

Atmospheric turbulence studies of a 16 km maritime path

Christopher I. Moore^a, Harris R. Burris^b, Mena F. Stell^b, Linda Wasiczko^a, Michele R. Suite^a, Rita Mahon^c, William S. Rabinovich^d, G. Charmaine Gilbreath^e, and William J. Scharpf^a

^aU.S. Naval Research Laboratory, Code 8123, Advanced Systems Technology Branch, 4555 Overlook Ave SW, Washington, DC 20375

^bResearch Support Instruments, Inc., 4325-B Forbes Boulevard, Lanham, MD 20706

^cThe Titan Corporation, 11955 Freedom Drive, Reston, VA 20190

^dU.S. Naval Research Laboratory, Code 5654, Photonics Technology Branch, 4555 Overlook Ave SW, Washington, DC 20375

^eU.S. Naval Research Laboratory, Code 7210, Radio/IR/Optical Sensors Branch, 4555 Overlook Ave SW, Washington, DC 20375

ABSTRACT

The Naval Research Lab (NRL) is currently operating a lasercom test facility (LCTF) across the Chesapeake Bay between NRL's Chesapeake Bay Detachment (NRL-CBD) and NRL-Tilghman Island. This lasercom test facility has successfully demonstrated 32 km retro-reflected links at data rates up to 2.5 Gbps. Along with lasercom link studies, atmospheric characterization of the NRL-CBD to Tilghman Island optical path has been investigated. These studies range from passive optical turbulence monitoring based on angle-of-arrival measurements of a spotlight's apparent motion, to intensity and angle-of-arrival measurements of a retro-reflected laser beam. Currently the LCTF is being upgraded from a retro-reflected link to a direct one-way link from NRL-CBD to NRL-Tilghman Island. Initial measurements of atmospheric turbulence effects in this one-way configuration have recently been performed. Results of these past and current atmospheric turbulence studies are presented.

Keywords: Lasercom, free-space optical communications, scintillation, atmospheric turbulence

1. INTRODUCTION

The Naval Research Laboratory (NRL) is currently investigating the performance of free space laser communications (lasercom) at laser wavelengths in the eye safe c-band of erbium doped fiber amplifiers (EDFA – ~1530-1565 nm) in a maritime environment. This research will quantify the performance of maritime lasercom versus atmospheric conditions to assist in determination of lasercom's role for future Naval communications systems.

To achieve this goal, NRL has established a 16 km lasercom test facility (NRL-LCTF) across the Chesapeake Bay. The test facility consists of a building on a cliff 30 meters above the water – the typical height of a mast mounted communication terminal on a Navy ship – 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). Over the last few years, an array of twelve retro-reflectors situated 15 meters above water level at NRL-Tilghman Island has been used to “fold” the path of a lasercom system to allow testing from NRL-CBD with minimal activities at NRL-Tilghman Island (Figure 1). This folded 32 km path has been used intermittently to gather samples of lasercom performance and atmospheric conditions over short durations (few hours). 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} Measurements of atmospheric turbulence conditions have also been made although with insufficient regularity to fully characterize test bed atmospheric conditions. Additionally, no attempt has been made to measure atmospheric transmission within the 1500 nm wavelength band useful for eye-safe Naval lasercom.

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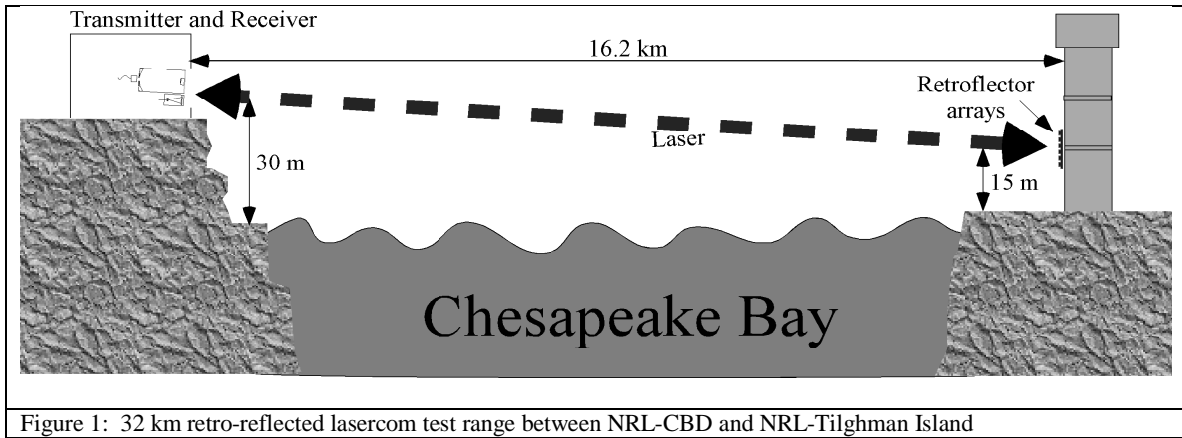


Figure 1: 32 km retro-reflected lasercom test range between NRL-CBD and NRL-Tilghman Island

An upgrade to the test bed is currently underway to fully characterize lasercom link performance versus atmospheric conditions 24/7 as well as implement a variety of techniques and hardware improvements to improve maritime lasercom link performance. Upgrades to allow long term monitoring will focus on building a 16 km one way lasercom link from NRL-CBD to NRL-Tilghman Island with simultaneous monitoring of atmospheric turbulence and transmission (Figure 2). One important aspect of this upgrade is a slow (<1 Hz) tracking system to follow the slow beam wander that is observed over the Bay. This slow beam wander is due to vertical thermal gradients or layering over the water that refracts the beam predominantly in elevation³ by angles up to approximately 1 milliradian for our elevated path across the Chesapeake Bay.

This manuscript gives a summary of atmospheric turbulence results observed in the past as well as recent results investigating turbulence effects that impact the design requirements for the one-way test bed currently under construction. These recent results focus on measuring angle-of-arrival (AOA) fluctuations using both a position sensitive detector (PSD) and cameras to determine viable tracking methods to follow slow apparent beam wander of the lasercom beam.

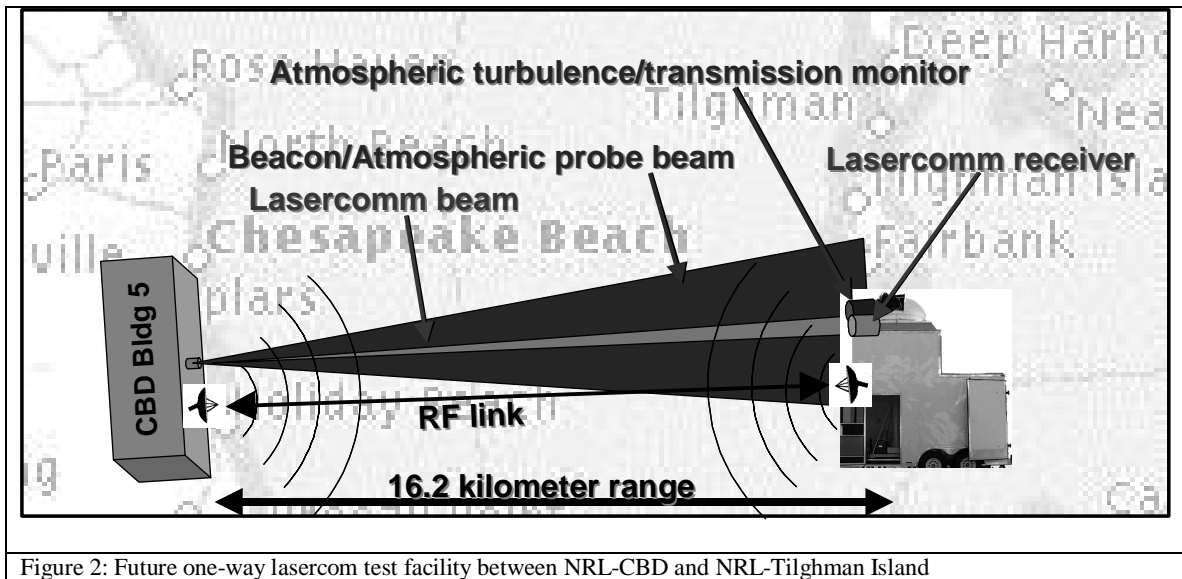


Figure 2: Future one-way lasercom test facility between NRL-CBD and NRL-Tilghman Island

2. PAST TURBULENCE MEASUREMENTS

Atmospheric turbulence measurements at the NRL-LCTF have been performed using a passive optical monitor^{4,5} based on measuring AOA fluctuations of an incoherent source. Similar experiments have been performed over a shorter path across the Potomac River in Washington, DC.⁵ A simple diagram of the turbulence monitor is shown

in Figure 3. This system was built at NRL due to the unavailability of commercial turbulence monitors capable of operating over a 16 km range. The monitor uses a Schmidt-Cassegrain telescope with a 1300 mm focal length and a 5" aperture to image a spotlight on the tower at Tilghman (see Figure 4) onto a silicon CCD through a 50 nm bandpass filter centered at 850 nm.

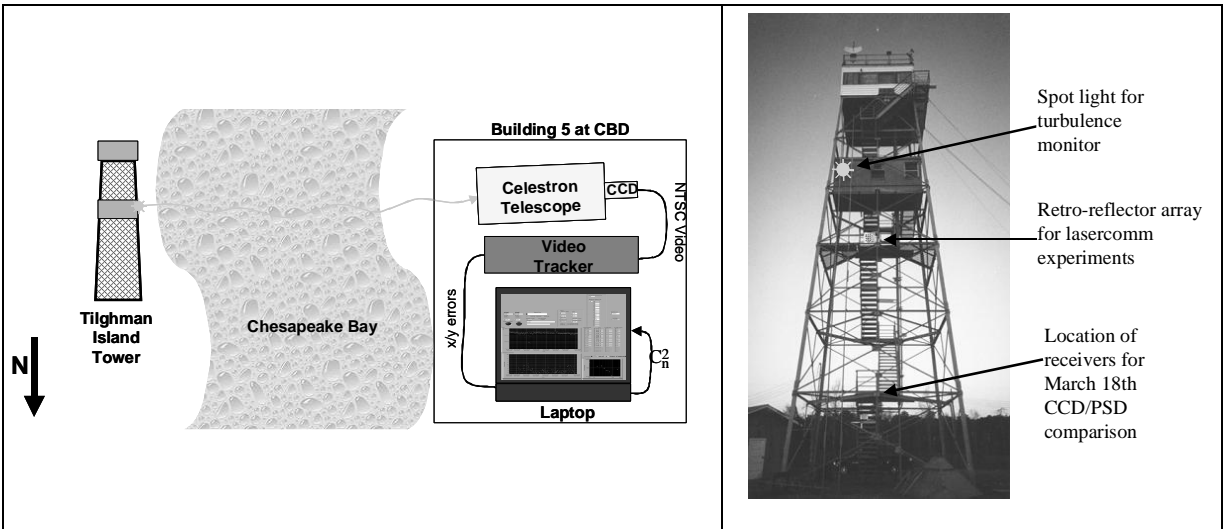


Figure 3: Optical turbulence monitor measuring angle-of-arrival (AOA) fluctuations of an incoherent source

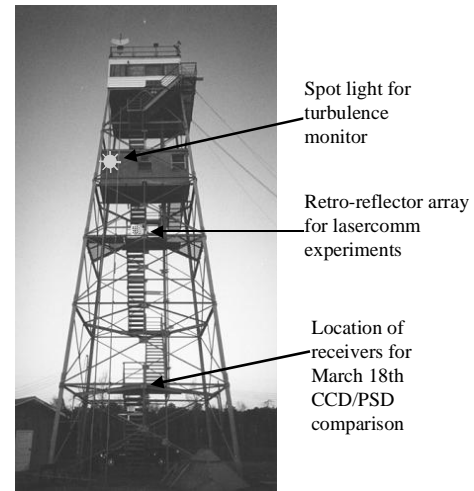


Figure 4: Tower on Tilghman Island showing locations used for experiments. The tower is approximately 30 meters tall.

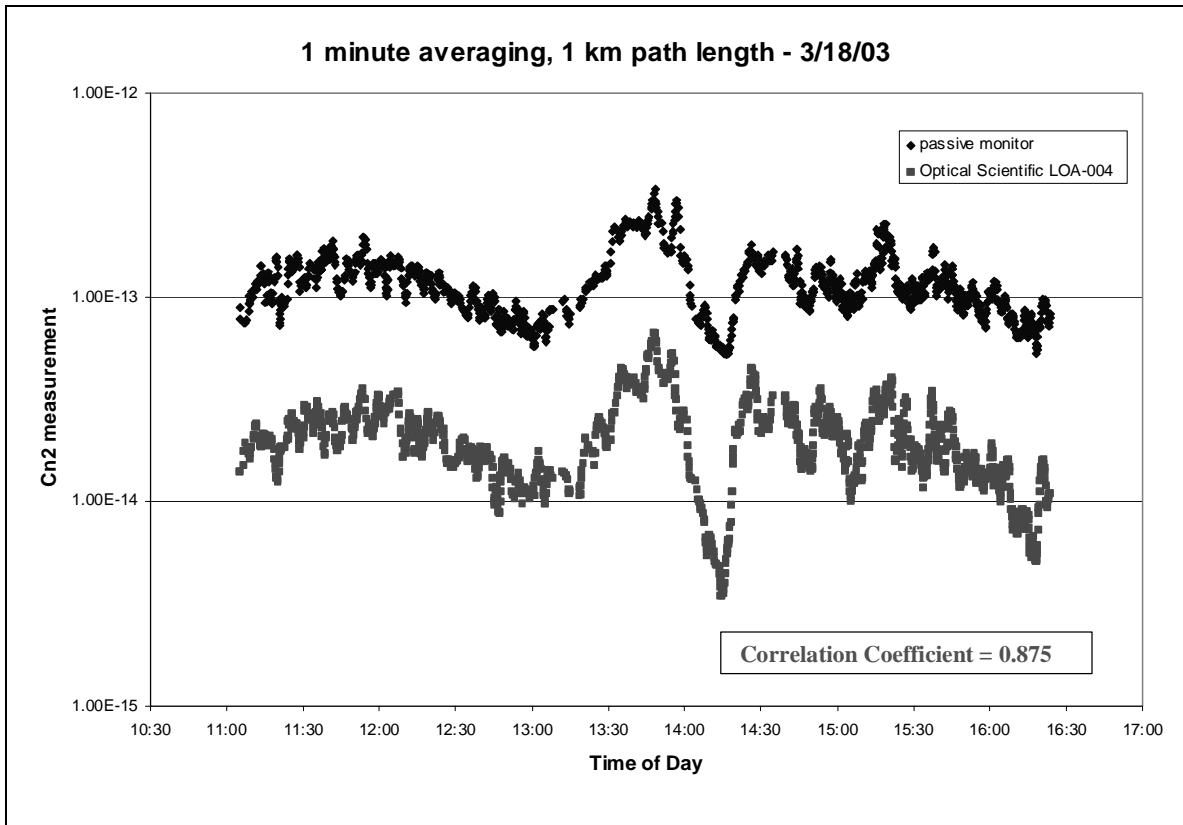


Figure 5: Simultaneous measurement of C_n^2 using NRL's passive optical turbulence monitor and a commercial scintillometer (model LOA-004) from Optical Scientific

The predicted relationship between fluctuations in the angle of arrival radial variance (σ_β^2) and the path averaged C_n^2 is:⁶

$$C_n^2 = \frac{\sigma_\beta^2 D^{1/3}}{1.093L}, \quad (1)$$

where L is the path length, D is the receiver aperture diameter, and a spherical wave is assumed. C_n^2 measurements obtained with this monitor have been shown to correlate well with measurements taken with a commercial scintillometer (see Figure 5) over a short ~1 km path. Aside from an absolute offset in measured C_n^2 values, the relative values correlate well with a correlation of 0.875. The source of the offset is unknown at this time

Figure 6 shows the compilation of approximately 3 months of turbulence data taken over the Bay at the LCTF. Apparent from this is the relatively small range of C_n^2 values observed (one order of magnitude) compared to those typically measured over land (typically four orders of magnitude or more). Also of note is the observation that C_n^2 values rarely rise above 10^{-14} making turbulence mitigation appear to be much simpler in the maritime environment. These values may be further reduced if the commercial scintillometer is correct, since C_n^2 measurements made with our passive optical turbulence monitor would be four times lower than currently measured.

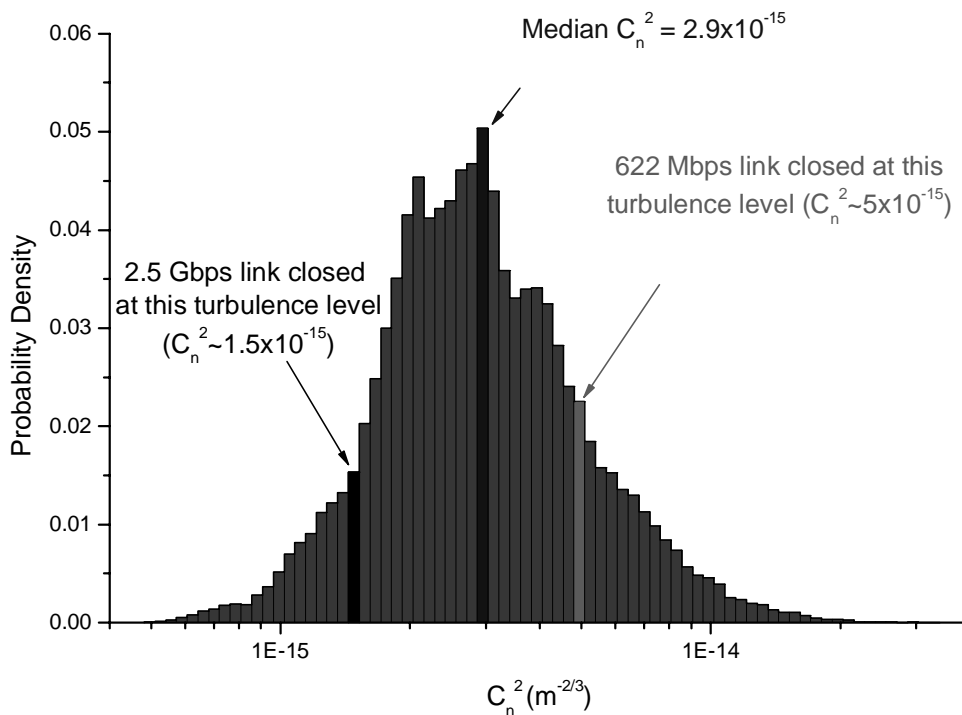


Figure 6. PDF of C_n^2 data taken over the Chesapeake Bay from April - July 2003 (from passive turbulence monitor; estimated from angle of arrival variance)

3. TURBULENCE EFFECTS OVER THE MARITIME TEST RANGE

A variety of turbulence conditions are observed over the test range. The most common conditions are shown in Figure 7a and 7b. These images were obtained by recording single frames from video acquired with the Celestron

telescope and CCD camera used for the turbulence monitor. All images are of the tower on Tilghman Island from NRL-CBD. Figure 7a shows low turbulence conditions with $C_n^2 \sim 10^{-15}$. In this image high spatial frequency structure is visible and in video mode, minimal fluctuations are observed in time and the standard deviation of angle-of-arrival fluctuations of the light are a few μrad . Figure 7b shows medium turbulence conditions where high spatial frequency detail has been “washed out” and in video mode, the standard deviation of angle-of-arrival fluctuations of the light is 10’s of microradians. 7b was obtained with a $C_n^2 \sim 10^{-14}$. These two Figures represent the typical extremes of turbulence observed ($C_n^2 \sim 10^{-15}$ to 10^{-14}).

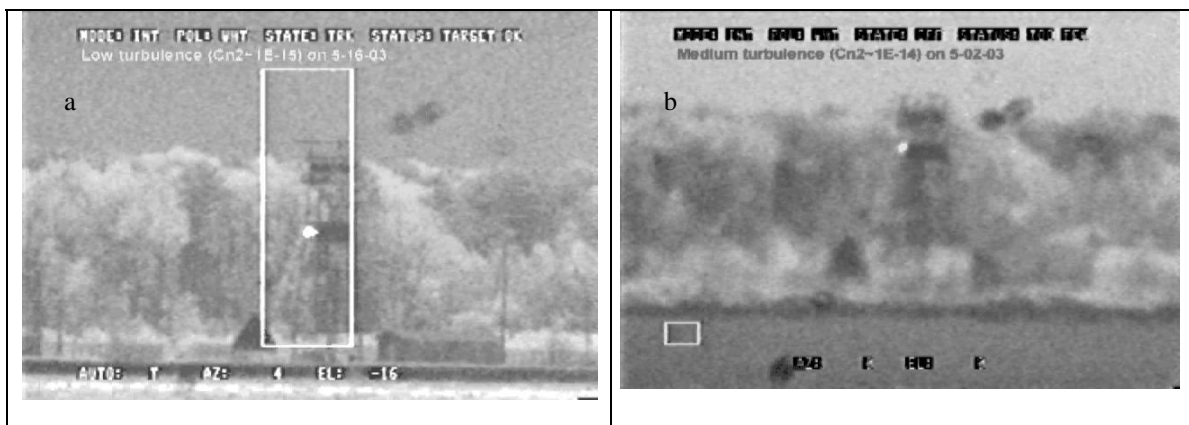


Figure 7: Images of Tilghman Island tower through 5” aperture, 1300 mm focal length Celestron telescope from NRL-CBD. (a) Low turbulence conditions ($C_n^2 \sim 10^{-15}$). (b) Medium turbulence conditions ($C_n^2 \sim 10^{-14}$)

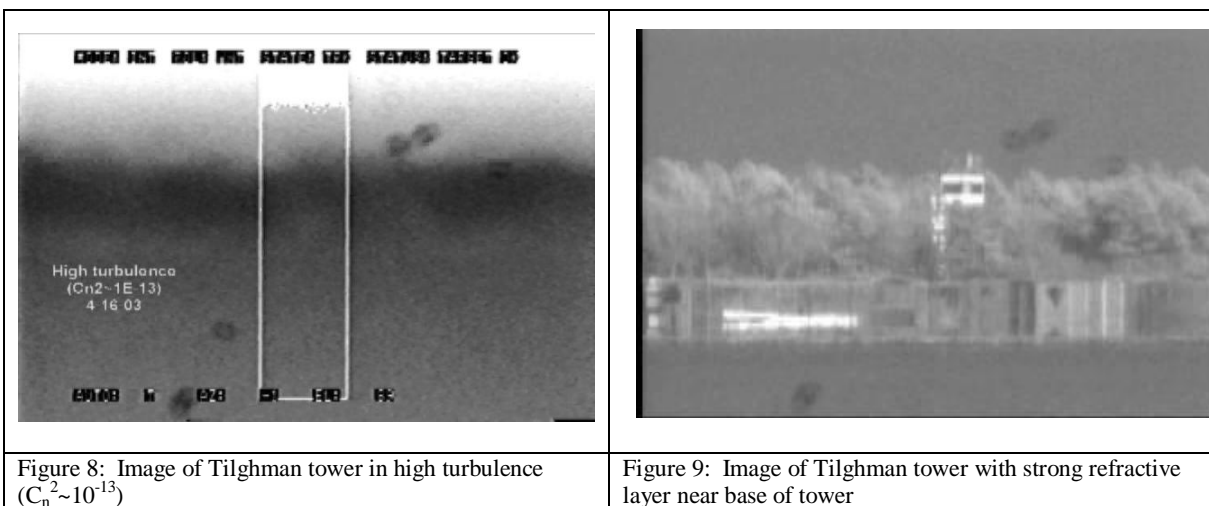


Figure 8: Image of Tilghman tower in high turbulence ($C_n^2 \sim 10^{-13}$)

Figure 9: Image of Tilghman tower with strong refractive layer near base of tower

Figures 8 and 9 show rare conditions, which have been observed on only a few days over the past several years. Figure 8 shows extremely strong turbulence where all high spatial frequency details have been “washed out” and even the horizon and spotlight are difficult to discern. Of note in this image is that the distortion is uniform throughout the image. Figure 9 shows a highly anisotropic condition where a refractive layer has developed apparently at the base of the tower. This has caused significant distortions to objects near the base of the tower (compare to Figure 7a). In time the distortion is observed to move up and down the tower, sometimes splitting and causing multiple images or apparent reflections of objects at Tilghman Island.

The distortion shown in Figure 9 is a severe example of the vertical refraction that is very common over the Bay due to thermal gradients above the water. Typically this refraction is benign and causes only slight apparent elevation changes in objects across the Bay with little distortion of their shapes from our 30 meter elevation above the water. These thermal gradients over water, their affects on optical radiation, and optical techniques to determine the temperature profile, are discussed in detail in reference 3.

The effect of these rare severe refraction layers on a lasercom beam reflected from the retro-reflectors on the Tilghman Island tower was measured on the afternoon of February 8th, 2005. The system used for this measurement is shown in Figure 10. A continuous wave (CW) 4 watt laser at 1548 nm with an initial divergence of 250 μ rad was propagated over the Bay, reflected from 12 two inch retro-reflectors and the return was collected with a 40 cm Schmidt-Cassegrain telescope and imaged onto a Phosphor/Si CCD camera from Spiricon sensitive to 1548 nm light. The video of the received spot was recorded and digitized. The digitized video was analyzed using MATLAB to find the centroid and power of the received laser spot. Due to the small divergence of the transmitter beam and the large angular changes that were caused by the refractive layers, frequent manual pointing changes of the transmitter gimbal were necessary to maintain alignment on the retro-reflectors and return power to the receiver CCD. The required pointing changes of the transmitter were predominantly in elevation and were directly correlated with the motion of the received spot on the CCD. From an imaging standpoint, the elevation changes were simply due to changes in the apparent position of the retro-reflector and the requirement to aim the beam at this apparent position.

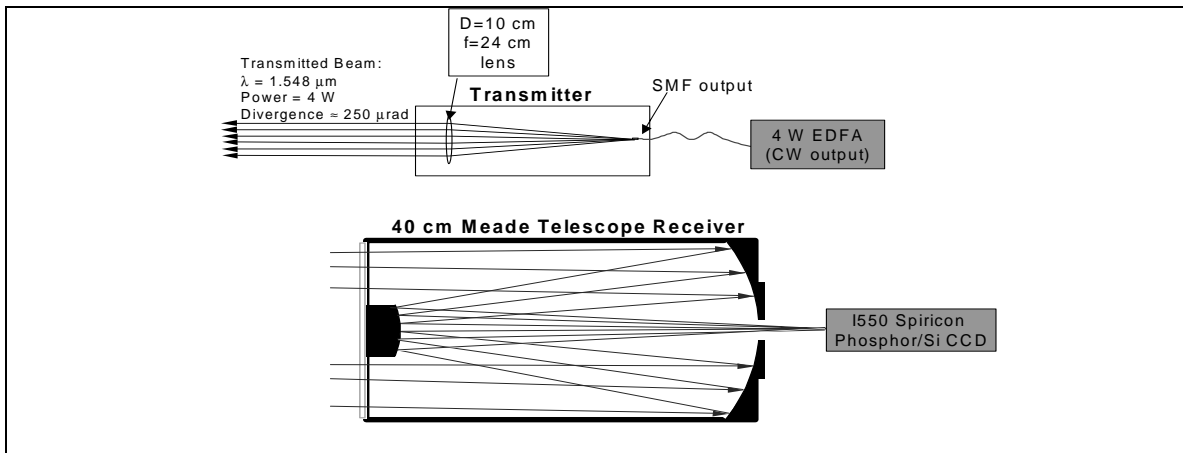


Figure 10: Laser transmitter and receiver used to measure power and motion of received laser spot after 32 km transit across the Bay.

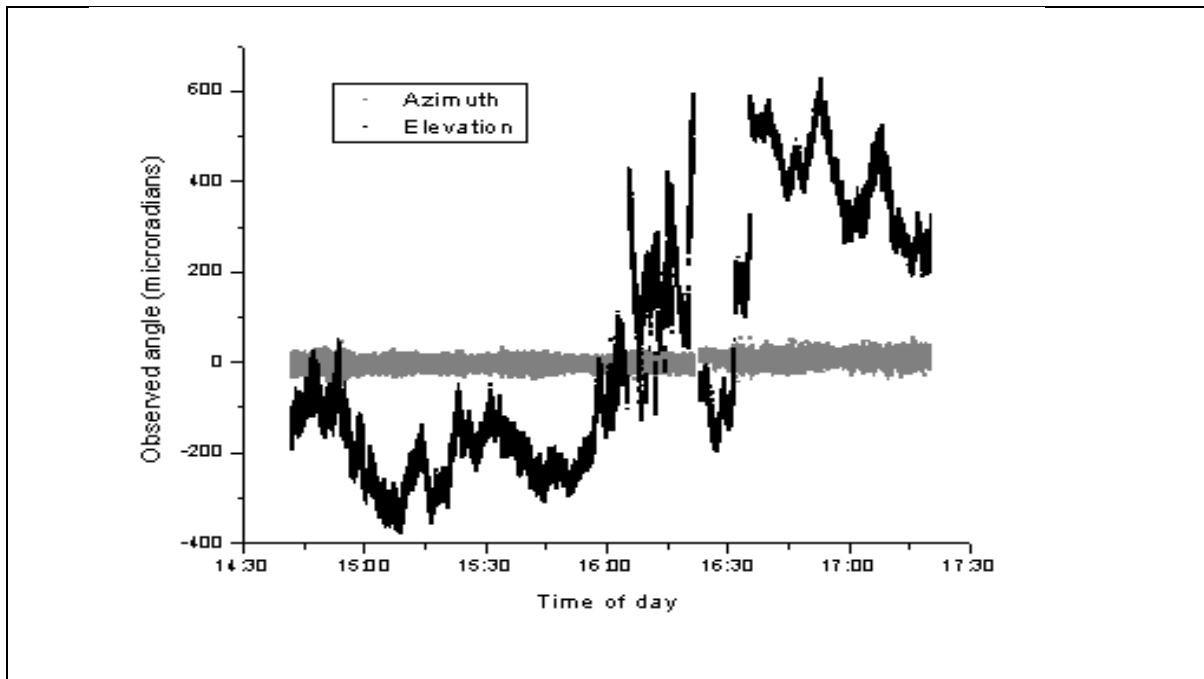


Figure 11: Apparent change in angle-of-arrival of received laser at NRL-CBD after reflection from retro-reflectors on Tilghman Island tower on February 8th, 2005.

Figure 11 shows the result of this experiment. As is apparent, very large changes in elevation angle-of-arrival into the receiver were observed while azimuthal angle-of-arrival showed no significant change. Also apparent are rapid changes in elevation angle at approximately 16:05, 16:20 and 16:40 that likely corresponded to sharp boundaries of thermal layers passing through the path to the retro-reflectors resulting in rapid jumps of the apparent retro-reflector elevation. The total angular deviation in elevation observed over this three hour period was very large (~1 mrad). The variance in elevation was $70627 \mu\text{rad}^2$ and in azimuth was $92.1 \mu\text{rad}^2$ over this period. Owing to this large asymmetry and the strongly anisotropic turbulence present in these atmospheric conditions, a measurement of C_n^2 based on radial variance (see equation 1) is meaningless and was not determined. Fortunately for tracking purposes, even the large rapid changes typically occurred over 10's of seconds. This makes the problem of following the beam through these transits a low frequency (<1 Hz) tracking problem and not a high frequency (>1 Hz) turbulence mitigation or adaptive optics problem. Of greater concern is the occasional breakup of the received beam into a vertical line or multiple spots at various apparent elevations on the receiver. Maintaining enough power in the receiver and tracking the "brightest spot" to close a lasercom link will be a challenge under these refractive layering conditions. Fortunately, these severe refractive conditions are rare and should not significantly affect the availability of a maritime lasercom link.

4. INITIAL INVESTIGATION OF ONE-WAY TURBULENCE AT THE LCTF

An upgrade to the NRL-LCTF is currently underway. This upgrade will place a transmitter on one side of the Bay and a receiver on the other side to better simulate a maritime link between two ships. As a precursor to this upgrade, a test was performed on March 18th, 2005 to determine the magnitude of AOA fluctuations and intensity scintillations in a one-way link using smaller receivers than our current 40 cm receiver. This day was an excellent day to perform this test owing to the relatively high turbulence levels measured with the passive optical turbulence monitor ($C_n^2 \sim 10^{-14}$). Another goal of this experiment was to determine if an inexpensive phosphor/Si 1550 nm COTS CCD (model SP-1550m from Spiricon; cost ~ \$2000) with limited dynamic range (NTSC video digitized to 8 bit grayscale) could be used to enable slow tracking (<1 Hz) for compensation of the refractive gradients observed over the Bay. For this test the same lasercom transmitter used for round trip links off the retro-reflectors was aimed at a test receiver placed one story up from the bottom of the Tilghman Island tower.

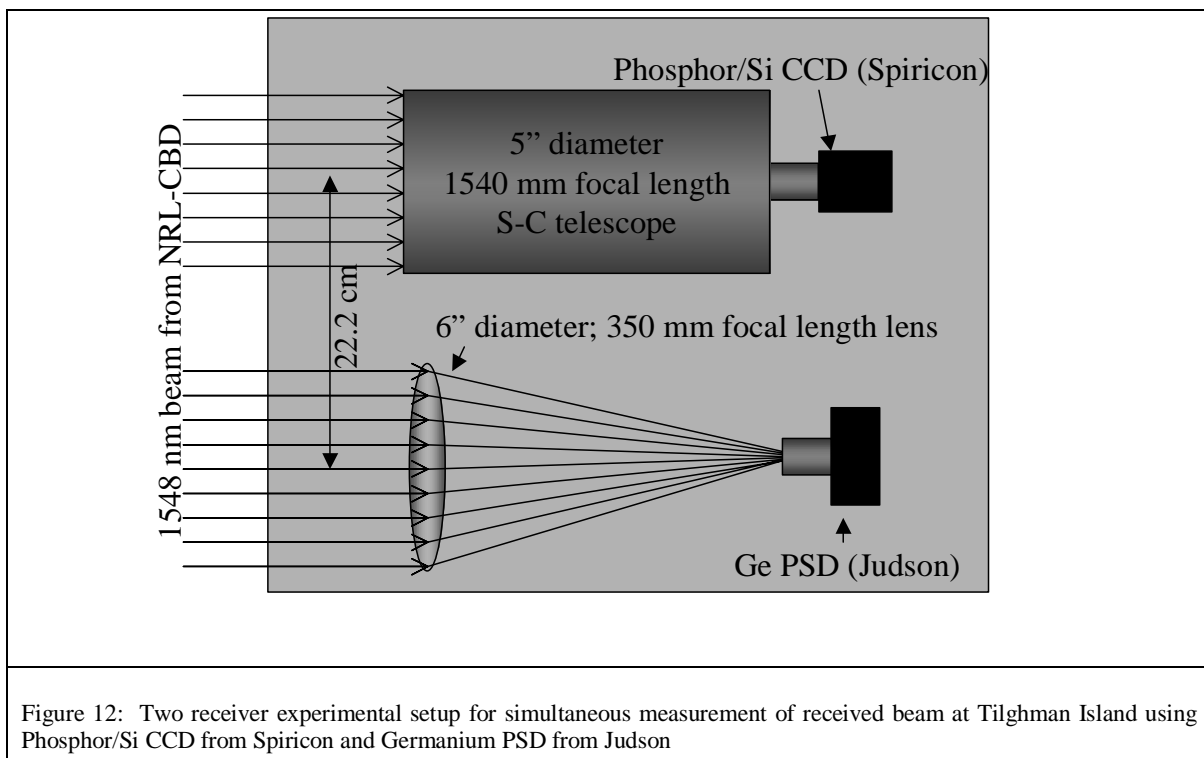


Figure 12: Two receiver experimental setup for simultaneous measurement of received beam at Tilghman Island using Phosphor/Si CCD from Spiricon and Germanium PSD from Judson

The test receiver setup is shown in Figure 12. The received laser light was focused on the CCD using a 5 inch diameter Maksutov-Schmidt telescope with an effective focal length of 1540 mm. In addition, a Germanium position sensitive detector (PSD) from Judson Technologies was co-bore-sighted with the CCD with a 6 inch diameter, 350 mm focal length refractive lens. This Germanium PSD has been used in multiple experiments and its measurement of received centroid position and power level has been well established.⁷ These two receivers were separated by 22.2 cm and data was acquired simultaneously to allow comparison. The CCD acquired data at a 29.97 Hz rate using a Dazzle DVC-150 NTSC-to-MPEG converter and stored on a laptop. The PSD acquired data at a 20 kHz rate using a 12-bit A/D PCMCIA card and the results were stored on a separate laptop. Post processing was used to average the PSD data and reduce its data rate to 29.97 Hz for comparison to the CCD. Both data sets were then processed using MATLAB to obtain the position of the centroids and relative received powers. Centroid angle-of-arrivals were calculated based on the received position in the focal plane of each receiver (Δx , Δy) and the focal lengths of the optics (f) using the small angle approximation $\theta_{az} = \Delta x/f$ and $\theta_{el} = \Delta y/f$. Due to the relatively low dynamic range of the digitized CCD signal (8 bits), the CCD was allowed to saturate on approximately 50% of frames to insure that the signal was not completely lost during fades. In addition, due to the non-linear process of generating visible photons in the camera's phosphor from the laser's 1500 nm photons, the CCD counts are non-linear with respect to received laser power. These should have minimal effect on the centroiding since the received spot was typically symmetric, but could have significant impact on received power measurements. The PSD and A/D's dynamic range were sufficient to allow optical filtering to stay below saturation levels and maintain significant signal during fades to measure the centroid and intensity.

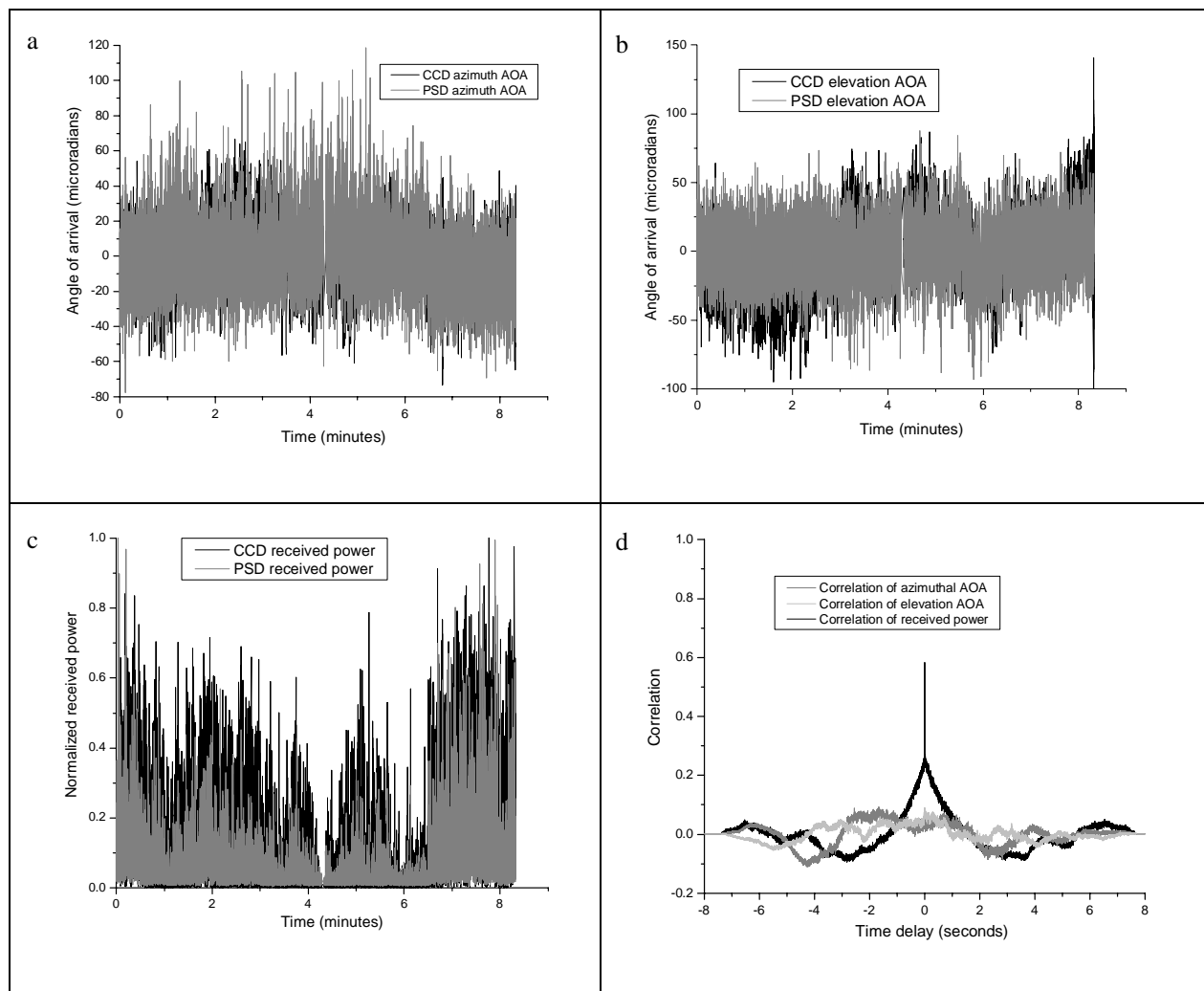


Figure 13: Comparisons of CCD and PSD receivers variations at a 29.97 Hz rate in azimuth AOA (a), elevation AOA (b), power (c), and their correlations (d)

Figure 13 shows the results of this experiment at a sampling rate of 29.97 Hz. Figures 13a and 13b show the angle-of-arrival variations in azimuth and elevation respectively over an 8 minute data collection period. Even with the saturation present in the CCD, the fluctuations in the received centroid position are similar amplitudes in both axes demonstrating the CCD is at least measuring the full excursions of the received laser spot. Figure 13c shows the relative powers measured on each detector. Figure 13d shows cross-correlations of the two curves in each of Figures 13a-13c. As is apparent, the measured angles-of-arrival for the two receivers are uncorrelated. However, even with the 22.2 cm separation between the two receivers, the received power is correlated with a peak value of 0.58.

The powers for each detector shown in Figure 13c have been normalized so that their peak value for each is one. This normalization was necessary for comparison since an absolute power calibration of each receiver with filters has not yet been performed. However, a very rough estimate of received power in the PSD has been performed. From this estimate, the median power collected in the PSD receiver over the 8 minute experiment was approximately 4 milliwatts and the minimum power observed was approximately 40 microwatts. Considering the significant turbulence present on the day of the test ($C_n^2 \sim 10^{-14}$), this is extremely promising for closing even high data rate lasercom links since COTS 10 Gbps receivers are available (e.g., SU-10ATR from Sensors Unlimited, Inc.) with typical sensitivities of -24 dBm (4 microwatts). Significant work will need to be performed to couple to the detector – typical size is 10’s of microns – but the raw power necessary to close the link is present.

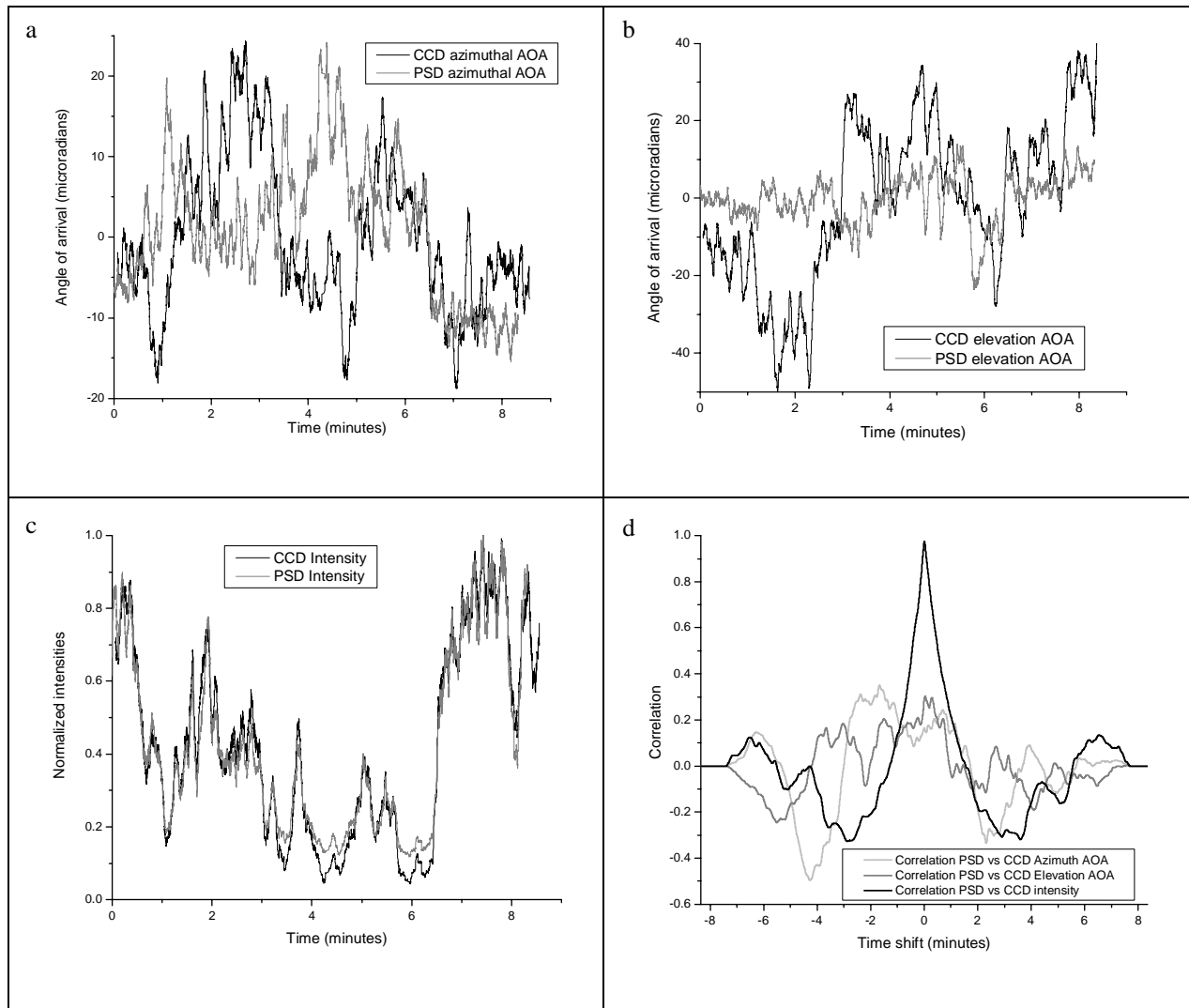


Figure 14: Comparisons of CCD and PSD receivers variations at a 0.2 Hz rate in azimuth AOA (a), elevation AOA (b), power (c), and their correlations (d)

Another goal of this experiment was to measure longer time scale angle-of-arrival fluctuations to understand requirements for a slow tracking system in our one-way link. Figure 14 shows measured AOAs and powers in the two receivers after a moving average with 151 points in the window. This smooths the data and filters out fluctuations at less than approximately 0.2 Hz rates which is a likely update rate for our slow tracking system. Figures 14a and 14b show the angle-of-arrival variations in azimuth and elevation respectively with higher frequencies filtered out (>0.2 Hz). Once again the AOA fluctuation amplitudes in both axes are similar although the elevation fluctuations on the PSD are slightly smaller. This is likely not a problem with the centroiding of the CCD due to saturation since saturation will “soften” hot spots in the received profile and cause smaller not larger AOA fluctuations. Figure 14c shows the relative power fluctuations at lower frequencies and a high degree of correlation is already obvious. Figure 14d shows cross-correlations of the two curves in each of Figures 14a-14c. Once again, the measured angles-of-arrival for the two receivers are uncorrelated and the received powers are highly correlated. In this case, the correlation factor is now very high at 0.974. This is extremely surprising especially due to the saturation and non-linear response in the 1550nm phosphor/Si CCD.

The high correlation of received power and uncorrelated AOA suggests that the power and AOA fluctuations in our experiment have two different sources. The most likely source is the location that these two fluctuations are generated. If intensity fluctuations are mainly generated by gross beam wander which is induced when the beam is small at the transmitter and the optical paths to each receiver overlap, a high degree of correlation would be observed. If AOA fluctuations are mainly induced near the receivers where the beam is large and the optical paths to each receiver are separate, the fluctuations would be uncorrelated. This hypothesis will be a subject of future study.

Of final note is the conclusion that a system using two separate receivers for a lasercom link and a tracking system is not a viable option for the receiver end of our new one-way lasercom link. Since the angle-of-arrival fluctuations from the two separate receivers were uncorrelated even after averaging out all fluctuations >0.2 Hz, a tracking system utilizing this method will obviously not work. Only a tracking system using a common optical path to the lasercom receiver will be useful in measuring and counteracting atmospherically induced pointing changes.

5. CONCLUSIONS

Multiple types of sensors have been used to investigate atmospheric turbulence over a 16 km maritime range across the Chesapeake Bay at NRL’s lasercom test facility (LCTF). A passive turbulence monitor measuring the angle-of-arrival of an incoherent incandescent spotlight has been used to characterize the turbulence strengths observed over the Bay. This monitor has shown that turbulence at the LCTF is relatively low and stable with typical values of C_n^2 between 10^{-15} and 10^{-14} . Owing to this low maritime turbulence, links from 155 Mbps in light rain and fog to 2.5 Gbps in clear weather have been successfully closed.² Also observed have been rare but interesting atmospheric phenomena involving refractive gradients causing severe image distortion and large elevation changes in optical paths to fixed locations on the opposite shore of the Bay. Laser transmission from a transmitter at NRL-CBD to retro-reflectors on the Tilghman Island tower and back to NRL-CBD during these occurrences of severe refractive gradients have shown optical path changes in elevation of approximately a milliradian over periods on the order of an hour.

The LCTF has been operated in a 32 km folded path configuration where a transmitter and receiver are collocated at NRL-CBD and the transmit beam is reflected off twelve 2 inch retro-reflectors situated on a tower on Tilghman Island. The LCTF is currently being upgraded to allow long term testing of one-way links between NRL-CBD and NRL-Tilghman Island. As an initial test of this one-way link configuration, two simple co-boresighted receivers – one using a CCD and another using a PSD – were setup on Tilghman Island and measured received power and angle-of-arrival fluctuations of a beam transmitted from NRL-CBD. Angle-of-arrival measurements from the two receivers were uncorrelated showing that a common optical path between lasercom receiver and tracking sensor is necessary to measure and counteract atmospherically induced pointing changes. The median received power level was measured to be on the order of 4 milliwatts and the minimum received power was on the order of 40 microwatts. This shows promise for closing links up to rates of 10 Gbps if coupling problems to small area high speed detectors can be solved. Also discovered was a strong correlation between received power in two receivers separated by a substantial amount (22.2 cm). For low frequency (<0.2 Hz) power fluctuations this correlation was measured to be surprisingly high at 0.974. The exact cause of this high correlation accompanied by the complete uncorrelation of angle-of-arrival fluctuations in the same data merits further study.

REFERENCES

1. Michael J. Vilcheck, Harris R. Burris, Christopher I. Moore, Mena F. Stell, Michele R. Suite, Mark A. Davis, Rita Mahon, Eun Oh, William J. Scharpf, William S. Rabinovich, Anne E. Reed, and G. C. Gilbreath, "Progress in high-speed communication at the NRL Chesapeake Bay lasercomm testbed", Proc. SPIE Int. Soc. Opt. Eng. 5160, 466 (2004).
2. H.R. Burris, C.I. Moore, L.A. Swingen, M.J. Vilcheck, D.A. Tulchinsky, R. Mahon, L.M. Wasiczko, M.F. Stell, M.R. Suite, M.A. Davis, S.W. Moore, W.S. Rabinovich, J.L. Murphy, E.S. Oh, G.C. Gilbreath, and W.J. Scharpf, "Latest results from the 32 km maritime lasercom link at the Naval Research Laboratory, Chesapeake Bay Lasercom Test Facility", Proc. SPIE Int. Soc. Opt. Eng., **This issue**, (2005).
3. William P. Hooper, Gerald E. Nedoluha, and Lee U. Martin, "Retrieval of near-surface temperature profiles from passive and active optical measurements", Opt. Eng. 41, 1586-1602 (2002).
4. Michael J. Vilcheck, Anne E. Reed, Harris R. Burris, Jr., William J. Scharpf, Christopher I. Moore, and Michele R. Suite, "Multiple methods for measuring atmospheric turbulence", Proc. SPIE Int. Soc. Opt. Eng. 4821, 300 (2002).
5. Mena F. Stell, Christopher I. Moore, Harris R. Burris, Michele R. Suite, Michael J. Vilcheck, Mark A. Davis, Rita Mahon, Eun Oh, William S. Rabinovich, G. C. Gilbreath, William J. Scharpf, and Anne E. Reed, "Passive optical monitor for atmospheric turbulence and windspeed", Proc. SPIE Int. Soc. Opt. Eng. 5160, 422 (2004).
6. Larry C. Andrews, Ronald L. Phillips, *Laser Beam Propagation Through Random Media*, p.146, SPIE Optical Engineering Press,(1998).
7. Christopher I. Moore, Harris R. Burris, Jr., Michele R. Suite, Mena F. Stell, Michael J. Vilcheck, Mark A. Davis, R. Smith, R. Mahon, William S. Rabinovich, Jeffrey P. Koplou, S. W. Moore, William J. Scharpf, and Anne E. Reed, "Free-space high-speed laser communication link across the Chesapeake Bay", Proc. SPIE Int. Soc. Opt. Eng. 4821, 474 (2002).