AD-785 007

REVIEW OF CURRENT RADAR INTERESTS AND EXTENDING RADAR SPECTRUM TO THE HF AND THE MILLIMETER WAVE BANDS

Merrill I. Skolnik

Naval Research Laboratory

Prepared for:

Office of Naval Research

August 1974

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 2869	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER AD-785 007
4. TITLE (and Subtitle) Review of Current Radar Interests and Extending the Radar Spectrum to the HF and the Millimeter Wave Bands		5. TYPE OF REPORT & PERIOD COVERED Final report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Dr. Merrill I. Skolnik		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D.C. 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NRL Prob. 53R02-59.101 62712N RF-12-151-402-4015
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Navy Department Washington, D.C. 20360		12. REPORT DATE August 1974 13. NUMBER OF PAGES 18
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Radar
OTH Radar
Millimeter Wave Radar
Radar Problem Areas

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. Department of Commerce
Springfield VA 22151

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report consists of two papers that are concerned with current radar interests. In one paper the various major applications are described and a listing of current problem areas is given. The other paper discusses the extension of radar outside the normal microwave bands to include the HF region at one end of the spectrum and millimeter waves at the other end.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REVIEW OF CURRENT RADAR INTERESTS*

and

EXTENDING THE RADAR SPECTRUM TO THE HF AND THE MILLIMETER WAVE BANDS*

Merrill I. Skolnik**
Radar Division

* Two papers prepared for presentation at the IEEE Northeast Electronics Research and Engineering Meeting (NEREM), Boston, Massachusetts, October 29, 1974.

** Prepared while on Sabbatical Leave at the Johns Hopkins University, Baltimore, Maryland.

Manuscript submitted July 23, 1974.

REVIEW OF CURRENT RADAR INTERESTS

This short paper was prepared to introduce the Technical Session on "Radar-Some Problems of Current Interest," at the 1974 NEREM Meeting in Boston. It will briefly list the major areas of current radar application and a few of the problems that confront modern radar.

CURRENT RADAR APPLICATIONS

Air Traffic Control - There are over 200 long-range and medium-range air surveillance radars in use by the FAA in the United States for the purpose of safely controlling air traffic. This may not be a large number of radars, but it is very important application because of the heavy reliance on air transportation. Another use of radar is for the surveillance of the ground traffic at major airports. A high resolution radar is employed for this purpose. In addition, microwave landing systems and the widely used ATC beacon system are based in large part on radar technology.

Aircraft Navigation - The weather avoidance radar used on aircraft to outline regions of high precipitation to the pilot is a classical form of radar. Although they may not always be thought of as radars, the altimeter (either FM/CW or pulse) and the doppler navigator are also radars. Sometimes ground mapping radars of moderately high resolution are used for aircraft navigation purposes. Some Military aircraft employ terrain avoidance or terrain following radars.

Ship Navigation - In terms of numbers, this is one of the larger applications of radar, but in terms of physical size and cost it is one of the smallest. It is also one of the most reliable radar systems. Automatic detection and tracking equipments are commercially available for use with such radars for the purpose of collision avoidance. Shore-

based radar of moderately high resolution is also used for the surveillance of harbors as an aid to navigation.

Space - Both the Gemini and the Apollo space vehicles used radar for rendezvous and docking, and Apollo also utilized it for landing on the moon. Some of the largest ground-based radars are for the detection and tracking of satellites.

Remote Sensing - All radars are remote sensors; however, as this term is now used it implies the sensing of geophysical objects, or the "environment." For some time, radar has been used successfully as a remote sensor of the weather and the atmosphere. It was also used in the past to probe the moon and the planets (radar astronomy), but this has been displaced by the successful use of manned and unmanned spacecraft. The ionospheric sounder, an important adjunct for HF (short wave) communications, is a radar and was first employed about fifty years ago. Current interests in remote sensing with radar deal with Earth resources, which include the measurement and mapping of sea conditions, water resources, ice cover, agriculture, forestry conditions, geological formations, and environmental pollution. The platforms for such radars include satellites as well as aircraft.

Law Enforcement - In addition to the wide use of CW radar to measure the speed of automobile traffic, radar has been employed as a means for the detection of intruders.

Military - By far the biggest user of radar and the one who has paid for almost all of its development is the military. Its traditional role in the military has been for surveillance, navigation, and for the control and guidance of weapons.

CURRENT PROBLEM AREAS

Extending the Coverage of Radar - The coverage of

microwave radar is basically limited by the line of sight, which depends on the height of the radar and the height of the target. No matter what coverage is obtained with radar, it is always natural to ask for more. Extending the range can be accomplished by elevating the radar, use of over-the-horizon radar in the HF band, or by taking advantage, when possible, of non-normal propagation conditions such as ducting.

Relief of the Operator - A man does very well as a radar operator so long as he is alert and is not confronted with too high an information rate. To assist the operator and to prevent saturation, digital computer techniques have been applied to the automatic detection and tracking of targets. The success of such techniques is due to the remarkable achievements in digital computer componentry during the last twenty years. The computer is also important for organizing and executing the control of the radar system and in the efficient use of its output.

Extraction of Target Information - The basic measurement of radar is the distance to the target. No other sensor can provide this as well as can radar. Radar also determines the angular location of targets and in some systems it uses the doppler frequency shift to measure relative velocity or to separate stationary from moving targets. Radar can obtain other information about targets, such as their size and shape, and can sort them by type. Means for extracting target information from the received signal is always of interest. A current example where significant progress has been made is in the remote sensing of the environment.

Operation in Clutter - Any method that allows a radar to perform its task in spite of the obstructions imposed by clutter is always welcome. Clutter includes unwanted reflections from land, sea, weather, clear air turbulence,

birds, insects, meteors and aurora.

Electromagnetic Compatibility - Radar must be able to operate properly in spite of interference from other electromagnetic sources. Likewise, the radar must not interfere with other users of the electromagnetic spectrum.

Equipment Improvements - Better subsystems and components are always desirable. A few of the equipment advances that would be welcome include: better isolation in CW radar, efficient linear transmitters, efficient low-duty-cycle solid-state RF power devices, wide-dynamic-range displays and receivers, wide-band wide-dynamic-range A/D converters, short-pulse high-power transmitters, and long-life highly reliable mechanically rotating antennas.

Affordable Phased Arrays - In one sense, this is an example of an equipment improvement and might be included in the above paragraph. It is listed separately since the value of the phased array antenna as a tool for the radar systems engineer is unquestioned. However, when economic matters are a consideration, arrays are not usually competitive with other means for accomplishing the same objectives. The high cost of computer software is a factor in any consideration of an array system, along with the array hardware costs.

Reasonable System Cost - Although it is a natural human trait to want to get the most for the least amount of money, this precept is not always practiced in the procurement of radar systems. It is easy in a highly sophisticated and changing technology like that of radar to be unknowingly extravagant. The cost of a radar is not just the dollars spent on acquiring the system. It also includes the costs to install, to finally make it work properly, and the cost of maintaining and operating it over its useful life. In addition to its cost in dollars there is the "cost" in weight and space if it is used in a mobile platform such as

an aircraft or ship. There is also the cost of the platform itself if the radar installation makes special demands, and the cost of the site if a land-based application. It is no secret as to how to minimize the total cost of a radar system. The user of a radar should ask only for what he really needs rather than what he desires, and he should make certain that before he pays the bill the radar he has bought works as specified.

Dependability - A radar should be of long-life, reliable, maintenance free (or if not, at least it should be easy, cheap, and quick to fix), and be simple to operate. No one will deny the desirability of such things, but it is surprising how seldom they are taken seriously during development, when over-runs in money or time occur.

Of all the above problem areas the most important, in the writer's opinion, are the last two. The user of radar must be able to obtain what he needs at a reasonable price and it should operate as it is supposed to whenever it is required to do so. These are not usually thought of as research and development areas, but they are probably as important as anything else being conducted in the research laboratories and in industry, and they might very well become serious R & D projects.

The above listing has been from the viewpoint of the systems engineer interested in applying radar for some useful purpose. They can be called problems in search of solutions. There are also solutions in search of problems. These are new techniques and components that their developers believe might offer improvements in radar. These will not be discussed here other than to state that they include such things as surface-wave acoustic devices, change-coupled devices, microwave transistors and other solid state RF devices, liquid crystal and solid state dis-

plays, microprocessors, adaptive antennas, conformal arrays, pattern recognition, and the whole myriad of techniques that are associated with millimeter waves. Progress in radar has been made by both the dogged pursuit of current problems one small step at a time, and by the occasional large advance introduced by some new, and usually unforeseen, technological development.

EXTENDING THE RADAR SPECTRUM TO THE HF AND THE MILLIMETER WAVE BANDS

Operational radar systems are found in the frequency range from VHF (about 200 MHz) to K_a band (35 GHz). This encompasses what is usually called the microwave region. Generally, the lower microwave frequencies are used for long range volumetric surveillance and the higher frequencies are used for precision measurements of target properties. There is always interest in applying radar beyond these limits; to the HF band at the lower end (down to about 2 MHz) and to the millimeter wave band (up to about 94 GHz, or 3.2 mm wavelength). This paper will briefly explore some of the advantages offered by operating radar beyond the usual frequency range and discuss some of the limitations encountered in attempting to do so.

Radar Below VHF. In the past, radar has been used with success at frequencies below VHF for the scientific exploration of the ionosphere (Thomson scatter)[1], meteors[2], and the sun[3]. At the lower frequencies, the generation of large power and the construction of large, fixed antennas is generally easier than at higher frequencies. Weather clutter is almost nil. However, the available bandwidths are small, beamwidths are broad, and the natural noise and man-made interference are large enough to limit receiver sensitivity. When the frequency is so low that the radar wavelength λ is large compared to target dimensions, the scattering from targets is proportional to λ^{-4}, and the radar cross section of normal targets of interest can be small. These limitations in using radar below VHF generally dominate the advantages and it is not too often that radar is considered seriously at the lower frequencies.

However, there are two characteristics of radars that operate at frequencies below VHF that offer some attractive-

ness. In the HF region of the spectrum it is possible to achieve over-the-horizon propagation with very long ranges (perhaps up to 4000 km or more) by refraction from the ionosphere.[4,5] This is sometimes called skywave propagation. It is also possible to achieve radar propagation beyond the line of sight at these frequencies by the ground wave mode, perhaps up to 400 km. The other interesting characteristic of radar operation in this frequency region is that most of the backscatter occurs from objects comparable in dimensions to the radar wavelength. Thus, information can be obtained about target properties that is not possible with radar at other frequencies. A good example is the interpretation of wave conditions over the ocean from the doppler spectrum of the backscattered signal.[6]

Therefore, if radar is of interest at frequencies lower than currently used operationally, it would be in the HF band where radar has some unique characteristics not found at higher frequencies.

Radar at HF. Although the official ITU (International Telecommunications Union) designation of the HF band is from 3 to 30 MHz, a radar that operates at "HF" might be anywhere from 2 MHz (just above the broadcast band) to 40 MHz or more. The mode of propagation is similar to that of short-wave communications and involves refraction from the ionosphere. The maximum range on a single refraction (hop) is about 4000 km. The long ranges associated with HF over-the-horizon (OTH) radar require that it be of high power and of large antenna aperture. The average power of an OTH transmitter might be several hundreds of kilowatts and the antenna gains might be from 20 to 30 dB. A large antenna is desired in order to achieve a reasonable beamwidth. (A one degree beamwidth at a frequency of 15 MHz requires an aperture with a dimension of about 1.2 km.)

The resolution in angle and in range is generally

poorer in an HF OTH radar than a microwave radar. This, plus the fact that OTH radars operate at long range, means that the amount of ground clutter (land or sea) illuminated by the radar is quite large when compared to the cross section of aircraft. If an OTH radar is to be successful it must be able to exclude the large clutter echo. This is accomplished by filtering the target signal from the clutter on the basis of their different doppler frequency shifts. The doppler signal processor has been the key element in the success achieved with OTH radar.

The doppler processing of the received signal not only permits the desired targets to be separated from the unwanted clutter, but it provides the chief means for resolving targets. It has already been mentioned that the resolving power of such radar is poor in both range and angle. However, targets whose doppler frequencies differ by 0.1 Hz or less can generally be resolved. At a radar frequency of 15 MHz, 0.1 Hz doppler resolution corresponds to a difference in relative velocity of about 2 knots.

It is refraction from the ionosphere which is located at heights from 100 to 400 km above the earth that allows the long range operation of HF radar. The ionosphere is not a perfect medium and its properties can vary with time as well as space. It can introduce loss and can limit the effectiveness of the doppler processing and the accuracy of the angular measurement. In addition, meteors and aurora can be strong sources of clutter that can interfere with detection. These adverse effects can be minimized by the proper choice of parameters. It is generally easier to compensate for the effects of ionospheric propagation with OTH radar than with short-wave communications since the radar backscatter received from distant ground clutter can be used as a probe to determine the best operating conditions. With the proper flexibility in frequency, transmitter

power, waveform, and vertical radiation angle, an HF OTH radar can have a reliability comparable to that of microwave radars.

Applications of HF OTH Radar. The ability of an OTH radar to detect targets at distances an order of magnitude greater than possible with microwave radar means that such radar can be utilized effectively where it is not convenient to site microwave radar, such as for coverage over vast ocean areas. With OTH radar it would be possible to detect and track aircraft in the commercial air-traffic lanes over the ocean. This would allow essentially the same type of radar air-traffic control over the oceans as is now practiced over land.

In addition to performing the familiar tasks of microwave radar, but over a greater area of coverage, the OTH radar can obtain information not possible with microwave radar. This difference is due to the much longer wavelengths of HF radar. The radar echo from the sea, for example, is due to those wave components of the sea spectrum that are of comparable wavelength to the radar wavelength as measured along the direction of propagation. (At grazing incidence, the radar responds principally to water wavelengths half the radar wavelength. These are called the resonant wavelengths.) Thus the echo from the sea with HF radar is indicative of water waves from less than 10 m in length to several tens of meters. A water wave of particular wavelength has a particular velocity that is governed by the laws of hydrodynamics. The spectrum of the sea return at a particular radar frequency consists of two principal lines, one corresponding to the resonant wave that is approaching the radar and the other corresponding to the resonant wave which is receding. The relative magnitudes of these two spectral components is a measure of the wind direction. The ratio of the value of the maximum component

to the value of the spectrum at zero frequency is a measure of the wind speed. From such observations it is possible to map the wind conditions over a large part of the ocean, and timely information can be obtained about weather conditions over ocean regions where such data is sparse. This information should aid in improving the prediction of weather conditions on a world-wide basis.

Radar above K_a Band. The frequencies above K_a band (35 GHz) are of interest because of the large bandwidths available. The atmospheric window at 94 GHz, for example, is wider than the entire microwave region. Large bandwidth means that the radar can have good range resolution and there is less likelihood of interference among equipments operating in the same band. Also, the physical size of an antenna required to achieve a specified beamwidth is inversely proportional to the frequency. The smaller wavelengths are responsive to smaller size scatterers than at the longer microwave wavelengths, so that information about targets can be obtained that is not possible at other frequencies. This has been taken advantage of in radars that operate at millimeter wavelengths to study the physics of clouds from the scattering obtained from water vapor. Thus radars above K_a band are of interest for the high resolution in angle and range, the information available from specific types of targets, and the freedom from interference.

There are some limitations in attempting to operate radar above the current frequencies for conventional applications.[7] Some of the limitations are of a practical nature, some are more fundamental. The extension of microwave transmitter and receiver technology to higher frequencies has not been encouraging. Transmitter powers decrease rapidly with increasing frequency, and receiver sensitivity worsens. (This is analogous to the diminishing

effectiveness of extending lumped-constant circuit technology to microwaves.) In the infrared region, optical techniques and the laser are available with reasonable power and sensitivity, but there is a wide part of the spectrum between microwaves and IR where technology is wanting.

Even if technology were not a problem, there are some basic limitations to operating above the normal radar bands. The smaller size antenna apertures, which at first glance appear to be an advantage, mean that such radar systems are not effective for volumetric search. The effectiveness of a search radar is measured by the product of the average transmitter power and the antenna aperture area. The choice of frequency does not enter explicitly. Thus, radars with small antennas are not useful for surveillence.

Another basic limitation of radars operating at higher than usual frequencies is the severe attenuation introduced by propagation through rain and the atmospheric gases. (If one operates outside the atmosphere, attenuation is not a problem.) The atmospheric attenuation is not uniform with frequency. There are "windows" where the attenuation is less, relative to adjacent frequencies. The first window above K_a band is at 94 GHz (3.2mm wavelength) and is approximately 23 GHz wide. Thus if a radar were to be employed at a frequency above those currently in use it would most likely operate at this band. When one speaks of millimeter wave radar, it is this band that is generally connoted.

Example of a Millimeter Wave Radar. In order to illustrate the capability of a surveillance radar at 94 GHz, an example is offered. We select as large an antenna (high gain and large aperture in terms of wavelengths) and as large a transmitter power as might be reasonable from an optimistic point of view. At this frequency a power source of 200 watts average power is large. The antenna beamwidth

is chosen to be 0.1°, corresponding to a gain of approximately 63 dB. With shaping of the beam in the vertical to give better coverage, the gain is lowered to 60 dB, which is a rather large gain for an antenna. The antenna diameter would be close to 7 ft. With a rotation rate of 5 rpm, there will be about 3.3 hits received per half-power beamwidth per scan. The noise figure of the receiver is optimistically taken to be 10 dB, and 10 dB system losses are assumed.

With a signal-to-noise ratio of 15 dB, the range in free space (vacuum) for such a radar is 69 n.mi., a very respectable value. However, at sea level the attenuation in clear weather at a frequency of 94 GHz is 0.4 dB/km. This reduces the range to about 16.5 n.mi. In moderate rain of 4 mm/hr, the attenuation is 2.5 dB/km and the range that results is about 4.6 n.mi.

Discussion. The more than seven octaves of frequency occupied by modern microwave radar has proven satisfactory for a large number of diverse radar applications. Radars are operated outside these limits when it is desired to achieve some property not possible with microwaves. This includes the attaining of long range surveillance at the lower frequencies and the precision measurements of the higher frequencies as well as the wide spectral range available with the higher frequencies. Extending the frequency at either end of the microwave spectrum is also advantageous when examining objects whose dimensions are comparable to the particular radar wavelengths. It does not seem likely, however, that there will be as extensive applications of radar in the near future outside the usual limits of frequency as there have been at microwaves.

References

1. J.V. Evans, "Theory and Practice of Ionosphere Study by Thomson Scatter Radar," Proc. IEEE, Vol. 57, pp 495-530, April, 1969.

2. A.C.B. Lovell, Meteor Astronomy, Clarendon Press, Oxford, England, 1954.

3. J.V. Evans and T. Hagfors, Radar Astronomy, McGraw Hill Book Co., New York, 1968.

4. J.M. Headrick and M.I. Skolnik, "Over-the-Horizon Radar in the HF Band," Proc. IEEE, Vol. 62, pp June, 1974.

5. Y.A. Michchenko, Zagorizontnaya Radiolokatsiya, Military Publishing House, Moslow, USSR, 1972. (Also available in in English transl. as Report JPRS 56925, the National Technical Information Service, Springfield, VA 22151.)

6. D.E. Barrick, J.M. Headrick, R.W. Bogle, and D.D. Crombie, "Sea Backscatter at HF, Interpretation and Utilization of the Echo," Proc. IEEE, Vol. 62, pp June 1974.

7. M.I. Skolnik, "Millimeter Submillimeter Wave Applications," Proceedings of the Symposium on Submillimeter Waves, New York, March 31, 1970, Polytechnic Institute of Brooklyn, N.Y.