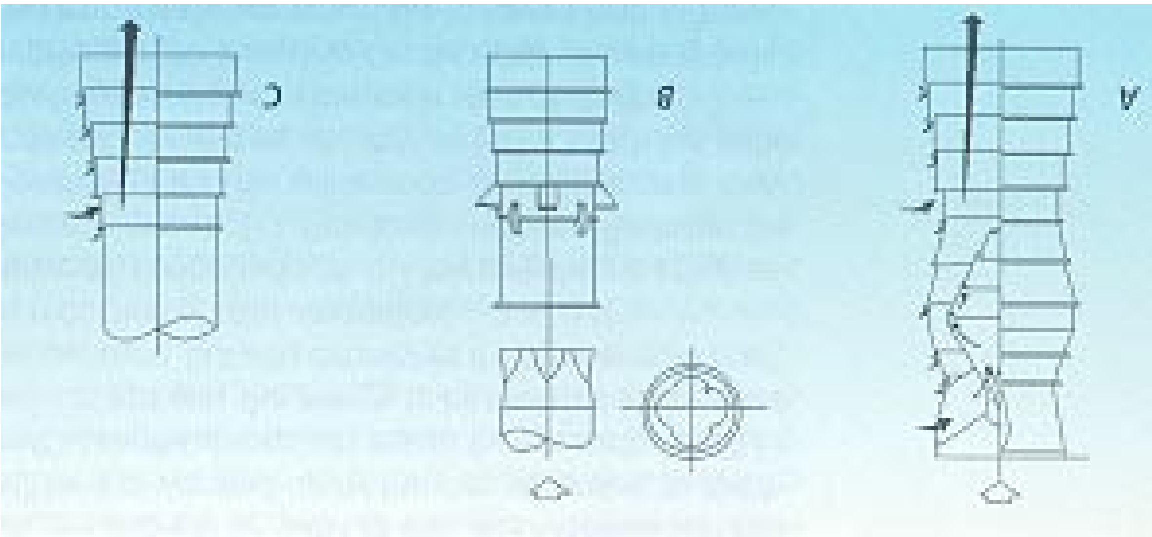

Figure 14 Diffuser(a), Eductor/Diffuser(b) and DRES Ball(c) (source: Davis)

INFRARED SUPPRESSION SYSTEMS (IRSS)

As was stated earlier, two main IR contributors in the MIR window; less pronounced in the FIR window, is the radiation of the plume and the stack. This is a major concern, because these objects tend to be located high up in the ship. For a sea skimming ASM "popping up" over the "*Optical Horizon*", they will form the first possibility to detect and lock-on to the ship.

Several navies have come up with solutions to lower the radiation of the hot metal parts of the stack. The Royal Navy uses e.g. their well known "Cheesegrater[15]" system and the USNavy the BLISS[16]/Eductor-cap. These systems use air entraining for convective cooling to lower the metal temperature. The RNLN is also operating a Cheesegrater system on board the Standard Frigates (SF-Batch III). On board the Air Defence frigates an "in house" (**NAME/MarTech**) stack design is employed. The terminal duct of the AD-frigates is produced of stainless steel (low ε) and

convectively cooled down with fan and waterspray.

[15] The Cheesegrater is a product of Darchem Company UK.
[16] Boundary Layer Induction Stack Suppressor

Examples of commercial IRSS systems are depicted in Figure 14. Based on the IR requirements, the naval engineer has to carefully trade-off the different available systems, because next to the "pros" of IR reduction, these IRSS systems will introduce "cons" like additional topweight (ship stability) and engine backpressures, which can be an important problem for diesel engines.

Simple Film Cooled Diffuser
A simple cooled diffuser only provides hot metal cooling for a limited range of viewing angles, see 14a. Film cooling slots are formed by an arrangement of a number of overlapping concentric rings. The diffuser is a passive device, i.e. fans are not required [Davis, 4].

Eductor with Film Cooled Diffuser
The Eductor/Diffuser system is a development of work performed at NPS[17], Monterey (USA), see Figure 14b. The system consists of an ejector nozzle mixing tube in conjunction with a film cooled diffuser. A clover leaf shaped nozzle enhances ejector mixing. The Eductor/Diffuser lowers the temperature of visible metals surfaces for a limited range of

[17] **N**aval **P**ostgraduate **S**chool

viewing angles as well. Significant plume cooling is achieved by bulk cooling. The system can be improved by means of fan assistance.
This system was introduced by the Royal Canadian Navy; the Iroquois Class Destroyers (DDH-280) were retrofitted with the Eductor/Diffuser system under the **TR**ibal Class **U**pdate **M**odernisation **P**roject (TRUMP), after this the system was among others projects implemented in the German Blohm & Voss MEKO 200 design (Hellenic Version).

DRES Ball
The original DRES Ball concept has been developed at the Canadian **D**efence **R**esearch **E**stablishment, **S**uffield, see Figure 14c. The DRES Ball comprises of a film cooled outer duct, surrounding a film cooled optical block centre body followed by a film cooled diffuser. The centre body has the function of blocking the view down the exhaust duct, so providing full overhead protection, for "*high divers*" and satellites. Four hollow struts supply bulk cooling air to lower the plume core temperature. Depending on the IR requirements the DRES Ball can be self sustaining (passive) or fan assisted (active). DRES Ball systems have been installed in the "Halifax-Class" Frigate (CPF[18]) of the Royal Canadian Navy and the Israeli Sa'ar V Corvette.

Other Plume Suppression Advantages
Both the Eductor/Diffuser and DRES Ball provide plume cooling, another advantage of plume cooling is, that gas impingement on the ship's superstructure, leaves it less heated. Next to this, Infrared Search and Track (IRST) systems are used by modern combatants for detecting[19] incoming missiles. IRST systems can be hampered by the ship's hot exhaust gases (Blind Arcs). These problems can be reduced by exhaust gas cooling.

PREWETTING SYSTEMS

As stated above, one of the most important contributors to the FIR signature is the "warm" metal hull and superstructure of the ship; "warm" means just above ambient temperatures. In a threat situation the prewetting system of a ship can be used to reduce the IR signature. The sea water which runs down the ship will reduce the contrast. In some prewetting systems the water is sprayed above the ship. The prewetting system is a good solution in case the ship is heated by the sun.

IR SIGNATURE REDUCTION LCF

Considerable design efforts have also been made to reduce the LCF IR signature, this in concert with TNO-FEL and the deployment of the modified IR-prediction code "NIRATAM[20]" and SHIPIR. The main IR contributors have been tackled in the following manner:

Reduction in the FIR-window
The internal of hull and superstructure has been appropriate 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 system will be installed. Under threat conditions, the prewetting system will bring hull and superstructure down to near ambient temperatures. 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.

Reduction in the MIR-window
The LCF CoDoG[21] propulsion configuration consists of two "boost" gas turbines (Rolls Royce Spey SM1C; 18.5 MW) and two cruising diesel engines (Stork Wartsilä 16V26ST; 5 MW). Four dieselgenerators (Paxman 12VP185; 1.65 MW) will take care of the necessary electric energy.

The LCF design has provisions for an "Eductor/Diffuser" system for

[18] **C**anadian **P**atrol **F**rigate
[19] The only detection possibility under "Radar Silence"

[20] NIRATAM is the acronym for **N**ato **Infrared A**ir **Ta**rget **M**odel, SHIPIR was not available to the RNLN in 1996.
[21] **Co**mbined **D**iesel **o**r **G**as turbines

the boost gas turbine propulsion arrangement to lower the temperature of the hot metal and the exhaust plume. The Eductor/Diffuser will be tailored to the LCF's IR signature requirements.

FUTURE TRENDS

Internationally and within the Royal Netherlands Navy technologies are being explored, which will impact Ship IR Signatures in the future (e.g. GE/NL MO2015 FRCC Study[22]). Two of these trends will be highlighted and discussed briefly.

Threat/Seekerhead
Seekerhead sensorics and signal processing will be improved. This will give the missile better possibilities to distinguish the ship and reject decoys. Possible (new) rejection techniques can be e.g. [Deyerle, 7]:

- Position comparison of ship and decoy; even if a ship manoeuvres at its maximum possibilities, 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[23] will exploit a Imaging Infrared Seeker, see Figure 15.

Some of these 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.

[22] Maritime Operations 2015 Future Reduced Cost Combatant
[23] Nytt Sjomalsmissil / New Surface Missile

Figure 15 The NSM will exploit an IIR seeker *(source: Kongsberg Aerospace)*

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. These systems will comprise software for signature assessment and evaluation. Hardware for data acquisition will consist of thermocouples and meteorological instrumentation[24]. 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 is managed. Such a system will make it more feasible to deploy specific IR peace and war time modes.

CONCLUSION / DISCUSSION

The importance of low IR Ship Signature design has been shown. Basic IR theory and simulation have been discussed, necessary to comprehend general IR signature management techniques and the presented LCF's IR design features.

In the previous paragraph two developments have been discussed,

on the attacking side and on the defensive side. These developments will impact IR Signature Management in the future. Next to these, other activities in the Marine Engineering realm are approaching, e.g. on the prime mover side; the introduction of InterCooled Recuperated Gas Turbines (ICR) such as the Westinghouse/Rolls-Royce WR-21 or the overture of the *"All/Full Electric Ship"*. On the Naval Architectural material side: the utilisation of composites for masts and superstructures, the availability of adaptive emissivity foils & smart materials/skins, the integration of IRLEPs, LSAPs and Radar Absorbent Paints (RAPs). On the design side, there is great interest in the Trimaran option. The Trimaran gives the possibility of discharging the exhaust gases between main hull and side hulls (Optical Blockage).
The impact or potentials of these new technologies on "IR" is not yet fully understood. To comprehend their impact to an appropriate extend, these topics have to be addressed in scientific research programs. International co-operation can be an cost-effective option.
Only in this way, the Royal Netherlands Navy can be ready for the future; i.e. to be capable to incorporate evaluated cost-effective IR management technologies in ("revolutionary") designs.

[24] Existing ship instrumentation will be used where possible.

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