Technical Report 1460
November 1991

Evaporation Duct Communication: Test Plan Part II

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ADMINISTRATIVE INFORMATION

This work was conducted under project RC32C11 of the Communications and Networking Block Program (N02B). Block N02B is managed by Naval Ocean Systems Center under the guidance and direction of the Office of Naval Technology. The work was funded under program element 0602232N and was performed in FY 1991 by members of Code 543, Naval Ocean Systems Center, San Diego, CA 92152-5000.

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SUMMARY

The Evaporation Duct Communication (EDCOM) project is an effort to evaluate an alternative ship-to-ship communication channel that exploits the natural environment. It is a unique project using a microwave communication circuit (similar to the commercial line-of-sight [LOS] microwave links that carry voice and data across the country) on an over-water, over-the-horizon (OTH) path where successful communication depends on the evaporation duct. A one-way, 83-km transmission path will be instrumented to simultaneously measure surface meteorological conditions and radio frequency (RF) characteristics of the communication channel. Bit-error rate (BER) will be measured at DS-1 transmission rates (1.544 megabits per second [Mbps]) and will be compared to propagation models that predict BER from knowledge of the surface meteorology. These comparisons will be used to validate or improve the propagation models so that the performance of similar communication circuits can be predicted from knowledge of the environmental conditions.

The EDCOM project has two objectives. First, EDCOM will demonstrate the feasibility of an OTH communication link that depends on the evaporation duct for successful link operation. Second, EDCOM will validate a propagation model that can be confidently used to guide the development and design of an alternative link for U. S. Navy ship-to-ship communications.

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INTRODUCTION

This report is a continuation and expansion of an earlier study (Anderson, 1991) that examines the feasibility of using the evaporation duct to support an alternative high-speed communication system for Navy applications. Meteorological and RF propagation models are reviewed. Data from a unique NATO propagation experiment are summarized and are used to show that the RF propagation model predictions (derived from a climatology of evaporation duct heights) accurately represent the measurements. Progress in the development of software to collect and analyze the RF data is reviewed. In addition, transmitter and receiver site preparation is documented.

EDCOM will simulate a ship-to-ship communication link that might be built. Typical shipboard antenna heights are 25 m above the ocean surface, which gives a LOS range of about 40 km. The EDCOM path between San Mateo Point and NOSC is 83.1 km in length, which is more than twice the LOS range. Two frequencies (7.5 and 14.5 GHz) are used to assess propagation effects. Commercial digital radio equipment (Loral/TerraCom models TCM-624A and TCM-628B) is used in a simplex mode (one-way transmission) to reduce costs. Two-way transmission is not necessary to assess propagation effects. Industry-standard DS-1 test-measurement sets (TauTron model 5108) are used to generate a quasi-random bit stream at a rate of 1.544 Mbps (DS-1) and to analyze the received bit stream in terms of bit-error rate (BER) and block-error rate (fixed-time-interval blocks that contain errors). From the top level, EDCOM will implement a commercial LOS microwave link. The major difference is the path length: EDCOM will use an OTH, over-water path that is more than twice the LOS range.

It is estimated that a shipboard communication system operating at 14.5 GHz can successfully transmit and receive a DS-1 signal at ranges of more than twice the radio horizon 81 percent of the time (Anderson, 1991). For the geometry and frequencies of the EDCOM experiment, radio propagation models predict that the evaporation duct will enhance average received signal level (ARSL) 50 dB above the diffraction limited case. ARSL is estimated to exceed the instantaneous received signal level (IRSL) required for "error-free" communication 81 percent of the time. However, ARSL greater than the required IRSL does not guarantee a usable communication link. For example, signal fading when ARSL is barely sufficient could cause IRSL to be less than that required for successful communication. Although the radio propagation model accurately predicts ARSL, IRSL is poorly modeled because it is a function of micro-scale meteorology, which is impractical to measure on even a moderate length path. Ultimately, link availability must be determined experimentally. Instantaneous BER and block-error rates are used to determine link availability.

METEOROLOGICAL AND PROPAGATION MODELS

For many years the evaporation duct has been recognized as a propagation phenomenon that can increase beyond-horizon radio signals many dB above diffraction field levels for frequencies above 2 GHz (Hitney, et al., 1985). Turbulent mixing in the surface layer (air–sea boundary) causes a rapid decrease in the water-vapor content of the air, which in turn creates a strong negative radio refractivity gradient that forms an evaporative duct. An RF signal can propagate with a low attenuation rate within the guide, which is formed by the sea surface and the evaporation duct height. Above the duct, the RF field strength decreases rapidly, but at ranges beyond the normal radio horizon, the field strength may be 10 to 100 dB greater than the diffraction field strength. The signal enhancement depends strongly on frequency because these ducts are vertically thin, typically less than 20 m.

In practice, boundary-layer theory relates bulk surface meteorological measurements of air temperature, sea temperature, wind speed, and humidity to the evaporation duct height. Evaporation duct height is computed using the Jeske (1971) model as implemented by Hitney (1975) with thermal stability modifications suggested by Paulus (1985). In a thermally neutral atmosphere (where the air–sea temperature difference is 0), the modified refractivity profile is

$$M(z) = M(0) + 0.125(z - (\delta + z_0)\ ln((z + z_0)/z_0)) \qquad (1)$$

where z is the height above the ocean, δ is the evaporation duct height, and z_0 is a length characterizing boundary roughness.

Numerical propagation modeling techniques agree with RF measurement results when single-station surface meteorological observations are available to determine the refractivity-versus-altitude profile of the evaporation duct (Katzin, Bauchman and Binnian, 1947; Richter and Hitney, 1988; Anderson, 1990). In this study, the evaporation duct is assumed to be (1) range-independent and (2) the dominant propagation phenomenon. Effects from both surface-based and elevated ducts (created by advection or subsidence of an air mass) are neglected because these ducts are infrequent, occurring only about 10 percent of the time (Patterson, 1982).

The waveguide propagation model, known as *MLAYER*, was originally developed by Baumgartner (1983), later modified by Pappert (1984), and is briefly described by Hitney, et al. (1985). *MLAYER* is based on the formalism developed by Budden (1961), and it solves the modal equation for an arbitrary vertical multiple-linear-segment refractivity profile using a root-finding scheme that locates all modes with attenuation rates less than a specified value. Surface roughness is accounted for by modifying the surface-reflection coefficient, which is based on the wind speed. Horizontal homogeneity of refractive conditions is assumed.

Measurements of air temperature, sea temperature, wind speed, and relative humidity are used to calculate the evaporation duct height δ. Eq. 1 is used to calculate the vertical refractivity profile needed by the *MLAYER* program. Measured wind speed is used to calculate the surface roughness parameter, σ, also used by *MLAYER*.

Results of propagation modeling by *MLAYER* are expressed in terms of path loss (L), the ratio of power transmitted to power received, assuming loss-free isotropic antennas. Propagation loss (which includes antenna pattern shaping) and path loss are equivalent terms in this analysis because the antenna radiation patterns are known and accounted for in the development. For a one-way transmission system, signal power at the receiver is

$$P_r = P_t + G_t - L + G_r \tag{2}$$

where P_t is power transmitted, G_t and G_r are transmitter and receiver antenna gains. The propagation model does not account for small-scale turbulent fluctuations in the atmosphere, which cause rapid changes in the IRSL.

Table 1 lists the power budget parameters for the transmitter/receiver systems operating at 7.5 and 14.5 GHz. Receiver sensitivity is defined as the minimum received signal power (at the input to the receiver) to maintain a 10^{-6} BER at DS-1 transmission rates. Path loss threshold is calculated by solving eq. 2 for L, knowing the transmitter power, antenna gains, and receiver sensitivity (signal power at the receiver). Because minimum receiver sensitivity has been substituted for received signal power, there is 0-dB signal-to-noise ratio (SNR), or margin, in the path loss threshold.

Table 1. Loral TerraCom transmitter/receiver specifications and power budget estimates.

Model Number:	TCM-624A	TCM-628B
Tuneable Frequency (MHz)	7125-7725	14400–15250
Transmitter Power (W [dBm])	0.66 [28. 2]	0.20 [23.0]
Antenna Diameter (m)	1.22	1.22
Antenna Gain (dBi)	37.0	42.7
Receiver Noise Figure (dB) (with preselector)	6.0	8.0
Receiver Sensitivity (dBm) @ 10^{-6} BER (DS-1)	–88.5	–86.5
Path Loss Threshold (dBm) @ 0 dB margin	190.7	194.9

Table 2 lists the expected availability of the two radio links (7.5 and 14.5 GHz) in relation to system margins of 0, 10, and 20 dB. The system margin is a factor to account for unknown losses (such as rapid fades) that may occur in link operation. Assuming a 10-dB margin, the 14.5-GHz link is expected to have an availability approaching 81 percent if there is no fading.

Table 2. Expected availability of the EDCOM links. Antennas are 25 m above msl. Path length is 83 km. Digital radio specifications are from table 1.

Frequency (MHz)	7500.0	14500.0
0 dB Margin	79%	88%
10 dB Margin	67%	81%
20 dB Margin	48%	71%

LORIENT, FRANCE PROPAGATION MEASUREMENTS

A unique radio propagation experiment was made in Lorient, France by the NATO AC243 Panel 3 Research Study Group 8 (RSG 8). An over-water, OTH path was instrumented for transmission frequencies of 3, 5.6, 10.5, 16, 35, and 94 GHz to assess evaporation duct effects on propagation. NOSC participated in the experiment by supplying equipment and by assisting in data analysis. The 5.6-, 10.5-, and 16-GHz frequencies bracket the EDCOM frequencies and are used to illustrate expected results from the EDCOM experiment. Figures 1 through 3 show the measured propagation loss with respect to measured evaporation duct height for the 5.6-, 10.5-, and 16-GHz frequencies. Each cross on the figures represents the median path loss measured in a 10-minute interval. Three shades of crosses are used to represent various time intervals: (1) the black crosses correspond to time intervals when the atmosphere was thermally neutral, (2) the darkest gray crosses correspond to time intervals when the atmosphere was thermally unstable, and (3) the lightest gray crosses correspond to time intervals when the atmosphere was thermally stable. The solid black line is the path loss predicted by the *MLAYER* program. It is calculated using a smooth surface (no roughness) for thermally neutral evaporation duct profiles. The predicted curve nearly splits the data between stable and unstable conditions, as it should.

The annual distribution of evaporation duct heights in the Lorient offshore area is shown in figure 4. This distribution is derived from the same climatological database as the distribution of evaporation duct heights used in the initial EDCOM study (Anderson, 1991). *MLAYER* results for the neutral evaporation duct profiles are weighted by the annual percent occurrence of evaporation duct height in order to give

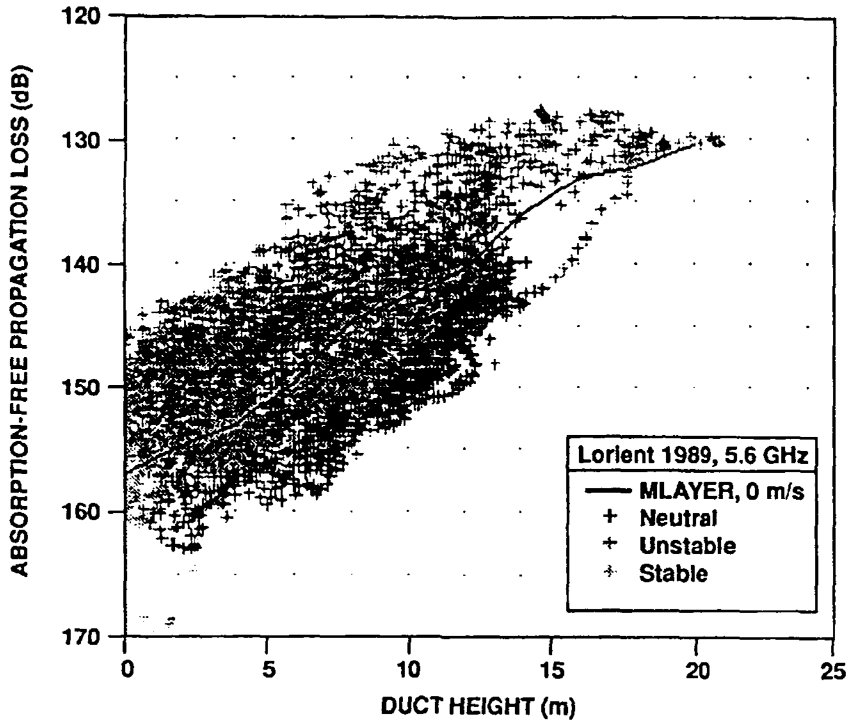


Figure 1. Measured (crosses) and predicted (solid line) propagation loss at 5.6 GHz for Lorient, France.

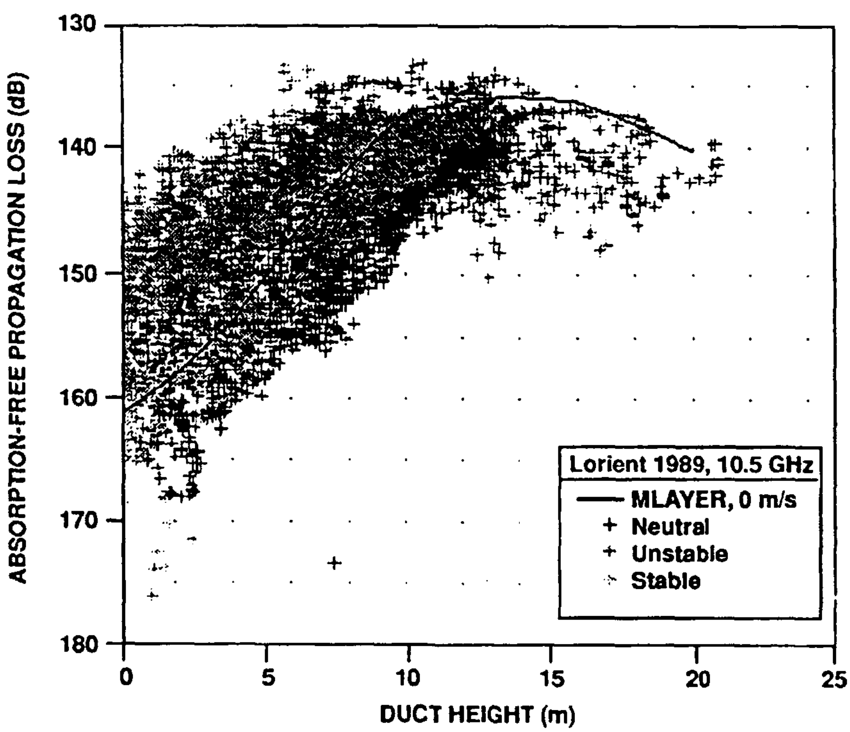


Figure 2. Measured (crosses) and predicted (solid line) propagation loss at 10.5 GHz for Lorient, France.

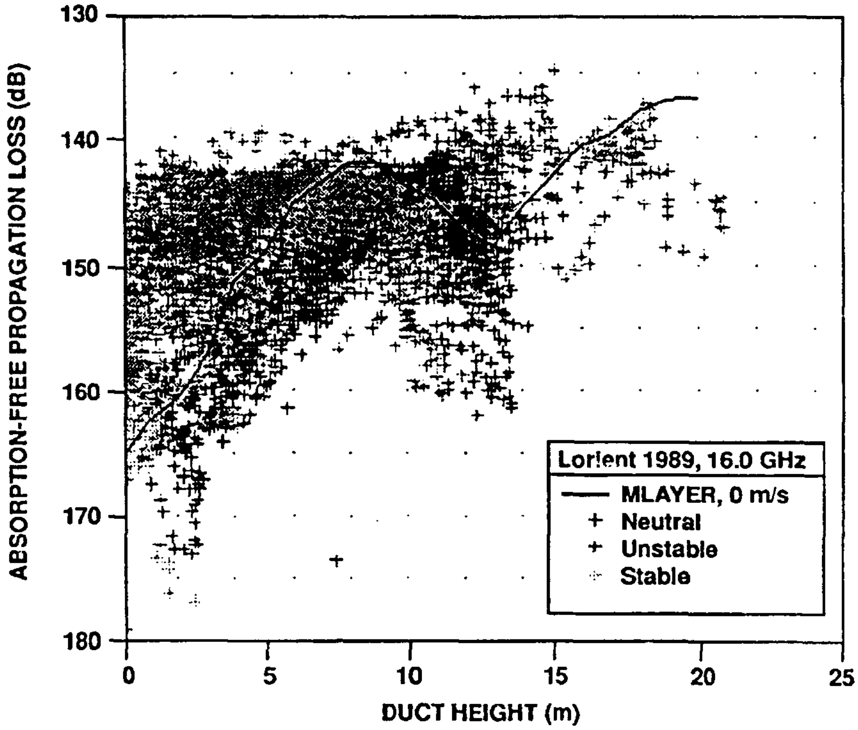
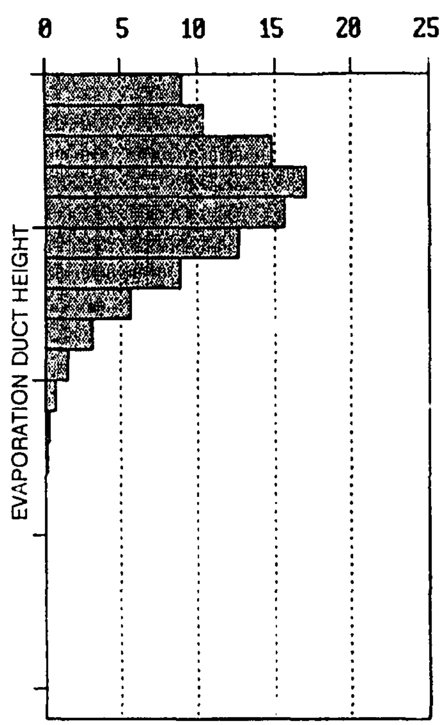


Figure 3. Measured (crosses) and predicted (solid line) propagation loss at 16.0 GHz for Lorient, France.

EVD HT (m)	% OCCUR
0 TO 2	9.0
2 TO 4	10.4
4 TO 6	14.8
6 TO 8	17.0
8 TO 10	15.7
10 TO 12	12.7
12 TO 14	8.9
14 TO 16	5.6
16 TO 18	3.1
18 TO 20	1.5
20 TO 22	0.7
22 TO 24	0.3
24 TO 26	0.2
26 TO 28	0.1
28 TO 30	0.0
30 TO 32	0.0
32 TO 34	0.0
34 TO 36	0.0
36 TO 38	0.0
38 TO 40	0.0
> 40	0.0



ANNUAL SURFACE DUCT SUMMARY

SURFACE OBS: MS 145

LATITUDE:	40 TO 50 N
LONGITUDE:	0 TO 10 W
AVG EVD HT:	8.2 m
AVG WIND SP:	15.0 knots
SAMPLE SIZE:	241624 OBS

UPPER AIR OBS: RS 7110

BREST/GUIPAVAS, FRANCE

LATITUDE:	48.45 N
LONGITUDE:	4 42 W
SBD OCCURRENCE:	1.0%
AVG SBD HT:	68 m
AVG NSUBS:	327
AVG K:	1.39
SAMPLE SIZE:	3257

Figure 4. Annual evaporation duct height distribution for the offshore area of Lorient, France.

the accumulated frequency distribution of path loss, which is compared to the measured distribution. Figures 5 through 7 compare the predicted frequency distribution to the measured frequency distribution for the 5.6, 10.5, and the 16 GHz signals. The comparisons are excellent. For example, at 16 GHz (figure 7), the predicted and observed occurrence of signal levels at free-space or greater (145.5 dB or less path loss) are equal. For the 90 percent "availability" value (10 percent exceeding), the *MLAYER* program underestimates the path loss of all three frequencies, which implies that the EDCOM availabilities might be higher than expected.

If ARSL is considered the median signal level in a 10-minute period, the propagation and meteorological models are clearly excellent predictors of ARSL in the statistical sense. However, for digital transmissions in which the bit intervals are on the order of microseconds and less, IRSL is the controlling aspect of successful communication.

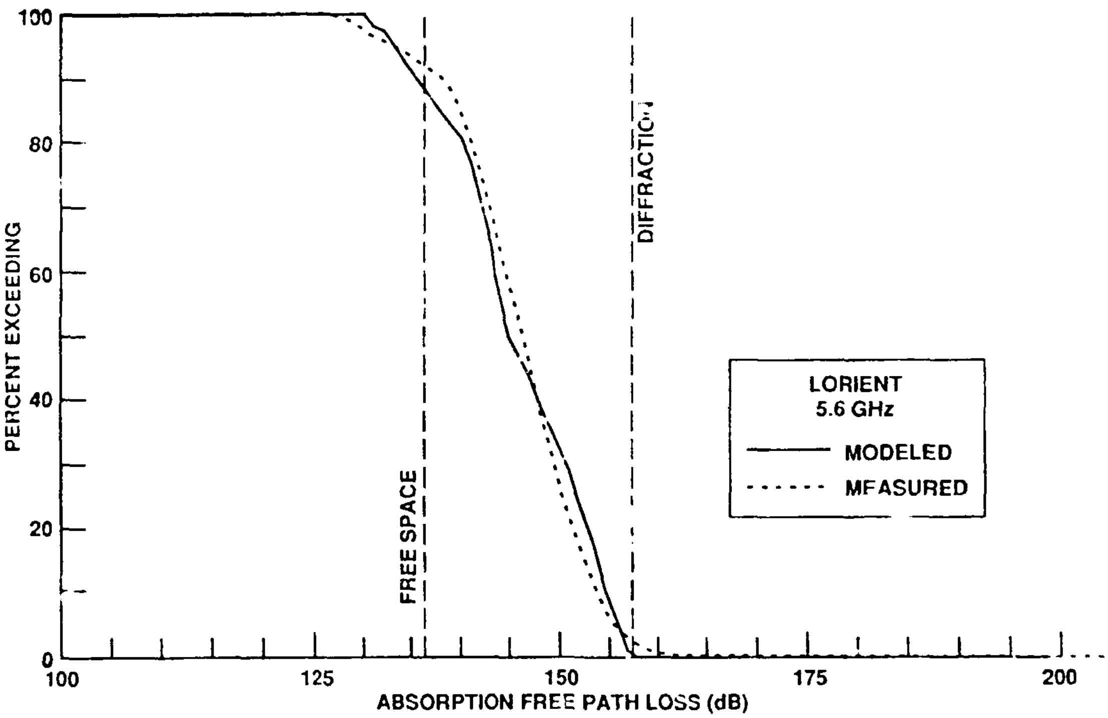


Figure 5. Predicted and measured path loss distribution at 5.6 GHz for Lorient, France.

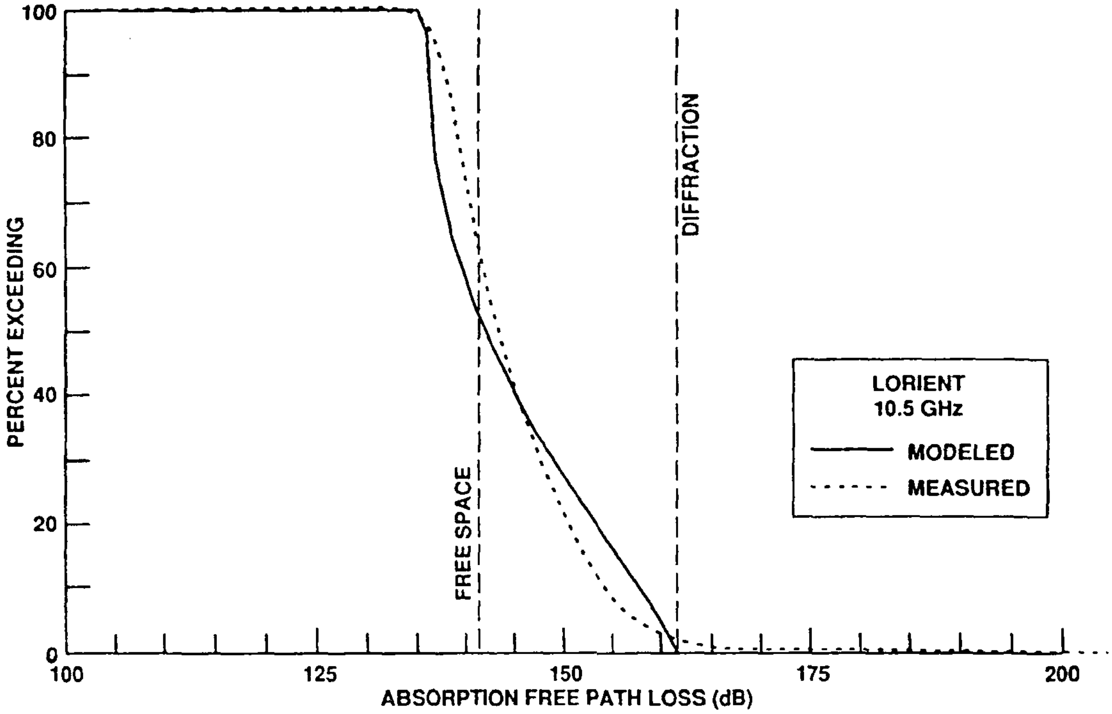


Figure 6. Predicted and measured path loss distribution at 10.5 GHz for Lorient, France.

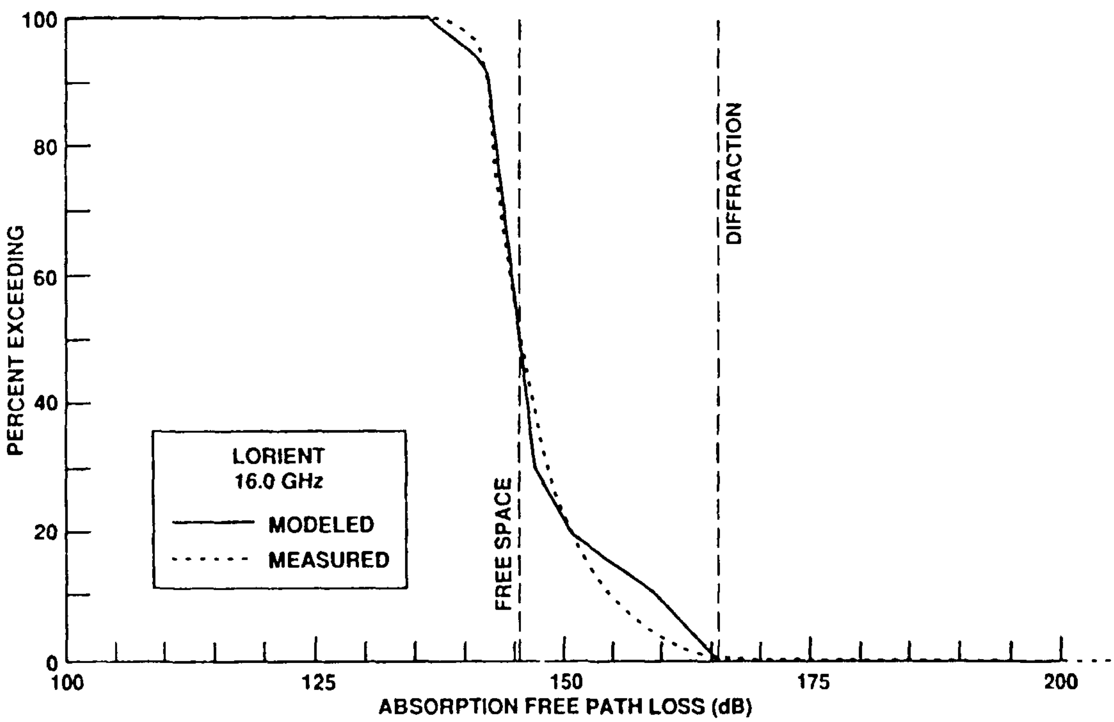


Figure 7. Predicted and measured path loss distribution at 16.0 GHz for Lorient, France.

DS-1 SIGNAL AND MEASUREMENTS

The DS-1 system is the most common short-haul digital transmission system in service in North America. It converts 24 voice telephone signals to a bipolar time-division-multiplexed (TDM) signal with a data rate of 1.544 Mbps. The basic element of the DS-1 signal is a frame, which is composed of 24 eight-bit words and a single framing bit for a total of 193 bits. Each word is a pulse-code modulated (PCM) sample of a voice signal encoded into eight bits.

The probability of a bit error is a strong function of the IRSL. The averaged probability of bit error is the expected bit-error rate (BER), which is equal to the probability of a bit error when IRSL is constant. For the relatively simple digital on-off-keying (OOK) receiver,

$$P_{bit\ error} = 1/2\ e^{((-Eb/No)/2)} \ , \qquad (3)$$

where Eb/No is the energy per bit referenced to the noise in a 1 Hz bandwidth (Couch, 1987). Other receiver types have more complex functions for the probability of bit error. However, their performance curves resemble right or left shifting of the OOK curve. This is evident from figure 8, which shows performance curves for several receiver designs. Loral will provide calibration curves for the EDCOM receivers. These calibration curves reference the probability of bit error to IRSL.

Errors in the digital signal are not independent events. BER alone is not sufficient for analysis either of channel availability or of error-correction schemes (Brown, 1989). Digital transmission test sets used by common carriers provide a full range of measurements of both BER and block-error rates to enable effective analysis of channel availability. The digital transmission test set used in the EDCOM effort is the TauTron 5108. It has independent signal input and signal output sections; selectable format and pattern generation of the DS-1 signal; more than 60 signal, frame, and pattern measurements; and flexible control over testing intervals.

The TauTron 5108 measures BERs ranging from 1.0 E-6 to 1.0 E-2, which corresponds to about a 7-dB IRSL dynamic range. Results from the EDCOM experiment will provide statistics for BER and block-error rates, which can be related to path loss through eqs. 2 and 3. If IRSL is assumed to be equal to ARSL, the predicted and expected path loss distributions are shown in figures 9 and 10 for the 7.5 and the 14.5 GHz signals. The abrupt transitions in the expected curve (eg, the transition from 100 percent to 27 percent in figure 9) are due to the limited dynamic range of the TauTron 5108 test sets.

EDCOM results will provide standard measurements of channel availability, which are needed for digital communication systems design. These results will have a direct impact on the design of alternative communication links for Fleet systems.

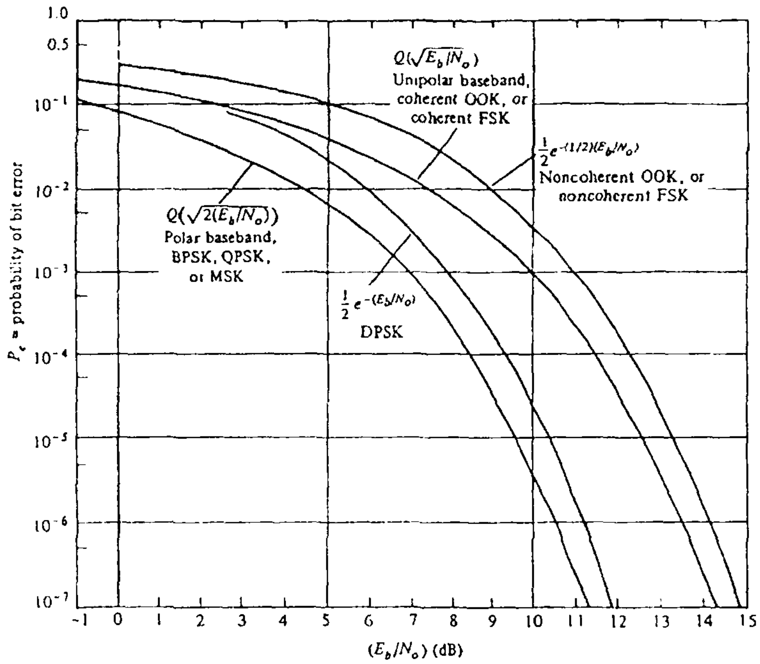


Figure 8. Probability of bit-error curves for various digital receiver systems.

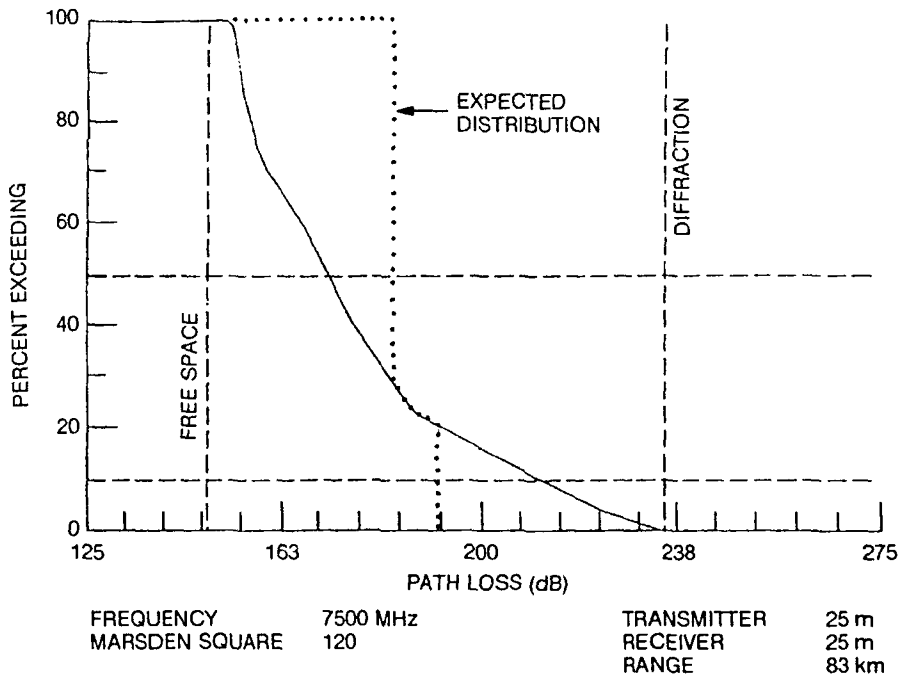


Figure 9. Predicted and expected path loss distribution at 7.5 GHz for the EDCOM measurement program. The receiver systems used have an approximate 7-dB dynamic range.

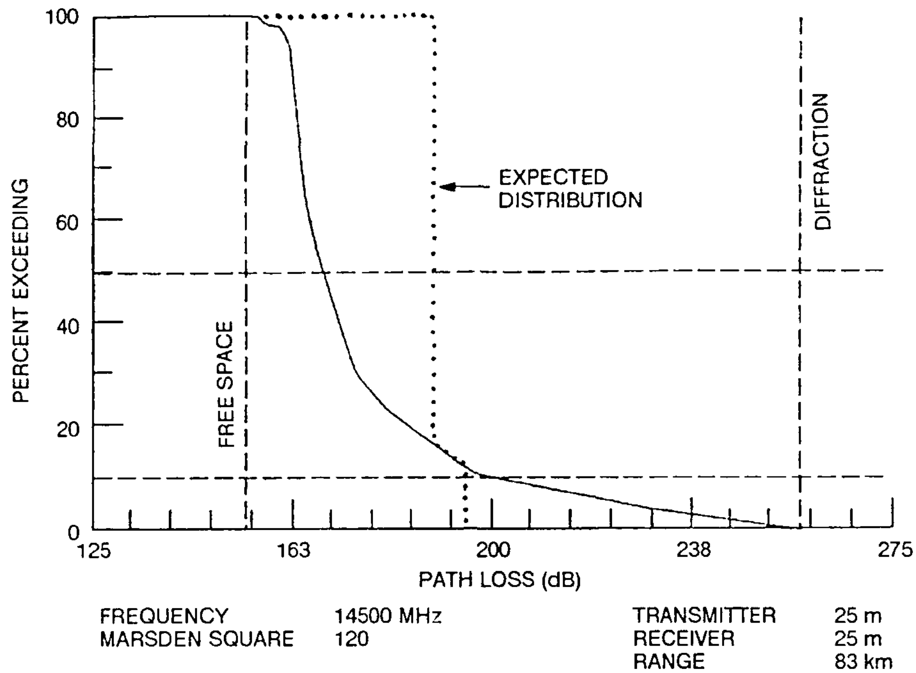


Figure 10. Predicted and expected path loss distribution at 14.5 GHz for the EDCOM measurement program. The receiver systems used have an approximate 7-dB dynamic range.

ACCOMPLISHMENTS

Substantial progress has been made in the preparations for the EDCOM experiment. However, the planned start date (August 1991) has slipped approximately 6 months because of delays in getting the Loral transmitter and receiver systems. These delays were caused by Desert Shield/Storm requirements, which preempted the production line. Loral expects to ship the antennas and mounts in early October 1991. The transmitter and receiver hardware are expected to be shipped in November 1991. If these schedules are met, measurements are anticipated to begin in February 1992. Progress in the software development, site preparation, and testing are reviewed in the next two subsections.

TRANSMITTER (REMOTE) SITE

The site at San Mateo Point (the northern coastal point of Camp Pendleton) will transmit DS-1 signals (at 7.5 and 14.5 GHz) and will record both the meteorological data and the quality of the transmitted DS-1 signal. This information will be transmitted to NOSC computers by a commercial phone-line modem. Figure 11 illustrates the data and the quality of the transmitted DS-1 signal. This information will be transmitted to NOSC computers by a commercial phone-line modem. Figure 11 illustrates the equipment configuration at the San Mateo Point site. The major accomplishments at the transmitter site include the following

1. An Interservice Support Agreement (ISSA) is in place. The ISSA is the primary document detailing responsibilities and obligations between NOSC and Camp Pendleton for the use of the site.

2. Site preparation is nearly complete. The concrete pad, antenna mast, power, and phone lines are installed. Security fencing is expected to be installed by early October 1991.

3. A field survey of the site has been completed. The site is located at Lat. 33°23'18"N, Long. 117°35'41"W. Ground level is 21.19 m above mean sea level (msl).

4. Control and data acquisition programs have been written, tested, and integrated. Transmitter site software is complete.

A four-port RS-232 communications board was added to the control computer, which caused problems in the software development. MicroSoft QuickBasic (Ver 7.1), MicroHelp QB/Pro, and ProCom software were tested and found inadequate to support more than two serial ports. Tests made with the Parasoft Multiline Interrupt Driver software were found adequate to support four-port RS-232 communication and were incorporated into the control program. All testing of the control program is complete.

Wind speed, wind direction, air temperature, and relative humidity are sampled every 6 seconds, averaged over a 5-minute interval, and recorded every 6 minutes. BER and signal amplitude for each of the 2 TauTron 5108s are sampled and recorded every 6 minutes. The output file is transferred daily to NOSC computers by a modem where it is converted to an Ashton-Tate DBase file for analysis and archival.

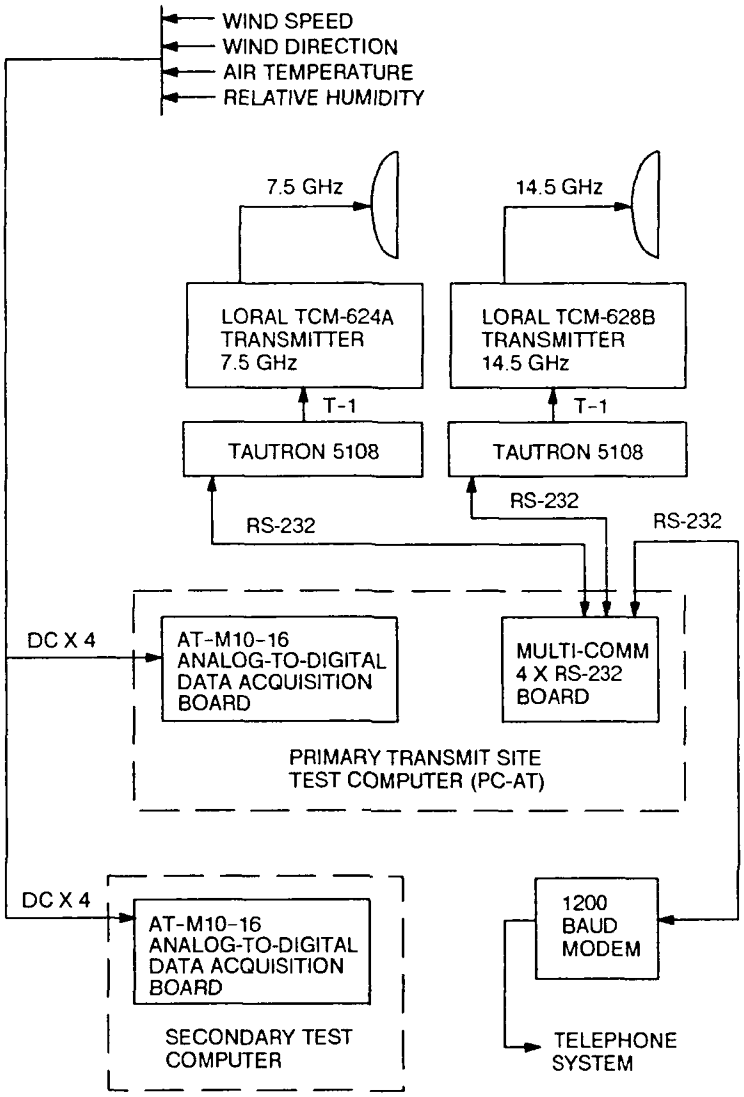


Figure 11. Transmitter site functional diagram.

RECEIVER (LOCAL) SITE

The receiver site is located at NOSC, Bldg. 599 (Seaside). BER and block-error rates of the 7.5 and 14.5 GHz DS-1 signals will be recorded as will the surface meteorological conditions. This information will be recorded on disk for later analysis and will be displayed on the computer monitor for near-realtime analysis. Figure 12 illustrates the equipment configuration at NOSC. The major accomplishments at the receiver site are

1. Site preparation is complete. Antenna mast, power, phone, and equipment shelter are in place.

2. A field survey of the site has been completed. The site is located at Lat. 32°41'47"N, Long. 117°15'10"W. Ground level is 20.20 m above msl.

3. Control and data acquisition programs have been written, tested, and integrated. Receiver site software is complete.

4. A high-speed test mode has been added to the software. In this mode, bit errors are extracted from the TauTrons at the highest possible rate (approximately every second) to obtain data on the correlation of high-speed fading between the 7.5- and the 14.5-GHz signals.

The control program runs tests in 6-minute cycles. A 5-minute test interval is followed by a 1-minute period for averaging and recording. Wind speed, wind direction, air temperature, and relative humidity are sampled at 6-second intervals, averaged over 5-minute periods, and recorded every 6 minutes. At the start of the 5-minute-test interval each TauTron is commanded to begin an autonomous test cycle. On completion, the following data are extracted from each TauTron:

- Average BER
- Number of pattern errors
- Number of pattern-errored seconds
- Number of error-free seconds
- Number of severely errored seconds
- Number of consecutive-error seconds
- Number of unavailable seconds
- Number of pattern-synchronous-errored seconds
- Number of pattern-loss seconds

Approximately every 6 hours, a high-speed test will replace the normal test cycle. In this mode, the instantaneous bit-error count is extracted from each TauTron every second for a 5-minute interval. These data will be used to establish cross-correlation statistics to assess frequency diversity.

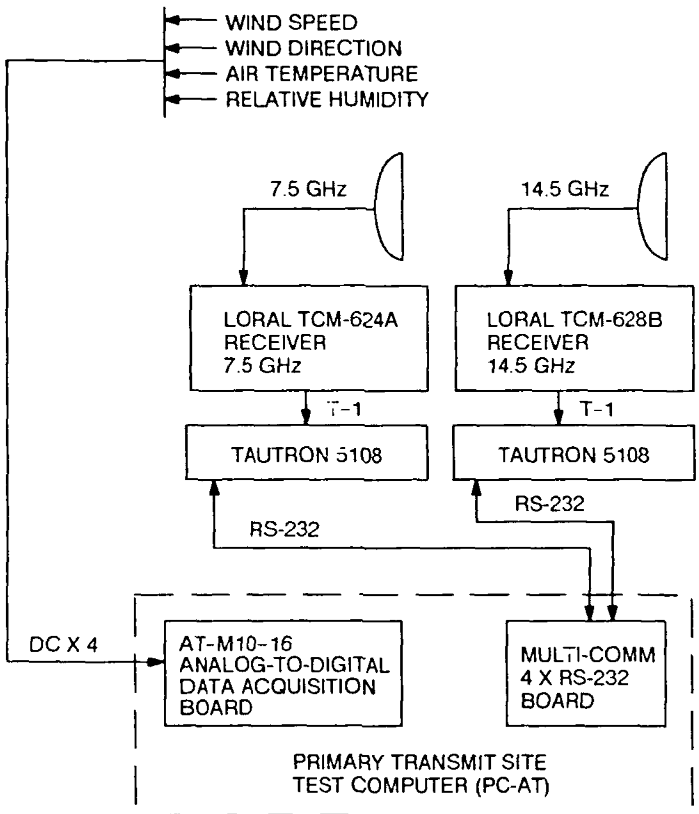


Figure 12. Receiver site functional diagram.

CONCLUSION AND RECOMMENDATION

The EDCOM experiment will provide the first set of measurements of channel capacity where the channel is critically dependent on the existence of the evaporation duct. This is a unique opportunity to study and evaluate an alternative communication channel that can possibly be used to alleviate Navy ship-to-ship communication problems.

It is strongly recommended that the measurement program be carried out.

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* NOSC Technical Notes (TNs) are working documents and do not represent an official policy statement of the Naval Ocean Systems Center. For further information, contact the author.

GLOSSARY

ARSL	average received signal level
BER	bit-error rate
BPSK	bi-phase shift key
dB	decibels
dBi	decibel over isotropic
dBm	decibel referred to 1 milliwatt
DPSK	differential phase shift key
DS-1	common carrier signal definition
Eb/No	energy per bit referenced to noise in 1 hz bandwidth
EDCOM	evaporation duct communication
EVD	evaporation duct
FSK	frequency shift key
GHz	gigahertz
IRSL	instantaneous received signal level
ISSA	interservice support agreement
km	kilometer
L	path loss
LOS	line of sight
m	meter
Mbps	megabits per second
MHz	megahertz
MLAYER	NOSC waveguide propagation model
MS	marsden square
MSK	minimum shift key
msl	mean sea level
NATO	north atlantic treaty organization
OOK	on-off keying

OTH	over-the-horizon
PCM	pulse-code modulated
QPSK	quad-phase shift key
RF	radio frequency
RS	radio station
RSG	research study group
SNR	signal-to-noise ratio
TDM	time-division multiplexed

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 1991	Final: Oct 1990—Sep 1991

4. TITLE AND SUBTITLE

EVAPORATION DUCT COMMUNICATION: TEST PLAN PART II

5. FUNDING NUMBERS

PE: 0602232N
PROJ: RC32C11
SUBPROJ: 84-CH85-06
ACC: DN300107

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Ocean Systems Center
San Diego, CA 92152-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

NOSC TR 1460

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Ocean Systems Center
San Diego, CA 92152-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

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13. ABSTRACT *(Maximum 200 words)*

This document is a continuation and expansion of an earlier study that examines the feasibility of using the evaporation duct to support an alternative high-speed communication system for Navy applications. This Evaporation Duct Communication (EDCOM) experiment is a unique opportunity to evaluate another communication channel that can alleviate Navy ship-to-ship communication problems. Therefore, it is strongly recommended to proceed with this measurement program.

14. SUBJECT TERMS

evaporation duct communication
line-of-sight
path loss
bit-error rate
over the horizon
average received signal level

15. NUMBER OF PAGES

27

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

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