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Technical Document 2658
May 1994

High-Data-Rate UHF Line-of-Sight Communication Experiment

Test Plan

R. C. North
D. Bryan
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ADMINISTRATIVE INFORMATION

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Released by
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Under authority of
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Communications Department

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SUMMARY

This report describes a high-data-rate, over-water, line-of-sight digital radio communication experiment to be conducted during FY 94. The experiment is the first of several experiments planned to simulate a realistic ship-to-ship communication link in band I of the military UHF spectrum (225–400 MHz). Data rates of T1 (1.544 Mbps) and 2xT1 (3.088 Mbps) will be transmitted via a simplex (one-way) link from NAVCOMTELSTA, Imperial Beach, California, to NCCOSC RDT&E Division (NRaD), San Diego, California, from June 1994 through August 1994. The test has been uniquely designed not only to demonstrate high data rates, but also to assess the reliability and bandwidth efficiency of future radio systems. The experimental procedure may also be used to provide similar benefits to other communication systems, naval or otherwise.

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1.0 INTRODUCTION

This report describes a high-data-rate (HDR), over-water, line-of-sight (LOS) digital radio communication experiment to be conducted during FY94. The experiment simulates a realistic ship-to-ship communication link in band I of the military UHF spectrum (225–400 MHz). Data rates of T1 (1.544 Mbps) and 2xT1 (3.088 Mbps) will be transmitted via a simplex (one-way) link from NAVCOMTELSTA, Imperial Beach, California, to NCCOSC RDT&E Division (NRaD), San Diego, California, from June 1994 through August 1994. The objective of the experiment is to

1. demonstrate T1 and greater data rates on an over-water LOS channel
2. determine the reliability of an HDR over-water LOS radio link
3. characterize the channel to evaluate other modulation/demodulation techniques.

These goals will be attained simultaneously by transmitting a known pseudorandom sequence repeatedly over a contiguous block of time. The received signal will be demodulated in real time, with statistics of the bit error performance recorded. In addition, the received 70 MHz IF signal will be sampled, downconverted, decimated, and stored at regular intervals. These data will be analyzed off-line to characterize the channel and its dynamics so that other modulation/demodulation techniques can be evaluated and compared in a realistic environment.

This experiment has been designed to have easily accessible (i.e., land based) transmit and receive sites so that the experimental procedure, measurement recording technique, and off-line data analysis software could be adequately tested and refined as inexpensively as possible while still incorporating an over-water propagation path. It is envisioned that future experiments will be almost identical to this one, but conducted from moving ships. The entire experiment and analysis technique is designed to be both RF and data rate independent. Thus, the same basic experiment could be conducted on an HF, UHF, or SHF channel (LOS or not) at any data rate up to ten's of Msps (which could be over 100 Mbps). The only restrictions are that (1) an IF (or RF) must be available which is less than 100 MHz, and (2) the transmitted modulation must be coherent *M*-PSK or *M*-QAM. The second restriction is from the analysis software (see [1] for more details), which could of course be modified for a different modulation if necessary. The reason for these restrictions will become clear in Section 3, but many present and proposed Navy communication systems fall within the capability bounds of the present experiment and instruments.

This report is organized as follow: Section 2 describes the experiment specifics, the instruments, and the expected propagation and fading conditions. Section 3 describes the data recording technique and the channel modeling procedure. Section 4 lists the time and frequency allocations for the experiment.

2.0 DESCRIPTION OF EXPERIMENT

2.1 TRANSMIT AND RECEIVE SITE INSTRUMENTATION

The transmit instrumentation will be located at building 99, NAVCOMTELSTA, Imperial Beach, and the receive instrumentation will be located at building 15, NRaD, San Diego. Figure 1 is a map of the simplex (one way) digital radio link. The length of the path is 13.1 km (7.1 nmi).

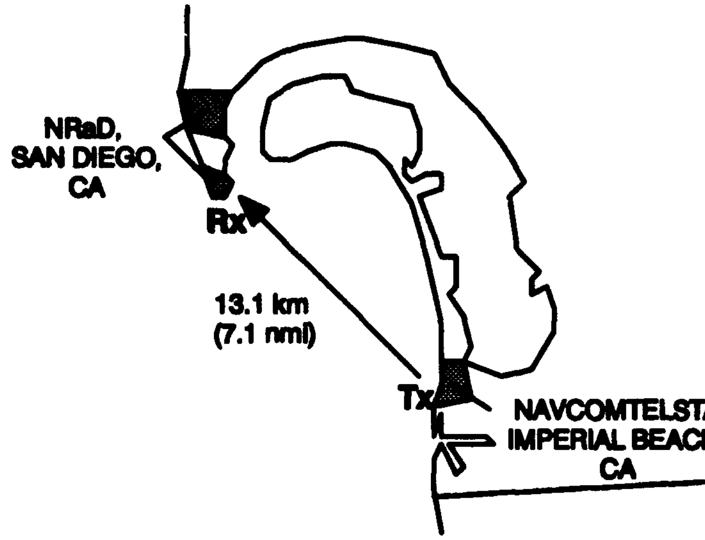

Figure 1. San Diego vicinity coastline showing location of transmit and receive instrumentation.

Figure 2 shows the configuration of the transmit site instrumentation. The TTC Fireberd bit error rate tester (BERT) was chosen because of its variable data rate (50 bps to 15 Mbps) and easy-to-change module interfaces. The Comstream CV101 is a commercial, full-duplex, modulator/demodulator (modem) capable of variable data rates up to 3.088 Mbps (2xT1). It can operate with either coherent BPSK or coherent QPSK. It implements differential coding, convolutional forward error correction coding, and V.35 scrambling under user control. Modes of operation are modified by commands entered via a dumb terminal. The Miteq upconverter was custom built for extremely linear amplitude and group delay operation for future experiments which plan on transmitting more bandwidth efficient modulations (for example, 8-PSK, 16-PSK, or 16-QAM) . For similar reasons, the Amplifier Research 25W1000-M7 25 watt (+46.5 dB at 312 MHz) linear amplifier was chosen. Finally, the AT-150/SRC dipole antenna, a common shipboard omnidirectional antenna, will be positioned to be approximately 25 meters (98.4 feet) above sea level, corresponding with typical UHF LOS shipboard antennas. (The highest shipboard antennas could be as much as 40 meters above sea level; see for example [2]). The instruments will be housed in a van mounted on the back of a High Mobility Multipurpose Wheeled Vehicle (HMMWV).

Figure 3 shows the configuration of the receive site instrumentation. The Watkins Johnson WJ8615–P is a commercial AM/FM receiver with very linear amplitude and group delay. It provides analog downconversion to a 70 MHz IF. The 1 watt (+30dB at 70 MHz) Amplifier Research 1W1000 is required to increase the signal level to that specified by the Comstream CM401 demodulator (–10 dBm to –50 dBm) and the Applied Signal Technology AST195 Wideband Snapshot Analyzer (–10 dBm to –40 dBm). Statistics on the bit error performance of the digital radio link are maintained and printed by the TTC Fireberd BERT. The AST195 Wideband Snapshot Analyzer is a SPARC2 computer with a high-speed A/D–D/A card (8-bit samples, sampled at up to 250 MHz), and an 80 MFLOP Mercury attached processor. Software for the AST195, which has been custom written by the authors, repeatedly takes a snapshot of the signal at 70 MHz IF, downconverts the 70 MHz IF to a second IF of 1.158 MHz ($= 0.75 \times f_{sym}$), decimates the data, and then stores the snapshot to disk (see Section 3 for a more complete description). When the disk becomes full, software running on the AST195 will temporarily suspend the data recording operation of the AST195 while the disk data are archived to high-capacity Exabyte tapes. The spectrum analyzer will be used for real-time visual analysis and debugging by using both the frequency spectrum data and the time-domain data at a single frequency (zero-span mode). The instruments will be housed in a room in building 15, NRaD.

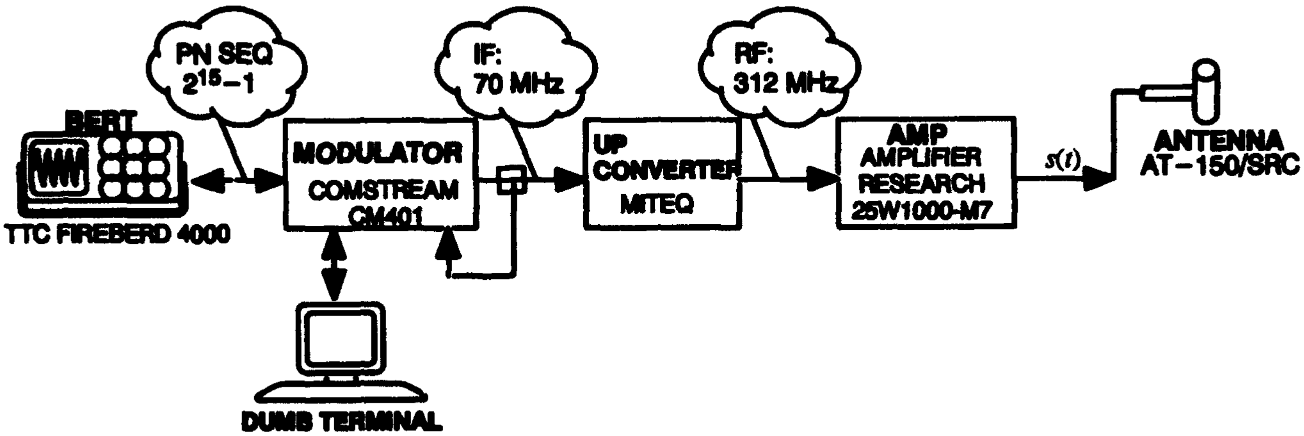

Figure 2. Transmit site instrumentation.

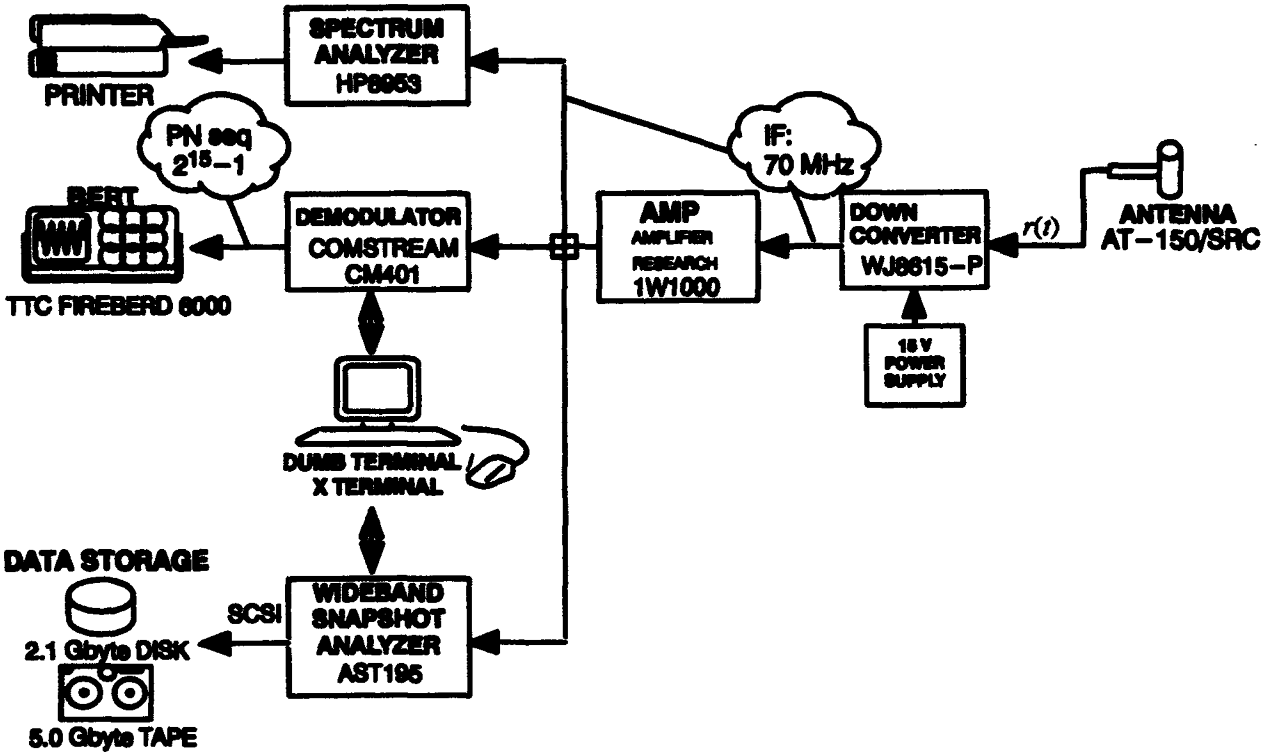

Figure 3. Receive site instrumentation.

2.2 LOSS CALCULATIONS

Table 1 summarizes all gains and losses incurred in the digital radio link (refer to figures 2 and 3). The transmitted power can be adjusted between a maximum output power of 10.0 watts. The free-space propagation loss is estimated by [3]:

$$L_{FS} = 32.45 + 20\log_{10}[d(\text{km})] + 20\log_{10}[f_c(\text{MHz})] \quad (\text{dB}) \tag{1}$$

which results in a 104 dB loss for the 13.1 km path at 312 MHz. This results in a maximum median received signal level (RSL) of –65.0 dBm. From experimental results it is found that the receiver threshold for a BER less than 10^{-6} is approximately –81 dBm for a BPSK signal at 1.544 Mbps. This gives a fade margin of 16.0 dB. Since this fade margin is slightly less than the expected worst-case fades (20 dB – 40 dB) (see Section 2.4), it is expected that some small percentage of outages could be observed.

Table 1. Path gains/losses and estimated median received signal power.

CM401 Output Power:	max =	–5 dBm	
1:2 Directional Coupler			–0.5 dB
Miteq Upconverter (2.5 MHz BW)			0 dB
25W1000 Linear Amp			+46.5 dB
50 ft Heliax Cable at 312 MHz			–1.0 dB
AT–150 Antenna Gain			0 dB
Total Transmitter Gain		+45.0 dB	
Transmit Power:	max =	+40.0 dBm / 10.0 watt	
Free-Space Propagation Loss at 312 MHz			–104 dB
AT–150 Antenna Gain			0 dB
15 ft. RG214 Cable at 312 MHz			–1.0 dB
Median Receiver Signal Level	max =	–65.0 dBm	
Receiver IF BW		2.00 MHz	
Receiver NF		10.0 dB	
Receiver Threshold BPSK @ T1		–81.0 dBm (BER = 10^{-6})	
Receiver Threshold QPSK @2*T1		–72.0 dBm (BER = 10^{-6})	
Receiver Threshold Coded QPSK @ T1		–84.0 dBm (BER = 10^{-6})	
Fade Margin BPSK @ T1		+16.0 dB	
Fade Margin QPSK @ 2xT1		+ 7.0 dB	
Fade Margin coded QPSK @ T1		+19.0 dB	
WJ8615 Downconverter			+25 dB
1W1000 Linear Amp			+30 dB
1:4 Power Splitter			–6 dB
Additional Attenuation			–0 dB
Total Receiver Gain		+49.0 dB	
Median CM401 input power:	max =	–17.0 dBm	

2.3 EQUIPMENT PERFORMANCE BASELINE

The BER performance of the equipment will be completely baselined in the lab by connecting the transmit instruments as shown in figure 2 to the receive instruments as shown in figure 3, with appropriate attenuation to account for the free-space propagation loss. This configuration is called an end-to-end test. Bit error rate (BER) versus E_b/N_o and RSL will be plotted for the end-to-end test without antennas and with closely spaced antennas (25 feet). The energy per bit, E_b, is defined as the product of the average signal power, S, and the bit duration $1/R$, where R is the data rate, and the noise power, N, is defined as the product of N_o and the signal bandwidth, W. Thus, E_b/N_o can be expressed as the product of the signal-to-noise ratio and the signal bandwidth-to-data rate ratio:

$$\frac{E_b}{N_0} = \frac{S}{N}\frac{W}{R} \tag{2}$$

The CM401 modem was tested by summing the transmitted signal with an attenuated wideband noise source (Noise/Com NC6108). Figure 4 shows the BER plotted as a function of the amount of attenuation applied to the noise source for a T1 BPSK signal with various combinations of differential encoding and V.35 scrambling. The present plan is to transmit without differential encoding or V.35 scrambling to measure the raw channel characteristics.

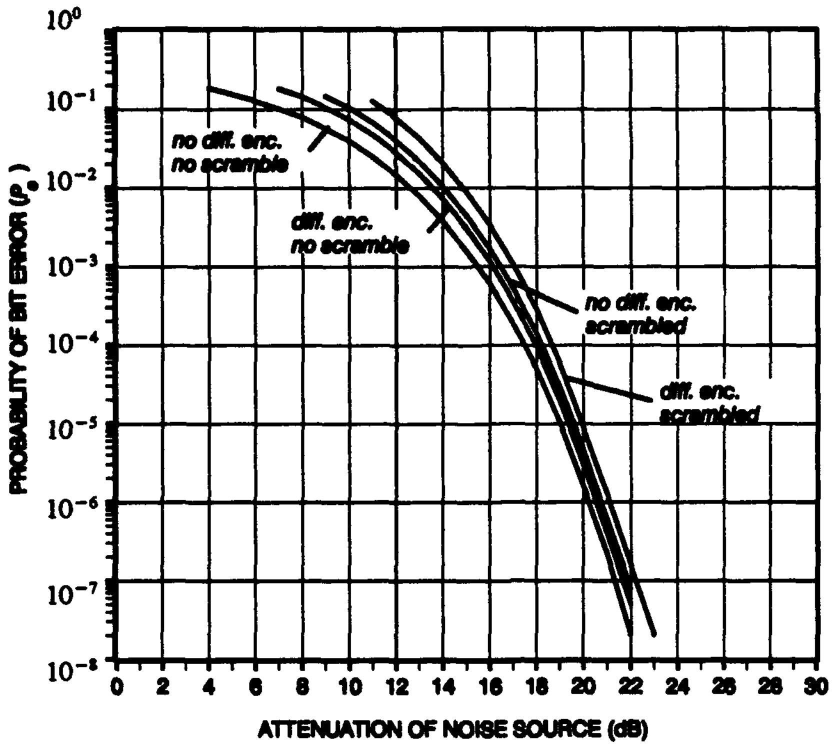

Figure 4. BER for BPSK at T1 (1.544 Mbps) for end-to-end test without antennas.

2.4 EXPECTED PROPAGATION AND FADING CONDITIONS

Section 2.2 calculated the median RSL based on the total transmitted power, free-space propagation loss, and transmit/receive antenna and cable gains. Over-the-air the received signal level will fluctuate in a random fashion about this median level. The reliability of a LOS digital radio is a function of the magnitude and rate of these RSL fluctuations. The reliability will be defined as

$$\text{reliability}(\%) = 100\% - \text{outage}(\%) \tag{3}$$

where the outage is usually expressed in percentage of seconds in which the BER is worse than 10^{-6}. For example, a reliability of 99.0% results in a average of 864 seconds/day (14.4 minutes/day) of outage induced by atmospheric conditions. Table 2 illustrates the relationship between reliability (sometimes called availability) and outage time. Variations from the median RSL can be caused by numerous atmospheric conditions, as shown in figure 5, including [4]:

1. Enhanced or reduced RSLs created by an *evaporation duct* close to the water surface. The RSL can be enhanced (reduced) if the receive antenna is (not) within the duct.

2. Multipath interference due to *refraction* of the transmitted signal off the troposphere. This tends to create frequency-nonselective (i.e., flat), rapid fading, which becomes more severe as the path distance increases.

3. Multipath interference due to *reflection* of the transmitted signal off the surface of the water. This tends to create frequency-selective, slow fading, which can be a function of the sea state.

4. Obstruction of the earth due to subrefractive conditions. This essentially creates a shadowing effect sometimes called earth bulging since the rays of the transmitted signal bend away from the earth.

Other nonatmospheric sources like ship and antenna movement can also create fluctuations in the RSL.

Table 2. Relationship between reliability and outage time.

Reliability %	Outage %	Outage Time		
		Year	Month	Day
0	100	8760 Hours	720 Hours	24 Hours
50	50	4380 Hours	360 Hours	12 Hours
80	20	1752 Hours	144 Hours	4.8 Hours
90	10	876 Hours	72 Hours	2.4 Hours
95	5	438 Hours	36 Hours	1.2 Hours
98	2	175 Hours	14 Hours	29 Minutes
99	1	88 Hours	7 Hours	14.4 Minutes
99.9	0.1	8.8 Hours	43 Minutes	1.44 Minutes
99.99	0.01	53 Minutes	4.3 Minutes	8.6 Seconds
99.999	0.001	5.3 Minutes	26 Seconds	0.86 Seconds
99.9999	0.0001	32 Seconds	2.6 Seconds	0.086 Seconds

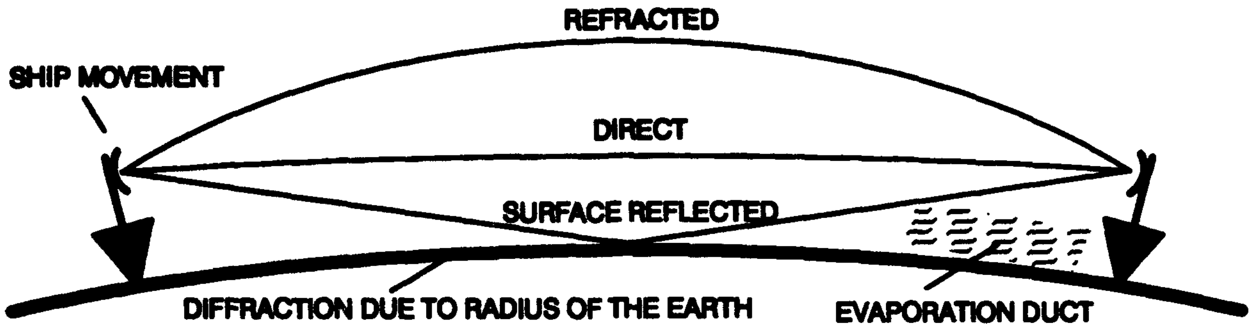

Figure 5. Possible atmospheric conditions which effect the received signal level.

Figure 6 shows the cumulative distribution of the refractivity gradient for San Diego for the months of February, May, August, and November from historical records [5]. Also shown in the figure are the regions of the four atmospheric conditions discussed above. The reflective multipath condition is by far the most prevalent condition in the San Diego vicinity, with a reasonable chance of refractive multipath and ducting occurring during the winter months (see [6] for more information on evaporation ducts for extending the range of communication links).

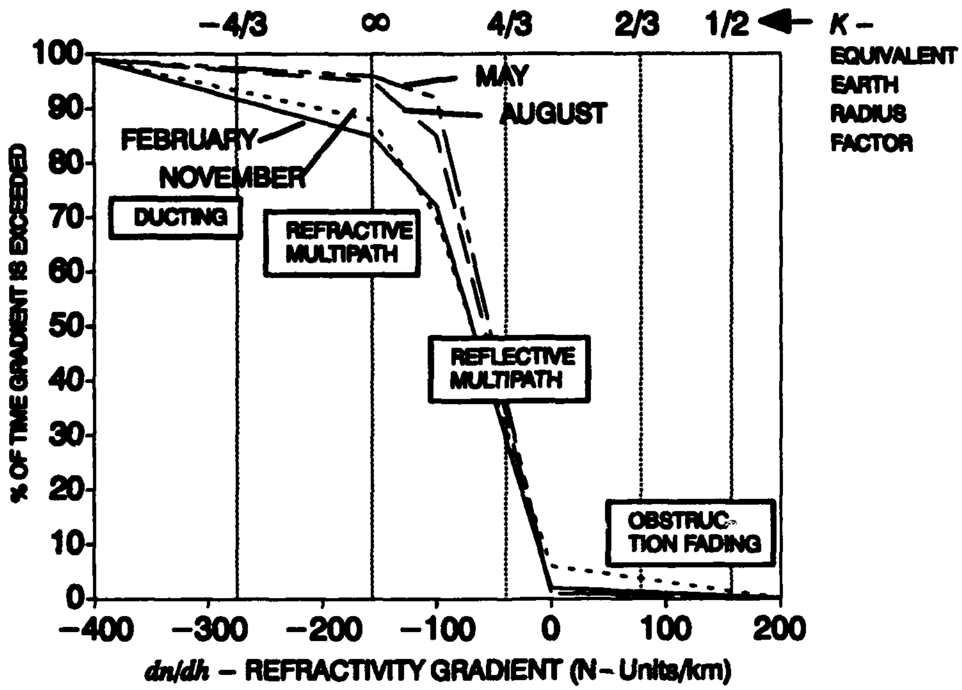

Figure 6. Refractivity gradient cumulative distributions for San Diego (from [5]).

Note that it is common in the communication literature to describe the refractive index gradient in terms of an equivalent earth radius:

$$K \approx \frac{157}{157 + \frac{\partial n}{\partial h}} \tag{4}$$

where n is the radio refractive index, h is the height, and K=1 is the true earth radius [3]. Figure 7 plots the straight ray representation of the terrain profile for the 13.1 km path for K = 2/3, 1, 4/3, and infinity. The refractive index gradient is assumed to be a constant. From the figure, it can be seen that the clearance of the direct path over the earth surface for K=2/3 is about 20 meters (66 feet) for an antenna height of 25 meters (82 feet). A common technique for determining the antenna height of a terrestrial digital LOS radio link is to make the clearance of the direct path over the earth surface for some K (typically K=2/3 or 1/2) greater than 0.6 times the radius of the first fresnel diffraction zone [3]. This minimizes diffraction losses during atmospheric conditions of subrefraction (earth-bulging). The radius of the first fresnel zone is given by

$$FR = \sqrt{\lambda \frac{d_1 d_2}{d_1 + d_2}} \tag{5}$$

where λ is the wavelength and d_1 is the distance from one antenna to the point of minimum clearance and d_2 is the distance from this point to the other antenna (i.e., $d_1 + d_2$ is the antenna-to-antenna distance). For a carrier frequency of 312 MHz and a 13.1 km path, FR = 56.1 meters (185 feet). Thus, the antennas would have to be 38.7 meters [= 0.6 x 56.1 + 5.1] (127 feet) above sea level to meet this clearance criterion for K=2/3. Clearly, this criterion can only be met by the highest antennas on a ship and in general will not be met in ship-to-ship communication at similar or greater distances.

The radio LOS range (sometimes called the radio horizon) can be defined as the range at which the direct path grazes the earth surface for some value of K. For K=4/3 and an antenna height of of 25 meters (82 feet), the radio LOS range is 41 km (22.1 nmi).

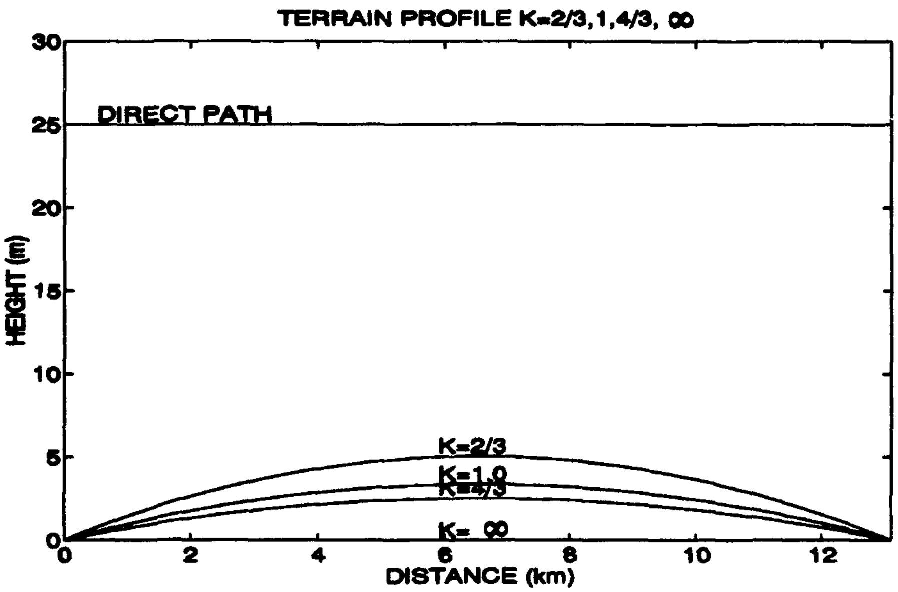

Figure 7. Terrain profile for 13.1 km (7.1 nmi) path.

Figure 6 predicts that the most common atmospheric condition will be multipath fading, $K \approx 4/3$. This condition clearly fits a two-path channel model, one direct path and one surface reflected multipath, given by Eq. 2.10 in [7]. In general, the surface reflection point (area actually) is dependent on K as will be the differential path length. However, for a 0^{th} ordered approximation, we will use the Pythagorean theorem and a flat earth approximation to estimate the differential path length. With this assumption, it can be shown that the differential path length is,

$$d_{\Delta}^{reflected} = d_{reflected} - d_{direct} \approx 2\sqrt{\frac{d^2}{4} + h^2} - d \tag{6}$$

The delay spread of this channel is $\tau_{\Delta} = d_{\Delta}/c$, where $c \approx 3x10^8$ m/s is the speed of light. Figure 8 plots the differential path length in meters and the delay spread in nanoseconds for $h = 25$ meters (82 feet) and $h = 40$ meters (131 feet). Note that the delay spread decreases with path distance. From figure 6, there is a much smaller chance that a refractive multipath condition could appear. The differential path length between a refracted path of 3 degrees (approximately the largest refraction angle possible) and the direct path is given by

$$d_{\Delta}^{refracted} = d_{refracted} - d_{direct} \leq 2\,\frac{d/2}{\cos(3^{o})} - d \tag{7}$$

and is also plotted in figure 8. Note that for the refracted multipath, the delay spread increases with path distance.

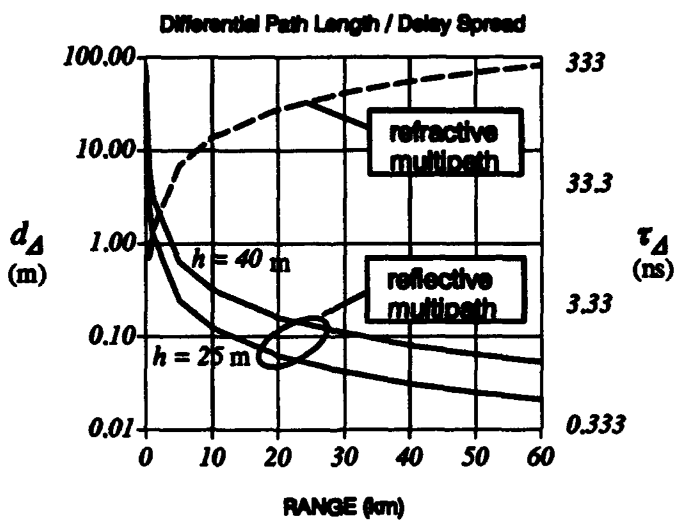

Figure 8: Differential path length and delay spread for antenna heights equal to 25 and 40 meters.

When the reflected path has a small scattering, as is typical from smooth surfaces, the multipath fading results in a frequency-selective channel frequency response with null separation given by [7]

$$\text{null separation} = \frac{1}{\tau_{\Delta}} \text{ (Hz)} \tag{8}$$

and spectral peak-to-null difference given by

$$\textbf{peak-to-null} = 20\,\log_{10}\frac{1+|\Gamma|}{1-|\Gamma|} \quad \text{(dB)} \tag{9}$$

where $|\Gamma|$ is the magnitude of the reflection coefficient. Table 3 lists the approximate magnitude of the reflection coefficients for a variety of common terrains. The magnitude of the reflection coefficient for calm sea water can be as high as 0.98, which results in as much as a 40 dB spectral peak-to-null difference! Figure 8 predicts that for the 13.1 km path and $h = 25$ meters, $\tau_{\Delta} \approx 0.1$ ns. From Eq. (8), this translates into a null separation is approximately 10 GHz. On the other hand, the 3 dB bandwidth required to transmit a T1 (1.544 Msps) signal is less than 2 MHz. Thus, the channel should appear like a flat, fading channel with up to 40 dB of RSL fluctuations depending on the sea state.

Table 3. Approximate magnitude of the reflection coefficient for real-life conditions (from [3]).

Calm Sea Water	0.98
Salt Flats	0.90
Desert Terrain	0.85
Cultivated Fields and Low Grass	0.78
Cotton Fields	0.72
Good Brush Coverage	0.65
Sagebrush, High Grassy Area	0.57
Partially Wooded	0.35
Rolling Hills with Very Good Tree Coverage	0.25
Heavily Wooded Forest Land	0.16

The primary means for maintaining a reliable communication link when the fading is flat and a single, omnidirectional antenna is being used is to increase the fade margin. This is discussed at some length for terrestrial LOS digital links in [8]. The amount of fade margin required for a given reliability is determined by the severity of the fading, which is a function of atmospheric conditions, antenna height, carrier frequency, and path length. In [8], the San Diego terrestrial environment is described as "difficult" due to the influence of the ocean on the atmosphere. The corresponding approximate fade margins required to maintain a given reliability are plotted in figure 9. The authors are unaware of a corresponding plot for any maritime LOS environments; however, one might expect that the fading could be equal to or *worse* than a "very difficult" terrestrial environment, which is plotted in figure 10. Using figures 9 and 10, it can be seen that for a BPSK signal transmitted at T1 (1.544 Mbps), the 15 dB fade margin computed in Section 2.2 should result in a 99.9% to 99.99% reliable communication link (better than 8.64 seconds/day of outage).

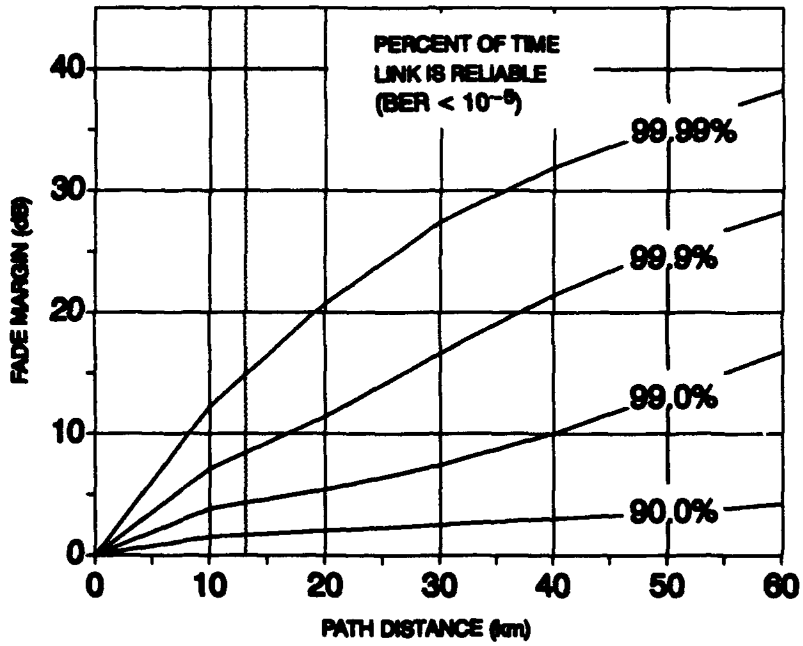

Figure 9. Approximate fade margins required for a "difficult" terrestrial, LOS link with flat fading. The path distance is assumed to be within the radio horizon and the carrier frequency is 300 MHz. (Data from table 6–1 of [8])

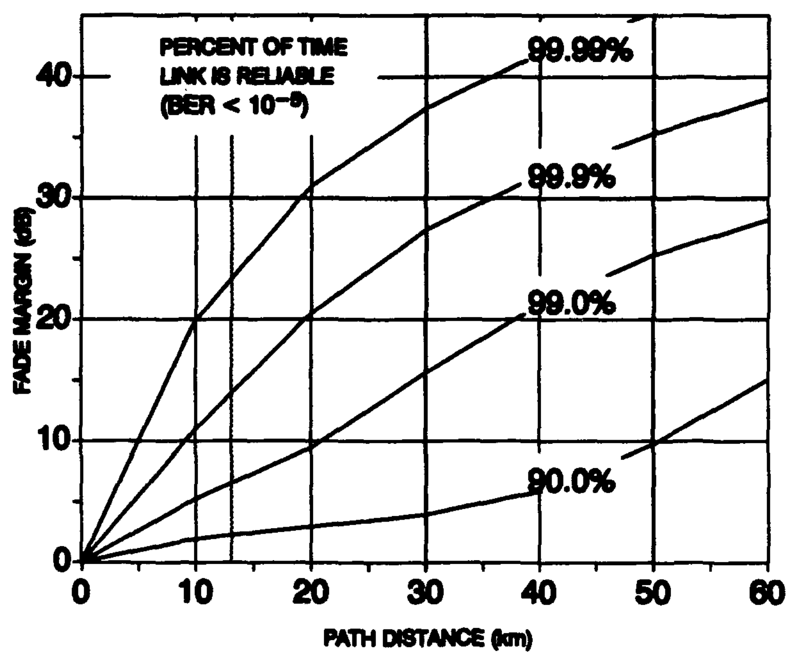

Figure 10. Approximate fade margins required for a "very difficult" terrestrial, LOS link with flat fading. The path distance is assumed to be within the radio horizon and the carrier frequency is 300 MHz. (Data from table 6–1 of [8])

3.0 DESCRIPTION OF MEASUREMENTS

3.1 MEASUREMENT TECHNIQUES

Three techniques will be used in parallel to measure and record communication data during the experiment (see figure 3). In addition, atmospheric data (water temperature, air temperature, wind speed and direction) will be obtained from NRaD, Code 563 (see [6] for a facility description). The first technique uses the conventional method of measuring and recording the RSL with a spectrum analyzer, either time-averaged spectrum data or time-domain data at a single frequency with the analyzer in "zero-span" mode. Present plans only allow for these data to be plotted on a as-needed basis, although the data could be easily stored via the HP-IB interface.

The second technique measures and records the statistics of the bit error performance with the TTC FIREBERD BERT. The BERT records performance statistics by observing the received bit error counts and received bit counts at 1 second intervals. Each 1 second interval is classified as available (AVL SEC), available and error free (EFS), available but severely errored (SES), or unavailable (UNA SEC) [9]. CCITT G.821 defines a period of time as unavailable when the BER in each second is worse than 10^{-3} for a period of 10 consecutive seconds. An available but severely errored second has a BER worse than 10^{-6} but better than 10^{-3}. Previously, we defined reliability (outage) as the number of seconds in which the BER was better (worse) than 10^{-6}. This can be found by subtracting UNA SEC and SES from the total number of seconds. This statistic is conveniently maintained on a minute time scale as degraded minutes (DEG MIN), which is outage minutes. These data will be printed with a time stamp on a regular basis (four times an hour) during periods of communication activity.

The third technique uses the Applied Signal Technology AST195 Wideband Snapshot Analyzer to sample the 70 MHz IF signal. The AST195 is a 6U VME chassis containing one SPARC2 card, one high-speed A/D and D/A card, and an 80 MFLOP Mercury engine card as well as two SCSI disk drives. It comes packaged with a graphical man–machine interface allowing for the analysis of communication channels on a per snapshot basis. Each snapshot can be sampled at up to a 250 MHz sample rate with 8 bits of accuracy. The snapshot memory is presently 64 Mbytes.

Custom-written software by the authors will perform the operations in figure 11 repeatedly. The input IF of $f_{IF}^1 = 70.0$ MHz is sampled at $f_{sample}^1 = 128 \times f_{sym} = 197.632$ MHz where the symbol rate is $f_{sym} = 1.544$ Msps. These data are downconverted to a second IF of $f_{IF}^2 = 0.75 \times f_{sym} = 1.158$ MHz by a mixing frequency of either $f_{mix} = f_{IF}^1 - f_{IF}^2 = 68.842$ MHz if the spectrum is not flipped or by $f_{mix} = f_{IF}^1 + f_{IF}^2 = 71.158$ MHz if the spectrum is flipped. The resultant data are then filtered with a low-pass filter (LPF) defined by a 3 dB bandwidth of $f_{LPF}^{3dB} = 1.5 \times f_{sym} = 2.316$ MHz and decimated by 32 so that the new sample rate is $f_{sample}^2 = 4 \times f_{sym} = 6.176$ MHz . The data and appropriate header information, including a time stamp, are stored on the disk.

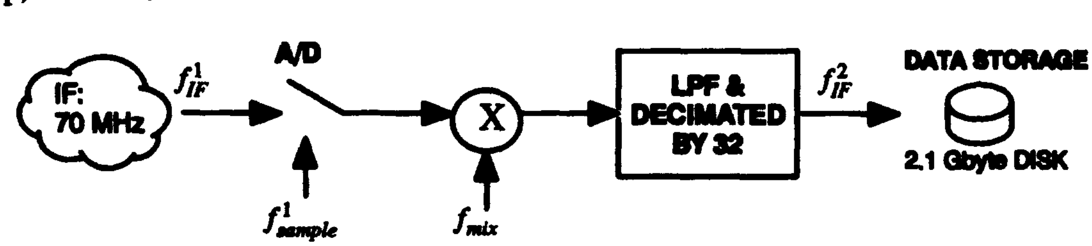

Figure 11. Signal processing performed on AST195 for data reduction and storage.

The spectrum of the stored data is shown in figures 12 and 13 for a T1 (1.544 Mbps) BPSK signal transmitted from the CM401 and from an "ideal" transmitter respectively. The ideal transmitter uses a standard raised cosine filter and shows no significant overlap between positive and negative frequencies for excess bandwidths up to 50% (12.5% shown in figure 13). However, the CM401 uses a 6-pole butterworth filter which does not have as sharp cutoff characteristics, and thus some overlap exists. At the present time, this overlap is not expected to be a problem; however, if it is, then the second IF will be increased. Table 4 lists the bandwidth characteristics of the CM401 for a T1 symbol rate (BPSK or QPSK).

Table 4. Transmitted signal bandwidth of a T1 signal from the CM401.

Transmit Symbol Rate:	1.544 Msps
Transmit 1dB BW:	1.41 MHz
Transmit 3dB BW:	1.53 MHz
Transmit 40dB BW:	3.42 MHz

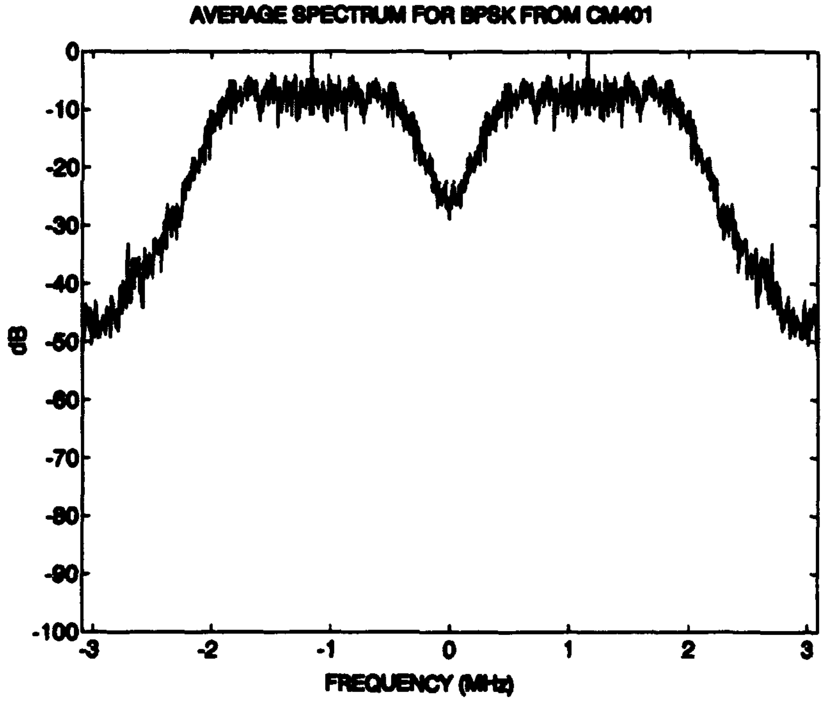

Figure 12. Spectrum of stored data for a T1 BPSK signal from the CM401.

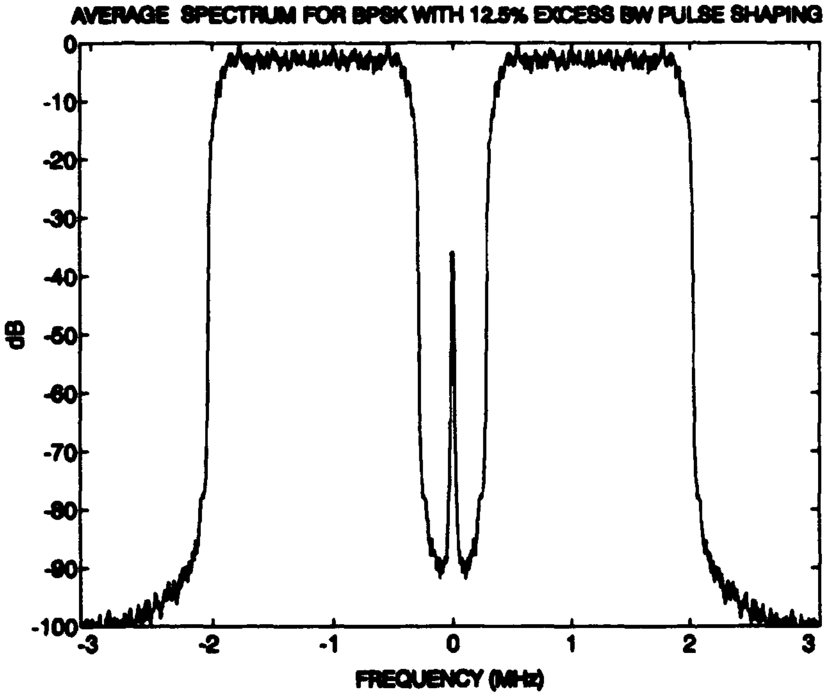

Figure 13. Spectrum of stored data for a T1 BPSK signal with raised cosine square pulse shaping with 12.5% excess bandwidth.

Table 5 lists the storage requirements for snapshot sizes of 8 Mbytes and 64Mbytes. An 8 Mbyte snapshot stores 42.45 ms of contiguous communication data which consists of 65,536 contiguous symbols. Since the transmitted PN sequence contains $2^{15}-1 = 32{,}767$ bits, the snapshot contains two complete PN sequences when the modulation is either uncoded BPSK or rate 1/2 coded QPSK and four complete PN sequences when the modulation is uncoded QPSK. After decimation by 32 and changing to 32-bit floating point variables, this results in 1 Mbyte of data to be stored for each snapshot. Quite a lot of data indeed! If the snapshots are taken every 2 seconds, the data will fill a 2.1 GByte disk in about 68.27 minutes. For this reason, software is being written which will only write the snapshots to disk during times of dramatic fluctuations in the RSL. In addition, more efficient sampling techniques like bandpass sampling are being investigated. Some of these techniques allow for the sampling rate to be as low as $f^1_{sample} = 8 \times f_{sym} = 12.352$ MHz with little performance degradation [1].

Once the 2.1 Gbyte disk is filled, it will be automatically archived on a 5 Gbyte Exabyte tape. The stored data will later be analyzed to

1. determine the statistics of RSL (see section 3.2)
2. fit the received data to a finite impulse response (FIR) channel model at every symbol time to characterize the channel dynamics and to use in evaluating other modulation/demodulation techniques
3. fit the received data to the classical terrestrial LOS channel model, the Rummler model

The latter two analysis techniques are described in more detail in [10]. The Rummler model is only appropriate if the channel is frequency-selective, i.e. it displays visible notches in the spectrum of the received data. As previously discussed, it is expected that a T1 (1.544 Msps) transmission rate will result in a flat (frequency-nonselective) fading condition so the Rummler model would not be an appropriate choice to model the channel.

Table 5. Snapshot size and storage requirements of AST195.

Snapshot Size	8,388,608 (2^{23})	67,108,864 (2^{26})	8,388,608 (2^{23})	67,108,864 (2^{26})
Time Between Samples	5.06 ns	5.06 ns	80.96 ns	80.96 ns
Snapshot Duration	42.45 ms	339.57 ms	679.1 ms	5.43 sec
No. of Samples / Symbol	128 (2^7)	128 (2^7)	8 (2^3)	8 (2^3)
No. of Symbols / Snapshot	65,536 (2^{16})	524,288 (2^{19})	1,048,576 (2^{20})	8,388,608 (2^{23})
Decimation Factor	32 (2^5)	32 (2^5)	0	0
Stored Samples / Snapshot	262,144 (2^{18})	2,097,152 (2^{21})	1,048,576 (2^{20})	8,388,608 (2^{23})
No. of Bytes / Sample	4 (32 bits)	4 (32 bits)	4 (32 bits)	4 (32 bits)
No. of Bytes Stored / Snapshot	1,048,576 (2^{20})	8,388,608 (2^{23})	4,194,304 (2^{22})	33,554,432 (2^{25})
No. Snapshots Stored / 2.1Gbyte (2^{31})	2048 (2^{11})	256 (2^8)	512 (2^9)	64 (2^6)
Time Between Snapshots	2 sec (minimum)	16 sec (minimum)	8 sec (arbitrary)	64 sec (arbitrary)
Time to Fill 2.1 Gbyte (2^{31})	68.27 min	68.27 min	68.27 min	68.27 min
Recorded Time Span	1.45 min	1.45 min	5.79 min	5.79 min

3.2 EXPECTED FADING STATISTICS

In the previous sections, the RSL was described as a time-varying random variable. It is common in terrestrial mobile environments to discuss three separate regimes based on the distance between the transmit and receive antennas, d, which characterize the RSL (see for example [11], [12], [13]). The regimes are called the power-law propagation regime, the log-normal shadowing propagation regime, and the Rayleigh fading propagation regime. While there will undoubtedly be some differences in the maritime mobile environment, the differences are expected to be limited to specifics inside these regimes.

The power-law propagation regime determines the median RSL as the receiver is moved radially away from the transmitter. Several terrestrial mobile communication experiments have shown that the median RSL decreases by d^{-n} for $2 \leq n \leq 6$ over regions of tens of kilometers [11], thus the name power-law. It should be pointed out that the free-space propagation loss given by Eq. (1) implies that the median RSL decreases by d^{-2}. This represents the loss due to the radiated power being evenly disturbed over the surface area of a sphere of radius d in the absence of any other objects. The difference between the actual loss and the free-space propagation loss is sometimes called the propagation factor [6] and is caused by conditions such as ducting, refraction, reflection, and shadowing, as described in section XX. The median RSL can be accurately estimated by software programs like SLAM [14]. For example, figure 14 plots E_b/N_o at the receiver against range for the parameters defined in Table 1.

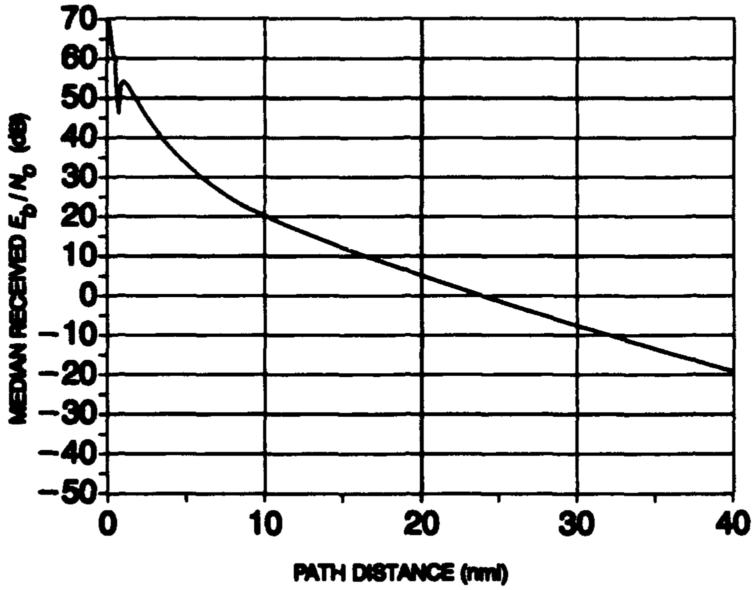

Figure 14. Median received E_b/N_0 plotted against range for 8 watts of transmit power at 312 MHz as predicted from SLAM.

The log-normal shadowing propagation regime determines the random variations of the RSL about the median RSL determined by the power-law trend for small shifts in range *d*. The classic example is that if the RSL is measured in decibels as the receiver is moved in a circle of radius *d*, it would fit a gaussian distribution (thus the name log-normal). These random variations cannot be exactly predicted by any software.

The Rayleigh fading propagation regime determines the random variation of the RSL about the median RSL determined by the power-law trend for very little or no shifts in range *d*. That is, the RSL tends to fit an exponential distribution, or equivalently the signal envelope tends to fit a Rayleigh distribution. For mobile environments, the log-normal shadowing and the Rayleigh fading are actually combined into a more complicated composite distribution of the RSL. For the experiment discussed in this report, no log-normal shadowing should be apparent, since the transmitter and the receiver are stationary. Thus, this experiment is likely to see pure Rayleigh fading or perhaps Rician fading, since in the maritime environment the direct path is rarely blocked and typically only 1 or 2 additional multipaths will be present.

To determine if a snapshot of data fits a Rayleigh model or a Rician model, the data will be (1) checked for sample-to-sample independence with the Kendall rank correlation test, (2) checked for stationarity with the Kolomogorov–Smirnov two-sample test (KS–2), and (3) tested for goodness-of-fit with the Chi-Squared test and the Kolomogorov-Smirnov one-sample test (KS–1) [15],[16]. In addition, the data will be plotted on Rayleigh paper for a visual verification of the test results. Rayleigh paper is designed so that only Rayleigh-distributed random variables plot as a straight line with slope equal to −1. Random variables with any other distribution plot as curved lines. Figure 15 demonstrates this by plotting four random variables on Rayleigh paper. Each random variable has a different probability density function (pdf), Rayleigh, Rician, uniform, and Gaussian-squared (Gaussian distributed random variable squared), and these are plotted in figure 16. Only the Rayleigh-distributed variable plots as a straight line with slope equal to −1. It should be noted that any generalized exponential distributed variable will also plot in a straight line, but with a slope different than −1 (see [17] for more details).

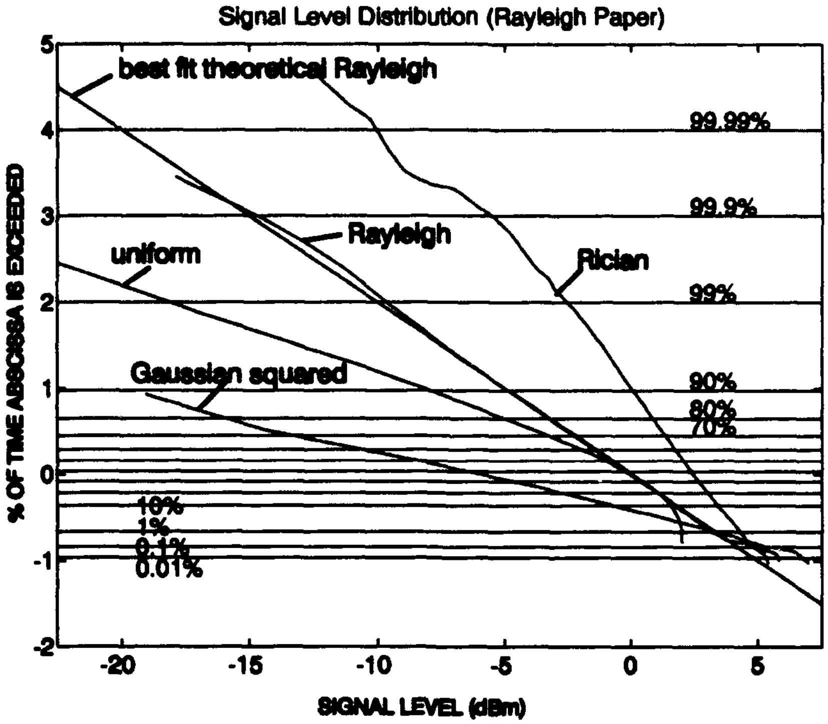

Figure 15. Rayleigh paper example for variables with Rayleigh, Rician, uniform, and Gaussian-squared distributions.

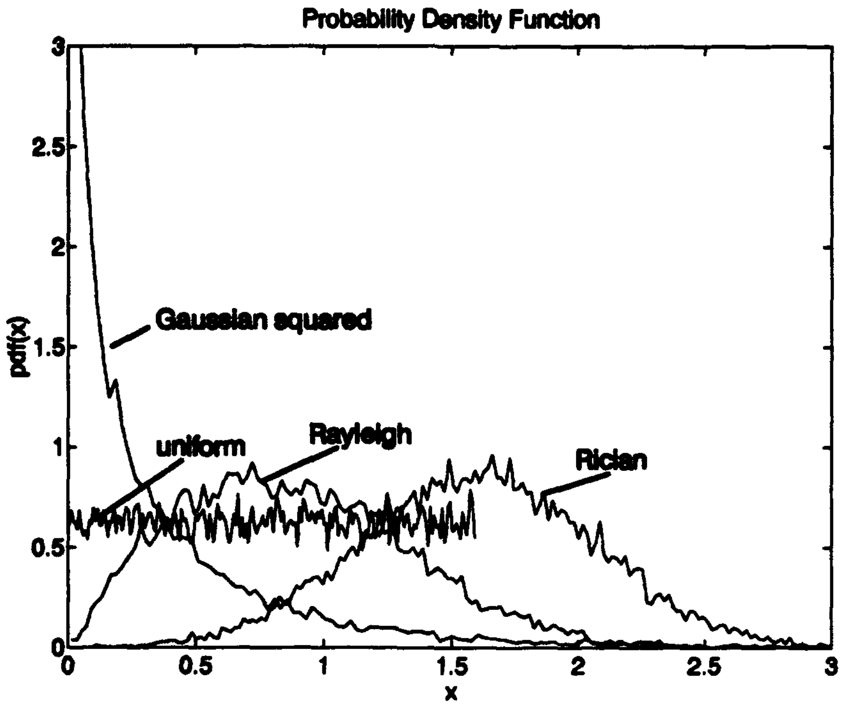

Figure 16. Estimated probability density functions of random variables in figure 15 (Rayleigh, Rician, uniform, Gaussian-squared).

The diurnal variations and fade rates are two other statistical measures of interest to radio system designers. Diurnal variations can be found from plotting the averaged BER every 15 minutes for several days at a time. Fade rate information can be obtained by plotting the level crossing rate versus the RSL. These data come from the RSL-versus-time plots like the one shown in figure 17. The time resolution of the data must be greater than the fastest fades; for example, sampling at several hundred hertz is typically sufficient for fade rates of tens of hertz. Figure 18 shows a typical level crossing plot for a fade rate of 2 Hz, 20 Hz, and 120 Hz.

Figure 19 displays a nomograph for computing the maximum fade rate for a moving vehicle on land [18]. As an example of its use, assume that a vehicle is travelling at 50 km/h (27 knots) and transmitting at 300 MHz carrier frequency to a stationary receiver. By drawing a line on figure 19 between known values, a worst-case fade rate of about 13 Hz is predicted. The authors are unaware of a similar nomograph for moving vehicles in the maritime environment but it is expected to be similar.

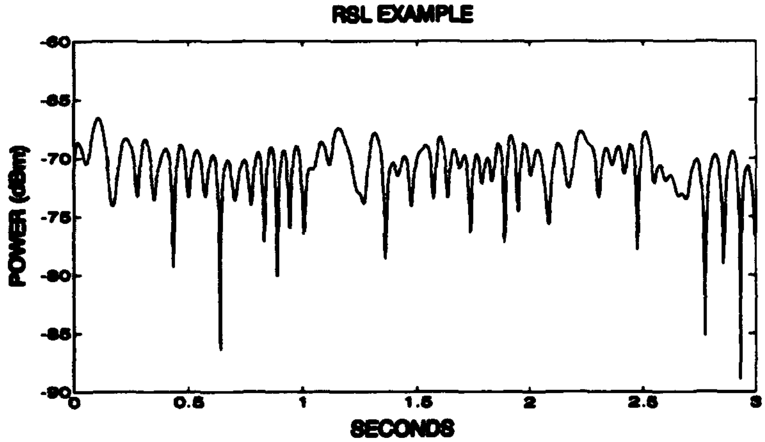

Figure 17. Example of the received signal level in a Rayleigh fading channel.

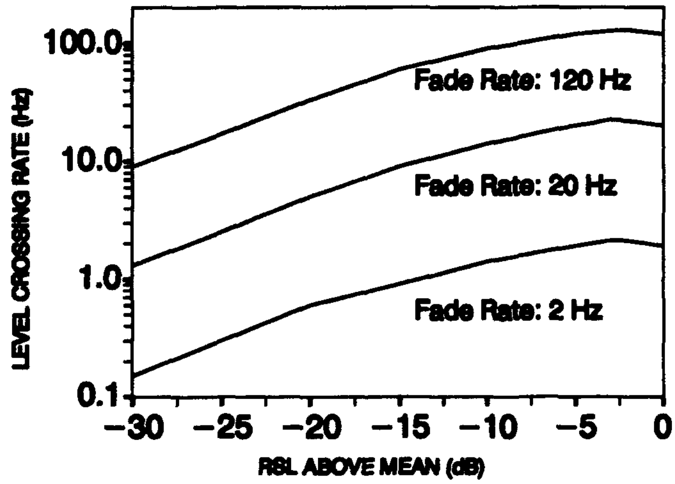

Figure 18. Example of the level crossing rate plot (from [18]).

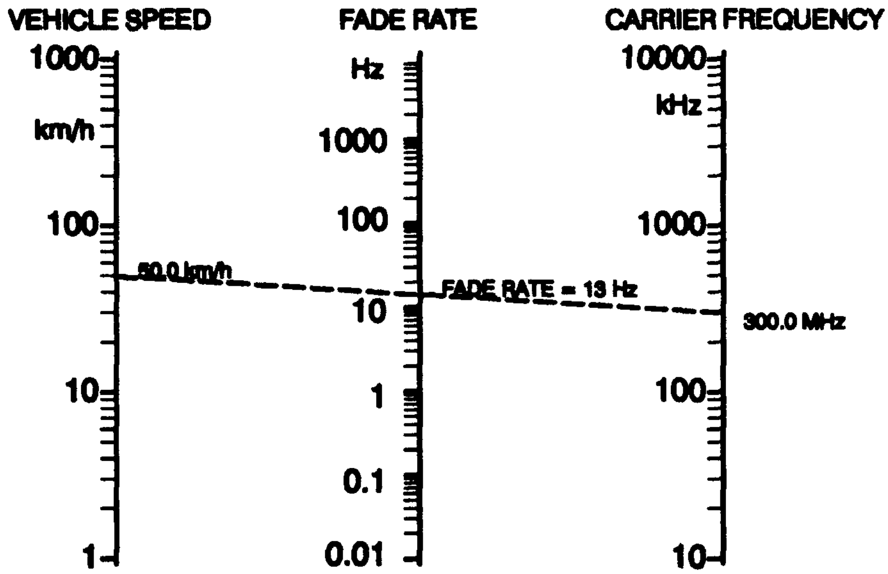

Figure 19. Example of a nomograph showing the relationship between terrestrial vehicle speed, maximum fade rate, and carrier frequency (from [18]).

4.0 TIME SCHEDULE

All site preparations are expected to be completed by late spring 1994 (May/June 1994 timeframe). End-to-end testing of all the equipment and computer control programs is anticipated to commence in May/June 1994 and continue for about 1 month. This phase of testing will include on-air testing and will baseline the equipment with BER curves versus RSL. Once the equipment and software have been verified, the transmit and receive instruments will be moved to building 99, NAVCOMTELSTA, Imperial Beach and building 15, NRaD, San Diego, respectively.

The initial over-air transmission will consist of a pure CW signal to further align the instruments, followed by full operation consisting of transmitting a T1 symbol rate with a modulation of uncoded BPSK (1.544 Mbps), uncoded QPSK (3.088 Mbps), or rate 1/2 coded QPSK (1.544 Mbps). The total experiment is expected to last three continuous months during the summer of 1994.

5.0 HDR UHF LOS RADIOS PRESENTLY IN U.S. MILITARY

The authors are aware of two HDR (defined here as over 100 Kbps) UHF LOS radios presently in the U.S. Military. The U.S. Army has been operating the AN/GRC–226 for tactical LOS links since roughly 1985. The AN/GRC–226 covers all three military bands of the UHF spectrum: band I: 225–400 MHz, band II: 610–960 MHz, and band III: 1350–1850 MHz. The full-duplex radio transmits a continuous-phase FSK modulation at TRI-TAC (256, 512, 1024, 2048 Kbps) data rates. Minimum transmit/receive carrier spacing is 50 MHz when a single antenna is used for transmission and reception. It also has an analog orderwire mode of operation to maintain communications in the most severe circumstances. Its maximum output power is 5-10 watts and the receiver sensitivity is a BER of 10^{-5} for an RSL of –92 dBm. Approximately 7000 units have been built and delivered to the U.S. Army by the Canadian Marconi Company, Montreal, Quebec, Canada. The U.S. Army is committed to these radios at least through the year 2000.

The U.S. Marine Corps is operating the AN/MRC–142 for tactical LOS links up to 35 miles. The AN/MRC–142 is installed in an HMMWV and is built to ford 5 feet of water. It is presently configured to operate in band III of the military UHF spectrum at data rates of 144, 288, and 576 Kbps; however, the radio is capable of 2048 Kbps and can be easily modified to operate in the other two UHF bands. The full-duplex radio transmits binary FSK modulation and requires a 63 MHz separation between the transmit carrier frequency and the receive carrier frequency when a single antenna is used. Its maximum output power is 3 watts and the receiver sensitivity is a BER of 10^{-4} for an RSL of –93 dBm. Approximately 500 of these units have been built and delivered to the U.S. Marine Corps by Loral TerraCom, San Diego, California. It should be noted that some tests are planned for at-sea tests with the AN/MRC–142 during the U.S. Naval exercise *Agile Provider* during April 1994. These tests are being conducted by NCCOSC NISE EAST, Portsmouth, Virigina.

6.0 CONCLUSION

This report has described a high-data-rate, over-water, line-of-sight digital radio communication experiment to be conducted during FY94. The experiment is the first of several experiments planned to simulate a realistic ship-to-ship communication link in band I of the military UHF spectrum. Data rates of T1 (1.544 Mbps) and 2xT1 (3.088 Mbps) will be transmitted via a simplex link from NAVCOMTELSTA, Imperial Beach, California to NRaD, San Diego, California from June 1994 through August 1994. The test has been uniquely designed not only to demonstrate high data rates, but also to assess the reliability of high-data-rate links over water and evaluate methods of increasing the reliability and bandwidth efficiency of future radio systems. The experimental procedure may also be used to provide similar benefits to other naval communication systems.

7.0 REFERENCES

[1] Bryan, D., R. North, and R. Axford, "Algorithms and Technquies for Characterizing Digital Radio Channels," *in progress*.

[2] "DD 963 Class Antenna Systems Booklet: USS Spruance," Naval Sea Systems Command, Washington, DC, code ID No. 53711.

[3] Saveskie, P., *Radio Propagtion Handbook*, TAB Books, 1980.

[4] Richter, J., "Over-Water Radio Propagation in the Frequency Range from 30MHz – 300MHz," NOSC TD 973, Naval Ocean Systems Center, San Diego, CA, July 1986.

[5] Bean, B. et al., *A World Atlas of Atmospheric Radio Refractivity*, U.S. Government Printing Office, Washington, DC, 1966.

[6] Rogers, L. T. and K. D. Anderson, "Evaporation Duct Communication: Measurement Results," NRaD TR 1571, Naval Command, Control, and Ocean Surveillance Center, RDT&E Division, San Diego, CA, Jan. 1993.

[7] North, R., R. Axford, and D. Bryan, "The Effects of a Multipath Channel and Interference on Coherent *M*-PSK Digital Communication Systems," NRaD TR 1636, Naval Command, Control, and Ocean Surveillance Center, RDT&E Division, San Diego, CA, Nov. 1993.

[8] Brockel, K. et al., "Tactical Line-of-Sight Radio Propagation Reliability," CECOM–TR–91–3, U.S. Army Communications–Electronics Command, Fort Monmouth, NJ, Oct. 1991.

[9] Telecommunications Techniques Corp. (TTC) FIREBERD 6000, reference manual (see Appendix C), Germantown, MD, Dec. 1992.

[10] North, R. C., "The Simulation and Estimation of Digital Communications Channels," NRaD TN 1718, Naval Command, Control, and Ocean Surveillance Center, RDT&E Division, San Diego, CA, January 1993.*

[11] Hess, G. C., *Land-Mobile Radio System Engineering*, Artech House, Inc., Norwood, MA, 1993.

[12] Yacoub, M. D., *Foundations of Mobile Radio Engineering*, CRC Press, Boca Raton, FL, 1993.

[13] Ivanek, F., *Terrestrial Digital Microwave Communications*, Artech House, Inc., Norwood, MA, 1989.

[14] James, R. and J. Rockway, "Super High Frequency (SHF) Link Analysis Model (SLAM) for Nonsatellite Applications," NOSC TD 1350, Naval Ocean Systems Center, San Diego, CA, June 1990.

[15] Personal correspondence with D. W. Stein, Naval Command, Control and Ocean Surveillance Center, RDT&E Division, Code 761, San Diego, CA, March 1994.

[16] Siegel, S. and N. J. Castellan, Jr., *Nonparametric Statistics for the Behavioral Sciences*, McGraw-Hill, New York, 1988.

[17] Hansen, P. M., "The use of Rayleigh Paper to estimate the parameters of the exponential and Weibull Distributions," NELC Technical Note 1783, Naval Electronics Laboratory, San Diego, CA, Dec. 1970.

[18] Casas, E. F. and C. Leung, "A Simple Digital Fading Simulator for Mobile Radio" *38th IEEE Vehicular Technology Conference*, pp. 212–217, June 1988.

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13. ABSTRACT *(Maximum 200 words)*

This report describes a high-data-rate, over-water, line-of-sight digital radio communication experiment to be conducted during FY 94. The experiment is the first of several experiments planned to simulate a realistic T1 (1.544 Mbps) ship-to-ship communication link in band I of the military UHF spectrum (225–400 MHz). The experiment plan calls for the one-way transmission from NAVCOMTELSTA, Imperial Beach, California, to NCCOSC RDT&E Division, San Diego, California, a 13.1 km (7.1 nmi) over-water propagation path. The test has been uniquely designed not only to demonstrate high data rates, but also to assess the reliability of high-data-rate links over water and evaluate methods of increasing the reliability and bandwidth efficiency of future ship-to-ship radio systems.

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