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TRANSPORTATION SYSTEMS CENTER/U. S. COAST GUARD L-BAND MARITIME SATELLITE TEST PROGRAM Test Summary: September – November 1974

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16. Abstract

Several L-band satellite communications tests with the NASA ATS-6 spacecraft and the U.S. Coast Guard Cutter SHERMAN are described. The tests included 1200 bit per second digital data, voice, simultaneous data and voice, ranging, multipath and antenna tracking. Preliminary results are discussed.

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PREFACE

The purpose of this program is to gather data relating to the design and the specification of future operational satellite systems which will serve the long range USCG mission requirements and objectives. Specifically, the experiment involves the evaluation of communications and ranging modems, omnidirectional and medium-gain antenna designs and the characterization of multipath fading in the L-band ship-satellite channel. The experiments involve the use of a laboratory multipath simulator to evaluate modem performance prior to field evaluation. The experiment will provide for the verification of this laboratory simulation of the multipath channel, so that future modem designs may be evaluated without field testing.

We wish to acknowledge the contribution of Mr. Howard Salwen of Proteon Associates, Inc., Waltham MA, who assisted in the detailed planning of the tests and in data reduction.

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LIST OF SYMBOLS

Adj	adjust
AGC	automatic gain control
ANBFM	adaptive narrowband frequency modulation
ANS	American National Standard
APPROX.	approximate
ATS-6	Application Technology Satellite-6 (NASA)
A-D	analog-to-digital
Auto	autotrack
b	bit
bps	bits per second
c	carrier power level (watts)
CW	continuous wave
C/M	carrier-to-multipath power ratio (dB)
C/No	carrier-to-noise power density ratio (dB-Hz)
dB	decibel
dBm	power relative to a milliwatt (expressed in dB)
d.c.	direct current
D	data
DAS	data acquisition system
DEC	Digital Equipment Corporation
DECPSK	differentially encoded coherent phase shift keyed
DEMOD	demodulator
el	elevation
EL	elevation
ft	feet
FFT	fast fourier transform
FM	frequency modulation
Hr	hour
Hz	hertz
i	an integer
ips	inches per second
IF	intermediate frequency
IRIG	Inter-Range Instrumentation Group
j	an integer; a frequency

k	an integer
kHz	kilohertz
kn	knots
L.F.	low frequency
L.O.	local oscillator
MARSAT	Maritime Satellite
MAX	maximum
MHz	megahertz
MODEM	modulator-demodulator
Min	minute
N	north; total sample number; narrowband
NASA	National Aeronautics & Space Administration
NB	narrowband
NBFM	narrowband frequency modulation
OMNI	omnidirectional
pdf	probability density function
PB	phonetically balanced
PN	pseudorandom noise
PRBS	pseudorandom binary sequence
RF	radio frequency
rms	root-mean-square
s	second
S	simultaneous
sec	second
SLA	slave
TEMP	temperature
TSC	Transportation Systems Center
USCG	United States Coast Guard
USCGC	United States Coast Guard Cutter
V	voice
W	west; wideband
WB	wideband
WHEC	Coast Guard High Endurance Cutter
XMIT	transmit
X'MTR	transmitter
Z	zulu time

ρ	correlation coefficient
θ	antenna boresight elevation angle
A_j	spectral amplitude
B_j	spectral amplitude
i_n	an integer
N_o	noise power density (watts/Hz)
P_e	error probability
p_j	power
x_i	sample
X_i	most significant 8 bits of i^{th} 16-bit word
Y_i	least significant 8 bits of i^{th} 16-bit word
z_{ni}	i^{th} sample of normalized amplitude
Z_{ni}	a variable
Δ_i	sample pointing error
$\hat{\Delta}$	mean of sample pointing error
σ_Δ	variance of sample pointing error
$\hat{X}$	mean value

1. SUMMARY

The first three series of maritime satellite communications tests, conducted during the months of September, October and November 1974, were successfully performed. An experimental communications system, designed, built and checked out at the Transportation Systems Center of the U.S. Department of Transportation, was installed aboard the 378 foot U.S. Coast Guard WHEC Cutter SHERMAN, in early September. Data were received from and transmitted to the ATS-6 satellite operating as a relay to and from the NASA Ground Station at Rosman, North Carolina. The SHERMAN proceeded across the North Atlantic to Lisbon, Portugal, and then returned, with data being taken at elevation angles from 35° to 2°. The tests performed included 1200-bit/second digital data, voice, voice and data simultaneously, ranging, multipath measurement, and antenna tracking using either monopulse autotrack or slave to a local inertial reference system. Data were successfully collected during approximately 95% of the available test time (see Table 1). Analysis of these data is presently in progress.

TABLE 1. MINUTES OF TEST DATA ACQUIRED AS OF 11-22-74

ACTIVITY	TOTAL SCHEDULED	SCHEDULED TO DATE	ACTUAL TO DATE
VOICE			
AUTOTRACK	1140	400	360 (4) (6)(8)
SLAVED θ	880	460	540 (4)
DATA			
AUTOTRACK	504	214	220 (1) (8)
SLAVED θ	1238	646	760 (1)(5)(8)
SLAVED $\theta/2$	550	280	180 (1) (5)
CIRCULAR *	690	360	270 (1) (9)
OMNI	190	100	80 (1)
REMOTE	90	40	20 (10)
VOICE/DATA			
SLAVED θ	660	320	300 (1)
RANGING			
SLAVED θ	530	240	205 (1) (2)
SLAVED $\theta/2$	300	150	105 (1) (2)
MULTIPATH			
CW (FORWARD)	7252	3210	3040 (ALL)
PN (RETURN)	500	200	170 (3)
DEMONSTRATIONS	600	0	0
ANTENNA	450	250	210 (1) (7)

(1) FAILURE OF DOWN-CONVERTER L.O. MULTIPLIER ON 9-19-74
(2) OPERATOR UNABLE TO TUNE UNIT ON ALLOTTED TIME
(3) FAILURE OF TRANSMITTER L.O. MULTIPLIER
(4) AUTOTRACK MISWIRING - TEST DONE SLAVED - - REPAIRED 8-15-74
(5) DPSK MODULATOR FAILURE AT ROSMAN
(6) AUTOTRACK ERRATIC - MULTIPATH AT 8.5^{o}; HIGH SEAS
(7) HIGH LEVEL CW NOT PROVIDED ON 1550.00 OR 1550.075 MHZ PER EMB FOR 11-22
(8) EXTRA TEST TIME USING TG-1 WAS TRANSMITTED, 11-16-74
(9) ROUGH SEAS PREVENTED CIRCULAR COURSE
(10) SYNTHESIZER L.F. PHASE JITTER CAUSED ERRATIC DEMOD. LOCK
(11) DECPSK DEMOD. INTERMITTANT TEMP PROBLEM

*AUTOTRACK, SLAVED, 2θ, θ, $\theta/2$, $\theta/4$, OMNI

2. L-BAND MARITIME TESTS

2.1 TEST SCENARIO

Table 2 shows the scenario for a typical test day. The various test activities are listed with their respective start and stop times given in hours and minutes from commencement of the test. The column labeled "Ship Heading" indicates whether the ship is to steer a fixed course perpendicular (⊥) to the line of sight to the satellite or follow a circular course (O) in order to view the satellite at all bearing angles. The column labeled "Antenna Mode" shows which antenna is to be used and how the medium gain antenna is to be pointed. The omni antenna is a low gain (~5 dB) hemispherical coverage antenna mounted on a fixed ground-plane ahead of the medium gain (~15 dB) antenna. The method of pointing the medium gain antenna is also indicated (SLA-Slave vs. Auto-autotrack). Note that in the slave mode the antenna boresight elevation angle is also indicated. In certain tests, the antenna boresight is intentionally offset from the satellite (e.g., 17.5° vs. 35°) in order to increase the amount of multipath power intercepted by the antenna. The column labeled "C/No" indicates the carrier-to-noise power density ratio at which the modem test is to be run. Modem C/No values are established at the 70 MHz IF input to the modem by adding a known amount of random noise to the signal. The indicated C/No values apply only to the communications and ranging modems and do not apply to the autotrack system. The remaining columns show the frequency tuning for the various modems and the CW multipath downconverter as well as for the return link signals. While the scenario shown for September 17th is generally a typical one, the test scenarios for individual test days differ in detail from day to day.

2.2 SYSTEM CHECKOUT

Dockside tests were performed via the satellite onboard the cutter SHERMAN at the U.S. Coast Guard Base in Boston Harbor on the 12th, 13th and 14th of September. A checkout cruise off the coast

TABLE 2. TEST SCENARIO FOR SEPTEMBER 11, 1974

DATE	TEST TYPE	APPROX. HOURS DATA	EL. ANGLE	LATITUDE	LONGITUDE	TEST CONDITIONS	
9/17	MODEM	4.0	35°	42°14.4'N	68°30'W	wind 15 kn	sea 1-2 ft
9/18	ANTENNA	0.5	35°	41°N	69°W	wind 8 kn	sea 1 ft
9/24	MODEM	3.5	35°	41°55'N	69°10'W	wind 17 kn	sea 5 ft
9/25	ANTENNA	0.5	35°	41°54'N	70°18'W	wind 8 kn	sea 1 ft
9/26	MODEM	3.8	35°	41°51'N	68°58'W	wind 6 kn	sea 2 ft
9/30	MODEM	3.8	35°	IN PORT	IN PORT	IN PORT	
10/23	ANTENNA	0.5	8.5°	40°04'N	26°46'W	wind 5 kn	sea 1 ft
10/24	MODEM	4.25	8.5°	42°10'N	27°20'W	wind 6 kn	sea 2 ft
10/25	MODEM	3.8	8.5°	42°25'N	27°20'W	wind 10 kn	sea 2 ft
10/28	MODEM	4.0	8.5°	42°06'W	27°19'W	wind 18 kn	sea 3 ft
10/29	ANTENNA	0.5	4.0°	42°06'W	21°18'W	wind 12 kn	sea 3 ft
10/30	MODEM	4.0	4.0°	42°07'W	21°21'W	wind 12 kn	sea 2 ft
10/31	ANTENNA	0.5	2.0°	42°02'W	18°25'W	wind 5 kn	sea 3 ft
11/12	ANTENNA	2.0	8.5°	39°40'N	26°40'W	wind 5 kn	sea 2 ft
11/13	MODEM	4.0	8.5°	41°53'N	26°54'W	wind 23 kn	sea 10 ft
11/14		4.75	8.5°	41°56'N	27°05'W	wind 55 kn	sea 25 ft
11/15		3.0	8.5°	41°49'N	27°07'W	wind 38 kn	sea 12 ft
11/16		3.0	11°	42°N	27°W	wind 10 kn	sea 5 ft
11/18		4.2	14.7°	41°55'N	35°56'W	wind 8 kn	sea 4 ft
11/19		4.0	17°	42°02'N	39°02'W	wind 25 kn	sea 4 ft
11/20		5.0	17°	41°54'N	38°57'W	wind 30 kn	sea 11 ft
11/21		4.0	17°	41°50'N	38°59'W	wind 12 kn	sea 5 ft
11/22	ANTENNA	1.0	22°	42°18'N	45°39'W	wind 27 kn	sea 8 ft
11/23	ANTENNA	0.5	28°	42°38'N	55°05'W	wind 30 kn	sea 7 ft

of Massachusetts was performed, with data taken on September 17 and 18. These tests verified correct operation of all components of the experimental equipment, except for antenna autotrack. Correct autotrack operation was not achieved until October 15.

2.3 DATA ACQUISITION

A list of tests performed to date is included in Table 3. The following is a brief summary of each test:

a) MODEM TEST - 9/17 Satellite elevation angle: 35° - The test was performed successfully in the slaved antenna mode. The autotrack mode was not functioning. All modems operated properly.

b) ANTENNA TEST - 9/18 Satellite Elevation angle: 35° - CW multipath and antenna parameters were recorded.

c) MODEM TEST - 9/24 Satellite elevation angle: 35° - A modem test was performed recording data, voice, and ranging signals. There was a limited amount of ranging. Wideband multipath was transmitted.

d) ANTENNA TEST - 9/25 Satellite elevation angle 35° - CW multipath and antenna parameters were recorded.

e) MODEM TEST - 9/26 Satellite elevation angle 35° - This voice and data test was successfully performed. Voice was recorded from 40-48 dB-Hz. Data were collected at 42 dB-Hz. Wideband multipath was transmitted.

f) MODEM TEST - 9/30 Satellite elevation angle: 35° - The modem test was successfully performed with voice, data, and ranging signals recorded. Wideband multipath was transmitted.

TABLE 3. TESTS PERFORMED

SATELLITE ELEVATION ANGLE: 35°

Start 1010z - 1410z

	From		To		SHIP HEADING	ANTENNA MODE	C/N_o(dB-Hz)	CHANNEL A	CHANNEL B		CHANNEL C	CHANNEL D	MULTIPATH	ADMINISTRATIVE VOICE
	Hr.	Min.	Hr.	Min.				HYBRID #1	HYBRID #2	RANGING	DCPSK/NBFM	CW	X'MIT PN	
Record Sea State														
Adj. C/N_o, Carrier Lock Up	0	00	0	05	⊥	SLA 35°	44	1550. 675V	1500. 600V		1500. 250V	1500. 075		1650. 977
Voice Test	0	05	0	25	⊥	SLA 35°	44	675V	600V		250V	075		977
Change RF Patch, Adj. C/N_o,	0	25	0	28	⊥	SLA 35°	40	675D	675D		675D	075		977
Data Test	0	28	0	36	⊥	SLA 35°	40	675D	675D		675D	075		977
Change C/N_o	0	36			⊥	SLA 35°	38	675D	675D		675D	075		977
Data Test	0	36	0	45	⊥	SLA 35°	38	675D	675D		675D	075		977
Change RF Patch, Adj. C/N_o, Retune CW	0	45	0	48	⊥	SLA 35°	40			1500. 600N		000		977
Ranging Test (NB)	0	48	0	56	⊥	SLA 35°	40			600N		000		977
Ranging Test (WB)	0	56	1	05	⊥	SLA 35°	40			600W		000		977
Change RF Patch, Adj. C/N_o, Retune CW	1	05	1	08	⊥	SLA 35°	43	250S	600S		675D	075		977
Simultaneous Voice & Data Test	1	08	1	25	⊥	SLA 35°	43	250S	600S		675D	075		977
Change RF Patch, Ant. el., Course, and C/N_o	1	25	1	27	⊥	SLA 35°	MAX	675D	675D		675D	075		
Data Test	1	22	1	37	0	SLA 35°	MAX	675D	675D		675D			
Change Ant. Mode	1	37	1	39		OMNI	MAX	675D	675D		675D			
Data Test	1	39	1	49	0	OMNI	MAX	675D	675D		675D			
Change Ant. Mode	1	49	1	51		AUTO	MAX	675D	675D		675D			
Data Test	1	51	2	01	0	AUTO	MAX	675D	675D		675D			
Change Ant. Mode, Turn on X'MTR	2	01	2	03		SLA	MAX	675D	675D		675D			
Data Test	2	03	2	13	0	SLA	MAX	675D	675D		675D		1050. 000	
XMIT PN	2	03	2	13	0	SLA 17.5								
Change C/N_o, Ant. Mode and Turn Off X'MTR	2	13	2	17	⊥	SLA 17.5	42	675D	675D		675D		1650. 000	
Data Test	2	17	2	35	⊥	SLA 17.5	42		675D		675D			
Antenna Tests	2	35	4	00	⊥	SLA								

g) ANTENNA TEST- 10/23 Satellite elevation angle: 35° - The receiver was locked onto the 1550.075 MHz signal. The received signal strength was -120 dBm and there were 3 to 4 dB signal fades. A digital tape was made recording antenna parameters and CW multipath data. The antenna was not able to autotrack when the antenna to satellite path passed through the superstructure of the ship. Carrier lock was lost, however, only when the antenna to satellite path had almost completely passed through the superstructure of the ship.

h) MODEM TEST - 10/24 Satellite elevation angle: 8.5° - On October 24 the first modem test was performed. It was noted that at approximately 13 hr 17 min into the experiment, the satellite signals went off. They were on again shortly. All the signals were received and all the modems were operating correctly. No problems were encountered. The received signal strength was approximately -110 dBm.

i) MODEM TEST - 10/25 Satellite elevation angle: 8.5° - The test started on time and the average received signal strength was -112 dBm with 3 or 4 dB fades. The signal strength was as high as -108 dBm at times. While the digital data were being recorded, it was noted that the 1200 b/sec modem data errors frequently came in bursts. This was another very successful test, as all signals were received and all equipment functioned properly.

j) MODEM TEST - 10/28 Satellite elevation angle: 8.5° - The CW carrier was received at -110 dBm to -114 dBm. Using the omni antenna during the first 10 minutes of the test, and receiver was constantly in and out of lock. During the autotrack portion of the test requiring the ship to take a circular track, the antenna to satellite path passed through the ship's superstructure without the autotrack receivers totally losing the signal. The received signal faded 20 dB momentarily and lock was lost for a second or two, but the beacon was reacquired and the autotrack mode continued to work well. CW multipath data were recorded all the time. This test was successful and all equipment worked well. It should perhaps be pointed out that during this test the satellite elevation angle was only 8.5°. Operation at low elevation angles places the antenna to satellite path on the skirt of the omni antenna pattern where the gain is changing rapidly. We have yet to examine the digital tapes to determine the amount of roll experienced in order to estimate the gain and gain variations occurring at the times of receiver drop-out.

k) ANTENNA TEST - 10/29 Satellite elevation angle: 4.0° - This test again required the ship to take a circular track for part of the test as was true for all the antenna tests. The average received signal strength (1550.000 MHz) was -109 dBm with a signal strength sometimes as high as -106 dBm. Fades of 10 dB were noted. Much fading (including some very deep fades) was noted on the CW downconverter. During the circular track the antenna autotracked well until the path between the antenna and satellite passed through the superstructure of the ship. At this time, the signal was lost and the antenna was unable to automatically reacquire. The antenna operated properly in the slave mode.

l) MODEM TEST - 10/30 Satellite elevation angle: 4.0° - No signals appeared until 9:23:53 Z when all the signals with modulation appeared at once. Much multipath was observed. The received signal strength was -112 dBm with 15 dB fades observed. Once again in the autotrack mode, when the antenna to satellite path went through the ship, the receiver lost lock and could not reacquire as the antenna went into X- and Y-axis limits, because the elevation angle was so low. The slave mode worked fine. The omni antenna received the signals at -122 dBm, but fades constantly drove the receiver out of lock. This test was very successful, and all equipment functioned as expected.

m) ANTENNA TEST - 10/31 Satellite elevation angle: 2.0° - The signal was received at -108 dBm, but there were 10 and 20 dB fades most of the time with 40 dB fades periodically. The slave mode operated flawlessly. Due to the very low elevation angle and the deep signal fades, autotracking was difficult. The CW multipath equipment recorded very deep fading, but at a slower rate than had been observed on the previous day. All equipment performed well, and the test was successful.

n) ANTENNA TEST - 11/12 Satellite elevation angle: 8.5° - This day was scheduled as an antenna test. At this ship location, reception was very poor. The maximum received signal level was -120 dBm, or about 10 dB below the expected level. This was attributed to the ship's location being on the edge of the satellite beam pattern.

o) MODEM TEST - 11/13 Satellite elevation angle: 8.5° - This was the first of several heavy weather days, with 25-30 knot winds and 10-foot seas. On this test we noted that on the simultaneous voice and data transmissions the carrier at 1550.250 MHz was approximately 2 dB stronger than that at 1550.600 MHz and 1550.675 MHz. This was observed on all subsequent simultaneous voice and data tests.

p) MODEM TEST - 11/14 Satellite elevation angle: 8.5° - This day provided the heaviest weather yet experienced. Wind velocity was 45-55 knots with 25-foot seas. All data were recorded in a normal manner. No problems were encountered, but a large amount of multipath was evident, with fades greater than 10 dB.

q) MODEM TEST - 11/15 Satellite elevation angle: 8.5° - When data recording commenced on this day, we immediately observed that the carrier was unmodulated. No modulation was observed for the first hour of the test. After approximately one hour, modulation appeared, and the remainder of the test was without incident. The problem was caused by a faulty modulator at Rosman.

r) MODEM TEST - 11/16 Satellite elevation angle: 11° - This was an extra day, not originally included in the schedule. All data were recorded normally, except that the digital (1200 bps) data modulation used a 63-bit PN sequence, instead of the normal 2047-bit sequence.

s) MODEM TEST - 11/18 Satellite elevation angle: 14.7° -
MODEM TEST - 11/19 Satellite elevation angle: 17° - All operations were normal for both days. No significant discrepancies or operational problems were noted.

t) MODEM TEST - 11/20 Satellite elevation angle: 17° - This test started 10 minutes earlier than planned for. Otherwide, all data were recorded without problems.

u) MODEM TEST - 11/21 Satellite elevation angle: 17° - All operations were normal this day. No significant discrepancies or operational problems were noted.

v) ANTENNA TEST - 11/22 Satellite elevation angle: 22° - This day was scheduled as an antenna test. For this test, we were scheduled to have an unmodulated carrier at 1550.000 MHz. However, no such signal appeared, so that although some data were taken, their value is nil.

w) ANTENNA TEST - 11/23 Satellite elevation angle: 28° - Approximately one-half hour of antenna data were recorded on this day. The test was then terminated due to rough seas.

2.4 EQUIPMENT PROBLEMS

On September 19, a failure in the receiver occurred. This failure was located in the antenna pedestal and found to be the L-band downconverter. Because of this failure, no data were recorded this day or the next. After returning to port, a new downconverter was installed which rectified this problem. Before the first scheduled MARSAT tests on the 23rd of October, while the ship was at sea, a failure was discovered in the upconverter in the antenna. This item was irreparable at sea. Thus no signals were transmitted from the ship from October 23 to October 31. A new upconverter was installed the week of November 3. It was also noted that the ship's air search radar interfered with the digital tape recorder, indicating that future investigations should be made to determine the extent of interference and its effects on operations. Thus the air search radar was turned off during all the tests.

Throughout the September campaign, it was impossible to achieve correct antenna autotrack operation. This problem was finally traced to an error in the contractor's wire list. The problem was corrected on October 15, and the antenna autotracked successfully throughout the October and November campaigns. Other significant failures included a frequency synthesizer used to tune one of the digital data modems, the failure of two A-D converters in the CW multipath downconverter, and an erratic problem in the Data Acquisition System. The DAS problem appears to have been caused by a memory and alignment problem in the digital tape recorder. The system is now operating properly.

3. ANALYSIS OF DATA

3.1 MULTIPATH

3.1.1 PN Multipath Probing

A total of 200 minutes of PN return link probing was scheduled, of which 40 minutes were lost due to the failure of the L.O. Multiplier in the transmitter upconverted. Preliminary analysis of the wideband multipath prober data indicated that even under the worst-case test conditions of 8.5 degree elevation and 20-foot seas, the multipath spread observed did not exceed 100 nanoseconds. Thus, the collected CW multipath data should provide valid channel models for all maritime-satellite signalling formats with bandwidths less than roughly 1 MHz.

3.1.2 CW Multipath Probing

Analysis of the CW multipath data has been held up due to a delay in completing the software necessary for analysis on the DEC PDP-10 computer here at TSC. Most of the delay has been attributable to somewhat faulty data which have impeded tape stripping and the setting up of disc files. The faulty data are not irretrievable but require, software expansion. Details of the CW multipath data reduction procedure are given in Appendix A.

3.2 ANTENNAS

3.2.1 Medium Gain Antenna

The TSC/USCG Maritime Satellite Test Terminal installed on the SHERMAN is equipped with a medium gain (15 dB nominal) antenna capable of being pointed at the satellite by means of an autotrack system or by slaving it to the ship's gyrocompass system. Antenna pointing is monitored through the use of a digital data acquisition system. This system converts and multiplexes onto digital tape the ship's gyrocompass signals (heading, roll and pitch) along with the antenna parameters (desired azimuth, desired elevation, X-axis position and Y-axis position) for later analysis of antenna pointing error. Additionally, the output from the CW multipath demodulator, tracking receiver AGC and lock indication, servo and autotrack error voltages and a time code are also recorded. A limited number of data segments have been examined via a Quick-Look program. The Quick-Look output indicates that, for the most part, the data appear reasonably well behaved with occasional errors occurring both in data and in the time code. The time code errors have caused a considerable delay in completing the software packages required for data analysis. Additionally, data errors occur sufficiently often as to require a screening of the data prior to the generation of disc files for subsequent analysis. Work is nearly complete on the data screening taks. A description of the antenna data reduction error is given in Appendix B.

3.2.2 Omnidirectional Antenna

A limited amount of modem data have been gathered using the omni antenna. Analysis of these 'omni' data has not yet begun.

3.3 MODEMS

3.3.1 Communications Modems

Three communications modems were used in the fall test series. Two of the modems were hybrid voice/data modems capable of operating in a voice-only, data-only or simultaneous voice-plus-data mode. Each of the hybrid modems employed differentially encoded coherent phase shift keying (DECPSK) for data transmission. One of the hybrid modems employed narrow-band FM for voice transmission, while the other used pulse duration modulation. Both modems employed quadrature modulation to provide simultaneous voice-plus-data capability. A third communications modem provided voice-only or data-only modes of operation. This modem employed narrow band FM for voice transmission and differentially encoded phase shift keying for data transmission. Primary analysis of the communications modem data will be carried out on the demodulated voice and data signals which have been recorded on an IRIG intermediate band analog instrumentation recorder. Signals related to the carrier-to-noise power density ratios, (C/No), were also recorded. Preliminary modem evaluation was made in real time through the measurement of average bit error rates by means of a commercial data analyzer. Analysis of the tape recorded modem data will not begin until approximately April 1.

Preliminary real-time analysis of the hybrid modem data is complete and the results are presented in Section 3.3.3. Details of the laboratory reduction of the 1,200 b/sec modem data are given in Appendix C. Analysis of the voice data will be done in conjunction with aeronautical voice test data at CBS Laboratories, Stamford, Connecticut. Analog voice modem signals are recorded on direct record channels of the same instrumentation recorder used to record the 1,200 b/sec modem data. The one-inch analog tapes will be played back at TSC where the voice data will be dubbed onto standard one-quarter inch audio tapes. The one-quarter inch tapes will be sent to CBS Laboratories where they will be scored via listening panels. Appendix C contains a brief description of the procedure used by CBS Laboratories.

3.3.2 Ranging Modem

A TSC designed ranging modem was used during the fall test series. This modem is capable of either narrow band (40 kHz) or wideband (312 kHz) operation. Carrier-to-noise power density ratios were varied (as in the case of the communications modems) by adding noise to the received signal. The resulting range readouts were recorded in digital form for future processing. Since an absolute time reference was not available, the collected range data will be used to determine error variences as a function of noise and multipath conditions. Processing of range data is awaiting the completion of the digital circuitry necessary to read the tapes. Data analysis should begin on or about April 1.

3.3.3 Experimental Results of Modem Tests

Figures 1 and 2 show the results of the data modem tests conducted at elevation angles of 8.5 degrees and 11 degrees with each of the hybrid modems operating in the "data only" mode at 1200 b/sec. The data plotted in Figures 1 and 2 were taken during the month of October under relatively calm sea conditions. Figure 1 shows the bit error rate performance of one of the hybrid modems, while Figure 2 shows similar data for the other hybrid modem. The solid curves in the figures show the theoretical error rate for a DECPSK modem and laboratory simulator data for the same two modems. These latter data are plotted for three signal-to-multipath values, C/M = 5 dB, 8 dB, and 11 dB and for a Doppler spread of 10 Hz considered appropriate to this maritime-satellite link. Note that most of the data falls between the theoretical curve and the 11 dB signal-to-multipath curve. Figures 3, 4, 5 and 6 show the results of tests conducted at satellite elevation angles from 8.5 degrees to 17 degrees using the same hybrid modems in the "data only" mode at 1,200 b/sec. Figures 3, 4, 5 and 6 show the results of data modem tests conducted at elevation angles to the satellite of 8.5 degrees to 17 degrees with the same two hybrid modems operating in the "data only" mode.

Figure 3 shows the bit error rate performance of one of the hybrid modems with ship located so that elevation to the satellite 8.5 degrees. Figure 4 shows similar data for the other hybrid. The solid curves in the figures were obtained from laboratory simulator derived data for the same two modems. These latter data are plotted for three signal-to-multipath values, C/M = 5 dB, 8 dB and 11 dB and four Doppler spreads 10 Hz, 100 Hz, 1000 Hz and 2000 Hz. Note, however, that the Doppler spread experienced on the maritime-satellite links is almost always on the order of 10 Hz or 20 Hz maximum.

Examination of Figure 3 shows that worst performance occurred on November 14 when 20-foot seas were encountered. These were the highest observed during the November test campaign. Specifically, the signal to multipath ratio appears to be on the order of 3 dB.

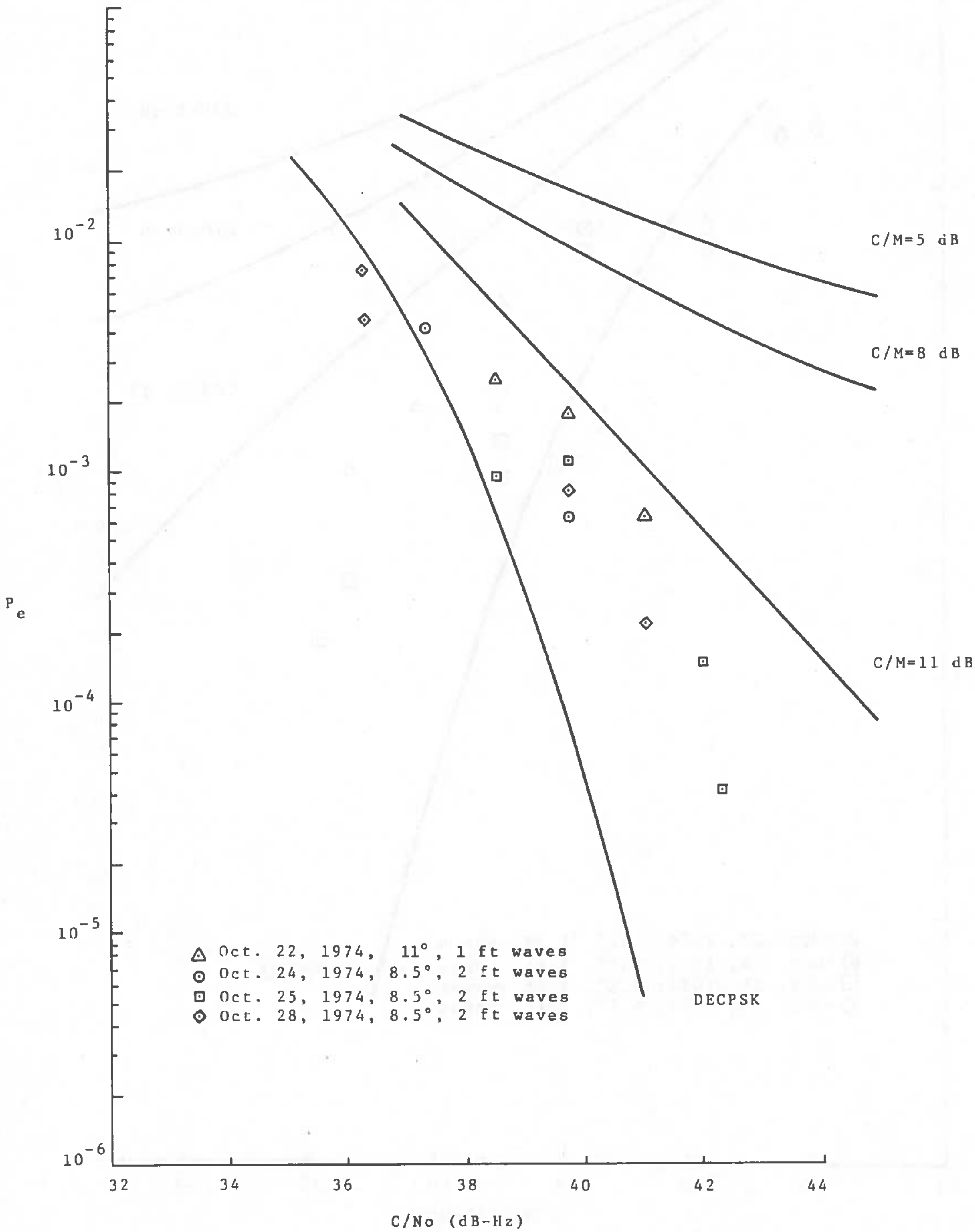

Figure 1. Error Performance of Hybrid I Modem at 8.5 and 11 Degrees Elevation Angle, 1200 b/sec Data Only

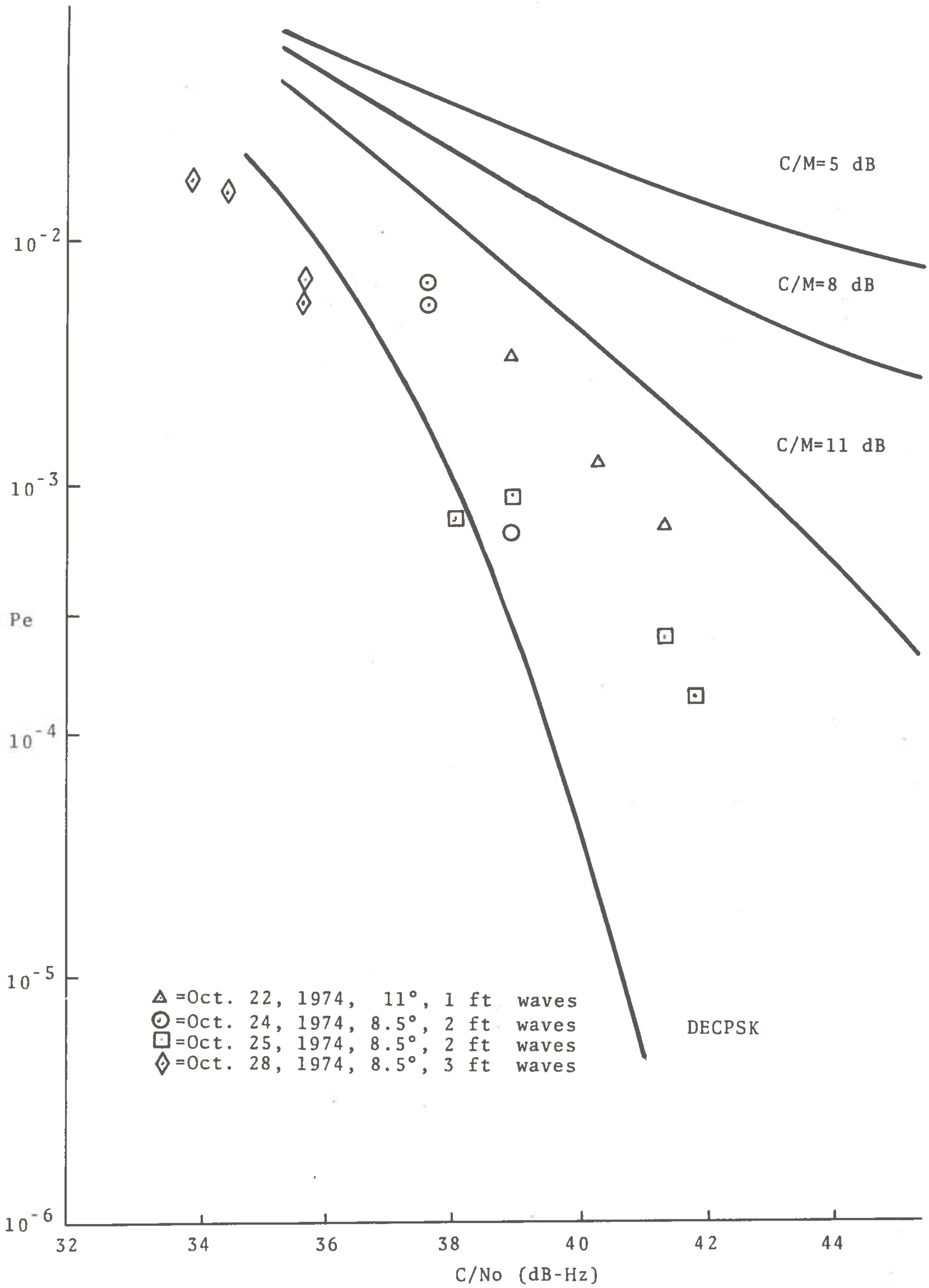

Figure 2. Error Performance of Hybrid II Modem at 8.5 and 11 Degrees Elevation Angle, 1200 b/sec Data Only

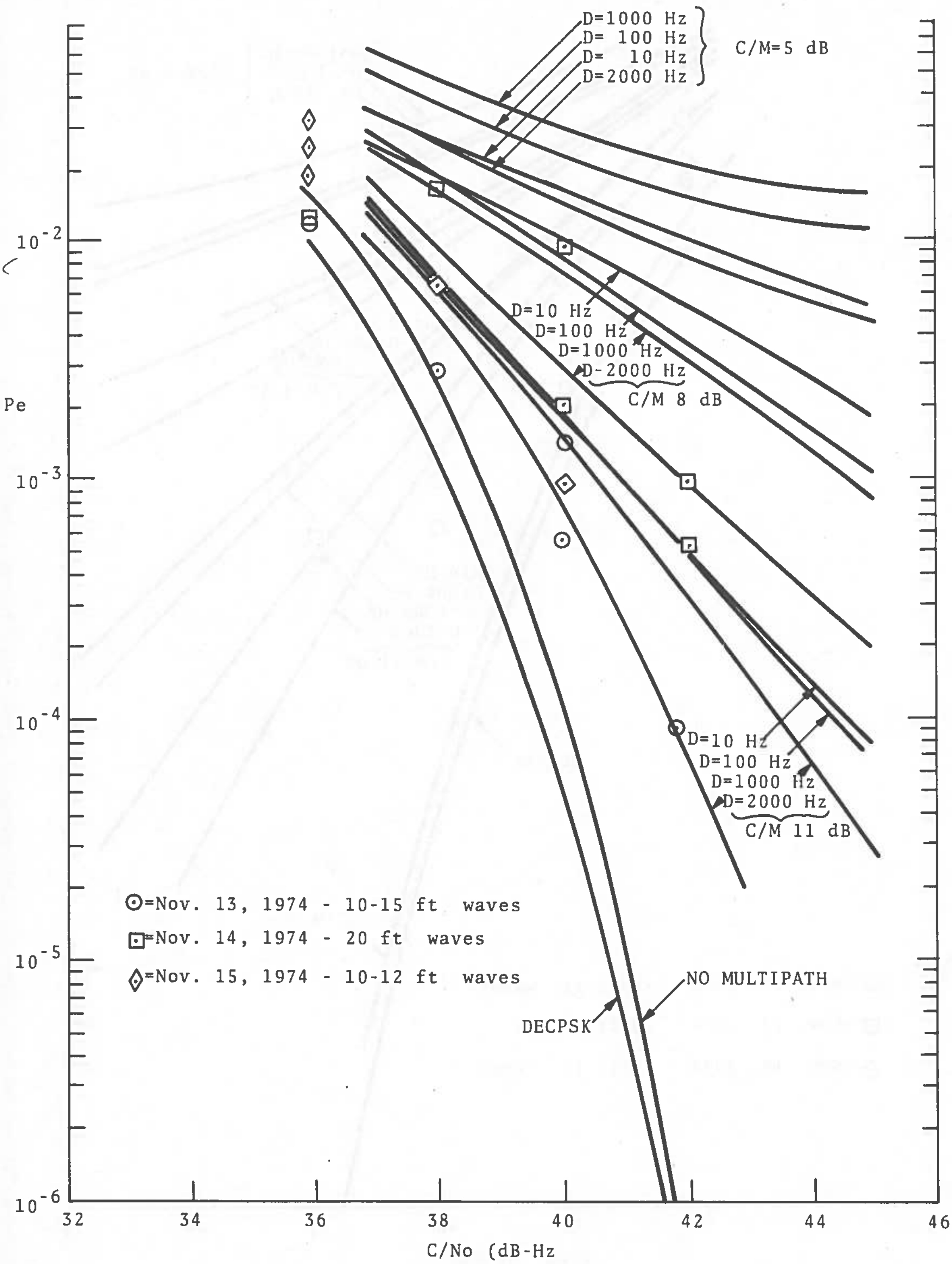

Figure 3. Error Performance of Hybrid I Modem at 8.5 Degrees Elevation Angle, 1200 b/sec Data Only

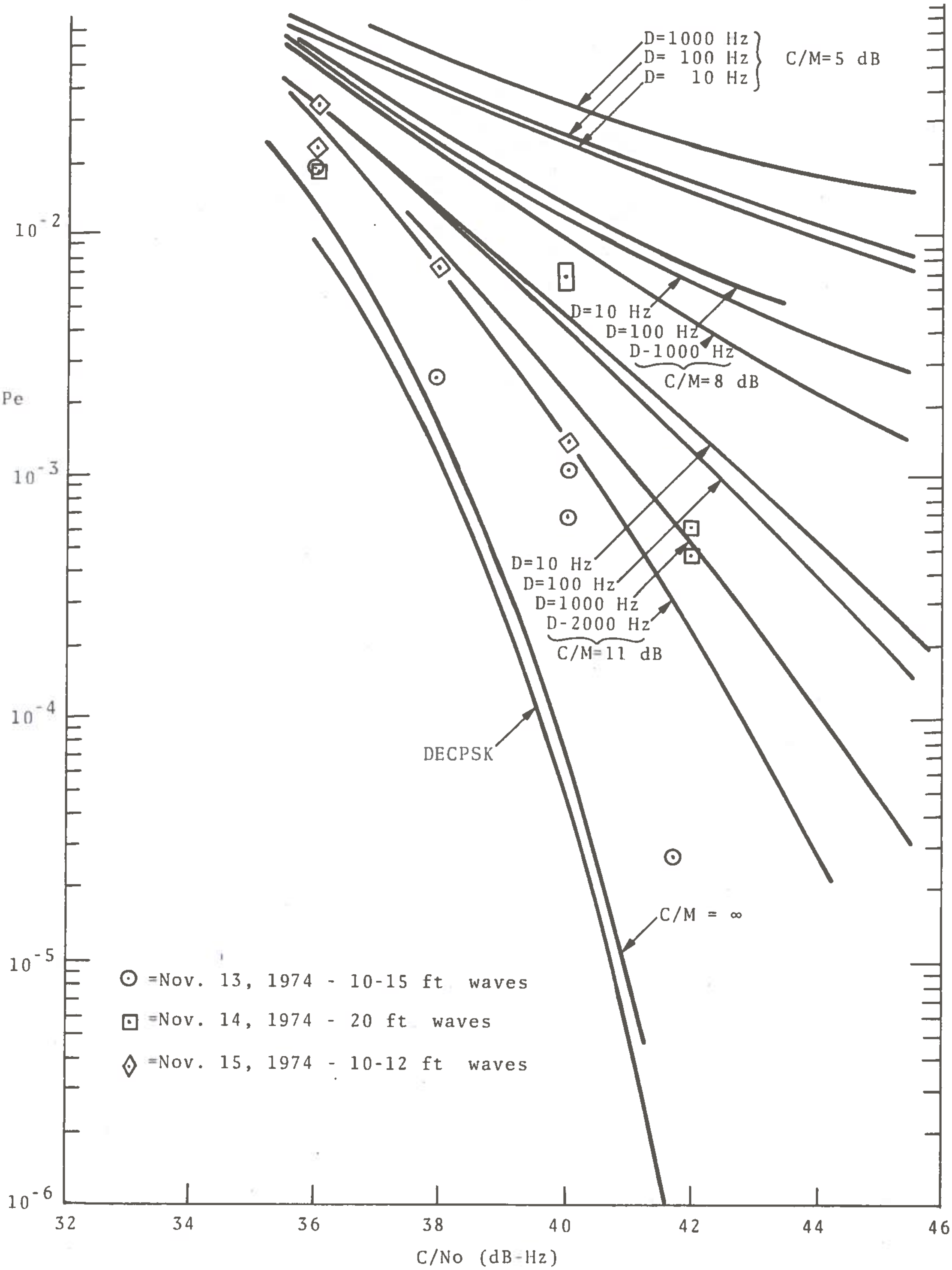

Figure 4. Error Performance of Hybrid II Modem at 8.5 Degrees Elevation Angle, 1200 b/sec Data Only

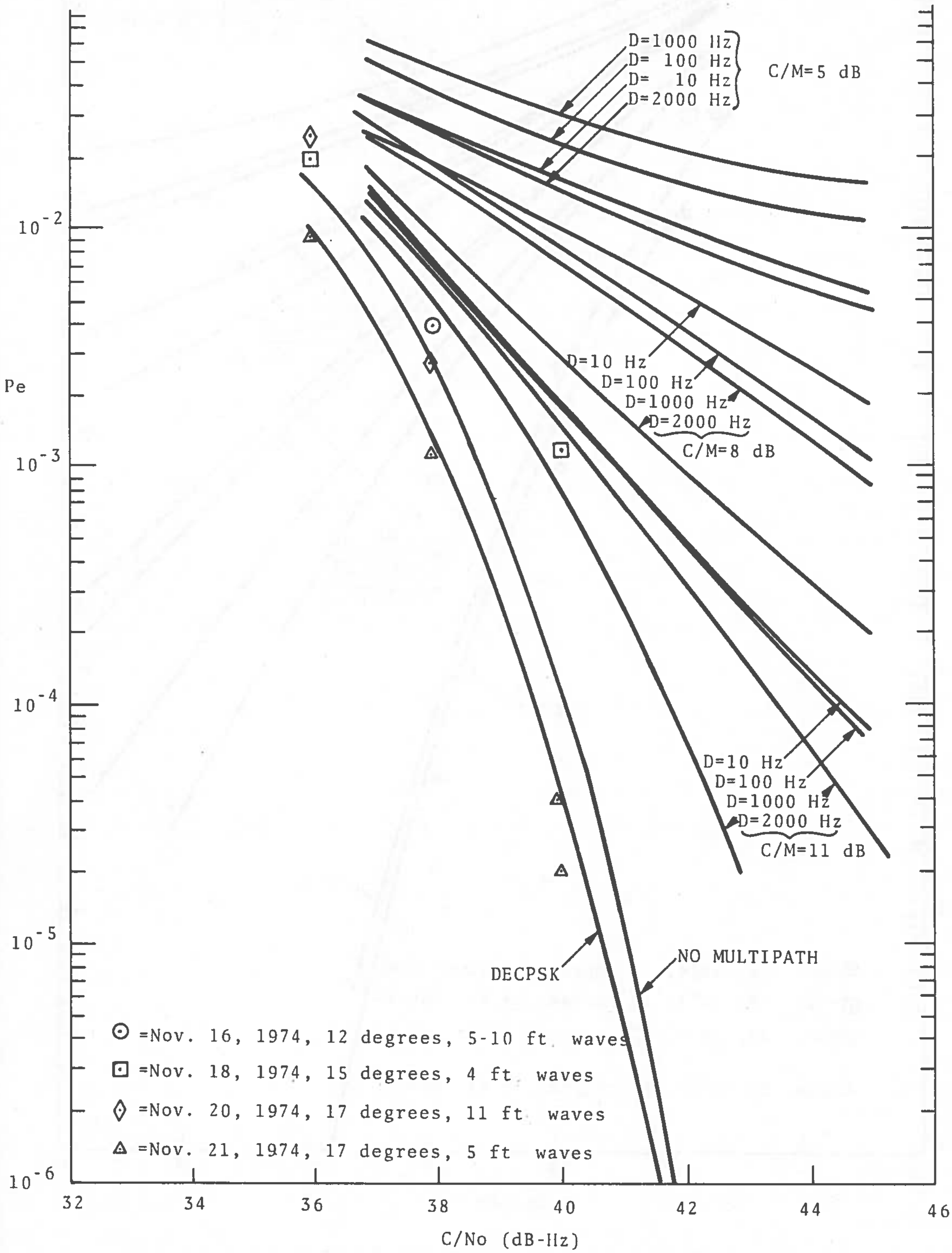

Figure 5. Error Performance of Hybrid I Modem at 12, 15 and 17 Degrees Elevation Angle, 1200 b/sec Data Only

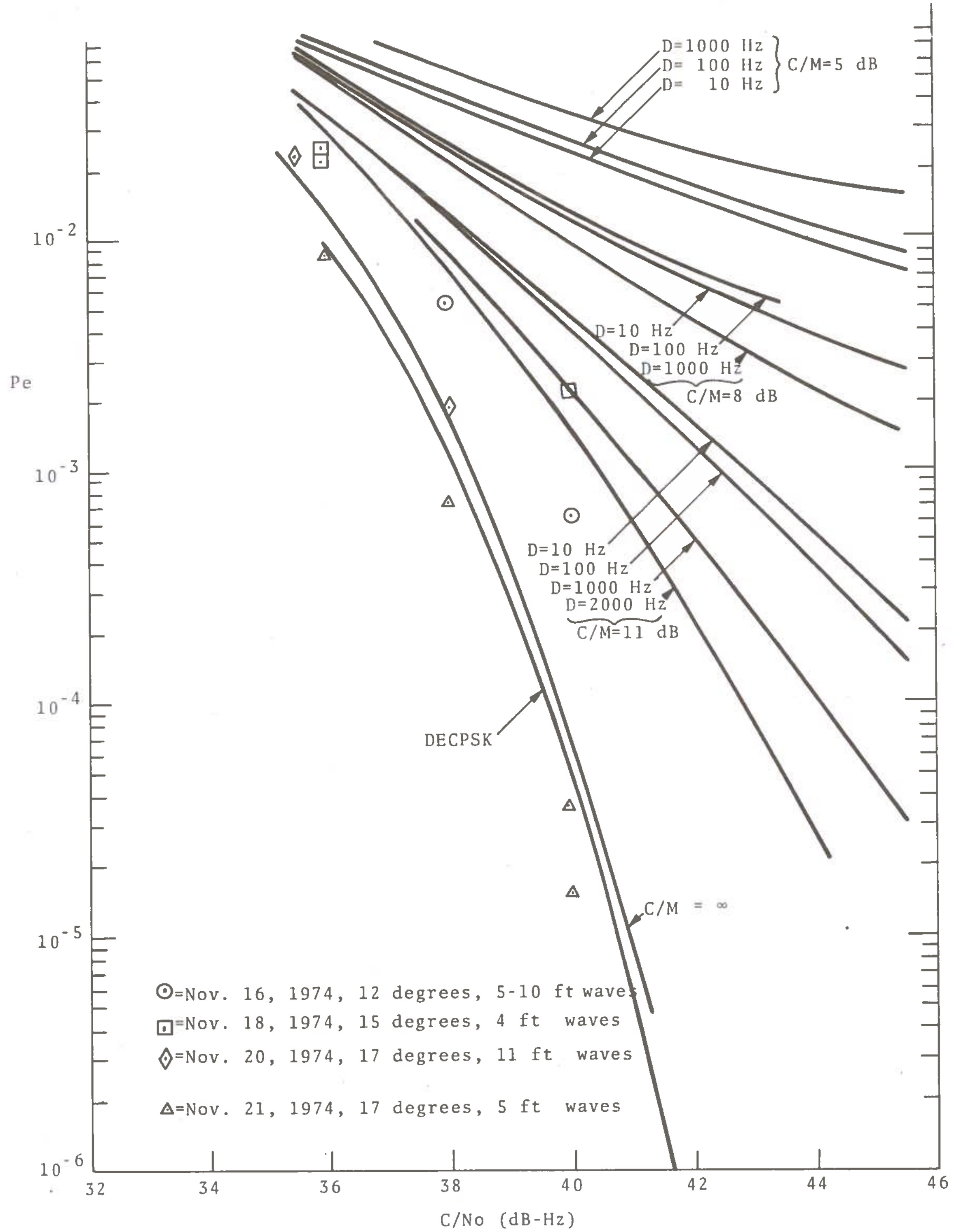

Figure 6. Error Performance of Hybrid II Modem at 12, 15 and 17 Degrees Elevation Angle, 1200 b/sec Data Only

Corresponding results were obtained with Hybrid II at the same time, as shown in Figure 4. Note also that during other parts of the Noverber 14 data run the signal-to-multipath ratio appears to be on the order of 11 dB.

The antenna beamwidth is roughly 35 degrees between half-power points. When the satellite is at 8.5 degrees elevation, the multipath specular reflection point is at -8.5 degrees. Thus the multipath is at the half-power point of the antenna in this configuration. In the face of 20-foot seas, this simple geometric interpretation is not valid. On the other hand, Figures 3 and 4 show that with somewhat calmer seas, such as on November 13, the performance achieved by the system in this geometric configuration is substantially improved. In particular, both modems are providing near optimum performance, with apparent signal-to-multipath ratios well in excess of 11 dB. Since the antenna is providing only 3 dB of multipath attenuation, the multipath power is therefore more than 8 dB below the direct path power in this case.

Figure 5 and 6 show the performances achieved at higher elevation angles. Performance improves steadily for both modems as elevation angle is increased and sea-state is reduced. Near optimum performance is achieved at 17 degrees elevation and with 5-foot seas.

It should be pointed out that the data presented in these figures are preliminary in nature. Tests conducted at C/N_0 values of 40 dB-Hz and less were ten minutes in duration, while the 42 dB-Hz data runs were scheduled to last for approximately two hours. Data shown in Figures 1-6 are generally based upon relatively short data segments.

4. CONCLUSIONS

While the results obtained to date are preliminary, the tests appear to be progressing well and generally as expected. Operation of the medium gain antenna has been satisfactory in both the Slave and the Autotrack modes. Antenna blockage by the ship's superstructure does not appear to effect adversely autotrack operation to the extent that might have been originally anticipated. Modem operation, as monitored in real-time through the use of a commercial data error analyzer under actual test conditions, appears consistant with error performance obtained in the laboratory using a multipath channel simulator. Loss of data due to equipment failures has been minimal. While errors in the antenna position data recorded by the digital tape recorder caused a significant delay in software development, little essential data were lost due to the fact that much of the data are sampled at a relatively high rate. Real-time observation of the effect of multipath scattering showed very little multipath at the higher elevation angles (say 17° and above) with multipath becoming significant at elevation angles of 8.5° and below.

Comprehensive data reduction (as opposed to quick-look data screening) is about to begin. The software packages necessary to analyze antenna pointing error have been written. An analysis of the anticipated variance of the medium gain antenna pointing in the Autotrack mode has been carried out for the antenna's Y-axis. This will permit a limited comparison of the antenna's measured operation against a predicted value. A calculation of the variance of the X-axis was not attempted due to the non-linearity introduced by the secant correction amplifier in that axis. The laboratory setup needed to reduce the 1,200 b/sec modem data is now complete, as is the equipment required to dub the voice intelligibility tapes. The software required to process the CW multipath is scheduled for completion by the end of March, with the hardware needed for the processing of the ranging data due to be completed by the end of April.

In summary, the USCG portion of the ATS-6 Experiment is progressing well. All equipment installed on the USCGC GALLATIN is operating properly. Preliminary indications of data quality are generally good, and the major task of detailed data reduction and analysis is about to commence.

APPENDIX A
CW MULTIPATH DATA REDUCTION AND ANALYSIS

Data reduction of the digital CW multipath recordings consists of three operations. The first task accomplishes data normalization, the second task provides amplitude fading statistics, and the third task provides averaged spectral characteristics. The data normalization operation eliminates the effect of satellite power transmission changes, satellite frequency drift, CW downconverter d.c. drift and gain variations.

The recorded data are normalized in blocks. The block length is denoted by markers in the Elevation Command recorded on the tape. Specifically, the beginning and end of a block interval will be marked by negative Elevation Commands. All CW multipath data between negative Elevation commands are normalized as follows: the recorded CW multipath data consist of 16-bit words. Each 16-bit word consists of two 8-bit bytes. Let the most significant 8 bit of the i^{th} 16-bit word be defined to be X_i. Let the least significant 8 bits by Y_i. For each block of data, the following is compared.

$$\overline{X} = (1/N) \sum X_i$$

$$\overline{Y} = (1/N) \sum X_i$$

$$\overline{X^2} = (1/N) \sum (X_i - \overline{X}_i)^2$$

$$\overline{Y^2} = (1/N) \sum (Y_i - \overline{Y}_i)^2$$

These average values are used to normalize the data, thus creating a new file of normalized data for the block. In particular, each normalized data point is defined by

$$X_{ni} = \frac{X_i - \overline{X}}{\left(\overline{X^2} + \overline{Y^2}\right)^{1/2}}$$

and

$$Y_{ni} = (Y_i - \overline{Y}) \cdot \left[\frac{\overline{X^2}}{\overline{Y^2}\,(\overline{X^2} + \overline{Y^2})}\right]^{1/2}$$

Furthermore, the new file is truncated so that the total number of data point-pairs saved is a integer multiple of 512. That is,

$$i_n = 0,1,2,3 \ldots (512k-1)$$

Next, the amplitude statistics of the CW multipath data are determined for each block. The amplitude data to be processed are derived from the normalized data file for each block by forming

$$Z_{ni} = \left[X_{ni}^2 + Y_{ni}^2\right]^{1/2}$$

The output is a plot of the histogram of the vairable Z_{ni}. Additionally, the 10-percentile, 50-percentile and 90-percentile values of the amplitude are computed.

The final operation derives the spectral characteristics of the data in each block. Spectral data are derived by means of an FFT operation. The operation proceeds as follows: the first 512 data point-pairs ($X_{no} \ldots X_{n511}$ and $Y_{no} \ldots Y_{n511}$) are weighted by a raised-cosine (Hanning) weighting function. For example

$$X_{nwi} = \frac{X_{ni}}{2}\left[1 - \cos\left(\frac{2\pi i}{512}\right)\right]$$

The weighted point-pairs constitute the input to the FFT program. The output of the program will be 512 complex spectral amplitude point-pairs. Let each of these be denoted as $A_j + B_j$. The power at each frequency, j, will be found, i.e.

$$P_j = A_j^2 + B_j^2$$

The 512 power measures for each 512 point-pair interval are accumulated so that the average spectral characteristics for the entire block can be found. In particular, the average power at frequency, j, is

$$\overline{P}_j = \left(\frac{1}{k}\right) \sum_{\ell=1}^{k} P_{\ell,j}$$

The final output of this operation is a plot of the average spectral characteristics of each data block.

APPENDIX B
ANTENNA DATA REDUCTION AND ANALYSIS

During the experiment the antenna was operated in both the slave and autotracking modes. This appendix is concerned with the antenna's performance based on the antenna pointing error, i.e., the actual angular error from the desired antenna boresight. In the autotracking mode the antenna's pointing accuracy is dependent on the noise generated in the preamplifier and in the monopulse sum and difference channels. This noise causes the antenna to jitter about its true pointing direction. The jitter is reflected in a corresponding variation in the antenna gain or the received signal level. To estimate the variance of this pointing error a simple unbiased estimate of the mean and variance was selected. The estimates were limited to unbiased ones (rather than a maximum-likelihood estimate for example) because of the nonlinear relationship between the antenna pointing direction and the servo drive axis. This nonlinearity is due to the antenna pedestal geometry, and makes it very difficult if at all possible to determine the probability density function (pdf) of the pointing error. Therefore, the estimates were limited to simple unbiased estimates, where the pdf is not necessary. The estimates are given as follows:

$$\hat{\Delta} = \frac{1}{N} \sum_{i=1}^{N} \Delta_i$$

$$\sigma_{\Delta}^2 = \frac{1}{N-1} \sum_{i=1}^{N} (\Delta_i - \hat{\Delta})^2$$

where N is the total sample selected and Δ_i are the sample pointing errors.

Since the antenna was operating in a multipath environment, it is important that a more complete statistical evaluation of the antenna data be made so that the multipath effects can be properly accounted for. The Y-axis positional jitter can be predicted from the receiver carrier-to-noise ratio and the system parameters. The estimates of the Y-axis position mean and variance will be determined relative to a confidence interval; that is, each estimate will have a specified probability of falling within a given interval of the desired mean and variance. In addition, a chi square or similar test will be performed on the data to determine how well the data fit the predicted-gaussian density of the Y-axis. This calculation will also indicate if the process remained stationary over a given period of time. Significant variations from the predicted results will give a qualitative evaluation of the effect multipath has on the antenna's performance.

In the slave mode the antenna pointing error will be averaged over a given test run. The mean and variance for the antenna pointing error, the ship's pitch and roll will be computed. The mean and variance are:

$$\hat{X} = \frac{1}{N} \sum_{i=1}^{N} x_i$$

$$\sigma_x^2 \doteq \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \hat{X})^2$$

where x_i is a sample of any one of the above variables and N is the total number of samples. The antenna pointing error will be correlated with the ship's dynamics, i.e., the ship's pitch and roll. A linear regression will be used to relate these parameters. Therefore, the correlation coefficient of the antenna pointing error and the ship's pitch and roll will be calculated as follows:

$$\hat{\rho}_{\Delta,x} = \frac{1}{N} \sum_{i=1}^{N} \frac{(\Delta_i - \hat{\Delta})(x_i - \hat{X})}{\sqrt{\sigma_\Delta^2 \ \sigma_x^2}}$$

where Δ_i, $\hat{\Delta}$ and σ_Δ^2 are the sample pointing error and its mean and variance and x_i, $\hat{X}$ and σ_x^2 are the corresponding parameters for the ship's pitch or roll. A plot of the normalized variables will illustrate the correlation of the two variables. Since the ship's pitch and roll are dependent on the random sea state, the expected antenna pointing error or receiver signal level will be obtained from the above plots.

APPENDIX C
MODEM DATA REDUCTION AND ANALYSIS

C.1 DIGITAL DATA (1,200 b/sec)

Analysis of the 1,200 b/sec digital data is being accomplished through the use of a commerical data error analyzer. The particular analyzer being used has the capability to measure bit error rate, block error rate, clock slip, carrier loss and skew. The 1,200 b/sec modem data streams are recorded on an analog tape recorder with a serial (IRIG-B) time code. Additionally, the clock waveform from each modem is also recorded. The modem data streams are Manchester encoded prior to recording and the recorded clock signals are used to simply recover the digital data stream on playback. The 1,200 b/sec modem tests employ a data frame consisting of a 2047 bit pseudorandom binary sequence, PRBS. The data reduction process operates in the following manner. The tape-recorded data are played back at 15 ips (vs 3 3/4 ips recording speed) in order to reduce the data reduction time. The data error analyzer will usually be set for a test length of 10^5 bits with a corresponding measurement time of 20.8 sec. In test lasting longer than ten minutes in real time (e.g., 20 minutes for the simultaneous voice plus data tests and approximately two hours for data at C/No = 42 dB-Hz) the data error analyzer will be set for a test length of 10^6-bits. In the "cycle mode" the analyzer will activate a printer after each 10^5-bit measurement and then automatically start the next 10^5-bit measurement. Data from a test which lasted ten minutes in real time will be played back in 2.5 minutes, allowing six sequential error rate measurements each lasting 20.83 sec with a three second pause between tests for printout. The results printed out at the end of each measurement will be Bit Error Rate, Clock Slip Rate, Block Error Rate, and either Carrier Loss or Skew. Bit Error Rate measures the number of bits in error divided by the total number of bits received in a given measurement. The measured bit error rate will be compared to the anticipated bit error rate based upon the carrier-to-noise power density ratio, C/No, and the observed multipath. Block Error Rate indicates the number of received 1,000-bit data blocks containing one or more errors divided by the total number of 1,000-bit blocks contained in a given measurement. For example, a measurement based upon 10^5 bits would contain 100 data blocks of 1,000 bits each. Block Error Rate will be compared to Bit Error Rate as an indication of error distribution. Clock Slip Rate is an indication of the number of times in a given measurement period that the input data have moved forward or backward in relation to the data stream clock. Carrier Loss indicates the number of data dropouts occurring in a given measurement. The Skew measurement is an indication of the percentage of errors in which "ones" were changed to "zeros" during a given measurement period. A normal reading is 50%. While the data error analyzer provides for the measurement of several types of errors, the Bit Error Rate will be the primary measure of data quality. Other measured quantities, Block Error Rate, Clock Slip Rate, etc., will be used to aid in the interpretation of test results.

C.2 INTELLIGIBILITY TESTING

Scoring of the voice intelligibility tests is done at CBS Laboratories, Stamford, Connecticut CBS Laboratories maintains a permanent listening panel of 10 members which meets regularly to perform evaluations of a wide variety of speech communications systems and devices, utilizing accepted procedures as may be required by the test conditions. These procedures have included such intelligibility tests as the PB-50 tests of American National Standard S3.2-1960 (Harvard Phonetically Balanced Word Lists), Modified Rhyme Tests, Fairbanks Rhyme Tests CNC Words, and other special tests.

Intelligibility tests are conducted using the PB-50 word lists of ANS S3.2-1960. Recordings of these word lists spoken by four professional talkers with General American Speech, each reading eight scrambled orders of all 20 lists, are the source material for intelligibility tests. Figure C-1 shows the format of voice tapes used during the ATS-6 tests.

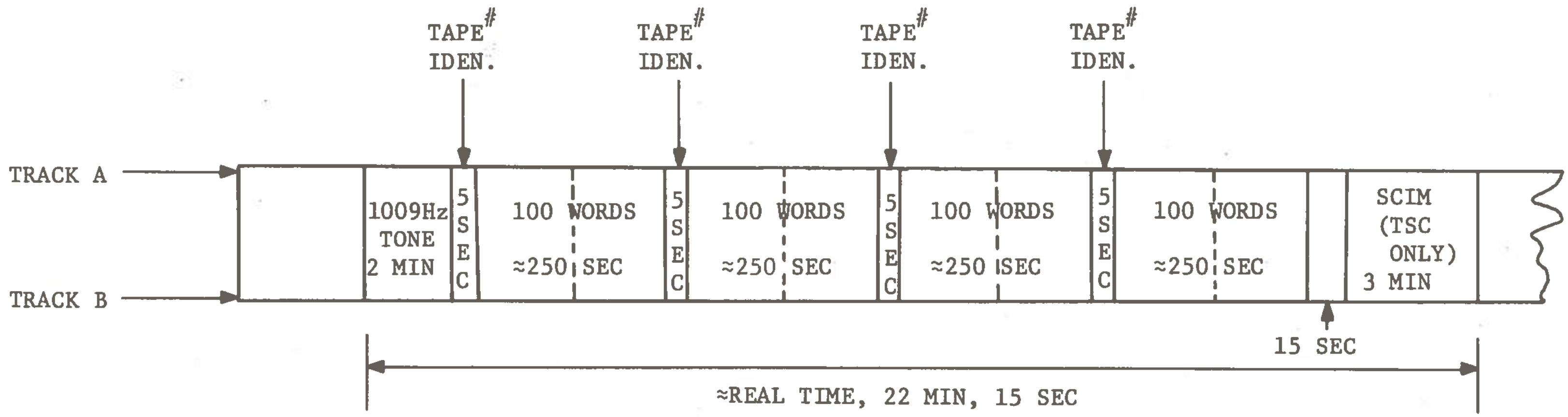

Figure C-1. ATS-6 Voice Tape Format

The listening panel members are 10 women, average age 33, who are audiometrically normal. Most of the listeners have had more than two years experience in intelligibility testing, resulting in high confidence and repeatability in evaluations.

Each test consists of 400 words (eight 50-word lists) chosen at random from a 1,000 word vocabulary. The time between words is 2.5 seconds and four speakers (100 words per speaker) are used for each test. Recordings of these word lists are transmitted through the ATS-6 satellite to the Coast Guard Cutter using the Hybrid I and Hybrid II modems and also using an ANBFM modem. Recordings of the demodulator outputs are played back to the listener panel. Voice intelligibility is simply a measure of the fraction of the number of words correctly interpreted by the panel averaged over its members. Engineering support for the testing program is provided by a qualified acoustical engineer who has worked with the listening panel since its inception. He will provide the necessary technical direction to insure the proper execution and validity of the results. A sample test result sheet is shown in Figure C-2.

C.3 RANGING DATA

Ranging consists of measuring the transit time of a signal, originating at the ground station, to the terminating stations aboard the Coast Guard Cutter and aircraft. The time delay is quantized in increments of 25 nanoseconds and recorded on magnetic tape at the rate of 4 readings per second. Several factors affect the absolute accuracy of the time delay measurement:

a. The measurement is made with phase-lock techniques, which have inherent jitter.

b. Multipath effects will cause a fluctuation in the absolute range measurement.

c. Motion of both the cutter and the aircraft will cause a gradual change in the range measurement.

Processing of these data to eliminate these errors will be done simultaneously by the Boeing Co. on the information recorded

CBS LABORATORIES, STAMFORD, CONNECTICUT

INTELLIGIBILITY TEST REPORT

* *

STATISTICS FOR BOEING AIRPLANE TEST NO. 78

SESSION NO. 834   DATE: 1/23/75

TEST MEAN SCORES (%):		ORDERED ARRAY
LIST 515	74.6	67
LIST 516	72	72
LIST 2217	87.8	73.8
LIST 2218	85.8	74.6
LIST 3919	67	82.8
LIST 3920	73.8	85.8
LIST 5701	82.8	86.4
LIST 5702	86.4	87.8

LISTENER RESULTS (%):

LISTENER	MEAN SCORES	STD. DEVIATION	STD. ERROR
1	76.5	7.9102104	2.7966817
2	89.75	5.9940447	2.1192148
3	80.25	9.88144	3.4936166
4	81.5	9.7833678	3.4589429
5	69.5	12.727922	4.5
6	74.25	9.1612538	3.2389923
7	79	10.954451	3.8729833
8	88	7.4833148	2.6457513
9	82	4.8989795	1.7320508
10	67	10.796825	3.8172541

CONDITION RESULTS:

MEAN PB WORD SCORE = 78.7750

STANDARD DEVIATION = 7.8547   STANDARD ERROR OF MEAN = 2.7771

95% CONFIDENCE LIMITS (7 DEGREES OF FREEDOM) = 6.5677432

HIGHEST TEST SCORE = 87.8000   LOWEST TEST SCORE = 67.0000

RANGE = 20.8000   MEDIAN = 78.7000

FREQUENCY DISTRIBUTION (TEN EQUAL CLASSES):

1	0	1	2	0	0	0	1	0	3

Figure C-2. Sample Voice Intelligibility Test Report aboard the aircraft and by TSC for the Coast Guard Cutter. Boeing is set up to accept Manchester encoded data from the analog tape directly and extract the data with a bit synchronizing circuit for generating a computer drive tape. A program has been written to print out data for each range measurement (converted to meters) along with the status bit information and the time of day. For each block of data, the following summarizing parameters are computed and printed out: the number of points accepted and rejected, the mean error in meters, the rms error in meters, and also the chi square variance.

The data reduction facilities at TSC are not as flexible as those at Boeing and will not accept data directly from an analog tape. At this time, we are building hardware to strip data from the analog tape and output them in the form of the range readings printed directly in nanoseconds, along with status bit indications. The data will then be reduced by hand to extract mean and variance information. This hardware will also have an interface to the TSC data facilities, with the expectation that eventually a computer drive tape might be generated to allow automatic processing of these data.

It is planned, as part of the overall data reduction task of this experiment, to undertake laboratory performance testing of the ranging modem in the presence of multipath interference to determine the effective multipath contribution on the overall phase jitter measurement.