Chapter 22
Civil Marine Radar

Andy Norris

22.1 INTRODUCTION

In terms of the number of systems in worldwide use, civil marine radar (CMR) is the largest radar market of all time. The number of vessels of all types currently fitted with radar probably amounts to around 3 million, but there are no official records to verify this estimate.

CMR breaks down into two main application areas. The vast majority are used at sea and on navigable waterways by ships and smaller craft; the others are used by port and coastal authorities for vessel surveillance from land-based sites. The latter group are normally known as *vessel tracking service (VTS*[†]*)* radars. Radars are available for leisure craft, fishing vessels and merchant ships, and all operate either in the 3 GHz or 9 GHz bands. Many navies also use standard or specially modified CMR for navigational purposes. Not only does it provide a suitable navigational tool but also its transmissions are identical to conventional commercial traffic, allowing safe navigation without necessarily highlighting a vessel's military purpose.

The biggest influence on the requirements of shipborne CMR comes from the International Maritime Organization[1] (IMO). A United Nations agency based in London, IMO is concerned with international maritime safety and the protection of the marine environment. In particular, IMO issues requirements and guidelines on the installation and use of radar equipment on commercial ships. These are vigorously enforced by the laws of individual maritime states. The purpose of shipborne radar, as defined by IMO, is to "assist in safe navigation and in avoiding collision by providing an indication, in relation to own ship, of the position of other surface craft, obstructions and hazards, navigation objects and shorelines."[2] The International Association of Marine Aids to Navigation and Lighthouse Authorities[3] (IALA) recommends operational and technical requirements for VTS radars.

This chapter explains the special requirements of CMR, both from a practical and a regulatory point of view, and looks at the technology and system concepts that are being used to meet these requirements. Until the first decade of the present century, CMR shipborne technology had been solely based on magnetrons as the basic source of transmitted power. Since 2004, IMO has encouraged the use of coherent radar solutions in an attempt to improve the detection of targets in heavy sea clutter conditions.

† A list of all used maritime abbreviations is included at the end of the chapter.

In the marine world, these have been called *New Technology Radars*. They are permitted to transmit any waveform at 3 GHz, providing the spectrum limitations on marine radar are not exceeded.[4] The limits have been agreed within the International Telecommunication Union[5] (ITU), a United Nations agency based in Geneva.

This chapter concentrates on the requirements and design of radars for commercial ships normally in excess of 300 gt (gross metric tonnage), where radar fitment is compulsory and highly regulated. Worldwide, there are about 50,000 of these vessels, and many are required to carry more than one radar. Three or even more radars are sometimes carried voluntarily by large ships. Radar forms an important part of a vessel's total navigation equipment fit. Increasingly, the bridge of a ship is designed as an integrated concept, covering navigation, communications, engine control, and cargo monitoring facilities. Figure 22.1 illustrates a modern *integrated bridge system* (IBS) as fitted on a cruise ship. The radar displays are seen to form a prominent part of the system. Radars fitted on smaller fishing vessels and leisure craft share many of the features of radars designed for ships but are necessarily more compact; a typical small boat radar is shown in Figure 22.2. Specific requirements for these radars, where they differ to any extent from the design of shipborne radars, are discussed within relevant parts of the chapter. Radar for VTS is separately covered in Section 22.10.

The challenges facing designers of shipborne radar are detailed within Section 22.2. These radars have to meet certain international standards, which are discussed in Section 22.3. Section 22.4 concentrates on the technology, and Section 22.5 looks at target tracking. Radar targets are being increasingly displayed with electronic chart data as an underlay. This is outlined in Section 22.6, together with other user interface issues. Section 22.7 looks at the links between radar and the relatively new *Automatic Identification System* (AIS), which replicates some functions previously provided solely by radar. Marine radar beacons, including racons, *Search and Rescue Transponders* (SARTs), and *Radar Target Enhancers* (RTEs), are described in Section 22.8. There is a short discussion in Section 22.9 on shipborne radar performance validation testing.

FIGURE 22.1 Ship's integrated bridge system (*Courtesy of SAM-Electronics GmbH*)

FIGURE 22.2 Small boat radar (*Courtesy Furuno USA, Inc.*)

Shipborne radar has had a remarkably long history. Its conception in the period from 1945 to 1948 was remarkably prophetic and still reverberates into the present century. For this reason, a short Appendix to this chapter outlines the early steps in the evolution of global standards for shipborne radar.

22.2 THE CHALLENGES

Environmental. Civil marine radar, particularly shipborne navigation radar, is a surprisingly demanding application. The radar head on a CMR comprises the antenna and turning gear, the receiver down to IF or to digital format and often the transmitter. It has to operate in extreme environmental conditions over an extended temperature range (down to –40°C in some parts of the world); in high levels of wind, vibration, and shock; and also in heavy precipitation and salt water spray. Even within the normally benign conditions on the bridge of a large modern ship, the display and radar processor can be subject to high levels of shock and vibration and must meet high variations in temperature (–15°C to +55°C). On small craft, the display and radar processor are often fitted in minimally enclosed areas and are subject to very damp and salty conditions. In these environments, the radar has to detect targets that can have echoing areas ranging from less than one square meter to many tens of thousands of square meters; important targets can have relative speeds ranging from stationary to 100 knots or more; the targets can be situated in extreme precipitation and sea clutter conditions; and the radar antenna is not mounted on a static nor a stable platform. The radar is used to prevent collisions and groundings at sea and is, therefore, an important safety related system, requiring integrity and reliability. For most commercial ships, the radar needs to meet stringent, internationally agreed performance criteria. Despite these requirements, systems are sold in a highly competitive market and prices are, therefore, kept keen. Prices range from around $10,000 for a complete but basic 9 GHz system to $40,000 and above for a fully featured 3 GHz system. Radar systems suitable for the leisure market can sell for less than $1,500.

TABLE 22.1 IMO Required Detection Performance in Clear Conditions (*Courtesy of IMO*)

Target Description	Target Feature: Height Above Sea Level (meters)	Detection Range in NM (for specified target size): 9 GHz NM	3 GHz NM	Target Type
Shorelines	Rising to 60	20	20	Distributed
Shorelines	Rising to 6	8	8	
Shorelines	Rising to 3	6	6	
SOLAS ships† (> 5,000 gt)	10	11	11	Complex
SOLAS ships† (> 500 gt)	5.0	8	8	
Small vessel with radar reflector meeting IMO performance standards	4.0	5.0 (7.5 m^2)	3.7 (0.5 m^2)	Point
Small vessel of length 10 m with no radar reflector	2.0	3.4 (2.5 m^2)	3.0 (1.4 m^2)	Complex
Typical navigation buoy	3.5	4.6 (5.0 m^2)	3.0 (0.5 m^2)	Not specified, point target assumed
Navigation buoy with corner reflector	3.5	4.9 (10 m^2)	3. 6 (1.0 m^2)	Point
Typical channel marker	1.0	2.0 (1.0 m^2)	1.0 (0.1 m^2)	Not specified, point target assumed

† Ships conforming to the IMO Safety of Life at Sea (SOLAS[9]) regulations

Detection Performance. In-the-clear detection requirements for such radars are not particularly demanding. An 80% probability of detection and a probability of false alarm of 10^{-4} is specified by IMO, as shown in Table 22.1.[2]

Taking into account all performance requirements, typical compliant systems for commercial vessels have peak transmit powers of 4 – 60 kW, the lower powers being confined to 9 GHz systems. Antenna gains from 28 to 33 dB are typical, with associated horizontal beamwidths ranging from about 2.5° to less than 1°. Pulse lengths are switchable, generally in the range from 50 ns to 1 μs, with PRFs ranging from 350 to 3,000 Hz or more. Pleasure craft systems typically have peak powers of 2 – 4 kW and utilize antennas with horizontal apertures as small as 450 mm and gains of about 24 dB. These all operate at 9 GHz. The greatest technical challenge in designing marine radars is to maintain good target detection in high levels of sea and precipitation clutter.

Precipitation Clutter. It is well known that circular polarization (CP) can be a counter to rain clutter because its reflection is predominately cross-polarized to incident circular polarization. However, very few shipborne navigational radars use CP, even though 10–20 dB improvement in rain clutter rejection is typically achieved from its application. Two important factors have contributed to this. First, it makes the antenna more expensive, exacerbated by IMO's requirements that 9 GHz radars must be at least switchable to horizontal polarization when searching for survival craft fitted with Search and Rescue Transponders (see Section 22.8). Second, by use of small range cells and by implementing conventional signal differentiation techniques, modern radars, particularly at 3 GHz, give reasonable performance in most commonly experienced precipitation clutter. Therefore, users and maritime authorities are generally satisfied with the performance of linearly polarized systems in precipitation.

Because precipitation clutter is distributed in a relatively uniform manner, passing the received waveform through a differentiator gives prominence to targets embedded within the clutter by ensuring that the average clutter level is kept well below saturation. The differentiator has minimal effect on normal targets because of their small extent in the time domain. This means that target visibility is improved. It should be noted that this technique does not give subclutter visibility. This process is conventionally named *Fast Time Constant* (FTC). The time constant of the differentiator is operator-adjustable with a so-called rain clutter control, which allows the target-to-clutter ratio to be optimized for the particular precipitation scenario.

The vertical pattern of a shipborne navigational radar antenna needs to be relatively wide to cope with the ship's pitch and roll, which is assumed to be a maximum of ±10°. (Use of a stabilized platform would not meet the market's price demands.) This limits the vertical beam-shaping that can be used to reduce both precipitation clutter and vertical lobing effects. However, the relatively short range of most targets of real interest means that the volume of the radar-illuminated precipitation is relatively low, helping to make the clutter rejection of the differentiator adequate for its purpose. Such clutter varies approximately with the fourth power of frequency, and so a 3 GHz system inherently experiences 19 dB less clutter than a 9 GHz system, assuming identically sized clutter cells. For this reason, on ships fitted with both 3 and 9 GHz radars, the 3 GHz radar is often preferable, except when maneuvering in close situations, for example, in harbors when the normally superior azimuth resolution of a 9 GHz radar is preferred.

Sea Clutter. The reduction of sea clutter to levels acceptable to the user is a far more difficult problem, and as yet, commercial radars do not meet all the ideal demands of users. Small craft and buoys can easily be obscured in sea clutter. In the days before precise *Global Navigation Satellite Systems* (GNSS), such as GPS, the safe navigation of a ship in coastal waters in poor visibility was dominated by the radar being able to discern navigation markers, such as buoys. Passive markers, including those supplemented by radar reflectors, can be notoriously difficult to detect in higher sea-states, and therefore, some markers are supplemented by radar beacons (called racons—see Section 22.8). Racons are relatively expensive and need maintenance in often difficult to access locations, so their use is restricted. While GNSS, enhanced by the growing use of electronic charts, has helped greatly in informing mariners of the precise position of their vessel, radar is still used as an important secondary source of position. Reliance on GNSS alone has been at the root of many marine accidents.

The main use of marine radar is to assist collision avoidance. Visual observation and radar remain the primary methods for determining the risk of collision with other vessels and also with floating debris and ice. Automatic Identification Systems (AIS—see Section 22.7) offer potential to assist with collision avoidance of cooperative targets, but it cannot be assumed that all vessels are fitted with AIS, particularly small craft, or that a target vessel's AIS is operational.

The traditional way for mariners to optimize their radar for detection of targets in sea clutter is by careful adjustment of the "gain" and "sea-clutter" controls. The gain control effectively alters the detection threshold. On a modern marine radar, the sea-clutter control is best described as a method for adjusting the shape of the radar's *sensitivity time control* (STC) in order to match it with the present level of clutter returns. STC is often also called *swept gain*. The STC law, and the way it varies by use of the manual control, can be complex. It is attempting to reduce the dynamic range of the received waveform and to provide, in association with the gain settings, optimized thresholds.

Nowadays, it normally involves sophisticated adaptive thresholding techniques, which are discussed in Section 22.4.

Although this helps to set the threshold to appropriate levels, it does not remove the intrusive "spiky" component of sea clutter that can make wanted targets difficult to observe. However, over a typical antenna scan time of a marine radar (2–3 seconds), the spikes are normally decorrelated, whereas returns from targets are generally correlated—therefore, the application of scan-to-scan correlation can improve the target-to-clutter ratio, but it will also remove weak and fast-moving targets. Many years ago, Croney[6] showed that significant improvements in detecting small targets in sea clutter could be obtained by ensuring that integration was performed at intervals longer than the decorrelation time period of the sea clutter. He used an antenna rotating at up to 600 rpm and a PRF of 5 KHz. This gave two correlated pulses per beamwidth, but the pulses from the next scan, 0.1 s later, were decorrelated from the former.

Crony noted that the rapid scanning of the antenna allowed the eye/brain functions of the operator to perform scan-to-scan correlation. Although it is easy for modern systems to perform this correlation digitally, the difficulties in having an antenna rotating at this speed (mainly now a cost issue) have prevented this from becoming established practice. However, more recent work in Canada has resurrected this idea for detecting floating ice hazards, where antenna rotation rates of 500 rpm and PRFs of 12 KHz have been proposed.[7] Terma A/S, a Danish company involved in supplying high performance marine radars, mainly in the noncommercial market, produces the Scanter™ radar, which has an option that simultaneously transmits on two frequencies from a squinting slotted waveguide array. This produces two beams separated by a few degrees in azimuth. The temporal beam separation is such that sea clutter can be decorrelated between the beams, further enhancing the detection of targets in clutter. This technique could potentially be used by solid-state CMRs. (Section 22.4).

On a conventional shipborne radar, an experienced operator can manually set the detection threshold to give the best setting over any given area, but this is often only effective over a small proportion of the total radar image. The use of automatic thresholding is able to give better detection over a complete scan but often cannot compete with a skilled operator optimizing detection over a restricted area. In some conditions, no existing radar gives the performance that a user ideally needs, despite the use of 50 ns pulses and sophisticated clutter processing technology.

Sub-clutter visibility is potentially obtainable from coherent CMRs, which have been made affordable by the continued reduction in cost of microwave power semiconductors (for instance, using Gallium Nitride technology), precision digitally controlled signal generators, and fast digital signal processors. Coherent CMRs are discussed under "Solid-state CMR" in Section 22.4.

Vertical Lobing. Clutter is not the only cause of detrimental performance of marine radar. Direct reflections from a target arrive at the radar antenna and combine vectorially with target reflections that have also been reflected by the sea's surface. This effect produces a summed signal at the radar antenna that is a function of both the target height and the radar antenna height above the sea, as these affect the path length difference of the direct and reflected radiation. Obviously, the effect is reciprocal for both transmit and receive paths. For a point target and a sea of defined roughness, the calculation to determine the resultant effect is relatively straightforward and results in the classic lobing pattern (see, for example, Briggs[8]). For a target with reasonable vertical extent, such as a ship, the lobing structure becomes very complex and is less likely to produce troublesome nulls. However, the detection of a small target, such as a buoy or a pleasure craft, enhanced by a radar reflector can create significant vertical lobing effects that can be a problem to the user. In particular, in very calm seas pronounced nulls can be experienced, and for users, it can be disconcerting when a target clearly evident from the bridge window is not visible on the radar display, despite the apparently good conditions.

Since smooth seas can also be associated with mist and fog, vertical lobing effects can become a significant problem because the reduced visibility means that radar often becomes the sole method of detecting other vessels. The absence of sea clutter gives the user a false sense of security that all targets will be easily visible. On ships fitted with both 3 and 9 GHz radars, frequency diversity becomes very useful as the spatial frequencies of the vertical lobes for the radar are different. Surprisingly, even though some radar companies provide the option, very few ships have facilities that allow the 3- and 9 GHz signals to be combined into a single radar display in an automatic process, maximizing the benefits of frequency diversity. Some large ships have an additional 9 GHz radar mounted on the bow at deck level. This has two advantages. First, the vertical lobing will have a different (lower) angular frequency to the main, high-mounted 9 GHz radar. Second, its performance in sea clutter will be enhanced, as the grazing angle to the sea will be closer to horizontal, thereby lessening the reflection coefficient of the clutter. The long range performance of the auxiliary system is, of course, compromised by its low position.

Moving Platform. A particular complication of shipborne radar arises because the antenna is mounted on an unstable moving platform. This movement has six components—three translational and three rotational, all of which are typically varying. The motions are complex; the translational components are surge, sway, and heave, and the rotational are roll, pitch, and yaw. Components can be quasi-harmonic when caused by wave motion. In practice, the ship is navigated on notions based on course, heading, and speed in Earth and sea-fixed coordinate systems. The additional wave-induced motions can produce uncompensated errors in radar-derived information, which add to any measurement errors in the course, heading, and speed of the vessel. This affects the precision obtained when displaying radar-derived data, which can differ when switching between the various radar stabilization modes used on CMR. For instance, in order to facilitate both collision avoidance and position fixing activities, shipborne radar displays have always had two particular stabilization modes: Head-up and North-up. The "up" direction refers to the vertical (y-axis) direction of the radar display; "Head" refers to the ship's heading. Head-up maximizes the relationship to the visual scene, and North-up aids comparison with paper charts. Nowadays, Course-up is also provided, as this eliminates small oscillations in the radar image due to the ship's yaw that occur when the display is set to Head-up. Each of these directional modes can be set with target tracking vectors shown as relative to the motion of the ship, the ground, or the average sea motion.

22.3 INTERNATIONAL STANDARDS

Spectrum use aspects of all radars, including frequency band of use and RF emission constraints, are controlled by the ITU.[5] Following ITU requirements, marine radars are permitted to operate in the 9.3 to 9.5 GHz band (X band) and in the 2.9 to 3.1 GHz band (S band).

The IMO International Convention for the Safety of Life at Sea (SOLAS)[9] is an established and accepted set of principles and rules aimed at ensuring that ships meet certain requirements to enhance both safety and protection of the environment. The member governments (flag States) of IMO have agreed that SOLAS requirements are embodied within their national maritime laws and regulations. Within Chapter V of *SOLAS - Safety of Navigation*, the requirements for the carriage of navigation equipment are defined. These vary according to the size and purpose of a ship. All passenger ships and all ships above 300 gt need to carry at least one radar with tracking facilities.

Footnotes within Chapter V of SOLAS identify the recommended IMO performance standards with which the equipment should conform. IMO has had recommended radar performance standards[2] since 1971, published as annexes to IMO Resolutions. However, by 1980, radar manufacturers were reporting difficulties because differing interpretations by national maritime administrations meant that radars had to be specifically designed to meet individual flag State requirements. The level of technical detail required to remedy this was outside the remit of IMO, and it was agreed that a Technical Committee (TC80) within the International Electrotechnical Commission[10] (IEC) would determine technically based interpretations of IMO radar performance standards. In addition, it was agreed that the IEC standards would include test procedures, which could be used by national maritime administrations (such as the Coast Guard in the United States of America) to test for conformance of specific designs by manufacturers to IMO and ITU requirements. Today, virtually all national administrations use IEC standards to assess radar and most other IMO-defined navigational and radiocommunications equipment.

IMO performance standards and the SOLAS Convention are regularly revised, so it is important to check the current status of the standards. IEC 62388[11] defines the technical and test standards based on the IMO radar performance standards. IEC standards also undergo regular revision. An average radar installation has a life normally exceeding 10 years, so radars designed and approved to previous standards will continue to be used for some years after new standards have been put in place. Retrofitted equipment must meet the latest standards.

IMO radar performance standards previous to those in force on 1 July 2008 require compatibility with existing racons (radar beacons) and at 9 GHz, Search and Rescue Transponders. This implies the continued use of short pulse radars. However, for the 2008 standards, IMO has encouraged improvements in sea clutter performance by dropping the need for racon compatibility at 3 GHz, thereby allowing other forms of modulation that would enable affordable coherent processing techniques. Because all ships above 300 gt need to carry at least a single 9 GHz radar, it means that racon (and SART) detection capability is maintained. This approach gives IMO an indefinite period to assess the impact of the new regulations on the detection of targets in sea clutter before deciding what should happen with radar, racons, and SARTs at 9 GHz.

Another major change in the requirements of older standards is that all new radars must include provision to display Automatic Identification System (AIS) targets and that their related information can be accessed on the radar display. The requirements for target tracking has also had a major revision, with automatic tracking facilities being required for all radars. The integration of electronic chart data as a background to radar images is also embodied within IMO standards. Radars with this optional facility are known as *Chart Radars*.

The minimum detection performance required in clear conditions is tabulated in Table 22.1. Measurements of range have to be within 30 meters accuracy (or within 1% of the maximum range scale in use) and within 1° bearing (azimuth angle). Navigational buoys with the characteristics given in Table 22.1 have to be detectable at a minimum range of 40 meters. Two "point" targets on the same bearing have to appear as two distinct targets if they are separated by more than 40 meters in range. A 2.5° azimuth resolution is also required. All these performance figures are considered to be peak errors, which can be assumed to mean 95% values, measured with standardized point targets. The IMO performance standards recognize that the detection performance of radars working within conditions of clutter will not necessarily give the performance defined for clear conditions. Manufacturers are required to provide effective manual and automatic anti-clutter functions and must specify the expected degradation in rain at 4 mm and 16 mm per hour and for sea states 2 and 5, including combinations of sea and rain clutter.

Radars designed for conventional vessels need to operate with relative speeds up to 100 kt. For high-speed craft, such as multi-hull fast ferries, the radars need to operate with relative target speeds up to 140 kt. Older standards required a minimum antenna rotation rate of 20 rpm, but this explicit requirement has been omitted from the new standards as other dependent requirements are adequately specified, such as the maximum relative speed of targets and tracking accuracies. The IMO performance standards specify that radar equipment should meet the environmental requirements and test procedures defined within IEC 60945.[12] This is a comprehensive set of requirements that are applicable to all ships' navigational and radio communications equipment. They cover such aspects as temperature, shock, vibration, corrosion, and resistance to water and oil ingress. Detailed requirements on electromagnetic emissions and immunity to the electromagnetic environment are mandated. IEC 60945 also specifies general requirements on ergonomics, software development, and safety. A further set of IEC standards contained within the IEC 61162 series,[13] define the messages used for navigation and radiocommunications equipment to interchange digital data. A shipborne radar is likely to be receiving messages from many items of navigation equipment, such as AIS, GPS, gyrocompass, log, and echo sounder, and is also likely to be communicating track information to electronic chart systems and possibly other radar displays.

A number of manufacturers produce radars specifically designed to be used on vessels using the world's major inland waterways. These are known as *river radars*. They are epitomized by their superior short-range performance and by having a display in "portrait" format in order to get maximum look-ahead along the waterway. The maximum display range on the shortest scale is typically 150 meters. These radars are normally designed to meet requirements for radars on vessels navigating the River Rhine.[14]

Radars for the fishing and leisure markets are not covered by SOLAS. Until 2004, such radars did not have an internationally recognized standard for manufacturers to follow. IEC 62252[15] is now the agreed international radar standard for "craft not in compliance with IMO SOLAS Chapter V" and was initially issued at the instigation of manufacturers. Now an increasing number of national maritime administrations are insisting that all new small craft radars sold in their jurisdiction conform to this standard. IEC 62252 recognizes three classes of radar. Class A is intended for commercial craft under 150 gt; Class B is for recreational craft; and Class C is for small recreational craft. The main performance requirements are detailed in Table 22.2.

TABLE 22.2 Radar Performance Requirements for Small Craft (*Courtesy of IEC*)*

			Coast-Line Detection Range		Point Target Detection Range		
Class	Beamwidth	Minimum Display Size	Rising to 60 m	Rising to 6 m	400 m^2 7.5 m ht	10 m^2 3.5 m ht	5 m^2 3.5 m ht
A	≤ 4.0°	≥ 150 mm	9 nm	5 nm	5 nm	2 nm	1 nm
B	≤ 5.5°	≥ 85 mm	5 nm	3 nm	3 nm	1 nm	N/A
C	≤ 7.5°	≥ 75 mm	5 nm	3 nm	3 nm	1 nm	N/A

22.4 TECHNOLOGY

Antennas. Antenna maximum sidelobes are specified for SOLAS and non-SOLAS radars in IEC 62388[11] and IEC 62252,[15] respectively. These are summarized in Table 22.3.

On non-SOLAS radars, the antenna rotation rate is specified to be not less than 20 rpm but is not directly specified for SOLAS-approved radars. In practice, antennas for existing shipborne radars normally rotate at 25–30 rpm; on high-speed craft, the rotation rate is typically 40–45 rpm. For SOLAS vessels, the antenna must be able to start and operate in relative wind speeds up to 100 kt; other environmental requirements for the antenna system are detailed in IEC 60945,[12] where there are specific tests for "exposed" equipment.

There are no explicit requirements on other antenna parameters for SOLAS-approved systems, such as beamwidths and gain, but these obviously need to be compatible with the total radar performance requirement. For instance, azimuth resolution has to be better than 2.5°; target bearing has to be determined to within 1°; and the system must operate in conditions when the ship is rolling and pitching ±10°. Typical antenna gains and beamwidths have been outlined in Section 22.2.

From the 1960s onwards, the use of a slotted waveguide linear array, mounted in a linear flared horn has been the most common antenna solution for shipborne radars. Because at least horizontal polarization has to be provided on 9 GHz SOLAS radars, slotted array solutions generally have their slots cut into the narrow wall of the horizontally mounted waveguide. A vertical slot (perpendicular to the waveguide edge) couples no power, but as the slot is increasingly angled, more power is coupled out. The slots are normally of a resonant length (half-wavelength) to couple out sufficient power. This extends the slot into the broad wall of the waveguide, but it also makes them easier to construct—conceptually by a sawing action into the narrow wall. Residual power at the end of the array (typically less than 5%) is dissipated into a matched load. Conventionally, the array is end-fed, although center-fed alternatives are sometimes used.

TABLE 22.3 Antenna Sidelobe Performance Requirements (*Courtesy of IEC*)

	Maximum Sidelobe Level (dB)	
Radar Class	Within ±10°	Within ±10°
SOLAS	–23	–30
Non-SOLAS Class A	–20	–23
Non-SOLAS Classes B & C	–18	–19

If slots were spaced at the guide wavelength in an attempt to get an equi-phase wavefront at the antenna face, then large grating lobes would be generated in the far-field pattern. This would occur because they would be spaced at a free-space distance of more than one wavelength. To overcome this, slots are spaced at nominally half the guide wavelength but are angled alternately to the vertical in order to induce the necessary phase reversals. In practice, the slots are placed slightly away from half the guide wavelength spacing to avoid slot-generated mismatches in the waveguide becoming resonant. This creates a tilted phase front across the array, which causes the beam to squint to an angle that is frequency dependent. Individual manufacturers produce radar systems operating over a restricted band, much less than the overall radar band, which removes any need for individual squint compensation when magnetrons are replaced. The required sidelobe performance is not demanding (Table 22.3), and so simple aperture distributions, such as pedestal-based cosine squared, are common. The small vertically polarized fields produced by each slanted slot need to be suppressed as they can otherwise lead to high cross-polarized sidelobes from the array, exacerbated by the phase reversal of the cross-polar component from slot to slot, causing cross-polar grating lobes. This can be achieved with a printed polarization filter in front of the array or by effectively creating, as part of the structure, a short length of open-ended waveguide in front of each slot, with dimensions that make it below cutoff for vertical polarization.

Slot characterization is normally performed by measurement, rather than by detailed electromagnetic analysis. This allows all construction details, including those required for polarization filtering, to be incorporated into the slot characterization; sufficient accuracy is difficult to achieve using numerical analysis. Provided the characterization is done carefully and good manufacturing techniques can guarantee tolerances, it is reasonably straightforward to produce affordable antennas that meet IMO requirements. The required vertical beamwidth is normally obtained by a linear flare. The flare angle is chosen such that it creates a reasonably phase-constant vertical distribution at its aperture. The vertical amplitude distribution approximates to a cosine because of the horizontally polarized field. Vertical beamwidths are typically about 25° wide at the 3 dB points.

Not unnaturally, cost, for a given performance, is the prime driver in the system designer's choice of antenna. While the conventional slotted linear array is widely used, there are examples where different cost tradeoffs have been made. For instance, the use of a dielectric block mounted directly in front of the slotted waveguide array, in place of the flared section, has been used as an alternative. The leaking energy from the top and bottom faces of the dielectric block adds with energy emerging from its front face, giving forward gain. It is the depth dimension of the dielectric block that determines the gain, somewhat analogous to the length of a Yagi antenna. This effect reduces the height of the antenna compared to a conventional design by about a factor of three, typically from about 300 mm to 100 mm at 3 GHz. This means that there is considerably less wind-loading. The dielectric constant of the block can be quite low, which, with the reduced wind-loading, results in a very lightweight structure. This saves costs in the antenna turning gear and makes the installation easier. An example of this type of antenna, produced by Kelvin Hughes, is illustrated in Figure 22.3.

Small craft radars have used printed arrays for some years, as well as slotted waveguide arrays. Small, horn-fed parabolic reflector systems have also been used. Antennas for small craft are normally housed within a radome, which protects the antenna and up-mast electronics of the radar environmentally and prevents the antenna from snagging the rigging. In particular, it assures that there is no danger to

FIGURE 22.3 Low-profile 3.9 meter S-band shipborne radar antenna (*Courtesy of Kelvin Hughes Ltd.*)

users from rotating mechanisms, since the radar head can be mounted in areas open to human access. Antennas using printed arrays use integral-printed power dividers. The arrays are usually two-dimensional, dispensing with the need for a flared section, and normally consist of radiating patches, rather than printed dipoles. Horizontal apertures of 450 and 600 mm are common. Printed technology is not generally used for shipborne antennas; slotted waveguide arrays remain the cost-effective solution for larger arrays, particularly as the higher power creates additional complications for printed power dividers.

Poor antenna siting is a common cause of radar performance degradation on ships as well as on smaller craft. Particularly on ships, it is surprising that installations are still being implemented that create significant blockage to the radar. Blind arcs are common from funnels and other superstructure, and there can be significant sidelobe degradation due to smaller structures, such as VHF antennas, causing blockage close to the radar antenna aperture.

RF Head. The RF head normally comprises the transmitter and the receiver down to IF or digital baseband, as well as the antenna and turning gear. Its design for both magnetron-based SOLAS and non-SOLAS radars follows conventional principles. The magnetron is connected to the antenna via a duplexer and a rotating joint. The magnetron has a typical operational life of about 10,000 hours and is by far the lowest lifed component in the whole system. The duplexer is nowadays a three- or four-port ferrite circulator. Use of a four-port device is preferred as it presents a better matched load to the magnetron and, therefore, gives a cleaner RF spectrum. The *low-noise front-end* (LNFE) subsystem is connected to the circulator via a PIN diode limiter, which protects the LNFE during pulse transmission.

The modulator to the magnetron is typically a *pulse forming network* (PFN), basically comprised of capacitors and inductors. Operator control of the pulse length effectively switches in different choices of reactive components. The discharge of the PFN is controlled by a high voltage switch, which is often a silicon-controlled rectifier; thyristors and FETs are also used. FET modulators are sometimes driven directly by a pulse input rather than a PFN. Finally, a pulse transformer matches the PFN to the impedance seen at the magnetron cathode. A pulse of around 10 kV is required to fire the magnetron. In order to get good performance over a wide range of pulse lengths, designs utilize a great deal of empirically derived knowledge, and actual circuits can be surprisingly complex. A 50 ns pulse hardly achieves any period of stability—rise times are normally restricted to about 10 ns in order to limit out-of-band interference, and fall times are usually longer. The extra high voltages involved can lead to poor reliability if the design does not adequately address the associated problems. Careful physical layout is essential and consideration must be given to the effects of operating in a potentially damp environment. Pulse timing can be purposely jittered on a pulse-to-pulse basis. Pulse-to-pulse correlation in the radar processor then very effectively blocks interference from other radars, albeit with a small but generally acceptable degradation in detection performance.

After the limiter, the LNFE is preceded by a bandpass filter to reduce the effects of out-of-band interfering signals. The LNFE consists of an RF amplifier (typically giving about 10 dB gain) and a balanced mixer, local oscillator, and IF head amplifier. These are normally supplied to the radar manufacturer by specialist companies as a complete subunit. The overall system noise figure is typically 4 to 5 dB, but lower figures are achievable. The frequency of the local oscillator is generally driven by a control signal, derived from within the IF amplifier. It includes facilities for manual frequency control by the operator. The latter can be useful, for instance, when looking for SARTs in heavy sea clutter, as it allows returns from own transmissions to be desensitized. The local oscillator uses a Gunn diode or an FET, giving a typical intermediate frequency of 60 MHz.

Detection and Processing. After the LNFE, a logarithmic amplifier reduces the dynamic range of the received signal to prevent limiting. A dynamic range of around 100 dB is typically achieved in perhaps an eight-stage amplifier. Filtering, consistent with the transmitted pulse length, is applied within the IF amplifier. The output from the log amplifier enters a diode-based envelope detector, converting the signal to baseband for subsequent threshold processing. Setting the threshold has become intimately connected with the sensitivity time control (STC) of the radar. The fundamental use of STC is to take out the distance-related dynamic range of received signals. At close range, STC classically follows an inverse fourth power law, merging to an inverse cubic law in the region where sea clutter dominates, in accordance with basic theory. Because transition range is a function of antenna height, a setting for this may be needed when the system is originally installed. The operator's manual sea-clutter control is used to adjust the transition range. Nowadays, the form of the STC curve and the effects of the manual control are based on the practical experience of individual manufacturers, which contributes greatly to the actual effectiveness of a particular radar in sea clutter. Even under manual control, the detailed shape of the STC curve may have a complex adaptive element to it, in order to optimize thresholds over a broader range.

Under automatic settings, thresholding becomes increasingly sophisticated but often still allows some manual optimization. The curve may adapt to internal calculations made on returns from the last pulse or from a succession of pulses. It may also include more complex clutter-mapping processes. All of this is attempting to create a constant false alarm rate across the radar display. Since the radar is sited on a moving platform, subject to complex dynamics, difficulties arise with clutter mapping. However, modern processors permit affordable thresholding algorithms of considerable complexity. Manufacturers keep their own processes highly confidential because of the effort that has gone into their empirical optimization. Theoretical clutter models have been generally found unsuitable to be used for optimization. Even optimizing for sea conditions found in one particular area can create suboptimal solutions in other areas, and therefore, data from a number of regions need to be used to design a globally effective product.

STC and thresholding is a process that is controlled in the digital domain but often applies analog gain processes at RF and IF (at both pre- and post-log amplification) as well as processes in the digital domain. Intimately connected with thresholding strategies are signal processing, such as FTC, pulse integration, and correlation processes, both pulse-to-pulse and scan-to-scan. Modern digital technology, with its processing speed, available word length, and large memory capability, allows the radar designer to have great flexibility in the strategy applied, and what are entirely separate processes in the analog world increasingly become an integrated digital process. Simple thresholding ideas are being replaced by complex logical processes, making a detailed evaluation of whether a potential target is present or not, even potentially merging into plot extraction and tracking processes.

More complex processing can also yield additional information that is useful to marine operators. For instance, by applying spectrum analysis techniques, it is possible to extract accurate sea-state information, including significant wave height and period, direction, and speed.[16] The Miros A/S Wavex™ system determines directional wave spectra scaled in m^2/Hz and parameters such as significant wave height and average wave period. An FFT is performed on data collected on a scan-by-scan basis; 32 scans of data are typically used in the analysis. The resultant information can be highly useful for large high-speed craft, perhaps traveling at up to 60 knots or more. It is also potentially useful for vulnerable vessels such as chemical carriers to ensure that appropriate action in heavy weather can be taken, particularly at night or in poor visibility. Ocean oil rig operations can also benefit from such systems. Information can be displayed to the user in the form of digital readouts of the primary parameters, as well as graphically displayed data. Installed systems normally extract the raw data from the existing 9 GHz radar and perform wave processing and display functions on a separate processor/display system. Spectrum analysis of this type can also detect oil slicks[17] because they reduce the amplitude of sea surface capillary waves. Such systems can be valuable on vessels assisting with clean-up operations and also for early detection of spills from oil rig operations.

It has been proposed[18] that additional processing of the cross-polar content of the received radar signal may be of benefit to marine operations where sea ice is a hazard. Due to structural changes that occur in older ice that affect the reflection of radar energy, it is possible to differentiate between potentially dangerous old ice, including glacial ice (icebergs), and single-season sea ice, which is normally less dangerous to navigation. This is because the cross-polar component of the reflection is significantly higher for old ice compared to new ice. The problem is how to affordably determine the cross-polar component.

In practice, it has been found that excellent ice detection can be made by optimized processing of conventional marine radar signals.[7] Because of the slow-moving nature of the targets of interest, averaging the radar image over many antenna scans using an optimized infinite impulse response (IIR) filter can give a very detailed image that allows the user to differentiate between ice and water areas. In particular, small ice features such as bergy bits (icebergs with dimensions above the waterline of less than 5 meters in breadth and greater than 1 meter in height) and growlers (less than 2 meters in breadth and less than 1 meter showing above the water line) are readily detected by such systems. Integration over 128 seconds has been found to be suitable, with the antenna rotating at 120 rpm. The increased capability of (ice) target detection in sea clutter with higher antenna rotation rates has also been demonstrated. Dramatic images of ice hazards can be produced by such radars, such as that illustrated in Figure 22.4.

FIGURE 22.4 Ice feature detection using IIR filtering on Rutter Sigma 6 radar processor (*Courtesy of Transport Canada*)

Solid-state CMR. Several factors have come together to promote the introduction of civil marine radars with solid-state transmitters. The most important of these is that affordable magnetron-based radars do not meet user demands when operating in heavy sea and precipitation clutter. Small craft and buoys become invisible on the display, creating danger to life. IMO recognized this problem and, in order not to constrain opportunities for innovative radar design, removed the requirement that 3 GHz radars be compatible with existing racons.

Gallium Nitride and other microwave power semiconductors,[19] developed primarily for broadband communications links, have enabled CMR manufacturers to use these in the radar transmitter to replace magnetron-based designs. Pulse compression techniques are used to reduce the required peak power. Even single Gallium Nitride devices can generate hundreds of watts of peak power, at mean powers easily sufficient for CMR applications. Also, advances in digitally controlled waveform generators have given designers the ability to create pulse-compressed waveforms with high precision and at low cost. These waveforms enable coherent processing of the received signal, giving additional doppler information that can be used to help separate targets from clutter. The use of frequency diversity techniques to give added target detection possibilities becomes potentially affordable, because of the flexibility of the signal generation technology. Cost has precluded the use of dual-magnetron transmitters for this purpose.

Demands from other services for more bandwidth, particularly from mobile communications operators, continue to put pressure on the ITU-determined marine radar spectrum limits (see, for example, Williams[20]). Since the peak transmitted power from solid-state CMRs is very low compared to magnetron-based radars, for example 200 W compared to 30 kW, the spectrum interference levels are much reduced and, therefore, extended use of this technology could result in better use of the RF spectrum. Also, the highly controlled waveforms are expected to create less spectral noise than typical magnetron-based CMR transmitters.

An example of a solid-state coherent radar is the Kelvin Hughes SharpEye™—the first introduction of such an IMO-compliant system to the CMR market. It has a peak output power of 170 W and a duty cycle of 10%. Figure 22.5 shows a photograph of the transmitter electronics. In order to obtain the required short-range performance, it transmits a frame of pulses with differing lengths. Each pulse within the frame is optimized to cover a specified range bracket. Overall, the pulse sequence completely covers the instrumented range and ensures that the IMO specified minimum range requirement is met.

In the receiver, frames are grouped into blocks called bursts. The duration of a burst is approximately equal to the time taken for the 3 dB points of the antenna azimuth beam to sweep past a point target; consequently, the number of pulses in a burst is directly related to the instrumented range and the antenna rotation rate. The echoes received during a burst are processed by a filter bank to extract the radial velocities of targets and clutter. Within the digital signal processor, detection thresholds for each of the filters within the bank are calculated adaptively, aiming at providing optimum control of false alarms while maximizing clutter suppression and target detection. Manual control of the thresholds is also provided to be compliant with IMO requirements.

Modern, fully solid-state radars need little analog circuitry within their designs; they operate on low voltages and have no time-lifed components such as magnetrons. This potentially makes them extremely stable and reliable, with a resultant low cost of ownership, therefore, meeting the increasing demands of ship operators.

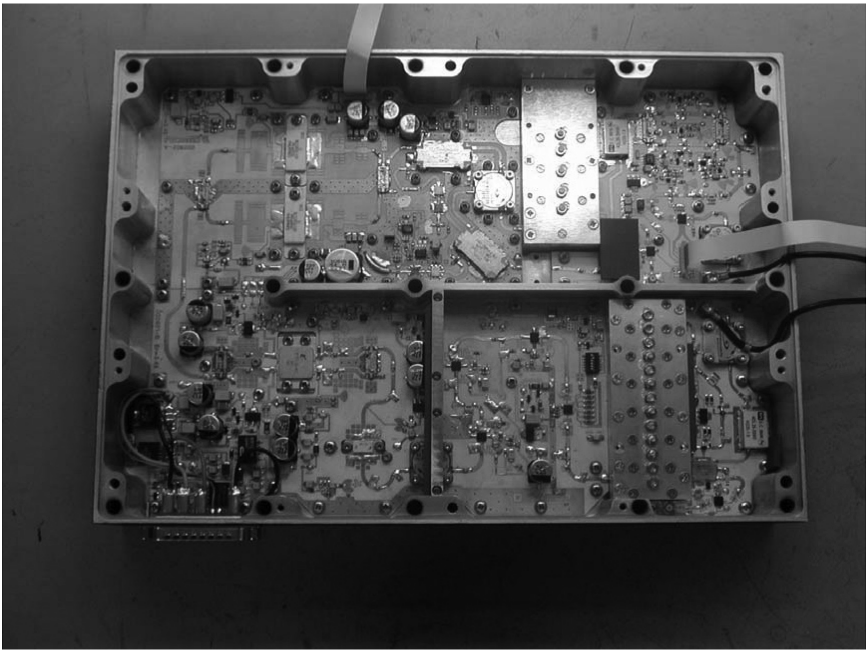

FIGURE 22.5 Kelvin Hughes SharpEye™ CMR S-band solid-state transmitter (*Courtesy of Kelvin Hughes Ltd.*)

In previous years, ships were required to have a radio officer, who could carry out radar repairs at sea. This is no longer the case. Reliability is a prime concern, as a non-operating radar can force the delay of the ship in port, at great cost to the operator.

22.5 TARGET TRACKING

The target tracking function of a shipborne navigation radar has historically been called an *Automatic Radar Plotting Aid (ARPA)*. This term is becoming obsolete. IMO now defines this process as *Target Tracking (TT)*, which includes target data obtained from AIS. The basic requirement calls for a minimum radar tracking capacity of 20 targets on ships less than 500 gt; 30 targets on ships between 500 and 10,000 gt; and 40 targets on ships over 10,000 gt. In addition, ships over 10,000 gt must have an automatic target acquisition capability. Actual systems commonly exceed these minimum requirements. Targets with a maximum relative speed of 100 kt must be trackable; this requirement is increased to 140 kt for radars on vessels capable of more than 30 kt. On the bridge, the navigator's requirements to aid collision avoidance include the need to know a target's *closest point of approach* (CPA) and *time to closest point of approach* (TCPA), both of which must be available for all tracked targets. The required tracked target accuracy at 95% levels is given in Table 22.4.

TABLE 22.4 Requirements for radar tracked target accuracy (95% levels)[11] (*Courtesy of IMO*)

Time of Steady State (minutes)	Relative Course (degrees)	Relative Speed (kn)	CPA (NM)	TCPA (minutes)	True Course (degrees)	True Speed (kn)
1 min: trend†	11	1.5 or 10% (whichever is greater)	1.0	–	–	–
3 min: motion‡	3	0.8 or 1% (whichever is greater)	0.3	0.5	5	0.5 or 1% (whichever is greater)

† Trend is an early indication (after 1 minute) of the target's speed and direction.
‡ Motion is the established assessment (after 3 minutes) of the target's speed and direction.

The tracking problem is complicated by the fact that basic radar measurements are made relative to the ship's motion, but the display may be set to relative or true motion. In addition, true motion can be ground or sea stabilized. Target vectors and associated data boxes can be shown in true or relative motion, whatever the frame reference of the radar display. A ship's orientation to north is given by a gyrocompass or "transmitting" magnetic compass—a compass with a digital interface. A log gives *speed through the water* (STW). This can be either a conventional rotating transducer driven by the movement through water or else an acoustic transducer measuring the doppler of the reflected signal. The latter can be set to assess speed either relative to the surrounding water (STW) or relative to the seabed, i.e., *speed over ground* (SOG). Mandatory carriage of a dual axis log (which measures speed in the forward and transverse directions) is required on ships above 50,000 gt. This is typically a doppler log. On smaller ships, GNSS is used to provide SOG and is often the user-preferred ground stabilization source for radar, even for a ship fitted with a doppler log. Doppler logs do not always give good speed readings on some types of seabed, for example, soft mud. Facilities must also be provided to allow the use of stationary tracked targets, such as radar conspicuous navigation marks, to provide the ground reference.

According to the design, the basic tracking function can be carried out in ship or ground/sea referenced frames, using conventional algorithms. The tracking process can be initiated manually or automatically. Automatic initiation is by a conventional plot extraction process confined within a user-defined area, which, at its simplest, could be a chosen range encircling the vessel. The defined area may also have user-defined exclusion zones. Algorithms for preventing plots from being formed on typically encountered wave features, perhaps lasting a few scans such as a traveling wave crest, need to be employed. Manual selection is effectively a plot extraction process operating over a small area surrounding the cursor. An alpha-beta tracker or other filtering technique is used to smooth measurement noise. The characteristics of this filter need to adapt to the quality of the received target signal. If tracking is carried out in ground referenced coordinates, the process automatically takes into account own-ship movements. In relative motion-based tracking systems, the filter needs to be aided with own-ship data.

Depending on the user-set mode, the data has to be converted to the correct reference frame and displayed appropriately. CPA and TCPA are continually calculated for all tracked targets, such that if limits preset by the user are breached, an alarm can be initiated. All tracked targets are displayed on the screen with their associated velocity vectors. Tracked targets may be selected by the user such that all information concerning that target, including CPA and TCPA, is displayed on the data panel of the radar screen. Lost targets create a visual and an audible alarm. Normal termination of tracking occurs when a target leaves the acquisition zone or when manually cancelled. A guard zone may also be set up by the operator. This may be identical to the acquisition zone but is there to provide an alarm if any tracked target passes into the zone.

In common with other radar trackers, strategies have to be evolved to cope with the target being potentially invisible in some scans. IMO requires that the specified performance is maintained when the target is invisible in up to 50% of scans. Also, for an effective system, strategies have to be evolved to reduce the possibilities of target identities being swapped, which can happen when targets move close together and subsequently diverge. In particular, tracking algorithms have to attempt to cope with the potentially large and fast change in the radar centroid as a target vessel turns. In the worst case, this can amount to almost the length of the vessel, 300 meters or so, for a large ship. It is an art to get a good tracker optimized for all situations, over a variety of vessel speeds, and to maintain an appropriate indication of change in heading without excess latency. Over-damped systems may give an apparently stable indication of the track of a target but can be very inaccurate when a target changes heading. From the point of view of safety of navigation, the change in heading is often the more important parameter. Target trackers from individual manufacturers can have quite different design and optimization strategies and can, therefore, differ in performance. Within IEC 62388,[11] there are defined test scenarios that all SOLAS-approved tracking systems must meet. IMO requires that the trend in a target's change of direction is shown within one minute and the prediction of the target's motion should be available within three minutes, as given in Table 22.4.

In principle, target tracking could be aided by data from AIS (Section 22.7). However, AIS data is best left out of the radar tracking process in order to keep them entirely independent. Once radar tracks have been formed, they can then be automatically compared to AIS data and associated into a single track, if desired by the operator. This gives complete independence to radar- and AIS-derived data, therefore, enhancing integrity checking.

22.6 USER INTERFACE

From the user's point of view, the most visible and important change in marine radar from its early days has been the development of processor-based display technology. In particular, modern well-designed displays are viewable over a wide variation of ambient lighting; they make effective use of color and give easy and clear access to the radar image and associated data. The days when the radar screen was only viewable in daylight on dim long-persistence monochrome CRTs through the aperture of a hood are long gone. More recently, high brightness color CRTs are being replaced by Liquid Crystal Display flat panel technology, which is helping to make the display more user accessible—large stand-alone radar consoles are no longer necessary, allowing improvements to the ergonomic layout of a ship's bridge.

User input devices vary by manufacturer. Some solutions rely on little more than a tracker ball and three control buttons. Others have a number of dedicated switches and rotary controls, as well as a cursor control such as a tracker ball or joystick.

Touchscreen technology is sometimes employed. Increasingly, systems also include a full alphanumeric keyboard to allow easy input of user-supplied data, especially for *chart radars* (radars utilizing an electronic chart-based underlay) and radars integrated with AIS. Radars designed for smaller vessels tend to have a completely waterproofed user interface as they are often used in more exposed areas and by operators with wet, salty hands. In general, tracker balls, although they give more precise control and are common on shipborne radars, have been found to be unsatisfactory in the environmental conditions found on small craft. Instead, mini joysticks or simple four-way rocker switches are typically used.

The operational area of a radar display is normally circular, although this is no longer a mandatory requirement. It originates from the historical use of conical display tubes but is retained by most manufacturers as it gives additional space outside of the operational area for the display of data and menus (see Figure 22.6). The minimum operational display area is defined as a diameter: 180 mm for ships less than 500 gt; 250 mm for ships from 500 to 10,000 gt; and 320 mm for ships above 10,000 gt. The minimum recommended display areas for small craft radar are given in Table 22.2. The color of radar targets and background is not mandated. The target trails that used to be provided by the designed-in persistence of original radar monochrome CRTs have to be provided electronically. The trail length is required to be user selectable in units of time. When True Motion is selected, trails can be chosen by the operator to be shown in either true or ship-relative reference frames. The position of the display cursor is always available in a data box in terms of range and bearing from own ship and/or latitude and longitude coordinates. It is this cursor that is used to select and deselect targets within the operational display area and to draw user-defined maps. It is also commonly used to set range and bearing markers.

A *consistent common reference point* (CCRP) to which all radar and other navigational data need to be referenced is identified on the ship. This point clearly becomes of major importance when close-in navigational calculations are being made. Having a defined CCRP also allows a scaled own-ship's symbol to be shown on the radar display when appropriately short-range scales are selected. The symbology of this graphic, together with all other symbols and abbreviations on the display, should meet IMO requirements.[21] This ensures that operators are familiar with the radar presentation when working on different ships. The radar display should also comply with IMO's performance standards for navigational displays.[22]

Certain range scales (maximum displayed ranges) are mandatory, covering 0.25 to 24 nm. In practice, range scales above 24 nm are normally provided, typically up to 96 nm. Range rings may be optionally switched in by the operator to help estimate distances. Precise range measurements are made with the use of a *variable range marker* (VRM). At least two VRMs are needed, each with numerical readout in the data area of the display. An accuracy of 1% is required (but not better than 30 meters). A bearing scale around the periphery of the operational display must be visible. This scale can help users determine the ship's direction from viewing the *heading line* (HL), which has to be shown on the display; only temporary extinguishing of the HL is permitted. In addition, a ship's heading is normally available within a data box outside of the operational area. The radar origin can be offset from the center of the operational area by the user; the bearing scale adjusts accordingly.

Two or more *electronic bearing lines* (EBLs) have to be provided with continuous numerical readout. Although these are normally centered on the ship (at the CCRP), they can also be offset to any position. Readouts relative to own ship's heading or true north can be set. The EBL origin can also be set such that it follows own-ship movement or is

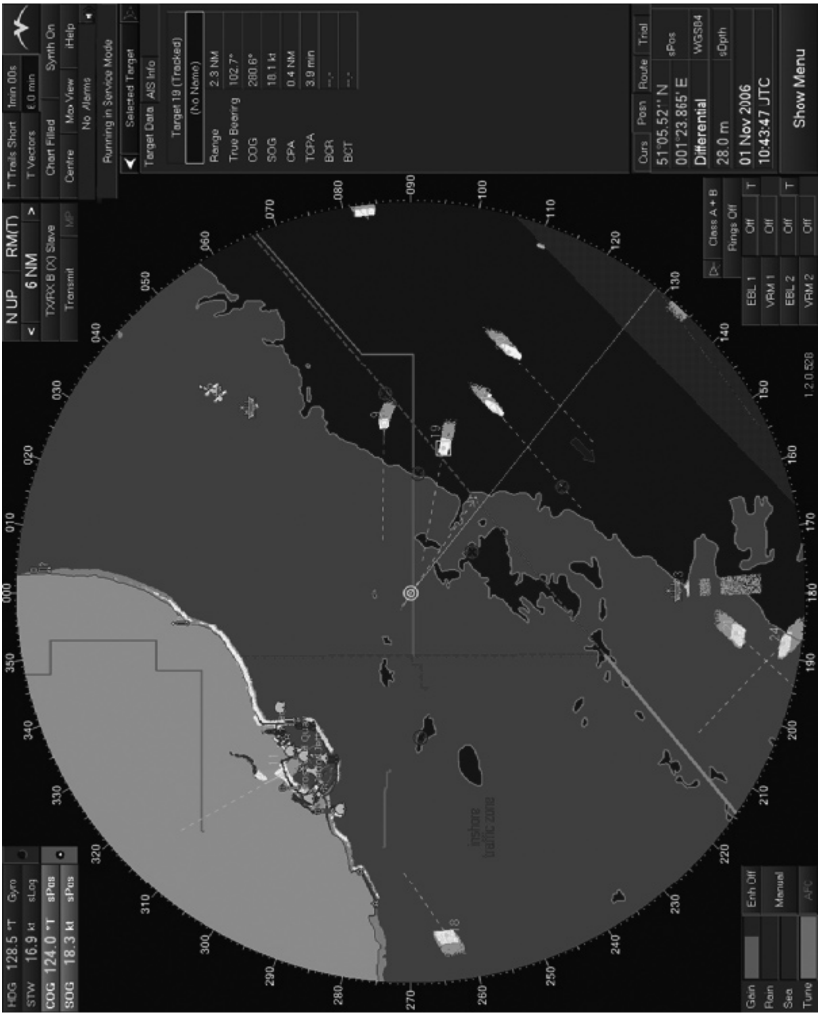

FIGURE 22.6 A ship's radar display (*Courtesy of Northrop Grumman Sperry Marine BV*)

geographically fixed. The distance and bearing of one point to another on the display can be determined, normally by use of a specific menu item and appropriate control of the display cursor. The actual implementation of EBLs, VRMs, and offset measurements is often effected by a common graphical tool, which is used to position and drag lines and circles across the display by means of the cursor. Many mariners find the use of ship-referenced parallel index (PI) lines to be highly useful. A PI is a straight line on the radar display that is user-set to a fixed "compass" bearing and a fixed perpendicular distance from the radar origin. At least four of these have to be provided. These can be individually switched into use and set by bearing, beam range, and length. PIs are typically used to ensure that a ship is maintaining a safe ground track, with reference to a ground-fixed conspicuous radar target.

Chart Radars. The capability and relatively low cost of modern processing and display systems allow great flexibility in the presentation of information to users. For many years, SOLAS-compliant radars have had the capability to employ user-defined maps as an underlay to the radar image. Many maps can be created and stored for future use. Although this facility is still widely used, the use of vectorized electronic chart data as a radar underlay is becoming more common. In IMO terms, they are known as *chart radars*. All approved chart radars have to be capable of displaying officially recognized vector data. This data is known as the *Electronic Navigational Chart* (ENC). It is issued on national authority and complies with an International Hydrographic Organization[23] (IHO) standard known as S57.[24] ENC data is normally displayed on approved electronic chart systems called *Electronic Chart Display and Information Systems* (ECDIS),[25] and may be used by ships in place of paper charts. ENC data is kept up-to-date by hydrographic offices that issue update files on a regular basis. An IMO-approved chart radar must also be able to accept these updates. Charts and their updates are loaded by CD-ROM or via a satellite communications link. On some systems, the chart radar may have access to a server on the ship that centralizes the distribution of such data to all equipment needing chart information.

The user has the ability to choose the ENC vector layers shown on the display of a chart radar. For instance, this may just include the coastline, navigation marks, and a single depth contour, considered safe for the draught of the ship. If the ship is navigating on ECDIS, rather than a paper chart, it is likely that both the radar and the ECDIS will be commonly set to Course-up or Head-up modes. North-up is no longer a particular advantage when the chart is not confined to such a presentation, such as paper charts. Most ECDIS equipment can optionally show radar-derived data, normally as tracked target vectors but sometimes as the radar image itself. This data is obtained from the radar processor via a digital interface, giving an apparent convergence of ECDIS and radar displays. Certainly, this is true at a basic design level, but IMO is keen to differentiate between the two. An ECDIS is used to plan and monitor passages; a radar is used primarily as a collision avoidance tool but also to aid position fixing, particularly by identifying ground-fixed radar conspicuous objects including coastlines. This results in many differences in the detailed requirements of radar and ECDIS displays. However, from a design point of view, the display processing requirements are very similar and can therefore use virtually identical hardware. As well as saving design costs, this enables an easy transition to *multifunction displays* (MFDs). An MFD can be instantly switched between radar and ECDIS, as well as other functions, enabling dynamic reconfiguration on a ship to optimize display use for particular circumstances. Clear indication of the selected mode becomes necessary for safety and statutory reasons.

Most small craft radars now being sold include the option of a chart underlay facility as a relatively low-cost option. In general, these use unofficial vector chart data, issued by specialist private companies. This data is more affordable than ENCs and is directed to this particular market. Because of cost and space constraints, a single display normally acts as both radar and electronic chart. Theses displays are all effectively MFDs and can, therefore, also be used as an electronic chart system without radar input.

22.7 INTEGRATION WITH AIS

The maritime Automatic Identification System[26] (AIS) is a target information system that performs similar functions to airborne Secondary Surveillance Radar (SSR), such as Air Traffic Control Beacon System (ATCRBS) and Identification Friend or Foe (IFF). However, the vast majority of transmissions are not the result of any interrogation, as it mainly operates as a broadcast system, based around a *Self Organizing Time Domain Multiple Access* (SOTDMA) communications protocol. The communications link, including the SOTDMA definition, is defined by the ITU.[27] Ships automatically transmit current navigational data and other information on VHF marine-band channels assigned for AIS use. The transmitted information is received by other ships and also by shore stations, such as coastal authorities and VTS facilities. Shore stations and ships also have the ability to specifically interrogate shipborne AIS transponders to initiate the sending of particular data. AIS has three major uses: to enhance the bridge team's situational awareness, to aid VTS activities, and to provide data to assist national security. The intention of IMO is that ships will normally display AIS data on the radar screen as it complements radar-derived data, adding to the integrity of the presence, position, and velocity of targets and also giving increased target information. In principle, a conventional secondary radar solution could have been adopted but international consensus favored the SOTDMA approach, as it was capable of providing higher levels of data exchange, particularly to aid VTS and security activities. An important advantage of the chosen AIS solution is its radio frequency. It is sufficiently low so that reasonable communications are maintained in situations where there is no visual or radar line-of-sight. This can be important in harbor, river, island, and estuary regions, where shielding by the terrain or buildings can affect radar range.

A shipborne AIS station broadcasts information divided into a number of sets. These comprise static data, such as the ship's name, type, length, and beam; dynamic data, including position, SOG, COG, and heading; and voyage-related data, such as destination port and ETA, depth under keel, and hazardous cargo type. The dynamic data is broadcast at a rate consistent with the vessel's velocity and whether it is changing course, as shown in Table 22.5. Static and voyage-related data is normally broadcast every 6 minutes. To provide sufficient bandwidth, two specific VHF 25 KHz channels are used, with stations alternating between channels at each message. There are 2,240 message slots per channel every minute. Minutes are aligned to Universal Time Coordinated (UTC), which is obtained from an integral GNSS receiver. The SOTDMA algorithm effectively reserves future slots for stations that are in reception range of each other, preventing mutual interference.

AIS for SOLAS use is known as *AIS Class A*. There is a Class B system that is designed for non-SOLAS use.[28] This system uses the same VHF channels as Class A, and the transmissions are necessarily compatible, but to avoid overloading the VHF data link (VDL), Class B uses Carrier Sensing TDMA. This is aimed at confining

TABLE 22.5 AIS Position Reporting Intervals (*Courtesy of IMO*)

Ship Dynamics	Reporting Interval (seconds)
At anchor or moored and not moving faster than 3 knots	180
With a speed of between 0–14 knots	10
With a speed of between 0–14 knots and changing course	3.33
With a speed of between 14–23 knots	6
With a speed of between 14–23 knots and changing course	2
With a speed of greater than 23 knots	2
With a speed of greater than 23 knots and changing course	2

Class B systems to use only slots unallocated to Class A users. Class B systems will delay their own transmissions if slots are not available. (There is an additional option of an SOTDMA-based Class B system.) Importantly, Class A and B systems receive each others' transmissions.

The combination of AIS and radar-derived data gives benefits to navigation because of the complementary nature of the two systems. The relative range and bearings of a target derived from AIS data are entirely independent of the radar measurements of these parameters. Clearly, any observed differences in radar and AIS positions will then indicate an error in some process, provided the differences are outside the expected noise in the measurements. This can be highlighted for the user. A high positional correlation increases the integrity of the observation, particularly as speed and course measurements can also be used in the comparison. Lack of any correlation can also give the user information that may be helpful. If only radar data is received, it may be that the target is not fitted with AIS, which means it could be a small craft, floating debris, or ice. It could also mean that a vessel's AIS is not operating or is transmitting erroneous positional information. If only AIS data is received, the radar image may be obscured by clutter, a headland, or even a poorly setup or faulty radar installation. Normally, just a few targets will be uncorrelated, highlighting that these few should be given additional caution if they are significant to own-ship navigation, at least until they can be positively identified, perhaps visually. If no targets are correlated, it suggests that own ship has a significant problem, perhaps with its radar, GNSS position, or more commonly, a gyrocompass offset.

If there is good positional tie-up or even an understanding of why radar information may be lacking, for example, due to heavy sea clutter, the additional information transmitted on AIS can be extremely useful. For instance, a target's heading is transmitted by AIS. This information is not available from radar (only the course can be determined), and yet heading is used as the basis for determining collision avoidance action. The AIS transmitted heading should align with the target's visual aspect and, therefore, the navigational lights on a vessel. Vessel names can be added automatically to target tracks on the radar/AIS display, and if there is a need to communicate on VHF with a particular target, the radio call sign is also available from the AIS data. The destination port and ETA can sometimes be useful in determining the likely intentions of targets, although such assumptions must be treated warily.

A significant advantage of radar is that it does not need cooperative targets. It attempts to detect all objects of potential interest. Its inherent Relative Motion mode of operation makes it ideally suited for collision avoidance use—particularly as in this mode it has no requirement to need own ship's geographical position. However, radar is basically confined to line-of-sight operation; its performance can be significantly degraded by clutter, and its tracking capability is compromised when targets are changing course or passing close to other targets. AIS has reasonably good capability in non-line-of-sight situations because of its lower frequency. It quickly reports a target's change in heading or course, including rate of turn data, if it is available on the target vessel. AIS is not affected by sea clutter and can report absolute position accurately—to normally better than 10 meters or even a meter or two, if reporting differential GNSS-derived positional data. However, AIS relies on cooperative targets; is prone to gross errors in data accuracy, mainly caused by setup errors; and totally relies on reasonably accurate GNSS data being available. A GNSS blackout, perhaps caused by intentional or unintentional jamming, would prevent AIS from being an effective system, possibly over a wide area and for an appreciable time.

Future systems might increasingly exploit the complementary aspects of radar and AIS. This could improve the overall target-tracking capability available to ships and will give support for detecting cooperative targets in clutter. Possibly, the knowledge from AIS that a target is likely to be at a particular range and azimuth could direct concentrated processing techniques in that area, perhaps using pattern-matching algorithms as well as optimizing the false-alarm rate in the immediate area of the AIS-reported target. It is ironic that the very targets that may be hidden in clutter are smaller vessels that do not mandatorily carry AIS. Also, a Class B system only transmits once every 30 seconds at a maximum and so will be less useful for aiding radar even though it can usefully alert navigators that a small target is present.

The use of AIS as an *aid-to-navigation* (AtoN) has been put forward as a possible replacement for racons, which are described in the next section. In principle, AIS AtoNs could replace racons, but in practice, it would be a retrograde step as they cannot be used independently of a position fix system, such as GNSS. However, they can be usefully employed to indicate the integrity of the actual position of the mark, which may have dragged or become unattached, and other additional data, such as sea currents. The AIS transceiver does not have to be situated on the actual mark and could be shore-based to ease maintenance. Used in this way, they are known as Virtual AIS AtoNs.[29] Up-to-date information concerning the mark and its integrity can be automatically or manually fed-in by port authorities. Such systems can also be used for alerting mariners of the position of recent wrecks and other temporary and perhaps visually unmarked navigation hazards.

22.8 RADAR BEACONS

Radar beacons have played an important role in marine navigation ever since the early days of radar. They basically detect incident pulses from marine radars and instantaneously transmit a distinctive signal that identifies the beacon and its position on a radar display. There are three main uses of such beacons. The first of these is for enhancing visual aids to navigation, such as buoys and landmarks, to enable them to be prominently identified on a radar display. These are normally called *racons* (as a contraction of *radar beacons*). Such systems form an important navigational service that is well liked by mariners. The second use is for *Search and Rescue Transponders* (SARTs), which are mainly designed to be deployed from life rafts after a marine accident. The third category of use is for radar enhancement of small targets, such as pleasure craft. These are called *radar target enhancers* (RTE) or active radar reflectors.

Racons. The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) sets the performance standards for racons.[30] These incorporate the technical characteristics set out in a specific ITU-R Recommendation.[31] Because racons normally form only one subsystem of an AtoN. they therefore need to be small in size and power efficient since they are rarely connected to a main power supply. They often operate in an extreme environment, such as on a buoy buffeted by the sea. Racons are specified to meet an extended operational temperature range of –40° to +70°C. Modern racons operate by detecting an incident pulse and then measuring its frequency and responding at the same frequency, thereby reducing the interference potential with other in-band radars. They are often dual-band (3 and 9 GHz). The ITU recommends that for pulse lengths of 0.2 μs or longer, the frequency accuracy of the responding signal should be within ±1.5 MHz, and for pulses of less than 0.2 μs, the frequency should be within ±3.5 MHz. Swept frequency racons are effectively obsolescent but are still permitted. These work by having an internal RF source that is slewing in frequency across the entire radar band with a saw-tooth waveform at a rate between 60 and 120 seconds per 200 MHz. All received pulses are responded to but the interrogating radar will receive a racon burst only once every one to two minutes when its receiver is in band to the particular transmission.

IALA recommends that racons have suppression techniques to avoid responding to radar sidelobe transmissions. This is not an easy task to implement and probably impossible to make infallible. Basically, the racon needs to build a table of radar signatures that it is currently receiving, based on frequency and pulse length. It then identifies whether high level and lower level pulses of the same signature are being received and makes the assumption that these are from the same radar. It sets a threshold level for individual radars such that it only responds to high-power main beam interrogations. Typically, peak transmit powers are about 1–2 watts. Antennas are usually omnidirectional in azimuth but can have a restricted elevation beamwidth and typically have an overall gain of about 6 dB. Prime power consumption in average traffic can be less than 1 watt.

The modulation on the response signal of a racon paints a Morse code image on the radar display. The code identifies a particular AtoN and appears in the radial direction, conventionally commencing with a dash. This dash starts a short distance beyond the actual position of the AtoN because of inherent delays in the response time of the racon. However, delays giving an error of less than 100 meters are readily achievable. In good conditions, the AtoN primary radar image will be displayed on the radar screen, helped if a passive radar reflector is also a part of the AtoN. Racons have to include muting periods to allow ship radars to look for small targets in the vicinity of the racon identifier.

The long-term future of racons is unsure, although maritime authorities are assessing the situation.[32] Mariners like them as they are useful, familiar, and give ship-relative data. However, it is difficult to see how they will survive in their original form as marine radar moves away from utilizing magnetron-based systems. Also, compared with earlier years, when racons were essential, many more navigational aids are becoming available that assist positioning. These include multiple GNSS services, differential GNSS, AIS, and enhanced VTS facilities. There are also great improvements in onboard navigational aids such as electronic charts and integrated navigation systems.

The reliance of navigation on a single system, such as GPS, or even a single technology, such as GNSS, is not acceptable to the maritime community and neither to aviation. For instance, it is easy to jam all GNSS users over a wide area because of the small amplitude of the received signal. This means that radar and other positioning systems are likely to be always used as essential navigational tools. The overall requirements for the electronic navigation of ships, including VTS reporting systems, are being examined by IMO and IALA, with the intention of determining a future e-Navigation concept (*e* for *electronic/enhanced*). The continued need for racons or a replacement technology will inevitably form part of this program. If the continuous availability of precise positional information cannot be totally relied upon, then it is probably essential that some form of ship-relative system to identify fixed navigational marks is available.

SARTs. Search and Rescue Transponders[33] (SART) form part of IMO's Global Maritime Distress and Safety System[34] (GMDSS). These are 9 GHz radar transponders that are mainly designed to be used on survival craft (such as life rafts) in emergency conditions. They are relatively small and affordable. On being triggered by a radar pulse, a SART emits a 12-cycle frequency-swept saw-tooth waveform covering 9.2 to 9.5 GHz. The extension down to 9.2 GHz covers the band used by search aircraft. The very fast upward frequency scan is accomplished in 0.4 μs; the downward scan takes 7.5 μs. This forms the possibility of a displayed trace on the radar screen, consisting of 12 radial dots and dashes as the upward and downward scans cross the passband of the radar receiver, with the first dot at a slightly longer range than the SART position. In practice, the upward sweep is so fast that the dots are normally not visible on the display and only the dashes can be seen. Even these can be quite difficult to locate in adverse sea clutter conditions.

The first dash displayed on the radar screen could be up to 0.8 nm away from the actual SART position and so search craft have to take precautions not to run down the survival craft when bearing down on the signal. At short ranges, the swept gain of the radar may truncate the nearer dashes. Also at short ranges, because there is no sidelobe suppression circuitry, SARTs can be triggered by radar sidelobes. To prevent adjacent SARTs from continuously triggering each other, there is a short delay after a SART transmission before it may be triggered again. To detect SARTs in heavy sea clutter, it is often best to detune the radar receiver, eliminating all other returns. Some radar manufacturers provide a SART search mode that sets the radar optimally for their detection, including inhibiting pulse-to-pulse correlation and optimizing filter bandwidths. AIS-based SARTs have now been proposed. These may eventually replace radar-based SARTs because the latter are difficult to detect in adverse conditions.

Radar Target Enhancers. Radar target enhancers[35] (RTEs) are used increasingly by small craft because, for their size, they offer a better enhancement in radar cross section than can be given by a passive reflector. In principle, they are simple devices. In-band received signals are amplified and retransmitted with minimum delay. Delays can be kept to a few nanoseconds, less than the equivalent dimensions of the craft, ensuring co-located returns of the enhanced signal and natural radar reflection. To prevent positive feedback between receiver and transmitter, the transmit and receive antennas are normally physically separate, one above the other, providing isolation. Isolation can also be increased by transmitting on an orthogonal polarization to that received. Providing they are operating with linear gain, there are no adverse effects from radar sidelobe interrogation. However, at close ranges, the signal from the main beam of the radar may saturate within the RTE, effectively enhancing the levels of the RTE received signal through the radar sidelobes. The ITU regulations limit RTEs to an EIRP of 10 watts, with a minimum gain of 50 dB.

22.9 VALIDATION TESTING

The factors affecting the range performance of a radar system are well known, and increasingly sophisticated design methodologies have greatly improved the detection of all forms of radar. The final proof, however, is how the radar actually performs at sea. As stated previously, shipborne radars are validated as meeting IMO performance standards by being independently type approved to technical standards issued by the IEC. The IEC standards include defined methods of testing. For a given target and radar antenna height, it is relatively easy to define and execute a test to determine that a point source target with a specific echoing area is detected at a given range in a minimal clutter field. It is very difficult to extend this to determine, in a repeatable and quantitative manner, the performance of the radar against point targets in predefined clutter conditions. For this reason, some basic performance tests have necessarily been loosely defined to allow scope for approved test laboratories to make their own qualitative judgments on basic radar performance, normally based on opportunistically testing the radar over the sea and in precipitation in a variety of situations. Judgments on performance can, therefore, be quite subjective and are naturally affected by the conditions actually encountered during the tests. Cost considerations can severely limit the length of test programs and thereby the range of scenarios used. Radars under type approval are typically installed on a trial vessel for such tests or use a land site overlooking the sea.

This scenario is becoming increasingly unsatisfactory as advances in requirements for safety and the protection of the environment mean that it is necessary to ensure that type approval is consistently applied and is, therefore, measured in a quantitative manner. In an attempt to resolve this, some work has been performed to try to better formalize marine radar clutter performance tests, including some research performed on behalf of the UK Maritime and Coastguard Agency.[36] This approach was aimed to minimize any special configuration of the radar under test. It is based on a system that generates simulated target and clutter waveforms. These are picked up by the antenna of the radar under test from a nearby transmitting source, typically situated about 100 meters from the radar antenna. Co-located with the transmitting source is a receiver, which detects the transmitted radar signal and continually analyses its frequency, pulse length, and amplitude as the radar antenna rotates. From this information, a signal waveform is synthesized on a pulse-to-pulse basis, replicating reflected signals from targets and clutter. The synthesis procedure calculates appropriate fluctuating target and clutter returns from any desired theoretical model—which could also, in principle, include models derived from recorded data of real target and clutter reflections. Because the simulated signal is predominately entering the radar through the sidelobes of the radar antenna—except when the radar main beam aligns with the simulator antenna—the synthesized signal needs to be automatically adjusted in amplitude to compensate for the actual sidelobe sensitivity in the direction of the simulator. Effectively, the synthesizer has to amplify the transmitted signal according to the inverse of the amplitude of each pulse received from the radar. The challenges in designing an affordable system include the large dynamic ranges that have to be encompassed and the processing speed needed to determine the characteristics of the transmitted signal.

In principle, a number of clutter and target models could be established by international agreement, such that they were considered to be representative of conditions around the world; agreed-upon test criteria could then be determined, and simulator systems could be based at marine radar–type approval laboratories. It has been found that the system is adversely affected if set up close to large radar-reflecting objects, such as buildings, and so needs to be located ideally in relatively open spaces, similar to that found on an antenna far-field test range. To enable tests to be more easily carried out, direct injection of test targets and clutter into the RF path is feasible. However, this involves a certain amount of adaptation of the radar under test, which may be considered inappropriate.

The potential move at 3 GHz to pulse compressed radar offers additional challenges in the design of a universal simulator, as the system described is based on testing noncoherent pulsed radars. Systems based on digital RF memory may have to be devised, storing waveforms that can be subsequently processed. Target and clutter models would obviously need to appropriately take into account doppler effects introduced by the movement of their equivalent scatterers.

22.10 VESSEL TRACKING SERVICES

Radar heads for port control and coastal surveillance systems have some requirements in common with those for shipborne radars. This originally resulted in many of the well-known suppliers of shipborne radar getting involved in this area. They could offer attractive prices as the subsystems were derivatives of the relatively high volume shipborne market. Over time, much of the market has become more sophisticated, and because of this, specialist organizations now dominate the supply of systems for this application. The large costs associated with a major vessel tracking services (VTS) operation, including massive antenna support towers, operations buildings, specialized software, and disaster-proofed broadband communication systems, mean that the costs of a more optimized radar head often become a relatively insignificant addition. This also means that switchable linear and circular polarization modes are more common on VTS systems. However, basic low-cost VTS systems still commonly use subsystems intended for shipborne use, giving good cost savings compared to custom-made systems.

There are significant differences, however, in the requirements for a VTS radar compared to a shipborne system. The VTS antenna is mounted on a static platform. This means that the vertical pattern can be more optimally shaped. Also, since the design does not have to cope with the shock, vibration and instability experienced on ships' radar masts, larger antennas become feasible. This allows azimuth beamwidths to be narrower, therefore, reducing the size of clutter cells. The required coastal area to be covered can be large, and getting the best range out of a few radar heads situated on tall towers is often more cost effective than utilizing many smaller installations. Because VTS often forms part of a nation's security network, then a longer range capability than that just required for port operations may be necessary. This implies that very high antenna towers are often needed, in some cases up to 100 meters. This exacerbates vertical lobing effects, which may need to be reduced by the use of vertical pattern shaping. The long-range requirement often means that greater transmitter power than that used on shipborne radars is needed, even though VTS antenna gains can be higher. Pulse lengths must be kept short to get good clutter immunity, but simultaneously, long-range performance is required, again increasing the required transmitted power. VTS radar heads are usually not operator configurable because a number of operators can typically be using data from one head.

There are more opportunities to enhance performance because of the fixed antenna position; for instance, sea clutter mapping becomes easier because the antenna is not on a moving platform. Also, the clutter conditions can be less variable because of the restricted geographical area of operation, and there are no degradations in the accuracy of the displayed radar image in having to compensate for a ship's heading with compass input. In particular, target tracking is performed from a stable and static platform. However, it is generally necessary to track many more targets than is required on a shipborne radar, and normally VTS has fully automatic plot extraction and track initiation. Also, more information on tracked targets may need to be easily available. Much of this additional data can be automatically supplied by AIS. The radar data often has to be relayed many miles, to perhaps a number of operational centers. It may need to be combined with data from a number of radar heads and, therefore, will be quite synthetic when displayed on operators' screens, reducing the possibilities of individual operator adjustment. Extensive data communications networks become a critical aspect in the performance of the VTS. High reliability of the system is required because of safety, environmental protection, and security aspects. A total system availability of 99.9% is not uncommonly specified, implying an average downtime of less than 2 minutes per day.

Another major difference compared to shipborne radar is the custom nature of the installation. Radar heads are fixed, and there is a specific requirement for certain performance parameters to be met in the particular localized environment. Sea clutter, although very variable, will have certain local characteristics, enabling more effective optimization of the processing. In particular, the actual performance can be more easily measured against design requirements.

The design of high-performance antennas for VTS applications has a similarity to air traffic control antennas, in that they both ideally require a tailored elevation pattern. The ideal pattern shaping for a high-mounted VTS antenna requires a sharp cut-off above the horizon and a tapered pattern below. Energy directed above the horizon increases precipitation clutter and also reduces the antenna gain. At angles below the horizon, the gain should nominally follow a cosecant squared power law. This is aimed at giving a constant signal strength from a target of fixed RCS, independent of range. These are often known as *inverted* or *inverse* cosec squared antennas to differentiate them from air traffic control radar antennas that have their shaping at angles above the horizon. Such shaping optimizes the pattern to the application, greatly enhancing overall performance. Typically, the pattern shaping is enabled by a doubly curved reflector fed from a point-source primary feed. An example from Easat Antennas is illustrated in Figure 22.7. This is a 7.5 meter reflector antenna with a 35 db gain at 9.3 GHz. It has an inverse cosecant-squared elevation pattern and a 0.3° azimuth beamwidth. It is remotely controlled to give horizontal or circular polarization. The vertical pattern shaping interacts with the STC of the radar receiver, and it is, therefore, necessary to take this into account in the system design. To improve detection, frequency diversity is often used on prime systems.

IALA has issued detailed recommendations[37] on the operational and technical performance requirements for VTS equipment. There is much useful information in the recommendations, and they are essential for procurers and designers of VTS radar equipment. They cover both coastal and waterway installations. Many major rivers of the world carry vast amounts of cargo on ships that can be surprisingly large. The meandering nature of rivers and relatively abrupt turns in canal systems, together with the natural and manmade obstructions to radar, mean that waterway vessel traffic systems are generally covered by many low-power radar heads on relatively low towers.

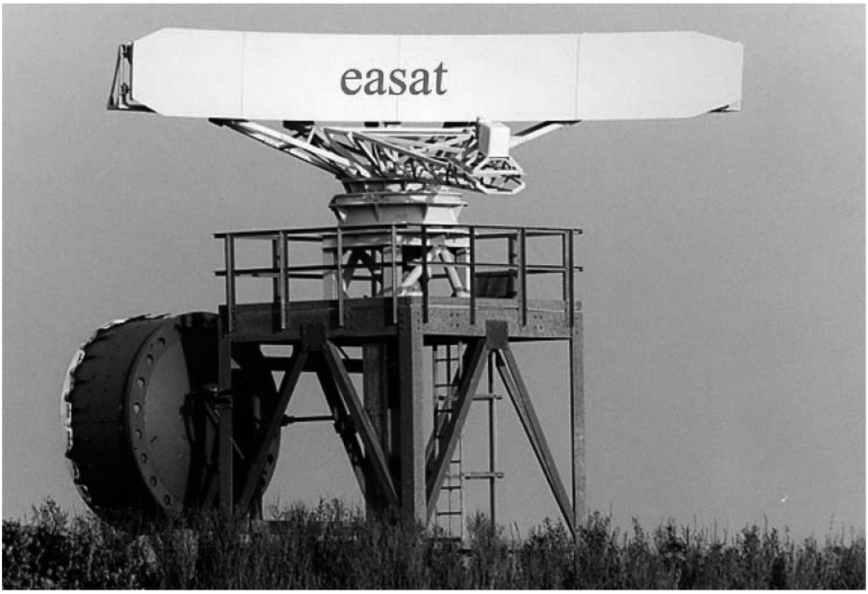

FIGURE 22.7 Dual-polarized doubly curved VTS radar antenna (*Courtesy of Easat Antennas Ltd.*)

Because of their number, such radars tend to be minimally adapted shipborne radars as they offer adequate performance at relatively low cost.

Interestingly, the IALA recommendations allow CCTV solutions to compete with radar when there is very low traffic density. Automatic tracking of a single target is then required. However, on basic radar-based systems, IALA expects a 100 target track capability and a plot extractor that can deal with more than 1,000 plots per rotation. On an advanced system, more that 300 targets may have to be tracked with a possibility of more than 5,000 plots per antenna revolution.

APPENDIX THE EARLY DAYS OF CMR

The use of commercial marine radar arose directly from the rapid development of radar technology for military applications during World War II. Even as early as 1944, some attention was being given to the peacetime role of radar as a navigational aid for commercial shipping. In 1946, an "International meeting on radio aids to marine navigation" was held in London and attended by representatives from 23 countries.[38] The meeting was chaired by Sir Robert Watson-Watt. It was seen that radar on commercial vessels had an important part to play in anti-collision, coastal navigation, and pilotage decisions. (*Pilotage* is navigating in waters where a qualified pilot is required to be onboard.) The future compulsory fitting of radar to ships was contemplated, as was the desirability of an internationally agreed upon minimum performance standard, with requirements for nationally issued certificates of type approval. The need to include the use of radar within the International Collision Regulations was clearly seen, together with the need for certification of users.

In 1946, the UK favored operation at 9 GHz, presumably as it more affordably met the UK perceived azimuth requirements of 3° resolution and 1° accuracy. The United States identified operational problems at 9 GHz that could be experienced in the extreme rainfall conditions found on the U.S. eastern seaboard. These caused "blackouts" on early 9 GHz systems—defined as an effective range of less than 1 mile. As a consequence, the U.S. favored operation at 3 GHz. The shortest pulse lengths then commonly available (around 250 ns) made the clutter cells large, resulting in 9 GHz radars being very susceptible to rain clutter, particularly as clutter processing techniques were in their infancy. In 1946, there was no question that a commercial ship could afford both a 3 and a 9 GHz radar, as the expense of even a single radar system was seen to be a limiting issue. Because of cost, it was already envisaged that fitment would be confined mainly to certain classes of passenger ships that had a definite need to carry radar, particularly those working in the north Atlantic, in congested areas or areas subject to fog or ice.

The early trials in the UK concentrated on a single 9 GHz demonstration system fitted to a naval vessel. It was based around a 40 kW magnetron capable of 250 ns pulses at a PRF of 1,000 Hz. It was interesting that the speed of rotation could be varied between 20 and 100 rpm. Despite the perceived modernity of today's chart radars, it was connected to an optional *Chart Comparison Unit*, which was an optical system allowing the radar image to be displayed in coincidence with a paper chart. The facility to allow "North-up" operation was always seen to be a vital requirement for marine navigation radar. Parallel trials in the United States were conducted on a number of candidate systems, using a broad range of frequency bands. The initial trials were conducted in the Great Lakes and were overseen by the Coast Guard.

The radar standards proposed in 1946 were not adopted internationally, although the UK issued national performance standards based on them in 1948. The UK standard was also adopted by a number of other countries. It was not until 1971 that international marine radar standards were agreed by the Intergovernmental Maritime Consultative Organization (IMCO, the original name of IMO). However, the use of radar on ships was first formally recognized by IMO in 1960 in an Annex to the International Regulations for Preventing Collisions at Sea. The influence of the 1946 proposed international standard was evident in the 1971 performance standards, even to the extent of using identical wording in a number of places.

The similarity in performance requirements is still evident in the latest revisions of the IMO performance standard. For instance, the 1946 proposed performance specification included the need to give a clear indication of coastlines rising to 200 ft at 20 miles, of a 500 gross registered ton ("Imperial" units) vessel at 7 miles and of a 30 ft fishing vessel at 3 miles. The modern performance requirements, summarized in Table 22.1, still use these figures but with parameters, except ranges, given in equivalent metric units.

The technical vision of the 1946 meeting was remarkable. For instance, it was seen that in the future it would be possible to overlay radar data automatically onto a chart image displayed on a "television" type screen. This was not to be realized on commercial systems for 50 years. Also, it was observed that such display systems could accomplish more than one function and not just be used for showing radar on a chart. This anticipated the concept of multifunction displays, now in use on some integrated bridge systems.

It is interesting to note that Kelvin Hughes and Decca obtained the first type approval for commercial marine radar in 1948; effectively, both are still supplying marine radar today. Kelvin Hughes has retained its name and Decca is incorporated into the Sperry Marine organization of Northrop Grumman Corporation. The 1948 Kelvin Hughes Type 1 radar had a peak power of 30 kW, 0.2 μs pulse width, and a PRF of 1,000 Hz. The 5 ft (1.5 meter) cheese antenna had horizontal and vertical beamwidths of 1.6° and 11°, respectively, rotating at 30 rpm. There was an antenna heater to prevent icing, and the transmitter and the receiver (to IF) were "upmast" (integrated within the antenna turning unit.) The display was a 9 in (23 cm) cathode ray tube plan position indicator. The similarities with systems being sold in the 21st century are perhaps more surprising than the obvious differences.

LIST OF MARITIME RADAR-RELATED ABBREVIATIONS

AIS	Automatic Identification System
AtoN	Aid to Navigation
CCRP	Consistent Common Reference Point
CMR	Civil Marine Radar
COG	Course Over Ground
CPA	Closest Point of Approach
EBL	Electronic Bearing Line
ECDIS	Electronic Chart Display and Information System
ENC	Electronic Navigational Chart (The data for ECDIS)
FTC	Fast Time Constant (differentiator)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
gt	Gross tonnage (metric tonnes)
HL	Heading Line
IALA	International Association of Lighthouse Authorities
IBS	Integrated Bridge System
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
ITU	International Telecommunications Union
MFD	Multi-function Display
PI	Parallel Index line
NT Radar	New Technology Radar (Marine term for coherent solid-state radars)
nm	Nautical mile (= 1842 meters)
SART	Search and Rescue Transponder
SOG	Speed Over Ground
SOTDMA	Self Organizing Time Division Multiple Access
STW	Speed Through the Water
TCPA	Time to Closest Point of Approach
VTS	Vessel Traffic Services
UTC	Universal Time Coordinated
VRM	Variable Range Marker

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