Progress in high-speed communication at the NRL Chesapeake Bay Lasercomm Testbed

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ABSTRACT

The Naval Center for Space Technology at the Naval Research Laboratory has been operating a long-range, maritime, free-space optical communications 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. The facility permits one-way communications with the transmitter and receiver at opposite ends as well as double pass communications using a retroreflector array on Tilghman Island and the transmitter and receiver located together at Chesapeake Beach. Over the past year, a ball lens has been incorporated to couple the returned free-space light into an optical fiber. This ball lens makes the coupling much less sensitive to angle. With the lens, averaged coupled power into the receive fiber increased from 50 μW to 130 μW. Link statistics including fade rate and bit error rate are included for a typical summer afternoon for the double pass configuration.

Keywords: Free-space optical communication, lasercomm, bit error rate

1. INTRODUCTION

For two years, the Naval Center for Space Technology (NCST) in cooperation with the Optical Science 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 Chesapeake Bay Detachment (CBD), and the east end is located at Tilghman Island. 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 modulators and erbium doped fiber amplifiers (EDFA) developed and built at NRL along with commercially available components[1]. In addition to conventional lasercomm, the facility at CBD is used in communication links with a modulated retroreflector[2,3]. These links include ground to UAV and shore to ship links transferring real-time video and other data. Outside entities desiring a long FSO link to test their own equipment have used the Chesapeake Bay LasercommTestbed.

2. EXPERIMENT DESIGN

In this propagation test at CBD, the transmitter and receiver are both located at the west site, and retroreflectors on Tilghman Island are utilized to complete the optical path in the link. In this experiment, a modulated laser beam was propagated across the bay and retroreflected back. A pattern generator and bit error rate (BER) tester were co-located and operated from the CBD west site. In this test, the receiver did not need clock recovery because the clock can be fed directly from the pattern generator to the BER tester electrically. With a double pass, the range is extended, and the link

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now crossed 32.4 km of water. The laser transmitter and optical receiver were located about 30 m from the surface of the water, and the retroreflectors located about 15 m above sea level. Figure 1 is an illustration of the long link geometry.

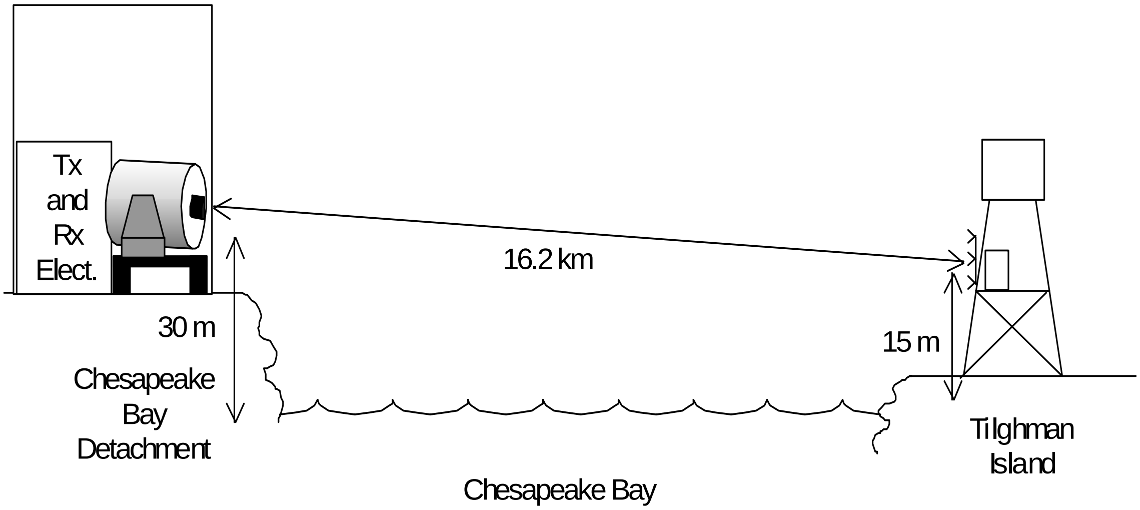


Figure 1: Chesapeake Bay Lasercomm Testbed Geometry

The communications link begins with the pattern generator. An Anritsu ME522A generated a pseudorandom bit sequence (PRBS) at 622 Mb/s. The sequence length was 2^{15}-1 bits. The clock was fed directly to the BER tester. The signal was then sent to an OC-48 transmitter. The wavelength of the transmitter optical output was 1542 nm. The modulated optical output was amplified in an EDFA built by NRL Optical Science Division resulting in a 30 mW CW optical signal. This preamplified signal was then sent to a more powerful EDFA, also built by NRL[4,5] which amplified the optical power to 1.6 W CW. The amplified output was fiber-coupled with the exit of the fiber at the focal point of a 4-inch lens with an 11-inch focal length. This optic transmitted a nearly collimated, 4-inch diameter beam.

The transmitted beam was then sent across Chesapeake Bay to the retroreflector array. This array consisted of twelve two-inch retroreflectors arranged in a rectangular pattern, three horizontal by four vertical, on five-inch centers. The transmitter was located on a gimbal with a 35-microradian step size. By panning the gimbal in single steps, we estimated the divergence of the output to be about 250 microradians. This divergence is based on the amount of returned laser light as the transmitted beam was panned across the retroreflector array. Intensity fluctuations made it difficult to determine a 1/e point for divergence, so our measurement is somewhat qualitative. We did not do any averaging to try to establish a more accurate divergence measurement.

The receive aperture was a 16-inch Meade LX200 Schmitt-Cassegrain telescope. The output of the telescope was turned by a flat mirror and then split into two paths. Five percent of the returned light went through a lens, a 1550 nm long pass filter, and ND filters to an InGaAs camera from Sensors Unlimited. This optical path allowed for imaging the pupil of the telescope. The remaining 95% of the retuned light was coupled into a 62-micron-core multimode fiber using a 10 mm diameter ball lens. The average power coupled into the fiber typically varied between 30 and 200 µW. The detector required an average optical input power of –31 dBm for a BER of 10^{-10}. This corresponds to a signal level of .8 µW. The fiber-coupled optical return was directed to a 622 Mb/s OC-12 receiver. From this receiver the electrical signal went to an OC-48 transmitter whose optical signal was then directly coupled to an OC-48 receiver. This combination of an OC-48 transmitter and receiver acted as an automatic gain control (AGC) circuit in the absence of a high-bandwidth radio-frequency (RF) amplifier with AGC. The resulting electrical signal was fed into an Anritsu ME522A BER tester. The pattern generator was set with variable output, 0.0 V offset, 1.0 V amplitude, and non-return to zero (NRZ) data. Likewise the BER tester was set for variable input with 0.0 V threshold, and NRZ data. The phase on the clock signal was adjusted to –200 ps by trial and error to achieve the best BER results. A block diagram appears in Figure 2.

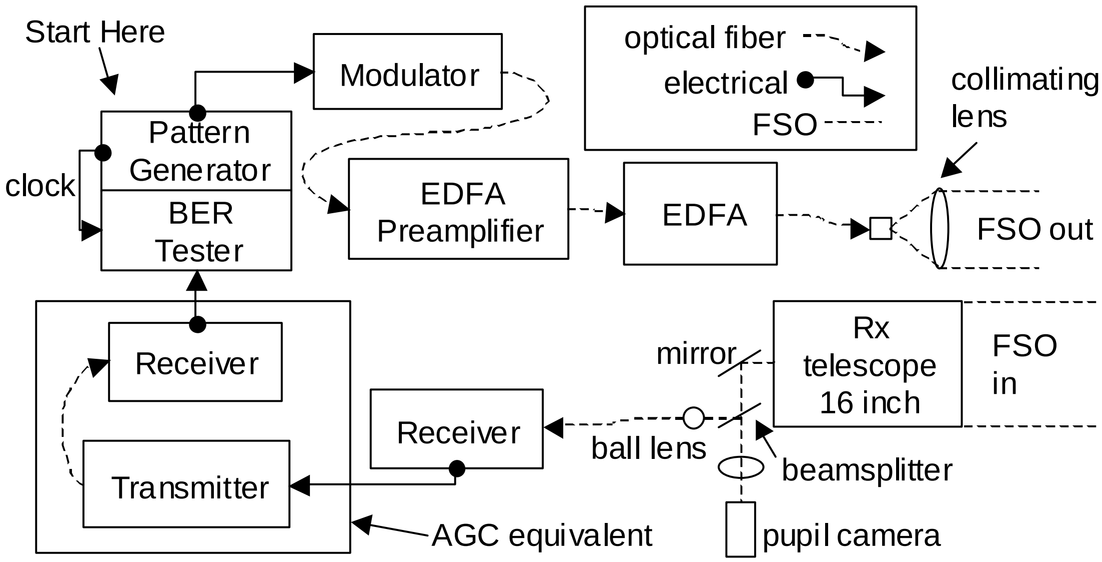


Figure 2: Transmit and receive block diagram

3. DATA

Data contained in this paper represent typical data for a July afternoon. The weather was slightly overcast and in the middle eighty degrees F. The following chart shows the average of the weather conditions during each hour of testing.

Time	Temperature (F)	Humidity (%)	Windspeed (mph)	Pressure (in Hg)
11:50-12:50	84.0	67.7	5.1	29.7
13:40-14:45	85.9	60.8	6.8	29.7

Table 1: Averaged weather data at CBD for BER test periods.

One weather-related measurement not collected was C_n^2. The absence of this measurement is due to the failure of our C_n^2 monitor while BER data were collected. Some C_n^2 data were captured just before the BER testing began, and a significant amount of data has been collected at the site[6]. In analyzing the available data, the value of C_n^2 recorded just before BER testing was higher than 86% of the data collected overall for May 12 through July 17, 2003. On the morning of July 11, C_n^2 was rising, and it reached $2.5x10^{-15}$ by 11:00. We estimated a value of C_n^2 of about $5x10^{-15}$ for these tests, based on the weather conditions and historical C_n^2 data collected at the site. In later tests performed on July 15, 2003, we achieved the same BER performance with a C_n^2 measurement varying between $2x10^{-15}$ and $5x10^{-15}$.

The BER was calculated in 1-minute intervals spanning an hour for two different hour-long periods in the afternoon. The first hour began just before noon at 11:52, and the second hour began at 13:44. Figures 3a and 4a show the BER data during these two samples. For some periods of testing, one or more consecutive minutes passed without errors. For these periods with zero errors, the worst case for BER measurement would be that the next bit was wrong. For intervals that sustained zero errors, we added up the number of bits that were transmitted without errors. We assumed that the first bit of the next one-minute interval (the next interval in which there was at least one error) was wrong. This bit was counted as a single error for the error-free period. We calculated a BER under this assumption and recorded that BER for all one-minute intervals in the error-free period. This number would be the worst possible BER for that period. Note that there were several intervals with zero errors, and most had a BER of less that 10^{-6}.

The pointing of the transmitter was not adjusted while data were taken. Hence, pointing offsets caused by temperature gradients were not corrected except between data collection periods. These pointing changes have been consistently witnessed at the facility. As the temperature gradient over the water changes throughout the day, the resulting index of refraction gradient changes the pointing of the transmitted beam in the vertical direction. This effect can explain in large part the rise in BER toward the end of each hour. The deterioration was evident in both data sets.

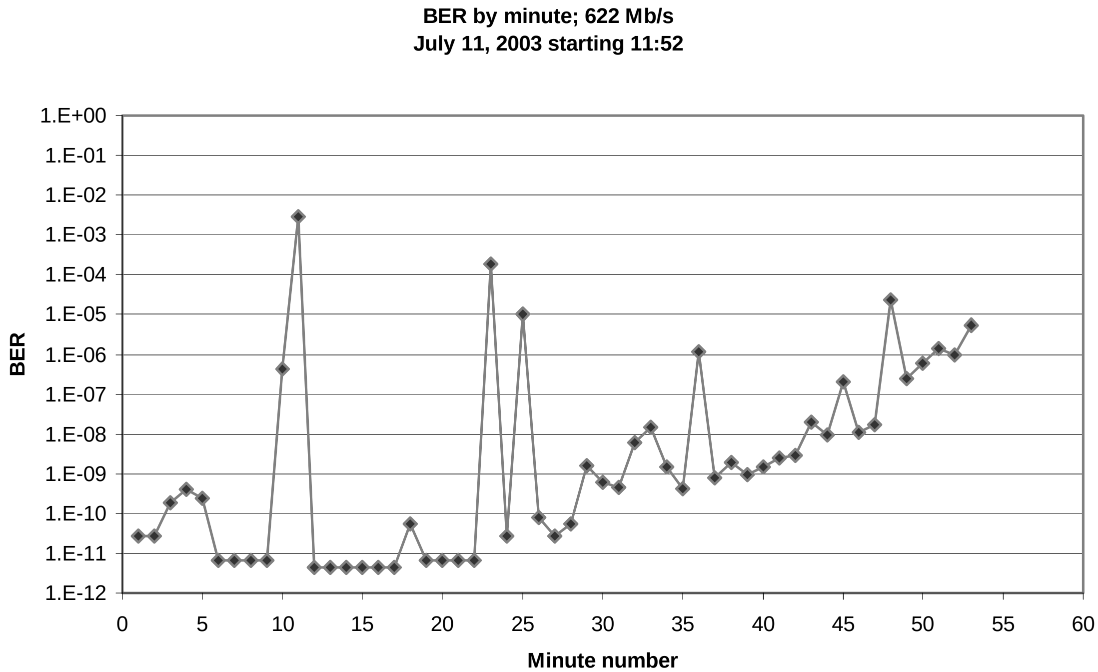
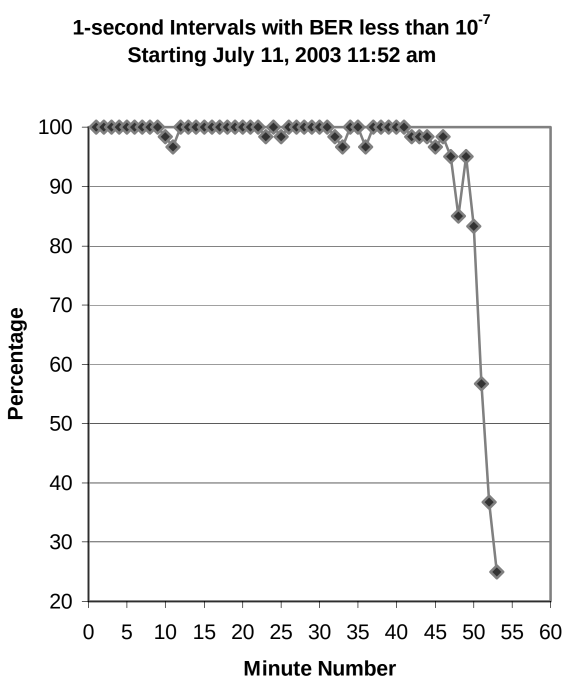
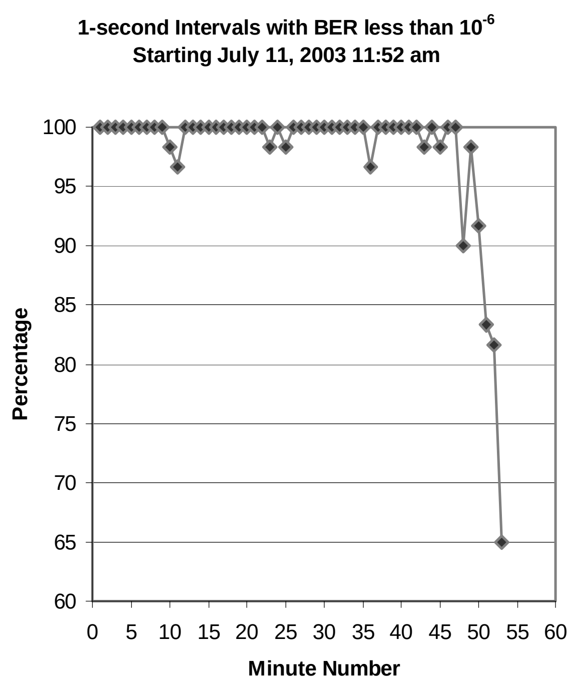


Figure 3a: BER test 1. Note the increase in BER due to lack of active pointing.





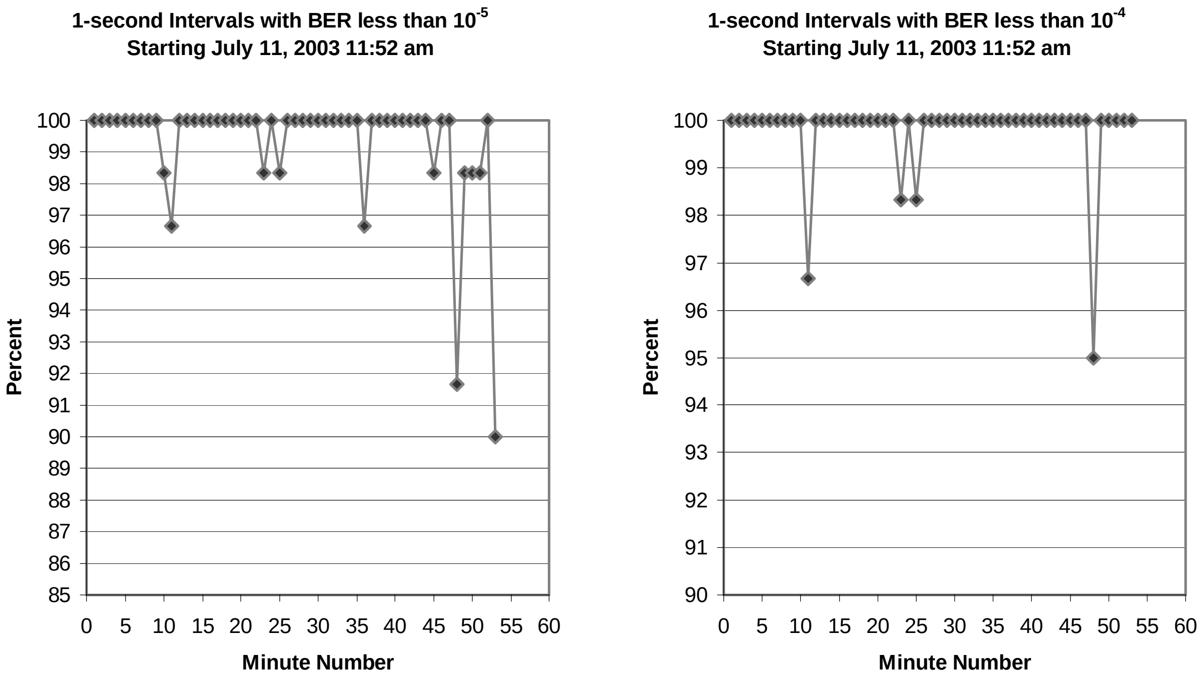


Figure3b-e: Percent of intervals with BER better than various thresholds for test 1. Note different y-axis scales.

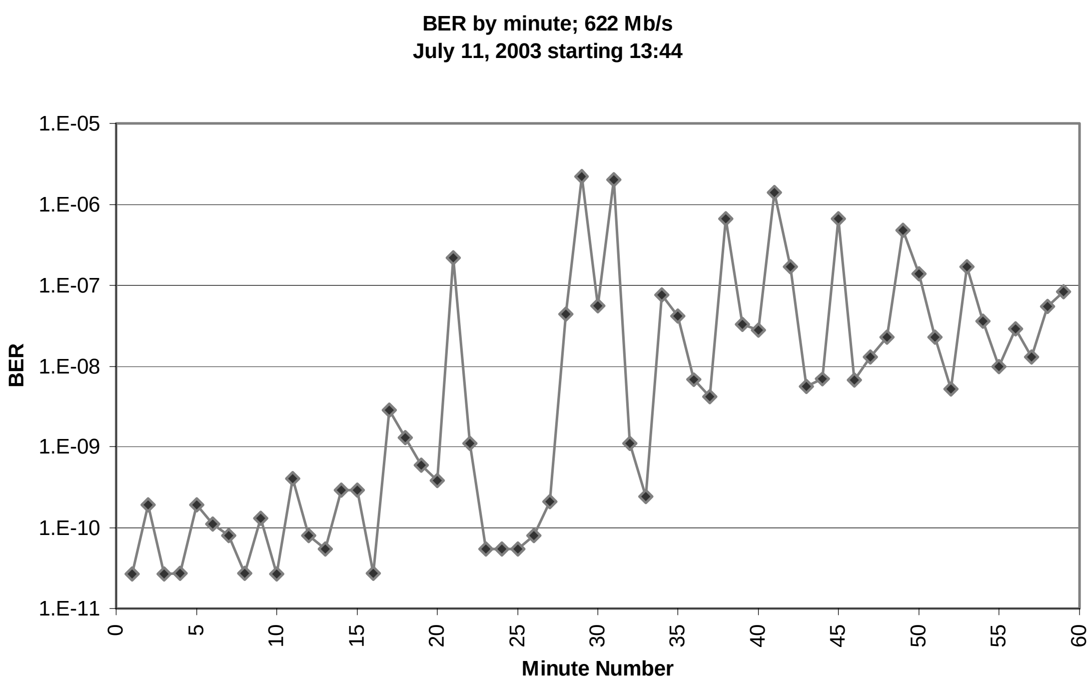


Figure 4a: BER test 2. The lack of active pointing is again manifested in an increasing BER.

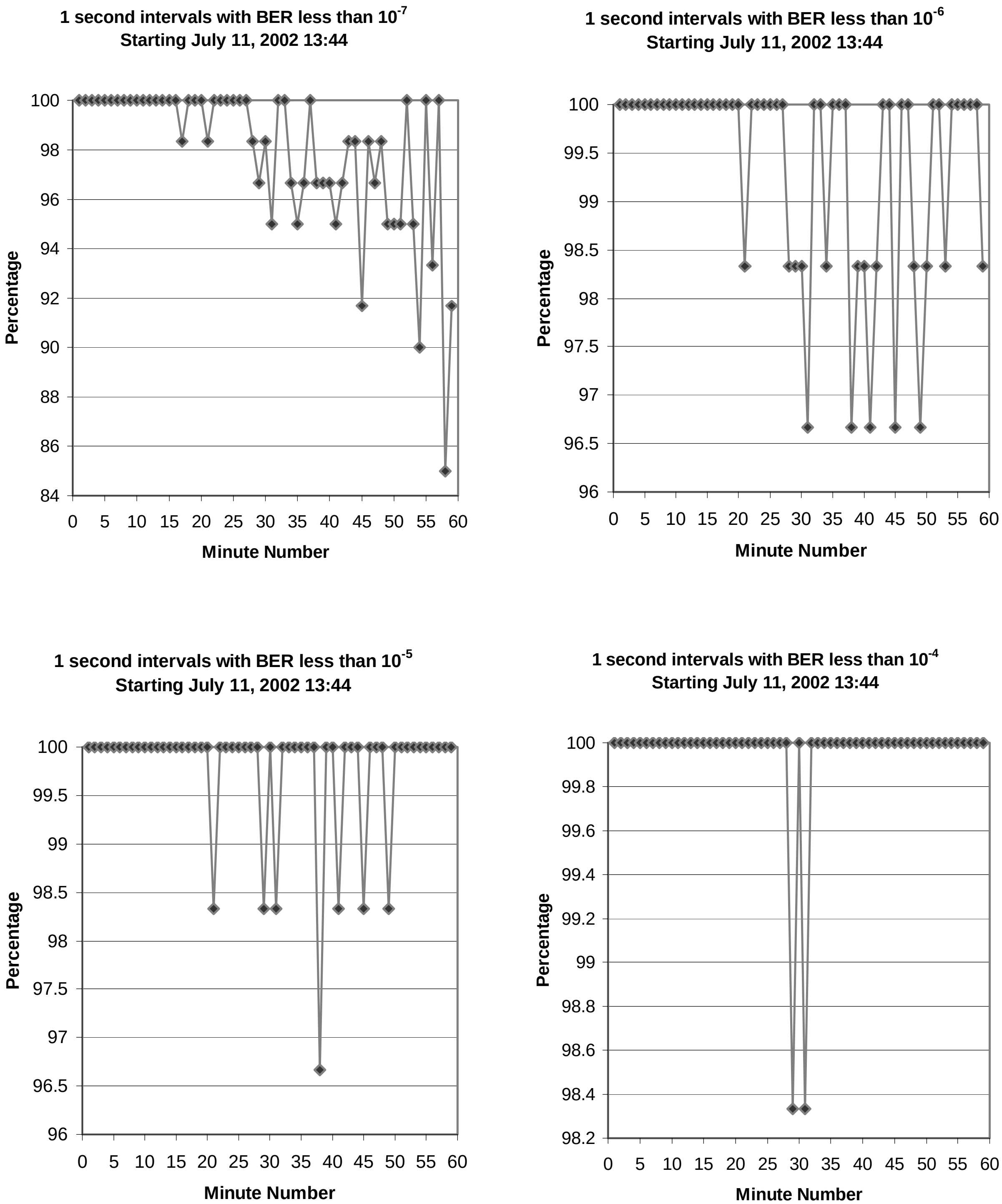


Figure4b: Percent of intervals with BER better than various thresholds for test 2. Note different y-axis scales.

Figures 3b-e and 4b-e show the nature of the errors incurred at the test facility. In each one-minute interval for which the BER is recorded, there are 60 1-second intervals over which the BER tester measures the BER. At the end of the 1-

minute interval, the tester reports the overall BER, the number of errors, and also the percent of 1-second intervals for which the BER is better than various thresholds. The thresholds are 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}, and 10^{-7}. The most illustrative interval is number 12 of the first test. The BER was the highest of all intervals, $>10^{-3}$, however, 96.6% of the intervals had a BER less than 10^{-7}. This is an example of the large burst errors that occur when the optical link travels through the atmosphere. The BER tester lost sync during at least one interval, and many errors occurred at once, instead of having the errors distributed evenly over many intervals. Burst errors can occur if the focus spot of the received laser light wanders off of the optical fiber into which it is being coupled. Once the BER tester loses sync, more bits will be lost until synchronization is re-established. The BER tester reports burst errors and sync losses. In this data, sync losses caused bursts of up to 10^8 errors. This analysis shows that while the BER averaged over a minute may be high, the errors are concentrated in large bursts so that the communication link performs nearly error-free 95% of the time.

Interleaving and forward error correction (FEC) would improve these losses. As the charts show, an interleaved FEC scheme that could correct a BER of 10^{-6} would make at least 48 minutes of the first hour totally error-free. In the second hour, at least 43 minutes would be completely error-free. Looking at the individual seconds within the minute intervals, the burst errors become evident. If FEC for a BER of 10^{-6} were applied to the first hour, all of the remaining errors would be contained in less than 57 of the 3,600 seconds. The rest of the time would be error-free. Of the 57 seconds that would contain errors, 47 would have been in the last four minutes where it seems obvious that the alignment required adjustment. In the second hour, less than 22 seconds would contain any errors. Interleaving is necessary to spread the burst errors evenly over the un-interleaved data stream on the receive end of the link. If the errors remained in bursts, FEC alone could not provide correction.

4. RESULTS AND DISCUSSION

These BER results were achieved without any corrections or mitigation strategies. There was no correction for transmitter pointing or for angle of arrival in the received laser signal. Nor were there any adaptive optics. The PRBS also lacked any type of forward error correction. Some improvement was achieved in coupling the light into the fiber using the ball lens. Previous lasercomm experiments have been hindered by poor coupling into the fiber (a few μW), and the coupling was always very sensitive to the angle of the fiber. Hence, as the turbulence randomly changed the angle of arrival of the laser beam into the receiving telescope, the angle of the light being coupled into the fiber also changed, resulting in very little light entering into the fiber and the detector. The ball lens made the coupling efficiency much less sensitive to angle. With this addition, we were able to couple an average of 130 μW into the fiber. This coupled average power did fluctuate from about 30 μW to sometimes over 200 μW. This averaged coupled power increased from 50 μW in previous tests without the ball lens.

As can be seen from the data, the maritime atmosphere at the site causes gross pointing offsets over time, primarily in the vertical direction. These offsets were not corrected while data were gathered. There was also no correction for angle of arrival fluctuations. While the ball lens mitigated angle of arrival effects, a fast steering mirror could correct for angle of arrival fluctuations. Last, there was no error correction implemented. Forward error correction, while limiting data rate, could correct many of the bit errors. With the burst errors that the site endures, forward error correction with interleaving may be the best solution to improve BER. There was also no adaptive thresholding implemented, though work is currently underway to develop this technique.

5. CONCLUSION

Optical data link tests were conducted at the NRL Chesapeake Bay Laser Com Testbed to characterize the challenges to be faced when propagating laser light in a maritime environment. Data rates of 622 Mbps at 1542 nm propagated across 34.4 km yielded typically a BER level better than 10^{-6}. However, the tests indicate that the vertical temperature gradient has a very strong effect on pointing. These results motivate implementation of additional features at the facility including a fast steering mirror, adaptive thresholding, forward error corrective coding, and possibly adaptive optics. A simple slow active pointing scheme to correct for transmitter pointing offsets would improve performance also. With these improvements, it is anticipated that we will be able to support several Gbps across the bay. We possess modulators and receivers to operate a 20 Gb/s optical link with a geometry identical to this one. Our current limitation is in test equipment. We have recently obtained test equipment to work at 3.5 Gb/s with access to equipment that will operate at 10 Gb/s.

6. REFERENCES

1. C.I. Moore, H.R. Burris, M.R. Suite, M.F. Stell, M.J. Vilcheck, M.A. Davis, R. Smith, R. Mahon, W.S. Rabinovich, W.J. Scharpf, and A.E. Reed, “Free-space high-speed laser communication link across the Chesapeake Bay”, *SPIE Proc.*, **4821**, pp. 474-485, 2002.

2. G. C. Gilbreath, W. S. Rabinovich, T. J. Meehan, M. J. Vilcheck, R. Mahon, Ray Burris, M. Ferraro, I. Sokolsky, J. A. Vasquez, C. S. Bovais, K. Cochrell, K. C. Goins, R. Barbehenn, D. S. Katzer, K. Ikossi- Anastasiou, Marcos J. Montes, "Large-Aperture Multiple Quantum Well Modulating Retroreflector for Free-Space Optical Data Transfer on Unmanned Aerial Vehicles", *Society of Photo-Optical Instrumentation Engineers, Opt. Eng.* **40(7)** pp. 1348—1356, July 2001.

3. G.C. Gilbreath, W.S. Rabinovich, T.J. Meehan, M.J. Vilcheck, M.F. Stell, R. Mahon, P.G. Goetz, E. Oh, J.A. Vasquez, K. Cochrell, R. Lucke, S. Mozersky. “Real-time video transfer using multiple-quantum-well retromodulators”. *Proceedings of the SPIE*, **4821**, 2002. Pp. 155-162.

4. Koplow, J.P. ;Moore, S.W. ;Kliner, D.A.V. “A new method for side pumping of double-clad fiber sources”. *IEEE Journal of Quantum Electronics*, **39(4)**, April, 2003, pp. 529-40.

5. Di Teodoro, F. ;Koplow, J.P. ;Moore, S.W. “Diffraction-limited, 300-kW peak-power pulses from a coiled multimode fiber amplifier”. *Optics Letters* **27(7)**, 2002, pp. 518-20.

6. M.F. Stell, C.I. Moore, H.R. Burris, M.R. Suite, M.J. Vilcheck, M.A. Davis, R. Mahon, E Oh, W.S. Rabinovich, G.C. Gilbreath, W.J. Scharpf, and A.E. Reed . “Passive optical monitor for atmospheric turbulence and windspeed”. *Proceedings of SPIE*, **This issue**, 2003.