

Latest Results from the 32 km Maritime Lasercom Link at the Naval Research Laboratory, Chesapeake Bay Lasercom Test Facility

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ABSTRACT

The Naval Center for Space Technology at the Naval Research Laboratory reports the latest results from the long-range, maritime, free-space lasercom test facility located between Chesapeake Beach, MD and Tilghman Island, MD. The two sections of the facility are separated by 16.2 km of the Chesapeake Bay. Using a new OC-48 receiver developed by NRL's Optical Science Division with a sensitivity of -33dBm for 10^{-9} bit error rate at 2.5 Gbps, we have closed a 32.4 km maritime lasercom link (round trip across the Chesapeake Bay) and performed bit error rate testing while transmitting 1.13 Terabytes of data. Bit error rate testing was also performed at lower data rates when atmospheric conditions were not favorable for high speed (2.5 Gbps), including testing at 150 Mbps through light fog and rain. In addition, we have set up a system for digitizing and transmitting full-color, uncompressed, video along with six audio channels and three RS-232 data channels over the maritime link. The digital link operated at 311 Mbps and could be maintained indefinitely, depending on atmospheric conditions. Several complete videos were transmitted in entirety or in part as well as live video from a handheld camcorder to test the system operation and robustness. The transmitter and receiver were co-located on the western shore of the bay at the NRL Chesapeake Bay Detachment. The data for both the bit error rate testing and the video was transmitted across the bay and returned from an array of retroreflectors located on a tower at Tilghman Island on the eastern shore. The lasercom links were closed with static pointing and with no active atmospheric aberration mitigation such as adaptive optics or fast steering mirrors on the receiver optics.

Keywords: Free-space lasercom, maritime, bit error rate, free-space optical communication

1. INTRODUCTION

For several years, the Naval Center for Space Technology (NCST) in cooperation with the Optical Science Division and the Remote Sensing Division at the Naval Research Laboratory (NRL) has been operating a free-space optical communications (FSO) testbed across the Chesapeake Bay. The west section of the testbed is located at the Chesapeake Bay Detachment (CBD), and the east end is located across the bay at Tilghman Island (TI). Both locations are in Maryland, and they are separated by 16.2 km of water. This facility is utilized for field-testing of optical components such as modulators¹, erbium doped fiber amplifiers^{2,3} (EDFA), and detectors developed and built at NRL along with commercially available components⁴. In addition to conventional lasercom, the facility at CBD is used to test communication links established with a modulating retroreflector^{5,6,7}. These links include ground to UAV and shore to ship links transferring real-time video and other data. Outside organizations desiring a long maritime FSO link to test their own equipment have used the Chesapeake Bay Lasercom Facility. The free-space lasercom test facility (LCTF)

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has also been valuable for the testing of equipment delivered to the Navy under SBIR's and other government sponsored research initiatives.

In addition to testing advanced components developed at NRL for FSO applications, another primary purpose of the test facility has been to characterize laser propagation through a long distance maritime channel and to provide a baseline estimate of the feasibility of FSO communication channels for use by the Navy in ship-to-ship communications as part of a hybrid RF-FSO communication package. The established heights of the facilities over the bay (30 meters at CBD and 15 meters at TI; Figure 1) approximate typical heights of candidate locations for FSO equipment installation on Navy ships. The one-way distance across the test facility of 10 miles (16.2 km) is representative of separation distances that could be encountered in Navy battle groups. By using returns from a passive retroreflector array on the tower at TI, distances longer than the actual round-trip distance of 20 miles can be simulated due to the small fraction (~0.4%) of the initially transmitted laser beam that is reflected^{4,10}.

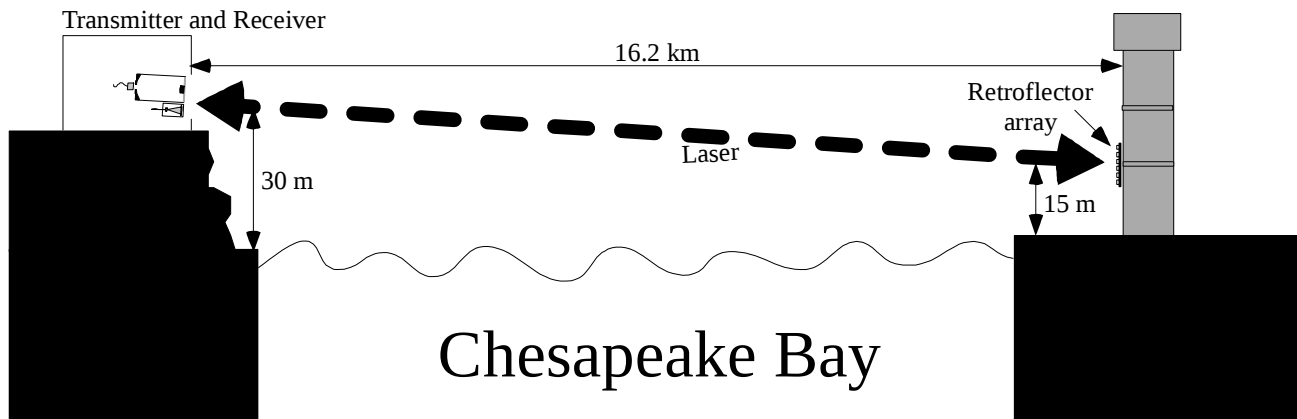


Figure 1: The layout of the free-space lasercom test facility at CBD. The transmitter and receiver were situated on a 30 meter cliff at CBD and the retro-reflector arrays were attached to a tower on Tilghman Island 15 meters above the water.

2. BACKGROUND – PREVIOUS PROPAGATION STUDY RESULTS

Previous atmospheric propagation studies performed at the free-space LCTF have included several efforts such as measurement of angle of arrival fluctuations at the FSO receiver with a Germanium position sensing device (PSD), development of a long range angle of arrival monitor (with C_n^2 estimation), measurement of intensity fluctuation power spectra under varying conditions for comparison to theory, and FSO link BER testing at various bit rates^{4,8,9,10,11,12}. These efforts have been toward establishment of a baseline of expected atmospheric conditions and possible FSO link performance in a maritime environment. The philosophy followed in these studies has been to attempt to quantify expected FSO link performance with primarily passive methods for atmospheric turbulence mitigation.

In Figure 2, the histogram for C_n^2 (estimated from angle of arrival fluctuations for the propagation path shown in Figure 1) indicates that in a maritime environment, the turbulence (or perhaps more importantly for lasercom applications, the angle of arrival variance) over a propagation path at the height shown is fairly benign compared to the majority of propagation studies done over land. The comparatively low C_n^2 values routinely encountered over this link have allowed BER testing to be performed with success in various conditions with no active turbulence mitigation methods^{4,10}. The results of some of the recent testing will be discussed in more detail in section 5 below.

Although atmospheric turbulence averaged over the path is relatively low, angle of arrival fluctuations of the received laser beam cause the effective focused spot size to be much too large (see Figure 3) to efficiently couple into a single mode fiber. Since the majority of commercially available high speed telecom optical receivers are fiber coupled with single mode fibers, FSO receivers must be special ordered with multimode fibers or with no fiber coupling. The majority of our FSO efforts have used laser wavelengths of 1550nm to take advantage of the development done by fiber telecom companies, as well as to take advantage of the much higher flux levels allowed while still being below the minimum permissible exposure (MPE) for eye safety. However, these wavelengths (C band, ~ 1535 – 1565nm) require InGaAs detectors. The noise and electrical characteristics of commercially available InGaAs detectors are typically much worse than silicon such that high speed InGaAs detectors must be very small (on the order of 30 micron diameters

for 2 – 3 GHz bandwidths). Recent developments in InGaAs technology look very promising for making detectors with low k-factors and active areas on the order of 100 – 200 microns while maintaining the bandwidths greater than 1GHz; however, the work presented in this paper was performed with currently available commercial InGaAs receivers with multimode fibers.

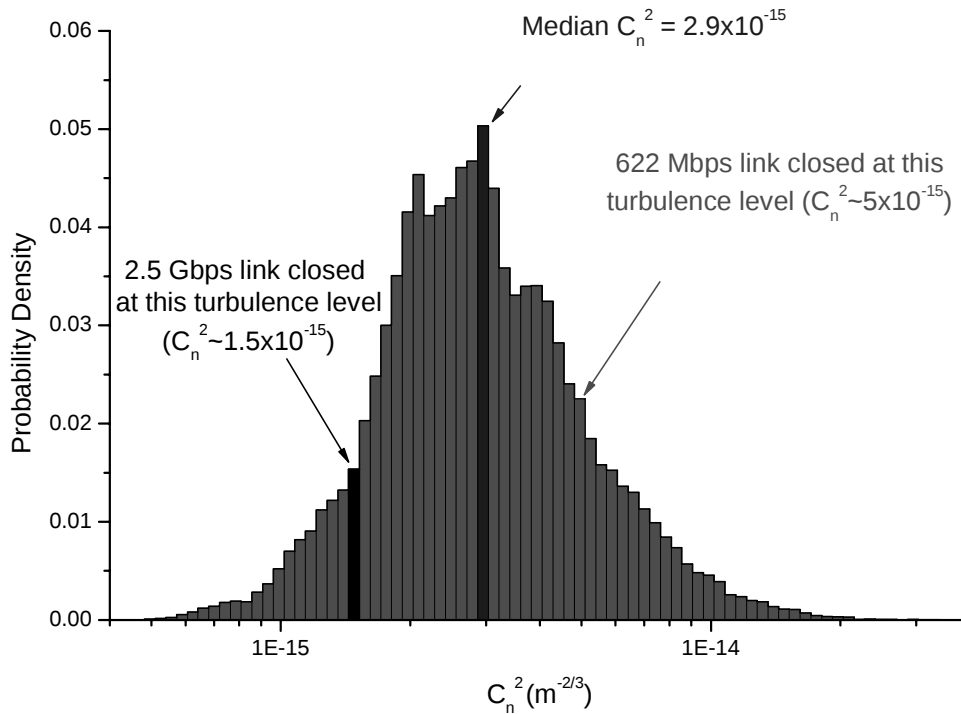


Figure 2. PDF of C_n^2 data taken over the Chesapeake Bay from April - July 2003 (from passive turbulence monitor; estimated from angle of arrival variance)

Figure 3 represents data taken with a Germanium PSD with a telescope with a four-meter effective focal length. The spread of the received focal spot indicates that the optical system requires modification in order to couple into a multimode fiber or onto a small diameter InGaAs detector efficiently. An effective method for accomplishing this is shown in Figure 4. By inserting a very short focal length, half-ball lens into the optical system, the spot motions can be de-magnified and brought much closer to the dimensions of the detector or multimode fiber core. This is the basic optical system used in our receivers at the LCTF for long distance BER studies and for video transfer.

3. TRANSMITTER DESCRIPTION

A block diagram of the FSO transmitter used for the BER testing is shown below in Figure 5. The electronic output signal from the pattern generator of an Agilent 86130A 3.6 Gbps Bitalyzer BER tester drives an OC-48 STX-48-HP-LR1 optical transmitter module from Optical Communication Products (OCP). The optical output of the STX-48 (0 dBm at 1548nm) is amplified with an EDFA preamp built by Optical Sciences Division at NRL to ~ 20 mW. This signal is then amplified with a two stage commercial EDFA from Keopsys up to a maximum of 5 watts. Single mode fiber coupling is used between all of the laser components. The output of the 5 watt Keopsys EDFA is allowed to diverge in air from the end of the output fiber to the four inch collimating lens. The collimating lens has a nominal focal length of 24 cm. The distance from the fiber to the collimating lens is adjusted with a micrometer to achieve a

divergence of $\sim 200 - 250$ microradians. The collimating lens assembly is mounted on a motorized gimbal from Sagebrush with 35 microradian angular resolution. The output beam transverse profile is a TEM₀₀ Gaussian.

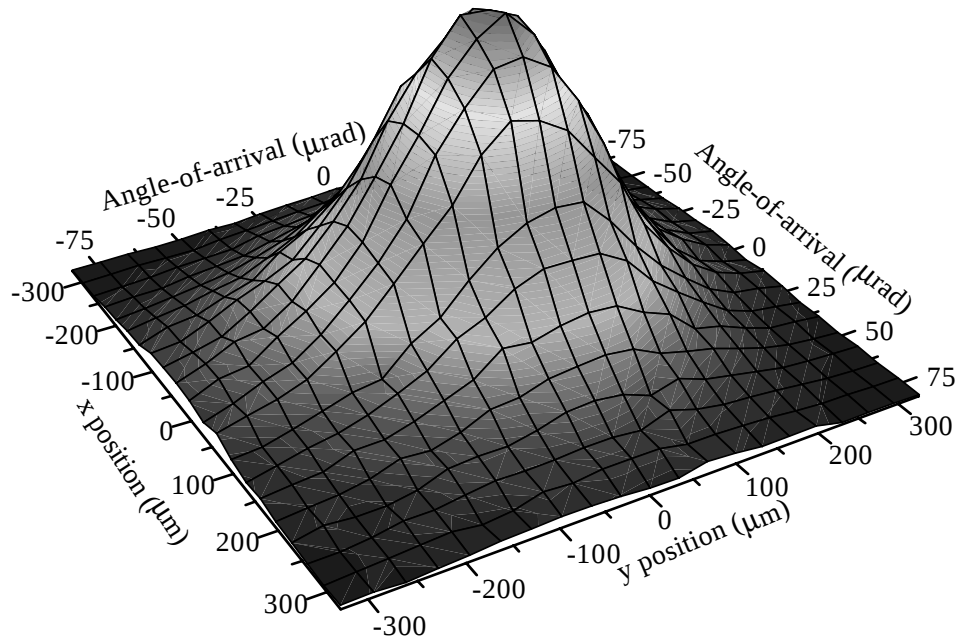


Figure 3. Received angle-of-arrival (AOA) fluctuations (2 minutes on 5x5 mm² Germanium PSD)

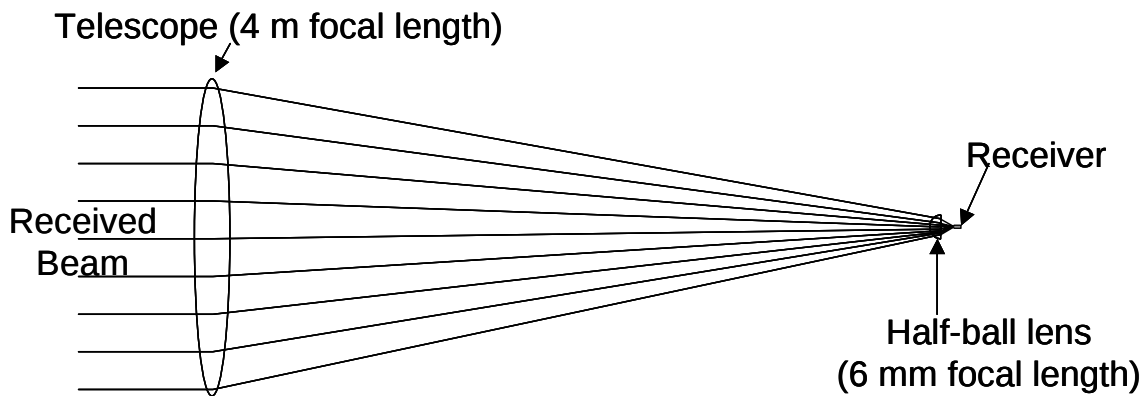


Figure 4. De-magnify the received beam to decrease focal spot motion and blurring below the dimensions of the receiver

For video transmission, the same receiver configuration is used as for the BER testing except that the initial optical input to the NRL-made EDFA preamp is from the Multidyne DVM-2000-FTX Video/Audio/RS-232 multiplexer and SMF optical transmitter. The initial output of the video transmitter module is -2.2 dBm at 1542nm, and at a bit rate of 300 Mbps.

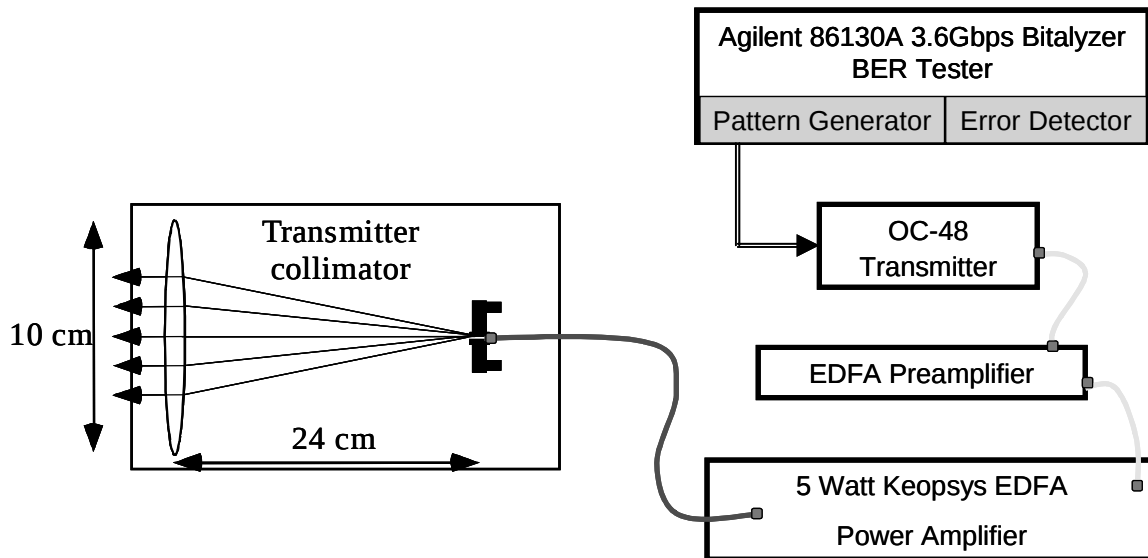


Figure 5. Transmitter configuration for BER testing

4. RECEIVER DESCRIPTION

The FSO receiver shown in Figure 6 and the transmitter shown in Figure 5 are arranged in a bistatic configuration with a 40 cm separation of their respective axes. The receiver is a 16-inch Meade telescope mounted in an Az-El gimbal. As shown in Figure 4, the Meade has an effective focal length of 4 meters, and its output is coupled into a 62.5 micron core multimode fiber using a short focal length half-ball lens. The multimode fiber provides the input to either an OC-12 Optical-Electronic-Optical (O-E-O) converter or to a new OC-48 O-E-O converter. Both of the O-E-O converters have multimode fiber inputs and were developed by Optical Sciences Division at NRL. The O-E-O converters provide sensitive detection and compatibility with optical fiber networks and test equipment. For BER testing, the single mode fiber output of the O-E-O converter is connected to an OC-48 receiver module from OCP for conversion back to electronic before applying the received signal to the error detector of the Agilent 86130A BER tester. For video transfer, the single mode fiber output of the OC-12 O-E-O converter is used directly as the input to the Multidyne DVM-2000-FRX SMF optical receiver.

4.1. O-E-O Converter construction

The OC-12 O-E-O converter is used for 150 and 622 Mbps BER Testing. It is constructed with COTS components from OCP. The multimode fiber coupled OCP receiver is an SRX-12, InGaAs PIN diode with -31 dBm sensitivity at 622 Mbps. The receiver is coupled to an OCP STX-12 transmitter module with an output of -5 dBm at 1310nm.

The OC-48 O-E-O converter is used for 2.5 Gbps BER Testing. It also is constructed with COTS components from several different manufacturers. A block diagram of the OC-48 O-E-O converter is shown in Figure 7. The optical receiver is a Fujitsu receiver, model FRM5W231DR, InGaAs APD with transimpedance amplifier (TIA). The detector has a $30\text{ }\mu\text{m}$ diameter active area, and is coupled to a 62.5-micron core multimode fiber. It has a 2.5 Gbps data rate (2.0 GHz BW) and a sensitivity of 1.0 A/W at 1550nm. The TIA has a transimpedance of 600 ohms. The receiver is in a butterfly PC board mount package and has noise current density of 6.5 pA/rtHz and rated sensitivity of -34 dBm for 10^{-10} BER. The electrical output of the Fujitsu receiver is passed through a Picosecond Pulse Labs, model 5915-100-1.87GHz, low pass filter with a -3dB cut-off at 1.87 GHz, before being applied to a Maxim Semiconductor multirate clock and data recovery chip (CDR). The CDR chip is a model MAX3872 with adjustable rate (OC-3, OC-12, OC-24, and OC-48), adjustable detection threshold, and an integral limiting amplifier. The output of the CDR chip drives an OCP OC-48 optical transmitter module. The transmitter module is an STX-48-HP-LR1 rated at 0 dBm at 1310nm.

The OC-48 O-E-O converter sensitivity was measured in the laboratory for 1550nm and for a BER of 10^{-9} . The sensitivity at OC-48 was -33 to -34 dBm (more than one O-E-O converter was made and tested). The sensitivity at OC-3 and at OC-12 was -37 dBm .

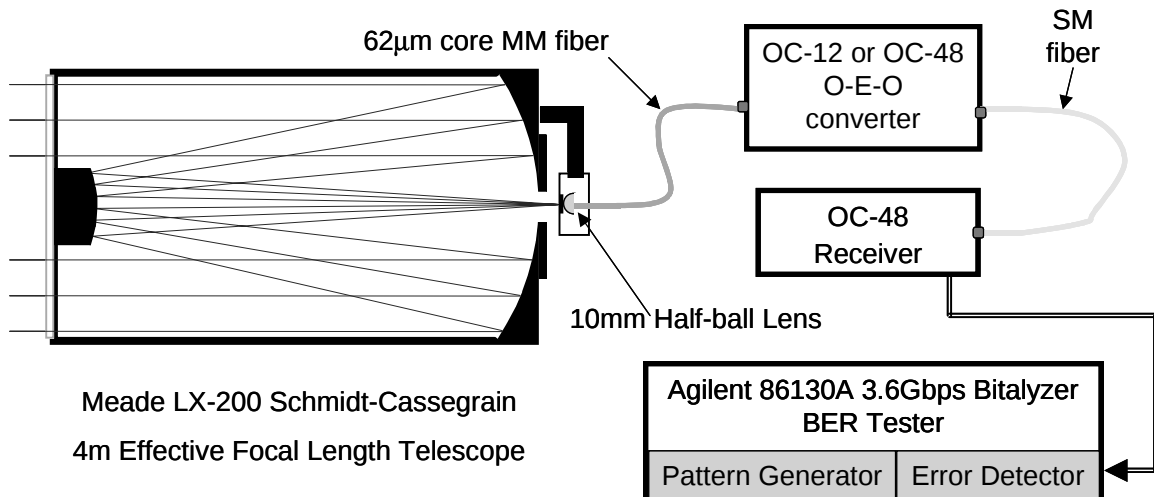


Figure 6. Receiver configuration for BER testing.

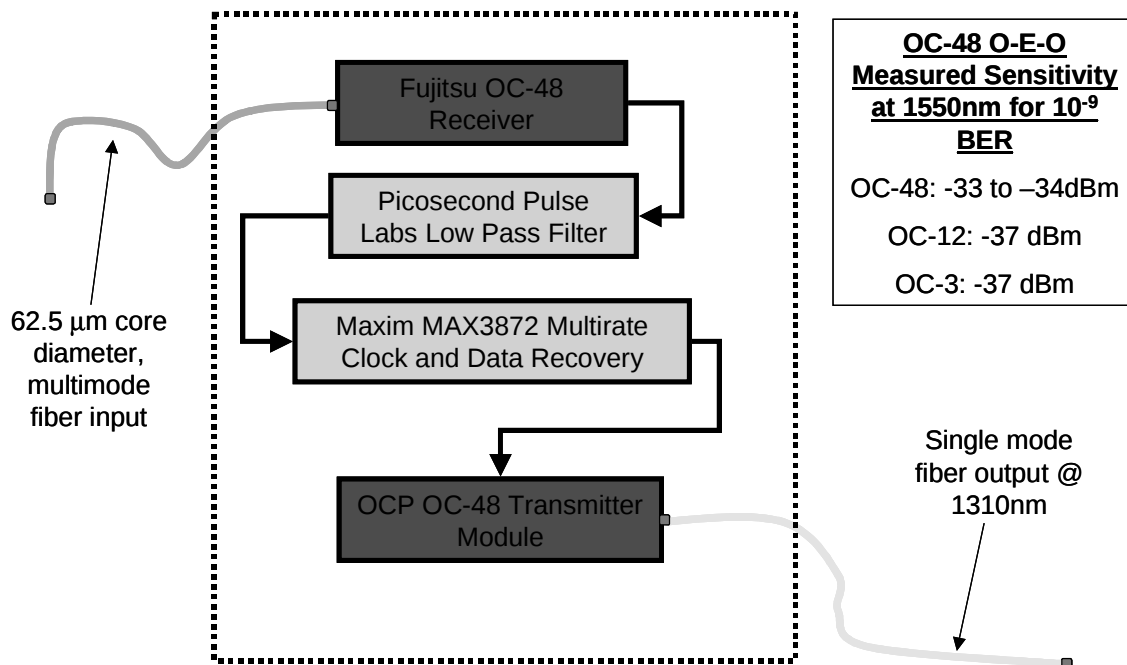


Figure 7. OC-48 O-E-O Block Diagram.

5. BER RESULTS

BER testing at various rates and under various weather conditions have been performed for several years at the NRL LCTF with no assists from closed loop tracking, fast-steering mirrors, adaptive optics, or forward error correction coding. Many of the results have been previously reported^{4,9} including the results shown in Figure 8 at 622 Mbps (OC-12). They are included again in this paper as an example of the effects of vertical thermal gradients that effect optical propagation over the water of Chesapeake Bay. Strong, slowly changing, thermal gradients over the water cause the transmitter pointing to slowly change in elevation over times of several minutes depending on the time of day and the weather conditions¹³. When performing BER testing with no active pointing and tracking, the maximum error-free

period is determined by the index of refraction gradient changes over the bay. These gradients can have characteristic change times from 10's of seconds to hours. The OC-12 BER data in Figure 8 shows the effect of this changing thermal gradient. Near the end of the test period, the pointing of the transmitter beam is being deflected vertically, causing the BER to increase. The data was taken with no adjustment of pointing. After stopping the test, a slight change in elevation pointing of the transmitter brought the BER back to 0 errors.

Typical conditions used during BER testing at the LCTF are: transmitted laser power = 2 - 5 Watts; wavelength = 1550 nm nominally (C band, 1535 – 1565nm); 32.4 km roundtrip off of an array of twelve two-inch retroreflectors on the tower at TI; transmitted beam diameter = 4 inches with 200 - 250 microradian divergence; receive aperture = 16-inch Schmidt-Cassegrain telescope; receive light coupled to 62.5 micron core diameter multimode fiber using 10-mm diameter half-ball lens; fiber coupled receivers used for all testing.

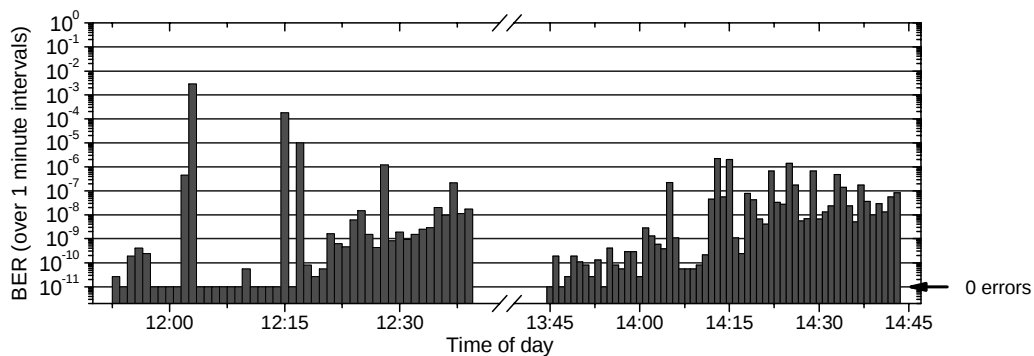


Figure 8. 622 Mbps BER testing across Chesapeake Bay (32 km); Medium turbulence ($C_n^2 \sim 5 \times 10^{-15}$) and average visibility (light haze); BER over 1 minute intervals during two one hour tests (No pointing adjustments!).

The BER results shown in Figure 10 were taken during a period of light fog and rain. The tower at Tilghman Island was not visible and pointing of the transmitter beam was accomplished by scanning over the known region of Az and El coordinates. By reducing the data rate to 150 Mbps (OC-3), the link could be closed with reasonable bit error rates. The value of C_n^2 was not available during this testing because the light on Tilghman Island used for measuring angle of arrival variance could not be seen or imaged. As the fog became increasingly heavy, it became correspondingly more difficult to maintain the link with a reasonable BER. Figure 9 has visible still photographs of typical test range visibility (left) and the visibility during the BER testing in fog and rain (right).



Figure 9. Visible photograph over test range in average visibility



Visible photograph over test range during rain/fog BER testing

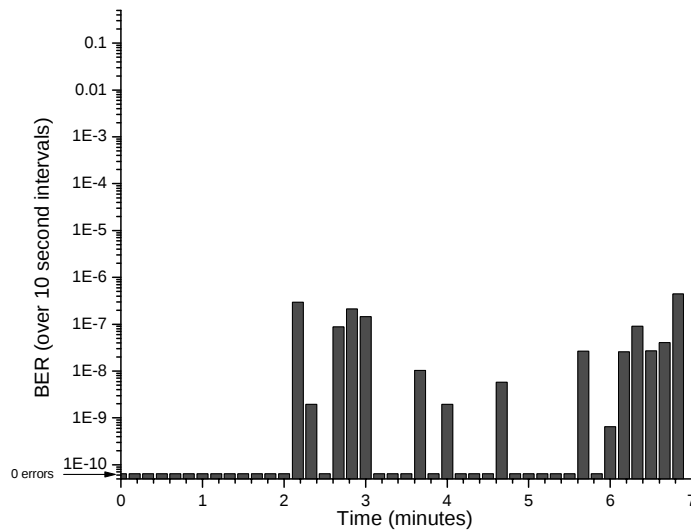


Figure 10. 155 Mbps BER testing across Chesapeake Bay (32 kilometers); Unknown turbulence ($C_n^2 \sim ?$) and poor visibility (light rain and fog)

Figure 11 contains BER results done at OC-48 (2.5 Gbps) during low turbulence conditions. The estimated C_n^2 was $\sim 1 \times 10^{-15}$ averaged over the path. The transmitted power was 4.3 watts and the path was 32.4 km (folded with an array of twelve two-inch passive retroreflectors). Two data sets were taken for a total time of $\sim$ one hour. During this time, approximately 1.13 Terabytes of data were transmitted and received with either no errors or short duration burst errors. As usual, there were no assists from closed loop tracking, fast-steering mirrors, adaptive optics, or forward error correction coding. The errors that did occur were burst errors as is typical in an FSO link. The one large burst of errors occurred when the beam was blocked for a ship passing through the channel.

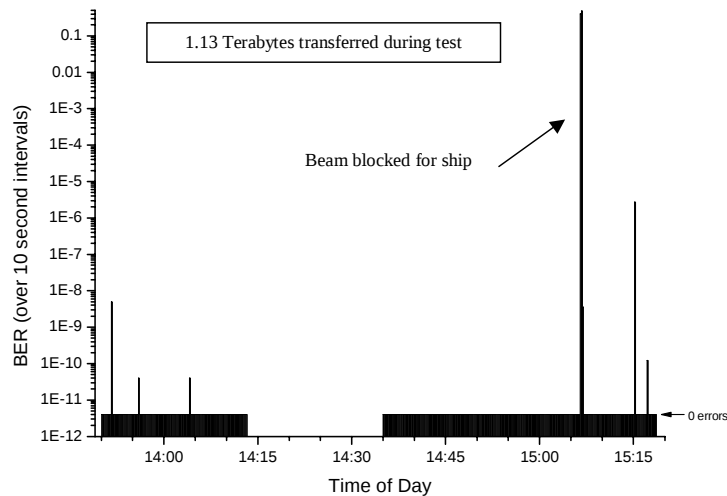


Figure 11. 2.5 Gbps BER testing across Chesapeake Bay (32 km); Low turbulence conditions ($C_n^2 \sim 1 \times 10^{-15}$) and average visibility (light haze)

6. VIDEO/AUDIO TRANSFER EXPERIMENT

In order to test and demonstrate the utility of the 32.4 km FSO link in a variety of atmospheric conditions, commercial equipment was used to interface video and audio data to the optical system and to recover the data after transmission over the link. A Multidyne model DVM-2000-FTX Video/Audio/RS-232 multiplexer and single mode fiber (SMF) optical transmitter was used to supply the seed optical signal to the EDFA preamp shown in Figure 5. This transmitter will multiplex one full color NTSC video input (12 bit digitization of the NTSC signal), six audio inputs (24 bit/channel), and three RS-232 inputs (max rate/channel = 9600 baud). The output is a 1542 nm digitized optical output at -2.2 dBm average power with a data rate of 300 Mbps on SMF. The multiplexed, serialized optical signal was amplified in the preamp EDFA and the Keopsys 5 watt EDFA shown in Figure 5 before being transmitted across the bay to the retro array on Tilghman Island.

The optical return was coupled into a 62.5 μm core multimode fiber which was connected to the OC-12 O-E-O converter described above in section 4. The recovered optical data output from the O-E-O converter required no further amplification before applying it to the input of the Multidyne de-multiplexer. The Multidyne model DVM-2000-FRX SMF optical receiver and Video/Audio/RS-232 de-multiplexer has an InGaAs optical receiver with a sensitivity of -28 Dbm and an SMF pigtail. It de-multiplexes the serial optical stream and produces one full color NTSC video output, six audio outputs, and three RS-232 outputs.

The video transmission experiments operated with 36 dBm (4 W) of average output power. Several full length DVD's were transmitted to determine how long the link could be maintained. "Bursty" fades of the lasercomm link caused minimal video degradation and infrequent "pops" in the audio resulting in overall high received video and audio quality. The slow vertical transmitter pointing change caused by thermal gradients over the water could be detected by an increase in the number of "pops" in the audio. Pointing of the transmitter gimbal could be changed in small steps (35 microradian step size) to correct the pointing without interrupting the video transfer.

Figure 12 is a photograph of the Multidyne video equipment. Figure 13 contains several still images from a U.S. Navy recruitment video that was transferred over the link. In general, an entire two-hour video can be transferred across the link and viewed at the receiver with minimal detectable drop-outs.

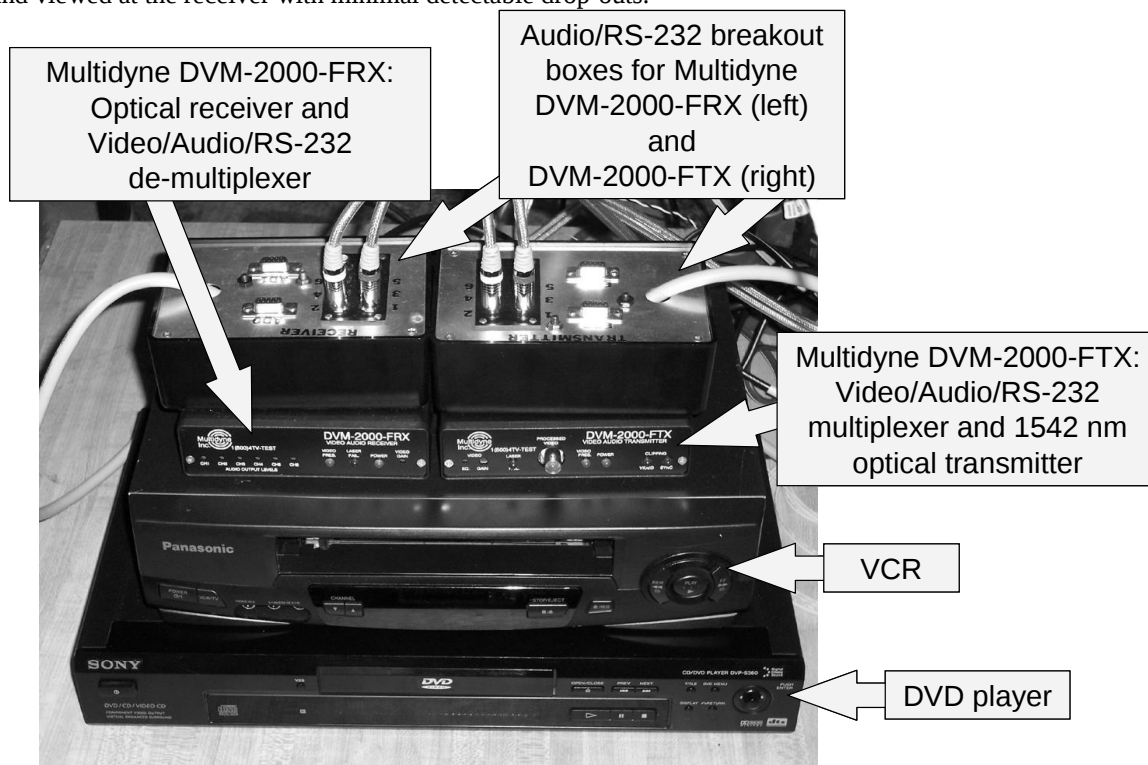


Figure 12. Photograph of Multidyne COTS video equipment.



Figure 13. Still frames from “Navy: The Journey of a Lifetime” VHS transmitted over Bay at 300 Mbps 23 July 2004, $C_n^2 < 1 \times 10^{-14}$, heavy haze, $T_{\text{air}} = 27^\circ \text{C}$, $T_{\text{water}} = 26^\circ \text{C}$, Humidity = 71%

7. CONCLUSIONS AND FUTURE EFFORTS

NRL has developed and field-tested a high-sensitivity (-33 to -34 dBm) OC-48 O-E-O converter with a multimode fiber input. This receiver has been used to close a 32 km lasercom link at bit rates up to 2.5 Gbps. BER testing has been done at the NRL LCTF in a variety of atmospheric and turbulence conditions, including BER testing at 150 Mbps in light fog and rain.

We have integrated COTS video/optical multiplex and de-multiplex distribution boxes into NRL’s 32 km lasercomm test facility across the Chesapeake Bay and have transmitted NTSC quality video and 24 bit stereo audio data over the link. The LCTF has successfully transmitted video for long periods of time (hours) in a variety of atmospheric conditions: low turbulence ($C_n^2 \sim 1 \times 10^{-15}$); medium turbulence ($C_n^2 \sim 5 \times 10^{-15}$); good visibility (minimal haze; $\text{vis} > 20$ km); average visibility (light haze; $10 \text{ km} < \text{vis} < 20 \text{ km}$); and reduced visibility (heavy haze; $\text{vis} < 10 \text{ km}$). The link was attempted and failed during a medium fog event ($\text{vis} < 5 \text{ km}$).

Future efforts at the NRL LCTF will include a major thrust at developing a one-way automated FSO link across the bay with an RF modem for data transfer and control. This will not only provide a convenient method for one-way testing of the 16.2 km optical link, but will provide a test bed for examining aspects of hybrid RF-optical systems and simulating ship-to-ship FSO links.

NRL will also continue the efforts in high speed, large diameter, low noise InGaAs receiver development including low noise InGaAs APD arrays. NRL will continue the work in signal processing directions for improvement of FSO links, such as development of adaptive thresholding for APD receivers and novel detection schemes using wavelet transforms.

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