IR Signature Suppression of Modern Naval Ships[1]

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ABSTRACT:

Most modern naval ships include some form of infrared signature suppression (IRSS) to reduce the ship susceptibility to IR guided anti-ship missiles. In some cases the IRSS may be very basic while in other ships great care has been taken in the ship design process to achieve a very low signature. The trend in recent years with new ship programs is towards a more systematic and comprehensive approach to IRSS.

In previous years it was considered enough for a ship IR signature specification to consist of a single statement: the ship IR signature shall be minimized. This is no longer good enough. New ship design programs are including detailed IR signature management studies that include IR suppression tradeoff studies, detailed susceptibility analysis and cost benefit analysis. These studies consider the operating environ[1]ment, the ship layout, and the anticipated threats. More and more of these studies are including detailed three dimensional computer modeling of ship IR images in realistic operating environments. These models are allowing the analysts to study important effects such as solar heating or reflection, sea surface clutter, flare decoy deployment and other complex processes that could not be considered in any detail until recently. All of these mean that new ships are being designed with lower signatures and improved survivability.

This paper discusses the main contributions to ship IR signatures and what means are available to reduce or eliminate these signatures. Examples are given to illustrate the benefits and costs of IRSS under different operating conditions.

SHIP IR SIGNATURE OVERVIEW:

A ship signature is made up from two main components: Internally generated, and Externally generated. Internally generated signature sources include rejected heat from engines and other equipment, exhaust products from engines, waste air from ventilation systems and heat losses from heated internal spaces.

The primary internal IR source results from the main machinery onboard any vessel, in particular drive engines and electrical generators. The magnitude of signatures produced by other sources such as heated windows, weapon systems, and deck mounted machinery is insignificant in comparison if main machinery is not suppressed.

Externally generated sources result from the surfaces of a ship absorbing and/or reflecting radiation received from its surroundings. The primary sources of background radiation are: the sun, sky radiance, and sea radiance.

Effective IR suppression of a ship must consider both sources. Some argue that there is no point to suppressing the internally generated sources (plumes, uptakes, hot spots) because it is not possible to suppress the external sources. This ignores the fact that there is no solar heating at night or when the sky is overcast. It also ignores the fact that the sun also generates clutter. With some active measures such as water wash, the external sources can be taken care of to some degree.

MAIN SHIP MACHINERY:

Of all internally generated sources of IR, waste heat and combustion products from a vessel's main machinery is the most significant. Figure 1 illustrates the ways in which the heat from a ship's machinery can manifest itself in the form of IR emissions.

Five types of IR sources, or "hot-spots" can be identified in Figure 1. First are the warm sections of hull, indicating the location of engine compartments on the other side. Heat

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Figure 1 Infrared Image of a Typical Unsuppressed Ship

radiating from running machinery heats the air in these compartments, that in turn convects to the uninsulated hull of the ship. Next are the funnel spaces, heated by engine room ventilation air and hot exhaust uptakes running through them. With no insulation installed on funnel walls (as in this case), the funnel exterior is heated much like the sections of ship's hull.

At the top of the two funnels can be seen the extremely hot (300-400°C typically) exhaust uptake metal. The relatively large area (2-5 m^2), high temperature, and location high on the ship make visible uptake metal the largest single contributor to internally generated signatures. Adding to the uptake metal hot-spot are the emissions from hot exhaust gases. A soot-free exhaust plume contains mostly hot CO_2 gas and water vapor, that radiates in a narrow spectral band from 4.1 to 4.6 µm. Much of the radiation in this waveband is quickly absorbed by the atmosphere, but some of this radiation can penetrate through many km of atmosphere. Even at ranges of 10 km or more, the plume can still be a very significant contributor to ship IR signature. Figure 2 presents the spectral emission from a typical GE LM2500 plume at a number of ranges.

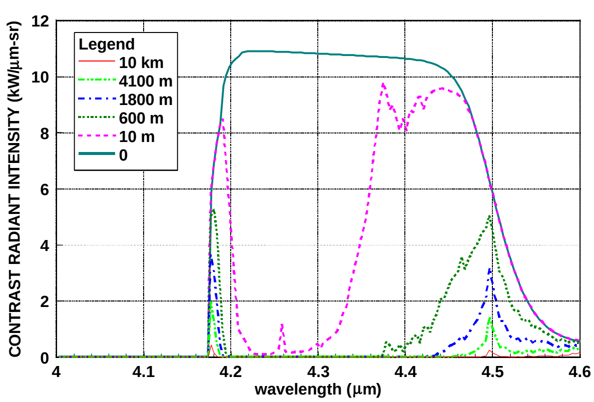


Figure 2 Spectral Emission of 75 kg/s @ 500°C Plume

The final hot-spot shown in Figure 1 that is a result of ship main machinery is the hot communications mast. The mast and other parts of the ship can be heated by hot plume impingement. The mast hot-spot is a concern in instances when a tailwind causes the plume to impinge upon a ship's mast. Unsuppressed plumes can heat masts and mounted electronics to 100-200 °C, resulting in a very large hot-spot high above the water. The high impingement temperatures may also result in failure of the sensitive electronics mounted on the mast.

To eliminate, or at the very least minimize the severity of the warm hull sections and funnel sides requires application of basic thermal design. Compartments should be ventilated to a sufficient extent as to keep compartment temperatures at below 50°C. Any compartments or funnel spaces that are heated to above ambient should have thermal insulation applied to all external bulkheads. Application of even 25 mm (1") of glass wool insulation can reduce outer skin temperatures to an acceptable contrast temperature. As a guideline, hull surfaces heated from within should not exceed a contrast temperature of ±5°C. Other compartments around the ship that may have temperatures different from ambient should also be considered. Negatively contrasted surfaces resulting from cool, air conditioned electronics bays for example are to be avoided as well.

The remaining hot-spots (ie. hot uptake metal, plume, plume impinged mast) are most effectively treated by suppressing their source, the hot exhaust gases from the main machinery. Simple suppression devices provide an optical block, or film cooling of hot uptake metal, ignoring the importance of hot plume emissions. Plume cooling is also required, so as to reduce direct IR emissions from the plume, and reduce mast temperatures under impingement situations. Figure 3 illustrates four popular IRSS devices in use today.

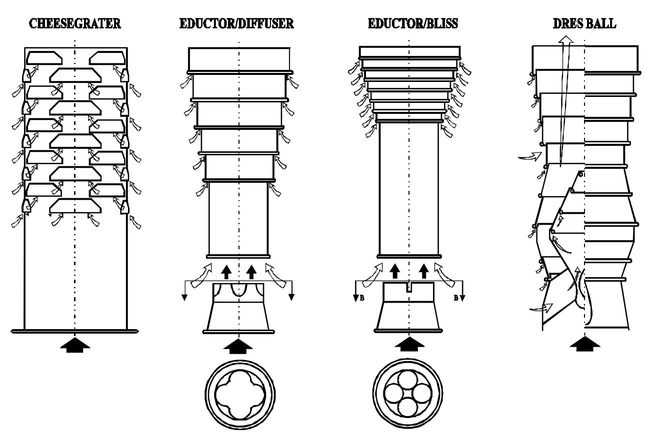


Figure 3 Popular Engine Exhaust IRSS Devices

Each of these four devices use a film of cool ambient air to suppress the visible metal. Resultant metal temperatures are similar for all four devices, approximately 20-30°C above ambient. This is considered to be a sufficient level of suppression to protect against today's threats.

The ability of each device to cool the average plume temperature varies significantly amongst the four. The objective of the UK cheesegrater is to cool metal not the plume. For this reason the UK device adds little mass flow of cooling air to cool the plume. It should be noted that the cheesgrater requires fans for it to operate and if these fans are turned off, hot gases may enter the funnel spaces. The US eductor-BLISS entrains cooling air in its mixing tube and diffuser section, for both plume and metal cooling. In a similar way the DAVIS (Canada) eductor/diffuser and DRES-ball both entrain cooling air for metal and plume cooling. It is believed that the more efficient diffuser section in the eductor/diffuser and DRES-Ball results in superior plume cooling. The DAVIS devices have been shown to achieve average plume temperatures of 200-250°C. The DRES-ball has the added advantage of full optical blockage, providing overhead protection as well as sea-skimming.

It should be noted that all IRSS devices will impose some level of back pressure on an engine, dependant upon the level of plume cooling desired. Devices can be designed to give cooling with no back pressure, but average plume temperatures will be considerably higher. An example of this relationship is given in Figure 4 for an eductor/diffuser device installed on the typical LM2500 engine exhaust.

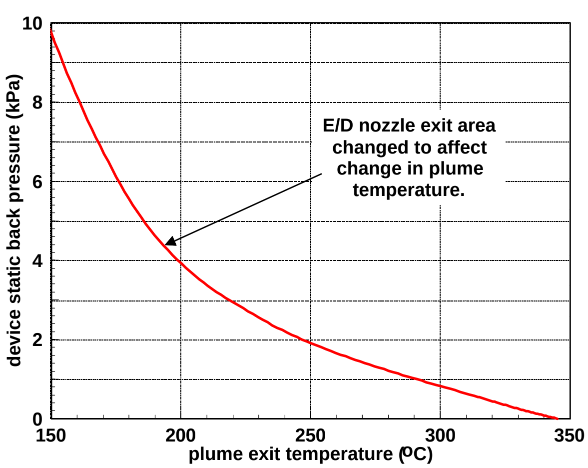


Figure 4 Back Pressure Imposed By Eductor/Diffuser

SOLAR HEATING:

Beyond the small, hot sources (high radiance) of IR such as engine exhausts, the only other major contributor to a ship's signature is from its external surfaces; hull, decks, and super-structure bulkheads. Typically ship surface temperatures are much lower than that of exhaust uptakes and plumes. However, because of the large area even very small contrast temperatures can result in a significant signature. This is especially true under solar heating conditions.

At night-time, if a ship's hull is well insulated, a ship's surface is at an equilibrium somewhere between air and sea temperature. As the sun rises in the sky, the ship's surface temperature quickly heats up to a large contrast with ambient. Sun elevations larger than 10° can result in contrast temperatures in excess of +10°C.

Suppression of an excessive hull temperature is regarded as a difficult, if not impossible task. The large surface areas involved, and wide range of environmental factors influencing ship skin temperatures pose an interesting challenge. Three solutions have been proposed at present:

i) use low solar absorbtivity/thermal emissivity paints to reduce surface heating and IR emission;
ii) wash solar heated surfaces with sea water; and
iii) blanket entire ship in a cloud of heavy water mist.

Special Paints:

The selection of special paints is a very complex issue and there is no single correct answer. There will always be a tradeoff between the best solution for sunny conditions versus the best solution for night time or cloudy day conditions.

For example, under sunny conditions, a hull paint should:

i) not absorb solar radiation below 3 μm wavelength (i.e. low emissivity to short wavelength); and
ii) absorb all radiation above 3 μm (i.e. high emissivity to mid and long wave).

With this type of surface the hull would heat up less due to the sun, but it would not reflect the sun in the important 3-5 and 8-14 μm wavebands. However, low reflection means high emission, and if the hull is heated above the ambient it will emit strongly in the 3-14 μm range. This type of spectral paint is available but is expensive and its effectiveness can be dramatically reduced by surface contaminants such as oxidation, dirt, etc.

Under overcast conditions it would be desirable to have low emission paints (or "low ϵ"). In this case the ship would emit less and reflect its surroundings more. It should be noted that the low ϵ will gradually trend towards higher ϵ

due to factors such as salt build-up, engine exhaust, soot and dirt.

Little unclassified data on the in service experience of ships that use special low ϵ paints has been available. At the time of this paper, no report could be found that compares the overall susceptibility of ships with typical paints vs ships with special paints. Without extensive field trials and signature measurements it is not possible to recommend an alternate surface finish with confidence. Therefore, standard navy grey paint is assumed to be a reasonable trade-off between low emission/absorption and low reflection.

In addition to diffuse reflection, paints also tend to reflect specularly over a narrow range of incidence angles. This behaviour is quantified as the bidirectional reflectance distribution (BRDF). Figure 5 presents two IR images of a ship turning with the sun across its beam. Within a narrow angle (~2-4°), the ship appears highly reflective. Some IR seekers can ignore the suns radiation because of its spectral distribution and large intensity. However, if ships start reflecting the sun as a normal operating condition this will be taken advantage of by seeker designers.

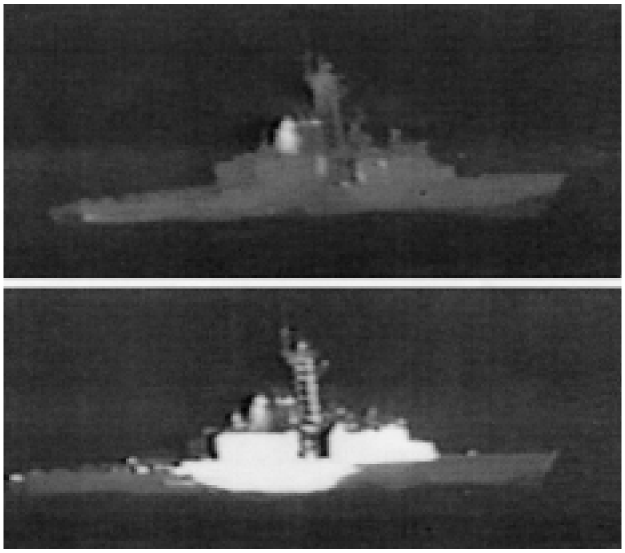


Figure 5 Solar Glint From Typical Navy Grey Paint

Water Wash:

The second suppression technique consists of actively cooling the hot parts of the ship's surface with sea water. During the Gulf War, ships used existing NBC (Nuclear Biological Chemical) water wash systems or hastily retrofitted wash systems to cool their surfaces. With some careful planning during the installation of NBC systems, new ship programs could have active hull cooling systems capable of effectively cooling the ship's surface to ambient temperatures without significant additional cost.

To be the most effective, a water wash system must be capable of cooling the entire surface of the ship to ±5°C contrast from +30-60°C. The wetting system should be designed to distribute water uniformly over the subject area so that no hot spots remain. The variation in the surface temperature after cooling should be less than 5°C.

Figure 6 shows the effect of water wash on a painted (Canadian navy grey) plate oriented towards a sunny sky. In this case a typical navy deck sprinkler was used to wash a horizontal panel (5° incline), with a water flow rate of 0.22 m^3/m^2-hr (8 gal/ft^2-hr).

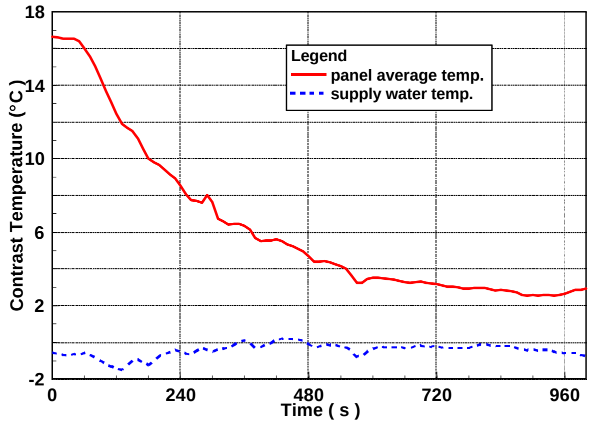


Figure 6 Cooling Time of a Water Washed Panel

As can be seen from the figure, the water wash reduces the plate temperature to below +5°C contrast in approximately 7 minutes.

The water wash system should be divided into separate zones so that water wash can be applied on only those zones that need cooling. As a minimum the water wash systems should be separately controlled for the port and starboard sides of the ship.

Care must be taken not to over-cool the surfaces of the ship. A large negative contrast imposes an effective a target to modern seekers as a positive one. By using a feedback system, water could be turned on and off as needed, maintaining the surface of the ship at a relatively constant low contrast temperature.

The use of sea water wash to cool ship surfaces has a number of other concerns associated with it. One is that a wet surface will reflect solar radiation in a specular manner and therefore solar glint effects will be increased with water wash. However, this glint effect is usually limited to a narrow range of view angles and therefore is considered acceptable when considering the large potential benefits from hull cooling.

Water wash systems can introduce other problems including corrosion and salt buildup. By suppressing the hull in high threat situations, the water wash system would only need to be used occasionally and therefore these problems are not considered to be impossible to overcome.

Mist Systems:

An extension of the water wash concept leads to a possible third solution to an excessive hull signature. It has been proposed that a thick cloud of water mist be sprayed about the ship, in effect hiding the ship from the view of IR seekers. No data has been found on the effectiveness of this type of system as an IR countermeasure. However, this system if properly managed could enhance the performance of other countermeasures such as decoys.

Some shortcomings of a water mist system are the obscuring of onboard optical sensors, and the build up of salt in spray nozzles and all over the surface of the ship. Also, to engage such a system would require the ship to come to a complete stop, or else the water cloud would be blown away.

The use of any of these three hull IRSS methods does not eliminate the requirement for proper insulation and ventilation design, and the use of main machinery suppression.

BACKGROUND EFFECTS:

The IR signature of a ship cannot be considered without accounting for the background in which it resides. For a seeker to locate and track a ship, the ship must appear different than its background.

The appearance of the background depends on a number of factors including:

i) Solar disk radiation;
ii) Solar scatter by the atmosphere (dust, aerosols);
iii) Solar reflection/scatter from clouds;
iv) Solar reflection from sea surface;
v) Solar interference (shadows) from clouds; and
vi) Sky and path radiation.

All of the factors listed above add to the complexity of a ship-in-background IR scene. In other words they are background clutter to the missile. These effects all combine to create a random, time varying background appearance in the IR. They also affect the appearance of the ship through the ship's absorption/reflection of IR radiation from the cluttered environment around it. Figure 7 shows an IR image of a typical cluttered marine background.

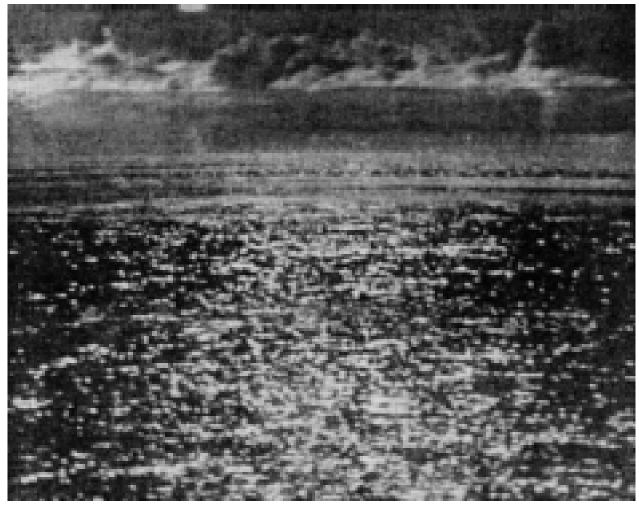


Figure 7 IR Image of a Typical Cluttered Scene

The effect of clutter on the IR guided threat is to make it more difficult for the seeker to lock onto the ship. Usually seeker lock is achieved when the target presents a signal to noise ratio (SNR) of a specified magnitude, say SNR = 5. If there is no noise in the background then the noise in the SNR is the seeker internal noise. Modern IR seekers can have very low internal noise levels. This means a seeker can lock on a very small target signal with uncluttered background conditions.

In a cluttered scene the seeker is no longer limited by its own internal noise, but rather it will be limited by the background noise level. Therefore if the noise in the background (i.e. the clutter) is large then the seeker needs a larger target signature for lock. For this reason IR suppression effectiveness depends very much on the threat and the background conditions.

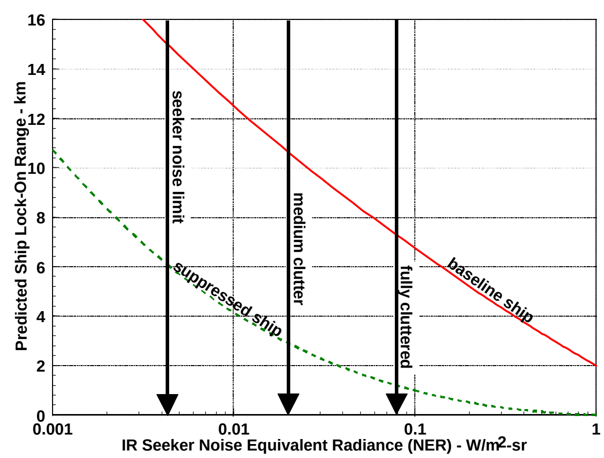


Figure 8 Predicted Effect of Clutter on Lock-On Range

Figure 8 shows how clutter can affect predicted lock ranges for simple seeker. The benefits of IRSS are amplified by background clutter. By eliminating the more intense sources of IR radiation onboard a ship, it appears more like the background. When the variations in radiance over the ship are comparable to those in the background, the ship becomes difficult to distinguish from the background.

SAMPLE SUSCEPTIBILITY STUDY:

To understand the effectiveness of the suppression techniques discussed above, some form of susceptibility study must be performed. The following section presents a sample of a susceptibility study where a generic frigate is considered under two basic operating conditions. First the ship is considered under night time clear sky conditions. Second, the ship is considered during sunny day, clear sky conditions. As will be seen the IR signature conditions vary dramatically for these two cases.

The 3D IR signature modeling software NTCS (see Vaitekunas (1996)) was used to perform the study. The ship's geometry was entered into the program using a standard CAD program. Figure 9 shows a solid rendered view of the ship model that was used.

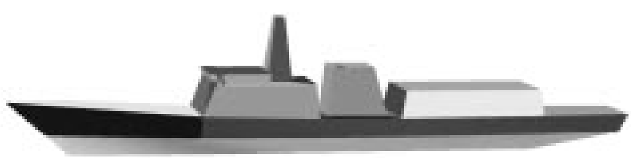


Figure 9 Solid Rendered View of Generic Frigate Model

Known temperatures of hot-spots, and the radiating properties of the ship's surfaces were entered into the model. When combined with LOWTRAN models of standard marine environments, the appearance of the generic frigate under a broad range of conditions could be produced.

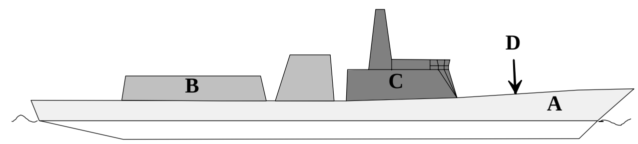
The use of computer modeling permits sensitivity studies to be performed that would be prohibitively expensive to do via experiment, or that are impossible due to logistical reasons. Some topics of investigation that can be examined include:

i) effect of sun position on ship surface temperatures;
ii) estimate ship signature from any observer location;
iii) identify contributions of hot-spots to susceptibility; and
iv) objectively compare effectiveness of different suppression options under identical operating conditions.

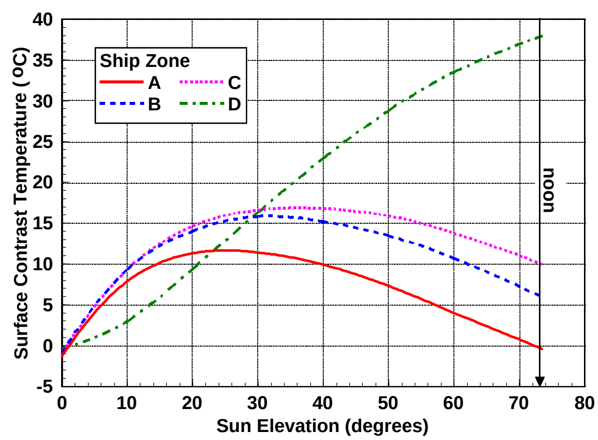
Examples of each of these four topics are presented here for the generic frigate model.

Effect of Solar Position:

The first topic is the study of the sun's influence on a ship's surface temperatures. The computer model allows for the ship to be coated with paint having any IR properties desired. The ship can also be set to travel in any direction, at any speed, in any environment. As an example, the generic frigate was placed in a mid-latitude summer environment, cruising at 20 knots. Figure 10a shows a map of isothermal zones identified around the ship. Zone D denotes the decks of the ship. Figure 10b plots the predicted contrast temperature of each of the zones over the course of a day. The sun was assumed to be located directly off the ship's beam at all times.



a. definition of isothermal zones



b. average surface temperature vs. sun elevation

Figure 10 Predicted Effect of Sun Elevation

From Figure 10 it can clearly be seen that the contrast temperature of a ship's surfaces can easily be above +10°C for most of the day. This point supports the need for effective hull suppression techniques.

Another useful topic of study is the calculation of a ship's IR signature from any observer location. This information can be used to determine the relative strength and visibility of various hot-spots. Figure 11 shows a polar plot of contrast radiant intensity for the generic frigate model. The ship is travelling in the same environment as used for Figure 10, at 30 knots on two LM2500 engines, with no engine suppression. The sun is positioned directly of the starboard beam, at an elevation of 30°. The plot is made for an observer 500 m away, looking down on the ship at a 15° angle.

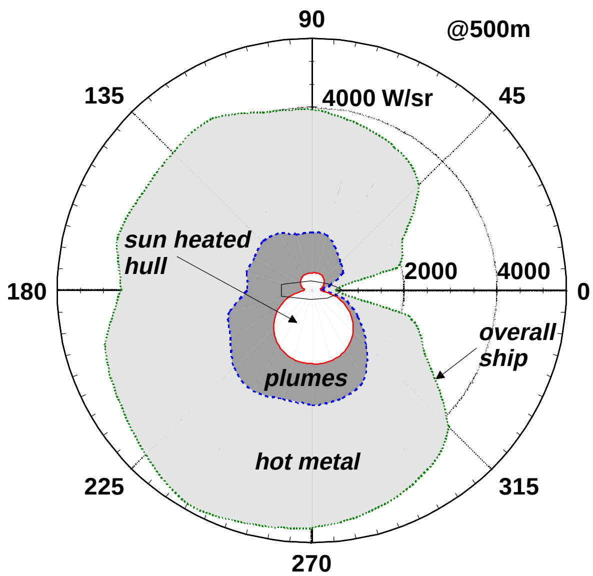


Figure 11 3-5μm Polar Plot of Signature Components

The figure suggests that the ship's signature is dominated by visible uptake metal. The figure also suggests that the contribution made by the plumes is of the same order of magnitude as the sun heated hull, at this range. The shape of the curve in Figure 9 is indicative of typical ships. The hull radiance distribution is dependant on visible area, resulting in a "figure 8" shape. Meanwhile, the uptake metal and plumes have a roughly circular distribution, with a dip in radiance appearing for views from ahead of the ship. This dip is a result of the mast and superstructure obscurring the engine exhausts.

Polar signature data can be easily generated in the same manner as Figure 11 for any desired operating condition or environment. This information can be used to assess the IR signature of future ship designs, with the aim of minimizing them for particular conditions.

Effects of Hot Spots vs Hull Contrast:

A very useful way to compare the importance of hot spots vs hull is to use estimated seeker lock ranges. For the examples presented here, a simple model of a noise limited imaging seeker was used with the following characteristics; FOV 9°x 7°, IFOV 1.0 mrad, NER 0.0043 W/m^2-sr, SNR 5. The seeker algorithms used by NTCS to calculate lock-on ranges are beyond the scope of this paper, but are discussed in detail by Vaitekunas (1996).

Figure 12 shows the predicted lock ranges vs hull contrast temperature for the model seeker for a generic frigate from the side on view angle. The figure also shows the predicted lock ranges for important hot spots such as the unsuppressed plume, warm funnel side etc. The plot also shows lock ranges for supressed plumes. As can be seen, the benefits of IRSS are clear for low hull contrast temperatures. However, as the hull contrast increases the benefits of IRSS are lost due to the high hull signature. This is not saying that IRSS is not worthwhile – it is saying that the hull signature must also be managed to balance it with the other suppression systems.

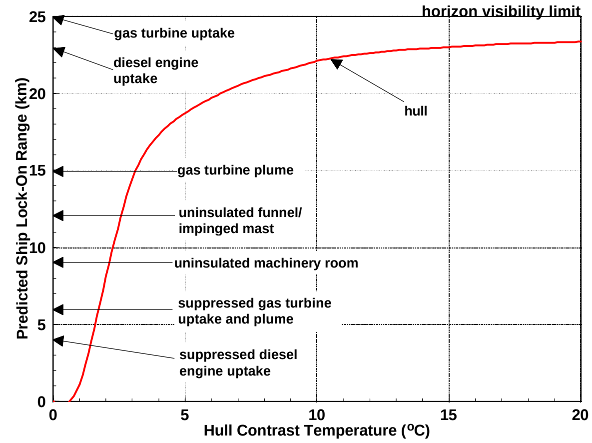


Figure 12 Predicted Lock Range vs Hull Contrast Temp.

Ship signature management means that the operators are aware of their current signature status, so that they can act accordingly. In threat situations it may also be desirable to have automatic systems that manage the ship signature (i.e automatic control of water wash, cooling fans, etc.) . This requires onboard signature measurement and analysis capabilities. With sophistiaced computer models such as NTCS, such onboard signature managers are feasible today.

Comparison of Different IRSS Systems:

To be able to make the correct design and procurement decisions regarding these systems, it is important to understand the trade-offs involved in each. The performance of different engine suppression devices or hull suppression systems can be predicted under the same, uniform conditions using computer modelling software such as NTCS. Such a comparison using trial data would be difficult and expensive, especially when several different manufacturers need be involved.

An example of the type of comparison that can be done is given here. In this case the comparison considers the performance of the four engine IRSS devices illustrated in Figure 3. Figure 13 presents a screen capture from NTCS showing the generic frigate model with an eductor/diffuser suppression system (ship on right) and an eductor-BLISS system (ship on left).

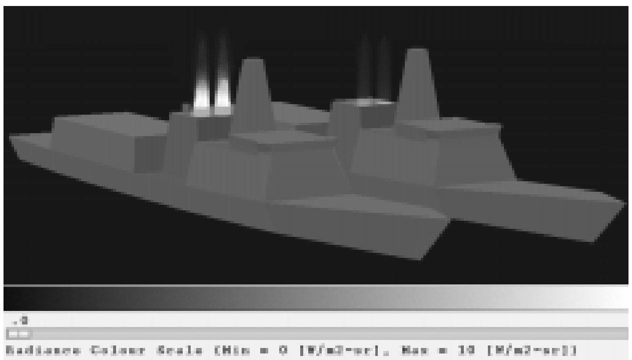


Figure 13 NTCS Visual Comparison of IRSS Methods

The devices are compared in the figure for the frigate in mid-latitude summer, travelling at full power (30 knots) on two LM2500 engines. The difference in performance between the two systems is readily apparent.

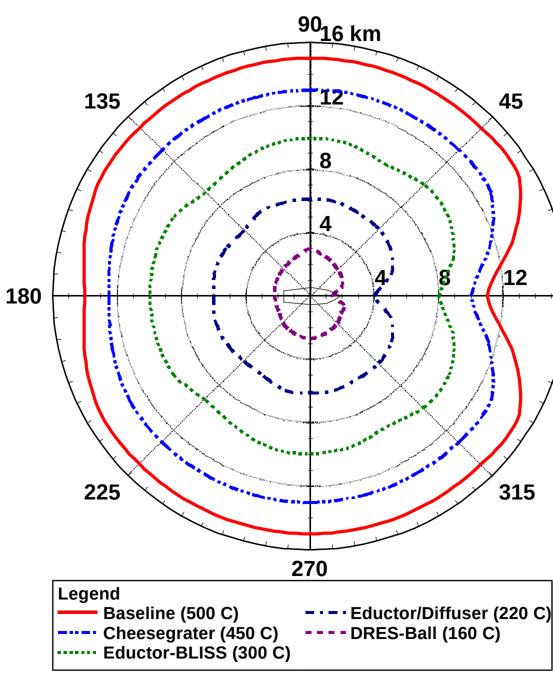


Figure 14 Lock-On Range Comparison of IRSS Devices

Figure 14 compares the predicted lock-on range of the generic frigate model using the four different suppressor types: the cheesegrater, the eductor-BLISS, the eductor/diffuser, and the DRES-ball. Each of the four devices are compared to the baseline frigate travelling at night under fullpower on its two LM2500 engines. The ship is assumed to be sailing level, so no uptake metal is visible. Note that the assumed plume temperature for each device is noted in the figure's legend.

The lock-on ranges presented in Figure 14 allow the four suppression methods to be directly compared. Clearly the eductor/diffuser and DRES-ball devices provide the highest level of suppression.

Other IR suppression methods can be investigated in a similar manner using modeling software. An example is the effectiveness of water wash systems. Computer predictions of ship susceptibility can be used to help design an efficient water wash system, or to study the performance of existing NBC systems when used for hull suppression.

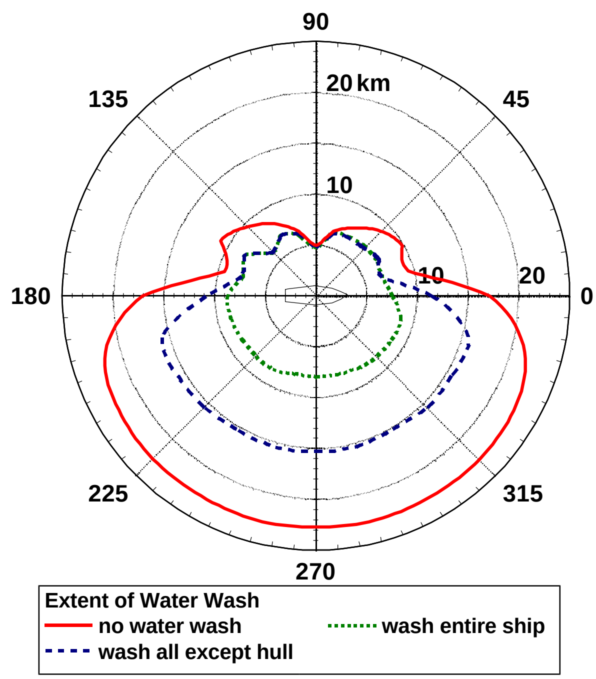


Figure 15 Effect of Different Levels of Water Wash

Figure 15 illustrates this idea by comparing the predicted lock-on ranges of the generic frigate with varying levels of water wash. The frigate is cruising on suppressed diesel engines at 20 knots, with the sun at 30° elevation, directly off the starboard beam. Hull contrast temperatures in the unwashed case correspond to those presented in Figure 8. Washed surfaces were assumed to be at ±2°C contrast with the ambient air temperature, in this case 15°C.

Figure 15 shows the dramatic reduction that may be realized by suppressing the hull with water wash. The figure also suggests that to achieve the largest reduction in ship susceptability, the hull must be suppressed in addition to the superstructure.

CONCLUSIONS:

In today's environment of increasingly sophisticated IR threats, the importance of knowing a ship's signature over a range of operating conditions is very important. Through IR signature suppression, a ship's susceptibility can be dramatically reduced. Identifying potential hot-spots, and selecting the most cost effective suppression solution can be difficult.

The areas of primary concern with regards to ship signature have been addressed in this paper, as well as some possible methods of suppression. Through computer simulation, the effectiveness of these suppression techniques have been examined.

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