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Specifications for Reflectors and Radar Target Enhancers to Aid Detection of Small Marine Radar Targets

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This paper considers the need for better detectability of small targets at sea using marine radars in the 3 and 9 GHz bands. The problems of using radar reflectors and radar target enhancers to improve radar cross section, particularly when clutter is present, are discussed in detail. The IMO carriage requirement and the lack of suitably robust specifications are highlighted, and a proposal is made for a standard family of radar reflectors to meet the requirement. Radar target enhancers are also considered together with how these and radar reflectors should be mounted for best effect.

KEY WORDS

1. Radar. 2. Marine. 3. Augmentation. 4. Design.

1. THE DETECTABILITY PROBLEM.

1.1. *The Need for Radar Cross Section Enhancement*. When civil marine radar was introduced, the collision threats were steel ships that proved to be excellent reflectors of radar transmissions. Even so, the cursive display sometimes failed to reveal target echoes amidst unwanted clutter returns from waves and rain until rather short range. This was usually tolerable at the slow speeds then current, so little attention had to be paid to radar cross section (RCS), the measure of target retro-reflection.

Currently an Automatic Identification System (AIS) is being introduced, but it will not supersede radar as the primary anti-collision tool. Several of the diverse types of ship now at sea, including some high-speed craft (HSC, capable of more than 30 kts), have poor RCS by reason of small size, streamlined shape and sometimes non-metallic construction. Adequate reflection can no longer be taken for granted; yet the much higher closing speeds necessitate greater detection range. The small radar reflectors or radar target enhancers (RTE) sometimes carried to aid RCS are insufficient in severe clutter in the 9 GHz radar band and may be completely ineffective in the alternative 3 GHz band.

The inability of radar to detect and form tracks on small targets, often moving fast, in heavy weather has become life threatening. Problems are spreading from pleasure yachts and small fishing vessels to some larger vessels covered by the International Convention on Safety of Life at Sea (SOLAS). The most vigilant operators using the finest radar may sometimes find themselves in hazardous close-quarter situations.

1.2. *Proposed solution*. The International Maritime Organization (IMO) is addressing this serious safety problem by calling for new small ships to carry a reflector or other means to enhance their RCS. The specification of the aid, and how it is to be carried, is still under discussion. As a contribution to the debate, this paper presents reasoned specifications for a proposed family of aids. The aids may be passive or active and are suited to a set of clutter scenarios and to most small ships within SOLAS, or to be carried on a voluntary basis by other motor and sailing vessels. Mounting criteria are included.

The great diversity of ship types and the weather they encounter necessitates a simplified or 'broad brush' approach. Although calculated detectabilities (Skolnik, 1983) will perforce be inexact, they should be sufficiently correct for practical purposes, particularly bearing in mind the difficulties of estimation of weather conditions.

After examining the reflection process, the required RCS necessary for reasonable assurance of timely detection by typical big-ship radars is estimated for a set of clutter scenarios appropriate to weather of several severities. It is shown why small vessels may exhibit insufficient RCS for detection at safe range in the severest clutter they normally encounter. After reviewing the draft IMO carriage requirement, a family of specifications is developed for reflectors that would make most classes of small vessel detectable in appropriately severe clutter at safe range. Radar target enhancers can give high RCS without the inherent bulk of passive reflectors. The problems of RTEs are outlined and suggestions made for an extension of the reflector specification to them. Finally the method of mounting the chosen aid to realise its full potential is considered in relation to the yaw and roll likely to be experienced.

2. THE REFLECTION PROCESS.

Variation of RCS with azimuth or elevation angle is depicted by two-dimensional Polar Diagrams (polar graph of RCS versus azimuth or elevation angle of illumination). All three dimensions can be combined as a Target Pattern Map (TPM) in Cartesian coordinates whose colouring, shading or contour lines represent RCS values.

2.1. *Metal Reflectors.* Radar rays striking a metal target induce current loops on its surface. These re-radiate the incident energy, the surface forming an antenna. The echo is the component of re-radiation toward the radar. RCS is a measure of the retro-reflecting quality of the target.

2.1.1. *Macro-geometry.* Reflected energy from a flat metal plate target is mirror-reflected into a beam at the complementary angle to the incident ray. As with any antenna, target width (or 'aperture') has to be many wavelengths to give narrow beamwidth. If the wavelength is λ and c is a constant:

$$\mathrm{RCS} = \mathrm{c} \times (\mathrm{area})^2/\lambda^2, \tag{1}$$

for a flat plate viewed normally, $\mathrm{c} = 4\pi$.

It follows that no small reflector can have high RCS except at short wavelength, fundamentally because it cannot reflect more energy than that incident upon it; RCS in the marine 3 GHz band, where $\lambda = 10$ cm, is one tenth the marine 9 GHz band's value where $\lambda = 3{\cdot}2$ cm. The statement of reflector size can be simplified by writing size as for example 10/100, meaning 'effective RCS in the 3 GHz band is 10 square metres and in the 9 GHz band is 100 m^2.'

Any target develops RCS only when part of its reflected beam is in the direction of the illuminating radar, so slanting the target plate rapidly reduces RCS.

2.1.2. *Micro-geometry.* RCS is also affected by fine detail of the shape; for

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Table 1. Octahedral Reflectors.

Size (m^2 at 3/9 GHz) Effective	RCS, m^2 (dBm) 3 GHz band Nominal	Effective	9 GHz band Nominal	Effective	Enclosing Sphere Diameter	Volume
0·25/2·5	Unstated	0·25 (−6)	*10 (10)	2·5 (4)	0·5 m	0·066 m^3
1/10	4 (6)	1 (0)	40 (16)	10 (10)	0·71 m	0·19 m^3
3/30	12 (11)	3 (5)	120 (21)	30 (15)	0·93 m	0·93 m^3
10/100	40 (16)	10 (10)	400 (26)	100 (20)	1·26 m	1·05 m^3

*IMO Res. A. 384(10), nominal 10 m^2 at 9 GHz

example, if the plate is distorted through a quarter wavelength or more the beam is broadened. RCS then falls, but is maintained through a broader angle – a slanted plate now develops some RCS.

2.1.3. *Decibels.* Partly to make large ratios easier to handle, RCS is often expressed in decibel form: 1 m^2 becomes 0 dBm^2 ('decibels relative to a square metre'). Decibels are 10 × (logarithm of ratio), thus 2 m^2 becomes 3 dBm^2, 0·1 m^2 is −10 dBm^2, etc. 5 dB is a ratio of 3·2:1. Stating a target has RCS 10 or 20 dBm^2 means that it reflects towards the radar +10 or +20 dB (10 or 100 times) the reflection from a metal sphere of cross sectional area 1 m^2 (diameter 1·13 m) at the same location.

2.2. *Metal Corner Reflectors.* A ray striking an internal corner formed by two plates at right angles bounces twice before returning to the radar. High RCS is maintained in one plane through a broader angle of 30°. Micro-geometry is still important: if the right-angle at the joint is distorted by pulling the plate edges apart by a quarter-wavelength or more, RCS falls sharply.

Three plates forming a trihedral corner give wide beamwidths in both planes. Octahedrals – clusters of eight trihedrals – are used as reflectors to enhance RCS of small targets such as boats and buoys. When correctly mounted with one trihedral upwards and one downwards, six are active, giving main peaks at 60° azimuth intervals, alternately offset ±12° in elevation. The nominal RCS of the device is usually taken as the peak value of the TPM, say 10 m^2. At the equator, there are six nulls where in solid angles of 10° × 10° the effective RCS falls below 1/4 the nominal value, to less than 2·5 m^2 (4 dBm^2) at 9 GHz, and detectability is severely compromised. Equation 1 applies, and RCS is proportional to $(\text{side length})^4$, $(\text{volume})^{4/3}$ and $(\text{frequency})^2$; so the effective RCS at 3 GHz is 0·25 m^2 or −6 dBm^2 and a '10 m^2' octahedral has effective size 0·25/2·5.

When heeled to 12°, the azimuth polar diagram changes to three peaks separated by very deep nulls 70° wide, further reducing effective size and restricting the useable angle of heel to less than 10°. This poor performance becomes even worse when, as often happens, the octahedral is wrongly mounted point-up.

Table 1 relates RCS to size. For example, size 0·25/2·5 octahedrals just fit within a 0·5 m diameter sphere; size 10/100 (100 m effective at 9 GHz) would be 1·26 m in diameter, occupying a volume just over 1 m^3. The broad nulls make octahedrals unsatisfactory reflectors.

2.3. *Proprietary Reflectors.* The only existing specification (ISO 8729, 1987) is

IMO Resolution A. 384(10) for reflectors of nominal 10 m^2 in the 9 GHz band. It permits cheap and simple octahedrals, including their potentially hazardous $10° \times 10°$ nulls and is equivalent to 0·25/2·5.

Many proprietary reflectors consist of complex clusters of trihedrals. Other manufacturers use different principles, e.g. lens reflectors, but their bulk is similar. The better designs have quite good minimum RCS through moderate angles of heel, with narrow nulls which are usually tolerably shallow, giving reasonably uniform echoes. Shape is often cylindrical and volume is around 2/3 that of an octahedral of the same effective RCS. Because reflectors inherently cannot return more than the energy intercepted, a reflector whose RCS is 100 m^2 at 9 GHz (10 m^2 at 3 GHz) cannot occupy much less than 0·6 m^3.

2.4. *Non-metals*. Rays striking a non-metallic block partly reflect specularly and partly proceed into the block with some absorption. On exit there is again partial transmission and reflection, like the optical reflections at a window pane. Overall, reflection is much weaker than for an equivalent metal sheet, so non-metallic targets always have relatively low RCS and corner reflection effects are negligible. The engine, galley and other substantial internal metalwork of a wooden or glass reinforced plastic (GRP) boat may reflect well, but the hull absorbs both the incident and reflected rays, particularly when wet. Non-metallic vessels always have rather poor RCS. Persons on deck may contribute 0·5 m^2 each. It is difficult to substantiate assertions that wet sails reflect strongly.

2.5. *Point Reflectors*. Symmetry causes a sphere to have constant RCS at all angles of view – it is isotropic. Its polar diagrams are circles and the TPM is boringly devoid of content, the RCS being everywhere the same. Figure 1 shows a sphere S of

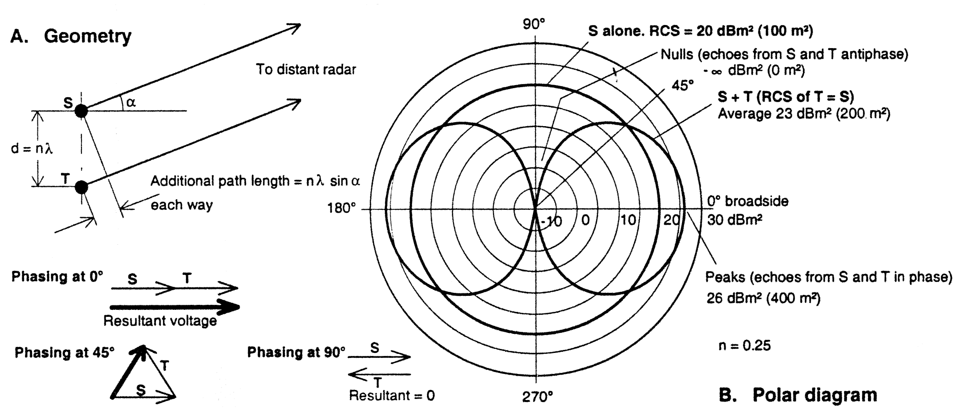

Figure 1. Pair of isotropic point reflectors illuminated by distant radar. (A) shows how the difference in path lengths, and hence phasing of the echo components, depends on angle of illumination. (B) is the polar diagram when the points are separated by a quarter-wavelength and the reflectors each have RCS 100 m^2 (20 dBm^2). Combination distorts the uniform reflections of each reflecting element into two peaks separated by deep nulls.

RCS 100 m^2 (20 dBm^2), illuminated at angle α by a distant radar of wavelength λ. Figure 1B includes its polar diagram (a circle), drawn to the usual decibel base. The arbitrarily chosen origin is -10 dBm^2 (0·1 m^2) and the periphery represents 30 dBm^2 (1000 m^2).

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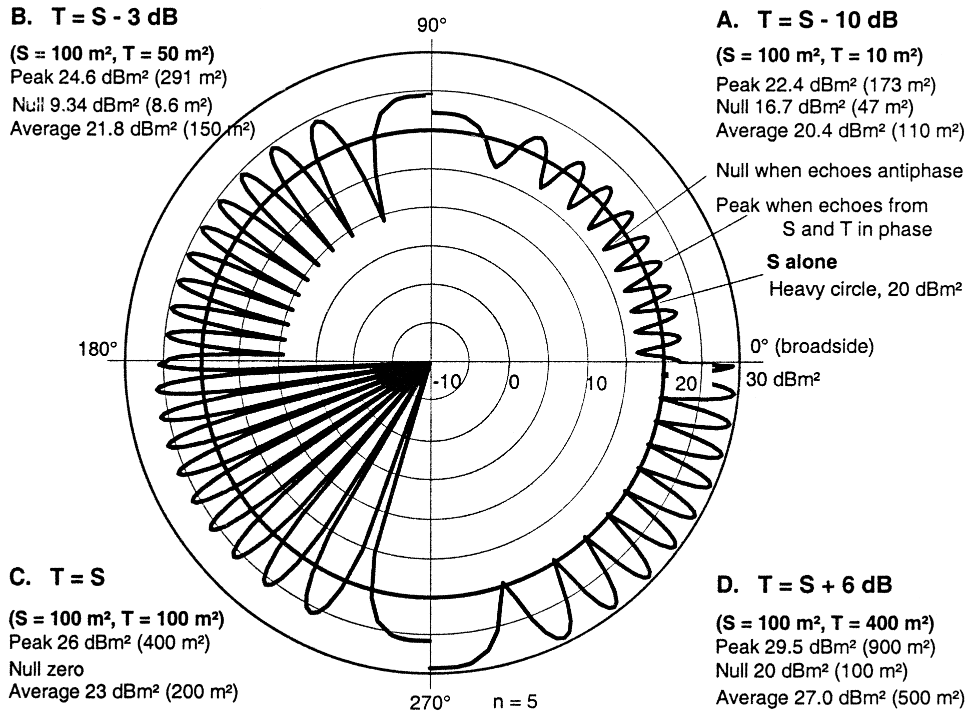

Figure 2. Polar diagram, two reflectors spaced 5 wavelengths. Geometry as Figure 1A, n = 5. Reflector S 100 m^2 as before, size of reflector T varied quadrant to quadrant.

2.6. *Combination of Reflectors*. A second sphere T is shown in Figure 1A, spaced d metres from S, where d is n wavelengths ($d = n\lambda$). When the radar is broadside on ($\alpha = 0°$ or 180°), S and T are at the same range. Their voltage vectors, each V, have the same phase. They add, giving resultant voltage 2V.

As power is proportional to V^2, total echo power is not doubled but quadrupled. At this peak in the diagram, the echo is the same as from a resultant reflector of RCS 400 m^2 (26 dBm^2).

2.6.1. *Quarter Wavelength Spacing*. As α increases, the path lengths begin to differ, the vectors get out of phase and the resultant RCS falls. When $\alpha = 90°$ or 270° the vectors cancel and RCS is zero, expressed as $-\infty$ dBm^2. Adding the second reflector has destroyed the echo of the first. Taken over the whole 360°, RCS averages S+T and is 200 m^2 (23 dBm^2), but Figure 1B shows the resultant diagram is by no means uniform. The resultant RCS at lobes and nulls is:

$$\text{Peak RCS} = S + T + 2\sqrt{(ST)} \tag{2}$$

$$\text{Null RCS} = S + T - 2\sqrt{(ST)} \tag{3}$$

2.6.2. *Wide Spacing*. In Figure 2, the spacing has been raised to 5λ and S remains 20 dBm^2. For illustration, each quadrant A, B, C, D shows different RCS for reflector T. The pattern is now much busier, with 40 (= 8n) lobes, more or less equally distributed through the 360°; average spacing = 45/n°.

RCS when averaged over a lobe-lobe interval is of course always S+T. As T is increased, the RCS ripple becomes more severe with deeper nulls, until, in quadrant

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C, S = T and null RCS is zero. RCS exceeds S alone for about 6°, is lower for about 3° and so on. There is 67% probability that the radar will see an enhanced RCS with 33% probability of degraded resultant RCS. RCS in nulls exceeds S alone only when T > 4S, shown in quadrant D.

Addition of more reflectors in the same plane would further complicate the polar diagram, null widths and depths becoming irregular. When there are reflectors in both planes, as in ships, the TPM resembles a hedgehog, with peaks and nulls distributed throughout the TPM.

2.7. *Summary*. These simple examples point to some general conclusions:

(a) Addition of two (or more) reflectors gives a resultant polar diagram that is by no means uniform.
(b) Average RCS is raised.
(c) When both reflectors are the same order of size, deep nulls are unavoidable.
(d) Unless the added reflector is big, nulls have less RCS than the first reflector alone.
(e) There are 8n nulls in the diagram, average spacing 45/n degrees.
(f) Null widths increase at small physical spacing and long wavelength, e.g. small vessels in the 3 GHz band.
(g) Width of nulls approximates 1/3 null spacing:

$$\text{Null width} \sim 15/n^\circ = 15\,\lambda/d = 1{\cdot}5/d \text{ degrees at 3 GHz,} \quad (4)$$

(e.g. 1·5° for 1 metre spacing).

3. DETECTION IN CLUTTER.

3.1. *Worst Likely Weather and Clutter Environment*. Detection range is calculated from the Radar Range Equation (Briggs, 1996) in which echo strength is proportional to RCS. In a recent study for IMO (IMO, 1999), Comité International Radio Maritime (CIRM) assumed SOLAS ships should remain detectable in sea state 6 (SS 6: wind speed 28–47 kts, North Atlantic), with meteorologically 'heavy' rain of 16 mm/hr. Sea clutter does not worsen at sea states exceeding 5. Although more benign environments may be appropriate to smaller vessels, it is assumed SOLAS ships should remain detectable in what here is termed Oceanic clutter: any sea state, with rain 16 mm/hr over the whole path. Rain through the whole path introduces attenuation, somewhat reducing detection range.

3.2. *Necessary Detection Range*. The target must be detected early enough to form a radar track, used by the Officer of the Watch (OOW) to decide and execute a collision avoidance manoeuvre. CIRM point out that IMO (IMO, MSC 64(67)) sets an operational requirement for radar in the presence of sea clutter to give a clear indication of a 'standard reflector' up to 3·5 nm. From this CIRM argue that the target should have enough RCS for detection at 3·5 nm. This allows a container ship (travelling at 24 kts) 230 seconds total from initial detection of an oncoming 30 kts HSC. Targets are often obscured from the scanner by deck cargo at very short range, or may lie beneath its beam. The following discussion assumes that targets should remain detectable in the clutter scenario between 0·25 nm and 3·5 nm.

4. NECESSARY RCS FOR DETECTION.

4.1. *Factors Involved.* Target echoes have to compete with clutter returns within the same detection cell. Modern radars maximise detectability by optimisation of such factors as scanner beamwidths and pulse length, and by employment of advanced software to pick out the echo amidst clutter, a hard task as both fluctuate. Performance has now been improved to near the fundamental limitation – the inherent similarity of weak echoes to clutter. Echo to clutter ratio must exceed about 5 dB for successful detection.

The following list of the major factors affecting detection in clutter includes approximate rates of change of performance.

(a) Scanner Aperture. The sea area and atmosphere volume illuminated, hence the clutter returned, depend inversely on scanner width. A scanner of 1/3 the width picks up 5 dB more clutter.

(b) Radar Band. On all SOLAS ships, 9 GHz radar is mandatory. Small ships seldom carry a 3 GHz set but its superior performance in rain, clutter being 12 dB lower, makes it popular on ships over 5000 gt which have to carry a second radar. Unfortunately the RCS of most targets and aids also drops somewhat at 3 GHz. OOWs may choose to observe on either band. Sea clutter is similar in each band. Polarisation must be horizontal at 9 GHz but may be vertical at 3 GHz. Vessel traffic service (VTS) radars favour 9 GHz.

(c) Height. A scanner at 30 metres – perhaps so high to clear deck cargo – looks down on the surface at a less acute angle, picking up 5 dB more sea clutter than a scanner at 10 m. Horizon range also rises by up to 40%, increasing detection range somewhat in benign clutter.

(d) Sea clutter rises 5 dB per sea-state number up to SS 5, where it stabilises. It also rises 5 dB from downwind to upwind. Estimation of sea state is subjective, one expert's SS 4 being another's SS 3. Wave crests may physically obscure low targets.

(e) Precipitation, particularly rain, in the radar/target path attenuates echoes beside returning clutter. Rates can be 'excessive' (40 mm/hr) in storms, obliterating large echoes. 'Heavy rain' of 16 mm/hr is more typical. Halving rain rate reduces clutter by 5 dB.

$$\text{Clutter power} \propto (\text{rain rate})^{1\cdot 6} \tag{5}$$

(f) Radar Control Settings. The OOW adjusts several radar operating parameters to optimize detection of the target of current interest. For example, when a long-range scale is selected to reveal distant large targets, detection cell size increases and more short-range clutter is collected, perhaps masking small nearby targets. OOWs may be too busy to make the successive adjustments necessary for optimum detection of all targets, large and small, close and distant.

4.2. *Necessary RCS, SOLAS Ships.* CIRM's paper computed performance for representative modern large ship radars, working with point reflectors, for Oceanic clutter. Leading parameters were:

3 GHz radar: frequency 3·05 GHz, peak power 30 kW, scanner width 3·8 m
9 GHz radar: frequency 9·41 GHz, peak power 25 kW, scanner width 1·9 m
Mounting heights: scanner 30 m, reflector 4 m

Detection criterion: blip/scan ratio 50%. This is the minimum required (IMO, A 823(19)) for ARPA to maintain target track or for an experienced observer to perceive a target paint amid clutter on the display screen.

Table 2. Calculated detection ranges, (nautical miles). Source: CIRM.

Radar band	3 GHz		9 GHz	
Reflector RCS, m^2	1	10	10	100
Reflector RCS, dBm^2	0	10	10	20
Calm sea, no rain	0–4·5	0–8·5	0–7·5	0–14·0
SS 6, no rain	3·0–4·5	0–8·5	0–1·0: 2·5–7·5	0–14·0*
Calm sea, rain 16 mm/hr	0–2·5	0–8·0	0–1·2	0–3·5
†SS 6 + rain 16 mm/hr	Not detected	0–8·0	0–1·0	0–3·5
†Oceanic clutter				*Corrected Value

Table 2 summarises the computed detection ranges. Analysis indicates that radar parameters were optimised for each target/clutter combination. Ranges observed in practice might well differ significantly because of minor radar service degradation, which can considerably affect visibility in clutter.

In the Oceanic clutter environment, at 3 GHz, the 10 m^2 target met the 3·5 nm range criterion with a margin in hand, estimated as 2 dB; but the 1 m^2 reflector remained undetectable at any range. At 9 GHz, RCS of 100 m^2 just matched the 3·5 nm range criterion. The target therefore should have RCS of at least 6 m^2 (8 dBm^2) at 3 GHz and 100 m^2 (20 dBm^2) at 9 GHz. A passive reflector of 100 m^2 at 9 GHz automatically has 10 m^2 RCS at 3 GHz, giving a couple of dB margin in that band. It is concluded that for reasonable certainty of detection in Oceanic grade clutter, a size 10/100 reflector should be carried by small SOLAS vessels, which should then be detectable at all sea states coupled with rain rate up to at least 16 mm/hr.

4.3. *Necessary RCS in Less Severe Clutter*. When the vessel is likely only to encounter less severe clutter, smaller RCS suffices for detection at 3·5 nm range. For example, at 3 GHz, a 3·0 m^2 reflector is 3 dB below the 6 m^2 needed in SS 5 and 16 mm/hr. From Section 4.1., 3 dB corresponds to 3/5 of a sea state number, giving SS ($5-3/5=4{\cdot}4$), say SS 4 to 5. From Equation 5, acceptable rain rate reduces to 10·4 mm/hr, say 10 mm/hr. In the 9 GHz band, this reflector has 30 m^2 RCS and would operate in SS 4 with 8 mm/hr rain. Thus a 3/30 size reflector is detectable at either band up to SS 4 plus 8 mm/hr rain, which we call Rough grade clutter. Going down a further 5 dB, a 1/10 size reflector is suited to Moderate clutter of SS 3 plus 4 mm/hr, and finally a 0·25/2·5 size reflector to IMO Resolution A. 384(10) should be relied on only when clutter is Slight: SS 2 plus 1·4 mm/hr rain.

Table 3 summarises performance of each size reflector, limiting clutters being shown in bold italics.

5. SHIPS AS REFLECTORS.

Data on the reflection qualities of modern small ships and HSCs is scarce. TPM may be determined by calculation from constructional drawings, by measurement of a physical model or by measurement of the vessel itself. All these methods are difficult and costly. It is easier to infer RCS from the tonnage, adding assumed null width and depth. Ship designs are so varied that we have to make broad approximations. The effective centre of reflection (ECR) probably lies near the centre of the projected area of exterior metalwork at the bearing in question.

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Table 3. Clutter scenarios for detection of small targets at approximately 3·5 nm.

Reflector size	0·25/2·5		1/10		3/30		10/100	
Band, GHz	3	9	3	9	3	9	3	9
RCS, m^2	0·25	2·5	1	10	3·2	32	10	100
RCS, dBm^2	−6	4	0	10	5	15	10	20
Sea state	2 to 3	***2***	3 to 4	***3***	4 to 5	***4***	Any	***Any***
plus rain, mm/hr	2	***1·4***	5	***4***	10	***8***	21	***16***
Clutter grade	Slight		Moderate		Rough		Oceanic	

5.1. *Large Ships.* Traditional ships with near-vertical hull and accommodation plating contain many reflecting elements – flat and curved steel panels and corners – spaced several wavelengths apart and average RCS is high. Measurements in the 9 GHz band indicate that, on an even keel, average RCS usually approximates to or somewhat exceeds gross tonnage. As a rule of thumb:

$$\text{RCS} \sim \text{gt (RCS in m}^2\text{, gt in tonnes).} \tag{6}$$

RCS tends to fall a few dB at 3 GHz, although less sharply than predicted by Equation 1. Near head-on, the flare of the bow often reduces RCS by a few dB. RCS usually falls when the ship heels.

Large ships have so many reflecting elements that their TPMs are patterns of many seemingly random peaks and nulls in both azimuth and elevation. Because panels are never quite flat, their reflections combine to partially fill the nulls, which rarely go deeper than about 5 dB (1/3). Occasionally a big plate comes normal to the radar, causing a massive RCS spike which is far too intermittent for reliable detection. TPMs differ in shape between the bands, with fewer but wider nulls at 3 GHz.

Equation 6 indicates that conventional ships of say 1000 gt probably average 1000 m^2 RCS at 9 GHz, falling in nulls to about 320 m^2. As this comfortably exceeds the necessary RCS for virtually any clutter condition, detection is reasonably certain, except in excessive rain.

5.2. *Small Ships – 'Stealth'.* To hide themselves from hostile radar, naval vessels employ several RCS-reduction 'stealth' techniques:

(a) Slanted hull and superstructure panels to angle reflections away from the radar.
(b) Minimum number of panels, each dead flat, to widen nulls and reduce reflection spillover towards the radar.
(c) No dihedral or trihedral corners – avoidance of ladders and other fussy details.
(d) Non-metallic superstructure.
(e) Internal metalwork masked by lossy coatings.

This list all too well describes many modern small civilian vessels, which are also unsatisfactory reflectors for other reasons. In all:

(a) gt is low, Equation 6.
(b) Stealth features may further reduce RCS by several dB.
(c) The few reflecting elements coarsen the TPM, with wider nulls and increased chance of deep cancellations.
(d) Panels tend to be flatter, giving narrow lobes but wider nulls.

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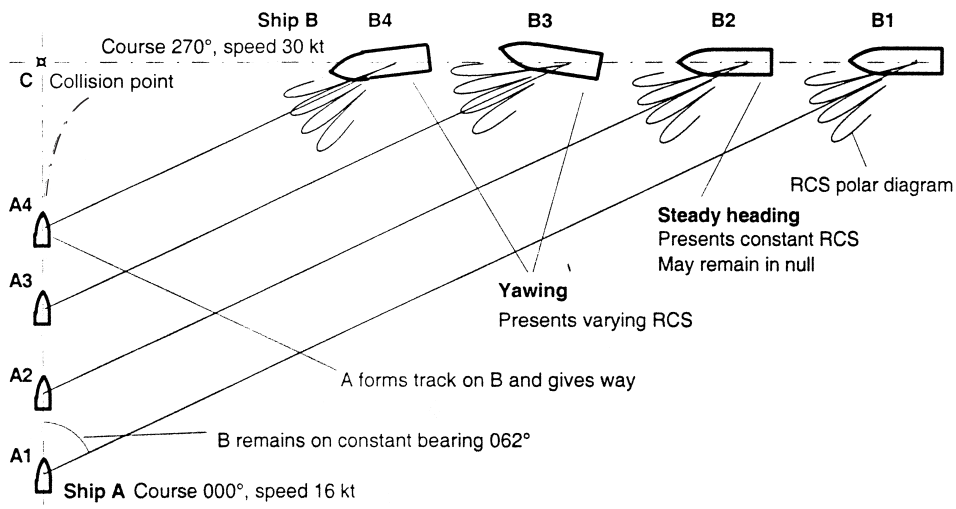

Figure 3. Effect of yaw on RCS. Ships A and B are on collision courses. At instants 1 and 2, B is on a steady heading and continually presents an RCS null to A. At instants 3 and 4, B is yawing, presenting variable RCS including lobes, enabling detection by A. Rolling has similar results.

(e) Small ships pitch and roll further, tending to slant 'vertical' panels and reduce RCS.

Most of these factors apply particularly strongly at 3 GHz.

As a counterbalance, small HSC and craft below SOLAS size are less likely to venture into severe clutter, reducing the RCS necessary for detection.

5.3. *Lobe Spacing, Yaw and Roll.* Figure 3 shows two ships A and B on course for collision at C. Before determining its obligation to manoeuvre under the Collision Regulations, A must form a track of B's echoes – a process requiring at least 50% probability of detection on several scans.

At instant 1, B is steering on a good automatic pilot without yaw or roll. It happens to present an RCS null to A. Later, at instant 2, A continues to look into the null and detection remains impossible. At instants 3 and 4, B yaws by more than the lobe spacing of its polar diagram, showing A the whole range of RCS values. There are now enough strong echoes for B to be detected and tracked. Rolling introduces a similar sampling process.

If average RCS is enough for 50% PD, detection is likely when maximum lobe spacing of the target is less than its peak-peak yaw or approximately twice its root-mean-square value (rms, approximating the standard deviation). Detectability is determined by effective RCS within nulls only a few degrees wide, not average or peak RCS.

Yaw and roll depend on vessel size and on weather. The wide nulls of a small vessel may be offset by wide yaw or roll, especially in bad weather where clutter is most troublesome.

6. MULTI-PATH RECEPTION.

When the sea is fairly calm, rays reach a reflecting element indirectly via a forward reflection at the sea surface as well as directly from the scanner. The indirect path is slightly longer so its phase differs and the rays interfere. For given scanner and element heights, the interference fluctuates between constructive and destructive as range changes. The process repeats on the return leg. Interference nulls may cause echo loss at certain intermediate ranges. Ships contain reflecting elements distributed in height from the waterline up. One element's null coincides with another's peak, preventing multi-path nulls. The indirect ray slightly raises echo strength. Targets on the waterline operate in a diffraction regime without multi-path. Putting a reflector up the mast merely adds one more element to the total. Only if the unaided RCS is very small on the bearing in question do multi-path nulls occur. Rough seas reflect too poorly to cause significant multi-path.

7. PROPOSED IMO REFLECTOR CARRIAGE REQUIREMENT.

7.1. *Draft Requirement*. To improve safety of small vessels within SOLAS, IMO is working towards a requirement for newbuildings to carry reflectors to enhance their RCS. IMO's Safety of Navigation Sub-committee, meeting as NAV45 in London in September 1999, drafted a clause (IMO, Draft SOLAS) requiring SOLAS ships constructed after 1 July 2002 to carry a reflector:

> If under 150 gross tonnage and if practicable a radar reflector, capable of operation at 9 and 3 GHz, or other means to ensure they are detectable by ships navigating by radar.

Gross tonnage was chosen as the size criterion to avoid the practical difficulty and expense of measuring ships' RCS. Existing carriage requirements include a size break at 150 gt. Equation 6 shows a 150 gt conventional ship has approximately 150 m^2 average RCS at 9 GHz, giving a small margin for nulls above the necessary minimum of 100 m^2 for detection in Oceanic clutter. At 3 GHz, RCS is probably about 60 m^2, comfortably above the necessary 8 m^2. It is less certain that 150 gt ships with 'stealth' characteristics will have quite enough RCS to assure detection. The 'other means' proviso in the new Regulation opens the way for compact radar target enhancers, discussed later.

There is little force in the objection that over-large echoes from reflectors on small craft will confuse navigators. Display paints of modern radars do not spread and may not change brilliance when the echo strengthens, and nowhere is echo strength mentioned in the Collision Regulations.

7.2. *Cautions*. For decades OOWs will continue to encounter exempt older ships, as well as many non-SOLAS vessels outside the Requirement. It will remain vital to continue to think 'small target', making frequent radar adjustments to maximise detection of weak echoes. The intent of the Requirement would be nullified if manufacturers or users started to ignore targets below 100 m^2 RCS at 9 GHz or 8 m^2 at 3 GHz.

Likewise skippers of small vessels must not assume carriage of an aid ensures detection. Not only is detection statistically a random process, but the radar may be switched off, defective, inappropriately adjusted, or unobserved. Carriage of a reflector does not relieve the obligation to keep a proper lookout. Though the prudent will take IMO's 'ensure' with a pinch of salt, the Regulation should eventually contribute significantly to the safety of small ships. It seems impracticable to provide reflectors big enough for detection in extremes of tropical rain.

7.3. *High Speed Craft*. Small HSC are being widely introduced. These predominantly passenger vessels are particularly vulnerable in collision. They move fast and often have stealth characteristics. Their licences may prohibit operation in high sea states. Nevertheless, carriage of RCS aids would considerably assist detectability in heavy rain and moderate seas. One hopes IMO will soon extend the carriage requirement to them by revision of SOLAS Chapter 10.

7.4. *Non-SOLAS Vessels*. While introducing reflector/RTE specifications for SOLAS ships, it seems worthwhile to include variants suited to the many vessels to which SOLAS does not apply, such as fishing vessels and pleasure yachts that are at collision risk when sailing in shipping lanes in poor weather. Although 9 GHz RTEs or small '10 m^2' reflectors to IMO Resolution A.384(10) are often carried, more general voluntary carriage would be fostered by existence of tighter specifications including a choice of RCS values and beamwidths.

8. PROPOSED OUTLINE SPECIFICATIONS FOR REFLECTORS.

8.1. *Desirable Features*. It is assumed at first that the reflector is mounted high; how high will emerge later. If the hull and superstructure lie in a wave trough, or the TPM shows a null to the radar, the vessel's RCS becomes negligible. The reflector alone now provides the echo and to be effective it should:

(a) Operate in both radar bands.
(b) Have effective RCS no less than the necessary RCS for worst likely clutter at 3·5 nm per Table 3.
(c) Maintain effective RCS through an elevation angle bracket equalling likely heel of the target class in its worst clutter grade.
(d) Have null widths less than twice the likely rms yaw or roll in the weather of its worst clutter grade.

8.2. *Existing Reflector Specification*. The only existing specification is ISO 8729 referenced by IMO Resolution A. 384(10). It is unsatisfactory for the following reasons:

(a) No reference is made to 3 GHz.
(b) Excessively wide and deep nulls are tolerated, to encompass octahedrals.
(c) Only one small size is included, characterised by its peak RCS of 10 m^2 rather than the effective 2·5 m^2; set so low to reduce size, mass, windage and cost.
(d) Elevation beamwidth, suited to octahedrals, is unnecessarily wide for motorships but insufficient for yachts.
(e) The special characteristics of RTEs are not addressed.

8.3. *Proposed Standard Reflector Family*. Except for the small 0·25/2·5 size based on ISO 8729, we propose each reflector should be specified in wide (WE) and narrow (NE) elevation beamwidth versions. This family of seven devices should cater for the great majority of vessels under 150 gt without the over-specification inherent in a 'one size fits all' approach.

Table 4 lists the proposed family, with their effective (not peak) RCS in both radar bands, suggested permissible maximum null widths (the same in azimuth and elevation) and suggested minimum elevation angle through which these parameters should be maintained, to cater for heel and roll. Next follow the clutter conditions in which the reflector will provide sufficient RCS for timely detection per Table 3. The vessel's minimum yaw (1/2 null width) and maximum heel plus roll (equals aid elevation) within which the reflector delivers its effective RCS, are followed by an indication of the vessel types to which the reflector is suited.

Table 4. Proposed family of standard reflectors.

Aid Parameters					Worst Environment			Vessel		
Size	Effective RCS m^2 3 GHz	Effective RCS m^2 9 GHz	Null width max	Elevation min	Type	Sea state number	Rain mm/hr	RMS yaw min	Heel + rms roll max	Type
10/100NE	10	100	2°	±5°	Oceanic	Any	16	1°	5°	A
10/100WE	10	100	4°	±40°	Oceanic	Any	16	2°	40°	B
3/30NE	3	30	4°	±10°	Rough	4	10	2°	10°	C
3/30WE	3	30	8°	±30°	Rough	4	10	4°	30°	D
1/10NE	1	10	10°	±10°	Moderate	3	4	5°	10°	E
1/10WE	1	10	10°	±30°	Moderate	3	4	5°	30°	F
0·25/2·5	0·25	2·5	10°	±10°	Slight	2	1·4	5°	10°	G

Although motor vessels could probably accommodate the bulk and weight of the larger reflector sizes without much difficulty, the bigger reflectors are much too bulky for yachts, that would find RTEs of similar performance much more attractive. Table 4 vessel types:

A. Motorships in SOLAS.
B. Ocean-going large yachts (round world racers, etc).
C. Sea-going fishing vessels, large motor yachts, etc.
D. Sea-going sailing yachts.
E. Smaller motor vessels.
F. Yachts operating in coastal waters.
G. Boats operating in sheltered waters.

8.4. *Actual Performance*. Some yachtsmen are sceptical of reflectors, holding there are no real improvements in detectability to offset the obvious penalties of weight aloft, stress on mast, interference with sails and cost. Recent controlled trials (Practical Boat Owner, 1999) of a reflector on a 7 metre yacht seem to refute this. For the yacht alone in calm water, the 9 GHz azimuth polar diagram had highest peaks around 1 000 m^2; but there were nulls 10° wide in which RCS was less than 3 m^2. Here Table 3 indicates the yacht would have been undetectable at 3·5 nm in more than SS 2 with rain about 2 mm/hr. When a good-quality 2·5 m^2 reflector was hoisted up the mast, RCS never fell below 10 m^2, indicating detection in SS 3 and 4 mm/hr. A 9 m^2 reflector raised minimum RCS to 25 m^2, detectable to 3·5 nm in SS 3 to 4 plus rain 7 mm/hr. These results more or less conform to Equation 3.

9. RADAR TARGET ENHANCERS.

9.1. *Operation*. So far this paper has concentrated on passive reflectors, with their simplicity but necessary bulk. RTEs open the possibility of small devices which maintain high RCS over wide elevation angles. Suppliers are currently addressing the private yacht market, which demands moderate 9 GHz performance at low cost. It is hoped that availability of recognised performance specifications might encourage production of twin-band models of higher RCS, despite certain technical difficulties.

An RTE is an electronic device containing a microwave amplifier connected between small receive and transmit omni-directional antennae. Received radar pulses are amplified and retransmitted at increased power (so the RTE is an active device) without significant delay, lengthening, coding or other change. The radar displays a response at RTE position, looking exactly like the echo of a passive target or reflector. The antenna radiation patterns can be smooth enough to eliminate nulls from the TPM. Wide elevation beamwidths can be obtained by sacrificing antenna gain. RTEs are completely inoperative outside their designed frequency band.

Some models provide a wheelhouse indication of interrogation, warning the watch keeper to redouble vigilance but in no way absolving need for a visual lookout. The electrical power requirement of a few watts is trivial to SOLAS ships and well within the capacity of many yachts. RTEs usually have narrow tubular construction (to separate the antennae and prevent self-oscillation); current 9 GHz models are about 1/2 metre tall, twin-band models would probably be taller.

By the inverse square law, halving the range of a distant RTE increases the power it receives $\times 4$. The amplifier delivers $\times 4$ response power. The inverse square law again applies, to give $\times 16$ echo at the radar. As a reflector would also give $\times 16$ echo, the RTE has a definite RCS:

$$\text{RCS} = G^2 A \lambda^2 / (4\pi), \tag{7}$$

where: G = antenna gain, A = amplifier gain, λ = wavelength.

Antennae of wide elevation beamwidth have low gain, necessitating higher amplifier gain for a given RCS. For example size 10/100 NE might have G = 8 (9 dB), with A = 200 (23 dB) at 3 GHz and 20000 (43 dB) at 9 GHz. Size 10/100 WE would need G = 1 (0 dB), necessitating 18 dB more amplifier gain, adding to cost and technical difficulty.

The ITU-R Recommendation (ITU, 1995) for RTEs limits maximum response power to 10 W EIRP (equivalent isotropic radiated power), including antenna gain. This was presumably to restrict any spurious out of band interference, but leads to unsaturated RCS at 9 GHz as low as 9 m^2, insufficient for detection in Rough clutter. 3 GHz performance is not addressed.

9.2. *Additional Parameters*. As well as the basic parameters of Table 4, some special features of RTEs have to be defined:

(a) Polarisation: RTE antennae have to suit the radar polarisation; horizontal and vertical (perhaps by use of slant polarisation) at 3 GHz, horizontal at 9 GHz. Viewed from ahead, a heeled RTE becomes partly cross-polarised, reducing effective RCS when heel exceeds 30°.

(b) Operating frequencies: The device has to operate throughout both marine radar bands, 2900–3100 MHz and 9300–9500 MHz.

(c) Rated transmitter power: At short range the amplifier reaches its maximum available power output. Further halving of range now gives only $\times 4$ rather than $\times 16$ echo, so effective RCS falls to a quarter. This is called saturation. Here RCS $\propto$ (range)^2. Thus an RTE which is detectable above clutter at moderate range may become undetectable when saturated at short range. Saturation range increases with radar transmitter power and scanner size (high EIRP), and reduces as RTE rated EIRP increases. As a minor benefit, saturation makes RTEs rather less prone to display unwanted sidelobe echoes. It is difficult to provide sufficient RCS to surmount clutter at short range. At 0·25 nm range, rated transmitter power might have to exceed 100 watts (requiring relaxation of the 10 W EIRP limit). It is certainly unrealistic to expect RTE responses to remain detectable in severe clutter down to 0·25 nm range. The problem is compounded when elevation beamwidth is wide.

(d) Duty: Passive devices automatically respond to each interrogation, but RTEs have to be specified to respond to say 100 radars without overload.

10. MOUNTING THE AID. A. 384(10) calls for reflectors to be 4 metres above sea level. There is nothing 'magic' about this particular value, and the reasoning behind its adoption seems forgotten. When vessel unaided RCS is significant, the aid becomes merely another reflecting element in the assemblage. In the event of phases opposing when aid and vessel echo amplitudes are equal, even when the aid itself is free of nulls, the composite TPM will exhibit deep interference nulls. To preserve detectability, their width should be reduced to less than twice the minimum likely rms yaw or roll angle. This necessitates adequate displacement from the ECR, achieved by mounting in accordance with Equation 4. ECR uncertainty should be allowed for by addition of say 1·0 metre. This gives the following criteria.

(a) Minimum height $= \mathrm{ECR}+1+3/(\text{rms roll angle})$ metres. (8)

(b) To avoid masking, minimum height should also exceed the significant wave height for the worst applicable sea state (suggested as SS 6 for the Oceanic case, otherwise per Table 4). In benign clutter, detection range increases more or less pro rata with horizon range, so it increases somewhat if the reflector is raised. On the whole, the attendant inconveniences seem to outweigh any benefit from great mounting height. In the case of RTEs, height is that of the lower antenna.

(c) Mount forward of ECR by at least $1+3/(\text{rms yaw angle})$ and to give an unobstructed view forward and to port, any blind arc lying over the starboard quarter, for anti-collision reasons.

These considerations lead to Table 5, which gives mounting positions relative to ECR for suggested minimum yaw and roll values likely to be experienced by the targets. In practice, it would probably be satisfactory to mount high on the foremast or on the roof of the superstructure. RTEs must be kept well clear of own vessel's radar beam, if any.

Table 5. Mounting requirements.

Vessel type	Worst sea		Height		Fore and aft	
Table 4	Sea state number	Sig. Wave height metres	Minimum roll degrees rms	Above ECR metres	Minimum yaw degrees rms	Fwd of ECR metres
A	6	6	1	4	1	4
B	6	6	2	2·5	2	2·5
C	4	2·4	2	2·5	2	2·5
D	4	2·4	4	1·75	4	1·75
E	3	1·2	5	1·6	5	1·6
F	3	1·2	5	1·6	5	1·6
G	2	0·5	5*	1·6	5*	1·6

*Constrained by null widths permitted in ISO 8729.

11. CONCLUSIONS. CIRM calculated the RCS which civil marine radars in the 3 and 9 GHz bands need for detection in Oceanic clutter at a range of 3·5 nm, this range giving time for anti-collision manoeuvre. From this three less severe clutter scenarios are suggested (in Table 3) with associated lower values of RCS to reasonably assure detection at 3·5 nm. Study of reflection mechanisms confirms that the three-dimensional RCS profile or target pattern map of any unaided vessel is likely to contain numerous peaks and nulls in azimuth and elevation. Detection at safe range is jeopardised if the target continuously shows a null. It follows that permissible null width is indicated by the likely minimum yaw and roll in the worst weather in which the vessel is likely to find itself.

From these considerations, a family of reflectors has been suggested as a basis for formal specifications, Table 4, with sufficient choice of RCS, maximum null width and effective azimuth angle to suit most small vessels in their worst likely conditions of clutter, yaw, roll and heel – sailing vessels heeling more than motorships. RTEs have the prospect of giving high RCS without the inconvenient bulk inherent to passive reflectors. By outlining the problems peculiar to RTEs, additional factors have been identified for inclusion in the specifications, enabling them to qualify as 'other means' of ensuring detection in IMO's new draft carriage requirement.

The composite TPM of an aid – reflector or RTE – plus its host vessel differs from either TPM alone. Suggestions are included for correct positioning of the aid, well clear of the effective centre of reflection of the vessel, to realise its full benefit without inadvertent introduction of hazardously wide nulls.

12. RECOMMENDED ACTIONS. Computer modelling along CIRM's lines should be extended to the whole range of clutter/RCS scenarios, ideally for several radar size/height combinations; a lengthy process which would need official funding. Many more properly designed trials should be conducted to check how far aids really do improve detection of small vessels in clutter, an even lengthier task.

The outcome would be agreement of formal IMO/ISO specifications for a family of RCS aids, including reflector and RTE alternatives. This would facilitate introduction of the IMO carriage requirement, encourage development of better RTEs and, not least, foster voluntary carriage by small vessels outside SOLAS, reducing their risk of collision with ships navigating by radar.

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