Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

THE UPWIND/DOWNWIND DEPENDENCE OF THE DOPPLER SPECTRA OF RADAR SEA ECHO

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final report on one phase of a continuing problem.

5. AUTHOR(S) *(First name, middle initial, last name)*

M. B. Laing

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 19, 1971	22	5

8a. CONTRACT OR GRANT NO. NRL Problem R02-37 b. PROJECT NO. A31-310-65270-R008-01-02 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7229 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Dept. of the Navy (Naval Air Systems Command) Washington, D.C.

13. ABSTRACT

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Radar echoes						
Phase detectors						
Frequency analyzers						
Coherent radar						
Four-frequency Radar (4FR) System						
Doppler radar						
Fast Fourier transformations						
Polarization (waves)						
Sea Clutter						
Doppler spectra						
Direct and crosspolarized echo						
Multiple frequency radar						
Frequency diversity						

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(PAGE 2)

Security Classification

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PROBLEM STATUS

This is a final report on one phase of the problem; work on other phases is continuing.

AUTHORIZATION

NRL Problem R02-37
Project A31-310-65270-R008-01-02

Manuscript submitted December 1, 1970.

THE UPWIND/DOWNWIND DEPENDENCE OF THE DOPPLER SPECTRA OF RADAR SEA ECHO

INTRODUCTION

During the past two decades there has been an intensive study of the ocean surface as a radar scatterer. Most of this effort, however, has been expended in the study of the ocean's radar cross section rather than on the doppler characteristics of the radar return, with the net result that the physical processes affecting the noncoherent radar return are better understood than those underlying the coherent return. This concentration on the noncoherent radar return stems, at least in part, from the fact that doppler measurements are more difficult to obtain than power measurements and require a far more sophisticated radar system. For this reason, it has not been until the last few years that doppler data have been available in both sufficient quantity and quality to allow a comprehensive study of the effects of the sea, wind, and radar parameters on radar returns.

In this respect, the Naval Research Laboratory (NRL) has made a major contribution with the Four-Frequency Radar (4FR) System, which is capable of making nearly simultaneous recordings of both the coherent and noncoherent aspects of the radar return over a frequency range from UHF to X band, for horizontal and vertical polarizations. A portion of the data collected with the 4FR System in both the North Atlantic during February 1969, where wind velocities of up to 24 m/sec and wave heights as great as 8 meters were recorded, and in the more moderate conditions of the sea near Puerto Rico in July 1967, was analyzed by Valenzuela and Laing (1). A model was developed that predicts the wave height dependence of the spectral bandwidth, but cannot explain its polarization dependence.

In this present study, data from the North Atlantic experiment, along with that obtained during January 1970 near Bermuda, have been investigated in detail for the specific purpose of determining the upwind/downwind dependence of both the width of the spectrum and the difference in mean frequency between horizontally and vertically polarized spectra (differential doppler) of radar sea echo. The results of this investigation indicate that the upwind/downwind ratio for the bandwidth is nearly unity, but the differential doppler has an upwind/downwind ratio of nearly two to one. These results, along with data collected in low-wind, high-sea conditions, indicate that the differential doppler is primarily dependent on the wind speed, but that the spectral bandwidth of the radar return depends on ocean wave height. In addition, the investigation confirmed earlier findings concerning polarization and frequency dependencies, as well as indicating that there is a general drift of the radar scatterers in the direction of the wind and wave motion.

INSTRUMENTATION

The NRL 4FR System has already been described in detail in the literature (2), and therefore only a brief summary of its characteristics will be given here. The 4FR System is an airborne, coherent, pulsed radar that uses both frequency and polarization diversity to make near simultaneous measurements of the elements of the radar scattering matrix. Operational frequencies are 428 MHz (UHF or P band), 1228 MHz (L band), 4455 MHz (C band), and 8910 MHz (X band). Although measurements are made with near simultaneity on all frequencies, the returns are not from the same portion of the sea surface since the

P- and L-band antennas are mounted back-to-back with the C- and X-band antennas. Because of this arrangement, the standard procedure for collecting upwind/downwind data is for the aircraft to fly a course into the wind, with the X- and C-band antennas directed forward, so that upwind data are collected for various depression angles on X and C band, with downwind data being collected on P and L band. The antennas are then rotated 180° and the measurements repeated, yielding upwind data for P and L band, and downwind data on X and C band. To complete the information, the airplane is then flown downwind and the same procedure is repeated.

Although the 4FR System is capable of making radar cross-section measurements, and in fact normally does, the phase output channel of the system is of primary interest in the study of the doppler return. For this measurement, the returning radar signal is hard limited to remove amplitude fluctuations, and then fed to a phase detector which compares it to a reference signal. The resultant output is proportional to the cosine of the difference in phase between these two signals. This output is range gated and recorded on magnetic tape in a digital format that allows processing at a later date by a digital computer. Other information pertaining to the operating characteristics of the 4FR System may be found in the Appendix in the form of tables.

In order to be able to correlate the radar data with the sea and wind conditions, data collection missions are usually carried out in areas where some form of weather gathering facilities is available. The North Atlantic data used in this report were collected near the Ocean Survey Vessels "I" (59°N, 19°W) and "J" (52.5°N, 20°W) which issued hourly weather reports, including sea conditions. The data which were collected near Bermuda came from the area of Argus Island, a Texas tower which was instrumented to record both wind and wave conditions.

Table 1 contains a description of the sea conditions and other pertinent parameters affecting the data used in this report.

DATA PROCESSING

A small, general-purpose, digital computer was programmed to read the phase values from the magnetic tape and compute the power spectrum of the radar return from them by means of the Fast Fourier Transform (FFT). Since the resulting spectrum is an estimate of the relative power returned at each frequency, it is desirable to average a number of spectra together so that a greater confidence level can be assigned to the results. In order to accomplish this, the spectra of a number of consecutive data samples were computed and averaged on a frequency-by-frequency basis. The sample size used for an individual spectrum was chosen to give a frequency resolution that is approximately equivalent to a doppler velocity of 0.3m/sec. For P and L band this is approximately 1 sec of data, while for C and X band it amounts to 1/4 sec. Thirty individual spectra were averaged for P and L band to give a smooth curve, while one hundred and twenty were used on C and X band so that the resulting spectra would cover identical time periods. The resultant spectra are not, however, the spectra of the radar sea echo, but rather the result of a convolution of the spectrum of the radar sea echo and the platform motion spectrum. Because of this convolution, the measured spectrum of the sea return will be found to be centered about the mean doppler frequency f_d produced by the platform motion, which is given for a radar looking along-track by the equation

$$f_d = (2v/\lambda) \cos \gamma \tag{1}$$

where λ is the wavelength of the radar, γ is the antenna depression angle, and v is the relative speed of the aircraft with respect to the surface. Since f_d is normally greater than one-half the pulse repetition rate f_s, which is also the sampling rate for a pulsed

Table 1
Parameters Associated with the Sea-Echo Measurements

Date	Meteorological		Location	Aircraft		Radar	
	Wind Speed (m/sec)	Waveheight (m)		Altitude (m)	Indicated Airspeed (m/sec)	Pulse Rep. Freq. (pps)	Pulsewidth (μsec)
2/11/69	24.5	8.0	OWS "I"	480	97	683	0.5
2/13/69	18	7.0	OWS "J"	460	103	603	0.5
2/14/69	20	7.5	OWS "J"	460	103	603	0.5
2/17/69	2.5	4.6	OWS "I"	410	103	603	0.5
2/18/69	11	3.0	OWS "J"	460	103	603	0.5
1/23/70	6.2	3.7	Bermuda	180	103-115	683	0.5
1/26/70	7.5	1.5	Bermuda	750	89-108	683	0.5
1/27/70	8.2	1.8	Bermuda	180	87-108	683	0.5
1/27/70	8.2	1.8	Bermuda	610	87-110	683	0.5

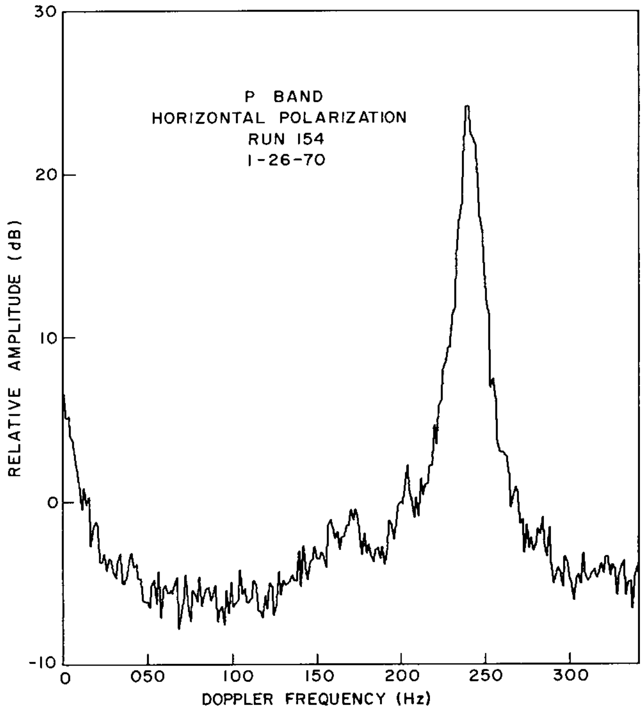
radar, the Nyquist sampling criterion is not satisfied, and the entire spectrum from 0 to f_d is therefore not recoverable. However, only a narrow band about f_d is actually of interest, and the signal spectrum is convolved with the spectrum of the sampling function, thereby giving rise to aliases of the doppler spectrum which appear centered at frequencies given by

$$f_a(n) = f_d \pm nf_s, \quad n = \pm 1, \ \pm 2, \ \pm 3, \ldots \qquad (2)$$

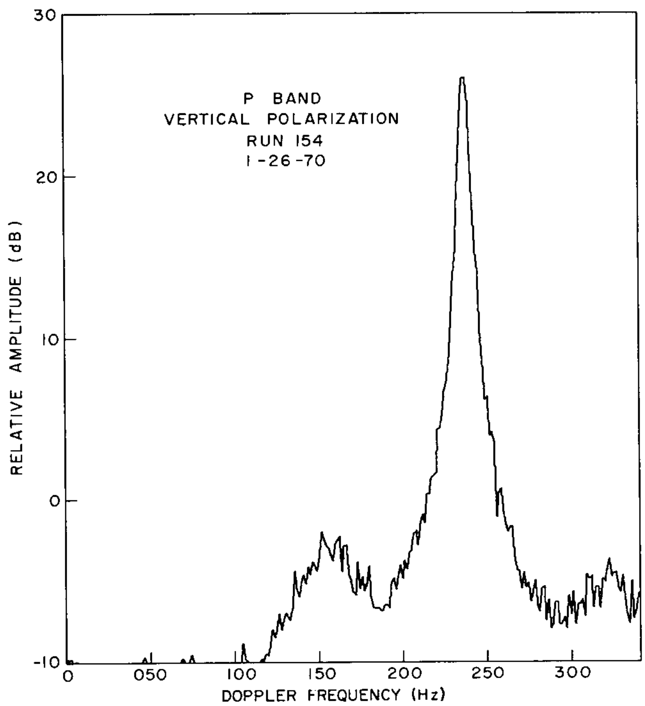
One of these aliases always lies in the range from zero to one-half the pulse repetition rate f_s, and if the frequencies are such that each frequency in the alias represents a unique frequency in the original spectrum, the alias is said to be unfolded, and the shape and relative amplitude are unchanged so that this alias may be used for analysis.

An examination of the typical averaged doppler spectra shown in Figs. 1-4 will demonstrate several of the points just mentioned. Figures 1 through 3 are the spectra taken from Run 154 (Jan. 26, 1970) with the antenna depressed by 10°. The P- and C-band spectra are good and may be used for analysis. The L-band spectra for this Run (Figs. 2a and 2b) are folded, and neither their bandwidths nor their mean frequencies can be found. Figures 4a and 4b are L-band spectra that are not folded, since the aircraft was flying downwind instead of upwind, which increased its ground speed. The P-band spectra are normally not aliases, and therefore show the true frequencies, while the C band has a true doppler return of about 2.5 kHz, with the L band from Run 156 being about 860 Hz. In terms of frequency, the C-band spectra obviously have the greater bandwidths, but when converted to velocity the vertically polarized C-band spectrum is actually the narrowest.

In order to facilitate the comparison of spectra, the frequency is transformed to the equivalent doppler velocity in accordance with Eq. (1). Note should be taken of the fact that the cos γ dependence is included in the transformation, which allows the internal consistency of the data to be checked. This transformation necessitates the finding of the true doppler frequency, which is most easily accomplished by estimating the aircraft

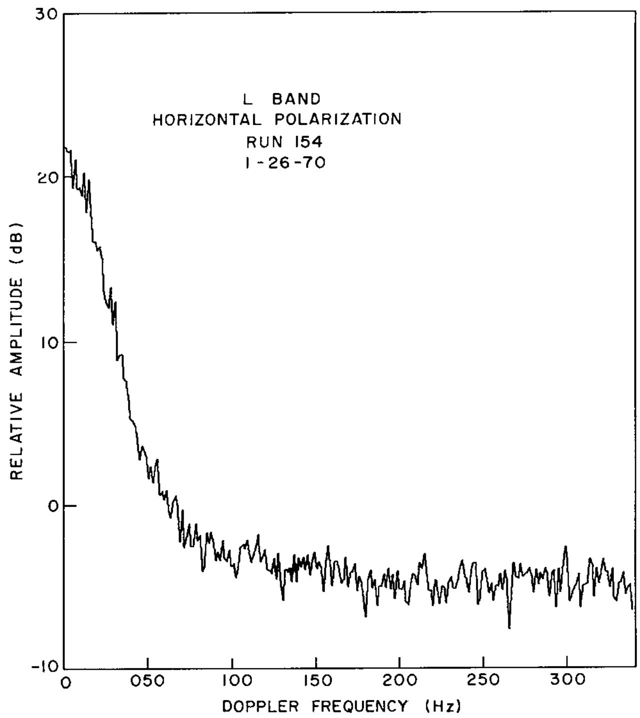


(a) horizontal polarizations

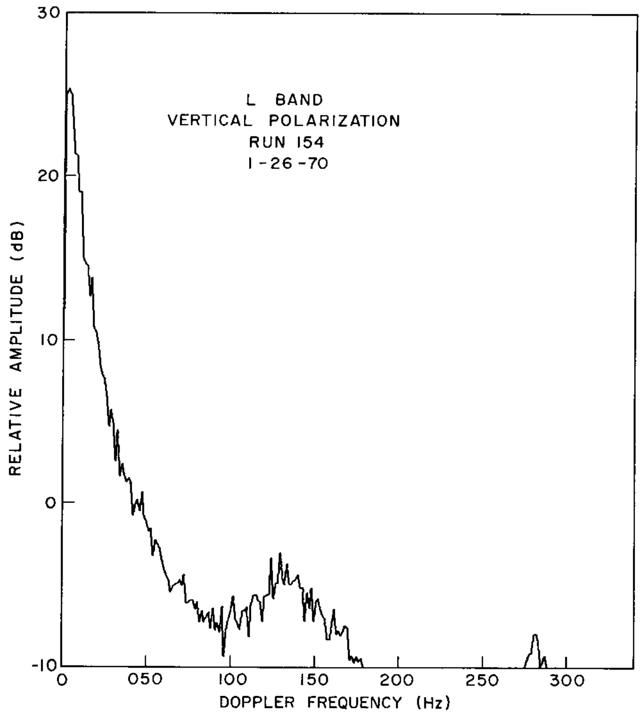


(b) vertical polarizations

Fig. 1 - Typical averaged doppler spectra of radar sea echo at P band

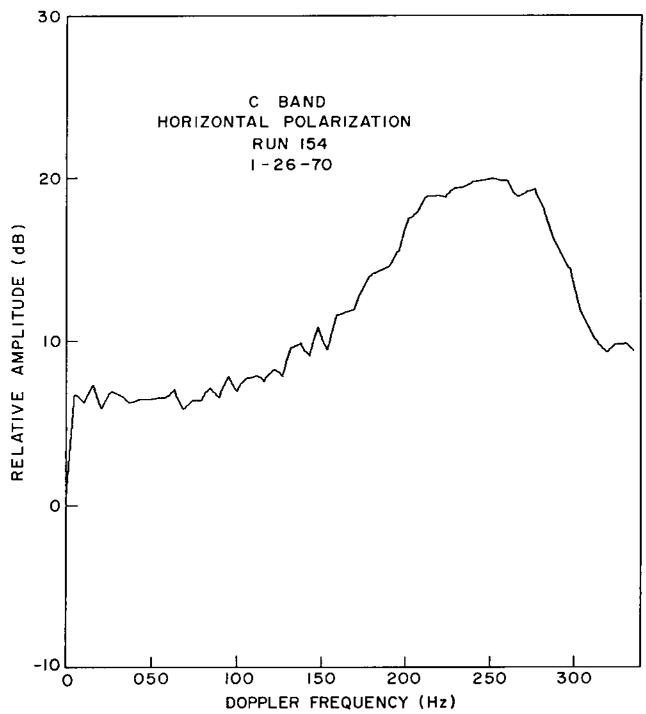


(a) horizontal polarizations

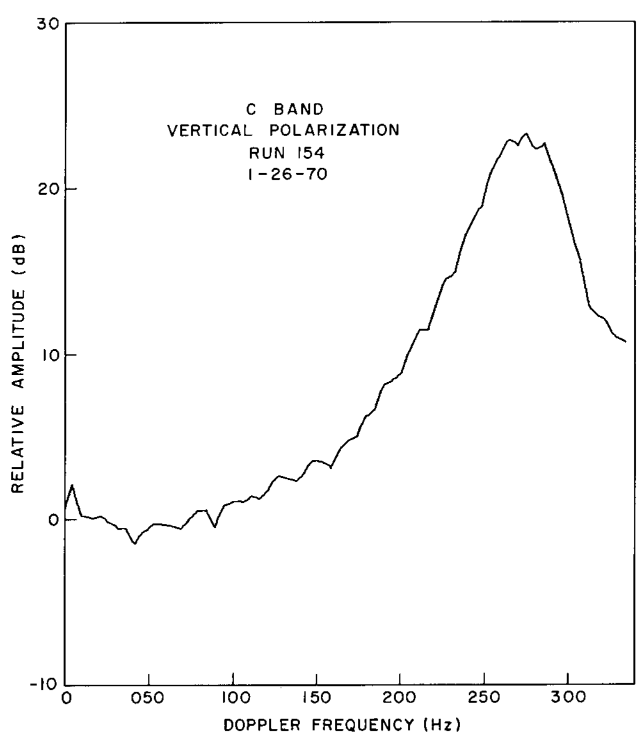


(b) vertical polarizations

Fig. 2 - Typical averaged doppler spectra of radar sea echo at L band, showing the effect of frequency folding

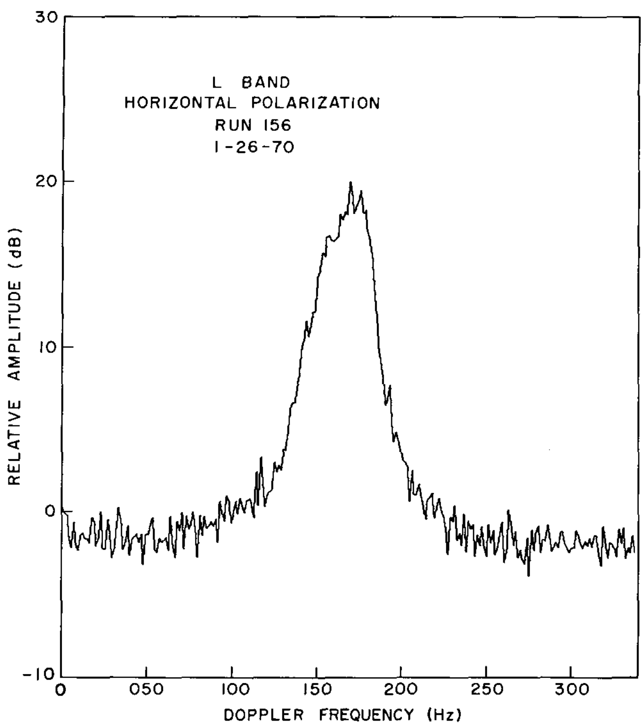


(a) horizontal polarizations

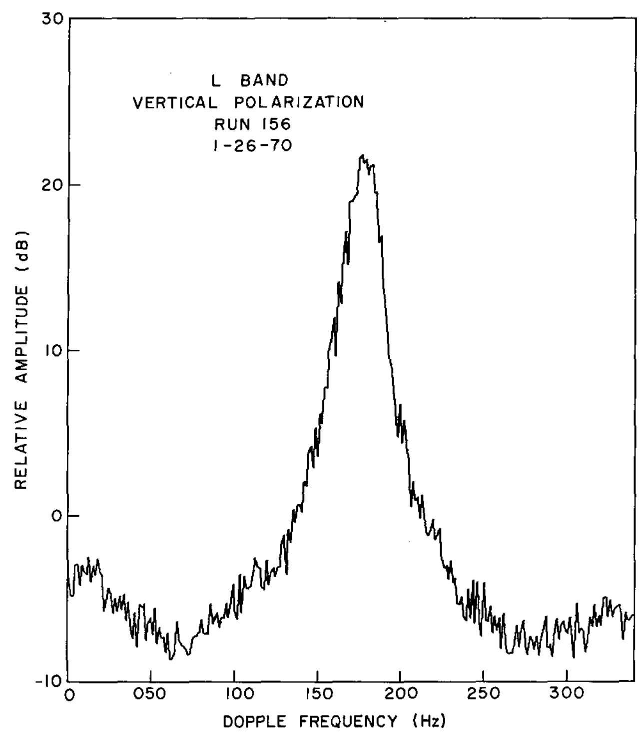


(b) vertical polarizations

Fig. 3 - Typical averaged doppler spectra of radar sea echo at C band



(a) horizontal polarizations



(b) vertical polarizations

Fig. 4 - Typical averaged doppler spectra of radar sea echo at L band, showing the effect of frequency unfolding

velocity from the P-band spectrum, which is normally unimaged, and computing the expected doppler frequency for the other radar wavelengths. This information may then be used to determine the harmonic of f_s that was used in the translation process, and thereby solve Eq. (2). Since the resultant doppler velocity is a measure of the difference between the speed of the aircraft and that of the radar scatterers, the mean velocity of the radar scatterers cannot be determined without knowing the true aircraft velocity. However, the doppler velocities indicated by the returns for each frequency and polarization can be compared since the aircraft velocity should be relatively constant from one pulse to the next. Of particular interest is the difference in mean frequency between the horizontally and vertically polarized signal, which is called the differential doppler.

In addition to the shift in mean doppler frequency, the platform motion also causes a broadening of the doppler spectrum. At least two significant factors contribute to the broadening of the intrinsic sea return spectrum: The first arises from the fact that both the azimuth and elevation angles of the individual scatterers vary throughout the finite area illuminated by the radar beam, and hence, the radial velocity varies throughout the resolution cell. The expressions for the estimated spread in velocities at the half-power points are given by Ridenour (3) as being

$$\Delta v_e = (vc\tau/2h)\ \sin^2\gamma\ \tan\gamma \tag{3}$$

for the elevation contribution, and

$$\Delta v_a = (v\theta^2/8)\ \cos\gamma \tag{4}$$

for the azimuthal contribution, where c is the velocity of light, τ is the radar pulse width, h is the aircraft altitude, and θ is the azimuthal beamwidth of the antenna. The second factor which also causes a broadening of the spectrum is the decorrelation of the radar scatterers which occurs because of the motion of the resolution cell on the sea surface during the interpulse interval due to the aircraft velocity. This broadening has been obtained at the half-power points by Barrick (4), and in velocity units is given approximately by

$$\Delta v_m = (\lambda v/c\tau)\ \cos\gamma, \tag{5}$$

and the total broadening due to all of these terms is taken to be

$$\Delta v = \left(\Delta v_e^2 + \Delta v_a^2 + \Delta v_m^2\right)^{1/2}. \tag{6}$$

The processes responsible for the broadening of the spectra are independent of the relative motion of the scatterers which produce the intrinsic spectrum of the sea return. Therefore, if the component spectra may be approximated by Gaussian curves, the half-power bandwidth Δv_s of the sea return can be removed from the measured spectrum Δv_t, provided that Δv is small in comparison with Δv_s. Since only spectra meeting this requirement are used in the bandwidth analysis, it is possible to estimate the velocity spread of the scatterers from

$$\Delta v_s = \left(\Delta v_t^2 - \Delta v^2\right)^{1/2}. \tag{7}$$

A third possible cause of spectral broadening is aircraft instability, particularly velocity changes which could cause a frequency shift over the sampling period. This mechanism is not considered to be of major importance, except in the case of X band. In this case, the low sampling rate, the large frequency shift caused by only a small velocity change, and the large frequency spread of the spectrum combine to cause some of the individual spectra in the average to be folded and, therefore, the resultant average to appear much broader than it actually is. For this reason, X-band data are not included in this report. Aircraft instability is also believed to be responsible for the slight broadening of the higher frequency spectra in comparison with earlier results which used shorter sample times.

EXPERIMENTAL RESULTS

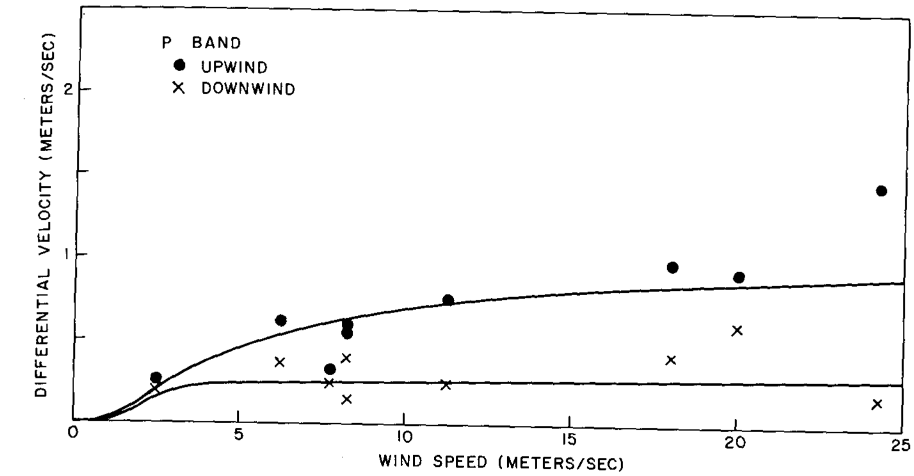
Previous Findings

Earlier investigations of the spectra of radar sea echo (1,5) yielded several important characteristics with respect to both spectral bandwidth and differential doppler. For example, the width of the spectra was found to be primarily a function of the wave height of the ocean surface, with the horizontally polarized spectra exhibiting a greater bandwidth than the vertically polarized spectra. In addition, the bandwidth was found to be dependent on radar frequency, showing the greatest magnitude for the P band and decreasing toward X band. On the other hand, the magnitude of the differential doppler was found to be a function of the wind speed, as well as of the radar frequency, being smallest for P band and increasing toward X band. The wave height dependence of the bandwidth of spectra and the wind dependence of the differential doppler found here are in general agreement with those found earlier.

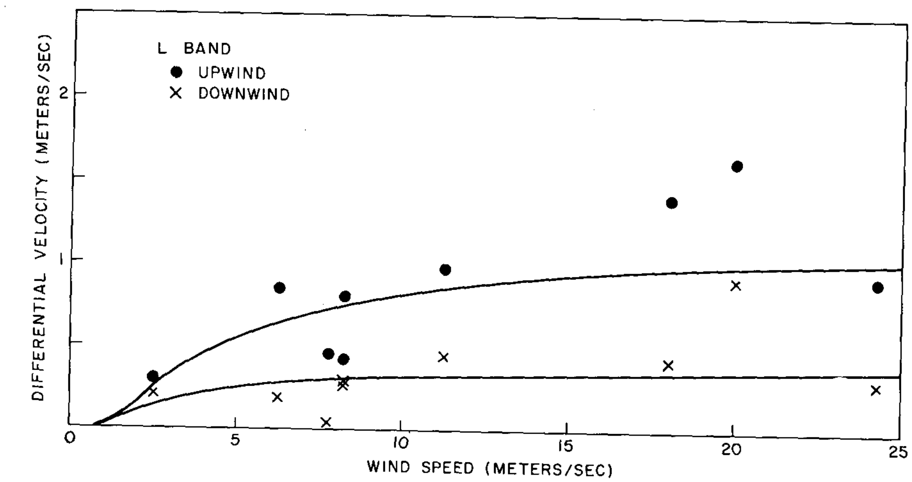
Differential Doppler

Although the data collected by the 4FR System does not yield a measure of the absolute doppler velocity of the scatterers on the sea at any given operational frequency, it can give a relative measurement between the horizontal and vertical spectra at all four frequencies. Since the measured doppler velocity is a function of the relative velocity between the aircraft and the scatterers on the sea surface, a fast-moving scatterer will have a higher frequency doppler return than a slow-moving scatterer when the aircraft motion is opposed to that of the scatterers, but will indicate a lower frequency doppler return when the aircraft motion is in the same direction. The previous investigations had indicated the possibility that there exists two separate sets of scatterers, one primarily responsible for the backscattering of vertically polarized energy, the other for horizontally polarized. Pidgeon's upwind data (5) also indicated that both sets of scatterers were moving in the same direction as the wind and waves, but that the set responsible for the horizontally polarized return had the greater velocity. An investigation of this point in more detail shows that the return for horizontal polarization is of higher frequency than that for vertical polarization when the aircraft was flying upwind, but lower when flying downwind, thus confirming Pidgeon's observation that the scatterers for horizontal polarization are moving faster than the scatterers for vertical polarization and in the same direction as the wind and waves.

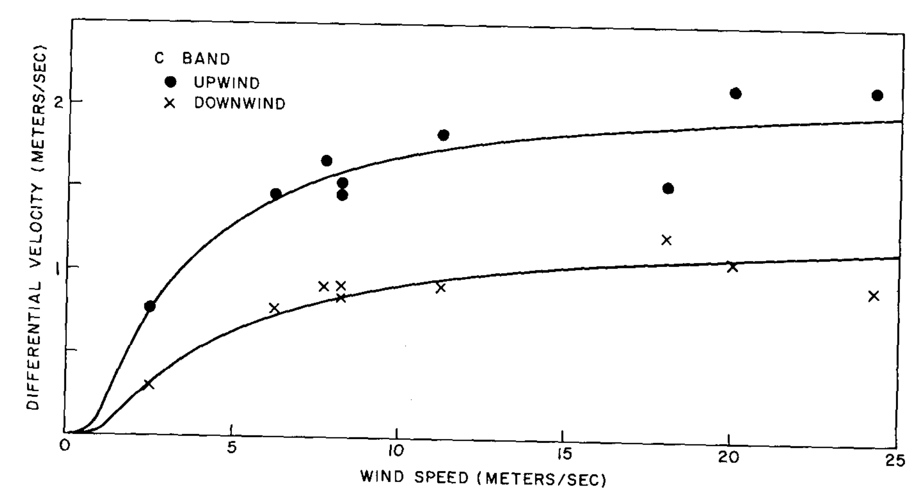
In Fig. 5 the differential velocity, obtained by means of Eq. (1), for the P, L, and C bands is shown plotted against wind speed. The magnitude of the differential doppler is an average over depression angles from 5° to 20° and includes data collected while "flying" both upwind and downwind. As can be seen, the differential doppler is nearly twice as large when the antenna is directed upwind as when directed downwind.



(a) P band



(b) L band



(c) C band

Fig. 5 - Average differential doppler (velocity) as a function of wind speed, for upwind and downwind conditions

Spectral Bandwidth

As indicated previously, platform motion causes a broadening of the intrinsic spectra of the sea echo, and therefore the measured widths (half power) of the spectra used in this report were corrected according to Eq. (7). On the average, the spectra obtained are slightly broader than those obtained in a previous investigation (1). This is to be expected because, with the FFT program, it is possible to include more individual spectra in the averaging, each with greater resolution, than in the previous work. Thus, the data used were from a longer time period, and therefore the possibility of mean frequency changes in the individual spectra is greater.

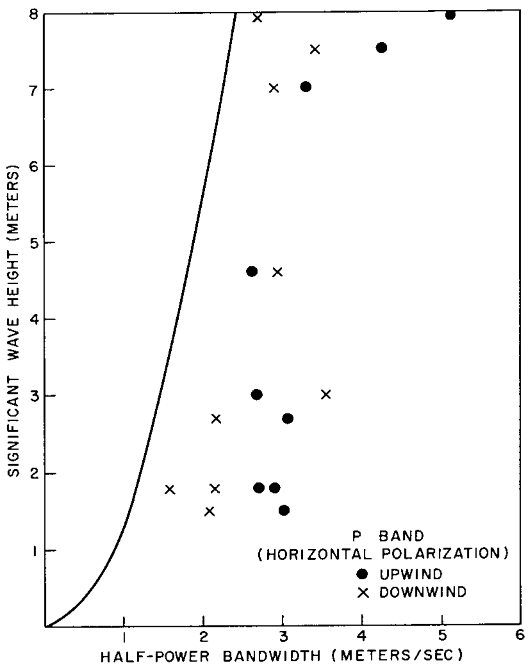
Figure 6 shows the corrected bandwidths of the spectra for the P, L, and C bands as a function of significant wave height for both upwind and downwind. Again, each point is an average over depression angles ranging from 5° to 20° and include data collected on both upwind and downwind flights. As noted previously, the upwind spectra tend to be broader than the downwind, although there is not the consistency found in the differential doppler, and the horizontally polarized spectra are obviously broader than the vertically polarized.

DISCUSSION AND CONCLUSIONS

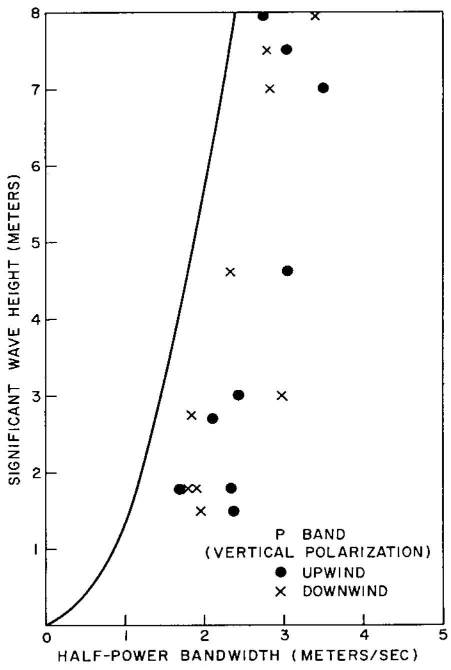
The results of this investigation of the doppler spectrum of the radar sea echo show that the mechanisms responsible for sea clutter are quite complex. There appear to be two sets of scatterers, or scattering mechanisms, one primarily responsible for the back-scattering of horizontally polarized signals, the other for that of vertically polarized transmissions, distinguished from each other primarily by the fact that the horizontally polarized return indicates both a greater spread in doppler velocity and a greater mean velocity than does the vertically polarized return.

A comparison of the spectral bandwidth of the upwind data with that of the downwind shows that the upwind data generally have a broader spectrum than does the downwind. The difference, however, is neither great nor is the downwind spectrum invariably narrower than the upwind, indicating that the bandwidth is not strongly dependent upon the wind. This conclusion is further supported by the fact that the bandwidths of the return follow the general trend predicted by the previously developed model (1) which ignores the wind and uses wave height only. The predicted trend is given by the curves in Figs. 6 (a)-(f). A close examination of these figures will also show that the bandwidth of the sea echo tends to decrease slightly with increasing radar frequency. This trend, however, is partially masked by the previously mentioned broadening due to the long sampling times used. Since this broadening occurs for all polarizations, the horizontal and vertical returns can be compared and, as can be seen, the horizontally polarized spectrum has a bandwidth that is characteristically larger than that of the vertical return.

In contrast to the spectral bandwidth, Figs. 5 (a)-(c) indicate that the differential doppler has an upwind/downwind ratio of nearly two, thereby indicating a strong wind dependence. This is borne out by the data collected on February 17, 1969, in the North Atlantic. Although the wind velocity recorded that day was low, being on the order of only 2.5 m/sec, the wave structure remained large, consisting of two swells of 3 and 3.5 meter heights, along with a sea of 0.46 meter height. The effective wave height was taken to be the square root of the sum of the squares of the individual heights, or about 4.6 meter. The differential doppler measured that day was among the lowest found and matched the other data when plotted against wind speed in Fig. 5. The spectral bandwidth, on the other hand, was of the order of magnitude expected for high waves and agrees with the other data when plotted against wave height, agreeing with the conclusion that the spectral bandwidth depends primarily on the wave height, while the differential doppler is a function of the wind speed.

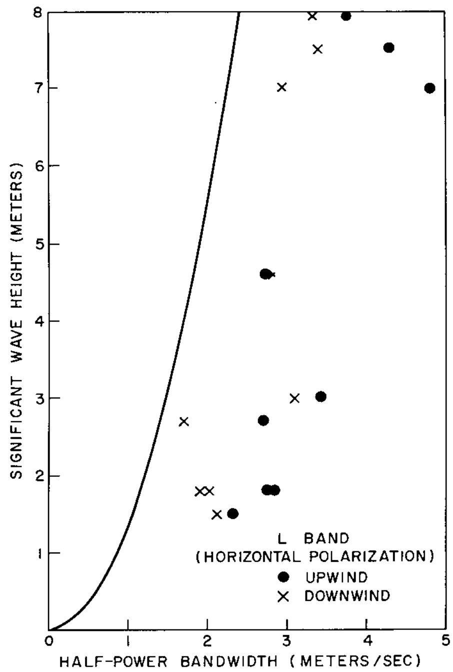


(a)



(b)

Fig. 6 - Average half-power bandwidth of the radar sea-echo spectra as a function of significant wave height, for upwind and downwind conditions, at P, L, and C bands. At each band the horizontal and vertical polarization results are separately shown.



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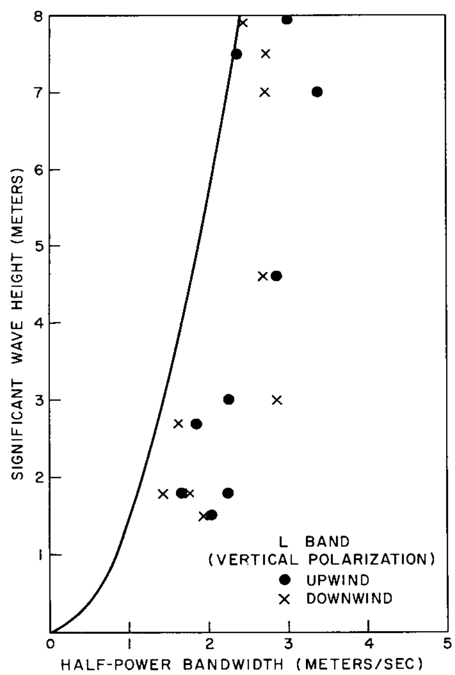

(d)

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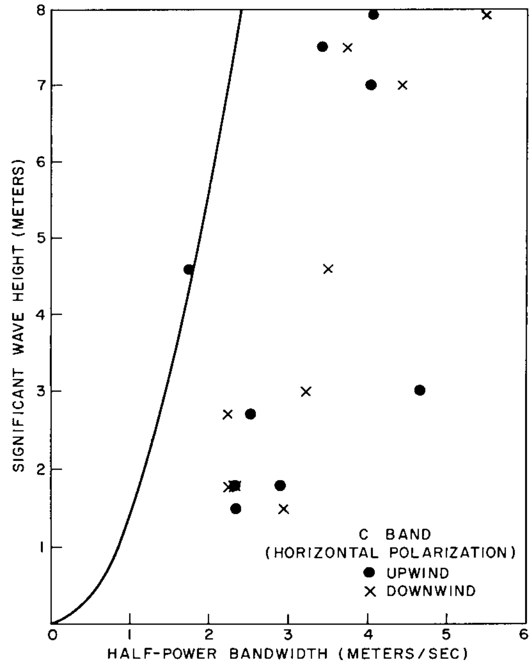

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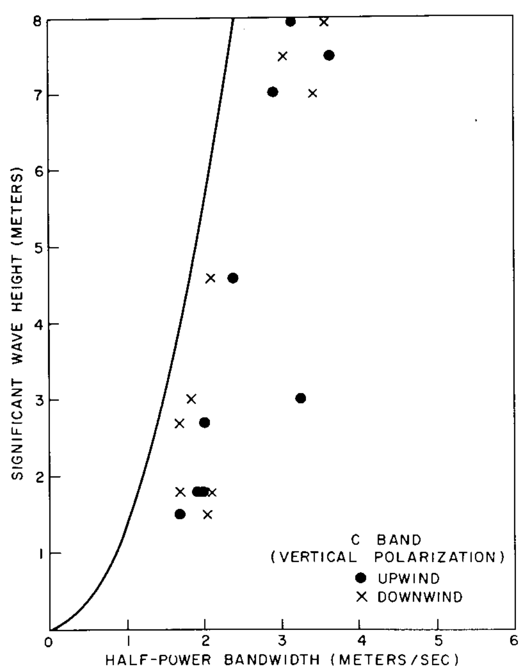

(f)

Fig. 6 - Average half-power bandwidth of the radar sea-echo spectra as a function of significant wave height, for upwind and downwind conditions, at P, L, and C bands. At each band the horizontal and vertical polarization results are separately shown.

Previous investigations (1,5) had indicated that the differential doppler tended to saturate for high-wind conditions. In view of this, the differential doppler measurements were fitted with exponential curves of the form $k_1 \exp(-k_2/v)$ where k_1 and k_2 are constants and v is the wind speed. These curves are plotted in Figs. 5 (a)-(c) and, as can be seen, give an excellent fit for the C-band data, but only a moderately good fit for the P- and L-band results. Curves of the form $k v^{1/2}$ were also tried and, using the least-square criterion for fit, gave as good, or better, results for the P- and L-band cases, but not as good for the C-band data. Before an empirical decision can be made on the actual functional dependency, more data will be needed, and then it is not beyond reason that the higher radar frequencies may show a trend toward saturation, while the lower frequencies may not. The data do show that the differential doppler increases with increasing radar frequency, in opposition to the spectral bandwidth, which decreases.

Further work is needed in the development of a realistic electromagnetic scattering model. In order to accomplish this goal, more information is needed not only on the radar sea echo, but also more knowledge of the hydrodynamics of the sea and its surface to account for the wind, polarization, and frequency dependencies found in the data.

ACKNOWLEDGMENTS

The author wishes to acknowledge the valuable advice and assistance given to him by Dr. G. R. Valenzuela in preparing the manuscript, to J. T. Ransone, Jr., and the 4FR System team, who conducted the field programs, and to J. W. Eng who assisted in processing the data.

REFERENCES

1. Valenzuela, G.R., and Laing, M.B., "Study of Doppler Spectra of Radar Sea Echo," J. Geophys. Res., 75 (No. 3):551-563 (January 1970)

2. Guinard, N.W., and Daley, J.C., "An Experimental Study of a Sea Clutter Model," IEEE Proc., 58 (No. 4):543-550 (April 1970)

3. Ridenour, L.N., ed., "Radar System Engineering," p. 658, New York:McGraw-Hill, 1947

4. Barrick, D.E., "Radar Signal Distortions Produced by Volume and Surface Distributed Scatterers," presented at 1968 URSI Spring Meeting, Washington, D.C.

5. Pidgeon, V.W., "Doppler Dependence of Radar Sea Return," J. Geophys. Res., 73:1333-1341 (1968)

Appendix

OPERATING CHARACTERISTICS FOR THE FOUR-FREQUENCY RADAR SYSTEM

Table A1
Power and Stability Parameters

Radar Frequency (MHz)	Long-Term Frequency Stability (maximum parts/day)	Short-Term Frequency Stability (maximum parts/0.01 sec)	Peak Power (kW)	Average Power (W)	Peak Power Special Mode (W)	Inter-pulse Phase Stability (maximum degrees)	Output Tube
428 (P-band)	1 in 10^6	5 in 10^9 - 10^8	35-40	140	10	4	7651 tetrode (RCA)
1228 (L-band)	1 in 10^6	5 in 10^9 - 10^8	35-40	140	10	4	7651 tetrode (RCA)
4455 (C-band)	1 in 10^6	5 in 10^9 - 10^8	25	100	10	5	SAC-290 Klystron (Sperry)
8910 (X-band)	1 in 10^6	5 in 10^9 - 10^8	40	160	10	6	V24C Klystron (Varian)

Table A2
Signal and Display Parameters

Repetition Rates	Submultiples of 81.959 kHz: 100.45, 200.90, 301.35, 394.07, 512.30, 602.71, 683.07, 788.16, 1463, 2926 Hz
Pulse Widths	0.1, 0.25, 0.5, 1, 2 μsec
Noise Figure	9-11 including all rf losses
IF Amplifier	
Center Frequency	37 MHz
Bandwidth	10, 4, 2, 1, 0.5 MHz
Type	lin-log, 25 and 50 dB dynamic range Limiting
Quantity	Two—One for horizontally polarized signals —One for vertically polarized signals
Range Gate	
Width	0.1, 0.2, 0.5, 1, 3, 5 μsec
Increment Readout	1 yd
Range Marks	
Width	1.0, 2.0, 5.0, 20 μsec
Spacing	1, 5, 20 naut mi
Video System	
Consoles	Total 3: 2 operators and 1 master control
Displays	Dual-beam A scope, B scope and PPI for each console. All flat face tubes.
CRT Size	5 in.
Signal Outputs (ungated and gated)	Vertical polarization signal amplitude Horizontal polarization signal amplitude Vertical/horizontal polarization phase Horizontal polarization/transmitted signal phase Vertical polarization/transmitted signal phase
Maximum Video Amplitude	2 V peak-positive

Table A3
Antenna System Performance

Radar Frequency Band	Polarization	Bandwidth (MHz)	Beamwidth (degrees)		Minor Lobe (dB)		Cross Polarization (dB)	Transmission Line Loss (dB)	Antenna Gain (dB)	Voltage Standing Wave Ratio	High Power Check
			Azimuth	Elevation	Azimuth	Elevation					
P	Horizontal	± 5	12.3	40	14.5	30.0	25	0.6	17.4	>1.44:1	OK
	Vertical	± 5	12.1	41.0	14.5	26.0	28	0.3	17.4	>1.38:1	OK
L	Horizontal	± 5	5.5	13.8	13.4	16.0	25	0.6	25.9	>1.35:1	OK
	Vertical	± 5	5.5	13.0	14.0	14.0	25	0.8	26.2	>1.28:1	OK
C	Horizontal	±10	5.0	5.0	23.2	24.5	>20	2.0	31.4	>1.55	Not Measured
	Vertical	±10	5.0	5.0	23.0	24.0	>20	2.0	31.4	>1.57	Not Measured
X	Horizontal	±10	5.0	5.3	23.6	23.5	>20	0.6	31.2	>1.30:1	OK
	Vertical	±10	4.7	5.0	23.6	24.2	>20	0.6	31.2	>1.12:1	OK

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20375	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP	
3. REPORT TITLE VAPOR PHASE EPITAXY OF GALLIUM ARSENIDE		
4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)* Interim report on one phase of the NRL problem.		
5. AUTHOR(S) *(First name, middle initial, last name)* Arrigo Addamiano		
6. REPORT DATE January 26, 1973	7a. TOTAL NO. OF PAGES 9	7b. NO. OF REFS 12
8a. CONTRACT OR GRANT NO. NRL Problem R08-44 b. PROJECT NO. RR 008-03-46-5673 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7523 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*	
10. DISTRIBUTION STATEMENT Approved for public release; distribution unlimited.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy Office of Naval Research Arlington, Va. 22217	

13. ABSTRACT

GaAs epitaxial layers of good semiconductor quality (comparable to bulk GaAs) have been prepared by the arsine method. The preparative technique and improvements are described. Overall, the arsine system has proved not only reliable but simple as well. The growth rates are reasonably high for practical device fabrication.

The epitaxial reactor undergoes continued cleanup during operation. After a few months of operation the residual donor concentration stabilizes at $\sim 10^{15}/cm^3$. By locating substrates in the As-rich, low-temperature zone, p-type layers can be grown; n-type layers are usually obtained with the substrates at about 725°C.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Gallium arsenide Epitaxy Semiconductor technology Arsine (handling of) Hydrochloric acid (handling of)						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

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PROBLEM STATUS

An interim report on the NRL problem.

AUTHORIZATION

NRL Problem R08-44
Project RR 008-03-46-5673

Manuscript submitted November 13, 1972.

VAPOR PHASE EPITAXY OF GALLIUM ARSENIDE

INTRODUCTION

Welker (1) pointed out in 1952 that gallium arsenide and other III-V compounds should be semiconductors similar to silicon and germanium. The work of the past twenty years has confirmed Welker's prediction. Gallium arsenide is now well established among the useful semiconductors, as indicated, for instance, by the recent International Symposia on Gallium Arsenide (2 - 4).

Interest in GaAs in the Solid State Technology Branch of the Electronics Division of NRL focuses mainly on potential applications for a variety of microwave devices. A program was initiated in 1970 to develop an in-house capability for chemical vapor epitaxial growth. At that time a careful survey of the literature yielded wide variations in deposition parameters for any given deposition method. It is the intent of the present work to establish a simple, reproducible technique capable of producing high-quality epitaxial layers with low carrier concentration ($\approx 10^{15}/cm^3$) and near bulk mobility.

CHOICE OF THE SYSTEM

Different vapor-phase epitaxial techniques are available for GaAs. Among them the most popular methods are the open-flow, "arsine" and "chloride" methods (5 - 8), which use AsH_3 and $AsCl_3$, respectively, as the source of arsenic. The arsine method has the following advantages: (a) immediate startup of the system; (b) better control of the arsenic concentration; (c) better control of the thickness of the epitaxial layers in the submicron range. For these reasons this method was preferred for our work.*

The reactions of interest in the arsine method are:

$$2Ga_{\ell} + 2HCl \rightleftarrows 2\,(GaCl)_v + H_2 \quad \text{(at 825°C)}. \tag{1}$$

$$3\,(GaCl)_v + \frac{1}{2}As_4 \rightleftarrows 2\,(GaAs)_s + (GaCl_3)_v \quad \text{(at 725°C in the substrate region)}. \tag{2}$$

Reaction (1) results in the formation, at relatively high temperature, of a volatile chloride of gallium, GaCl, which is carried downstream. In the deposition zone of the furnace, at about 750°C or slightly less, the GaCl reacts with arsenic vapor from the thermal dissociation of AsH_3 and forms GaAs on the substrates. For reaction (2) to go to the right with deposition of GaAs on the substrates, a temperature gradient must exist in the reactor. A two-zone furnace was used to insure the right temperature profile. Figure 1 shows the operating conditions in the two-zone furnace, which is 80 cm long and has an

*Exploratory work on the chloride method has been published elsewhere (9,10).

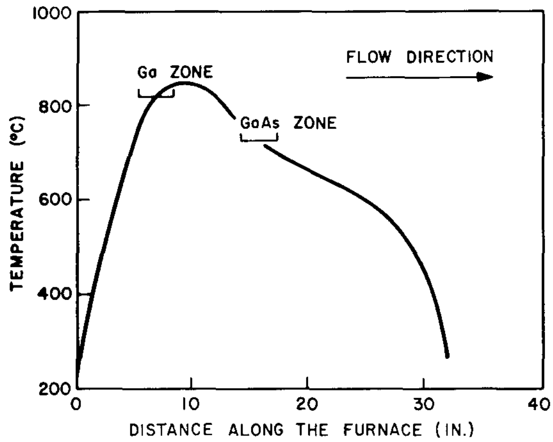

Fig. 1 — Operating conditions in the two-zone furnace

inside diameter of 5 cm. The fused-quartz reactor tube, with an overall length of 95 cm and an inside diameter of 4.5 cm, has separate inlets for the H_2 carrier gas, the HCl, the AsH_3 and the dopant gas (usually H_2Se). All the connections to the reactor tube are made of flexible Swagelock fittings; the mixing bottles used to dilute the HCl and AsH_3 with H_2 are made of stainless steel. The gas lines are made entirely of stainless steel; the introduction of even a short piece of plastic or rubber tubing in the lines results immediately in substantial deterioration of the quality of the epitaxial layers! High-purity H_2 tanks, showing no trace of oxygen or other impurities by mass spectroscopic analysis down to the ppm range, were used to supply the carrier gas and to dilute the AsH_3 and HCl to the levels needed to obtain the low growth rates needed for high-quality growth. Tanks of 10% HCl — 90% H_2 and 15% AsH_3 — 85% H_2 were used as sources of HCl and AsH_3. The rates of flow of the gases were measured with commercial calibrated flow meters.

SEED PREPARATION

Polished ⟨100⟩ slices of semi-insulating, Cr-doped, GaAs were generally used as substrates. For more reproducible results the slices were cut 2° off the (100) plane. Immediately before use, the substrates were etched 5 min at room temperature in 5 H_2SO_4 — 1 H_2O_2 — 1 H_2O. Then they were soaked in NH_4OH for 5 min, rinsed in high-purity deionized water and then in electronic-grade methyl alcohol, and were introduced still wet into the reactor tube on a quartz plate of dimensions 4 in. by 1.25 in. by 0.125 in. The fused-quartz plate itself was placed in a dump tube, which extended through the length of the reactor tube and could conveniently be extracted from it for loading, unloading, and cleaning. It must be stressed that only high-purity water (having a resistivity of 14 megohm cm or more at room temperature) can be used for rinsing the substrates and the quartz ware. Use of relatively impure water results in nonreproducible growth and in less uniform layers.

OPERATING PROCEDURE

The deposition of epitaxial layers of GaAs on GaAs substrates, as practiced by us, requires the following steps.

1. With the furnace at room temperature and the reaction tube filled with flowing H_2, the dump tube containing the substrates is introduced into the reaction tube.

2. The reaction tube is then sealed, exhausted to less than 10^{-4} torr, and flushed five times with high-purity H_2.

3. The H_2 pressure is brought to a slightly higher value than the atmospheric pressure, and H_2 is flushed through all the lines and the mixing bottles for 30 min or more.

4. The furnace is energized. When a temperature of 600°C is obtained, AsH_3 is added to the H_2 flow and the flow rates checked for deposition conditions.

5. With the gallium boat at 825°C and the substrates at about 725°C, a mixture of HCl + H_2 is added to the flowing gases. Reaction with the Ga (Eq. (1)) occurs, and deposition of GaAs takes place on the substrates.

6. After the desired thickness of GaAs is deposited, the HCl flow is interrupted for 10 min, keeping AsH_3, H_2, and dopant, if any, flowing at constant temperature.

7. After this period the furnace is switched off and allowed to cool.

8. When the temperature is at 600°C, the AsH_3 flow is discontinued, the reaction tube is sealed off and overnight cooling in the H_2 atmosphere is allowed.

9. The dump tube is extracted from the furnace and the substrates are recovered and examined.

The conditions which resulted in high-quality growth are:

- Substrates: ⟨100⟩ GaAs cut 2° off the (100) plane
- AsH_3 flow: 20 ml/min of 15% AsH_3 in H_2
- H_2 added to the AsH_3: 70 ml/min
- HCl flow: 25 ml/min of 10% HCl in H_2
- H_2 added to the HCl: 70 ml/min
- H_2 carrier gas: 50 ml/min
- Temperature of the Ga boat: 825°C
- Temperature of the substrates: 725°C to 750°C
- Deposition rate: 0.2-0.3 μm/min

The deposition, or growth rate was measured by comparing the thickness of the substrates covered by epitaxial layers with that of an adjacent area which was covered by a thin chip of GaAs during growth. Direct measurements and Zeiss interferometric measurements both gave rate values in good agreement with each other and with those reported in the literature, i.e., 0.2 to 0.3 μm/min.

It was observed that the quality of the epitaxial layers changed if the substrates were moved through the hot zone. At about 725°C the undoped layers were routinely n-type and usually smooth, with a bluish tinge. In the region of the furnace exhaust, where a strong excess of As exists, the grown layers, usually of relatively poor quality, are p-type. Similar observations were made by Knappett (11), who reported that both p- and n-type epitaxial GaAs could be obtained by simply changing the Ga to As ratio in a chloride reactor, which usually gave p-type layers. The quality of the epitaxial layers obtained improved constantly in the course of our work. Table 1 compares some typical data obtained at the beginning of the work with data obtained at later dates. In all cases the growth time is about 30 min, which corresponds to layers 6 μm thick.

Table 1
Some Electrical Data for GaAs Epitaxial Layers
Grown on ⟨100⟩ GaAs

Sample	Resistivity (ohm cm)	Room-Temperature Mobility (cm^2/V s)	Charge Carriers (cm^{-3})
33	6.6×10^{-3}	511	1.8×10^{18}
34	3.2×10^{-2}	1417	1.4×10^{17}
45	1.8×10^{-2}	1212	2.8×10^{17}
51	6.7×10^{-2}	913	1.0×10^{17}
52	2.6×10^{-2}	1225	2.0×10^{17}
53	2.1×10^{-2}	1940	1.5×10^{17}
55	8.2×10^{-2}	1400	5.4×10^{16}
56	7.2×10^{-2}	2090	4.2×10^{16}
72	2.8×10^{-1}	3400	7.0×10^{15}
75	2.3×10^{-1}	4200	4.1×10^{15}
77	6.0×10^{-1}	4500	2.5×10^{15}

Mobilities in the four-figure range and carrier concentrations in the low 10^{15} range are currently obtained. These values are close to the corresponding values obtained for single-crystal GaAs. Thus the immediate objective of this research has been attained.

DISCUSSION

The arsine method has proved capable of producing epitaxial layers of near-bulk-value qualities; however, it is usually considered to be quite risky because arsine is a very poisonous gas. In the course of our work, however, we experienced no serious difficulty in handling the arsine. Because of its corrosive action, however, the HCl has given occasional troubles, such as leaky valves and flow meters. In one case the pressure gauges and the tanks had to be replaced three times in a row. The use of very dilute HCl might prevent these inconveniences and the hazards due to relatively concentrated HCl. Since the 10% HCl must be further diluted with H_2 for optimum results, it might be possible to start with tanks of HCl of the right concentration and to eliminate the mixing procedure. Similarly, an arsine concentration lower than 15% might be used without further dilution with H_2. If this is done, the practice of the arsine method can be made very simple indeed.

Overall the arsine method, as used, has proved simple and reliable. The "cleaning up" of the reactor in the course of time, which results in progressively better epitaxial layers, is a feature observed by numerous other workers in the field and may be due to different factors such as (a) cleaning up of the reactor itself, (b) boiling off of impurities from the gallium boat (even though the gallium used is free from metals, ubiquitous impurities such as oxygen, are usually present), and (c) purification of the gas lines and of the gas tanks. Since the flow rates for deposition are quite small, the gas tanks last for a considerable time, and relatively stable growth conditions exist over a long period before new tanks need to be used.

Temperature is undoubtedly the most important physical parameter affecting the rate and quality of growth. This is because a small increase in the substrate temperature (say 20°C) will result in dissociation of the substrates, with losses of As, whereas a small decrease in the temperature results in a noticeable increase in the growth rate and in inferior quality of the epitaxial layers. Optimum conditions exist only in a limited zone of the reactor. Possible improvements which we may suggest include locating the substrates at an angle (say 30°) to the direction of gas flow, rather than parallel to it, possibly with the addition of a slow rotational movement, as is used in practice for the preparation of Ga(As, P) (12). With a stationary substrate, parallel to the gas flow, uniform growth occurs in a zone having a length of 1 in. This limits the useful size of the substrates. Our most uniform layers were obtained on substrates approximately 6×6 mm^2.

ACKNOWLEDGMENTS

I thank J. E. Davey for his continued interest in this research. I am obliged to P. H. Klein of the Central Materials Research Activity (Code 6060) for the donation of a boule of GaAs and to N. Saks, W. Schmidt, and H. Grant for help with the instrumentation and the electrical measurements.

REFERENCES

1. H. Welker, Z. Naturforschung 7a, 744 (1952).
2. *Gallium Arsenide*, Proceedings of the International Symposium, 1966, The Institute of Physics and the Physical Society, London, 1967.
3. *Gallium Arsenide*, Proceedings of the Second International Symposium, Dallas, 1968, The Institute of Physics and the Physical Society, London, 1969.
4. *Gallium Arsenide*, Proceedings of the Third International Symposium, Aachen, 1970, The Institute of Physics and The Physical Society, London, 1971.
5. J.J. Tietjen and J.A. Amick, J. Electrochem. Soc. 113, 724 (1966).
6. B.E. Berson, R.E. Enstrom, and J.F. Reynolds, RCA Review 31, 20 (1970).

7. J.R. Knight, D. Effer and P.R. Evans, Solid-State Electronics 8, 178 (1965).

8. D.V. Eddolls, J.R. Knight and B.L.H. Wilson, in Ref. 2, p. 3.

9. A. Addamiano and J.E. Davey, J. Crystal Growth **10**, 194 (1971).

10. A. Addamiano, J. Crystal Growth **11**, 351 (1971).

11. J.E. Knappett, Solid-State Electronics **14**, 185 (1971).

12. R.A. Ruehrwein, "Manufacturing Methods for Epitaxially Growing Gallium Arsenide-Gallium Phosphide Single Crystal Alloys, "Technical Report AFML-TR-68-619 AD 848463, (Oct. 1968). (See also Electronics, May 24, 1971, pp. 81-82).