SMI Defence Conferences 1999
Third Annual Stealth, Low Observables and Counter Low Observables

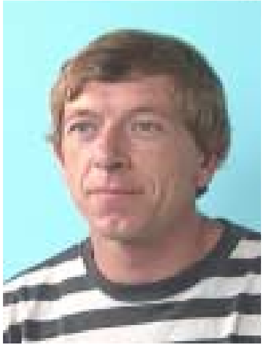
Leon F. Galle, Eric J.M. Heemskerk & Lucas J. van Ewijk

Naval Radar Signature Management
in support of
Above Water Ship Survivability

“THE DUTCH PERSPECTIVE”

Leon F. Galle *is working at 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 main 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.*

Hendricus (Eric) J.M. Heemskerk *is working on radarsignatures and propagation in the Radar Technology Group of TNO Physics and Electronics Laboratory (**TNO-FEL**). He obtained his MSc in Electronics at the Delft Technical University. He was active in the field of wideband antennas during 7 years at TNO-FEL and became program manager of radarsignatures and propagation in 1988. He was national representative in various NATO research study groups and chairman of NATO AC/323 SET-TG05 on ‘Maritime Target/Background Radar Signatures and Propagation at cm- and mm-Wavelengths’ and of the exploratory group NATO AC/323 SET-ET05.*



Lucas J. van Ewijk *received the M.Sc. degree in Technical Physics from Delft Technical University in 1986. Since 1988 he is employed by the Physics and Electronics Laboratory of the Netherlands Organisation of Applied Scientific Research (**TNO-FEL**). He has been working in the field of Radar Cross Section computations for an important part of the time and expanded his field of expertise with other kinds of electromagnetic computations. He has been involved in the development of High Frequency RCS computational codes, electromagnetic shadowing and EMI problems. His current interests include NCTR, multiple diffraction, EM screening and millimetre wave imaging. He has been a member of a NATO research study group on Millimetre Wave Imaging and is currently member of a group on Non Cooperative Target Recognition by radar.*

SYNOPSIS

Radar Cross Section (RCS) management is of paramount importance for a warship’s survivability. In this paper, the operational benefits of low RCS will be explained. Basic RCS theory, measurement and simulation techniques will be addressed. The RCS of representative geometrical objects will be generated. This to give insight to RCS management. A general overview will be given of the RCS design process of the new RNLN Air Defence Command Frigate "LCF" and the reduction features installed. The article will close with views on future trends.

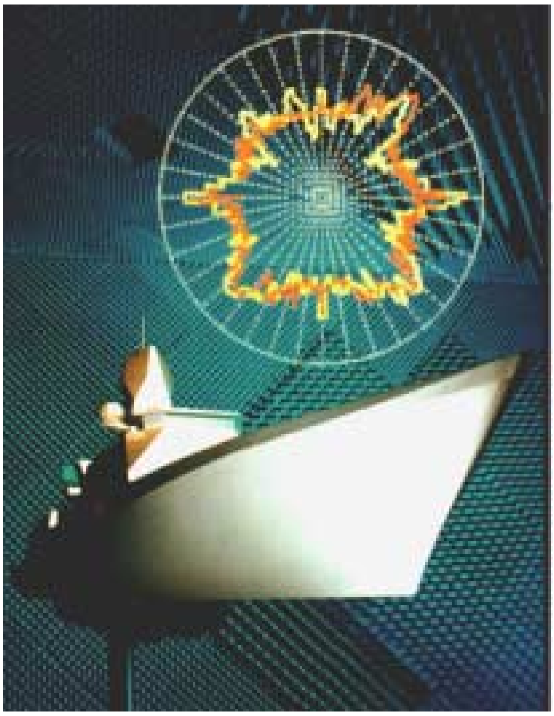


Figure 1. Subscale model of the Royal Netherlands Navy Air Defence and Command frigate.

> ***"Nicht aufzufallen, ist das erste Gesetz des guten Tones"***
> ***J. Langbehn "Rembrandt als Erzieher" (1889)***

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. This is true in the field of Infrared (IR) 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*", 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 Hsuing Feng 2. Future systems will be able to use RF and IR simultaneously to exploit synergism (Hybrid). Preceding publications, i.e. "Ship Survivability (Part I)" [Galle, 1] and [Roodhuyzen, Galle & van Koningsbrugge, 2], promoted to integrally take up the challenge of Survivability for ASMs. The two Survivability factors, *Susceptibility* and *Vulnerability*, have been introduced, see Figure 3.

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, seaborne, landbased and even spacebased remote sensing (satellites).

---

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

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

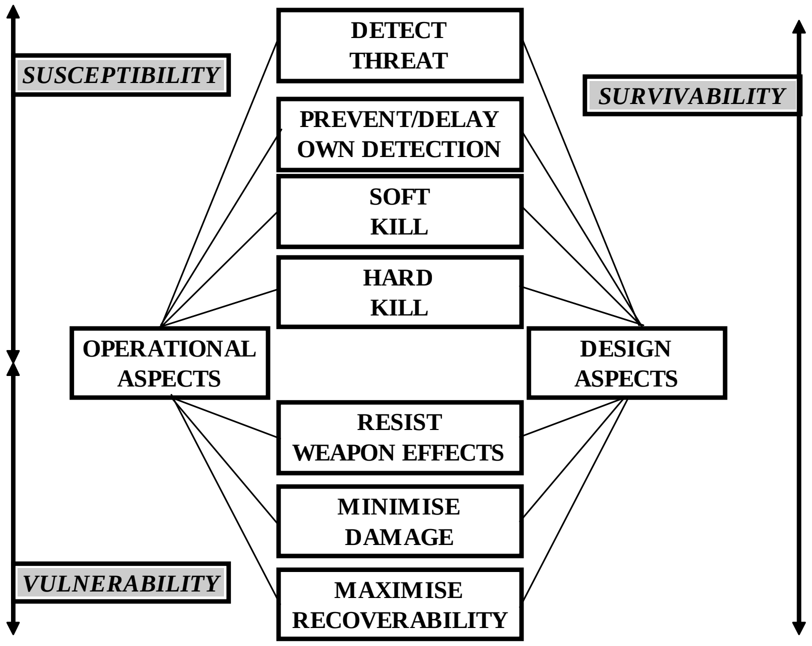


Figure 3 Generic Ship Survivability Scheme

The publication [Galle & Schleijpen, 3] addressed *IR Signature Management*; i.e. Ship Infra Red Signatures (Ship Survivability Part II) in the Royal Netherlands Navy .
This paper will elaborate on *Radar Cross Section* phenomena, its measurements techniques and simulation. An overview will be generated of the RCS of some representative geometrical objects. The RCS design process of the LCF will be addressed. Reduction features which have been installed in the new RNLN Air Defence Command Frigate "LCF" will be discussed.

RADAR SIGNATURES

In essence, the radar signature of a warship consists of two components:

- 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 force "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); by switching off his missile seekerhead transmitter and only using his receiver for homing in to the active jammer transmissions.
This active signature will not be dealt with in this paper. This paper will only deal with the passive radar signature.

• The **passive component, or Radar Cross Section (RCS)**, is the component 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) consists of metal, glass and/or plastics. All these parts of the exterior contribute to the reflecting properties

Table 1 Decrease of Detection Range by RCS Reduction

Unreduced RCS Value $\sigma = 10{,}000\ m^2$

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

OPERATIONAL BENEFITS OF LOW RADAR CROSS SECTION

It is important, to be aware of the phenomena which play a role in the detection of ships by radar systems. Radar detection is active; Electro Magnetic (EM) energy is transmitted to the target and reflection can be received. Detection by a (pulsed) radar system, will give bearing and range information. This in contrast to Infra Red detection, which is passive, and which gives bearing info only.

Retardation of RF-Detection, Classification & Targeting
It will be hard for a conventionally designed frigate-sized ship, to escape detection for 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 means of reduction of the ship's radar cross section.

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

$$R_{dct} = ((P_t GA\sigma)/(4\pi)^2 S_{min})^{1/4}$$

$$= \text{constant} * \sigma^{1/4} \qquad \text{eq. (2)}$$

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, 4] depicts some numerical examples of changes in detection range by RCS reduction. The reduction in detection range seems not spectacular, but will still be an important operational benefit, which will be explained in the paragraph "Future Trends".

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 ship's Electronic Warfare (EW) system and thus increases the reaction time.

Improved Soft Kill Effectiveness
In essence the active part of the warship's Electronic Warfare (EW) suite; i.e. the Electronic Counter Measures (ECM), will contain two options against RF-guided missiles: an (active) jammer-system either on board or off-board (AOD) and passive RF decoys. Passive RF decoys either float on the water or create a cloud of metalised glass fibres (chaff).

Chaff 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 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 3 gives the principles of chaff in the seduction role. Figure 4 yields generic results of chaff seduction efficiency as function of the ratio RCS of ship over chaff. It shows that a low RCS of the ship is of paramount importance for successful deployment of seduction chaff.

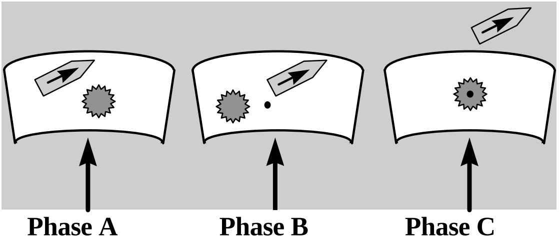
Table 2 Equivalent Increase in Jammer Gain by RCS reduction

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

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, while 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 targets can be "camouflaged" between the smaller, less valuable, platforms.

Deployment of decoys in the dilution or distraction mode is preferred over the usage in seduction mode. The positioning (and separation of decoy and ship) is less time critical because there is not yet a lock-on on the ship. A second reason is that if decoy and ship are both in the ASM's resolution cell, the missile's computing power, if present, is offered to distinguish between ship and decoy. Considerable RCS reduction (Low Observable and Stealthy Design) will help to postpone the lock-on, if the ASM breaks the horizon, and therefore extend the time frame for the decoy to be deployed in the distraction 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 3 Lock Transfer Principle for Chaff-S

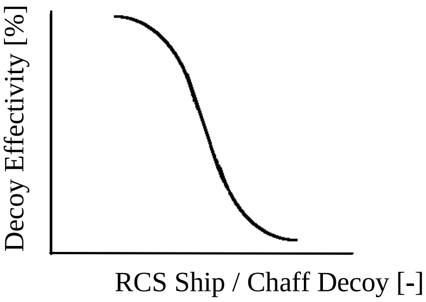


Figure 4 Generic Results of Chaff-S

Improved Jammer Effectiveness

On Board Jammer System

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

$$R_{BT} = ((P_t G\,\sigma B_j)/(\,4\pi\, P_j\, G_j B_m))^{1/2}$$
$$= \text{constant} * \sigma^{1/2} \qquad \text{eq. (3)}$$

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 then 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 with needs 20 dB or more [Adamy, 5]. This J/S ratio can be expressed in:

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

It shows that the ratio J/S is inversely proportional with the radar cross section, so lowering σ will improve J/S, see also Table 2.

Decrease of required RF power for Active Off-board Decoy

In case the ship's jammer 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[3] 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 is required which can be made technically airborne. 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, also taken from [Baganz & Hanses, 4] 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.

OPERATIONAL ANALYSIS

Based on the preceding considerations and by ship/threat scenario simulation and analysis, e.g. with the FEL SEAROADS-code, it is possible for Naval Staff to establish Radar Cross Section *"Staff Requirements"*. However it should be stressed, that in (in)ternational simulations so far, the benefits of signature reduction have always been underestimated [Krieger, 6].

If RCS staff requirements are laid down for a ship class, it is the task for the naval engineer to meet this requirements in a cost effective manner.

BASIC RCS THEORY

Definition of RCS

The radar cross section of a target is a measure of the amount of electromagnetic power it reflects towards a receiver.

The principals of Radar Cross Section, are best understood, if the radar range equation is considered. The radar transmitted power is P_t. This power is radiated by the transmit antenna with a Gain G_t. The antenna radiates this power in beam form of electromagnetic (EM) radiation to a target which is at range R. The target reflections are captured by the receiving antenna, with Gain G_r and fed to the receiver (Rx).

In this basic generic configuration, the (Monostatic) Radar Cross Section (σ) of a target determines the fraction of incident power which is "back scattered" to the radar, or in mathematical form:

Physical Definition

The Incident Power at the target per unit area, or Power Density, is:

$$[P_t G_t / 4\pi R^2] \qquad \text{eq. [5]}$$

The Power Density at the receiving antenna is:

$$[P_t G_t / 4\pi R^2][\sigma/4\pi R^2] \qquad \text{eq. [6]}$$

Introducing an effective Aperture of the receiving antenna A_e, the received power at Rx is:

$$P_r = [P_t G_t / 4\pi R^2][\sigma/4\pi R^2] A_e \qquad \text{eq. [7]}$$

Introducing wavelength λ and Gain of the receiving antenna:

$$G_r = 4\pi\ A_e/\lambda^2 \qquad \text{eq. [8]}$$

Substituting [7] in [8] and rearranging yields:

$$P_r = [P_t G_t/4\pi R^2][\sigma/4\pi R^2][G_r \lambda^2/4\pi] \text{eq.[9]}$$

Simplifying [9] with $G_t = G_r = G$ yields:

$$P_r = [P_t G^2 \lambda^2\ \sigma]/[(4\pi)^3 R^4]\ [W] \text{eq.[10]}$$

This "Radar Range Equation", in its simplest form, indicates that the received power (P_r) by the transmitting radar is proportional to the Radar Cross Section (σ).

Theoretical Definition

Next to this physical definition, the theoretical definition of RCS is (fully illuminated):

$$\sigma = \lim_{(R\to\infty)} 4\pi R^2\ [E_r^2/E_i^2]\ [m^2] \qquad \text{eq. [11]}$$

---

[3] Countermeasure against Active Radar Missile ENgagement

E_r = electric field magnitude at the receiver
E_i = electric field magnitude incident at the target

The dimension of RCS, in the linear space, is m^2 but because of its highly dynamic behaviour, RCS is also often expressed in "log-space" relative to one square meter (dBm^2) by:

$$\sigma(dBm^2) = 10*\{\log[\sigma(m^2)]\} \quad \text{eq. [12]}$$

Some numerical examples are depicted in Table 3.

Table 3 RCS in Linear & Log Space

Linear Space [m^2]	Log Space [dBm^2]
100,000	50
10,000	40
1,000	30
100	20
10	10
1	0

The RCS is dependent on target characteristics (shape, material), the radar characteristics (frequency, polarisation, full illumination) and the geometry (relative position/orientation of the target to the radar).

During field trials the measured or apparent radar cross section is obtained. In most cases this is not the theoretical free space RCS, since it includes environmental effects like propagation through the atmosphere, ducting and multi-path effects and also effects by not fully illuminating the target i.e. pulse width and beamwidth. In order to avoid misunderstandings the measured or apparent RCS is called here(radar signature. Several aspects will be briefly elaborated :

- **Radar Type**

The RCS differs for a monostatic and bistatic case. In the monostatic case transmitter and receiver are co-located, in the bistatic case the transmitter and receiver antenna are separated by a considerable distance. For most regular threat (Fighter jets, ASMs) conditions the monostatic case is considered.

- **Radar Modulation Type**

Radar modulation; either pulse, continuous wave (CW) or frequency modulated (FM) will influence RCS. A steady state RCS will be generated by a CW system, in comparison with a transient response for a short pulse radar system. Variation of frequency (FM) will result in changing RCS during the frequency sweep.

- **Radar Frequency**

The RCS is dependent on radar frequency. In general, for simple objects, the RCS will increase with frequency. However for ship targets, the frequency dependency of RCS is very complex and does not necessarily show the same frequency behaviour as simple objects

- **Radar Polarisation**

The RCS is dependent on the polarisation of the radar signal, transmit as well as receive. The dependency on polarisation can be fully laid down in a (2x2) "scattering matrix"; including two co-polarisations (for instance HH and VV) and two cross-polarisations (HV and VH

In case the full matrix (amplitude and phase) is available RCS values for all other polarisations e.g. right- and left-circular forms can be generated.

- **Target Aspects**

The highly dynamic behaviour of the Ships' signature during field trials can mostly be attributed to the change in presented aspect angle to the radar system. Small changes in the target aspect to the radar by the ship’s roll, pitch and yaw will cause differences in the range from each contributing scatterer on the ship to the radar resulting in constructive and destructive interferences and in a wander of the apparent centre of reflections over the ship. This phenomenon is known as glint. In most cases a ship behaves as a collection of many scatter centres. In that case the received signal exhibits strong fluctuations both in amplitude and in phase. This glint can result in possible aim-point problems for the missile radar. One might be interested to intentionally generate an artificial glint-like signal by passive adaptations to the ships geometry in order to mislead the missiles tracking system. Knowledge on the missiles tracking system is a prerequisite in that case.

- **Target Illumination**

It will be clear that the radar signature will be affected by the way the target is illuminated by the radar system. Partial illumination can be caused by a too narrow radar beamwidth at short ranges, too short pulse and masking of the ship by the curved earth horizon at long ranges in a surface to surface e.g. a sea skimming ASM scenario. Narrow beamwidth and/or short pulses may be intentionally applied to obtain high resolution information from the target or to increase the target to clutter ratio i.e. improve the possibility of detection.

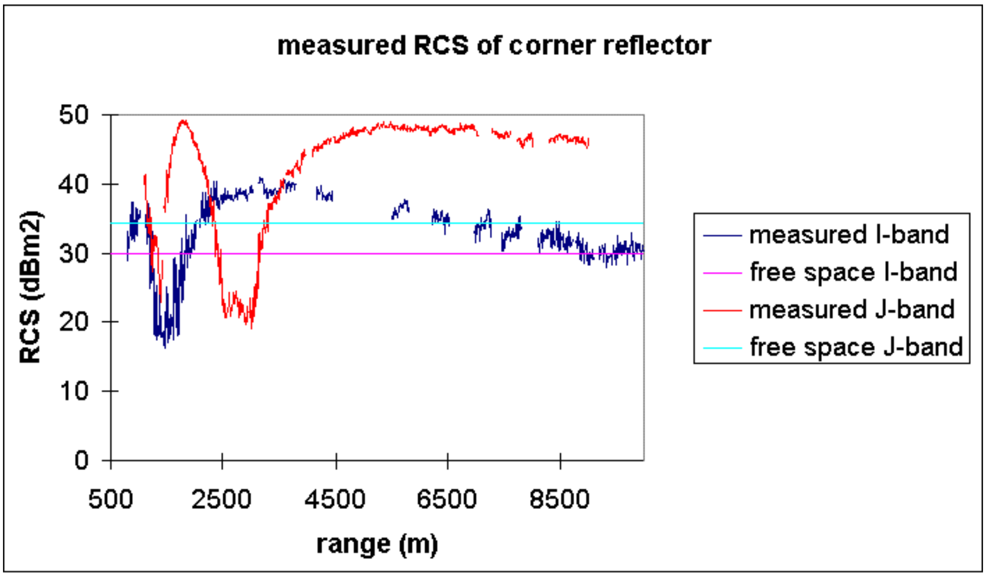


Figure 5 Measured Radar Cross Section of a corner reflector as function of range. Corner height 3 m above the sea surface, radar height 7 m. horizontal polarisation.

- **Environmental effects**

Ducting

The measured radar signature of a ship may differ significantly from its theoretical free space RCS. This is due to effects opposed by the environment (atmosphere and sea surface). The propagation through the atmosphere is determined by the vertical refractivity profile, which causes electromagnetic waves radiated by the radar to propagate along paths that are more strongly curved towards the earth (superrefraction and trapping) or in some cases less curved (subrefraction) as compared to standard atmosphere. This affects the level of the received signals reflected by the target and so the targets radar signature. This profile causes so called **ducting**. Above sea the most important one is evaporation ducting (a duct starting extending from the sea surface up to a height of about 20-25 m) which depends on the air-to sea temperature difference, relative humidity, air pressure, wind speed and direction. Other type of ducts are surface based ducts characterised by a trapping layer that occur up to several hundred metres in height, which may effect over the horizon detection, and elevated ducts which affect air-to-air propagation. Ducting can cause extended detection range at long ranges, but also reduced detection at shorter ranges. For ranges and frequencies at which usually radar signature measurements are made only evaporation duct is important.

Multipath

Multipath due to the presence of the sea surface will also affect the received signal levels. In essence next to the direct-direct path three other paths can be present:

- *direct-indirect (ship→ sea surface);*
- *indirect-direct, (sea surface → ship) and*
- *indirect-indirect (sea surface → ship→ sea surface).*

Theoretically multipath alone can cause a signal enhancement of 12 dB or generate deep nulls. An example of the effect of ducting and multipath is given in Figure 5. This figure shows the measured radar signature of a corner reflector (theoretical RCS is 30 dBm^2 at I-band and 34.5 dBm^2 at J-band) at an height of 3 m above the sea surface as a function of the range to the radar for 7.7m duct height. The radar is positioned at a height of about 7 m above the sea surface. The figure shows also the frequency dependency of the effects of these phenomena.

Actual enhancement will depend on the radar-target geometry, the properties of the target ship, the sea state and ducting conditions. With increasing sea state the sea surface becomes rougher and the multipath effects will be reduced. Also the radar signature of a ship will be affected by multipath. However it will be depended if the ship behaves as a collection of non-dominant scattering sources or contains a dominant scatterer. Co-operative research is going on to model these environmental effects and to apply these models to the measured RCS of the ship to obtain the free space RCS.

RCS OF TYPICAL GEOMETRICAL OBJECTS

The RCS of targets is strongly dependent on the shape, as has been mentioned earlier. Also, there is no direct relationship between the physical area of the object and the RCS. To demonstrate these phenomena we performed some RCS calculations with the computer program RAPPORT, which will be elaborated later, of various geometrical shapes.
The area of all the objects used, projected on a plane perpendicular to the line of sight at 0° azimuth and 0° elevation angle equals 1 m^2, so when viewed with the human eye, the objects seem equally large. In the following two graphs, Figure 6 & 7, the RCS is given as function of azimuth angle and elevation angle. The angular dependence clearly shows for several of the test objects. The horizontal axis shows aspect angle, either azimuth or elevation, the vertical axis shows the RCS in dBm^2.

- **Flat Plate**

The flat plate has a large RCS when viewed perpendicularly. The RCS falls of with the aspect angle quite fast. The angular dependence is the same for azimuth angle as for elevation angle, which is not surprising because the object is similar for both movements.

- **Cylinder**

When the RCS of the cylinder is viewed as function of azimuth angle only small undulations can be noted. These are caused by the representation of the cylinder as small flat facets, necessary for the RAPPORT-calculations. As function of elevation angle the behaviour is similar to that of a flat plate.

- **Sphere**

The RCS of the sphere is constant for both aspect angle variations, which could be expected because the object is the same whatever angle it is viewed from. The small undulations are, like in the case of the cylinder, caused by the representation of the object as small flat facets.

- **Dihedral**

The dihedral is the first object in this list that exhibits multiple reflection effects. This is most clearly seen for the RCS as function of azimuth angle. Over the complete angular region that is investigated here the RCS is very large. Due to double reflection the RCS only decreases slowly as function of the aspect angle. For the elevation angle dependence it is quite different. Here we don't have any double reflection and the dihedral behaves similar to the flat plate.

- **Trihedral**

The trihedral exhibits double and triple reflection, so for both azimuth and elevation angle dependence this object has a large RCS for all angles that are investigated.

MEASUREMENTS RCS

For radar signature measurements . two small mobile in house developed radars are operated now by TNO-FEL: The first is a non-coherent high power low resolution radar called NORA operating at a single frequency in the I- and J-band. This radar can be equipped with an interferometer for tracking purposes or lock-break measurements. The second radar is the coherent high resolution radar CORA which uses a stepped frequency waveform and operates at from 8-18 GHz and 92-96 GHz. Also this radar can operate in an interferometer mode. This radar can be employed for signature measurements in a maritime environment, a tower-turntable facility and in an anechoic room. It is planned to extend the frequency range of this radar to 30-40 GHz. Features of both radars are given in table A1 and A2, see Annex 1. Data can be processed to obtain the conventional polar plots of low resolution radar signature as a function of aspect angle, high range resolution profiles as a function of aspect angle and ISAR images for specific aspect angles. The latter two indicate the location of scattering centres on the target, which information can be used in the RCSR process.
Typical examples of results obtained by CORA are given in Figures 8 and 9.

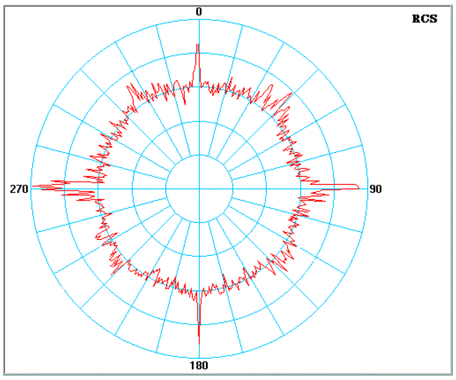


Figure 8 RCS of ship as a function of the azimuth aspect obtained by CORA.

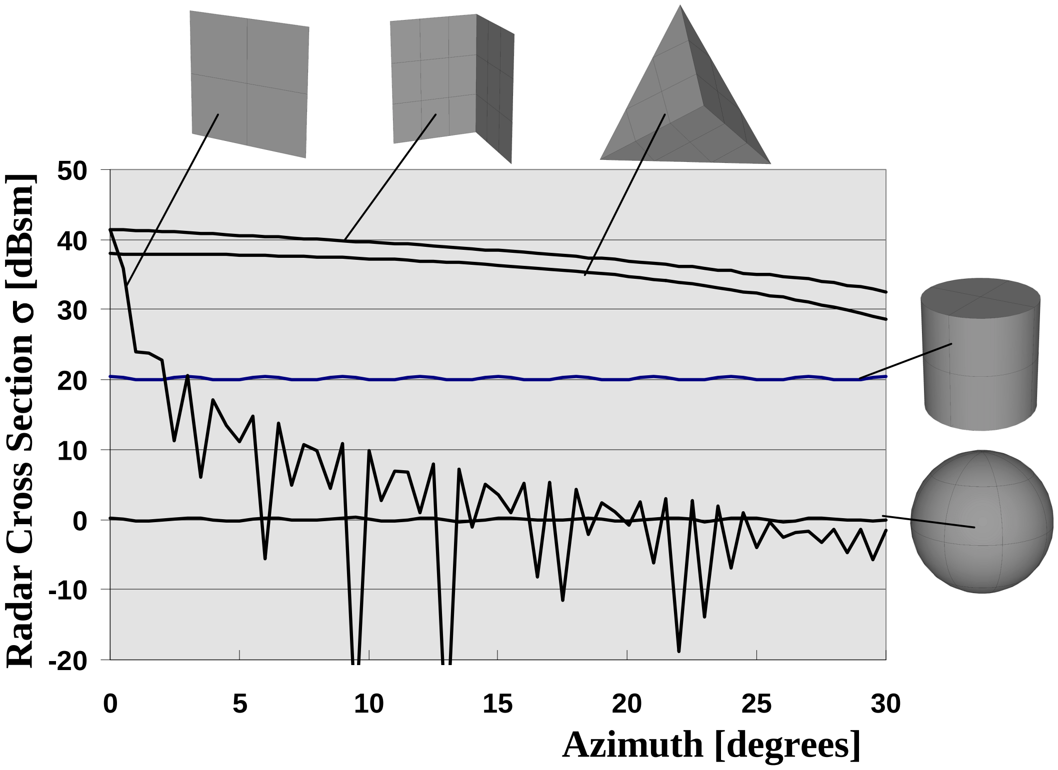


Figure 6 The RCS of a flat plate, dihedral, trihedral, cylinder (Presented area 1 m^2).

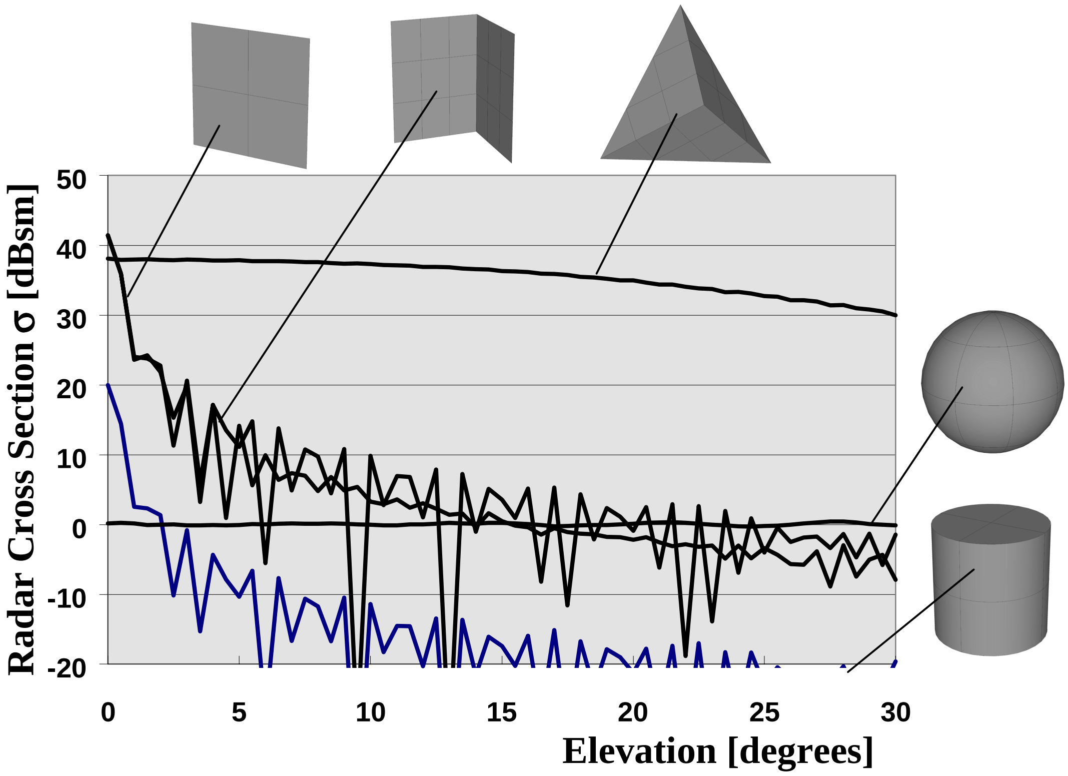


Figure 7 The RCS of a flat plate, dihedral, trihedral, cylinder and sphere (Presented area 1 m^2).

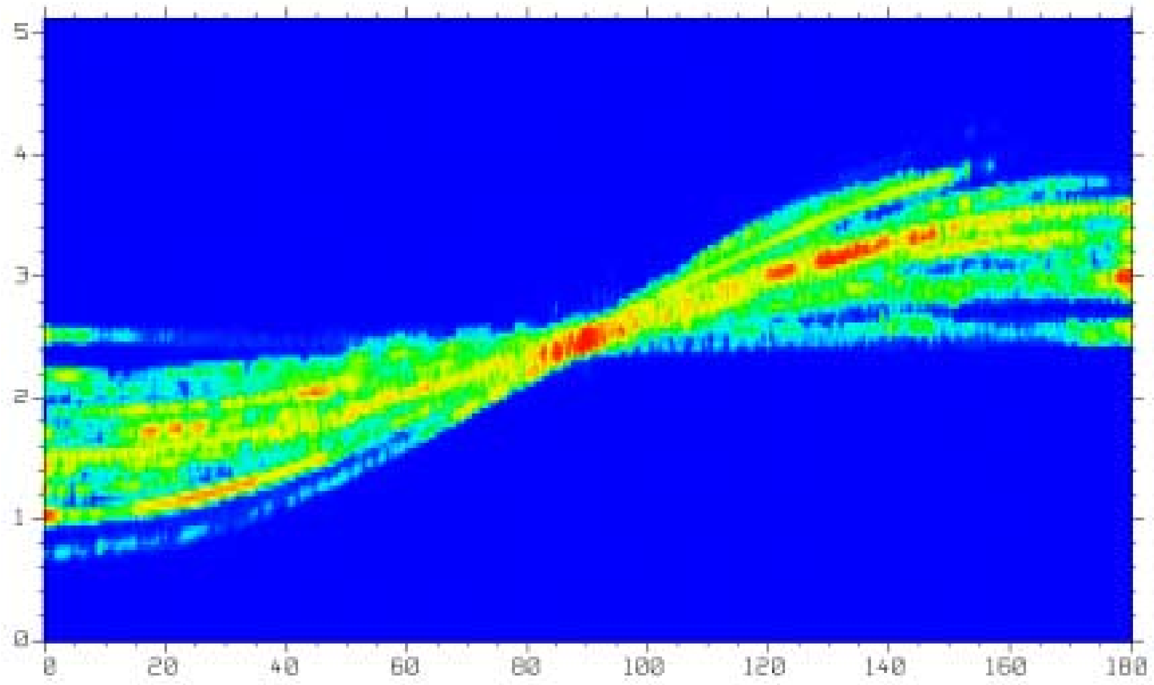


Figure 10 Range profile history plot of a scale model of a ship. At the horizontal axis the azimuth angle and at the vertical axis the range.

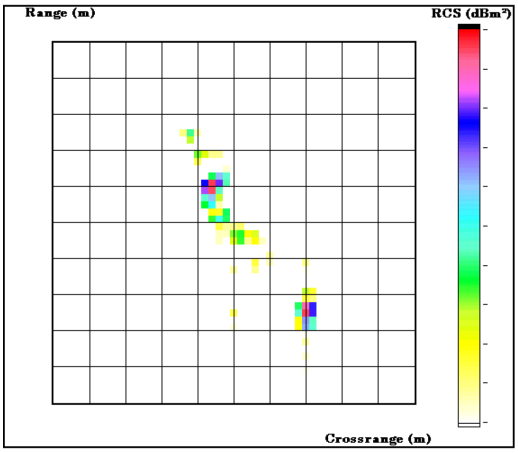


Figure 9 ISAR image of a ship obtained with CORA

RCS SCALE MODEL MEASUREMENTS

In a ship design stage, it will not be possible to perform life trials. However it will possible and very useful to check a design concept with scale model measurements.

If S is defined as the scaling factor:

$$S = \frac{\text{dimensions actual target}}{\text{dimensions scale model}}$$

Then the following relations are to be obeyed, see Table 4:

Table 4 RCS Scaling Rules

Quantity	Actual Target	Scale model
Length	l	$l' = l/S$
time	t	$t' = t/S$
frequency	f	$f' = f.S$
wave length	λ	$\lambda' = \lambda/S$
conductivity	σ	$\sigma'_c = \sigma_c.S$
permittivity	ε	$\varepsilon' = \varepsilon$
Permeability	μ	$\mu' = \mu$
RCS	σ	$\sigma' = \sigma/S^2$

with scaling Relation:

$$\sigma_{real} = \sigma_{s.m.}*S^2 \qquad \text{eq. [12]}$$

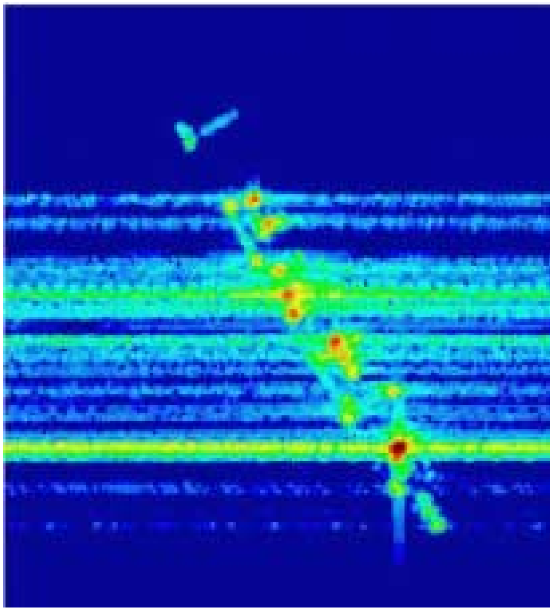


Figure 11 ISAR image of a ship

RCS SIMULATION

In order to compute the RCS of complex objects, like warships, it is necessary to use some assumptions and approximations in the governing Maxwell equations, otherwise this would be an impossible task. The major assumption relies on the fact that the object is very large with respect to the wavelength of the incident radiation. A wavelength which is very common in these calculations is 0.03 m (X-band radiation), so almost all parts of a ship comply to the restriction that they must be very large. Techniques based upon this assumption are generally called “high frequency techniques”.

The major approximation, as mentioned above, is the fact that the radar is located in the far field of the object, resulting in plane wave incidence of the radar radiation.

Widely used high frequency techniques are for instance Geometrical Optics (GO) and Physical Optics (PO). Both these techniques are capable of computing the RCS of complex objects in an efficient way. The advantage of PO is that it can handle flat surfaces, for which GO predicts infinite values, and the fact that it can predict scattered fields in a direction away from the specular direction, where GO fails.

Edge effects, caused by abrupt changes in the radius of curvature of objects, are neglected by both GO and PO, so another technique has to be used when these effects play an important role. This is particularly important for low RCS targets, like for instance missiles and some aircraft.

At the Physics and Electronics Laboratory a code has been developed for the analysis of radar signatures of complex objects. This code, “Radar signature Analysis and Prediction by Physical Optics and Ray Tracing" (RAPPORT), is used to predict the Radar Cross Section (RCS) of complicated objects like ships, vehicles and aircraft and to evaluate the effect of RCS reduction measures. The implemented algorithm is based upon a combination of Physical Optics (PO) and ray tracing, as proposed in [7]. Objects have to be described as a collection of flat polygonal plates, because of the adopted method to solve the PO integral [8]. RAPPORT makes use of an efficient backward ray-tracing algorithm to construct the illuminated part of the object, from which the RCS can be computed for any desired number of reflections and frequencies. The accuracy with which this illuminated area is determined can be controlled by a user defined parameter. This feature makes it possible to model very large complex objects like ships and it greatly facilitates the generation of inverse synthetic aperture radar (ISAR) images of the target.

Figure 10 shows a computed history plot of range profiles taken from a 1:75 scale model of a ship. A range profile shows the reflection centres as function of range along the object. It can be used to determine where the major contributions of the RCS originate from. In order to pinpoint dangerous scatter centres, the ones that are visible over a large angle interval, several range plots are made. In the figure 600 range plots are shown with an angular resolution of 0.3°. The range resolution is 0.04 m. The RCS is given in a colour code ranging from blue (low RCS) to red (high RCS).

In the computed ISAR image of a ship in figure 11 a colour code is used for the RCS, ranging from blue (low RCS) to red (high RCS). The contours of the ship can clearly be seen, as are the major reflection centres. These contours can usually not be seen in measured ISAR images because the dynamic range for computations is by far higher than it is for measurements.

In order to overcome the problems with edges that PO based codes encounter, a software tool based on the Method of Equivalent Currents [9] has also been developed at TNO [10]. With this program, called RCS_MEC, the scattering by sharp edges can be computed. To obtain a better representation of the RCS of a target, the scattered fields due to edge diffraction can subsequently be combined with the scattered fields due to reflection, as computed by RAPPORT.

Numerical techniques, that do not use the approximations of the high frequency techniques, are capable of directly solving electromagnetic scattering problems starting either from Maxwell curl equations or from the Chu-Stratton integrals, that can be derived from the Maxwell equations. This can result in highly accurate solutions and are most commonly used as exact solutions for validation purposes of approximated solutions. The use of these techniques for RCS calculations is limited, however, due to the enormous computer resources that are needed for even small objects. At the TNO Physics and Electronics Laboratory a Finite Difference Time Domain (FDTD) code has been developed which solves the Maxwell curl equations directly. Objects of 10 λ cubed can be used for analysis, in real life this means objects of approximately 30 cm cubed. Obviously this method is not applicable for ships, the main objective of the code is to investigate scattering phenomena and to compute small parts of other problems, for instance the computation of the RCS of parts of large antennas.

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’s RCS 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”.

RAPPORT has a coupling with the NAME[4] (MarTech) **C**omputer **A**ided **D**esign CAD-Software CATIA.

RCS REDUCTION LCF

Radar Cross Section Warships

As explained earlier, the RCS of a warship 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. Superstructure parts which form orthogonal angles between two planes (dihedral) or between three planes (trihedral) are the most dominant scatter centres for contemporary vessels. In former paragraphs an overview of the most common shapes that are found on board a warship in combination with their level of reflected RCS have been described.

RCS Reduction Features LCF

Considerable (low cost) design efforts have been made to reduce the LCF radar signature. This in close support of the TNO-FEL RCS-prediction code "RAPPORT". Figure 13 yields the general Above Water Signature Design Process for the LCF. Strictly speaking the reflective energy of the LCF will not be reduced, but redirected i.e. the incident energy will not be absorbed by e.g. Radar Absorbent Material (RAM). RAM has some important disadvantages; it is expensive, both in initial costs and in maintenance (LCC).

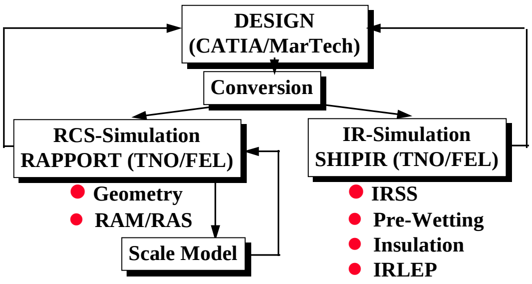


Figure 13 Above Water Signature Design Process for the LCF

Next to this, RAM is more frequency dependent. 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.

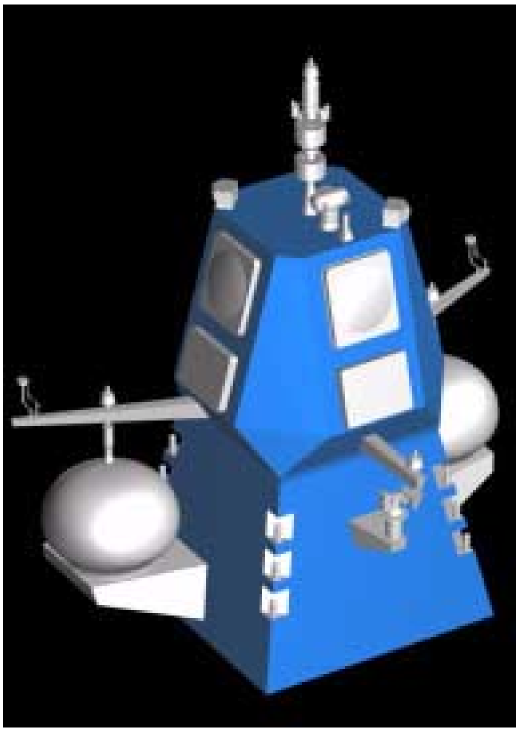


Figure 14 The LCF’s APAR Mast (Active Phased Array) designed for low RCS.

---

[4] `Design of Department of **N**aval **A**rchitecture and **M**arine **E**ngineering (MarTech)`

Figure 12 The Royal Netherlands navy Low Observable Air Defence Command Frigate LCF

The ship's hull only possesses, see Figure 12, tumblehome and flare strakes. 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 designed as a closed box structure, to prevent forming di- and trihedrals, see Figure 14.

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 the RCS-prediction code, the LCF design has been verified on the basis of a metal scale model (1:75), see Figure 1.

To warrant the ultimate LCF RCS design results, extensive RCS construction detail requirements have been included in the contract with the building yard (Royal Schelde).

FUTURE TRENDS

Internationally and within the Royal Netherlands Navy technologies are being explored, which will impact Ship RCS in the future (e.g. GE/NL MO2015 FRCC Study[5]). Some trends will be discussed briefly.

Threat/Seekerhead

Seekerhead sensors and signal processing will be improved. This will give the missile better capabilities to resolve the ship and reject decoys e.g. small Range Resolution cells.

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 Radar Cross Section more and more and, making revolutionary RCS ship design inevitable.

---

[5] Maritime Operations 2015 Future Reduced Cost Combatant

A low ship RCS will also have the possibility to force the attacker to enter the Hard Kill envelope (SAMs) of the defender. Principles like e.g. “Ships shoots Archer” can be exploited in contrast with the conventional “Ship defends against Arrows”. This decrease the number of defence hard kill rounds and increase the “Stay on Post Time”.

Onboard RCS Management Systems
Sophisticated onboard RCS Signature Management Systems will be developed to join the fleets in the future. Such a system will make it more feasible to deploy specific RCS peace and war time modes.

Advanced Mast Structures
Operational analyses have shown the benefits to be gained with low ship RCS levels. For contemporary low observable designs the dominant scatter centres are still to be found in the platform items. If a lower ship RCS is to be realised, then all other items e.g. weapon and sensor are to be taken care of as well. Especially antenna systems can have dominant contributions in this future "lower" observable or "stealthy" designs. RCSR can not be separated from other actions to improve the ships operability and survivability like IR signature reduction, electromagnetic interference problems, optimum sensor positioning etc. This leads to advanced mast structures or integrated topside designs.

Reduction of Antenna's RCS

The classical method to decrease the antenna's scattering mode is to cover the aperture with lossy (absorbent) material, so that incident energy is absorbed and not scattered back. However this methodology decreases antenna gain and therefore antenna efficiency.
New developments, which are not based on absorption and do not degrade antenna performance, are based on two main principles:

- Surface Shaping of the Radome;
- Frequency Selective Surfaces (FSS).

However combinations can be made with:

- conformal antenna arrays.

Surface Shaping
The Structural Scattering Mode can be minimised with redirecting incident energy in other directions than the illuminating source.

Frequency Selective Surfaces (FSS)
Frequency Selective Surfaces can be applied in the antenna design, in case the threat radar frequency and ship board radar system frequency are sufficiently separated. FSS behave as a closed surface for "out of band" (threat) frequency, but are "open" for the "in band" frequency for the own radar system. The radar system is enclosed by a radome, with an embedded FSS. By surface shaping of the radome, the threat radar energy is redirected from the source, but normal antenna operation is provided.

CONCLUSION / DISCUSSION

The operational benefits of low Ship RCS design has been addressed. Basic RCS theory and simulation have been discussed, this to comprehend general RCS signature management techniques. The LCF’s RCS design process and reduction features have been presented.

In the previous paragraph developments have been discussed. These developments will impact RCS Management in the future. To comprehend their impact to an appropriate extend, these topics have to be addressed in scientific research and development programs. International co-operation is cost-effective option.

Only in this way, the Royal Netherlands Navy will be ready for the future; i.e. to be capable to incorporate evaluated cost-effective RCS management technologies in (“revolutionary”) designs.

ACKNOWLEDGEMENTS

The authors acknowledge the Department of Naval Architecture and Marine Engineering (MarTech), 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.

ABBREVIATIONS

ADCF	Air Defence Command Frigate
AOD	Active Off-board Decoy
ASM	Anti Ship Missile
ARM	Anti Radiation Missile
BTR	Burn Through Range
CHAFF-D	Distraction Chaff
CHAFF-S	Seduction Chaff
ECM	Electronic Counter Measures
EM	Electro Magnetic
EMCOM	Emission Control
EO	Electro Optic
ESM	Electronic Support Measures
EW	Electronic Warfare
FEL	Physics and Electronics Laboratory
FSS	Frequency Selective Surface
HK	Hard Kill
HoJ	Home on Jam
ISAR	Inverse Synthetic Aperture Radar
LCC	Life Cycle Costing
LCF	Luchtverdediging en Commando Fregat
LPI	Low Probability of Intercept
RAM	Radar Absorbent Material
RAS	Radar Absorbent Structure
RCS	Radar Cross Section
RCSR	Radar Cross Section Reduction
REA	Radar Echoing Area
RF	Radio Frequency
RNLN	Royal Netherlands Navy
SCC	Ship's Control Centre
SK	Soft Kill
TNO	Netherlands Organisation for Applied Scientific Research

REFERENCES

[1] Galle, Leon F.
The Impact of Platform Design on Ship Survivability, part I (Features of the new RNLN Air Defence Command Frigate), Marineblad, 1997.

[2] 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.

[3] 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.

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

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

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

[7] 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.

[8] 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.

[9] 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.

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

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

BIBLIOGRAPHY

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

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

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

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

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

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

Annex 1 Characteristics of the FEL-CORA & FEL-NORA

Table A1 Characteristics of the low resolution radar NORA

Transmitter	I-band	J-band
frequency	9.4 GHz	16.5 GHz
peak transmit power	40 kW	40 kW
antenna 3-dB beam width	2.1°	1.3°
pulse width	1 µs	
pulse repetition frequency	1 kHz	
polarisation	horizontal or vertical	
Receiver		
min. detectable signal	-104 dBm	-102 dBm
antenna 3 dB beam width	6°	
antenna type	interferometer	
receiver type	logarithmic	
scale	linear in dB	
detector	peak	
dynamic range	>50 dB	
range gate	manual	
target tracking	manual with interferometer	
polarisation	horizontal or vertical	
results		
RCS	directly in dBsm	
RCS, bearing and heading	registration on floppy disk	
Output	on-line polar RCS plot	

Table A2 Characteristics of the coherent high resolution radar CORA

Transmitter	I-band	Receiver	
centre frequency	8-18 GHz	antenna 3 dB beam width	3.5°
peak transmit power	100 mW	antenna type	parabolic
antenna 3-dB beam width	3.5°	polarisation	horizontal or vertical
antenna type	60 cm parabolic	receiver type	linear
pulse width	3.2 µs	min. detectable signal	-100 dBm
pulse repetition frequency	adjustable typ. 10 kHz	dynamic range	>60 dB
polarisation	horizontal or vertical	detector	sample and hold
number of frequencies	max. 1024	range gate	manual
		target tracking	manual
output			
RCS, bearing and heading	registration on optical disk		
Output	on-line monitoring		