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POTENTIAL APPLICATIONS OF OTHER-RADAR TECHNOLOGY TO CIVIL MARINE RADAR

Merrill I. Sholnik, et al

Naval Research Laboratory
Washington, D. C.

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Potential Applications of Other-Radar Technology to Civil Marine Radar

MERRILL I. SKOLNIK AND WILLIAM N. SHADDIX

Radar Division

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POTENTIAL APPLICATIONS OF OTHER-RADAR TECHNOLOGY TO CIVIL MARINE RADAR*

ABSTRACT

Military radar research and development has generated many techniques which have distinct possible application to civil marine radar. Developments such as pulse compression, ship imaging, and solid state radar to name a few, which were selected for both appropriateness and potential interest to the civil marine radar community, are presented without regard to the economics involved. Recent advances in sea clutter theory and its potential impact on marine radar design are also discussed. An appendix is included which presents a summary of recent data on ship's cross section. It was found that the cross section in sq meters could be expressed as $\sigma = 52 \sqrt{f}\, D^{1.5}$, where f is the radar frequency in megahertz and D is the ship displacement in kilotons.

*This report was originally prepared as a paper for the Radio Technical Commission for Marine Services Special Committee No. 65 on "Ship Radar."

INTRODUCTION

This report reviews recent results of research and development in radar for possible application to civil marine radar. The commercial civil marine radar is probably the best example of a radar with high cost-effectiveness ratio. Over the many years of its application, the natural effects of competition in the commercial market have resulted in low cost with high performance tailored to one specific task. Most of the research and development in the field of radar has been supported by the military to meet its own specific needs. This generally results in sophisticated radars of high cost. Thus, it should be expected that any new development in the field of military radar could be expensive and, when applied to the commercial marine radar, it might easily increase its price by an order of magnitude or more. In this report, costs are not specifically considered. A number of developments are presented for their potential interest, and no claims are made that they would be economically competitive in the commercial field. The items selected were those that seemed most appropriate to the writer and is not claimed to be all inclusive.

The topics include:

Pulse Compression. The ability to achieve range resolution of the order of a few feet is possible without loss of pulse energy or detectability. This would enhance the detection of small targets in sea clutter and provide a measurement of a ship's projected size.

Imaging of Ships. With high resolution radar or synthetic aperture processing, a radar image of a ship can be obtained that could aid in classifying the ship as to its type and give its heading.

Sea Clutter Theory and Radar Design. Recent advances in sea clutter theory for a high resolution radar have provided guidelines for improved detector design and possibly antenna design.

Solid State Radar. The generation of microwave power using solid state devices is becoming more practical and might, in the future, have application to marine radar.

Reliability and Long Life. Electronic devices for satellites have demonstrated active life of many years, indicating that there is room for improvement in the life of shipboard radar.

Electronically-steered Phased Array Antennas. Although there has been much development work on phased arrays for radar, apparently they have no application in marine radar.

Extended Range via the Evaporation Duct. It may be possible to double the horizon-limited range of a shipboard radar by taking advantage of the evaporation duct, but the utility and reliability of such a technique has yet to be proven.

1. Pulse Compression

In a conventional radar with pulse width τ, the signal spectral width B_i is approximately equal to $1/\tau$. Hence, the usual rule is that the "optimum" radar IF bandwidth is approximately equal to B_i and the product of bandwidth and pulse width is approximately unity, or $B_i\tau \approx 1$. It is possible to either frequency or phase modulate the pulse so as to increase its bandwidth to a value $B \gg B_i$, thus making $B\tau \gg 1$. This modulated pulse is transmitted and, on reception, is passed through a properly designed "matched filter" that compresses the pulse to a value that would have been achieved if a short pulse of width 1/B had been transmitted. The amount the pulse is compressed is equal to $B\tau$. This is known as pulse compression and is a technique for enjoying the advantages offered by a long pulse of width τ (high energy content and good detection) and yet achieving the range resolution and clutter suppression that would have been obtained with a short pulse.

There are two major types of pulse-compression radars. The simpler and more popular is one in which the pulse is linearly frequency modulated over the bandwidth B in a time τ, the pulse duration. This is known as a chirp waveform. One method to achieve this is with a frequency sensitive (dispersive) delay line in which the time delay through the line is a linear function of the frequency. When a short impulse is applied to such a line, the output is a long pulse of width τ with a linearly varying frequency over the band B. This long pulse is amplified in the transmitter and radiated. The transmitter in a pulse-compression radar is generally a power amplifier like the klystron or the crossed-field amplifier (CFA) rather than a magnetron. On reception, the long pulse is fed backwards into the same dispersive delay line, and the line compresses the pulse to its original short width.

The other method to achieve a pulse-compression radar is with a particular form of pseudo-random phase modulation. A long pulse of width τ is divided into subpulses of width 1/B, and the phase of each subpulse is either left unchanged or reversed 180° according to a random selection or some pseudo random code. Upon reception, the pulse is processed so that the phases of the individual subpulses are unscrambled. The individual subpulses are added together after they all have the same phase. A short pulse is obtained whose width is the same as the width of the subpulses but with the total energy of the long pulse.

There are many possible variations of pulse compression radar. Most require that a power amplifier be used as the transmitter rather than a power oscillator such as a magnetron. It results in a more expensive

radar. As an example, a one μsec pulse width radar might be configured as a pulse-compression radar to give a compression ratio ($B\tau$ product) of perhaps 100 or so to yield an effective pulse width of 10 nsec (0.01 μsec). Present technology is such that the effective pulse width could be as short as a few nanoseconds, giving a range resolution of one or two feet. With this resolution, a target could be resolved in range so that its shape can be discerned. If a reasonably large antenna is used, and if the distance to the target is not too great, a two-dimensional image of the target can be obtained. The target-to-clutter ratio is increased almost in proportion to the $B\tau$ product (compression ratio) so that the detection of small targets, such as buoys, in sea clutter or rain is enhanced, assuming there is sufficient signal-to-noise ratio for adequate detection in the clear.

Present marine radars are capable of pulse widths as short as 0.05 μsec or 50 nsec. This may be sufficiently small in many instances to achieve the advantages offered by a high resolution radar, but the short pulse mode of the conventional marine radar generally operates at reduced average power compared to the long pulse mode. The pulse compression radar is not only capable of shorter compressed pulse widths, but it does so with no decrease in average power capability.

It should be mentioned that, although the pulse compression radar transmits a pulse with wider spectral content than a conventional radar, it does not in general cause increased interference problems. This is especially true if the other radars that would be potentially interfered with are also of the pulse compression type.

The pulse compression radar offers some interesting properties, but it is costly. Economic considerations limit its use to those applications where it offers an advantage not available otherwise.

2. Imaging of Ships

With high range resolution and large antennas, it is possible to provide a radar image of the ship target. Consider, for example, an X-band radar with a 0.05 μsec pulse width and a 9 ft antenna. The range resolution corresponds to 25 ft, and the angle resolution at two nautical miles is about 160 ft. With pulse compression it should be possible to reduce the range resolution to a few feet if it were desired to do so. Some improvement in the angle resolution is possible with a large antenna by "beam sharpening" or synthetic aperture processing, but it is not likely that these methods would be attractive in practice.

Radar images are not like optical images. The resolution is much poorer and there is "breakup" of the image due to the coherent nature of radar energy. Nevertheless, with sufficient target resolution to produce an image, it should be possible to measure the approximate size of the

ship and to ascertain its heading. It might also be possible to determine the general type of ship; for instance, whether it is a tanker, tramp, or a military ship.

In order to utilize the target image, it is necessary to display it with sufficient size to be discernable. This might be accomplished with an auxiliary display or by reserving an unimportant part of the usual display for a blow-up of the target. Ships whose image is desired for blow-up display might be designated by use of a light pen or equivalent designation device. Although an image might be obtained during a single antenna scan, a better display would be obtained by sector scanning the antenna beam about the designated target. To image a target with sufficient definition to discern its size and shape requires greater signal-to-noise ratio than for detection only. Thus, a higher power radar might be in order for imaging purposes.

It was mentioned that better resolution in the angle coordinate is possible, in principle, by the application of synthetic aperture processing. The change in target aspect due to the relative motion between target and radar provides phase changes in the echo signal that can yield a target image when properly processed. This is still experimental and may not even be possible with the usual ship's motions which result in unknown phase perturbations. Even if this were not the case, the cost and complexity of synthetic aperture processing is high. Although the angle resolution practical with a conventional radar antenna may not be all that is desired, the good range resolution possible with radar can still provide useful target imaging information.

3. Sea-Clutter Theory and Radar Design

Although the devising of a theory to describe the nature of radar sea clutter might seem to have mostly academic interest, recent advances in understanding the clutter echo mechanism have had potentially important consequences for marine radar design.

The conventional model for sea clutter considers the sea as if it were composed of a large number of individual, independent scatterers, each of which is of a size small compared to the total value. This gives rise to a fluctuating clutter signal that can be described theoretically by the so-called Rayleigh probability distribution function. It has been found experimentally, however, that sea clutter data from a radar with a small resolution cell (narrow beamwidth and a short pulse) does not fit the classical Rayleigh model. There is a greater chance of obtaining a momentarily large value of clutter return than predicted by the classical model. In the jargon of the radar theoretical analyst, the "tail" of the distribution is higher than predicted by the Rayleigh distribution. This means that the clutter seen by a high resolution radar is not composed of a large number of small scatterers, but that there also exist individual large scatterers. Other distribution functions have been examined to

attempt to fit the experimental data better than does the Rayleigh. The other possibilities include the "log-normal" and the "contaminated-normal" distributions. It is not necessary to describe these in detail; but suffices to say they are both characterized by distributions with "higher tails."

The higher values of clutter echo likely with a short-pulse, high resolution radar mean that they might be registered as false alarms, especially to an automatic detector. These large returns, called clutter spikes, will not likely be mistaken as ship targets by an operator since their radar cross section is of the order of a square meter or so and they do not persist long. They could, however, interfere with the automatic detection of small-size targets such as buoys and small boats. To reduce the incidence of false alarms due to the clutter spikes, the threshold in an automatic detection system can be raised. (An operator viewing a CRT display would probably do the equivalent mentally.) For high probability of detection and low probability of false alarm, the threshold may have to be raised as much as 10 to 20 db with a consequent loss in sensitivity. The only alternative heretofore was to accept the greater numbers of false alarms or a loss in sensitivity.

It has been shown recently that the false alarms and loss in sensitivity can be avoided if a different type of detection criterion is used.[1] The conventional radar, in essence, finds the mean value of the received pulses and, if a preset threshold is crossed, a target is said to be detected. This criterion is fine if the clutter is described by a Rayleigh distribution. With a log-normal or other distribution with high "tails," the detection criterion that worked well with the Rayleigh must be replaced. A detection criterion that offers considerable improvement is one based on the median rather than the mean. That is, the detector determines the median value of the radar echoes. If the median value exceeds a preset threshold, a target is announced. The median is more successful than the mean because it does not weight the few large pulses as heavily as would the mean. It is assumed, of course, that successive pulses are independent of one another.

One method of implementing a median detector is to count the number of pulses received within a scan that exceed a preset threshold. If a majority of the pulses exceed the threshold, the median must be greater than the threshold, and a detection decision is made. The m-out-of-n detection criterion, or double-threshold detector, employed in some radars is a close approximation to a median detector.

An interesting consequence of the log-normal distribution is that a wider beam antenna with lower gain may be more effective in a clutter-limited situation than one with higher gain. For example, with log-normal

[1] G. V. Trunk and S. F. George, "Detection of Targets in Non-Gaussian Sea Clutter," IEEE Trans, Vol AES-6, 620-628, Sep., 1970.

clutter consider a situation where the signal-to-noise ratio is 20 db per pulse and a 3-pulse scan-to-scan integration is performed. For this situation, the detection probability is 0.1 and the false alarm probability is 10^{-6}.[2] If the antenna is replaced by a smaller one with a wider beamwidth so that 10 pulses instead of 3 are integrated, the signal-to-noise ratio falls to about 15 db per pulse, but the detection probability is now greater than 0.99. Such is the nature of the log-normal distribution. The smoothing effect of a wider-beam compensates for the loss in gain. This is an unusual situation in radar design since it states that a small antenna is superior to a larger one. It occurs only with a high resolution radar detecting small targets limited by sea clutter. When a radar with a more usual resolution is employed, the large antenna would be preferred.

Log-normal clutter affects the accuracy of angle measurement in a different manner than clutter described by the Rayleigh distribution. The spikey nature of the clutter echo can result in considerably poorer measurement accuracy unless adequately taken into account during radar design.[3]

The resolution of a commercial marine radar is better than the usual military radar but not as good as the radars that definitely exhibit the non-Rayleigh type clutter. Thus, it is not now certain whether or not the marine radar would benefit from a design procedure based on non-Rayleigh clutter.

It has been shown that the detection of small targets in sea clutter is dependent on whether the sea clutter echo changes from pulse to pulse or if the sea echo appears "frozen." Thus, if all the pulses on a given scan are from a "frozen" sea, there is no improvement in signal-to-clutter ratio when a number of pulses are integrated. This is unlike the situation when the receiver sensitivity is limited by noise rather than clutter. When noise rather than clutter is dominant, integration of pulses improves the signal-to-noise ratio.

The correlation time of clutter at X-band is of the order of 10 msec. All pulses received within this time, when integrated, yield a signal-to-clutter ratio no better than that of a single pulse. A typical marine radar with a 1° antenna beam rotating at 20 rpm scans by a target in about 10 msec so that there is no benefit to integrating the pulses received during the scan when the target is clutter limited.

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[2] G. V. Trunk, "Further Results on the Detection of Targets in Non-Gaussian Sea Clutter," IEEE Trans, Vol AES-7, 553-556, May, 1971.

[3] D. K. Barton, "Radar Measurement Accuracy in Log-Normal Clutter," IEEE EASCON '71 Record, pp 246-251. (IEEE Publication 71 C 34-AES)

It has been shown in experiments that if a very high speed antenna is used, the clutter echoes will be decorrelated from scan-to-scan and an improvement in signal-to-clutter ratio (and therefore detectability) can be had.[4] In these experiments, the antenna rotated at 600 rpm.

Thus, the detection of small targets in clutter is possible by an increase in antenna rotation speed. This would improve the detection of buoys and small boats. On the other hand, since the detection of ship targets is generally limited by receiver noise rather than clutter, the higher speed antenna would have little to offer for improved ship detection.

Another result from recent studies of sea clutter is that there is a saturation effect of sea clutter with wind. That is, sea clutter increases with increasing wind speed, but above a certain value the increase is slow or almost zero. This has been suspected for a long time, but recent measurements have confirmed it. The radar sea clutter is very small with winds from 0 to 5 knots. From about 5 knots to about 15 or 20 knots the increase is large with increasing wind speed. Above 20 or 30 knots, the decrease is much slower with increasing winds. Thus, the radar sea clutter does not continue to worsen as rapidly as does the wave height with increase in wind.

4. Solid-State Radar[5]

Solid state devices have been used more and more in radar starting with the crystal diode detectors and mixers employed in the early forties. The development of the transister in the mid-fifties permitted all-solid-state receivers. Digital integrated circuits in the sixties allowed the utilization of sophisticated data processing to automatically utilize the radar outputs effectively. Microwave integrated circuits have caused a significant change in the construction techniques of the RF portion of the radar. All of the above are now available for use by the radar designer. They offer the possibility of lighter weight, lower power and lower voltages. Often advantage is taken of the smaller volume and lower power requirements to obtain more capability in the same size package.

It is also sometimes claimed that solid-state technology can result in greater reliability. This is potentially so, but it is not always translated into practice. With solid state, more capability can be packed into a given volume. Even if the reliability of each component is high, the larger number of components generally used with solid state systems

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[4] J. Croney, "Civil Marine Radar," Chapter 31 of Radar Handbook, Ed. by M. I. Skolnik, McGraw-Hill Book Co., New York, 1970.

[5] Several reviews of microwave solid state devices may be found in the August 1971 issue of the Proceedings of the IEEE; the August 1971 issue of the Microwave Journal; and the February 1971 issue of Microwaves.

tends to lower the total system reliability. An overall improvement in system reliability also might not be achieved in practice since the reliability of a radar is often determined more by such components as blowers, power supply capacitors, scanner motors and the like rather than by the transistor or the vacuum tube.

There are no solid-state developments at present that seem to be able to economically replace the cathode-ray-tube indicator. There are, however, encouraging developments in the generation of RF power with solid-state devices that might eventually be competitive to the magnetron transmitter. These devices have not yet been developed to the degree where they could be expected to now replace the magnetron as the primary RF power source in today's radars; but much work is being done, and they could be available in the not too distant future. It certainly appears likely that this technology could be used to configure a solid-state transmitter to have the performance characteristics of present magnetrons. It is not clear, however, whether they will be competitive economically. There are available on the market so-called "solid-state radars" that extensively use solid-state components and micro-circuits in the electronic units, but they still require a magnetron for the RF source and a CRT indicator.

During the past 6 or 7 years there has been considerable work in developing solid-state microwave power sources. The field is in a state of continual development, and it is difficult to predict the ultimate capability. Generally, individual solid-state devices are all of relatively low power compared with other microwave generators such as the magnetron or the klystron. Even though the power requirements for a marine radar are relatively low (say 3 kw peak, 1 w average) compared to other radar applications, present devices have not yet demonstrated such power with any confidence in the laboratory, much less in a form suitable for commercial utilization. Such capability from a single device might be forthcoming in the future or it might be now obtained by operating many devices in parallel or by arraying them as in a phased array antenna. There is considerable interest in solid-state generators for radar applications other than for marine use. Thus, new unexpected developments might be forthcoming; but, of course, they cannot be depended upon.

Except for the transistor, all of the interesting microwave solid-state sources are diodes. The transistor is probably the most important of all the solid-state devices at frequencies lower than about L band (1300 MHz). Its capabilities decrease rapidly with increasing frequency so that it is of little present utility at the frequencies at which marine radars are operated (S and X bands). Furthermore, the transistor peak power capability is not much greater than its CW limit so that in a marine radar system where the duty cycle is normally of the order of 0.001 it must be operated in a long pulse mode with some form of pulse compression to achieve the required resolution, thus complicating the system.

The several types of microwave power sources utilizing diodes may be classed as either bulk-effect (the Gunn and LSA diodes) or avalanche diodes (the impatt and the trapatt). The tunnel diode is another, even older, device but it has never achieved the promise originally touted for it and it is dominated by the others. Of all these devices, the LSA and the trapatt seem to be the most likely for pulsed radar operation. At S band a trapatt might be capable of 20 to 40 watts of peak power with an average power of 1 watt and an efficiency of 15 to 20%. The LSA might be capable of 200 to 300 watts peak, 0.2 to 0.3 watts average with an efficiency of 6 to 8%. These values, although based on laboratory accomplishments, are less than those often reported as the "state-of-the-art," but there is generally a considerable difference between what has been obtained in the laboratory under special circumstances and what can be achieved commercially. The power of such devices is generally greater at the lower frequencies. At S band the trapatt might be able to achieve 100 to 200 watts peak and 1 to 2 watts average at an efficiency of 25 to 30%. The LSA might give 500 watts peak, 0.5 watt average at 10% efficiency. LSAs require bias voltage of about 300 to 400 volts and trapatts about 60 to 100 volts.

None of these microwave power generators seem to cry out for commercial exploitation in marine radar at this time. Their reliability is yet to be proven and, even if the above values were readily achieved, a number of such devices would have to be combined in some manner to achieve the requisite powers. Because of the rapid progress of this field, the above statements might be proven wrong at any time, and further improvements should be expected. Improvements of this kind are the things equipment manufacturers have always been alert to, and when solid-state RF power devices are economically competitive for marine radar it will be unlikely that it will go unnoticed.

One other potential utilization of solid state technology in radar is as a low-noise amplifier in the receiver for improved sensitivity. The 10 db noise figure that seems characteristic of radar receivers with mixer front ends can be reduced to about 2 or 3 db with a parametric amplifier. The klystron is generally the preferred pump-source at X band, but solid-state pump oscillators are becoming more of interest as a competitor.

5. Reliability and Long Life

Although there has been considerable money spent to improve the reliability and life of radar, there are almost no good examples of a completely trouble-free radar. Perhaps the most success in achieving reliable equipment has been in the field of commercial marine radar. The mean-time-between failures (MTBF) claimed for the better sets has been between 500 and 1,000 hours or better.[6] (An average of 46 ships

[6] A. J. Harrison, "Radar Reliability on Trawlers," The Radio and Electronic Engineer, Vol 33, pp 27-30, January 1967

gave a radar MTBF of 1,385 hours.) Except for this class of radar, the achievement of a really reliable radar must usually be at the expense of a considerably higher initial cost. Few have been willing to pay the added initial cost to get a truly reliable radar. Instead, it is more usual to buy the cheaper set along with paper sales-promises.

The U.S. space program has vividly demonstrated that long-life electronics with trouble-free operation can be had. Perhaps the best example is that of the communications satellites. Traveling wave tubes of moderate CW power have operated for 3 to 4 years unattended without failure. Future satellite transmitters of higher power are being designed for a ten year continuous active life, and it seems that this is a goal that might actually be achieved.[7]

It is well recognized that satellites receive extra special care and attention in order to achieve a long reliable life. All components are carefully inspected and tested. Assembly is carried out in a controlled, clean environment. Another factor contributing to long life is that the satellite is especially designed to operate in a relatively constant, if "hostile," environment without the intervention of humans. The lack of human intervention might be thought to be a disadvantage, but it is probably one of the chief reasons that electronics for satellites has achieved long life.

It is, of course, not practical to expect the same reliability procedures used for satellite construction to be applied to shipboard radar. There may be some compromise inbetween, but it will undoubtedly raise the cost of the radar. If costs are figured on the basis of the entire life cycle of the radar or as the equivalent of an "insurance premium" then the more reliable radar might be justified. Although the example of satellites has been given to illustrate one extreme in the quest for reliability, there exist a significant number of examples of very high power microwave tubes for conventional land-based radar applications with lives of from 20,000 to 40,000 hours so that procedures far short of that used in satellites might prove worthwhile.

The life of a radar and the MTBF are not always determined by the microwave power source. As mentioned in the previous section on solid-state sources, the more mundane components often dominate the list of failures in radar. Nevertheless, the achievement of long life in the microwave power source in satellite applications and in some specific land-based radar applications gives confidence that the passive components and the other active components can also have long life if there is a desire to do so.

[7] J. Benton, H. Smith, and P. Wolcott, "Latest Advances in Space Traveling Wave Tubes," Communication Satellites for the 70's: Technology, Progress in Astronautics and Aeronautics, Vol 25, N. E. Feldman and C. M. Kelly, editors, 1971.

One other approach to reliability when the equipment is of relatively low cost, as is commercial marine radar, is through redundancy. By using two or more radars for the same application, the probability of having at least one available for service might be adequate for insuring reliable radar. The use of two radars at S and X bands, although it may have other advantages and is done for other reasons, does give an increased overall reliability. This solution to reliability, however, creates a greater maintenance problem as compared to the approach where the radar and its components are designed, procured, manufactured, and tested to ensure long life.

6. Electronically-Steered Phased Array Antennas

For the past twenty years there has been intense interest in developing the technology of electronically steered phased array antennas for application to radar. In a phased array, the antenna is stationary and the beam position is controlled electronically. There might be a single high power transmitter and receiver for the array with a separate phase-shifter at each element or there might be an individual solid-state transmitter, receiver, and phase shifter for each array element. The potential advantages offered by a phased array radar are: (1) rapid-beam agility that permits the radiated beam to be switched quickly from one target to another without the inertia associated with a mechanically steered antenna, (2) high average and high peak power by utilizing a separate transmitter at each element, (3) a convenient form factor that permits the antenna to be wrapped around the mast by using four planar apertures or one cylindrical aperture, (4) electronic stabilization of the beam in elevation, (5) generation of simultaneous, multiple, independent beams, (6) control of the current distribution across the aperture so as to achieve low sidelobes or shaped beams, and (7) because of the large number of individual components, its performance is likely to diminish gradually rather than catastrophically. The significance of these advantages is reduced by the fact that a phased array radar is more complex and more costly than conventional radar and cannot be tested without radiating into space. Furthermore, a phased array radar requires a computer to determine what phase settings to apply to each beam position and to determine how the beams should best be utilized. In a large array radar that attempts to employ the full flexibility of beam control, the cost of the necessary computer hardware and software can be a significant portion of the total system cost.

It seems doubtful that any of the potential advantages of a phased array antenna are applicable to a marine radar even when cost is no consideration. And the significantly high cost is usually the chief limitation in applying the array, even when it might possibly have some merit.

7. Extended Range Via the Evaporation Duct

Twenty-five years ago a paper was published[8] describing experiments in which extended range detection of ships was encountered. These detections made use of the low-lying evaporative duct that forms over water. The ducts vary in height between about 20 and 50 feet above the surface of the water and are apparently quite prevalent much of the time over a large portion of the world's oceans. It was found, for instance, that at X band, the signal trapped in the duct decreased at an average rate of 0.45 db per nautical mile.

To take advantage of the evaporative duct requires that the radar antenna and the target be within the duct. For example, in the tests referred to in the above, a small vessel was detected at a maximum range of 26.5 nmi when the X band radar antenna was at a height of 90 ft; but with the antenna at a height of only 6 ft, the same target could be detected out to 47.5 nmi.

In order to utilize this phenomenon to extend the range of surface-search radars beyond the immediate horizon, some additional facts must be gathered. Although it appears that the presence of a suitable evaporative duct is quite likely, there is no quantitative data available with which to make performance predictions. Also, the radar antenna must be located quite low on the ship, perhaps even over the side. This might result in a difficult mechanical problem if the radar is to survive in heavy seas. It also means that there might have to be more than one radar utilized if complete azimuth coverage is to be obtained.

8. Other Topics[9]

A few other items briefly mentioned in passing are:

Magnetic Recording. The video output of a radar can be readily recorded on magnetic tape for playback at a future time. These units are commercially available. They may be used for training purposes, or onboard ship they might provide a record that could be used to reconstruct the situation in the event of collision or other accident.

CFAR (Constant False Alarm Receiver). The receiver can be made to have a constant false alarm rate. This is important in systems with automatic detection. It is not too easy to apply in marine radar where different forms of clutter and receiver noise limit the receiver sensitivity.

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[8] M. Katzin, R. W. Bauchman, and W. Binnian, "3- and 9-Centimeter Propagation in Low Ocean Ducts," Proc IRE, Vol 35, pp 891-905, Sep 1947.

[9] More information on many of these topics can be found in the Radar Handbook, edited by M. I. Skolnik, McGraw-Hill Book Co, New York, 1970.

Log FTC. Provides some relief from extended weather clutter. It is a form of CFAR for Rayleigh type clutter. Subclutter visibility is not provided, only a more uniform scope presentation.

Automatic Video Threshold. This is another form of CFAR that establishes an adaptive threshold by examining a number of range cells ahead and behond the range cell of interest and thresholding on the maximum value. It presents a cleaner (less clutter) display, but no subclutter visibility.

Digital MTI. Modern digital circuitry is used to separate moving from stationary targets. Since both moving and stationary targets are of interest, its utility is limited.

Scan Converters and Bright Display. Permits the superposition of two or more radar outputs on a single bright display. Useful when more than one radar is employed.

Circular Polarization. Reduces rain clutter relative to ship echo.

Automatic Target Detection and Tracking. Based on computer processing with either manual or automatic inputs. Potential application is collision avoidance.

Frequency Diversity. Pulse-to-pulse frequency diversity can increase the radar's ability to detect small targets in sea clutter, but no better than a short pulse or pulse-compression radar occupying the same spectral bandwidth. It will reduce the angular scintillation of an angle-measuring radar when the target is of large size and will generally produce a better "image" of the target in an imaging (high resolution) radar.

Polarization Diversity. In some sea conditions, it has been shown that vertical polarization is better than horizontal for detecting small targets in sea clutter, but horizontal is generally preferred. However, an improvement in target-to-clutter ratio for ships can be had by cross-correlating the horizontal and vertical components of a dual-polarization radar, but this improvement does not seem warranted for marine radar.

Measurement of Radar Cross Section. Facilities exist at the Naval Research Laboratory for the dynamic measurement of the radar cross section of ships at L, S, C, and X bands with either horizontal or vertical polarization. In the appendix, it is shown that a good approximation to the ship's cross section at X band is $\sigma = 3500D^{1.6}$ where σ is in square meters and D, the ship displacement, is in kilotons.

APPENDIX

Radar Cross Section of Ships

The results of measurements of the radar cross sections of several classes of ships are presented in Fig. 1a. These represent the 50 percentiles (median values) of the radar cross section distribution function plotted in square meters and averaged about the port and starboard bow and quarter aspects of the ships. All data were obtained at essentially grazing incidence.

It was found empirically that the data could be expressed by a simple equation at each frequency:

X band (λ = 3.25cm)
$$\sigma = 3500\ D^{1.6}$$

S band (λ = 10.7cm)
$$\sigma = 2200\ D^{1.6}$$

L band (λ = 23cm)
$$\sigma = 1000\ D^{1.6}$$

where σ is the cross section in square meters and D is the ship's displacement in kilotons. Additional data representing the 20 and 80 percentiles of the radar cross section distribution function were examined and processed to determine, by a least squares method, the equations which would represent the best fit for the data considered for all three percentile levels (20, 50 and 80), three frequency bands (L, S and X), and seven ships with different displacements.

Two approaches were taken to examine the sensitivity of the ship displacement exponent and the value of the constant in the generalized expression. Taking each percentile data group individually and computing the constant for an optimized slope, the three following equations were derived:

$$\sigma = 30.38\sqrt{f}\ D^{1.37} \quad \text{(20th percentile)}$$

$$\sigma = 44.80\sqrt{f}\ D^{1.55} \quad \text{(50th percentile)}$$

$$\sigma = 100.00\sqrt{f}\ D^{1.51} \quad \text{(80th percentile)}$$

The next case was to calculate an optimized slope using all the data from all percentile levels and derive the constant for each individual percentile level. The resulting equations are:

$$\sigma = 26.72\sqrt{f}\ D^{1.45} \quad \text{(20th percentile)}$$

$$\sigma = 51.86 \sqrt{f}\, D^{1.45} \qquad \text{(50th percentile)}$$

$$\sigma = 112.53 \sqrt{f}\, D^{1.45} \qquad \text{(80th percentile)}$$

Selecting a single equation that could be used to approximate the data over the range of frequencies and displacements considered, one representing the 50th percentile value with optimized slope and constant and expressed to two significant figures is

$$\sigma = 52 \sqrt{f}\, D^{1.5}$$

where f is the frequency in megahertz. A demonstration of correspondence between calculated and measured values using this equation is shown in Figure 1b.

The variation with azimuth of the radar cross section of a large Navy auxiliary ship taken at S and X bands and using horizontal polarization is shown in Figures 2a and 2b. The 20, 50, and 80 percentiles of the cross section distribution function are plotted here in dB above 1 square meter (40 dBsm = 10,000 square meters). The values cover a 360-degree aspect profile in 2-degree azimuth increments for grazing incidence (zero degrees elevation).

Investigations at NRL of radar target characteristics of ships have been carried out using very short pulse, high resolution radars. One such X-band radar operated with a pulse length of 20 nanoseconds and a range resolution of 10 feet examined the nuclear merchant vessel, N. S. Savannah. The radar returns were analyzed to determine to what degree correspondence existed between those returns and the ship's structure. It is seen in Figure 3 that peaks do correspond to the portion of the ship from which large returns might be expected. High resolution radar at X-band is now receiving emphasis as ship traffic monitors in congested harbors such as San Francisco as part of the Coast Guard's Marine Traffic System.*

* H. J. Hindin, "High Resolution Radar to Monitor San Francisco Harbor in X band," Microwaves, Vol. 9, November 1971.

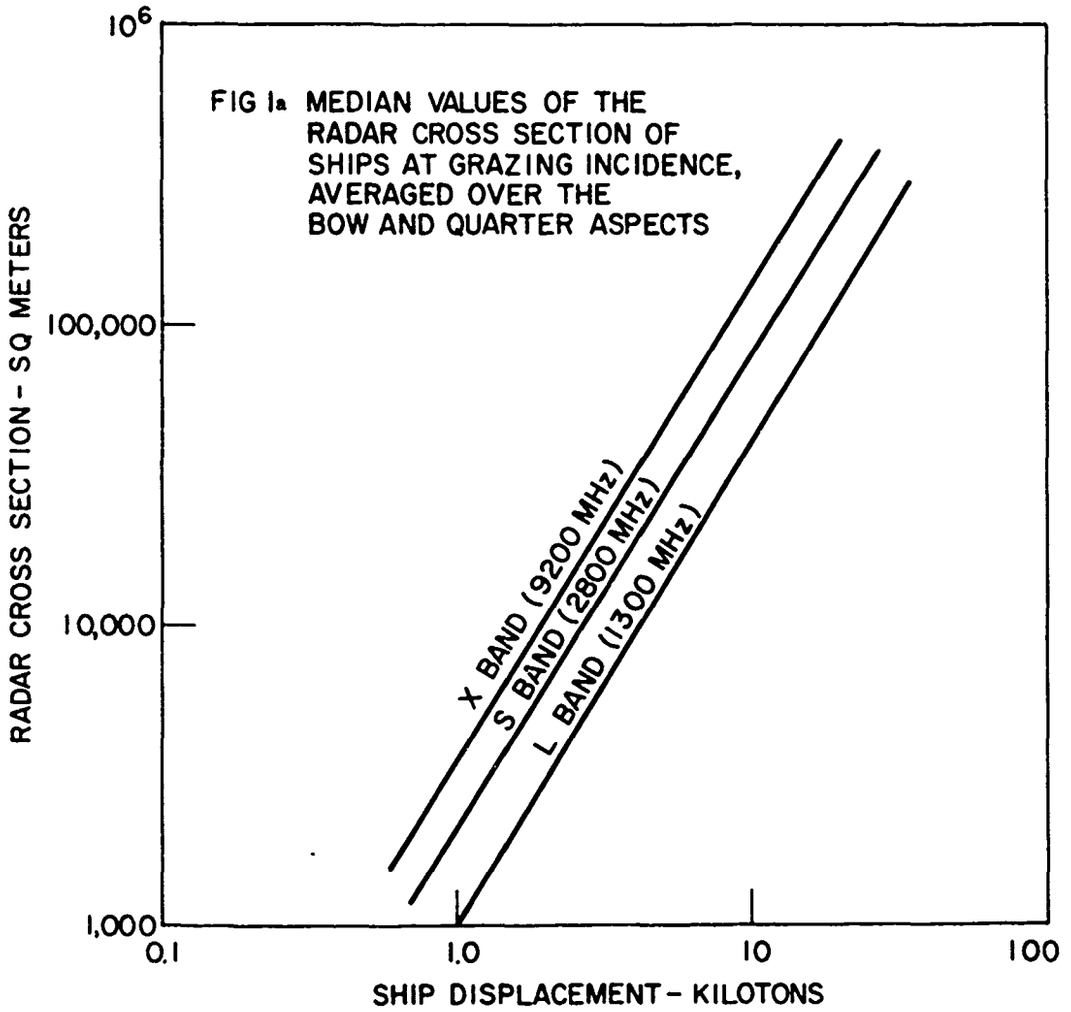


Fig. 1a - Median values of the radar cross section of ships at grazing incidence, averaged over the bow and quarter aspects.

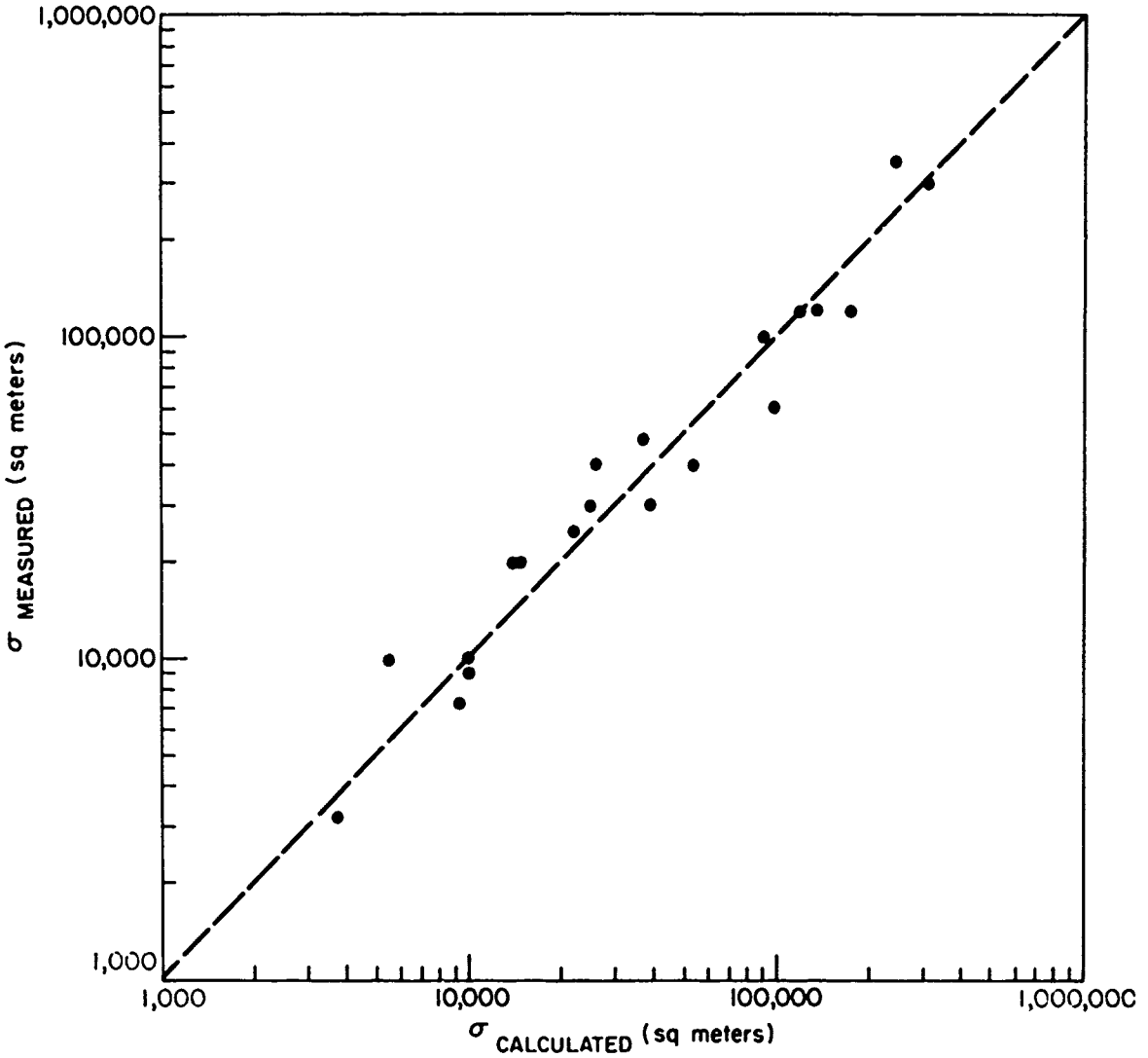
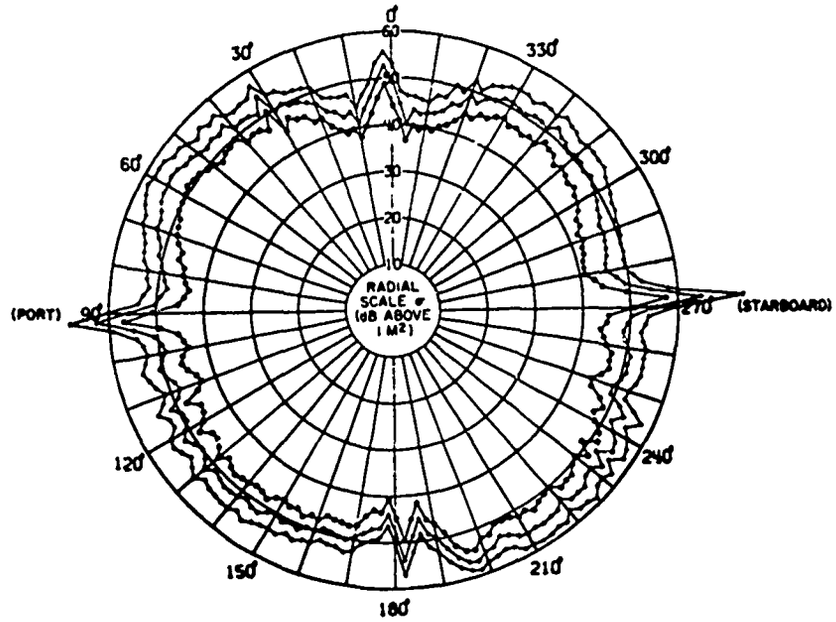
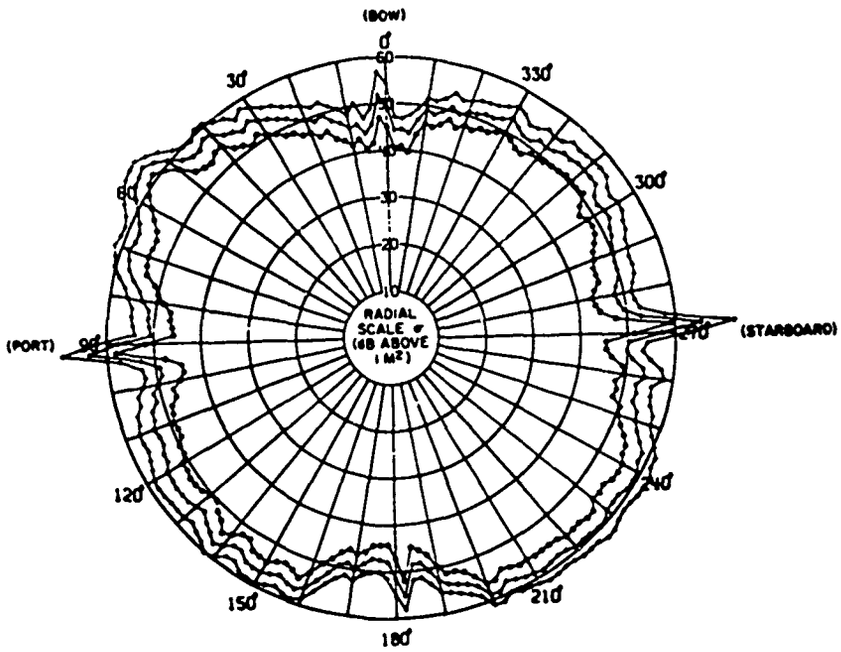


Fig. 1b - Calculated and measured cross section comparison



(a)



(b)

Fig. 2 — Azimuth variation of the radar cross section of a large Naval Auxiliary Ship at (a) S-band (2800 MHz) and (b) X-band (9225 MHz), both with horizontal polarization

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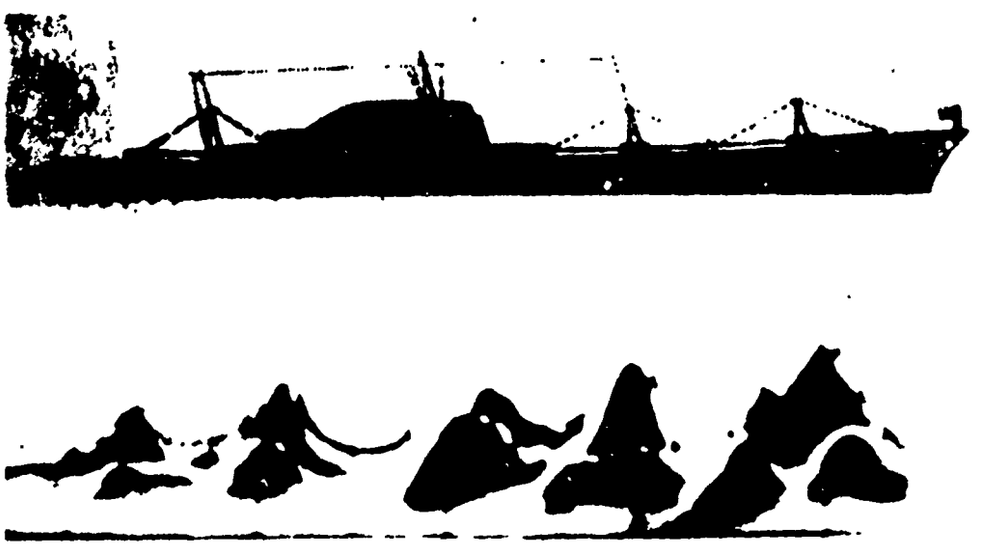

Fig. 3 - High range resolution (10 ft) radar "image" of N. S. Savannah