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13. ABSTRACT

Personnel at the Naval Research Laboratory (NRL) have conducted a radar backscatter measurement program in the vicinity of Argus Island, Bermuda as part of the Joint Ocean Surface Study (JOSS I) sponsored by the Naval Oceanographic Office. The 4FR System was employed to obtain calibrated sea return data for various sea states as a function of radar wavelength, polarization, and depression angle. Surface truth was acquired simultaneously, utilizing laser altimetry, aerial photography, and observers stationed on Argus Island. Processing of the radar backscatter data is complete, and the median value of the normalized radar cross section (NRCS) σ_0 of the sea has been determined as a function of radar and surface parameters. These data have been incorporated with the data resulting from previous measurement programs to form a comprehensive data bank of the parametric behavior of the median value of σ_0, from which the following conclusions may be drawn:

1. The NRCS of the sea approaches a limiting value with increasing roughness for all frequencies and polarizations.
2. For depression angles 5° to 60°, the growth of the NRCS may be approximated by simple empirical formulas.
3. For the rougher conditions observed in the JOSS I mission, the NRCS data implied the presence of the equilibrium range spectrum.
4. The spectrum exhibited a characteristic dip at the higher wave numbers for calm sea conditions.
5. The cross-polarized return approaches a limiting value with increasing wind.

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PROBLEM STATUS

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

AUTHORIZATION

NRL Problem R07-20.402
Project WR 0-0167

Manuscript submitted February 23, 1971.

RADAR SEA RETURN — JOSS I

INTRODUCTION

To achieve a better synoptic description of ocean weather for the prediction of safe ship routing and air-sea interaction of studies, techniques and instrumentation must be developed which are capable of remotely sensing the state of the sea. Personnel of the Naval Research Laboratory (NRL) have developed techniques which are directly applicable to these goals and have also instrumented an aircraft (EC-121) to make the necessary field measurements which include surface wind, significant wave height, and the wave-height spectrum.

To satisfy these objectives, a measurement program was conducted in the vicinity of Argus Island, Bermuda as part of the Joint Ocean Surface Study (JOSS I) sponsored by the Naval Oceanographic Office. The NRL 4FR System was employed to obtain calibrated data in the form of the range-gated amplitude and phase of the sea return. In the course of the program, radar cross-section (RCS) data were collected for various sea states as a function of radar wavelength, polarization, and depression angle. Surface truth was acquired utilizing a laser altimeter and aerial cameras. At the same time, observers stationed on Argus Island recorded wind and wave-height information. In addition, RCS data in a fetch-limited environment were recorded during the flights enroute to and from Bermuda and NAS, Patuxent River, Maryland.

The on-site data at Bermuda were collected according to the following flight plan (Fig. 1), in which Argus Island (A) was used as a reference. Three recording legs were flown in each of the upwind, downwind, and crosswind directions, at three altitudes. One leg was flown at a 45° angle relative to the wind (leg 7), and additional low-altitude legs were flown when possible (legs 11 and 12). The use of three altitudes in the flight program was necessitated by the difficulty of encompassing the entire dynamic range of the sea return as a function of antenna depression angle without changing the receiver gain settings. The altitudes shown in Fig. 1 are nominal, and the type of data recorded at each altitude is noted. The lower altitudes were determined by visibility of the ocean surface as required by the aerial cameras (C) and laser altimetry (L).

Radar data (R) were recorded on each leg by fixing the antenna depression angle (azimuth along the flight path) and sampling the return over approximately a 40-sec period. This procedure was repeated for a number of depression angles on each leg. Then the antenna was rotated 180° in azimuth and the same set of angles sampled. In this way, data were obtained in two opposite directions on a given leg. The depression angles usually set are 5°, 10°, 20°, and 30° at low altitudes (legs 1 to 3, 11, 12); 20°, 30°, 45°, and 60° at medium altitude (legs 4 to 7); and 70°, 80°, and 90° at high altitude (legs 8 to 10).

Generally the measurement program began at about 0900 (local time). Table 1 lists the gross surface conditions measured by the Argus Island observers (1) along with the depression angles at which RCS data were obtained. Two of the missions were subdivided into smaller time periods to correlate the data with changing wind velocity.

In addition to the data acquired on-site at Bermuda, similar data were recorded in a fetch-limited environment during enroute flights on Jan. 19, 1970 and Jan. 29, 1970.

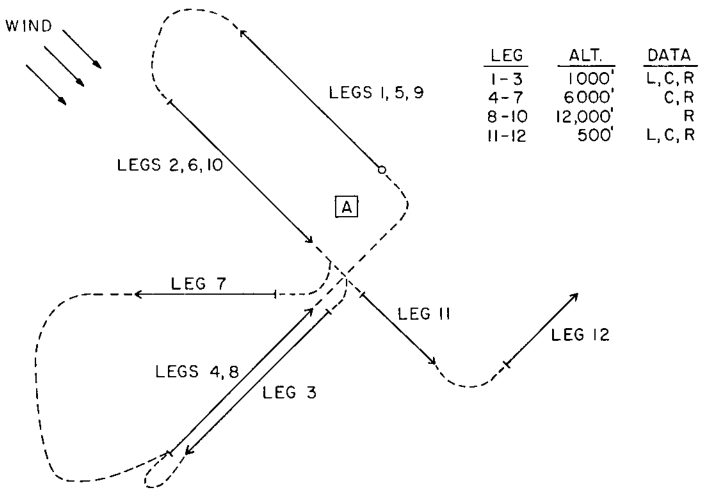


Fig. 1 - Bermuda flight plan

Table 1
Gross Surface Conditions, Bermuda 1970

Date	Local Time	Wind Velocity (knots)	Significant Wave Height (ft)	Depression Angle (°)
20 Jan 70	0905 - 1347	18 - 22	5 - 6.2	5 - 90
22 Jan 70	0932 - 1302	23 - 27	8.8	5 - 90
23 Jan 70	0911 - 1200	11	6.4	5 - 90
	1220 - 1255	8	6.4	5 - 30
26 Jan 70	0912 - 1159	14 - 16	5	5 - 90
27 Jan 70	0900 - 1100	15 - 17	6.2 - 7.6	5 - 45
	1100 - 1200	12 - 15	7.6	30 - 70
	1200 - 1300	11 - 12	5 - 7.6	5 - 90
28 Jan 70	1149 - 1428	21 - 25	5 - 7.6	5 - 90
29 Jan 70	0955 - 1028	3 - 5	-	10 - 45

Because of the vast amount of radar, laser, and photographic data acquired by NRL during the program, it is not feasible to attempt to assemble all the results in one report. It is the objective of this report to document the RCS data recorded on-site as a function of the radar and surface parameters, and to incorporate these results in the context of previous experiment and theory.

THE MEASUREMENT SYSTEM

The 4 FR System is an airborne coherent pulsed radar capable of transmitting a sequence of four frequencies alternately in horizontal and vertical polarization. These frequencies are X-band (8910 MHz), C-band (4455 MHz), L-band (1228 MHz), and P-band/uhf (428 MHz). The details of the system and its absolute calibration by means of reference spheres have been well documented (2) and will not be repeated here. The main characteristics of the 4FR System are given in Table 2. The system allows many choices of pulse repetition frequency (prf), pulse length, i-f bandwidth and range-gate width. The values used for these parameters during the JOSS I program were prf, 683 (except on Jan. 29, 1970, 603); pulse length, 0.5 μsec on X- and P-bands, 0.51 μsec on L-band, 0.56 μsec on C-band; i-f bandwidth, 10 MHz; and range-gate width, 24 nsec.

DATA PROCESSING

The amplitude of radar sea clutter is best described by its probability distribution. The calculation of the distribution is accomplished through the use of a general-purpose digital computer which accepts the raw range-gate samples and is suitably programmed to calibrate the data for all of the desired parameters. The basic outputs of this processing system are cumulative probability distributions of the received power (P_R in decibels) of the sixteen possible frequency-polarization amplitude components recorded by the 4FR System over the total recording period (~40 sec). A sample plot is shown in Fig. 2. The distribution has been plotted versus a normal probability scale. In this format, a log-normal distribution would be plotted as a straight line. The coding in the upper left of each plot would indicate the date, run, and signal component, e.g., for Fig. 2, run 127, 17 (Code for CHH). By means of the sphere measurement, the received power may be calibrated in terms of the normalized RCS (σ_0), as shown. The median value of σ_0 was read from these plots and tabulated for all seven signal components for each data run. During the seven missions flown around Argus Island, over 600 such data runs were recorded in addition to the necessary calibration procedures described previously. For each mission, median σ_0 values were grouped according to wind direction and depression angle for each signal component. The median of these sample medians was computed and tabulated for each mission. The results for the direct polarizations are listed in Tables 3 through 12 and the cross polarizations in Tables 13 through 22, with the appropriate wind field and wave height as observed from Argus Island during the data recording period. The total sample generally included four data runs (~160 sec). The NRCS values are given for upwind, downwind, and crosswind (not including 45° crosswind) for all angles except 90°. Omissions in the tables are caused by operational problems resulting in lack of data for that particular case, as for example, a signal below the minimum detectable by the radar.

WIND DEPENDENCE OF THE NRCS

The dependence of NRCS on the radar parameters has been considered in detail in previous reports (2-4); hence, we will restrict the discussion of the Bermuda data to dependence on the surface parameters. To estimate the effect of increasing sea state on the NRCS, σ_0, it is necessary to select a surface parameter which will reflect increasing roughness. As a basis of comparison, the median wind velocity was chosen and plots of median σ_0 (dB) vs wind were made for all signal components at all angles and wind directions. These plots show good agreement between the JOSS I measurements and previous results from the North Atlantic and Puerto Rico. For convenience, a tabulation of the Puerto Rico 1965 data (Refs. 3,4) was made and is included in the Appendix.

Table 2
4FR Radar System Parameters

Frequency Band and Polarization	Az Beam-width (deg)	El Beam-width (deg)	Az Minor Lobe (dB)	El Minor Lobe (dB)	Cross Polarization (dB)	Antenna Gain (dB)	Peak Power (kw)	Ave Power (w)	Pulse Width (μsec)	PRF (pps)
P-band							25	140	0.25 - 2.0	100 - 1463
Horiz	±12.3	40	14.5	30	25	17.4				
Vert	12.1	41	14.5	26	28	17.4				
L-band							25	140	0.25 - 2.0	100 - 1463
Horiz	5.5	13.8	13.4	16	25	25.9				
Vert	5.5	13	14	14	25	26.2				
C-band							35	100	0.1 - 2.0	100 - 1463
Horiz	5	5	23.2	24.5	>20	31.4				
Vert	5	5	23.2	24.5	>20	31.4				
X-band							25	160	0.1 - 2.0	100 - 1463
Horiz	5	5.3	23.6	23.5	>20	31.2				
Vert	4.7	5.0	23.6	24.2	>20	31.2				

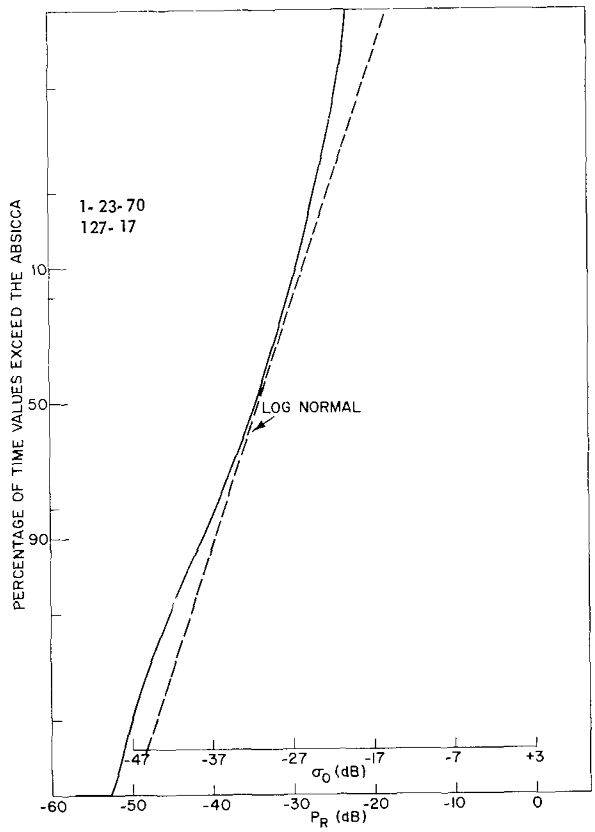


Fig. 2 - Sample cumulative probability distribution

Table 3
Median Values of σ_0
Jan. 20, 1970: Wind velocity 18-22 knots;
wave height 5-6.2 ft, time 0905 - 1347

Depression Angle (deg)	Wind Direction*	σ_0 (dB)							
		X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
5	U	-36	-41.5	-38	-44	-36	-47	-	-
	D	-35.5	-46.5	-37	-48	-39.5	-54.5	-	-
	C	-41.5	-44	-43.5	-47	-41	-53	-41	-53.5
10	U	-31.5	-38	-30.5	-39.5	-32.5	-45.5	-	-
	D	-33.5	-45	-32.5	-47	-35.5	-52	-35.5	-
	C	-37.5	-39.5	-37.5	-41	-37	-50.5	-34.5	-48.5
20	U	-	-35	-26.5	-36.5	-27	-41	-	-
	D	-31	-40	-27.5	-41	-30.5	-45	-30	-42
	C	-35.5	-40.5	-34	-40.5	-31	-45	-33	-43
30	U	-26	-31	-26	-34.5	-28	-39	-31.5	-39
	D	-27.5	-36	-27	-38.5	-28.5	-41	-31.5	-38
	C	-32	-37	-32.5	-39	-30.5	-41.5	-31	-38.5
45	U	-24	-26	-23	-28	-29.5	-33.5	-26.5	-29
	D	-23.5	-28	-23.5	-31.5	-26.5	-32	-26	-30
	C	-30	-32.5	-30.5	-36	-29.5	-34.5	-25	-28.5
60	U	-20.5	-18.5	-18	-19.5	-24	-25.5	-22.5	-23
	D	-21.5	-20.5	-20	-22	-20.5	-23.5	-20	-20.5
	C	-22.5	-19.5	-20.5	-21	-20.5	-22.5	-18	-18.5
70	U	-11	-11.5	-9.5	-12	-12.5	-14.5	-10.5	-10.5
	D	-10.5	-10.5	-9.5	-12	-12	-14.5	-8.5	-8.5
	C	-11.5	-13.5	-12	-13.5	-12.5	-14.5	-11.5	-12.5
80	U	-5.5	-4	-1.5	-2.5	-1.5	-2.5	-	-
	D	-4.5	-2	0	-.5	-6	-6	-	-
	C	-4	-2	+.5	-1	-2	-2.5	-	-
90	-	+1	+3	+6	+4	+3.5	+1.5	-	-

*U = upwind, D = downwind, and C = crosswind.

Table 4
Median Values of σ_0
Jan. 22, 1970: Wind velocity 23-27 knots;
wave height 8.8 ft; time 0932 - 1302

Depression Angle (deg)	Wind Direction*	σ_0 (dB)							
		X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
5	U	-32	-37	-32.5	-39.5	-35.5	-44.5	-37	-52
	D	-33	-42	-33.5	-44.5	-38.5	-51	-39	-51.5
	C	-36.5	-38	-38.5	-42.5	-38.5	-47.5	-39.5	-52.5
10	U	-28.5	-34.5	-27.5	-36	-32.5	-45	-34.5	-48.5
	D	-29	-39.5	-28.5	-41	-35.5	-51.5	-34	-50
	C	-33.5	-38.5	-33.5	-40.5	-36.5	-49	-34.5	-49.5
20	U	-27	-34.5	-24.5	-34	-26.5	-41	-27.5	-46
	D	-28.5	-40	-26.5	-39.5	-33	-46.5	-27	-47.5
	C	-31	-39	-31.5	-39.5	-32.5	-46	-29.5	-46.5
30	U	-22	-30	-21	-30	-28	-37.5	-24.5	-38.5
	D	-22	-30.5	-20.5	-31.5	-29.5	-42	-27	-37.5
	C	-28	-35	-27.5	-36	-31.5	-39	-29	-40.5
45	U	-19	-24	-17.5	-24.5	-23	-29	-23.5	-30
	D	-20	-26.5	-20	-27	-27	-33	-24	-32
	C	-23	-29	-23.5	-29	-29.5	-35	-23.5	-31
60	U	-14	-16.5	-13.5	-17	-18.5	-21.5	-18	-23
	D	-14	-16.5	-13.5	-18.5	-20	-23	-18.5	-24
	C	-18	-20	-17	-19.5	-20	-23	-18	-23
70	U	-9	-9	-7.5	-11	-11.5	-14	-17.5	-15.5
	D	-8.5	-9	-5.5	-10.5	-12.5	-13.5	-16	-16
	C	-10	-10	-9	-12.5	-13.5	-15.5	-16.5	-16.5
80	U	-3	-3	-	-	-5	-7.5	-5.5	-7
	D	-1.5	-3	-	-	-2.5	-5	-3.5	-5
	C	-2.5	-3.5	-	-	-4	-6.5	-4	-6
90	-	+2.5	+1.5	-	-	+2.5	-1	+1	-2

*U = upwind, D = downwind, and C = crosswind.

Table 5
Median Values of σ_0
Jan. 23, 1970: Wind velocity 11 knots;
wave height 6.4 ft; time 0911 - 1200

Depression Angle (deg)	Wind Direction*	σ_0 (dB)							
		X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
5	U	-33.5	-39.5	-34	-42.5	-35	-47	-38	-53
	D	-35	-46	-36	-49	-39	-54.5	-39	-58.5
	C	-39	-42	-39.5	-45	-40	-52	-38	-56.5
10	U	-29	-38	-30	-41	-32	-46.5	-32	-47
	D	-31.5	-45.5	-33	-48	-35	-52.5	-34	-51.5
	C	-37.5	-44	-38	-44.5	-36	-51.5	-32.5	-50
20	U	-	-	-28	-39	-28.5	-42	-	-
	D	-	-	-28.5	-43.5	-31	-46	-	-
	C	-32	-	-36	-47	-32	-45.5	-	-
30	U	-28	-35	-26.5	-36	-28	-37	-29	-38
	D	-27.5	-36.5	-26.5	-38	-30.5	-41.5	-29.5	-40.5
	C	-33	-40	-33.5	-41	-29.5	-40	-28.5	-38.5
45	U	-22.5	-28	-23	-29	-24.5	-30.5	-24	-29
	D	-24	-30.5	-23.5	-31.5	-25.5	-32.5	-24.5	-30
	C	-29.5	-33.5	-28.5	-34	-25.5	-32	-23	-29
60	U	-16.5	-20.5	-17	-21.5	-21	-22.5	-20	-21
	D	-18	-21.5	-18	-21.5	-21	-24	-20.5	-22.5
	C	-22.5	-25	-21	-24.5	-19.5	-22.5	-17.5	-21.5
70	U	-12	-11.5	-9	-12.5	-14	-16	-15.5	-15.5
	D	-12	-12.5	-9.5	-13	-14	-13.5	-15.5	-13.5
	C	-13	-13.5	-10	-13.5	-13.5	-14.5	-14.5	-15
80	U	-2.5	-2.5	0	-1.5	-2.5	-3.5	-2	-1.5
	D	-1.5	-3	+1.5	-2	-2.5	-3	-2	-1
	C	-3	-3.5	+1	-2	-3.5	-3.5	-2	-1.5
90	-	+4	+2.5	+9	+5	+4	+3.5	+6	+5

*U = upwind, D = downwind, and C = crosswind.

Table 6
Median Values of σ_0
Jan. 23, 1970 (legs 11+): Wind velocity 8 knots;
wave height 6.4 ft; time 1220 - 1255

Depression Angle (deg)	Wind Direction*	σ_0 (dB)							
		X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
5	U	-41	-47	-43	-50.5	-38	-52.5	-38.5	-59.5
	D	-40	-52	-41.5	-53.5	-41	-58	-39.5	
	C	-43	-46.5	-43.5	-48.5	-38.5	-52	-38	-59.5
10	U	-35	-42.5	-34.5	-45	-37	-52	-34.5	-53
	D	-35	-50.5	-35	-52	-38.5	-55.5	-36.5	-56
	C	-37.5	-43	-38.5	-45.5	-35.5	-49	-32.5	-49.5
20	U	-33	-40	-30	-41.5	-33.5	-46	-30	-48.5
	D	-32	-45.5	-32.5	-46.5	-34	-47.5	-29.5	-48.5
	C	-38.5	-45.5	-36	-45	-34	-46.5	-27	-47.5
30	U	-28.5	-37	-27	-37	-30.5	-41	-28.5	-39.5
	D	-27.5	-40.5	-28	-41	-29.5	-40.5	-28	-38.5
	C	-35	-42	-32.5	-41	-29	-39.5	-25.5	-36.5

*U = upwind, D = downwind, and C = crosswind.

Table 7
Median Values of σ_0
Jan. 26, 1970: Wind velocity 14-16 knots;
wave height 5 ft; time 0912 - 1159

Depression Angle (deg)	Wind Direction*	σ_0 (dB)							
		X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
5	U	-33	-37.5	-33.5	-38.5	-37	-48	-39	-60.5
	D	-35.5	-44.5	-38.5	-48.5	-41	-55	-41	-63
	C	-38.5	-38	-39.5	-41.5	-40.5	-51.5	-39.5	-59
10	U	-29.5	-36	-29	-38.5	-32.5	-46.5	-33.5	-51.5
	D	-31	-41.5	-31.5	-45	-35	-51	-34	-55
	C	-35	-38	-36.5	-41	-35.5	-48.5	-34.5	-53
20	U	-24	-36	-25	-36.5	-27	-44	-28	-49
	D	-27.5	-40.5	-27	-41.5	-27.5	-45.5	-28	-49.5
	C	-31	-37.5	-31.5	-40	-31	-44	-27.5	-51
30	U	-23.5	-31	-22.5	-33.5	-25.5	-37.5	-26.5	-39.5
	D	-23	-33.5	-21.5	-36	-25	-38	-27	-41
	C	-25	-34	-29	-37.5	-27.5	-39.5	-27	-39.5
45	U	-19.5	-24.5	-21.5	-27	-22.5	-30	-23.5	-32.5
	D	-20.5	-26.5	-22	-29	-22.5	-31.5	-24.5	-33
	C	-25.5	-29.5	-27	-31	-24	-32.5	-23.5	-32.5
60	U	-14.5	-16.5	-16	-19	-18	-22.5	-19	-26.5
	D	-16.5	-19	-17.5	-21.5	-17.5	-22.5	-19	-24.5
	C	-18.5	-20	-19.5	-22	-18.5	-23.5	-18.5	-26
70	U	-10	-10	-9.5	-10.5	-9.5	-14	-16	-17
	D	-9	-9.5	-9	-11	-9.5	-13	-15.5	-17.5
	C	-11	-11.5	-10.5	-13	-11	-13.5	-14.5	-16.5
80	U	-4	-1.5	0	-.5	-1	-4	-1.5	-5
	D	-4	-1.5	0	0	+.5	-3	0	-4
	C	-3.5	-2	0	-.5	-1	-4	-.5	-4.5
90	-	+3	+4	+6.5	+4.5	+7	+3.5	+5	+.5

*U = upwind, D = downwind, and C = crosswind.

Table 8
Median Values of σ_0
Jan. 27, 1970 (legs 1-7): Wind velocity 15-17 knots;
wave height 6.2 - 7.6 ft; time 0900 - 1100

Depression Angle (deg)	Wind Direction*	σ_0 (dB)							
		X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
5	U	-35.5	-39	-36	-42	-	-	-39	-55
	D	-39	-48	-39.5	-50	-38	-54	-40.5	-57.5
	C	-45.5	-44.5	-46.5	-49	-41.5	-51.5	-39.5	-59
10	U	-33.5	-39	-32.5	-41.5	-34	-48.5	-34.5	-50.5
	D	-36	-46	-34.5	-49	-37	-53	-34	-53
	C	-39	-44	-40	-46.5	-37.5	-51	-34	-51
20	U	-28	-37.5	-28.5	-39	-30.5	-47	-30	-48.5
	D	-33.5	-45	-31.5	-46	-32	-47.5	-29	-47
	C	-36.5	-45.5	-37	-45	-32.5	-47.5	-28.5	-48
30	U	-24	-35.5	-26.5	-36.5	-29	-40.5	-27.5	-42
	D	-27.5	-39	-28.5	-40.5	-29.5	-42	-26.5	-39.5
	C	-32.5	-40	-33	-45	-29.5	-41	-25.5	-38.5
45	U	-23	-32	-24.5	-31	-25.5	-35.5	-	-29.5
	D	-24.5	-35	-26	-34	-24.5	-35.5	-	-34
	C	-28.5	-36	-31	-39.5	-25	-34.5	-	-36

*U = upwind, D = downwind, and C = crosswind.

Table 9
Median Values of σ_0
Jan. 27, 1970 (legs 5-6, 6, 4, 7): Wind velocity 12-15 knots;
wave height 7.6 ft; time 1100 - 1200

Depression Angle (deg)	Wind Direction*	σ_0 (dB)							
		X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
30	U	-27	-34.5	-29.5	-37	-31	-40.5	-31	-42
	D	-29.5	-38.5	-32	-41	-30.5	-41	-30.5	-41.5
	C	-37	-40.5	-38.5	-42	-32.5	-41.5	-30	-41
45	U	-23.5	-28	-24.5	-31	-26	-33	-25	-32.5
	D	-25.5	-31.5	-26.5	-33	-26.5	-33.5	-25.5	-32
	C	-31.5	-34.5	-32	-34.5	-30	-36	-24.5	-30.5
60	U	-18	-20.5	-20	-22.5	-20.5	-25	-20	-25.5
	D	-19	-23	-21	-23.5	-19	-24	-18.5	-24.5
	C	-24	-25	-24	-24	-22	-25.5	-20	-25.5
70	U	-	-	-11.5	-14	-11	-	-	-
	D	-	-	-12.5	-14	-11	-	-	-
	C	-14.5	-	-14.5	-14	-12.5	-	-	-

*U = upwind, D = downwind, and C = crosswind.

Table 10
Median Values of σ_0
Jan. 27, 1970 (legs 8-12): Wind velocity 11-12 knots;
wave height 7.6 - 5.0 ft; time 1200 - 1300

Depression Angle (deg)	Wind Direction*	σ_0 (dB)							
		X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
5	U	-41.5	-44.5	-43.5	-50	-	-	-	-
	D	-	-	-	-	-45	-62	-44.5	-
	C	-51	-50	-	-54.5	-45	-58	-41.5	-
10	U	-38.5	-44.5	-39.5	-46	-37	-53.5	-36	-54.5
	D	-38.5	-49.5	-40.5	-53	-35.5	-51	-32	-51
	C	-40.5	-48	-41	-51	-37.5	-54	-35.5	-55
20	U	-40.5	-48.5	-39	-47	-34	-49.5	-32	-53
	D	-41	-49	-42	-52	-35.5	-49.5	-31	-53
	C	-35	-45.5	-38.5	-47	-37.5	-53	-	-49.5
30	U	-36	-43	-35.5	-43.5	-30.5	-42	-28.5	-42
	D	-35.5	-43.5	-35.5	-45.5	-31.5	-43	-31.5	-42
	C	-	-	-	-	-	-	-	-
45	U	-31	-35.5	-31	-35	-26.5	-34.5	-24.5	-33.5
	D	-32	-37.5	-31.5	-36.5	-27.5	-35	-25.5	-
	C	-	-	-	-	-	-	-	-
60	U	-	-	-	-	-	-	-	-
	D	-	-	-	-	-	-	-	-
	C	-	-	-	-	-	-	-	-
70	U	-14.5	-11	-	-10.5	-14	-14	-20	-21
	D	-15	-12.5	-	-11	-12.5	-13	-18.5	-20
	C	-17	-14	-	-12	-14	-13	-20	-21.5
80	U	-7	-5.5	-3	-2	-1.5	-3	-4	-5.5
	D	-7	-5	-3.5	-2	-1	-2.5	-3.5	-5
	C	-7.5	-6	-2.5	-2	-2.5	-3	-4	-5.5
90	-	0	+1	+4	+4.5	+5	+2.5	+.5	-2.5

*U = upwind, D = downwind, and C = crosswind.

Table 11
Median Values of σ_0
Jan. 28, 1970: Wind velocity 21-25 knots;
wave height 5 - 7.6 ft; time 1149 - 1428

Depression Angle (deg)	Wind Direction*	σ_0 (dB)							
		X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
5	U	-33.5	-38.5	-32.5	-41	-35.5	-47	-35.5	-51
	D	-34.5	-43	-35	-47.5	-38	-51.5	-39	-55.5
	C	-39	-42	-40.5	-44.5	-40.5	-51	-40.5	-58.5
10	U	-29	-36.5	-29.5	-38.5	-32.5	-48.5	-32.5	-48
	D	-30	-43	-31	-46.5	-32	-49.5	-31.5	-48
	C	-36	-39.5	-36.5	-41.5	-32.5	-46.5	-34	-48
20	U	-26	-36	-25.5	-36	-27.5	-41.5	-25	-44.5
	D	-27	-39	-26	-38.5	-26.5	-42.5	-26.5	-47.5
	C	-34	-40	-32	-40.5	-30	-45	-26.5	-47.5
30	U	-22	-31.5	-20.5	-31	-23	-35.5	-24.5	-36.5
	D	-22	-32.5	-23	-34	-24.5	-38	-25.5	-39
	C	-29	-35.5	-29.5	-38.5	-27.5	-38.5	-27	-38.5
45	U	-16.5	-24	-16.5	-24	-19.5	-28.5	-19.5	-27
	D	-18	-26	-17.5	-26.5	-20	-29.5	-19.5	-28
	C	-26	-32	-27	-32.5	-23.5	-32	-21	-30
60	U	-12.5	-15.5	-12.5	-18	-14	-20	-14.5	-21
	D	-13	-18.5	-14.5	-19	-13.5	-20.5	-13.5	-20.5
	C	-19	-22.5	-18.5	-24	-17	-23	-14.5	-22
70	U	-11	-10	-10	-11	-11	-12	-16.5	-19
	D	-10.5	-9.5	-10	-11.5	-10	-11	-16	-17
	C	-12	-10.5	-11	-12	-11.5	-12.5	-17	-18.5
80	U	-4	-3	-1	-3	+.5	-2	-2.5	-3.5
	D	-4	-3.5	-1	-3.5	+1	-1.5	-1	-2.5
	C	-5	-4	-1	-3.5	-.5	-3	-3.5	-5
90	-	+2.5	+1	+5.5	+2	+8.5	+4	+4.5	+1

*U = upwind, D = downwind, and C = crosswind.

Table 12
Median Values of σ_0
Jan. 29, 1970: Wind velocity 3-5 knots;
time 0955 - 1028

Depression Angle (deg)	Wind Direction*	σ_0 (dB)							
		X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
5	U	None					None		
	D								
	C								
10	U	-50.5	-54.5	-46	-	-34.5	-53	-35	-
	D	-	-	-	-	-35	-	-35.5	-
	C	-48.5	-52.5	-46	-55	-34	-52.5	-33.5	-56.5
20	U	-44	-57	-38.5	-53.5	-29.5	-48.5	-30	-54
	D	-47.5	-61	-41	-57.5	-30.5	-50	-31	-56.5
	C	-45	-58	-37.5	-54	-33.5	-51.5	-27	-55.5
30	U	-39.5	-50.5	-35	-47	-26	-39.5	-27	-41
	D	-41.5	-55	-36.5	-49	-26	-40.5	-27	-43.5
	C	-39	-51	-35	-46.5	-25	-40.5	-26	-42
45	U	-36.5	-43.5	-31.5	-39	-23	-32.5	-	-31
	D	-37.5	-44.5	-32	-39	-22	-34	-	-33
	C	-35	-42.5	-30.5	-37.5	-20.5	-31.5	-	-30.5

*U = upwind, D = downwind, and C = crosswind.

Table 13
Median Values of σ_0
Jan. 20, 1970: Wind velocity 18-22 knots;
wave height 5 - 6.2 ft

Depression Angle (deg)	Wind Direction*	σ_0 (dB)				
		X_{VH}	X_{HV}	C_{HV}	L_{VH}	L_{HV}
5	U	-48	-50	-47	-48	-46.5
	D	-48	-48.5	-	-51.5	-51
	C	-51	-54	-	-53	-53
10	U	-42.5	-43.5	-45	-44	-45
	D	-46.5	-45	-49	-48.5	-48
	C	-46	-47	-51	-48.5	-48.5
20	U	-39.5	-39.5	-41.5	-40	-39.5
	D	-40.5	-39	-44	-42.5	-43
	C	-44.5	-43.5	-47.5	-43.5	-44
30	U	-37.5	-	-41	-41	-41
	D	-39	-	-43	-41.5	-41.5
	C	-41.5	-	-46	-43.5	-44.5
45	U	-38	-38.5	-40	-41	-40
	D	-38	-39	-42	-38.5	-37
	C	-41.5	-42.5	-43.5	-41	-40
60	U	-34.5	-35.5	-36.5	-36	-38
	D	-36	-37	-37	-33	-34.5
	C	-35.5	-37.5	-38.5	-33.5	-35.5
70	U	-28	-32	-31	-26.5	-25.5
	D	-27.5	-31	-29.5	-26.5	-25
	C	-31.5	-34.5	-33	-26.5	-25.5

*U = upwind, D = downwind, and C = crosswind.

Table 14
Median Values of σ_0
Jan. 22, 1970: Wind velocity 23-27 knots; wave height 8.8 ft

Depression Angle (deg)	Wind Direction*	σ_0 (dB)						
		X_{VH}	X_{HV}	C_{HV}	L_{VH}	L_{HV}	P_{VH}	P_{HV}
5	U	-43	-44.5	-49	-45.5	-47.5	-49.5	-53
	D	-45.5	-47.5	-45.5	-49	-51.5	-49.5	-53
	C	-46	-47.5	-	-48.5	-50.5	-50.5	-54.5
10	U	-42	-41	-42	-44.5	-45.5	-46.5	-49.5
	D	-43.5	-42	-44	-47.5	-48.5	-45.5	-48.5
	C	-45	-44	-47.5	-48	-49.5	-46.5	-49
20	U	-41	-39.5	-39.5	-40	-40.5	-42.5	-44.5
	D	-42.5	-41.5	-42.5	-44.5	-45.5	-42.5	-44.5
	C	-42.5	-42	-44.5	-45	-45	-43.5	-45.5
30	U	-37	-35.5	-36	-39.5	-41	-39.5	-42
	D	-37	-35.5	-36	-41.5	-42.5	-39.5	-42.5
	C	-39.5	-38.5	-40.5	-42	-45.5	-42.5	-45
45	U	-35	-35	-35	-35.5	-36.5	-38	-42
	D	-35	-34	-35	-38	-39.5	-40	-41.5
	C	-36.5	-35.5	-38	-38	-40	-39	-42.5
60	U	-31.5	-30	-31	-32	-32.5	-37	-38
	D	-31	-29.5	-31	-33.5	-34	-37.5	-39
	C	-33.5	-32	-33.5	-33.5	-34.5	-37	-38.5
70	U	-27.5	-25.5	-26	-25.5	-25.5	-29	-29.5
	D	-26.5	-24.5	-25	-26	-26	-29.5	-30
	C	-29	-27	-27	-27	-27.5	-28.5	-29

*U = upwind, D = downwind, and C = crosswind.

Table 15
Median Values of σ_0
Jan. 23, 1970 (legs 1-10): Wind velocity 11 knots; wave height 6.4 ft

Depression Angle (deg)	Wind Direction*	σ_0 (dB)						
		X_{VH}	X_{HV}	C_{HV}	L_{VH}	L_{HV}	P_{VH}	P_{HV}
5	U	-46	-46.5	-52.5	-47	-47.5	-50.5	-55.5
	D	-48	-48.5	-55	-52.5	-54	-53	-60.5
	C	-48	-49	-54	-52	-54	-50.5	-57.5
10	U	-44	-43	-45.5	-44	-44	-44	-47
	D	-48	-46	-49	-47.5	-48.5	-46.5	-50.5
	C	-50	-49.5	-52	-49	-48.5	-44.5	-49
20	U	-	-	-42	-40.5	-40.5	-	-
	D	-	-	-43.5	-43	-42.5	-	-
	C	-	-	-50	-44.5	-44	-	-
30	U	-42	-41	-45	-39.5	-40	-39	-43
	D	-40.5	-41	-45.5	-42	-44	-42	-47
	C	-45.5	-	-	-42	-42.5	-39.5	-45.5
45	U	-40	-39.5	-39	-38	-38	-38	-42.5
	D	-40	-39.5	-39.5	-38.5	-39	-40	-44
	C	-43.5	-43.5	-44.5	-39.5	-39.5	-38	-41
60	U	-37	-36	-36	-33	-33	-34.5	-37
	D	-37.5	-36.5	-36	-33.5	-34	-36	-39
	C	-40.5	-39.5	-38.5	-33	-32.5	-35	-37
70	U	-30	-27	-30	-28	-25.5	-29	-30
	D	-30.5	-27	-28.5	-25.5	-24	-28.5	-29.5
	C	-31.5	-29	-30	-27	-25	-30	-30.5

*U = upwind, D = downwind, and C = crosswind.

Table 16
Median Values of σ_0
Jan. 23, 1970 (legs 11+): Wind velocity 8 knots; wave height 6.4 ft

Depression Angle (deg)	Wind Direction*	σ_0 (dB)						
		X_{VH}	X_{HV}	C_{HV}	L_{VH}	L_{HV}	P_{VH}	P_{HV}
5	U	-52	-53	-	-51.5	-52.5	-53	-59
	D	-52.5	-52.5	-	-54	-56	-55	-61.5
	C	-52	-53.5	-	-50.5	-51.5	-52.5	-57
10	U	-49	-48	-49.5	-49	-49	-49	-52.5
	D	-51.5	-50.5	-52	-51.5	-51.5	-50.5	-54.5
	C	-49	-49	-52	-47	-48	-45	-49
20	U	-44.5	-44	-46.5	-45	-45	-43.5	-49
	D	-47	-49	-50	-45	-45.5	-44	-48
	C	-50	-	-	-45	-45.5	-43	-46.5
30	U	-45.5	-42.5	-43.5	-43.5	-44	-42.5	-45
	D	-44	-44.5	-44	-41.5	-41.5	-42.5	-45
	C	-47.5	-48	-47	-42	-42	-40	-42.5

*U = upwind, D = downwind, and C = crosswind.

Table 17
Median Values of σ_0
Jan. 26, 1970: Wind velocity 14-16 knots; wave height 5 ft

Depression Angle (deg)	Wind Direction*	σ_0 (dB)						
		X_{VH}	X_{HV}	C_{HV}	L_{VH}	L_{HV}	P_{VH}	P_{HV}
5	U	-44	-46	-49	-49.5	-50.5	-58	-60
	D	-47.5	-51.5	-50	-52.5	-55	-58	-63.5
	C	-45	-49.5	-50	-52	-53	-57.5	-59.5
10	U	-42	-42.5	-44	-45.5	-46.5	-47.5	-51.5
	D	-44.5	-46	-46.5	-48.5	-48	-51	-52
	C	-44	-48	-49	-47	-48	-50	-51.5
20	U	-41	-40.5	-41	-43	-40	-44.5	-47.5
	D	-42	-43	-42	-43	-40	-46.5	-47.5
	C	-43.5	-43.5	-45	-44	-44	-44	-48
30	U	-37	-39	-39	-40	-39	-42	-42.5
	D	-38	-40	-39	-39	-38	-42.5	-42
	C	-40.5	-43.5	-42.5	-41	-40.5	-43.5	-43.5
45	U	-35.5	-36	-38	-36	-36.5	-40.5	-41
	D	-36	-37.5	-38.5	-36.5	-35.5	-41	-40.5
	C	-37	-40	-41	-38	-37.5	-40.5	-41
60	U	-32	-32.5	-34.5	-33	-31.5	-40	-40
	D	-33	-33.5	-35	-32.5	-31	-39.5	-39
	C	-33.5	-33	-36	-33	-31.5	-40	-39
70	U	-28	-27	-29.5	-25.5	-24	-33	-30
	D	-27	-26.5	-28.5	-25	-23.5	-33	-32
	C	-29.5	-28.5	-31.5	-26	-25	-33	-30.5

*U = upwind, D = downwind, and C = crosswind.

Table 18
Median Values of σ_0
Jan. 27, 1970 (legs 1-7): Wind velocity 15-17 knots; wave height 6.2 - 7.6 ft

Depression Angle (deg)	Wind Direction*	σ_0 (dB)						
		X_{VH}	X_{HV}	C_{HV}	L_{VH}	L_{HV}	P_{VH}	P_{HV}
5	U	-46	-48.5	-50.5	-	-	-52	-59
	D	-50.5	-54.5	-	-51.5	-53	-52.5	-58
	C	-51.5	-57.5	-	-53	-55.5	-54	-59
10	U	-45	-47.5	-47.5	-47	-49	-47	-52
	D	-48	-50.5	-50.5	-49	-50	-48	-51.5
	C	-49.5	-51.5	-52.5	-50	-51	-47	-50
20	U	-42.5	-43	-44	-45	-43.5	-44.5	-47
	D	-46.5	-46	-47	-46	-44.5	-43.5	-48
	C	-49	-50	-50	-46	-45.5	-43	-48
30	U	-41.5	-40.5	-42	-42.5	-42	-40	-43
	D	-42.5	-43.5	-44	-43	-42	-40.5	-42
	C	-44.5	-46	-48.5	-43	-42	-40.5	-42
45	U	-40.5	-40	-41.5	-40.5	-38	-38	-39
	D	-41.5	-40.5	-42	-40	-37.5	-38	-39
	C	-43	-44	-46	-40	-37.5	-37	-38

*U = upwind, D = downwind, and C = crosswind.

Table 19
Median Values of σ_0
Jan. 27, 1970: Wind velocity 12-15 knots; wave height 7.6 ft

Depression Angle (deg)	Wind Direction*	σ_0 (dB)						
		X_{VH}	X_{HV}	C_{HV}	L_{VH}	L_{HV}	P_{VH}	P_{HV}
30	U	-41	-44	-	-43	-45	-44	-49
	D	-43.5	-	-	-43	-45	-43.5	-48.5
	C	-45.5	-	-	-45	-44	-42.5	-47
45	U	-40	-40.5	-44	-40	-40	-42	-45
	D	-41	-42	-44.5	-39.5	-40	-41	-44
	C	-43.5	-47.5	-	-42.5	-43.5	-40.5	-45
60	U	-36	-37	-37.5	-35.5	-35	-38.5	-40.5
	D	-37	-37.5	-38.5	-34	-33	-37.5	-39.5
	C	-39.5	-39.5	-42	-36	-36	-38	-39.5
70	U	-30.5	-28.5	-31.5	-27.5	-25	-30.5	-30.5
	D	-31	-30	-31.5	-26	-23.5	-27	-26.5
	C	-32.5	-29.5	-33.5	-29	-27	-30	-30

*U = upwind, D = downwind, and C = crosswind.

Table 20
Median Values of σ_0
Jan. 27, 1970 (legs 8-12): Wind velocity 11-12 knots;
wave height 7.6 - 5 ft

Depression Angle (deg)	Wind Direction*	σ_0 (dB)						
		X_{VH}	X_{HV}	C_{HV}	L_{VH}	L_{HV}	P_{VH}	P_{HV}
5	U	-52	-	-	-	-	-	-
	D	-	-	-	-57	-	-61.5	-
	C	-57	-	-	-57	-	-58.5	-
10	U	-50	-51.5	-55	-51	-51	-50.5	-53.5
	D	-52	-54	-59	-49	-49.5	-46	-49
	C	-53	-56	-58.5	-51	-51	-49	-52
20	U	-54	-55.5	-52	-47.5	-49.5	-49.5	-54
	D	-53.5	-	-	-48.5	-48	-46.5	-48.5
	C	-50	-52.5	-52.5	-51.5	-51.5	-43	-
30	U	-50	-53.5	-	-44	-44	-44	-46.5
	D	-48.5	-52.5	-	-44.5	-45	-45.5	-47.5
	C	-	-	-	-	-	-	-
45	U	-46	-47.5	-48	-40.5	-40	-40	-42
	D	-47	-48.5	-48.5	-41	-40.5	-	-44
	C	-	-	-	-	-	-	-
60	U	-	-	-	-	-	-	-
	D	-	-	-	-	-	-	-
	C	-	-	-	-	-	-	-
70	U	-	-	-	-	-31	-	-29.5
	D	-	-	-	-29.5	-28.5	-	-
	C	-	-	-	-	-	-	-

*U = upwind, D = downwind, and C = crosswind.

Table 21
Median Values of σ_0
Jan. 28, 1970: Wind velocity 21-25 knots; wave height 5 - 7.6 ft

Depression Angle (deg)	Wind Direction*	σ_0 (dB)						
		X_{VH}	X_{HV}	C_{HV}	L_{VH}	L_{HV}	P_{VH}	P_{HV}
5	U	-44.5	-47	-49.5	-48	-49	-50.5	-55.5
	D	-47	-49.5	-	-49.5	-50	-52	-57
	C	-48	-52.5	-	-52.5	-53	-54	-58.5
10	U	-41.5	-42.5	-43.5	-46.5	-46	-45	-48.5
	D	-46	-46	-46.5	-46	-45	-45.5	-47.5
	C	-44.5	-47.5	-49	-46.5	-48	-44.5	-48.5
20	U	-42	-39	-40.5	-41	-41	-42	-43
	D	-42.5	-42	-41	-41	-40	-43	-45.5
	C	-45.5	-45	-45.5	-44	-43	-43	-44.5
30	U	-38	-38.5	-37	-38.5	-36	-38	-40.5
	D	-38.5	-38.5	-38.5	-39	-38	-40	-43
	C	-41	-43	-42	-41	-40.5	-41.5	-43.5
45	U	-35	-33.5	-34	-35.5	-33	-35.5	-38.5
	D	-35.5	-34	-34.5	-34.5	-33.5	-36	-38.5
	C	-39.5	-39.5	-41	-38.5	-37	-38	-40.5
60	U	-31.5	-29	-32	-30.5	-28	-34.5	-35.5
	D	-32.5	-30	-33	-30	-27	-34.5	-34.5
	C	-36	-35	-36.5	-33	-31	-35	-35.5
70	U	-23.5	-	-	-25	-24.5	-	-
	D	-23.5	-	-	-24.5	-24	-	-
	C	-25	-	-	-26	-26	-	-

*U = upwind, D = downwind, and C = crosswind.

Table 22
Median Values of σ_0
Jan. 29, 1970: Wind velocity 3 - 5 knots

Depression Angle (deg)	Wind Direction*	σ_0 (dB)						
		X_{VH}	X_{HV}	C_{HV}	L_{VH}	L_{HV}	P_{VH}	P_{HV}
10	U	-	-	-	-49	-51	-51.5	-53.5
	D	-	-	-	-48.5	-49	-52.5	-55.5
	C	-	-	-	-48.5	-46.5	-51	-50.5
20	U	-59.5	-	-	-46	-44.5	-50.5	-51.5
	D	-61.5	-	-	-48	-46	-52	-53.5
	C	-57	-57.5	-	-48	-45.5	-48.5	-49
30	U	-60	-60	-53	-41	-40	-46.5	-47.5
	D	-60.5	-59	-53.5	-42.5	-40	-47.5	-47
	C	-57	-57	-52	-41	-38.5	-44.5	-44
45	U	-57	-56	-49	-38	-36	-40.5	-41
	D	-56.5	-55	-49.5	-39	-36	-43	-42
	C	-54.5	-52	-48	-36.5	-34	-38.5	-38.5

*U = upwind, D = downwind, and C = crosswind.

Previous results have shown that σ_0 increases with wind velocity until a limiting value is read, and that this upper bound is predictable through a slightly rough scattering model (5) for both vertical and horizontal polarization. The effect is illustrated in Figs. 3 to 6, where the Bermuda data have been included with previous 4FR measurements. Previous investigation has shown that for X-band, the growth of the NRCS with wind can be approximated by a cube law for winds of 0 to 10 knots, while a less sensitive function, e.g., the square root, approximates the rate for higher wind speeds (6). The JOSS I program has provided much additional information in the critical region of 0 to 20 knots, hence an empirical growth law for σ_0 as a function of wind can now be determined with greater accuracy. A recent study by Valenzuela (7), not including the Bermuda data, has shown that for short wavelengths and vertical polarization, the NRCS of the sea over the wind velocity range of 0 to 50 knots may be approximated by a single equation of the form

$$\sigma_0 \approx e^{-c/U}, \tag{1}$$

where c is an arbitrary constant and U is the wind velocity. This exponential law has been fitted to the short-wavelength data on both vertical and horizontal polarization (Figs. 3 and 4) and appears to fit both polarizations better at the 10° depression angle (Fig. 3) than at 30° (Fig. 4). However, this may be caused simply by the relative scarcity of data points in the critical region of 0 to 10 knots. In general, an equation of the form of Eq. (1) will approximate the short-wavelength data for depression angles from 5° to 60°.

The same study (7) performed for the longer wavelengths (L and P bands) showed that the NRCS of the sea is less sensitive to wind at these frequencies, and may be approximated by an equation of the form

$$\sigma_0 \approx U^{2\nu}, \tag{2}$$

where ν is a constant to be determined. The long-wavelength data corresponding to the data of Figs. 3 and 4 are shown in Figs. 5 and 6 with a best-fit power law of the form of Eq. (2). As previously shown (7) the growth of the NRCS in L-band is slight and is virtually nonexistent for P-band. Examination of other cases shows that the fractional power law expressed by Eq. (2) also holds for depression angles 5° to 60°. Hence, the radar engineer, utilizing tabulated data and Eq. (1) or (2) may determine an empirical estimate of the growth of the NRCS of the sea for his particular case.

THE OCEAN WAVE SPECTRUM

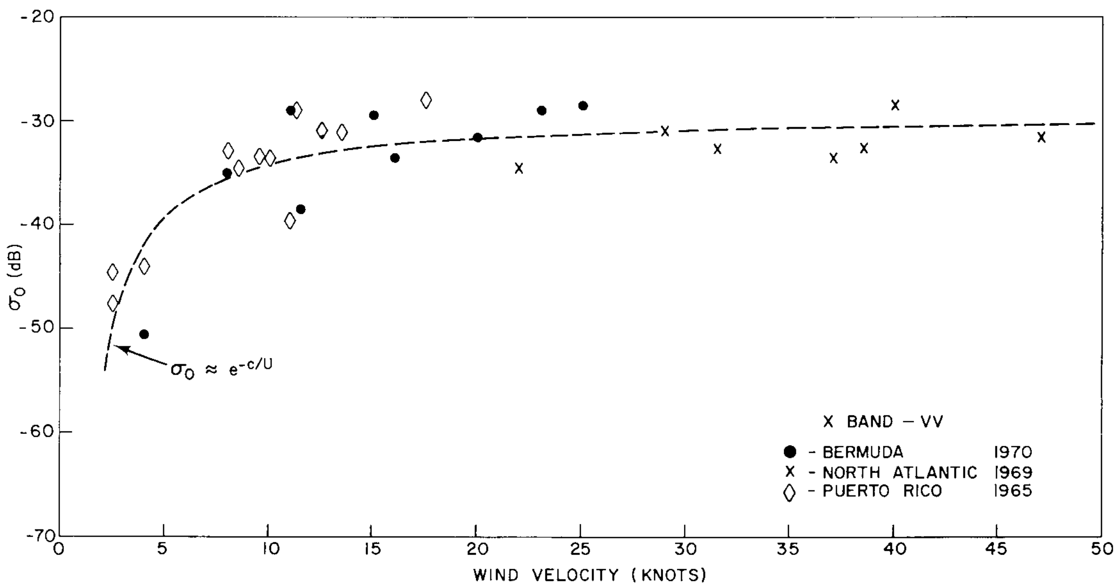
The ocean wave-height spectrum may be obtained directly from the NRCS measurement on vertical polarization as shown by Wright (8). Sample spectra from both rough and calm wind conditions are shown in Fig. 7, along with the Philips-Burling equilibrium range spectrum given by

$$W(K) = 6 \times 10^{-3} K^{-4}, \tag{3}$$

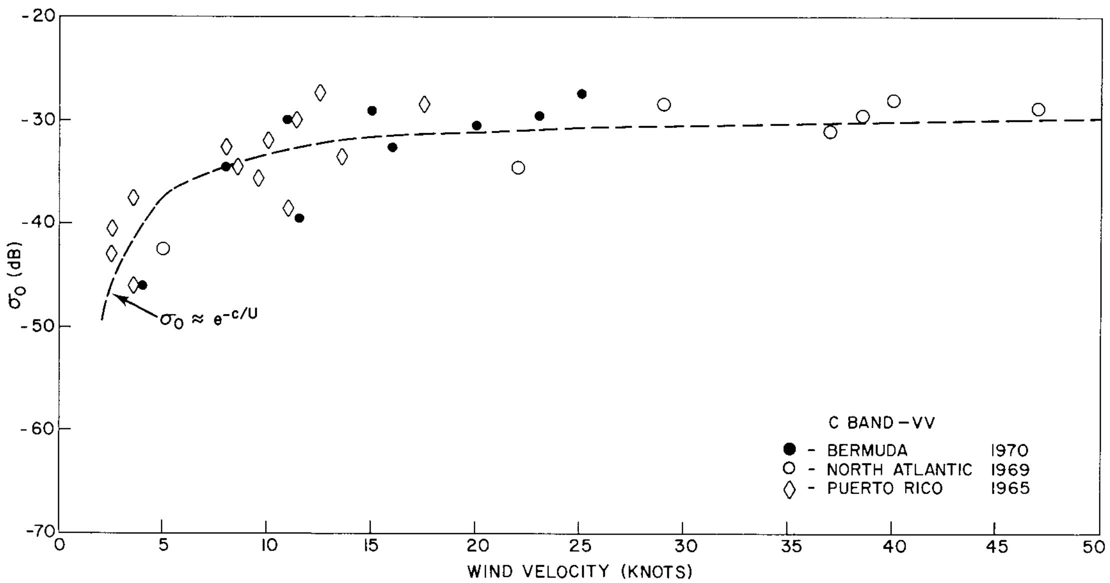
where K is the ocean wave-number. The rougher conditions are well approximated by Eq. (3), whereas the calm day (Jan. 29, 1970) shows a dip in the spectrum at the higher wave-numbers (X- and C-band radar wavelength data). This phenomenon has been reported previously for both open-sea and wave-tank measurements (7,8). Valenzuela (7) has pointed out that the general expression for the equilibrium range of this spectrum for gravity waves may be given by

$$W(K) \approx U^{2\nu} g^{-\nu} K^{-(4-\nu)}, \tag{4}$$

where g is the acceleration of gravity.

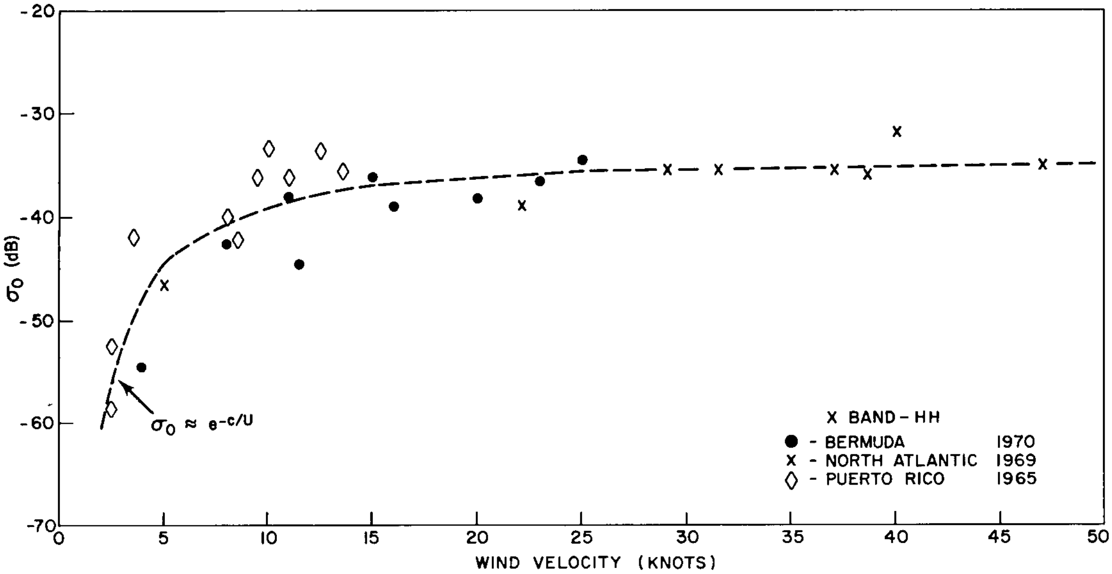


(a)

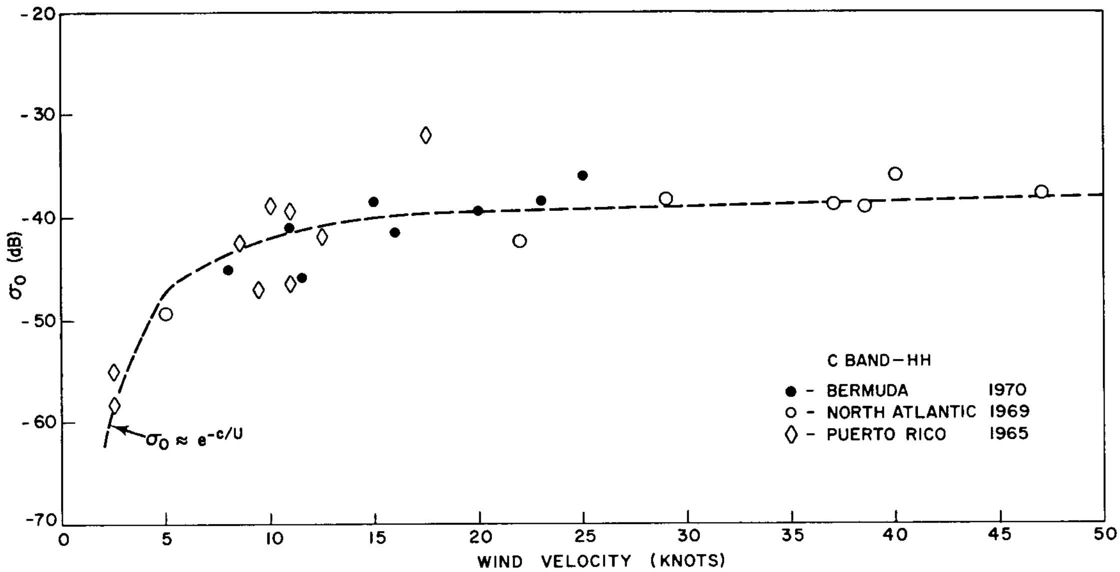


(b)

Fig. 3 - Median NRCS of the sea vs wind velocity; X and C bands upwind, 10° depression angle

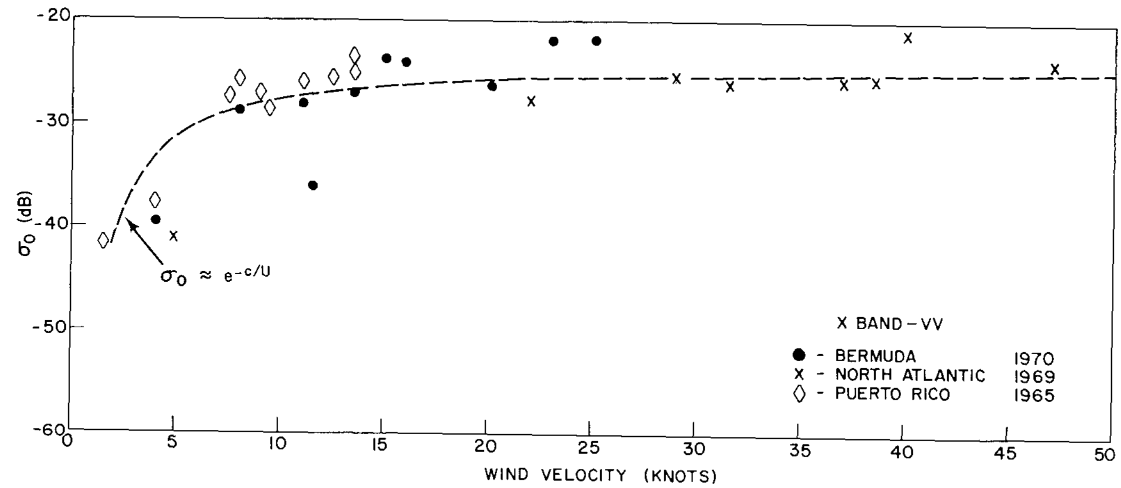


(c)

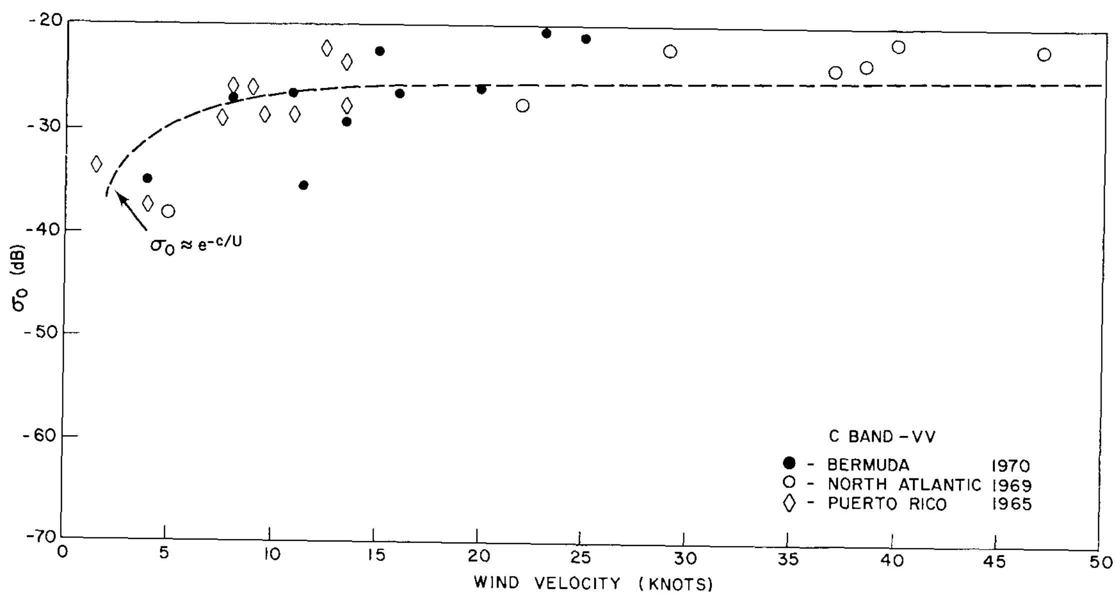


(d)

Fig. 3 (Continued) - Median NRCS of the sea vs wind velocity; X and C bands upwind, 10° depression angle

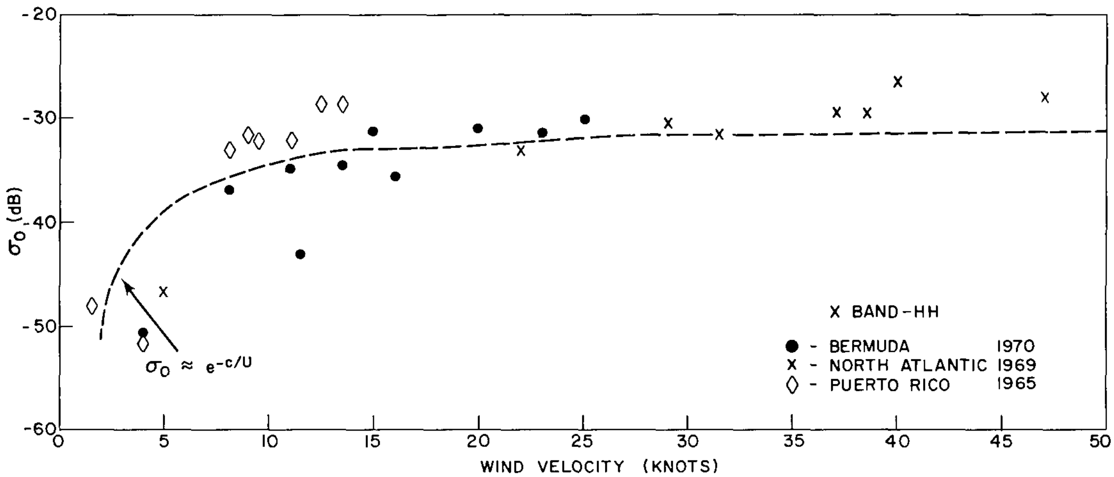


(a)

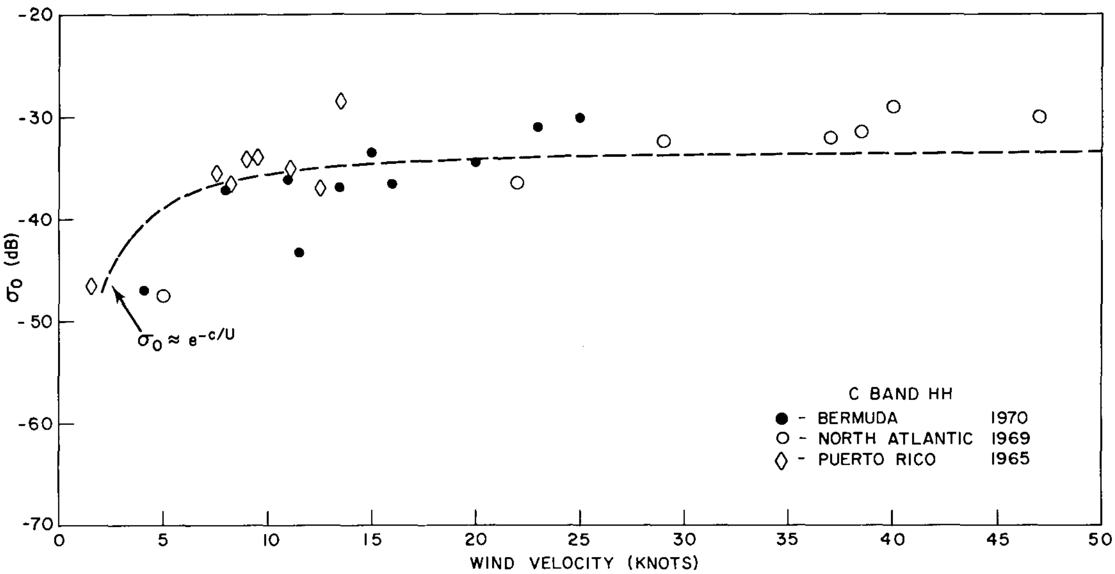


(b)

Fig. 4 - Median NRCS of the sea vs wind velocity; X and C bands upwind, 30° depression angle



(c)



(d)

Fig. 4 (Continued) - Median NRCS of the sea vs wind velocity; X and C bands upwind, 30° depression angle

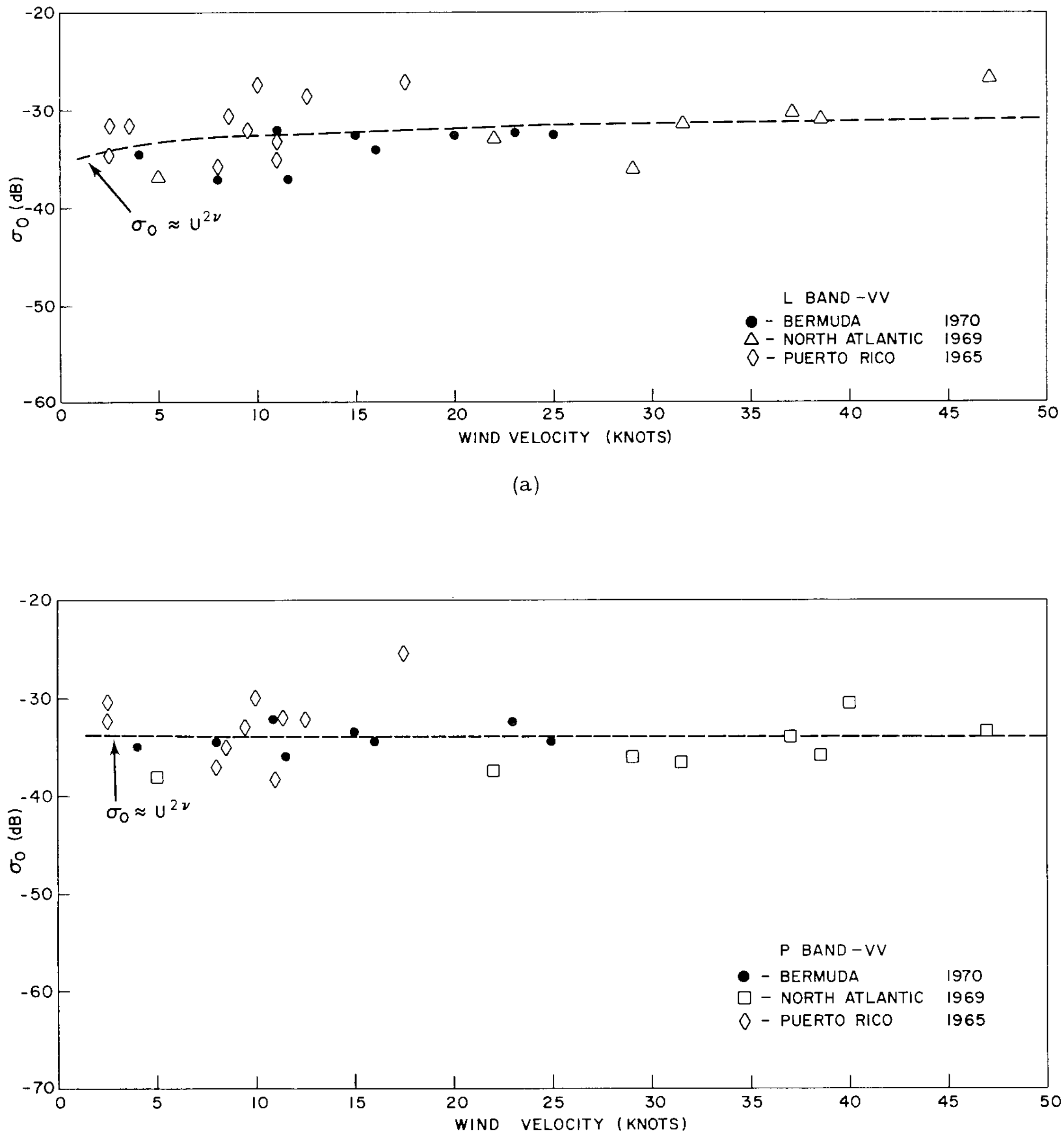
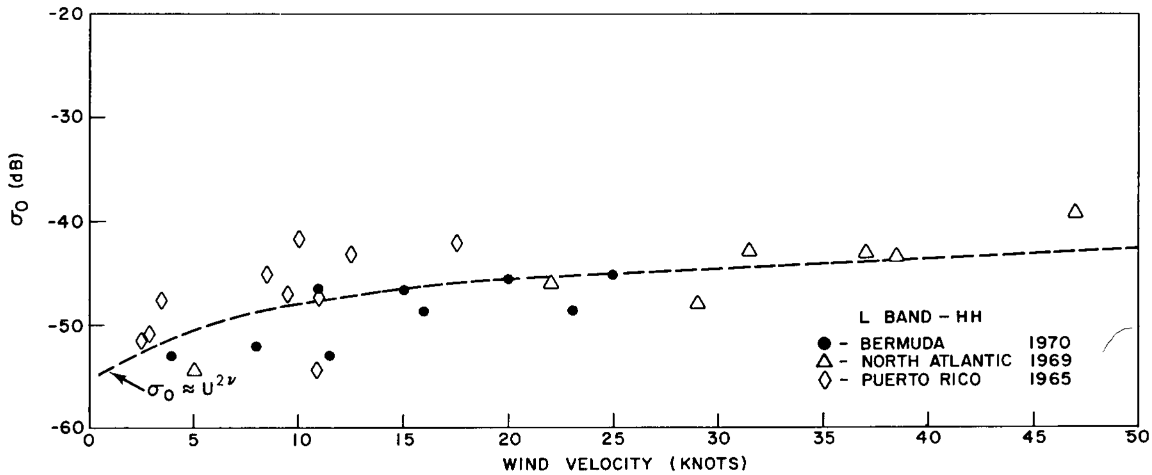
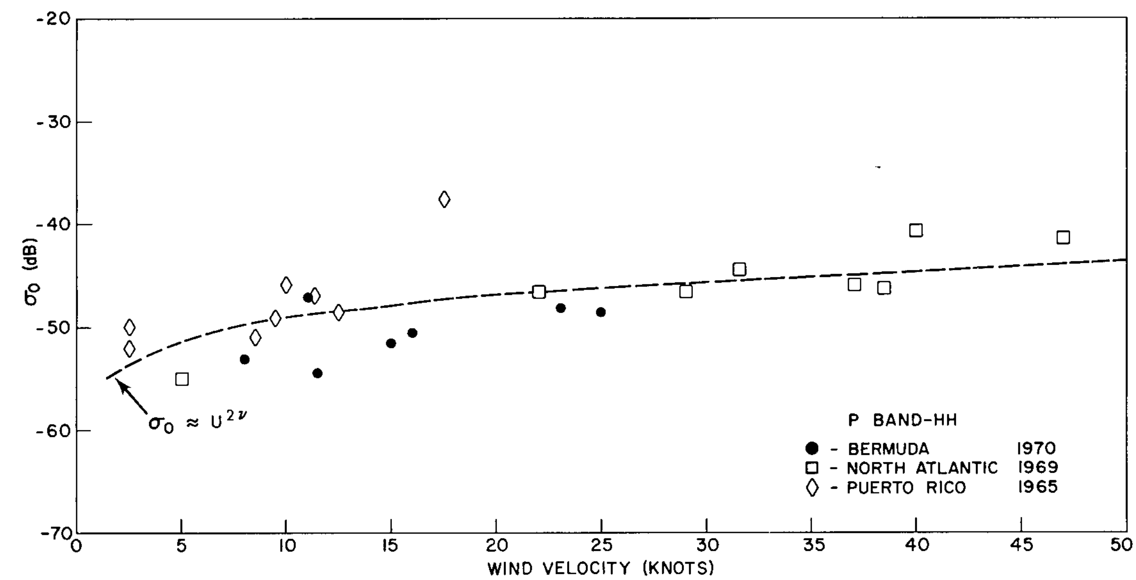


Fig. 5 - Median NRCS of the sea vs wind velocity; L and P bands upwind, 10° depression angle

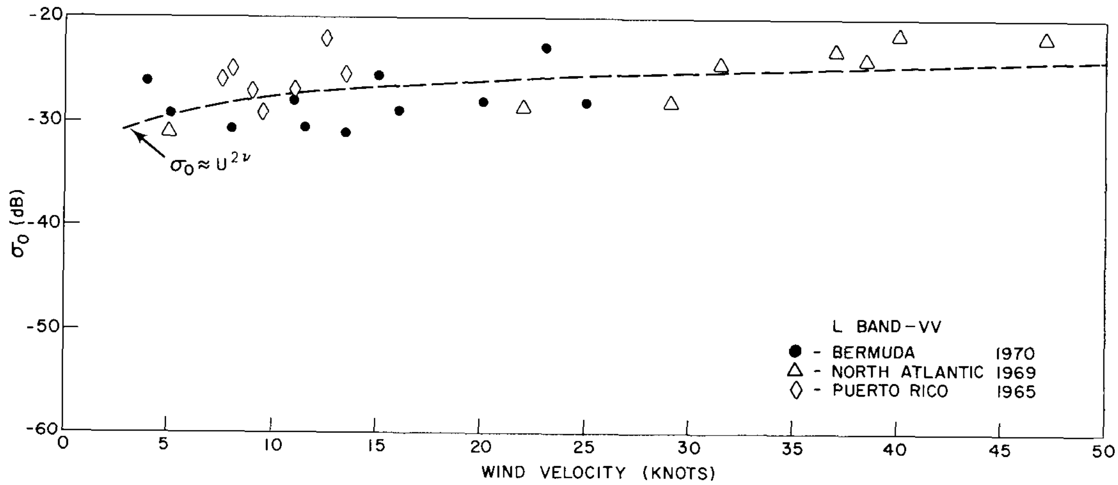


(c)

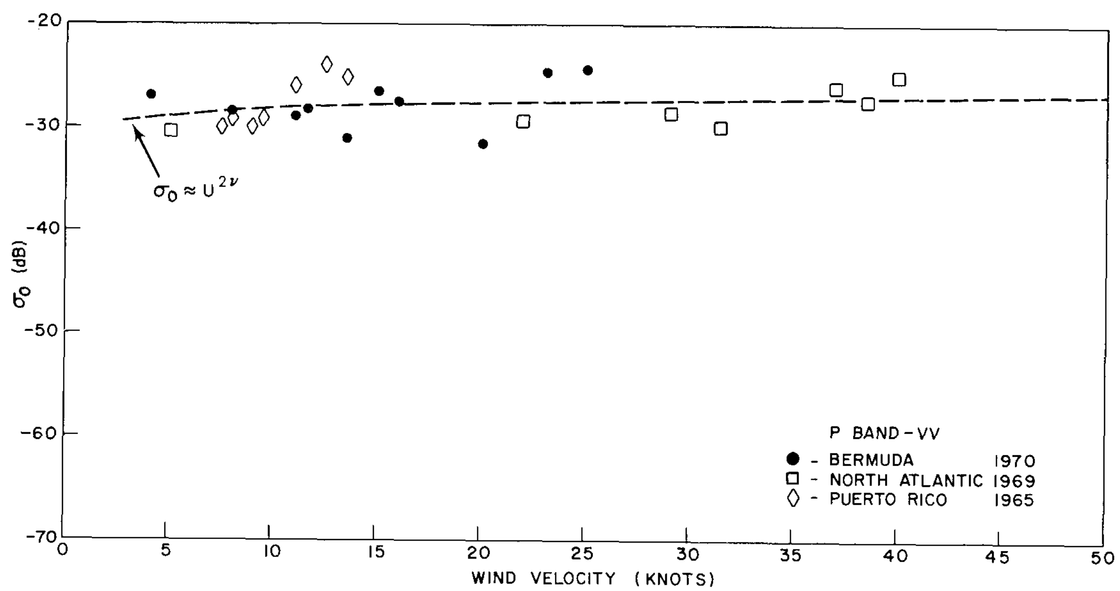


(d)

Fig. 5 (Continued) - Median NRCS of the sea vs wind velocity; L and P bands upwind, 10° depression angle

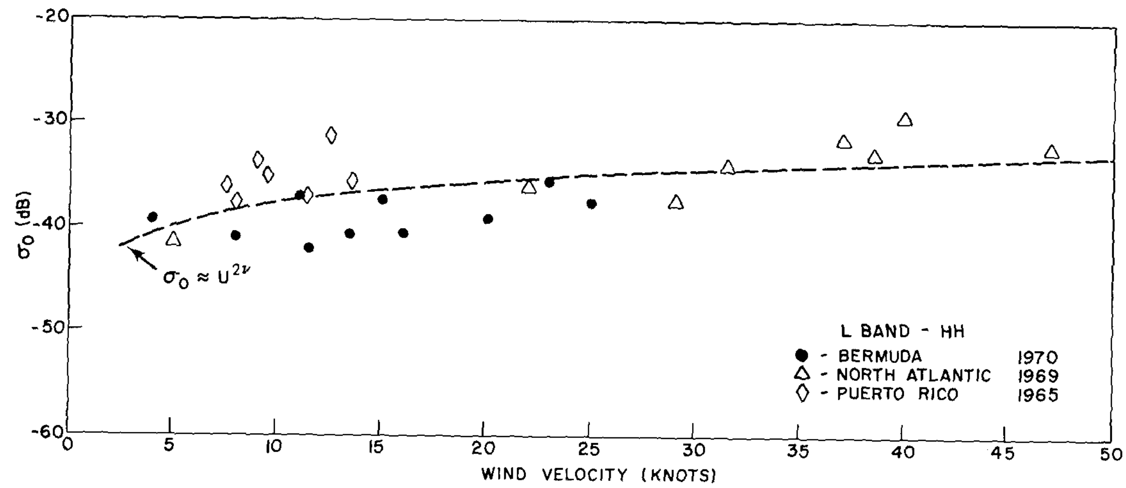


(a)

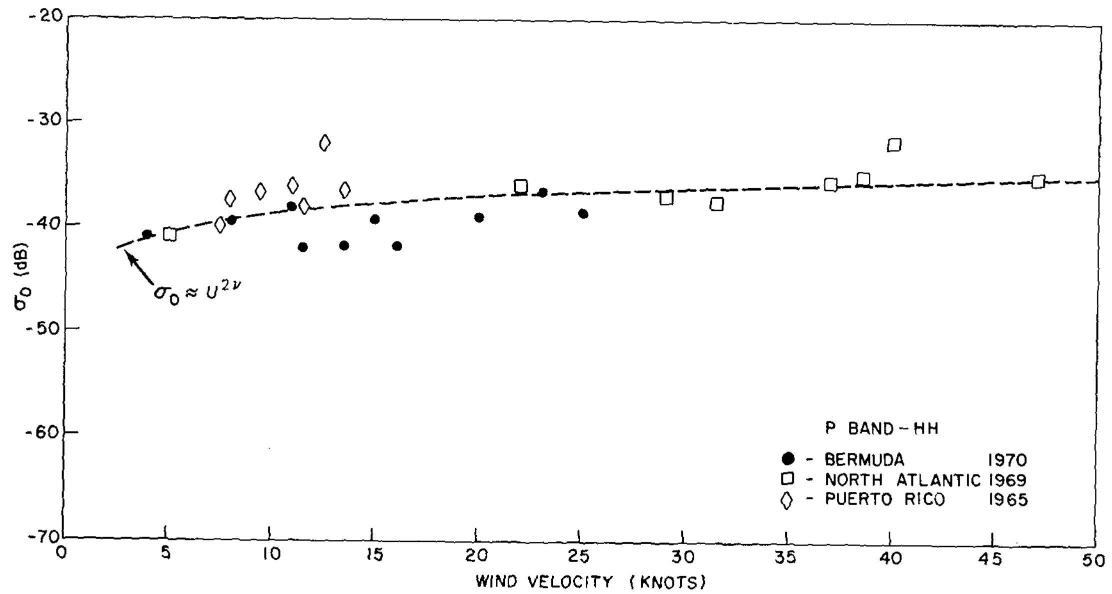


(b)

Fig. 6 - Median NRCS of the sea vs wind velocity; L and P bands upwind, 30° depression angle



(c)



(d)

Fig. 6 (Continued) - Median NRCS of the sea vs wind velocity; L and P bands upwind, 30° depression angle

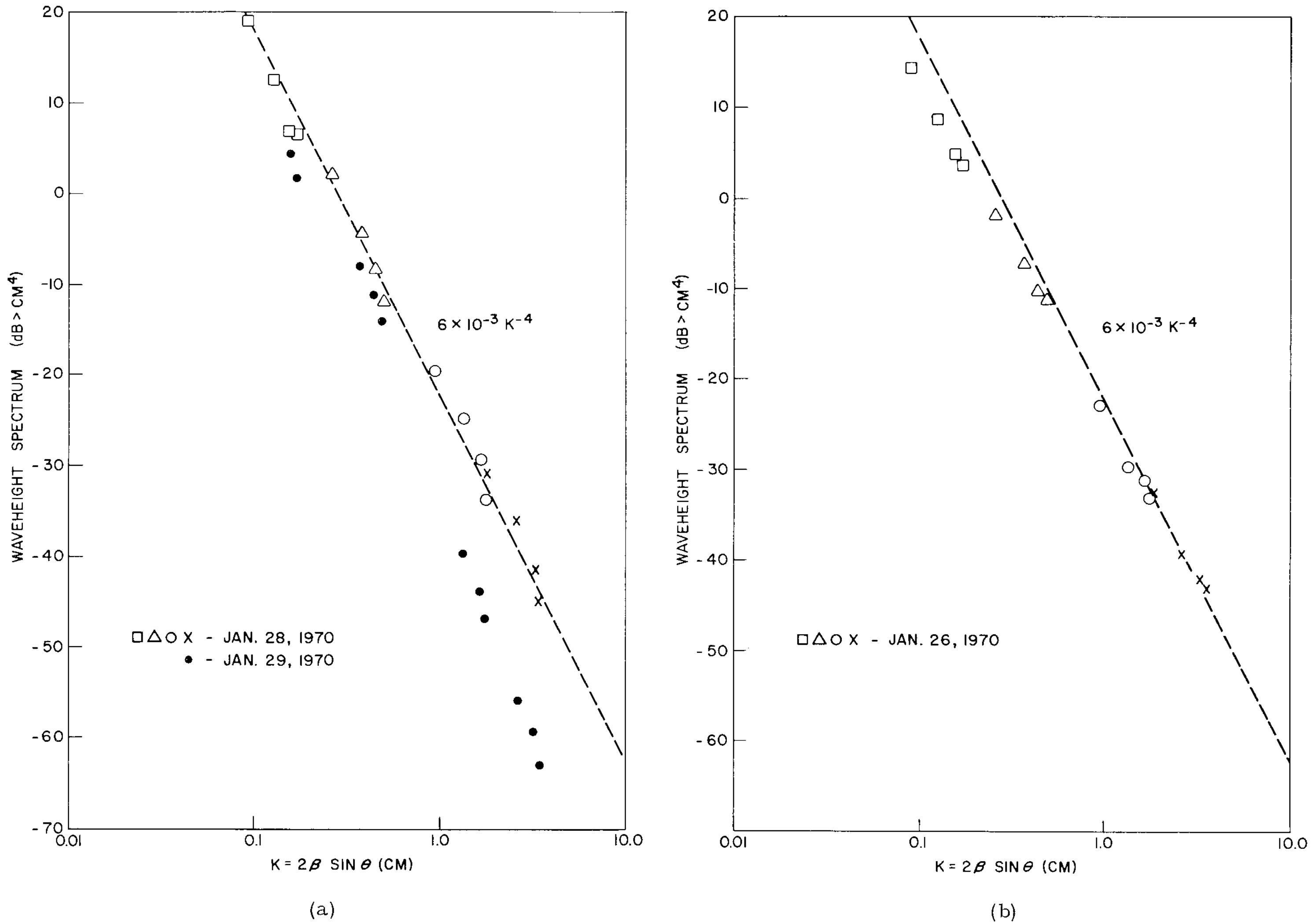


Fig. 7 - Ocean wave-height spectra, upwind

The value of ν found by curve-fitting Eq. (2) and the vertically polarized NRCS data may be inserted in Eq. (4) to obtain the spectrum power law, or the spectrum may be fitted directly to the data in the form given in Fig. 7. This was done previously (7), and close agreement was obtained between the two power laws so determined for large wave-numbers and wind speeds greater than 10 knots. This shows that the wind dependence for large wave-numbers is of a form which is consistent with the power law of the spectrum.

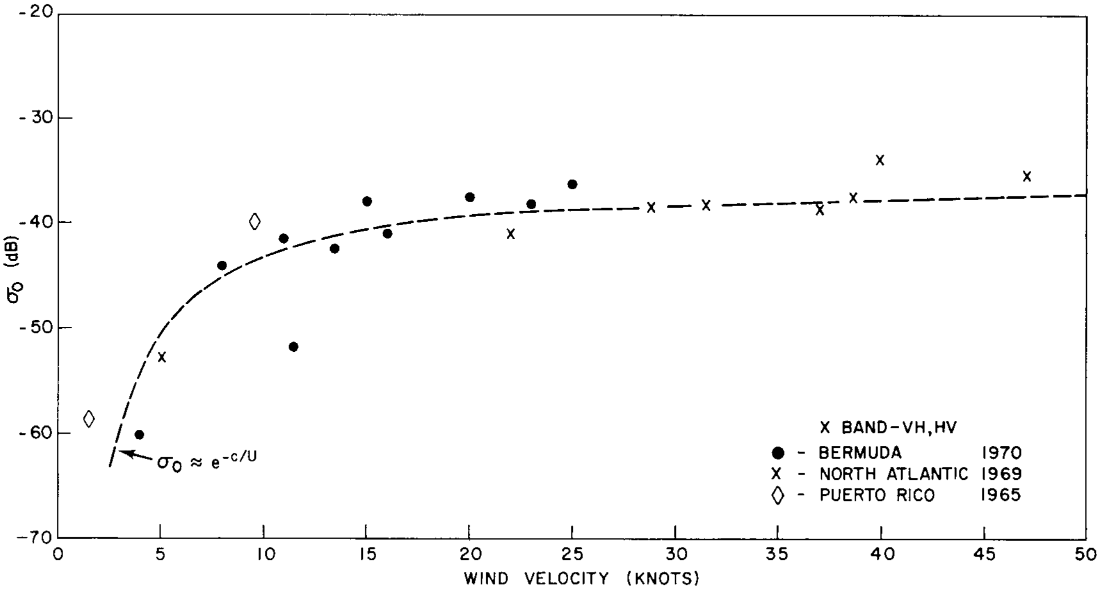
THE CROSS-POLARIZED NRCS

The success of the JOSS I program has resulted in a significant body of cross-polarized sea return for depression angles 5° to 60°. An example of the observed wind dependence is shown in Fig. 8, where σ_0 (dB) is the median of the VH and HV measurements calibrated independently. The NRCS seems to approach a limiting value on all frequencies. The growth laws given by Eqs. (1) and (2) appear to give a better fit for the long wavelengths than for the short wavelengths. The theoretical NRCS of the sea for a cross-polarized return has been calculated for the slightly rough surface model (Ref. 9). A detailed examination of the cross-polarized returns in terms of this model is in progress and will be reported separately.

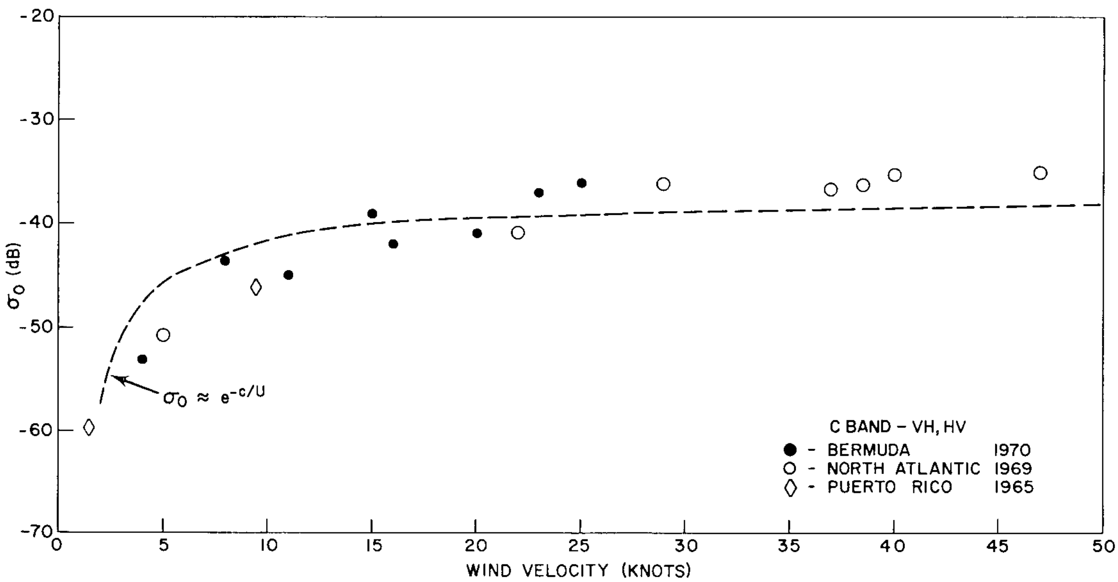
SYSTEM LIMITATIONS

The two basic uncertainties in the calibration of the 4FR measurement system are the receiver stability and the measurement of the sphere. The receiver stability is monitored by inserting a known signal in the rf line and recording it periodically through the data-collecting period. This signal serves to quantize receiver drift and any changes in sensitivity through the data-taking period. The sphere measurement possesses an uncertainty due to the variation of illumination of the sphere signal in the center of the beam. This uncertainty is minimized by repeating the sphere measurements on each radar frequency and then calibrating on the maximum value of the sphere return. The statistical scatter of the sphere return, about a $(\text{range})^{-4}$ slope, is the limit of error of the sphere measurement. Both of the above errors have been combined (worst case) and listed in Table 23. The limits apply to absolute values of σ_0 for each signal component, with exceptions noted below.

The exceptions to the above error analysis include measurements at depression angles of 90° (normal incidence) and measurements of the cross-polarized components. The measurement of 90° has inherent in it a problem of range gating at the center of the antenna beam, which is not present at other angles. The specular nature of the return at 90°, plus vertical platform motion, causes difficulty in continuous range gating at the center of the clutter pile. For this reason, although values are given at 90°, we have avoided drawing general conclusions for this particular case, until more accurate measurements have been made. The cross-polarized return is subject to contamination due to system crosstalk, mostly at the antenna and receiver. These data are calibrated by the appropriate direct-polarized sphere measurement, e.g., X_{VH} data are calibrated by the X_{HH} sphere, X_{HV} data are calibrated by the X_{VV} sphere. This procedure assumes no major differences between vertical and horizontal transmission. This is generally true, and in that case the cross-polarized values of σ_0 would have the same limits of error as the appropriate direct-polarized value. These limits of error account for the spread between VH and HV values in most cases, with one exception: For P band, the VH aspect is consistently higher than the HV, by amounts beyond those expected due to the above-mentioned errors. In this case, the best estimate of cross-polarized RCS is the median value of VH and HV.



(a)



(b)

Fig. 8 - Median NRCS of the sea vs wind velocity; cross-polarization upwind, 30° depression angle

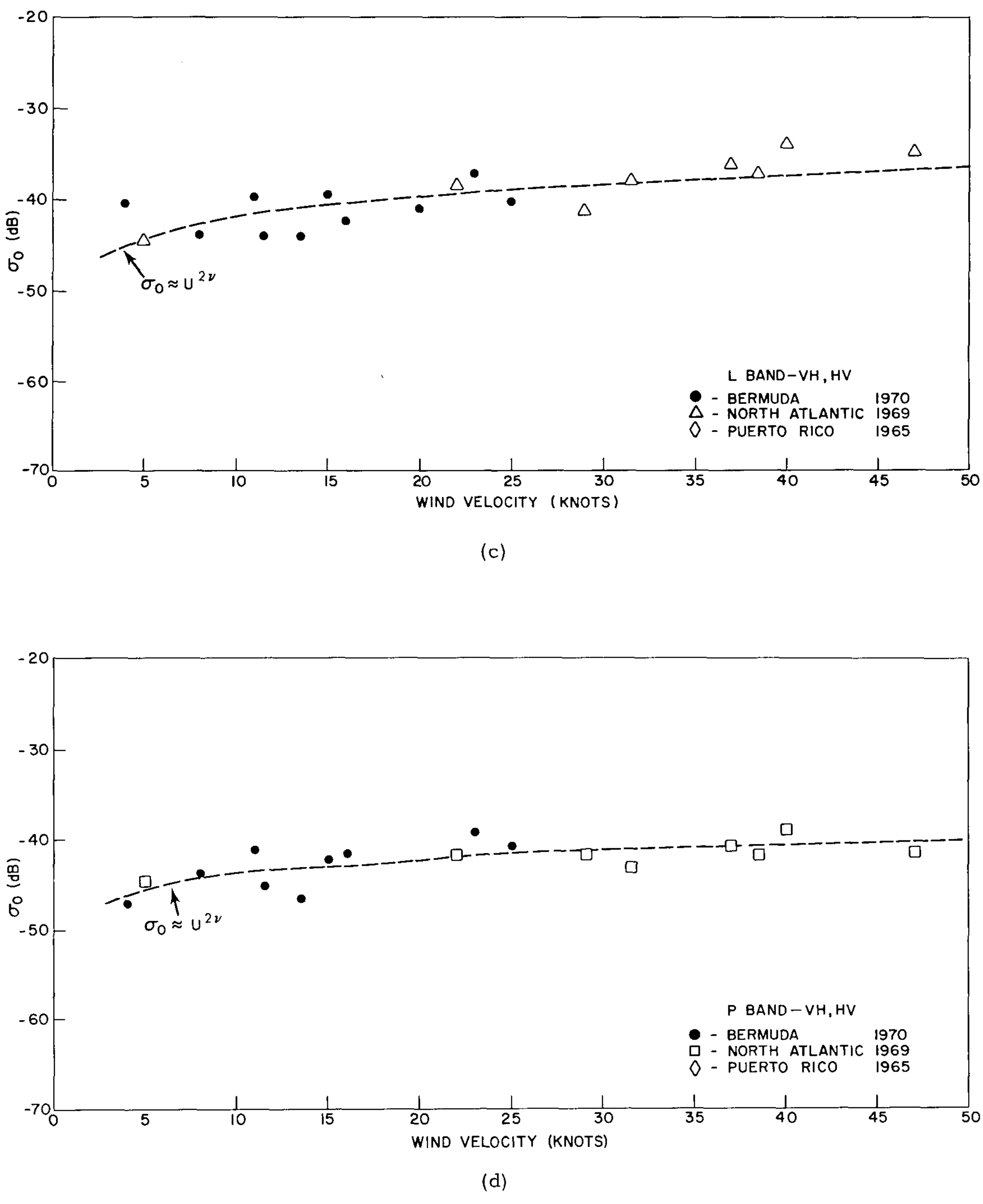


Fig. 8 (Continued) - Median NRCS of the sea vs wind velocity; cross-polarization upwind, 30° depression angle

Table 23
Summary of Errors

Date	X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
Jan. 20, 1970	±2.5	2	2	1.5	1.5	2	2	2.5
Jan. 22, 1970	2.5	2.5	2	1.5	2	2	2	2
Jan. 23, 1970	3	1.5	2.5	2	2.5	1.5	2.5	2.5
Jan. 26, 1970	2	1.5	2.5	2	1.5	1.5	3	2.5
Jan. 27, 1970	3.5	3	4	3.5	3	2	2.5	2
Jan. 28, 1970	4.5	2	2.5	2.5	3.5	2.5	3.5	3
Jan. 29, 1970	2	2	2	1.5	2	1	2	.5

CONCLUSIONS

The processing and analysis of the 4FR radar sea return recorded at Bermuda in January 1970 in association with JOSS I have been completed. Data were collected on both linear (VV,HH) and cross (VH,HV) polarizations. The amplitude component of the returns was processed to determine the NRCS of the sea as a function of radar and surface parameters. These results were incorporated with previous 4FR sea return data to form a comprehensive data bank of the parametric behavior of the median value of σ_0 from which the following conclusions may be drawn:

1. The NRCS of the sea approaches a limiting value with increasing roughness for all frequencies and polarizations.

2. For depression angles 5° to 60°, the growth of the NRCS may be approximated simply by the empirical formulas

$$\sigma_0 \approx e^{-c/U} \text{ for X, C bands}$$

$$\sigma_0 \approx U^{2\nu} \text{ for L, P, bands.}$$

3. For the rougher conditions observed in the JOSS I mission, the NRCS data implied the presence of the equilibrium range spectrum.

4. The spectrum exhibited a characteristic dip at the higher wave numbers for calm sea conditions.

5. The cross-polarized return approaches a limiting value with increasing wind.

FUTURE WORK

Work is continuing on the JOSS I program in several areas:

1. The determination of the ocean wave-height spectrum from the laser altimetry and aerial photography.

2. The comparison of the cross-polarized sea return with a theoretical model.

3. The investigation of the variation of the ocean spectrum over a long fetch.

As a continuation of these studies, the JOSS II measurement program will be conducted in February 1971 in the vicinity of Wallops Island, Virginia. The object of this program will be an extensive study of the nature of the sea return at vertical and near-vertical incidence with a view to developing a reliable sea-return model over the entire angular region from grazing to vertical incidence.

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Appendix

Tabulation of NRCS σ_0 (Median, in Decibels)
Data taken over Puerto Rico, 1965

July 15, 1965

θ	Wind	X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
4°-20°, wind = 15-20 knots (rain), wave height = 4-5 ft									
4°	U	-30	NG	-33.5	-37	-34	-42	-30.5	-
	D	-31		-36.5	-42	-39	-	-34.5	-
	C	-36		-41	-38.5	-39	-	-31.5	-
10°	U	-28		-28.5	-32	-27	-42	-25.5	-37.5
	D	-29		-29.5	-39	-28	-45	-24.5	-42.5
	C	-35		-38	-37	-33	-46.5	-25.5	-41.5
15°	U	-		-	-	-	-	-	-
	D	-		-	-	-	-	-	-
	C	-		-	-	-	-	-	-
20°	U	-26		-29	-29	-25	-37	-25.5	-38
	D	-26		-26	-36	-25	-40	-24.5	-37
	C	-32		-29.5	-33	-	-40.5	-	-40
30°-90°, wind = 12-15 knots (rain), wave height = 3-5 ft									
30°	U	-25		-28	-28.5	-25.5	-35.5	-25	-36.5
	D	-27		-29	-32.5	-26	-38	-25	-37.5
	C	-		-	-	-	-	-	-
45°	U	-23		-	-	-	-	-	-
	D	-		-	-	-23	-28	-22	-28
	C	-28		-26	-25	-22.5	-29	-18.5	-26
60°	U	-		-	-	-	-	-	-
	D	-		-	-	-	-	-	-
	C	-19		-17.5	-12.5	-15	-16	-	-15
70°	U	-		-	-	-	-	-	-
	D	-		-	-	-	-	-	-
	C	-8		-5.5	-3.5	-8.5	-7	-15.5	-15
80°	U	-		-	-	-	-	-	-
	D	-		-	-	-	-	-	-
	C	-4		-	-	-4	-3	-3	-.5
90°	-	+1.5		-	-	-	-	-3	-2

July 16, 1965

θ	Wind	X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
4°-15°, wind = 10-12 knots, wave height = 2-2-1/2 ft									
4°	U	-40	NG	-40	-44	-36	-	-36.5	-
	D	-42.5		-45	-	-36.5	-	-36	-
	C	-45.5		-45	-	-38	-	-33.5	-
10°	U	-39.5		-38.5	-46.5	-35	-54	-38.5	-
	D	-41		-42	-55.5	-30.5	-52	-37	-
	C	-38.5		-38	-42.5	-31	-48.5	-36	-50.5
15°	U	-		-	-	-28.5	-45	-31.5	-47.5
	D	-37.5		-36.5	-48	-	-	-	-
20°-30°, wind = 7-8 knots, wave height = 2-3 ft									
20°	U	-32.5		-30.5	-40.5	-29	-43.5	-27.5	-49
	D	-33		-33.5	-45	-30	-45	-28	-
	C	-33.5		-35	-43	-28	-43	-28.5	-51
30°	U	-27.5		-29	-35.5	-26	-36	-30	-40
	D	-30		-29.5	-40	-26	-38	-29.5	-41
	C	-		-	-				
45°-90°, wind = 8-10 knots, wave height = 3-4 ft									
45°	U	-22.5		-24	-24	-22	-29	-27	-35.5
	D	-26		-26.5	-29.5	-22	-29	-26	-35
	C	-29		-28.5	-30	-22.5	-29	-26.5	-33.5
60°	U	-15		-13	-14.5	-17	-19	-23.5	-25
	D	-17.5		-14.5	-15.5	-17	-18	-20.5	-24.5
70°	U	-10		-7	-6.5	-10	-9	-14.5	-16.5
	D	-11		-8.5	-6	-10	-9	-14.5	-18
80°	U	-		-3	-1	-	-	-	-
	D	-		-	-	-4	-3	-8.5	-7.5
90°	-	+6		+9.5	+8.5	-	+5.5	-3	-1.5

July 19, 1965

θ	Wind	X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
4°-90°, wind = 10-15 knots, wave height = 3-4 ft									
4°	U	-35.5	-36.5	-33	-41	-36	-41.5	-37	-
	D	-38.5	-43	-37	-47	-37	-	-37.5	-
	C	-45.5	-42.5	-44.5	-47	-36	-	-34.5	-
10°	U	-31	-33.5	-27.5	-42	-28.5	-43	-32	-48.5
	D	-37	-45	-36	-51.5	-28.5	-44.5	-28	-46.5
	C	-36	-39	-36	-47	-29	-42	-24	-45
20°	U	-30	-30.5	-27.5	-39	-25	-37.5	-24	-43
	D	-31	-39	-29	-43	-26	-39	-25	-41.5
	C	-36	-37.5	-	-44	-23	[illegible]	-	-37
30°	U	-25.5	-28.5	-22	-37	-22	-31	-24	-32
	D	-26.5	-31	-22.5	-38	-24.5	-33.5	-23.5	-32.5
	C	-	-	-	-	-	-	-	-
45°	U	-	-19	-	-27	-	-24	-	-30
	D	-	-21	-	-28.5	-21	-27	-	-28
	C	-	-	-	-	-	-	-	-
70°	U	-	-	-	-	-9	-7.5	-14.5	-13
	D	-	-2	-3	-4.5	-	-	-	-
	C	-	-1.5	-2	-5	-12	-9	-12.5	-13
80°	U	-	-	-	-	-2.5	-1.5	-2.5	-.5
	D	-	+3.5	+4	+4	-	-	-	-
	C	-	+5	+2	+2	-4	-1.5	-3	-1.5
90°	-	-	+14.5	-	+9	+4.5	+7	-1	+1.5

July 20, 1965

θ	Wind	X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
5°-45°, wind = 7-9 knots, wave height = 2-3 ft									
5°	U	-	-	-35	-	-	-	-	-
	D	-	-	-	-	-	-	-	-
	C	-	-	-	-	-	-	-37	-
10°	U	-33	-40	-32.5	-	-36	-	-37	-
	D	-35	-	-37	-	-36.5	-	-37	-
	C	-36.5	-	-37.5	-	-34	-	-36.5	-
20°	U	-29.5	-40	-30	-39.5	-30	-43	-28.5	-46
	D	-29	-43	-31	-43	-29.5	-44	-28.5	-46.5
	C	-34	-42.5	-35	-42	-31	-45	-29.5	-47
30°	U	-25.5	-33	-26	-36.5	-25	-37.5	-29	-37.5
	D	-25.5	-35	-28	-40	-26	-38.5	-28	-37
	C	-26.5	-33.5	-26.5	-36	-28	-39	-28.5	-37.5
45°	U	-	-	-	-	-	-29.5	-24	-35
	D	-22.5	-29.5	-24	-31	-	-	-	-
	C	-23	-25	-24.5	-27.5	-25	-31	-24	-32.5
4°, 60°-90°, wind = 10-12 knots, wave height = 2-3 ft									
4°	C	-42.5	-	-42.5	-	-43	-	-41	-
60°	C	-19	-20	-17.5	-18.5	-22.5	-20	-25.5	-20.5
70°	C	-10	-10	-8	-12	-14.5	-12.5	-20	-20
80°	C	-7.5	-7.5	-3.5	-6	-10	-8	-11.5	-11
90°	-	0	+3.5	-	-	-.5	-2	-1.5	-6

July 21, 1965

θ	Wind	X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
4°-90°, wind = 8-11 knots, wave height = 3-6 ft									
4°	U	-36.5	-38.5	-38	-44	-39.5	-	-41.5	-
	D	-41	-48.5	-42.5	-	-39	-	-41	-
	C	-40.5	-40	-41	-43	-	-	-38	-
10°	U	-33.5	-36	-35.5	-47	-32	-47	-33	-49
	D	-35.5	-45.5	-36	-50	-34	-51.5	-34	-53
	C	-37.5	-39.5	-36.5	-44.5	-34.5	-	-31.5	-51
20°	U	-31.5	-36.5	-30.5	-39	-30	-40	-29	-46.5
	D	-32	-42.5	-31.5	-43.5	-29.5	-41	-27.5	-45.5
	C	-34	-40	-32.5	-43	-30	-42	-30	-43
25°	U	-	-	-	-	-32.5	-40	-34.5	-43.5
	D	-33	-41.5	-32.5	-41.5	-	-	-	-
30°	U	-28.5	-32	-28.5	-34	-29	-35	-29	-36.5
	D	-28.5	-34	-30	-38	-30	-36	-28	-36.5
	C	-33.5	-36	-33.5	-39	-30	-37	-26.5	-37.5
45°	U	-23.5	-25	-24.5	-25.5	-25	-28.5	-24	-32.5
	D	-22	-24.5	-24	-27	-27.5	-29.5	-25.5	-33.5
	C	-29.5	-29	-29	-30	-27	-30.5	-23	-28
60°	U	-17.5	-20.5	-16.5	-	-21	-19.5	-19	-18
	D	-17	-19.5	-15	-	-22	-19	-22	-20.5
	C	-20	-15.5	-17.5	-20.5	-21.5	-19.5	-18	-18
70°	U	-11.5	-13	-9	-18	-10.5	-14	-15	-21.5
	D	-7	-9.5	-5	-13	-10.5	-14.5	-	-
	C	-10	-7.5	-7.5	-11	-9.5	-8.5	-16.5	-18
78°	U	-7	-7	-2.5	-7.5	-	-	-	-
	D	-	-	-	-	-5.5	-5.5	-9.5	-13.5
80°	U	-	-	-	-	-1	-1	-4	-6.5
	D	-1.5	-2.5	+2	-4	-	-	-	-
	C	-1.5	+1.5	+1.5	0	-1	+1.5	-4.5	-4.5
90°	-	+3.5	+7	+6.5	+6	+3.5	+5.5	-2.5	-2

July 22, 1965

θ	Wind	X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
4°-90°, wind = 10-12 knots, wave height = 5-7 ft									
4°	U	-35	-38	-37	-41	-40.5	-46.5	-40.5	-
	D	-35.5	-41	-39	-	-41	-	-41	-
	C	-39	-37	-43	-41.5	-43	-	-39.5	-
10°	U	-29	-36	-30	-39.5	-33	-47	-32	-47
	D	-30.5	-43	-33	-47	-34	-51	-29	-44
	C	-37.5	-39	-40	-38.5	-37.5	-51.5	-32	-53
20°	U	-27	-35.5	-29	-39	-30	-43.5	-27	-
	D	-28.5	-38	-31	-43	-29.5	-44	-25.5	-45.5
	C	-	-	-	-	-	-	-	-
30°	U	-26	-32	-28.5	-35	-27	-37	-26	-36
	D	-27	-34.5	-29.5	-38	-28	-39	-26.5	-35
	C	-	-	-	-	-	-	-	-
45°	U	-23.5	-29	-25	-29	-24	-29.5	-24	-32
	D	-24.5	-31	-25.5	-32	-24.5	-30	-21.5	-25.5
	C	-	-	-	-	-	-	-	-
60°	U	-20.5	-22	-19	-19	-20.5	-22	-16	-20.5
	D	-22	-24	-21.5	-22.5	-19	-21	-16	-19
	C	-	-	-	-	-	-	-	-
70°	U	-9	-8.5	-6	-5.5	-14.5	-13.5	-12.5	-13
	D	-6.5	-6	-4	-4	-15	-14	-13.5	-15.5
	C	-6	-7	-5.5	-6.5	-18	-15	-13	-15.5
78°	U	-	-	-	-	-6	-3.5	-6	-6.5
	D	-7.5	-7	-2.5	-4.5	-	-	-	-
80°	U	-4.5	-6	-1	-1	-	-	-	-
	D	-	-	-	-	-2.5	0	-10	-10.5
	C	-4.5	-7	-3	-3	-3.5	-2	-2.5	-4
90°	-	-1.5	-4	+3	+3.5	+2	+4	0	-2

July 23, 1965

θ	Wind	X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
30°-90°, wind = 8-10 knots, wave height = 2-3 ft									
30°	U	-27	-31.5	-26	-34	-27	-33.5	-30	-38
	D	-28	-33.5	-28.5	-38	-25	-34	-30	-38
	C	-28.5	-31.5	-28.5	-35	-26	-34	-28.5	-38
45°	U	-25.5	-28	-24	-27	-21.5	-25	-24.5	-32
	D	-25	-27.5	-25	-26.5	-20	-26	-24.5	-33
	C	-26.5	-30.5	-25	-28.5	-22	-26.5	-24.5	-30
60°	U	-20	-22	-18.5	-17	-15.5	-15	-19	-20
	D	-20.5	-21	-18.5	-18	-14	-15	-20.5	-19.5
	C	-22	-23	-19.5	-19	-15	-15.5	-19.5	-20
4°-20°, 70°-90°, wind = 8-12 knots, wave height = 4-6 ft									
4°	U	-39	-37	-39.5	-42	-35.5	-41.5	-41.5	-
	D	-41	-41	-41	-47	-39	-45	-42	-
	C	-45	-39	-44.5	-45	-39	-46	-39.5	-
9°	U	-33.5	-33	-33	-39.5	-31.5	-	-	-
	D	-36	-	-35.5	-	-33	-	-	-
	C	-34.5	-33.5	-	-	-33	-	-	-
10°	U	-33.5	-33.5	-32	-39	-27.5	-41.5	-30	-46
	D	-35	-43.5	-34	-48	-30	-44.5	-33.5	-49
	C	-36.5	-42.5	-34.5	-38.5	-32.5	-48	-33.5	-54
20°	U	-30.5	-33.5	-29	-38	-25	-38	-27.5	-44
	D	-32.5	-38	-32.5	-43.5	-26	-39	-27.5	-48
	C	-32	-35	-31.5	-38.5	-27	-39	-30	-49.5
70°	U	-15	-16	-11	-9	-8	-7.5	-8	-9.5
	D	-	-	-	-	-9	-5.5	-15.5	-11.5
	C	-14	-10	-6	-8.5	-7.5	-6	-9.5	-11
80°	U	-	-	-	-	+2.5	+5	-	-9
	D	-9.5	-5.5	-	-	-	-	-	-
	C	-11	-7.5	0	0	+2	+4.5	-	-12
90°	-	+1.5	-3	+6.5	+6	+6	+6.5	-3	-2.5

July 27, 1965

θ	Wind	X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
4°-15°, wind = 2-3 knots, wave height = 1/2-1 ft									
4°	U	-43	-	-	-	-42.5	-	-38.5	-
	D	-37	-40	-37.5	-43.5	-43	-49	-40	-
	C	-44	-44	-44	-49	-44	-	-40.5	-
8-1/2°	U	-	-	-	-	-34.5	-49.5	-33	-50.5
	D	-	-39	-37	-45.5	-	-	-	-
	C	-	-55.5	-40	-	-32.5	-51	-31	-50
10°	U	-44.5	-52.5	-40.5	-55	-31.5	-51.5	-30.5	-50
	D	-	-43	-37	-47.5	-31	-47	-29.5	-46.5
	C	-	-42.5	-40	-47.5	-33	-52.5	-32	-50
15°	U	-	-46	-39	-49.5	-	-	-	-
	D	-	-	-	-	-30	-47.5	-28	-52.5
	C	-	-	-40	-51	-34	-43	-31.5	-50
15°-65°, wind = 5-8 knots, wave height = 1-5 ft									
15°	U	-	-	-	-	-29.5	-46	-27.5	-53
	D	-	-36	-35.5	-39.5	-	-	-	-
20°	U	-	-42.5	-36	-47	-25.5	-43.5	-25.5	-45.5
	D	-42.5	-38.5	-34	-42	-27	-44.5	-25	-49
	C	-	-44.5	-36.5	-46	-25.5	-42.5	-30	-44.5
35°	U	-	-36.5	-32	-40	-	-	-	-
	D	-	-43	-36.5	-45.5	-	-	-	-
45°	U	-	-29.5	-30	-33.5	-21	-28.5	-23	-32.5
	D	-	-29	-35	-41	-20	-27.5	-21.5	-31
60°	U	-	-28.5	-25.5	-28	-18.5	-24	-21	-25
	D	-	-27.5	-23	-27	-19	-24	-20	-25.5
	C	-	-29	-26.5	-30	-17.5	-21	-20.5	-29
65°	U	-	-21	-21.5	-24	-	-	-	-
	D	-	-	-	-	-19.5	-21	-	-22.5

July 27, 1965

θ	Wind	X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
65°-90°, wind = 0-1 knots, wave height = 1/2-1 ft									
65°	U	-	-	-	-	-17.5	-19	-20	-22.5
	D	-	-15	-16.5	-18	-	-	-	-
70°	U	-	-16	-18.5	-19.5	-17	-19	-14.5	-16.5
	D	-	-	-	-	-14	-12.5	-18.5	-23
	C	-	-12	-17	-17	-14	-14	-16	-17.5
75°	U	-	-13.5	-18	-16.5	-7.5	-7	-14	-9
	D	-	-9	-14	-15.5	-	-	-	-
80°	D	-	-	-	-	-6	-	-	-
90°	-	-	+9	+8	+9	+7	+3.5	+2	+1
4°-20°, wind = 2-3 knots, wave height = 1/2-1 ft (slicks)									
4°	U	-	-	-47	-	-44	-	-43	-
	D	-	-	-47	-				
	C	-44.5	-45.5	-45	-				
8-1/2°	C	-	-46	-	-59	-	-52	-31	-50
10°	U	-47.5	-58.5	-43	-58.5	-34.5	-51	-32.5	-52
	D	-45.5	-59	-43.5	-59.5	-33	-51.5	-32.5	-50
	C	-52	-	-48	-	-37	-55.5	-34.5	-
15°	C	-	-53	-40	-56	-35.5	-45	-32.5	-53.5
20°	U	-	-52	-40	-52	-29.5	-45.5	-27.5	-48
	D	-	-	-	-	-	-	-	-
	C	-	-51	-39	-52.5	-29.5	-46	-26	-47.5
15°-35°, wind = 5-8 knots, wave height = 1/2-1 ft (slicks)									
15°	D	-	-47	-38	-50	-	-	-	-
35°	U	-	-	-	-	-28	-38.5	-27.5	-37
	D	-	-	-	-	-28	-39	-27	-37

July 27, 1965

θ	Wind	X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
60°-90°, wind = 0-1 knots, wave height = 1/2-1 ft (slicks)									
60°	U	-	-	-	-	-48	-51	-30	-34.5
	D	-	-52.5	-42.5	-47.5	-25	-30	-26.5	-31.5
	C	-	-43	-35	-36	-32.5	-36.5	-28.5	-32.5
65°	U	-	-	-	-	-20.5	-23	-22.5	-26.5
70°	U	-	-37	-36	-37	-28.5	-32	-21	-25
	D	-47	-38.5	-41	-40.5	-18.5	-20	-15.5	-17
	C	-	-27	-25	-26.5	-18	-19.5	-17.5	-19
75°	U	-	-6.5	-8	-6.5	-4	-1.5	-3	-1.5
	D	-	-.5	-2	-4.5	-10.5	-12	-14	-9
	C	-	-23	-22	-17.5	-	-	-16.5	-11.5
80°	U	-	-4	-6.5	-6	-	-	-	-13.5
	D	-	-	-	-	-6	-4	-7	-6
	C	-	-5	-5.5	-5	-9.5	-6	-14	-13
90°	-	-	+14.5	+14	+15.5	+9.5	+12	+3.5	+2.5

July 28, 1965

θ	Wind	X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
4°-20°, wind = 3-4 knots, wave height = 1/2-1 ft									
4°	U	NG	-39	-40	NG	-44.5	-	NG	NG
	D		-	-45		-43.5	-		
	C		-	-50.5		-43.5	-		
10°	U		-42	-37.5		-31.5	-47.5		
	D		-47	-38.5		-35	-54.5		
	C		-53.5	-45.5		-36	-		
20°	U		-41	-36		-	-		
	D		-	-		-31.5	-43.5		
	C		-53	-40		-29.5	-42.5		
60°-90°, wind = 0-1 knot, wave height = 1/2-1 ft									
60°	U		-25	-23		-25	-32.5		
	D		-	-		-	-		
	C		-26.5	-20		-18.5	-22.5		
63°	U		-	-		-17.5	-20		
	D		-	-		-	-		
	C		-	-		-23	-22.5		
70°	U		-	-		-12.5	-12.5		
	D		-	-25		-	-		
73°	U		-12.5	-		-	-		
	D		-	-		-	-		
	C		-14.5	-		-12	-12		
80°	U		-	-		-	-11		
	D		-	-23		-	-		
90°	-		+11.5	-		+11	+11.5		
4°-34°, wind = 3-4 knots, wave height = 1/2-1 ft									
4°	C		-44	-47		-44	-		
34°	C		-41	-31.5		-26	-36		

July 29, 1965

θ	Wind	X_{VV}	X_{HH}	C_{VV}	C_{HH}	L_{VV}	L_{HH}	P_{VV}	P_{HH}
4°-60°, wind = 2-15 knots, wave height = 2-3 ft									
4°	U	-38.5	-43	-41.5	-44.5	-38	-	-38.5	-
	D	-44	-	-47	-	-39.5	-	-39	-
	C	-44	-43.5	-46	-46.5	-40	-	-38.5	-
10°	U	-34.5	-42	-34.5	-42.5	-30.5	-45	-35	-51
	D	-37	-52.5	-39.5	-53.5	-31.5	-50.5	-35	-50.5
	C	-39	-43.5	-40.5	-47	-33.5	-50	-34	-46
15°	U	-30	-38.5	-31	-39	-28	-40.5	-30.5	-48
	D	-33.5	-46.5	-35.5	-49	-	-42	-29.5	-47.5
	C	-39	-45.5	-39	-44.5	-26.5	-40	-28.5	-47
20°	C	-35.5	-42.5	-37	-44.5	-28.5	-42	-26.5	-44.5
45°	C	-31.5	-34	-33	-31.5	-23.5	-28.5	-26.5	-30.5
60°	C	-22	-20.5	-24	-20.5	-18	-18	-19.5	-19.5
20°-90°, wind = 1-2 knots, wave height = 1-2 ft									
20°	U	-43.5	-	-44	-46.5	-24.5	-43	-26	-
	D	-47.5	-	-43	-	-30	-45.5	-30.5	-
	C	-41	-46.5	-40.5	-46.5	-25.5	-43.5	-28.5	-
30°	U	-41.5	-48	-33.5	-46.5	-	-	-	-
	D	-45	-51.5	-40.5	-48.5	-27	-38	-30.5	-43
	C	-41.5	-48.5	-38	-47	-25.5	-37.5	-27.5	-40.5
45°	U	-35	-39	-33	-31.5	-	-28.5	-26.5	-34
	D	-37.5	-40.5	-32	-33.5	-23	-30.5	-29.5	-36.5
60°	U	-26.5	-25.5	-26.5	-23	-19.5	-21.5	-24	-22
	D	-26	-25	-23	-21	-22	-21	-25.5	-23
	C	-23	-20	-23	-19.5	-17	-17	-20.5	-22
70°	U	-9.5	-7.5	-12	-6.5	-7.5	-8.5	-13.5	-10.5
	D	-11.5	-7.5	-12	-6.5	-7.5	-8.5	-13.5	-10.5
73°	U	-7.5	-9	-4.5	-3.5	-	-	-	-
	D	-	-	-	-	-	-	-7.	-7.5
80°	U	-1.5	+3	+.5	+5	-	-	-	-
	D	-	-	-	-	+1	+3.5	-2.5	+1.5
90°	-	+5	+7.5	+7.5	+13	+2.5	+7.5	-.5	+1.5

December 9, 1964

θ	Wind	X_{VV}	X_{HH}	C_{VV}
3°-90°, wind = 12-15 knots, wave height = 6-10 ft				
3°	U	-37.5	-	-
	D	-39	-	-
5°	U	-34	-36.5	-38.5
	D	-35.5	-	-
10°	U	-31	-35.5	-33.5
	D	-32	-41.5	-34
30°	U	-23.5	-28.5	-23.5
	D	-23	-	-25
60°	U	-16.5	-12.5	-15.5
	D	-16	-12	-14.5
70°	U	-4.5	-	-2.5
	D	-4.5	-	-2.5
90°	-	+9.5	+12	+9.5

December 10, 1964

θ	Wind	X_{VV}	X_{HH}	C_{VV}
5°-90°, wind = 4 knots, wave height = 2-4 ft				
5°	U	-44.5	-	-
	D	-	-	-
10°	U	-44	-	-46
	D	-44	-	-47.5
30°	U	-37.5	-51.5	-37.5
	D	-38.5	-52.5	-40
60°	U	-21.5	-27.5	-22.5
	D	-24	-28.5	-22.5
90°	-	+15	+11.5	+7

July 21, 1965

θ	Wind	X_{VH}	X_{HV}	C_{VH}	C_{HV}	L_{VH}	L_{HV}	P_{VH}	P_{HV}
4°-60°, wind = 8-11 knots, wave height = 3-6 ft									
4°	U	-	-	-	-	NG	NG	-	-
	D	-52	-52	-57	-				
	C	-	-	-	-				
10°	U	-	-	-	-			-45	-51
	D	-47.5	-47	-50	-54.5			-	-
	C	-	-	-	-			-	-
20°	U	-42	-41.5	-44	-50.5			-44.5	-50
	D	-44	-44	-44	-49			-43.5	-
	C	-	-	-	-			-	-
25°	U	-	-	-	-			-43	-48
	D	-43.5	-44.5	-44	-50			-	-
	C	-	-	-	-			-	-
30°	U	-40.5	-39.5	-43.5	-48.5			-	-
	D	-	-	-	-			-40.5	-46.5
	C	-	-	-	-			-	-
45°	U	-39	-37	-38.5	-46.5			-	-
	D	-	-	-	-			-39	-45
	C	-	-	-	-			-	-
60°	U	-35.5	-31.5	-33.5	-39.5			-	-
	D	-	-	-	-			-34.5	-40
	C	-	-	-	-			-	-

July 29, 1965

θ	Wind	X_{VH}	X_{HV}	C_{VH}	C_{HV}
7-1/2°-60°, wind = 2-15 knots, wave height = 2-3 ft					
7-1/2°	C	-52.5	-	-	-
10°	C	-50.5	-	-	-57
15°	C	-50	-	-	-
20°	C	-48	-	-	-55.5
45°	C	-46.5	-	-	-52.5
60°	C	-42	-	-	-47.5
30°-60°, wind = 1-2 knots, wave height = 1-2 ft					
30°	U	-58.5	-	-	-59.5
	D	-	-	-	-
	C	-	-	-	-57.5
45°	U	-54	-	-	-55
	D	-55	-	-	-53.5
	C	-	-	-	-
60°	U	-44.5	-	-	-46
	D	-47.5	-	-	-46.5
	C	-	-	-	-