Packet testing in free-space optical communication links over water

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ABSTRACT

NRL's Chesapeake Bay lasercom test facility (LCTF) offers a variety of ranges for researching free-space optical laser communication (FSO lasercom) links in a maritime environment. This paper discusses link performance over the 16 km one-way range at the LCTF. There are several methods to determine the link quality in FSO lasercom. Bit-error-rate (BER) testing and packet testing are two possible methods. Since errors generally tend to occur in bursts in FSO channels, packet testing may offer a better indication of the quality of service (QoS) rather than BER testing. Link performance measured via packet testing is being investigated in a variety of atmospheric conditions. Results of these experiments will be presented.

Keywords: Free-space optical laser communication, Bit-error-rate

1. INTRODUCTION

The Naval Research Laboratory (NRL) is currently investigating the performance of free space optical laser communications (lasercom) at NRL's Chesapeake Bay lasercom test facility (LCTF), which offers a maritime environment with varying atmospheric conditions over 16 km one-way and 32 km round-trip ranges. Bit-Error-Rate (BER) testing has been the most common method of characterizing the quality of a free-space optical (FSO) lasercom link. Link performance measurements can also be done through packet testing. Analysis of packet testing will be discussed to determine how to best describe the quality of service (QoS) of a FSO lasercom link because of the burst nature of the errors in FSO channels.

The LCTF consists of a building 30 meters above the water on the western shore of the Bay at NRL's Chesapeake Bay Detachment (NRL-CBD), and a small area of land located on the eastern shore at approximately water level (NRL-Tilghman Island). A circular array of twenty-five retro-reflectors is mounted 15 meters above water level at NRL-Tilghman Island (NRL-TI). The retro-reflector array folds the path of the lasercom system creating a 32 km round-trip link and makes it possible to co-locate the transmitter and receiver at NRL-CBD (Figure 1).

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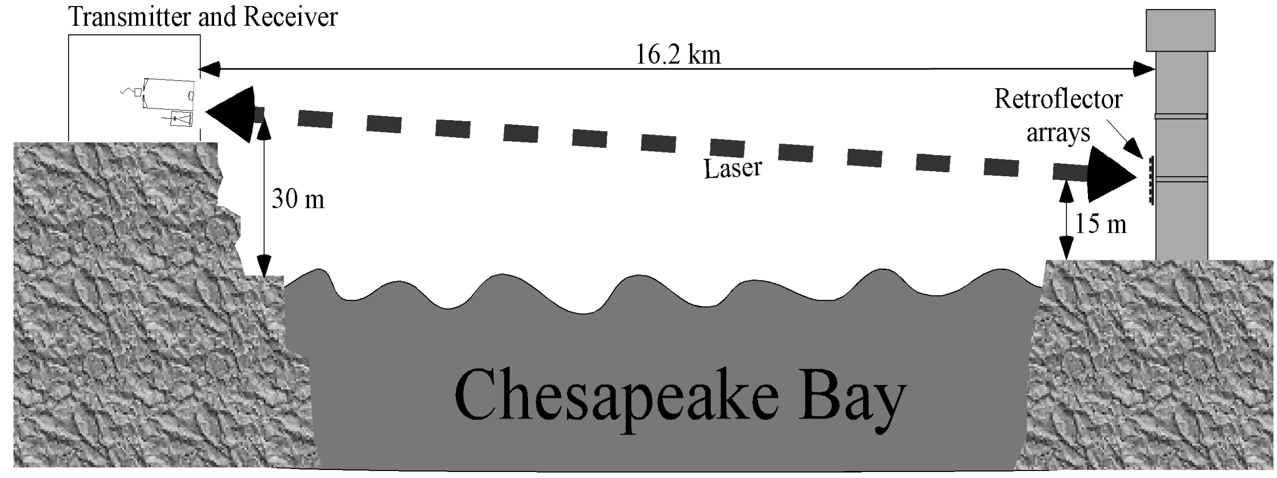

Figure 1: 32 km retro-reflected lasercomm test range between NRL-CBD and NRL-TI

Intermittent sampling has shown successful closure of maritime lasercom links at rates from 155 Mbps to 2.5 Gbps in conditions ranging from light rain and fog to clear low turbulence.[1,2] The LCTF is routinely used for BER and packet-error-rate (PER) testing on the 32 km round-trip FSO link, as well as the newly implemented 16 km one-way link as shown in figure 2. Data collected on the 32 km range can be found in references 1 and 2. This paper will discuss packet testing results on the 16 km one-way link.

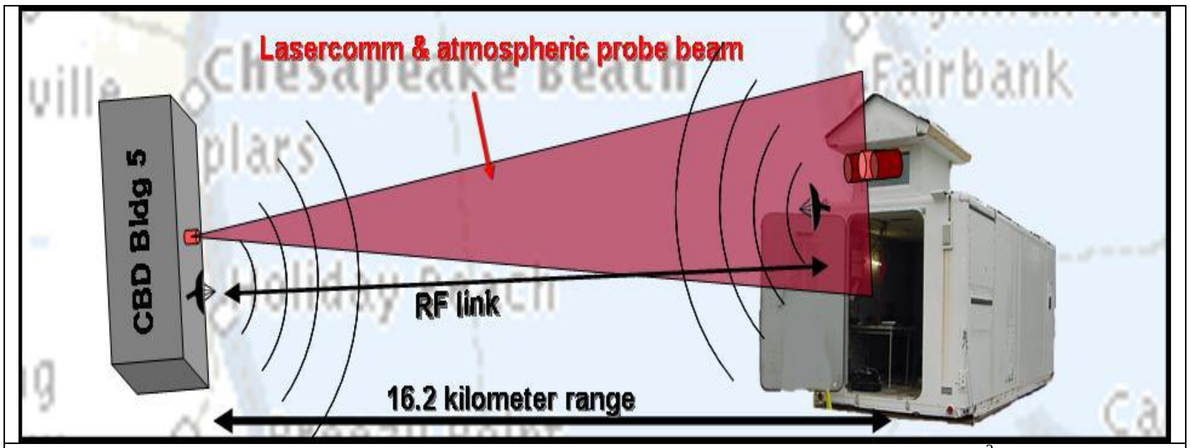

Figure 2: 16 km one-way lasercomm test facility between NRL-CBD and NRL-TI[3]

The 16 km one-way packet testing configuration of the lasercom transmitter, located at NRL-CBD on the west bank of the Chesapeake Bay, is shown in Figure 3. A laptop sends packets via Ethernet to an IMC Networks MiniMC 10/100 switching media converter. The MiniMC transmitter unit converts the 10/100 Base-T Ethernet to a 0 dBm optical signal that is SC connectorized to drive the EDFA preamplifier, or seed laser. The seed laser output is then amplified by a 5 Watt Keopsys erbium-doped fiber amplifier (EDFA) that operates in the eye-safe C-band range of wavelengths (1535-1565 nm). A 10 cm lens is set to collimate or slightly diverge the beam before it is sent through a standard glass window and across the Chesapeake Bay.

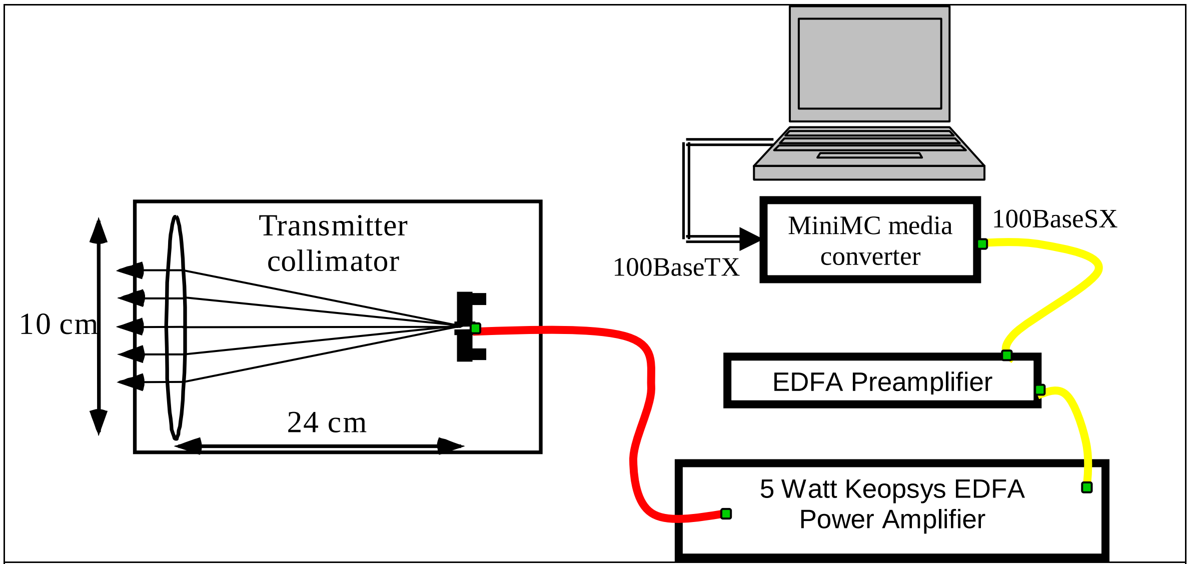

Figure 3. Transmitter configuration for packet testing at 100 Mbps on the 16 km one-way path

A lasercom receiver system has been installed at NRL-Tilghman Island to facilitate 16 km one-way operation. The system includes several components in order to record a variety of data to better characterize the impact of the maritime environment on the FSO lasercomm link, figure 4.

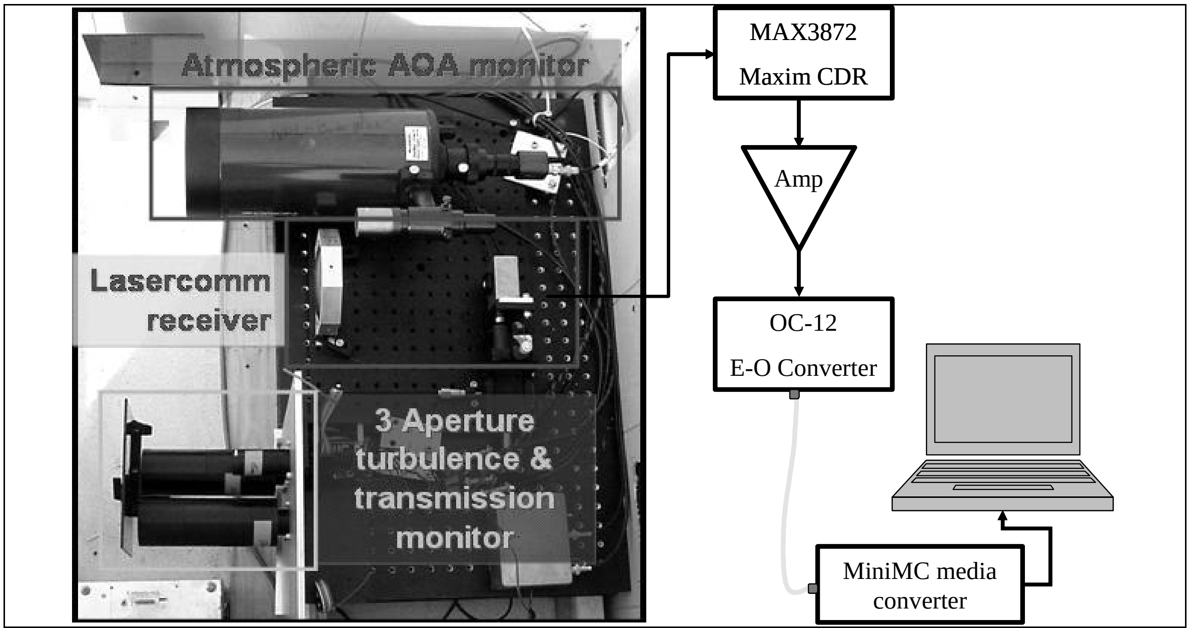

Figure 4: Receiver and monitoring system inside of the doghouse at NRL-TI.

The lasercom receiver is enclosed in a "doghouse" on the roof of a conex container at NRL-TI. An angle-of-arrival monitor and turbulence/transmission monitor are also housed alongside the lasercom receiver. Computers and diagnostic equipment are located inside of the conex container.

The lasercom receiver is a 200 micron diameter InGaAs Avalanche photodiode (APD) from Sensors Unlimited. The sensitivity of the 155 Mbps APD (SU001ATR) with differential trans-impedance amplifier (TIA) and on-chip automatic gain control (AGC) was measured in the lab to be -41 dBm. The beam is focused onto the APD using a 4 inch achromatic doublet and a 1 cm asphere (f# 0.8) from Geltech, giving it a large field-of-view. The receive signal from the APD is amplified and then fed into a MAX3872 Maxim clock and data recovery (CDR) board. For packet testing, an

OC-12 transmitter is used to convert the electronic data signal from the CDR board back to optical for the fiber input to the MiniMC receiver. The MiniMC receiver converts the detected optical signal to 10/100 Base-T. The packet testing configuration used in the 16 km one-way FSO lasercomm link uses modified IMC Networks MiniMC units that forgo the Ethernet standard handshaking protocol. These specialized MiniMC units have the same performance characteristics as the full duplex models. The sensitivity of the MiniMC receiver was characterized in the lab with single mode fibers and 62.5 micron core multimode fibers and was found to be -41 dB and -40 dB, respectively. The MiniMC is operated in the 100BaseT mode for all packet testing at the LCTF.

In addition to the lasercom receiver there are three Judson InGaAs TE cooled PIN diodes with different aperture sizes (15 mm, 32 mm, and 50 mm) that are co-aligned to monitor the turbulence and transmission.[4] They are TE cooled PIN diodes with matched TIA's and each one is combined with a 1550 nm bandpass filter. Signal histograms, averages, and scintillation index are calculated from the raw data collected from the three apertures at NRL-TI. Angle-of-arrival (aoa) is calculated using a 5 inch Orion telescope and CamIR 1550 camera fed into a video tracker from DBA Systems that tracks the centroid of the beam intensity.[5] The data is logged at NRL-TI and is then processed to be transmitted back to NRL-CBD at a slower rate.

Freewave RF Ethernet Modems are used to transmit, via UDP protocol, the processed data from each of the components of the receiver system at NRL-TI back to NRL-CBD at a data rate of ~100 kbps. The RF link allows data collection and control to occur at NRL-CBD. For the 16 km one-way link the pointing is determined by the received power on the three aperture detectors. A Newport FSM-200 fast-steering mirror is now installed in the transmitter system at NRL-CBD for improved accuracy in pointing for both the 16 km and 32 km links.[6] The FSM is AR coated for 1550 nm and has a closed loop bandwidth of $\geq$ 550 Hz at a 100 micro-radian amplitude. Four voice-coil actuators allow for rotation in the x and y axes. The optical angular range is $\pm$ 3 degrees with a resolution of less than or equal to 2 micro-radians.

Software programs written in LabVIEW 7 control the pointing of the FSM, control the packets transmitted from NRL-CBD to NRL-TI, and collect the receiver system data sent through the RF modems from NRL-TI to NRL-CBD. Computers connected to the receive MiniMC via Ethernet at NRL-TI collect, analyze, and average the data so that the amount of return data does not overload the RF link. Data received from the RF modems is recorded and displayed on the main control computer at NRL-CBD. Packets are constructed using a uniform white noise generator in LabVIEW 7 with known seed numbers so that the same pseudorandom pattern is constructed at both ends of the lasercom link for accurate packet comparison. The MiniMC units operate under the IEEE 802.3u 100Base-TX protocols. 100BaseTX uses 4B/5B, or "Block coding". Every four bits of data has an extra 5th bit added to increase the different bit patterns available. This enables the 5-bit patterns to contain the 1's necessary for clock synchronization even if the data is all 0's. This overhead requires the master clock frequency to be 125 Mbps to achieve the 100 Mbps data rate. 802.3 Ethernet, a common method of data transfer using packets, also achieves reliable synchronization. It uses Manchester Phase Encoding, one of the most widely used encoding techniques in data transfer. The transitions in the middle of each bit make it possible to synchronize the sender and the receiver consistently. Manchester encoding has a master clock speed matching the data speed. A normal clock signal and an inverted clock signal are used to create regular transitions so that synchronization is easily attained even if there are a series of 0's or 1's.

2. RESULTS

The following results describe packet testing data collected on the 16 km one-way lasercom link. Packet error data was taken over a long period of time on March 27th, 2006. The output power was 19.3 dBm over the entire collection period from 1-5pm. Figure 5 shows the raw packet error percentages for this data set.

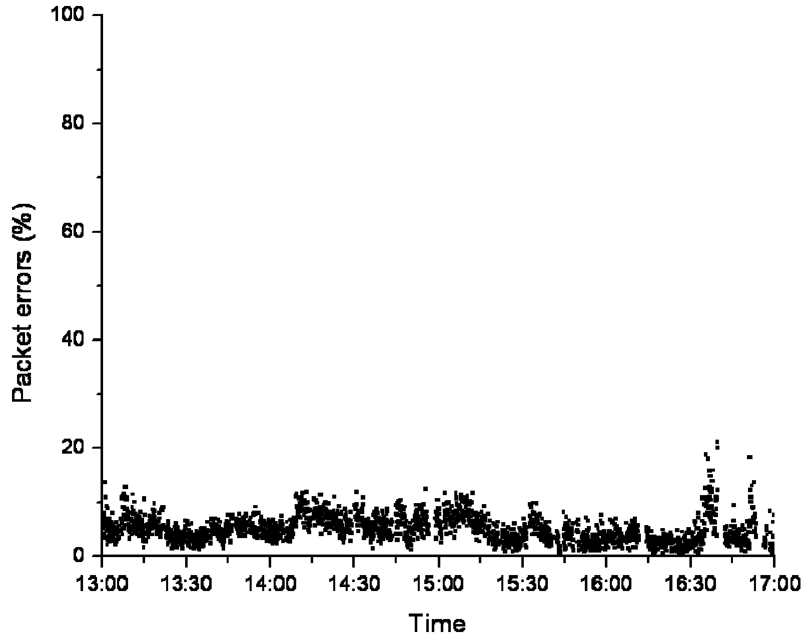

Figure 5: Raw packet error percent data recorded on March 27th, 2006.

The cumulative probability and probability distribution of these packet errors are plotted below in figure 6. The packet error rates are less than 10 percent for ~95 percent of the data set.

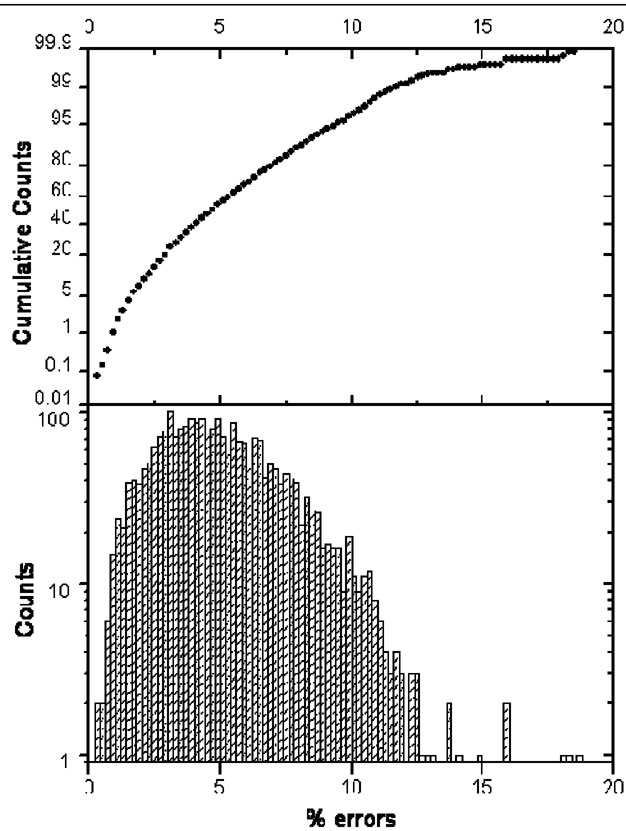

Figure 6: Distribution of packet error counts for the data collected on March 27th, 2006.

Figure 7 is the mean voltage and effective scintillation index data from the three apertures. The lower curves are the average voltages on each aperture and the upper curves are the effective scintillation indexes calculated from variance and mean every minute. Note the separation increase in the mean voltages at ~16:30 due to an increase in background light levels as the sun sets and illuminates the three aperture detectors. This also results in an increase in separation in the three effective scintillation indexes since the mean increases on larger apertures while the variance does not due to background. These backgrounds can be corrected for using relative average levels of the three apertures (see "Characterization of the Marine atmosphere for free space optical communication", LM Wasiczko et al, Proceedings of the SPIE: Atmospheric Propagation III, vol 6215).

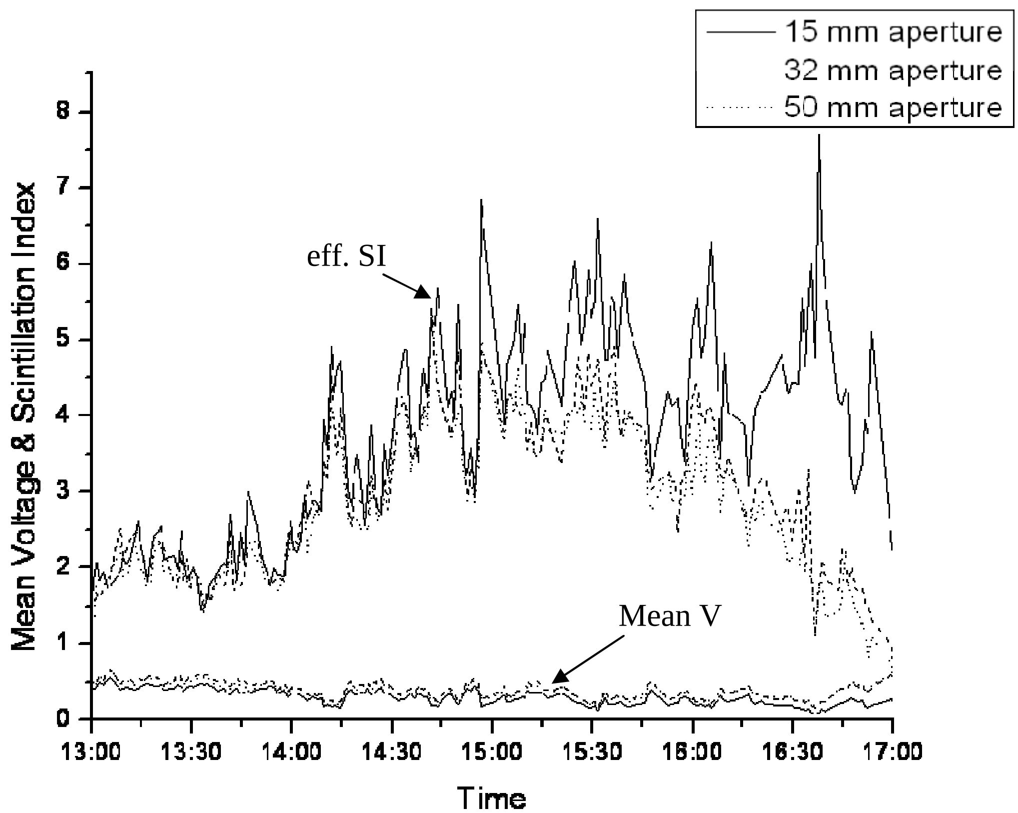

Figure 7: Mean voltage and effective scintillation index for all three aperture March 27, 2006 1-5pm.

Figure 8 below shows the large movements in relative elevation recorded from the angle-of-arrival monitor. The centroid of the beam changes by more than 800 micro-radians during this data set. The software controlling the fast steering mirror was upgraded to automatically re-align every 10 minutes and also to re-align itself if the signal return on the three apertures dropped by 50 percent in power.

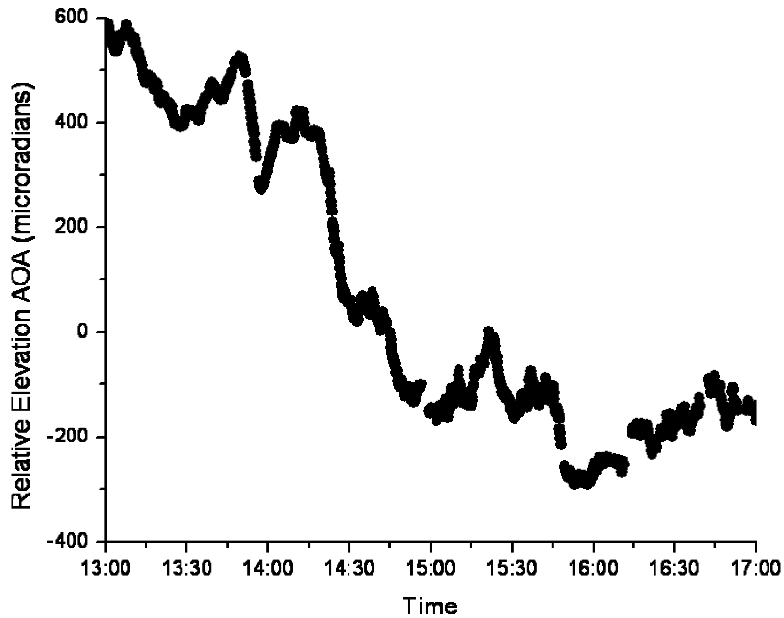

Figure 8: Relative elevation on the angle-of-arrival monitor recorded on March 27th, 2006.

Additional packet testing data is taken to compare packet errors to transmitter power. Ten minute intervals of packet error data are logged for five output power levels. The packet size is held constant at 2000 bytes throughout this data set. The data was collected on the afternoon of February 24th, 2006 with an average Cn^2 measured at $1.28x10^{-15}$. Figure 9 is the raw packet error data in time. The average packet error percentage versus output power is shown in figure 10. These figures illustrate how the packet error percentage decreases as the EDFA output power increases.

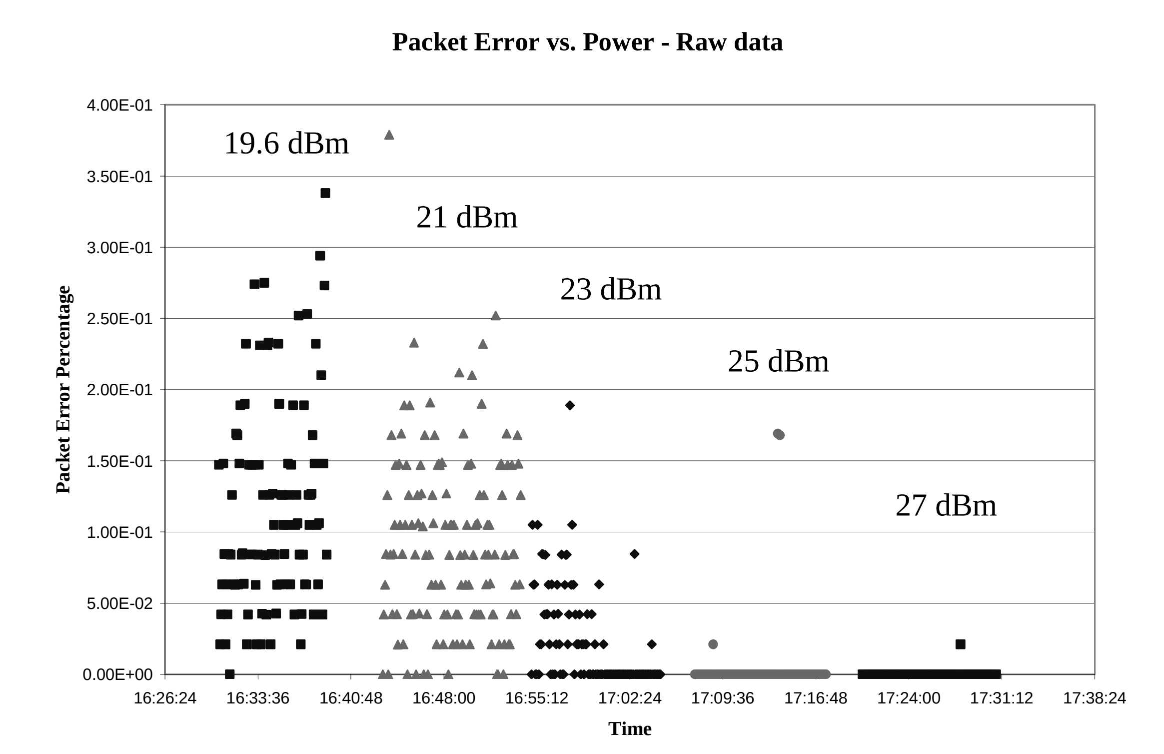

Figure 9: Raw packet error data for February 24th, 2006

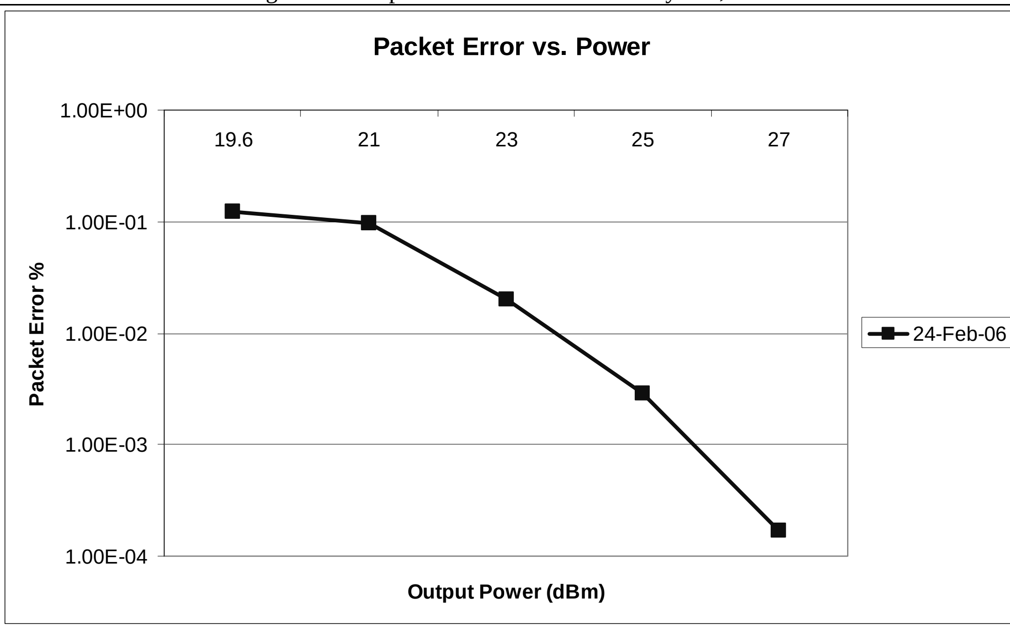

Figure 10: Averaged packet error data taken from 4:30-5:30pm on February 24, 2006.

Further analysis was done to characterize the effects that packet size has on packet error. At various laser output power levels (21-33 dBm) the packet data was collected and compared at five different packet sizes (100, 200, 500, 1000, and 2000 bytes) on March 15th, 2006. Cn^2 varied from 3×10^{-15} $m^{-2/3}$ to 7×10^{-15} $m^{-2/3}$ throughout the afternoon that the data was taken. When the transmitter output power is optimized for the atmospheric conditions there is no significant increase in packet error with packets sizes of 500 bytes and larger, as shown with the 28.5 dBm dotted line in figure 11. However, when the output power is not optimal there is a noticeable increase in packet errors as the packet size is larger than 1000 bytes. If the output power level is too high, as shown by the 33 dBm top curve, the power spikes cause the lasercom receiver to saturate and induce errors on the link. Conversely, if the output power is too low the scintillation effects cause more link errors, as shown by the 24 dBm middle curve. The larger the packet sizes the higher the probability that the spikes or fades will occur during a packet and the power at the receiver will reach saturation or it will drop below threshold. Either of these cases results in a sharp climb in packet errors for packet sizes above 1000 bytes, as shown by the solid lines in figure 11.

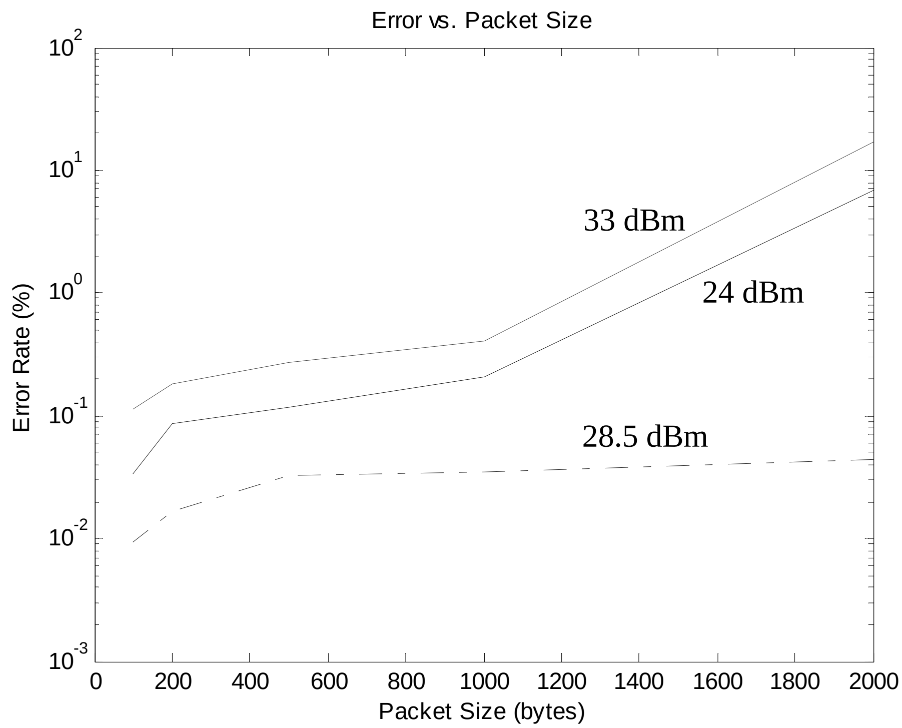

Figure 11: Packet error versus packet size and output power data taken on March 15th, 2006.

3. CONCLUSIONS

Characterization of FSO packet transfer in a maritime environment at NRL's LCTF has just begun. Packet error rate data has been presented for various atmospheric conditions on the 16 km one-way free-space laser communications link across the Chesapeake Bay. Packet testing data was collected for several transmitter power levels and/or packet sizes. It has been observed that optimal packet error rates are found over a relatively narrow range of transmitter powers (< 9 dB for the atmospheric conditions present in the experiment). If the output power is too low the fades cause the power on the lasercom receiver to drop below the receiver's detection threshold. If the output power is too high the peaks in received power cause the receiver to saturate. In both cases the packet error rates increased by two orders of magnitude with packet sizes greater than 1000 bytes. However, when the output power is optimal the packet errors show no noticeable increase as packet sizes increase. Long term packet testing has been performed in high turbulence (scintillation index ~4) with long time scale beam wander (> 800 μrad). Even in these adverse conditions, packet error rates below 10% were observed for 95% of the time. These initial results suggest that packet testing is a much better indication of FSO QoS owing to past experience at the LCTF where a BER of 10^{-2} would be observed in similar atmospheric conditions. Future work will quantify these results with direct comparison of packet error rates to bit-error rates.

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