RADAR CROSS-SECTION OF WARSHIPS

BY

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Introduction

Of all the means available to detect the presence of a warship at long range, the most precise and commonly used is radar. Radars mounted on warships, aircraft, and satellites can be used to determine the disposition of enemy forces and provide the information needed to press home an attack with guns, bombs, and missiles. Interest has recently been aroused in reducing or modifying the radar signature of warships in order to make them less easy to detect and to increase the effectiveness of their Electronic Warfare equipment (which is designed to deny information to enemy radar), thus rendering them less vulnerable to attacks in which radar plays a key role. The parameter which describes the radar signature of a warship, or indeed any radar target, is the Radar Cross-Section (RCS). Some confusion can arise because, as will be explained, the RCS often bears little relation to the physical cross-section of the target and may be over 10 000 times greater or, alternatively, smaller than the target's actual area! The alternative term, Radar Echoing Area, is no more useful than RCS in dispelling this confusion. To appreciate the significance of RCS it is necessary to understand the operation of radar and, in particular, the principles of the Radar Range Equation.

The Radar Range Equation and RCS Definition

Radar is an acronym for Radio (Frequency) Detection And Ranging. The electromagnetic waves which are used to detect targets and determine their range are in the region 300 MHz to 300 GHz (wavelengths 1 m down to 1 mm). Surveillance radars are of the pulsed type which emit a short pulse of electromagnetic energy and detect the presence of a target by the energy which is reflected from it. The ranging capability is obtained by measuring the time between the original emission and the arrival of the reflected pulse. The area covered by the radar is determined by the type and shape of the antenna or, in the case of a phased array radar, electronically. The radar energy is not emitted uniformly in all directions but is concentrated into a narrow beam in order to increase sensitivity and to provide bearing information.

The fundamental equation describing radar performance and the source of the definition of RCS is the Radar Range Equation. In its simplest form, which is quite adequate to explain the principles involved, the Range Equation is based on the physical properties of electromagnetic waves in free space (that is, in a vacuum away from the influences of the earth's magnetic field). The energy of the radar pulse under these conditions follows the laws of spherical spreading which dictate that, if the energy were emitted uniformly in all directions, the area illuminated would increase by the square of the distance from the source. As the energy moves out from the source, the area illuminated is an ever-increasing spherical surface. However, a radar antenna ensures that the transmitted power, P_t, is not radiated uniformly but is concentrated into the limited solid angle of the beam, thereby increasing the power density within the beam. This increase within the beam is determined by the factor termed the transmitter antenna gain, G. The power density a distance R from the transmitter is thus given by:

$$\frac{P_t G}{4\pi R^2}$$

as this radar illuminates a proportion 1/G of the area of space $4\pi R^2$ which lies a distance R from the transmitter.

If the target were to scatter uniformly in all directions (isotropically) all the energy which illuminated its area, σ, then the power returned to unit area of the radar would be:

$$\frac{P_t G \sigma}{(4\pi R^2)^2}$$

The effective area of the radar antenna on reception expressed in terms of the wavelength of the electromagnetic wave, λ, is G $\lambda^2/4\pi$; thus the returned power received by the radar is[1]:

$$Pr = \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4} \sigma$$

Modifications are introduced into this formula to represent practical situations such as the non-uniformity of illumination across the target, losses on scattering from the target or differences in antenna gain on reception and transmission. Such modifications do not affect the principles underlying the simpler form of the equation and will not be pursued. Of major importance, however, is the assumption that the target scatters the radar pulse isotropically. Although some simple-shaped objects (for example a sphere) approach this ideal, targets such as flat plates and those as complex as warships do not behave in a way which justifies this assumption. For instance, most of the energy scattered from a flat plate is essentially reflected in a beam that is typically as narrow as that of the illuminating radar beam. Only when the plate is perpendicular to the beam is significant power returned to the radar. When in this orientation the plate returns the same energy as a very large isotropic scatterer. Conversely, when the plate is angled to the beam the energy is largely concentrated away from the direction of the radar and the amount received is equivalent to that from a very small isotropic scatterer. To account for this the term, σ, is used to represent the area of an fictitious isotropic scatterer rather than the geometric area illuminated and it is this parameter which is referred to as the Radar Cross-Section.

The definition of RCS is thus, in essence, the cross-sectional area of *the imaginary isotropic scatterer which would return to the radar the same power as the target in its particular orientation to the radar beam*[1].

The Radar Cross-Section depends on a number of factors:

(*a*) *Geometry and orientation of target.* These parameters are generally more important than the actual size of the target. A 1 m^2 flat plate oriented perpendicular to the beam can have an RCS at 15 GHz of 30 000 times its actual area. If angled at only $\frac{1}{2}°$ this falls to 10 000 m^2 for the 1 m^2 plate and can fall to zero at certain precise angles (FIG. 1). The RCS of some geometries can vary dramatically and rapidly with aspect angle whereas for others there may be little variation. In general complex targets such as warships are in the former category.

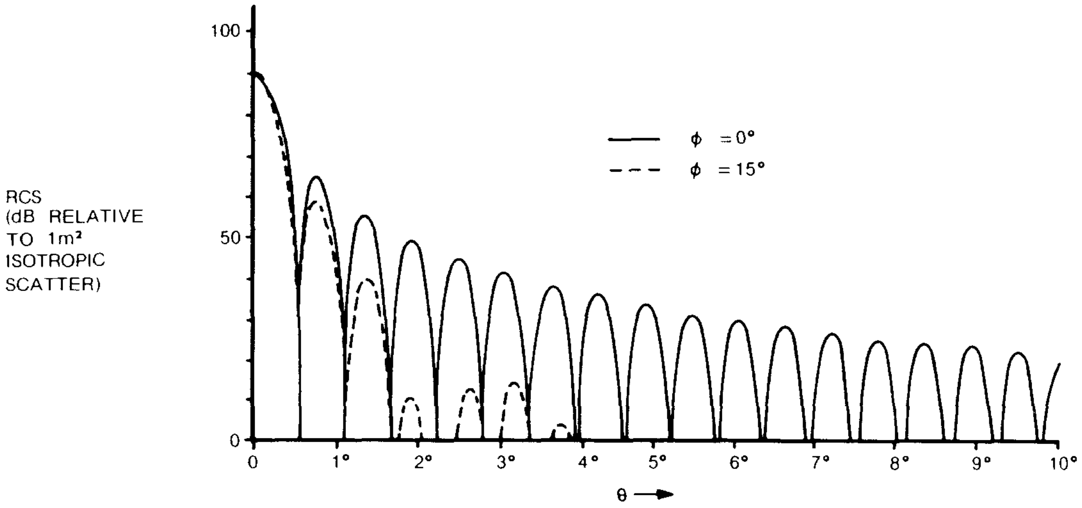


FIG. 1—VARIATION OF THE RADAR CROSS SECTION OF A FLAT PLATE 1 M × 1 M AT 15 GHZ AS THE ANGLE OF INCIDENCE CHANGES IN THE HORIZONTAL PLANE WHEN THE PLATE IS PERPENDICULAR ($\theta = 0°$) TO, AND TILTED BY 15° TO, THE RADAR BEAM IN THE VERTICAL PLANE.

(*b*) *Relative Size Compared to Radar Wavelength.* Provided the target is much larger than the wavelength of the radar transmission (which is generally between 0.3 mm and 300 mm) the behaviour of the beam scattered from the target is very similar to that of light (the Optical Region). Fortunately the major parts of ships fulfil this criterion. It is more difficult to predict the behaviour where the targets, or elements of them, are much smaller than the wavelength (the Rayleigh Region) or are comparable to the wave (the Mie or Resonant Region)[2]. Within these regions the amplitude of the returns, and hence the RCS, vary rapidly with the size of the target relative to wavelength. Parts of the ship of this size may contribute to the overall RCS by modifying slightly the effects of the larger parts, especially where wide-angle scattering sections have been excluded from the design.

(*c*) *Nature of Surface.* Steel or aluminium of ship's superstructure behave almost as perfect conductors when illuminated by radars and scatter and reflect radar radiation with negligible loss. GRP on the other hand is partially transparent, and when it is used for the ship's hull or in the superstructure, prediction of the RCS is made more difficult. Other materials including Radar Absorbent Material (RAM) absorb incident energy but, because the effect is resonant, this property is confined to a limited part of the radar frequency spectrum the range of which depends on the type of RAM.

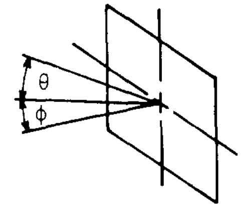
(*d*) *Polarization.* Radar emissions are polarized and some objects, such as wires, may vary dramatically in their RCS depending upon whether they are aligned with, or perpendicular to, the plane of polarization.

(*e*) *Nature of Radar.* The RCS discussed above assumes that the radar is monostatic (in which the transmitter and receiver use the same antenna or two antennas which are almost coincident). Where the transmitter and receiver are widely separated (the bistatic arrangement), then the Radar Cross-Section depends upon the orientation of the target to the two antennas. The GWS 30 Sea-dart missile, for instance, homes on to targets illuminated by a 909 CW radar. The RCS of an aircraft target illuminated by a radar in one direction and scattering in another (towards the missile) may differ dramatically from the RCS applicable to a surveillance radar on board the ship.

GENERAL CASES / *SPECIAL CASES*

Flat Plate

$$\sigma(\theta,\phi) = \frac{4\pi a^2 b^2}{\lambda^2}\left[\frac{\sin(ka\sin\theta\cos\phi)}{ka\sin\theta\cos\phi}\,\frac{\sin(kb\sin\theta\sin\phi)}{kb\sin\theta\sin\phi}\right]^2\cos^2\theta$$

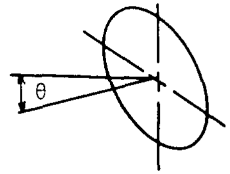


$$\sigma = \frac{4\pi a^2 b^2}{\lambda^2}\quad(\theta=\phi=o)$$

Circular Plate

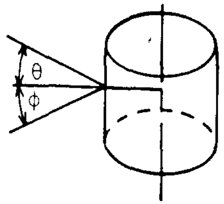
$$\sigma(\theta) = \frac{4\pi A^2}{\lambda^2}\left[2\,\frac{J_1(2ka\sin\theta)}{2ka\sin\theta}\right]^2\cos^2\theta$$

where J_1 is the first-order Bessel function.



Cylinder

$$\sigma = \frac{a\lambda\sin\theta}{2\pi}\left[\frac{\sin[(2\pi l/\lambda)\cos\theta]}{\cos\theta}\right]^2(\theta\text{ large})$$



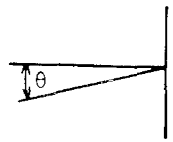
$$\sigma = \frac{2\pi a l^2}{\lambda}\quad(\theta=o)$$

$$= \left(\frac{2\pi l}{\lambda}\right)^2\quad(\theta=\pi/2)$$

Wire

$$\sigma = \frac{\pi l^2\sin^2\theta\left[\dfrac{\sin(2\pi l/\lambda)\cos\theta}{(2-\pi l/\lambda)\cos\theta}\right]^2\cos^4\phi}{(\pi/2)^2+\{\ln[(\beta\pi a\sin\theta)/\lambda]\}^2}\quad(\phi\text{ is polarisation angle})$$

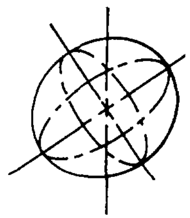
where $\beta = e^\gamma$ and $\gamma = 0\cdot5772157\ \ldots$ is Euler's constant; hence $\beta = 1\cdot781072\ \ldots$



$$\sigma = \frac{\pi l^2}{(\pi/2)^2+[\ln(\beta\pi a/\lambda)]^2}$$

General Ellipsoids

$$\sigma = \frac{\pi a^2 b^2 c^2}{(a^2\sin^2\theta\cos^2\phi + b^2\sin^2\theta\sin^2\phi + c^2\cos^2\theta)^2}$$



$\sigma = \pi a^2$ (sphere)
$\sigma = \pi a_1 a_2$ (double curved surface)

FIG. 2—RADAR CROSS SECTION EQUATIONS OF GEOMETRICAL SHAPES

Equations for the Radar Cross-Section of Simple Shapes

Before considering the RCS of a complex target, such as a ship, it is useful to review the equations for simple geometric shapes of which the target may be composed.

The equation for a flat plate is[2]:

$$\sigma(\theta,\phi) = \frac{4\pi A^2}{\lambda^2} \left[\frac{\sin(ka \sin\theta \cos \phi)}{ka \sin \theta \cos \phi} \frac{\sin(kb \sin \theta \sin \phi)}{kb \sin \theta \sin \phi} \right]^2 \cos^2\theta$$

where $k=2\pi/\lambda$ and θ and ϕ are the angles between the plate and the radar beam in two orthogonal directions. When θ and ϕ are both $\pi/2$ this has the maximum value of

$$\sigma = \frac{4\pi A^2}{\lambda^2}$$

which is the value of the cross-section of a *specular reflection*—the narrow beam optical-like reflection. As θ or ϕ increase, the value of σ falls rapidly to zero but then increases again before diminishing once more. Several such peaks occur, the maximum values decreasing with successive peaks. The spacing of the maxima depends upon the relative values of plate size and radar wavelength (FIG. 1), and, like all the equations in this paper, is only valid for the optical region described above.

One might expect the flat plate to behave like its optical analogy, a mirror, and produce a single strong specular reflection without the series of subsidiary peaks and troughs shown in FIG. 1. The difference is solely due to the fact that, in general, light is incoherent (not having a single phase) whereas radar emissions are coherent. As the plate is turned the path lengths of waves scattered from different parts of the plate interfere both constructively to produce peaks (when the scattered waves are in phase) and destructively to produce nulls (when they are out of phase). The interference of coherent waves is also responsible for other effects which are discussed below.

Equations of other simple geometric shapes are shown in FIG. 2. Objects with flat surfaces produce specular reflections and have a large RCS for certain aspect angles with the high values associated with specular reflections being offset by smaller values in other orientations. Smoothly varying surfaces, such as cylinders, have an RCS which is more constant with changes of aspect angle but is smaller. The RCS of these objects is thus, on average, close to that of an isotropic scatterer.

An important configuration which has a very high average RCS, and which can have a major influence on the overall RCS of ships, is an orthogonal conjunction of three flat plates—the trihedral reflector—(FIG. 3). This can have a high RCS which is comparable to the narrow angle specular values of a flat plate. When all three vertices are at an equal angle to the radar beam (which is then aligned with the axis of symmetry) then the return is similar to that of a flat plate of similar projected area. Some diminution occurs due to multiple reflections introducing losses not experienced with a flat plate. The RCS of the trihedral reflector seen from other aspects relates, to first approximation, to the projected area and is, for a trihedral of three equal square plates of side, a:

$$\frac{4\pi a^2}{\lambda^2} . \sqrt{3}(1-0{\cdot}0274\ \delta)\ a^2$$

where the first term relates to the maximum value and the second to the reduction from the maximum value resulting from the change of projected area when rotated by an angle δ from the axis of symmetry[3].

Dihedral reflectors are formed by two plates at right angles such as the superstructure and deck. This arrangement has an RCS which varies little

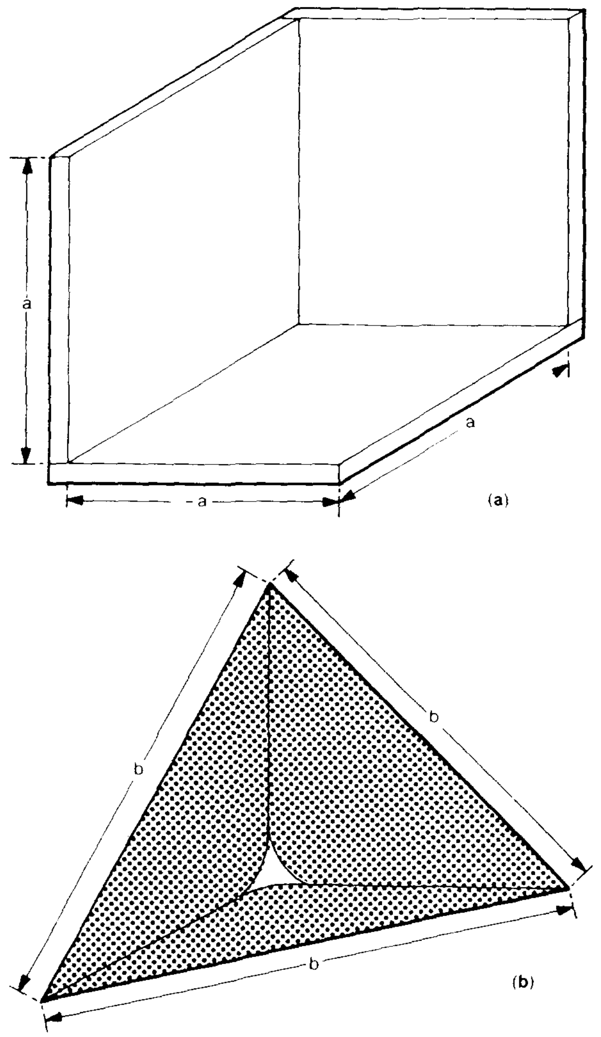


FIG. 3—SQUARE (a) AND TRIANGULAR (b) TRIHEDRAL REFLECTORS (COMMONLY MISNAMED 'CORNER REFLECTORS'). IN (b) THE CORNER HAS BEEN ROUNDED BUT THIS WILL HAVE NO SIGNIFICANT EFFECT ON THE RCS.

with angle provided that the radar beam is perpendicular to the junction of the two plates, but diminishes rapidly at other aspect angles.

Radar Cross-Section of Ships

As might be expected, the RCS of a ship is complex and comprises contributions from a number of different parts of the ship. The smoothly curving surfaces (such as funnels), dihedral and trihedral reflectors contribute returns which vary little with aspect angle and are added to those of flat surfaces which are inherently narrow-beam. Because of the coherent nature of radar waves the contributions do not add simply, and phase must be taken into account resulting in a far more irregular pattern than might otherwise be expected (FIG. 4).

The RCS is further complicated by the presence of equipment such as stanchions, bollards, doors, wire antennas, and other small items which also contribute to the fine structure of the RCS. Similarly, the RCS is effected by irregularities of the hull such as the 'hungry horse' effect where the hull plates become slightly concave between frames.

The ship's radar antennas modify the RCS produced by the ship's structure and may have a significant contribution. The antennas are designed to focus incoming radar energy but unless the radar illuminating the ship is operating at a frequency close to that of the ship's radar, the antenna feed will present a complete mismatch and return the energy with little loss. Surveillance and navigation radars will thus regularly enhance the RCS in any particular direction as they rotate. Of greater concern, however, are tracking radars which are locked on to incoming threats as soon as they are detected. Their antennas, generally of the parabolic type with a wide angle return, thus face towards the threat and enhance the RCS greatly when it is least desired. Fortunately, recent forms of radar, static phased arrays, form their beams electronically and act very much like any other flat plate when illuminated by another radar so could offer an amelioration of this problem in the future.

The RCS of a ship is not only highly variable but its apparent position can also vary rapidly because of the effects of a combination of a number of scatterers with different phases. The apparent centre of the RCS, the *glint*

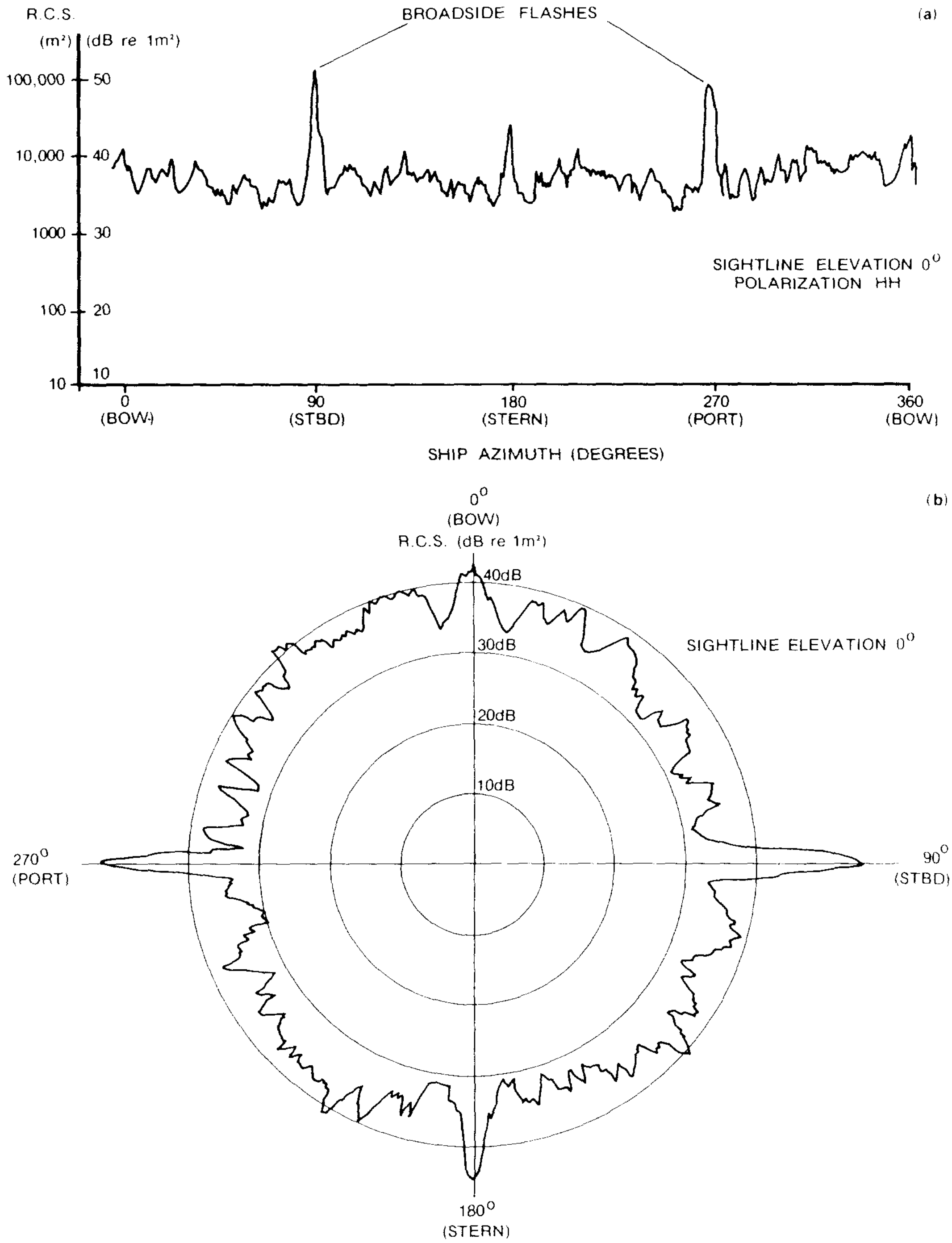


FIG. 4—TYPICAL SHIP RCS SPECTRA
(a) AZIMUTH PLOT
(b) POLAR PLOT OF SAME SIGNATURE

centre can move rapidly with changes of aspect angle and may even lie outside the ship on occasion.

As the RCS of a ship comprises a number of sharp peaks which are highly dependent upon aspect angle it is difficult to give typical values, or to compare values of different ships, without comparing RCS patterns, most of which are classified for warships. Reference 6 gives values for a minesweeper showing the variation with vertical aspect angle and various frequency bands, both horizontally and vertically polarized on two bearings. For comparison, the values over the bow quoted elsewhere are[5]:

Aircraft carrier	3000 m
Destroyer	1400 m
Small surface vessel	530 m
Patrol boat	85 m
Submarine schnorkel	5 m
compared with:	
Missile nose cone	1 m

Owing to the scattering nature of GRP, the RCS pattern of GRP vessels is unlike that of other warships because of the contribution of metal objects within the hull.

Whether a ship can be detected or not depends on a number of factors such as range and the power of the radar as well as the RCS. At extreme ranges it is often only the specular returns which can be detected. Because a ship moves in a seaway the opportunities for detection under these conditions may be limited. Even if the ship is in an orientation which is particularly favourable for detection (because the RCS is high for that aspect angle) rolling or manoeuvring may rapidly move the ship to a less favourable angle. The lower values of RCS may represent a return which is below the detection threshold of the radar system. This is termed 'fading' (FIG. 5). A steady return can be obtained only by increasing the radar power (rarely practical in an operational situation) or closing range.

Environmental Factors and Observed RCS

The effects produced by ship motion can be considered solely in terms of changing aspect angle but the return to the radar, and consequently the observed RCS, is also influenced by both sea state and the earth's curvature. There is some contention as to whether these effects should be included in the given values of RCS or applied in corrections to the range equation. In general they are considered as corrections. Multipath effects occur because the sea can act as a good radar reflector especially when calm. Accompanying the direct returns will be returns reflected from the sea's surface. These may differ in phase from the direct returns and will produce an interference effect which can cause the signal to fade. To ease calculation, it is assumed that the outward and return paths are either both direct paths or both reflected paths. (It can be shown that this is equivalent to calculations which also allow a combination of direct and reflected paths). Not only will the phase of the direct and reflected paths differ but so will their amplitude as there are losses involved in reflection and because the angles at which they strike the ship are different. The calm conditions which produce multipath fading are those in which ship's motion is the lowest and for which the returns would otherwise be fairly steady. The earth's curvature also has an effect on the target return which is both profound and important for ships (which are often detected close to the horizon by the search radar). Three principle regions can be identified (see FIG. 6 and references 2, p.126, and 4, p.472).

(*a*) *The diffraction region.* Although ships may, on occasions, be detected well beyond the normal radar horizon because of anomalous propagation conditions (ducting), the first region in which a ship can normally be detected is when the uppermost parts give a radar return (but the bulk of the ship is below the horizon and can only be detected by diffracted waves). As can be seen from the diagram, the range at which such detection can occur depends upon the height of the detecting radar. As the range closes within this region the increased visible area combined with diffraction effects means that the target return increases rapidly—approximately inversely as R^8.

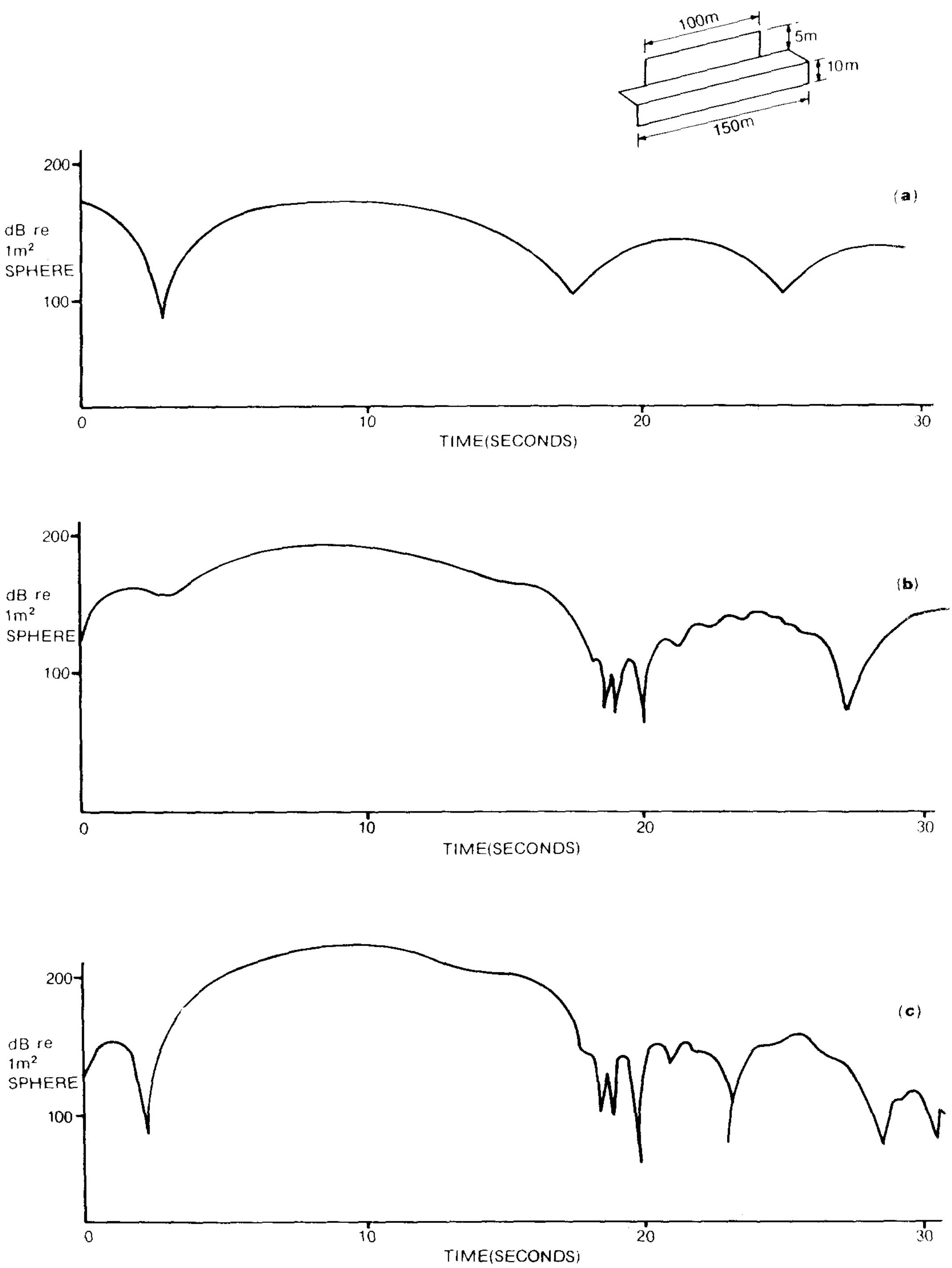


FIG. 5—VARIATION WITH TIME OF THE ABEAM RCS OF A ROLLING SLAB-SIDED VESSEL OF 150 M LENGTH (COMPUTER SIMULATION).
(a) SUPERSTRUCTURE ONLY
(b) HULL AND SUPERSTRUCTURE
(c) INCLUDING MULTIPATH EFFECTS
(INSET) DIMENSIONS OF MODELLED STRUCTURE REPRESENTING VESSEL

(*b*) *The intermediate region* where the whole ship is visible but the detecting radar is close to the horizon and consequently below the first multipath maximum. In this region the target return increases rapidly as range closes, but is a transition between the inverse R^8 relationship of the diffraction region and the classical R^4 relationship.

(*c*) *The interference region* where the height and range of the detecting radar are such that the whole ship can be seen and multipath effects are experienced. On average the target return follows the free space radar equation and increases inversely as R^4. As the vertical incidence angle increases multipath becomes less important but sea clutter becomes more significant and can hinder detection despite the increased RCS in this region. At very high angles clutter increases from its approximately constant 'plateau' value, the much higher values of its 'specular' region[8] affecting detection by high-flying aircraft and satellites.

The interference region is sometimes confusingly referred to as the 'near zone' (not to be confused with 'near field') and the other two regions as 'far zones'. Such definitions were originally applied to shipborne radars but are confusing when considering airborne radars.

Theoretical Estimations of RCS

In the absence of any other information, a very approximate estimate of the RCS of a ship when viewed close to the horizon (but in full view) is given by the formula[9]:

$$\sigma \simeq 52\sqrt{fD}$$

where f is the frequency in MHz and D is the full load displacement of the vessel. Such a formula cannot, of course, take into account the very complex nature of the RCS which comprises contributions from a number of scatterers which may not lie in the same plane and the magnitude of whose contributions depend upon frequency and polarisation.

Rigorously the total radar cross-section of a target, all of which is illuminated by a uniform plane wave, can be obtained by assuming each scatterer can be replaced by a point source at its radar centre. The contributions are summed using the relationship:

$$\sigma_{total} = \left| \sum_{k=1}^{N} \sqrt{\sigma_k} \exp\left(i4\pi d_k/\lambda\right) \right|^2$$

where the k^{th} scatterer of N scatterers has a radar cross section of σ_k at the wavelengths λ and lies a distance d_k from a reference plane at right angles to the direction of propagation of the beam. The assumptions of this method are:

(*a*) that the whole ship is illuminated simultaneously by the radar (i.e. that it lies within the radar resolution cell or, for pulse compression radar, within the imputed resolution cell).

(*b*) that the radar produces a plane wave (in fact it is curved with a radius equal to the range).

(*c*) that the illumination is uniform over the whole of the target.

None of these assumptions is wholly true but it is unnecessary to apply corrections except possibly in the latter case and then only when great precision is required.

A simpler estimate, and one which is almost as accurate for a complex case such as a ship, is the *Random Phase Method* which ignores the phase relationship, thereby averaging the contributions over all phase angles:—

$$\sigma_{total} = \sum_{k=1}^{N} \sigma_k$$

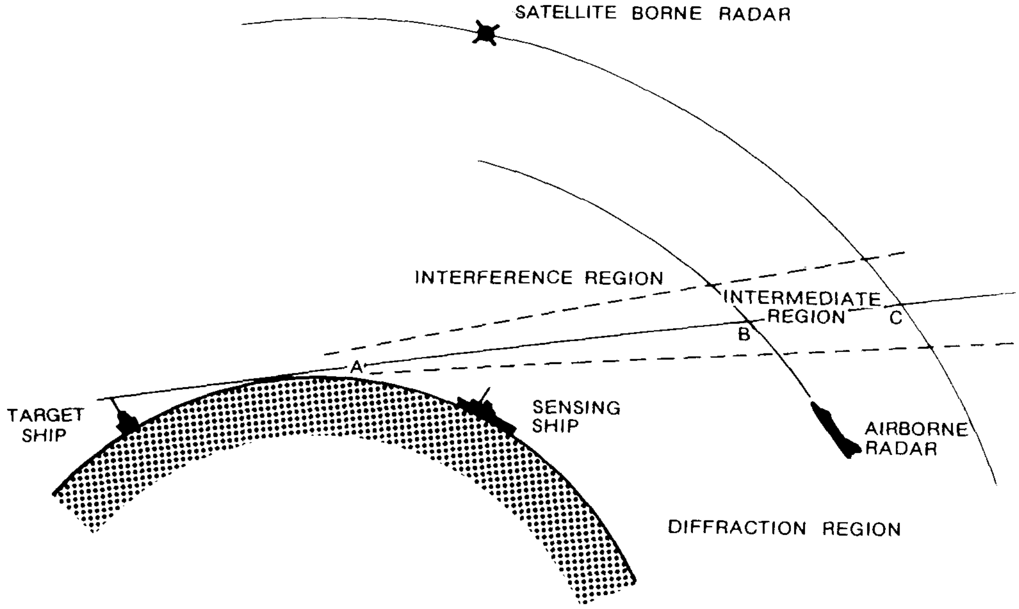


FIG. 6—RADAR DETECTION REGIONS FOR A SURFACE SHIP.
THE RANGES AT WHICH A SHIP WOULD BE DETECTED AT HORIZON LEVEL WOULD BE:
A FROM A SHIP
B FROM A HIGH-FLYING AIRCRAFT
C FROM A SATELLITE

This method will not predict where the highest values will occur but the variation from this average value can be estimated from:

$$\Delta^2 = \left(\sum_{k=1}^{N} \sigma^k\right)^2 - \sum_{k=1}^{N} \sigma_k^2$$

where Δ is the standard deviation. Formulae such as these are the basis of the increasing number of computer estimates which are made to supplement or replace empirical estimates using models; they are incorporated in programs which form part of the computer aids available to the M.Sc. courses at University College.

Determination of RCS using Models

During the warship's design it is important to have information available on the likely RCS characteristics. Whilst computer programs are increasing in usefulness, especially in the early stages of a ship design, the most common tool is a scale model. The models are typically 1/100 or 1/200 scale and constructed of a highly conductive metal such as copper or brass. The frequency of the measurement is scaled to ensure that the conditions are comparable to the full scale situation. High conductivity metals have a factor $\mu\epsilon$ which is similar to steel but if dielectrics are incorporated in the model, a scaling factor must be used[10].

On a model radar range it is not possible (even at reduced scales) to use distances comparable to the radar horizon at full scale. As the diameter, D, of the radar antenna used is generally comparable to the size of the model, sufficient accuracy can be obtained at distances of $16D^2/\lambda$ or less. Measurements taken closer than the boundary of the far field at $2D^2/\lambda$ will, however, lack accuracy and fail to reveal the correct fine structure of the RCS pattern.

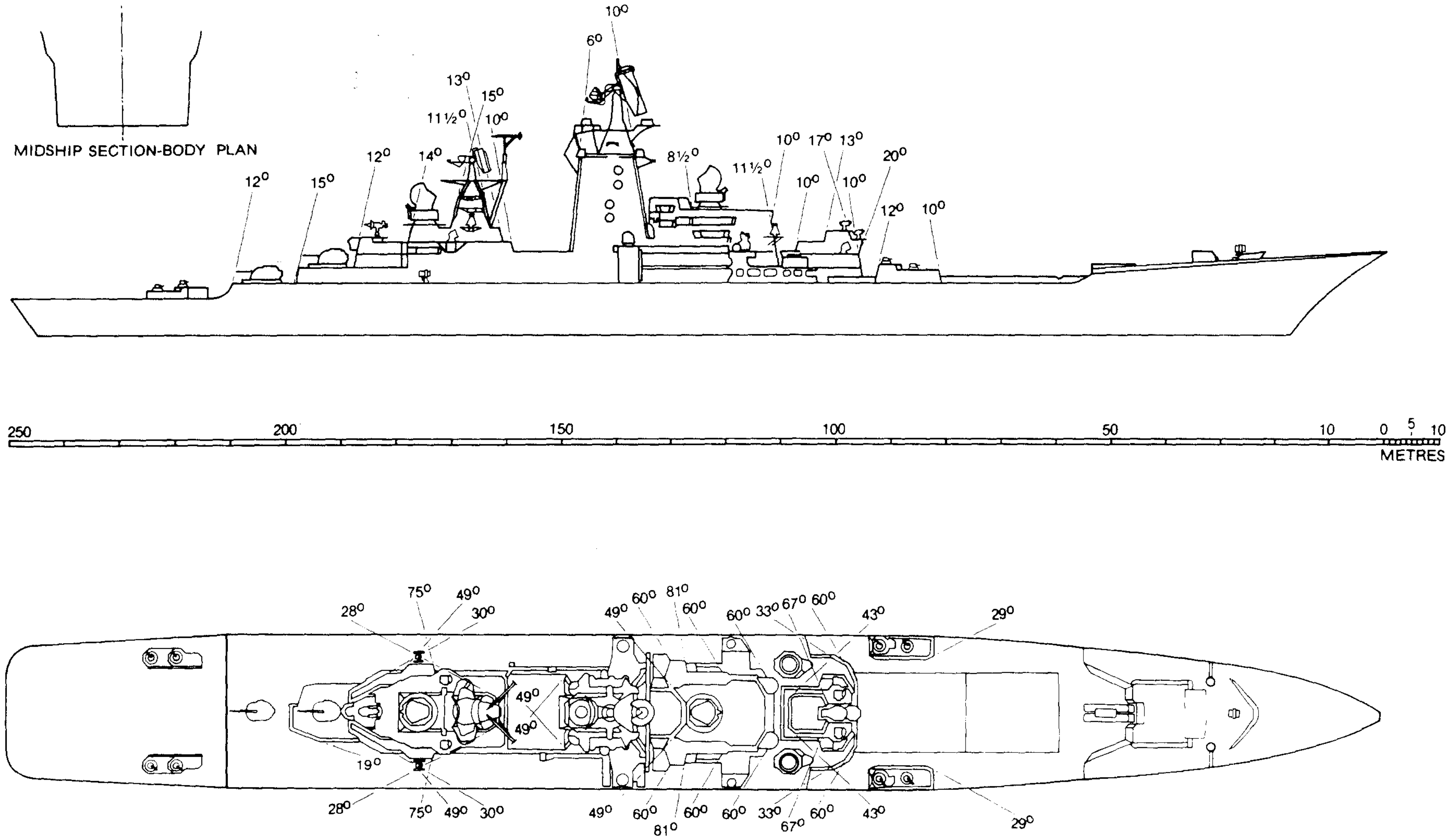


FIG. 7—'KIROV' CLASS SHOWING ANGLES OF MAIN REFLECTIVE SURFACES

For measurements to be valid, it is necessary to reduce the background signals. There are a number of techniques for achieving this—the use of anechoic linings for the radar range, an open-air range, or compensation for returns from the surroundings. Some errors are also induced by the supports for the model if the RCS of the ship alone is required (by mounting the model on a highly conducting bed-plate multipath effects can also be included in the estimate).

Reduction and Modification of RCS

Despite the importance of the use of radar for initial detection and in guiding radar homing missiles, there has been little attention paid in the past to reducing the RCS or modifying its characteristics in order to frustrate enemy attacks. Recently, however, there has been a growing interest in designs which attempt to achieve this aim both for ships and aircraft. As part of the Stealth programme several techniques have been applied to aircraft, for which the head-on RCS is of major importance, which have the potential to reduce current aircraft RCS from 100 m^2 to 10^{-6} m^2 (reference 12). Unfortunately, for warships which have a large and complex structure the task is more difficult and the threat is more diverse. The principle technique to reduce the average RCS is to remove all trihedral and dihedral reflectors. Their contribution can be significantly reduced by angling the plates so that they no longer meet at right angles. Even a small departure from 90° can reduce the wide-angle effect dramatically[11]. Unfortunately, the effect cannot be reduced by rounding the corner as is often, erroneously, believed.

A technique which modifies the RCS pattern, rather than reducing the overall energy returned, is to replace smoothly curving surfaces by flat plates. This produces a number of narrow beam-width flashes instead of the underlying steady component of RCS. An important adjunct to the removal of dihedral reflectors is another technique which modifies the RCS pattern. This is to concentrate the specular reflections away from the direction of highest threat, namely zero degrees elevation. By angling the ship's superstructure by a few degrees the specular reflections will only contribute to the RCS at the horizon at the extremes of the roll cycle. The angling is compatible with the need to remove trihedral and dihedral reflectors by avoiding perpendicular plates. The proposed introduction of increased flare into the hull-form of future R.N. vessels, although principally for naval architectural reasons, will also aid the reduction of RCS at zero elevation.

Specular reflections at higher angles of elevation than is currently common will be observed against a background of sea clutter. The clutter returns from waves persist for a timescale similar to the roll period of the ship. At these angles it is thus more difficult to distinguish between a number of specular reflections, fading as the ship rolls, and clutter.

The reduction and modification techniques which are beneficial at long range to frustrate detection are, in general, also beneficial in preventing effective targeting by missiles at closer ranges and in aiding ECM measures.

Modification of the RCS of existing ships is more difficult than for new design. The application of radar-absorbent material to trihedral reflectors does not modify their wide-angle characteristic but can reduce the amplitude of the return. Unfortunately, RAM is only effective over a limited range of frequencies so must be carefully matched to specific threats.

The potential gains of reduction and modification are complex and difficult to assess. Simplistically, a reduction in average RCS in the threat direction of 16 times is required to reduce the minimum detectable range of a ship by a factor of two. Forcing aggressors to close range from, say 40 km to 20 km before firing lock-before-launch missiles is a considerable benefit. If the pattern is modified, and the effects of diffraction and clutter are included, apparent gains are often enhanced. Homing missiles also have difficulty with a target that is providing a return that is not constant because of moving specular reflections and multipath effects especially when combined with a rapidly moving glint centre. If there is no steady baseline return the missiles will be more readily confused by ECM techniques some of which would otherwise have little chance of success.

A good example of the implementation of RCS modification measure is the Russian warship, *Kirov* (FIG. 7). Although the superstructure is built of flat plates, in neither plan nor elevation is there an evidence of a single right angle, thereby completely avoiding the possibility of trihedral or dihedral reflectors or curved surfaces which give wide-angle returns. The outer corners of the superstructure are not rounded but are chamfered with a flat plate. Not only are the superstructure plates angled but individual plates are at different angles ranging from 6° to 12° or greater. Radars at aspect angles of this magnitude will detect a number of peaks from these plates which, being at different angles and distance from the centreline of the ship, will interfere with each other to produce a scintillating return as the ship moves and rolls. The construction of a ship of this type is more costly than a traditional design based on perpendicular flat plates. Special provision has to be made, for instance, for doors (which must be vertical) into the angled superstructure. The U.S.S.R. obviously considers that this investment is worthwhile.

The Type 23 frigate will also have an angled superstructure. Considerable reductions in detectability are possible, both from the avoidance of trihedral reflectors and concentration of specular reflections away from the principal threat direction to a region where there is greater background clutter. The more fully flared hull will also help.

The counter to RCS reduction and modification techniques is more powerful radars and more sophisticated signal processing both of which would create problems for aircraft and missile designers. A move to millimetric frequencies may avoid multipath and fading but is not without its difficulties. The opposite approach, the move to high frequency (3 to 30 MHz)[13], whilst showing promise, currently requires large equipment and a long time to form an operational picture.

Summary

RCS is a parameter which describes the amount of energy returned towards a radar. For most targets it bears little relation to the actual area but is more strongly affected by orientation and geometry. A comparison of RCS patterns for vessels gives a good idea of the detectability of the warships by radar. Techniques, which need not be expensive, can reduce or modify the RCS pattern in order to decrease the possibility of detection and assist ECM measures in improving survivability from radar-guided attack.

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