Passive optical monitor for atmospheric turbulence and windspeed

M.F. Stell[a], C.I. Moore[b], H.R. Burris[a], M.R. Suite[b], M.J. Vilcheck[b], M.A. Davis[c], R. Mahon[d], E Oh[e], W.S. Rabinovich[f], G.C. Gilbreath[e], W.J. Scharpf[b], and A.E. Reed[b]

a) Research Support Instruments, Inc., 4325-B Forbes Boulevard, Lanham, MD 20706
b) U.S. Naval Research Laboratory, Code 8123, Advanced Systems Technology Branch, 4555 Overlook Ave SW, Washington, DC 20375
c) Honeywell T.S.I., 7515 Mission Drive, Lanham, MD 20706
d) Jaycor/Titan Inc., 1410 Spring Hill Rd., McLean, VA 22102
e) U.S. Naval Research Laboratory, Code 7215, Radio/IR/Optical Sensors Branch, 4555 Overlook Ave SW, Washington, DC 20375
f) U.S. Naval Research Laboratory, Code 5654, Photonics Technology Branch, 4555 Overlook Ave SW, Washington, DC 20375

ABSTRACT

Measurement of atmospheric turbulence conditions is critical for predicting the performance of a free-space optical laser communication (FSO lasercomm) link. A C_n^2 monitor based on angle-of-arrival (AOA) fluctuations has been built for characterization of atmospheric conditions at the NRL FSO Lasercomm Test Facility across the Chesapeake Bay. The monitor used existing lights in various locations as point sources for determining AOA fluctuations. Real time analysis of the AOA fluctuations was performed to determine the power spectrum of the fluctuations every few seconds. This additional power spectrum information allows much greater understanding of atmospheric conditions including estimation of average wind speed based on frequency shifts in the power spectrum distribution. The performance of the monitor was tested over short paths by comparison to a commercial scintillometer. In addition, the monitor was used at other sites to determine atmospheric conditions at a variety of locations. Results of these experiments are presented.

Keywords: atmospheric turbulence, angle of arrival fluctuations, C_n^2, free space lasercomm, scintillation

1. INTRODUCTION

Free space lasercomm experiments across the Chesapeake Bay (16 km range) and to a boat on the bay (1-3 km ranges) have been conducted at the Naval Research Lab (NRL) Chesapeake Bay Lasercomm Test Facility[1-4]. Knowledge of the atmospheric turbulence level over these ranges is essential for evaluating the performance of these links. In particular, angle of arrival (AOA) fluctuations caused by turbulence are the critical parameter for determining whether or not the lasercomm receiver registers a signal or a fade. Familiarity with these AOA fluctuations also assists with improvements made to these links through the use of a fast steering mirror[5] or adaptive thresholding[6]. Available commercial scintillometers and turbulence measurement devices have maximum operating distance limitations and cabling issues that make them unsuitable for use at our test range. Therefore, a passive system to determine the atmospheric turbulence strength was assembled. This monitor can be operated almost entirely from one end of the path of interest and removes the need to have personnel on both ends of the path. The monitor measures AOA fluctuations from a near point source located at one end of the path of interest, as shown in Figure 1. The monitor then uses these AOA fluctuations to estimate the atmospheric index of refraction structure constant, C_n^2, in order to quantify the turbulence level. Using geometrical optics and assuming a spherical wave (due to the approximation that the light source is a point source) with a small AOA, the relationship between C_n^2 and the radial AOA variance, σ_β^2, is given by:[7]

$$C_n^2 = \frac{\sigma_\beta^2 D^{1/3}}{1.093L} \tag{1}$$

where D is the receiver aperture diameter and L is the path length.

Free-Space Laser Communication and Active Laser Illumination III, edited by David G. Voelz, Jennifer C. Ricklin, Proc. of SPIE Vol. 5160
(SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.508051

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2004**	2. REPORT TYPE	3. DATES COVERED **00-00-2004 to 00-00-2004**
4. TITLE AND SUBTITLE **Passive optical monitor for atmosperic turbulence and windspeed**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,Code 8123,4555 Overlook Avenue, SW,Washington,DC,20375**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

This manuscript describes the design and testing of the turbulence monitor. Section 2 describes the experimental setup and operation of the monitor. Section 3 details the comparison of this monitor with a commercial scintillometer and results of experiments at various locations. This section also discusses the strong correlation observed between AOA temporal frequency content and transverse wind speed. Section 4 gives conclusions for these experiments.

2. EXPERIMENTAL SET-UP

The turbulence monitor was tested and used primarily at three different sites. Site 1 was a relatively short (1 km), land based path at Fort AP Hill, VA. Site 2 was a path across the Potomac River that ranged in length from 2 to 3.5 km. Site 3 was a 16.2 km path across the Chesapeake Bay – the site where NRL's lasercomm experiments were performed. The monitor setup, which was identical at all three sites, is illustrated in Figure 1. One end of the path was an incandescent light source. The other end consisted of a 5" diameter aperture telescope with a 1.3 meter effective focal length that imaged the light onto a CCD camera. The CCD camera sent NTSC video to a commercial video tracker (Titan Systems Series 6000). This video tracker was used for quick development of the system. It will be replaced by a position sensitive detector (PSD) in future work. The tracker calculated the horizontal and vertical pixel positions of the intensity centroid of all of the pixels that registered above a user defined threshold. Setting the tracker's threshold appropriately and using an 850 nm bandpass filter ensured that the tracker calculated this centroid based only on pixels illuminated by the light source. The tracker computed the x and y locations of this centroid at a 60 Hz rate and sent the values to a National Instruments analog to digital data acquisition card (NI-DAQCard AI-16E-4). Since atmospheric turbulence is typically dominated by low frequency components, this 60 Hz rate is sufficient for our turbulence studies.

The NI-DAQ card captured the centroid position data and transferred it to a LabVIEW program that used these values to calculate the AOA variance. Frequency information was obtained by changing the number of data points used to calculate the AOA variance. This number was varied from 2 points to 300 points. Given the 60 Hz tracker data output rate, using two points to calculate the variance computed the AOA fluctuations at 30 Hz or above while using 300 points determined the AOA fluctuations at 0.2 Hz or above. Thus, frequency bins with varying low frequency cut-offs were created. The variance was calculated using 2, 3, 4, 5, 6, 8, 10, 12, 15, 20, 30, 60, and 300 points at a time for a total number of 13 bins. This corresponded to low frequency cut-offs of 30, 20, 15, 12, 10, 7.5, 6, 5, 4, 3, 2, 1, and 0.2 Hz. These variances were averaged over a user defined time interval that varied in duration from 10 seconds to 1 minute to improve statistics and reduce noise. This was done by collecting an array of tracker data every user defined time interval. This data was dispersed into the frequency bins discussed above by first segmenting the data array into sub-arrays of the appropriate number of data points. The variance of each sub-array was calculated. This made an array of variances that was averaged and stored in the appropriate frequency bin. This process was then repeated for the next frequency bin.

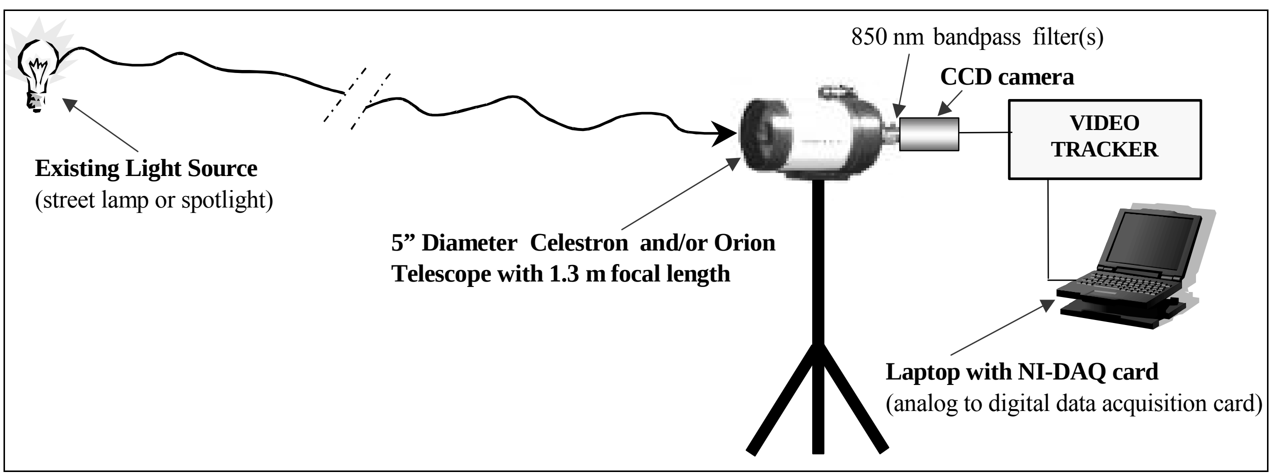

Figure 1: Passive turbulence monitor setup

Measurement of the x and y pixel positions of the intensity centroid with the video tracker allowed this monitor to obtain spatial information about the AOA fluctuations. The variance of the x pixel positions (σ_x^2) determined the AOA fluctuations in azimuth while the variance of the y pixel positions (σ_y^2) determined the AOA fluctuations in elevation. The total C_n^2 was computed from the radial variance, $\sigma_\beta^2 = \sigma_x^2 + \sigma_y^2$. A C_n^2 based entirely on the azimuthal variation was computed by using $\sigma_\beta^2 = 2\sigma_x^2$. Similarly a C_n^2 based entirely on fluctuations in the elevation direction was computed by using $\sigma_\beta^2 = 2\sigma_y^2$.

3. DATA AND RESULTS

3.1 Calibration at site 1 – over land at Fort AP Hill, VA

The passive turbulence monitor was tested using a 1 km path that was entirely over land at Fort AP Hill, VA. The C_n^2 estimated by this turbulence monitor was compared to that from a commercial scintillometer (Optical Scientific LOA-004) over the 1 km path. Figure 2 illustrates typical data obtained during this comparison. With a correlation coefficient of 0.875, the passive monitor correlated very well with the commercial unit. However there was a significant constant offset. Efforts are ongoing to determine the cause of this offset. A possible explanation is that the light source is not adequately represented by the spherical wave approximation assumed in Equation 1. If a plane wave is assumed instead, the estimated C_n^2 is decreased by a factor of 2.7,[7] thereby decreasing the offset, though not entirely eliminating it. The commercial scintillometer may have also been close to its operating distance limit. Future work will involve comparing the two over shorter and more varied paths to absolutely calibrate the passive turbulence monitor for C_n^2 measurements. The monitor is sufficient for current NRL lasercomm purposes since the AOA variance at the receiver is the critical turbulence parameter for a lasercomm system. The monitor gives an absolute measurement of this quantity.

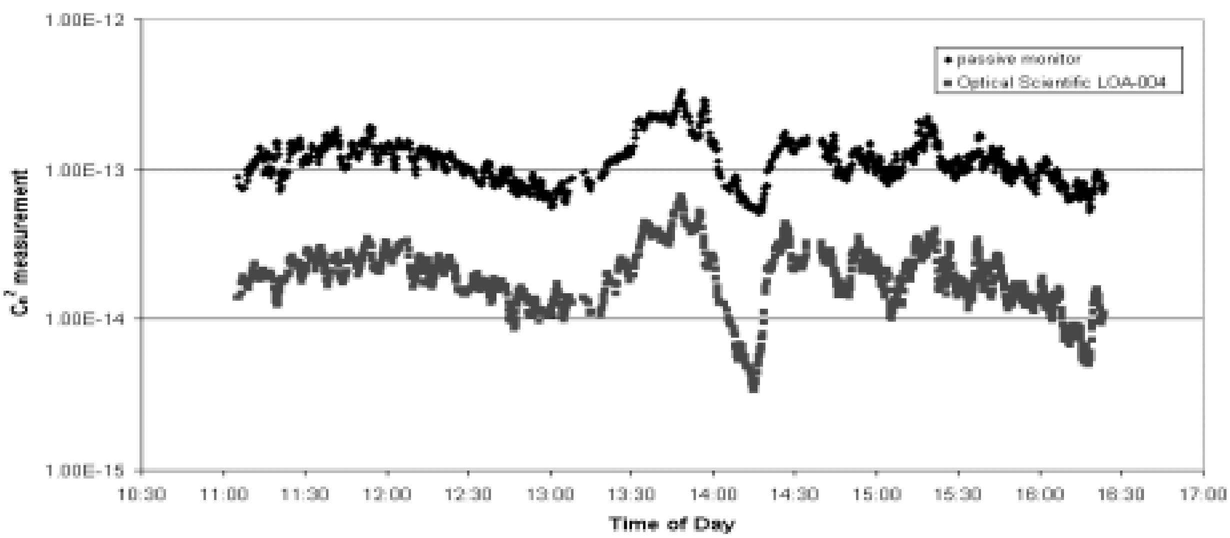

Figure 2: A comparison of the passive turbulence monitor to a commercial device – data taken on 3/18/03 over 1km of land and averaged every 1 minute

3.2 Data from site 2 – across the Potomac River

The passive monitor was positioned on the 5th floor of a building at NRL with a view across the Potomac River. Turbulence data was collected over paths ranging in length from 2 to 3.5 km and traversing both land and water. An incandescent lamp on the other side of the Potomac, either at Reagan National Airport (3.5 km path length) or at the Alexandria power plant (2 km path length) was used as the light source. Figure 3 illustrates these paths. Long term (10/2/02-10/16/02) AOA measurements across the Potomac to the Alexandria power plant are plotted in Figure 4. Specifically, the $1/e^2$ full width half maximum (FWHM) of the AOA fluctuations, assuming a Gaussian distribution, is plotted versus time. The highest (dark gray points) and lowest (light gray points) low frequency cut-offs listed in the previous section are illustrated. The fluctuations > 0.2 Hz are clearly much greater than the fluctuations > 30 Hz showing the dominance of low frequencies in the AOA fluctuations. Figure 5 shows this same data in terms of the C_n^2

estimates that were obtained using Equation 1. Some data was also acquired with the monitor placed outside at ground level. As expected, this data showed higher levels of turbulence than data taken on the 5th floor. The $1/e^2$ FWHM of the AOA from the 0.2 Hz and above bin ranged between 20 and 120 μrad rather than the 7 – 30 μrad shown here.

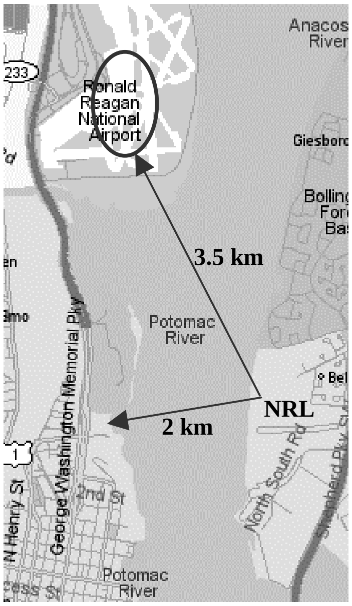

Figure 3: Turbulence measurement paths across the Potomac River.

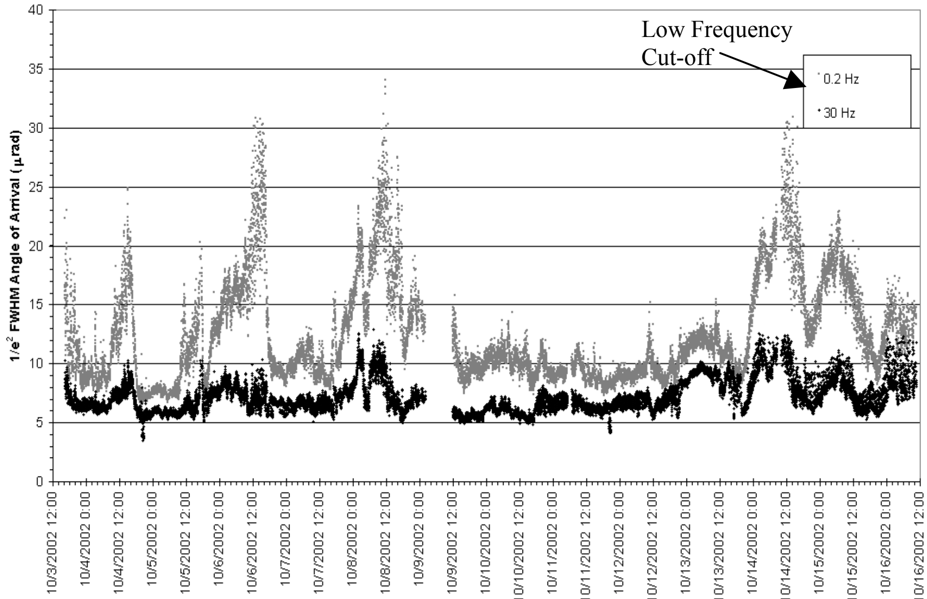

Figure 4: Long term angle of arrival measurements across the Potomac River illustrating frequency component contributions to the AOA fluctuations.

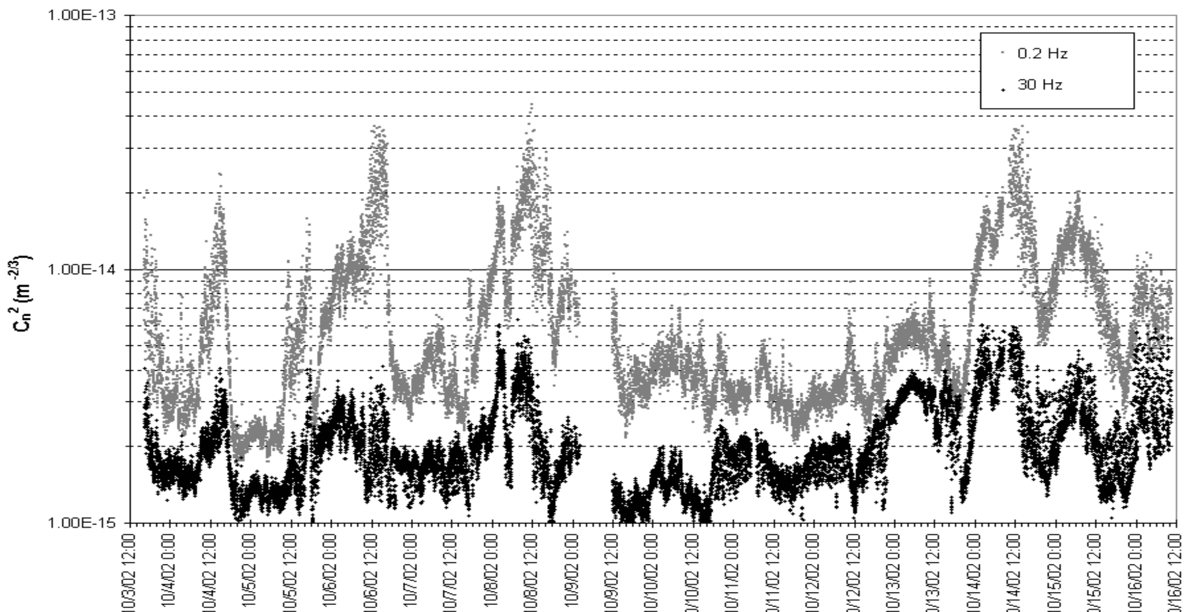

Figure 5: Path averaged C_n^2 estimates across the Potomac River based on AOA data shown in Figure 4 – 10/3/02 - 10/26/02

Long term data along a path from the airport to NRL (3.5 km) was difficult to obtain due to unreliable incandescent light sources. Not only did aircraft temporarily block the lights, but they were turned on and off as needed by airport personnel. However, short term data showed that the turbulence observed over this path tended to be higher than that observed over a path from the power plant. The $1/e^2$ FWHM of the AOA fluctuations for the airport path ranged between 15 and 45 μrad as opposed to the 7 – 30 μrad seen over the path from the power plant.

This difference can be explained by the fact that some of the path to the airport was over the airport's runway tarmac. This added turbulence to the initial portion of the incandescent light's path. On the other hand, the path from the power plant was mainly over water. Airport personnel have recently agreed to cooperate in experiments, which will allow better studies of the airport path.

3.3 Data from site 3 – across the Chesapeake Bay

Finally, the monitor was used to determine the turbulence levels for a 10 mile (16.2 km) path across the Chesapeake Bay. This path is shown in Figure 6. As shown in this figure, a spotlight placed on a tower on Tilghman Island acted as the light source for the monitor. The spotlight was a few feet above the retro-reflector array used in NRL's lasercomm experiments across the bay.[1-3] Turbulence measurements were taken in conjunction with NRL's lasercomm efforts.

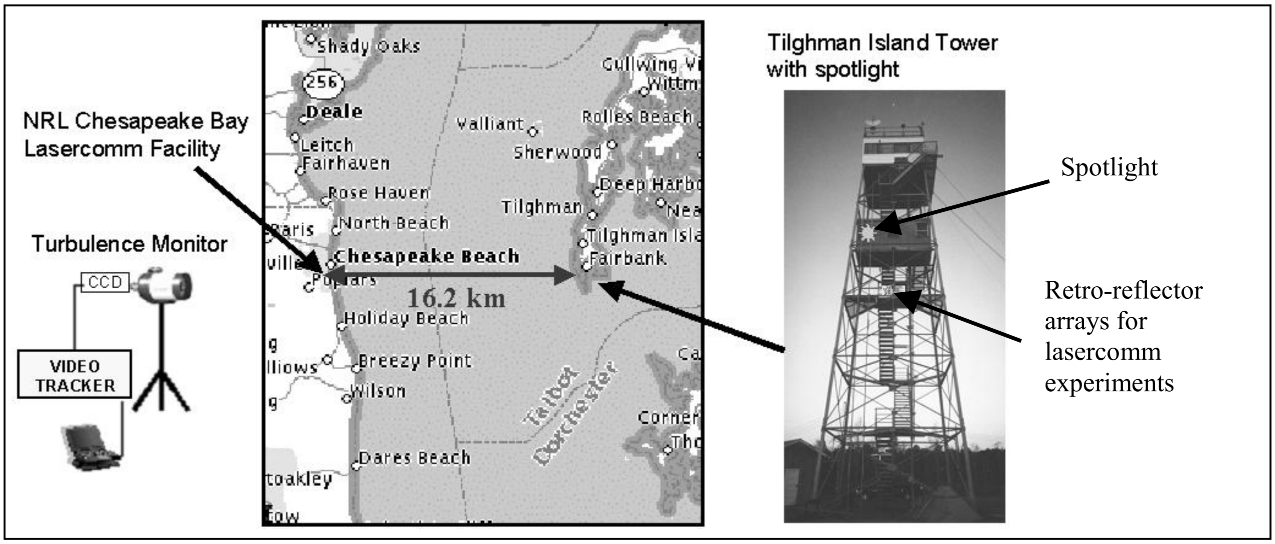

Figure 6: Turbulence measurement path across the Chesapeake Bay illustrating equipment on either end of the bay.

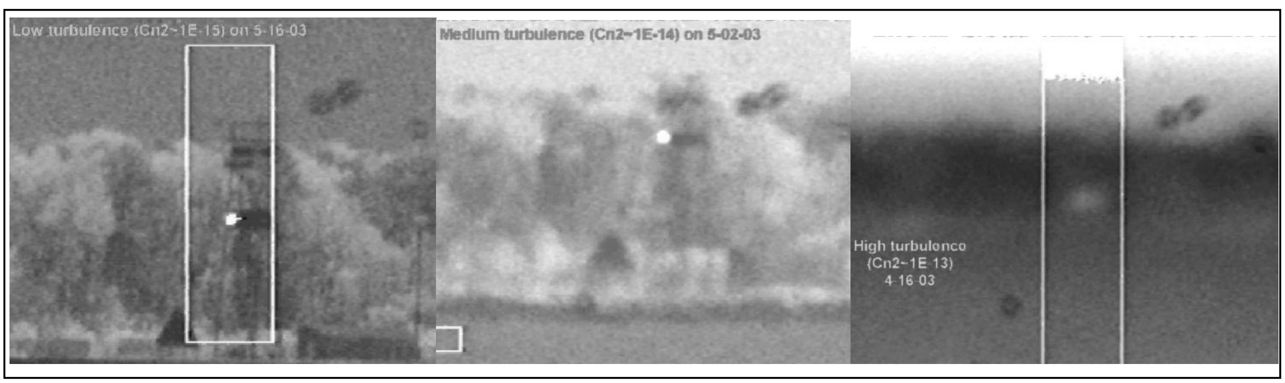

Figure 7: The Tilghman Island tower as imaged through the monitor's 5" diameter telescope under 3 different levels of turbulence. a) low turbulence $C_n^2 \sim 10^{-15}$ b) medium turbulence $C_n^2 \sim 10^{-14}$ and c) high turbulence $C_n^2 \sim 10^{-13}$

The effect of turbulence across the Chesapeake Bay is clearly illustrated in Figure 7. This figure shows a snapshot of the Tilghman tower, taken by the CCD camera attached to the monitor as shown in Figure 1, under three different turbulence conditions. The first snapshot was taken under low turbulence conditions ($C_n^2 \sim 10^{-15}$). The tower and the spotlight are clearly visible. However, even under such low turbulence there is significant AOA variation due to the length of the path. The second snapshot was taken under medium turbulence conditions ($C_n^2 \sim 10^{-14}$). Though distorted, the spotlight and tower are still visible. However, high spatial frequency objects have disappeared and a video stream shows large variations of the image in time. Also of interest is the lensing effect induced by thermal layers over the water. This lensing effect makes the bottom of the image seem elongated while the top of the image appears compressed. The third snapshot was taken under high turbulence conditions (C_n^2~10^{-13}). Here the tower has disappeared entirely. Under these conditions, the spotlight was a flashing blurred light that varied strongly in intensity. The times where the spotlight was not visible was caused in part by such a large degree of beam spreading that there was not enough contrast on the CCD camera to allow the spot to be resolved. Secondly, turbulence caused the spotlight to dance around so much that it sometimes entirely missed the monitor's 5" receiver aperture.

Since the tracker was not able to keep track for any length of time under the conditions in Figure 7c, the monitor was not able to measure this level of turbulence along this path. Three points must be highlighted here. First of all, such turbulence conditions were extremely rare. They were observed on only a few days during the spring where the water was much colder than the air. Secondly, the point of failure was the commercial tracker, which simply could not adjust to the varying contrast levels of the spotlight quickly enough. This will be partially rectified once the tracker is replaced by a PSD. Thirdly, turbulence levels of C_n^2~10^{-13} were routinely observed and measured by this monitor at the shorter distances utilized at sites 1 and 2 above. However, the much longer path length across the Chesapeake Bay proportionately increased the AOA variance. This highlights the fact that it is the AOA fluctuations, rather than C_n^2 that directly determine the feasibility of any link. Thus, the major concern in lasercomm is the value of the AOA fluctuations since it gives a physical representation of how turbulence will effect received light. The passive turbulence monitor gives an absolute determination of the AOA fluctuations making it an ideal diagnostic for a lasercomm link.

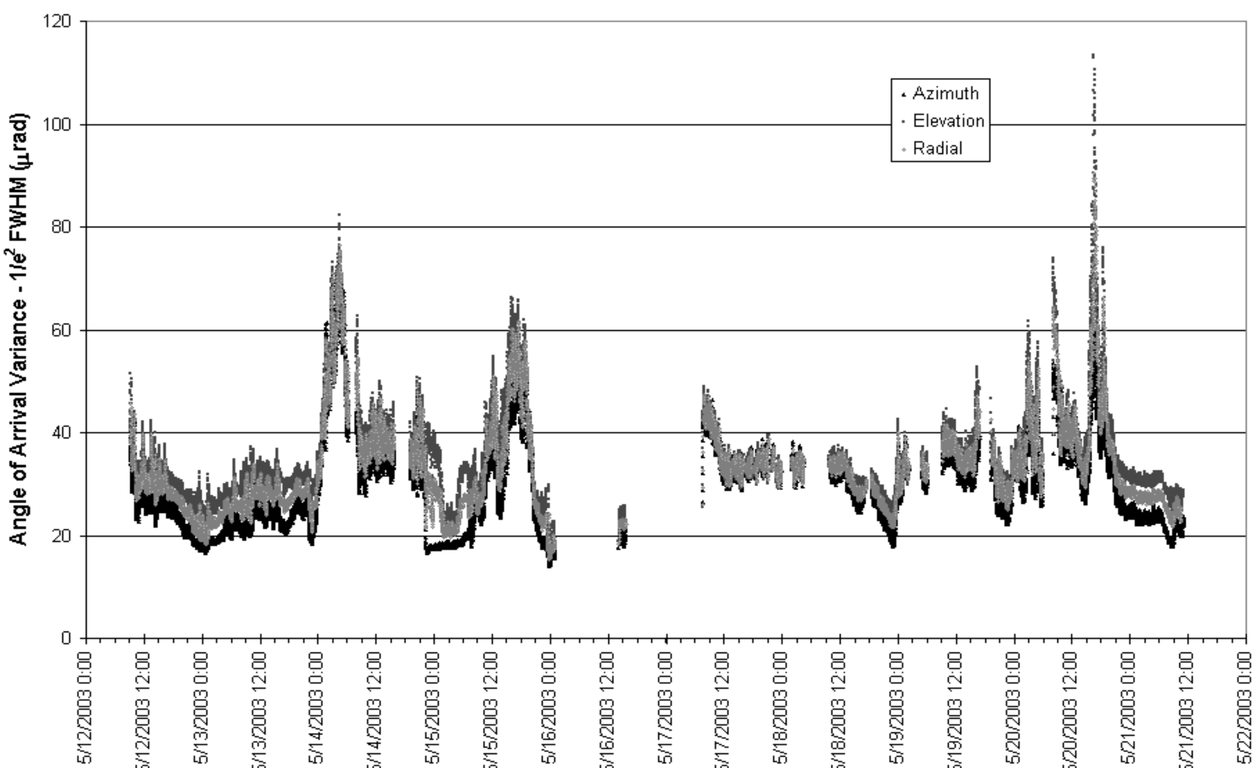

Figure 8: Long-term angle of arrival measurements across the Chesapeake Bay illustrating spatial components to the AOA fluctuations - 5/12/03 - 5/22/03

Figure 8 shows a typical long term AOA fluctuation data set taken across the Chesapeake Bay. C_n^2 was estimated via Equation 1 and plotted in Figure 9 for this same data set. Drop-outs in these two plots typically occurred when weather conditions obscured the tower spotlight (i.e. rain and/or fog) and the commercial tracker lost track. Track loss also occurred when the tracker began tracking on something else (like a boat or a glint of sunlight reflected from the tower during sunset) or under the rare conditions where the turbulence was so high that a measurement could not be obtained such as conditions illustrated in Figure 7c. Figures 8 and 9 also show the spatial influence on AOA fluctuation. The total radial AOA fluctuations are shown in light gray. AOA fluctuations due solely to elevation are in medium gray and those due solely to azimuth are in dark gray. These figures show that atmospheric turbulence effects over the bay are typically greater in elevation than in azimuth.

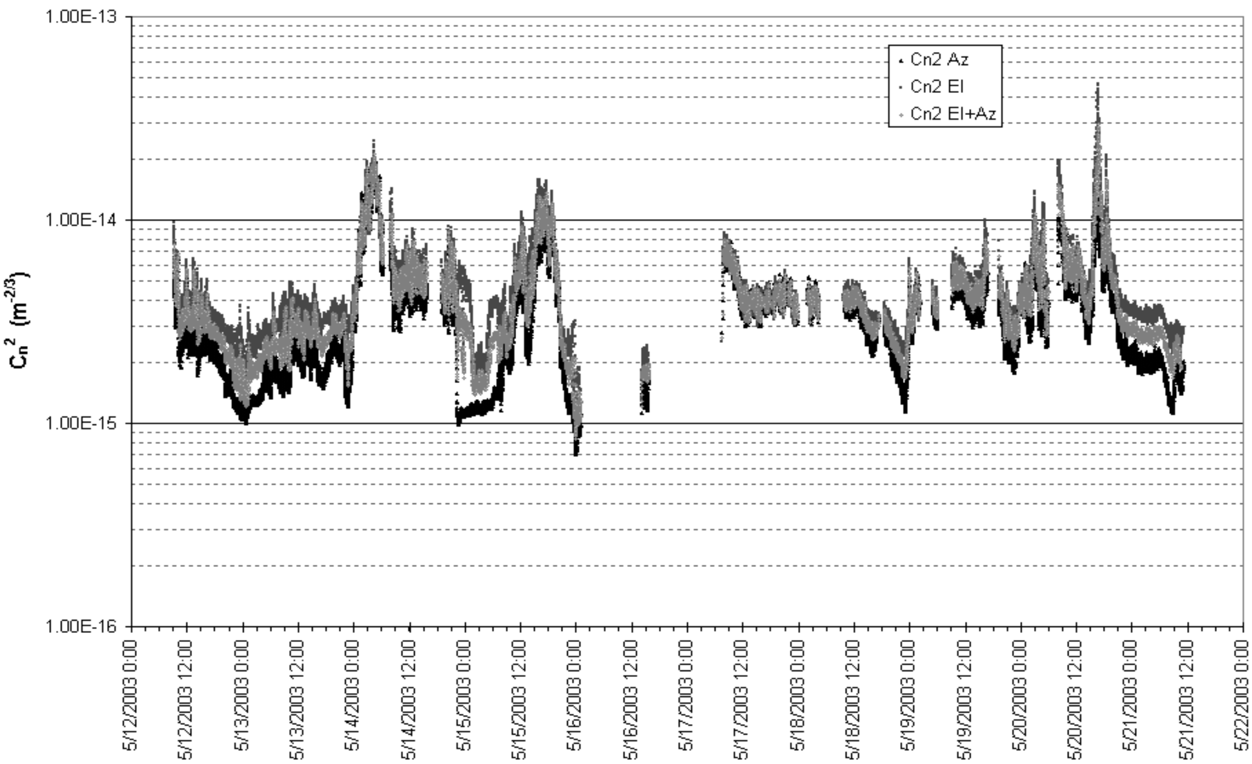

Figure 9: Path averaged C_n^2 estimates across the Chesapeake Bay based on AOA data from Figure 8 – 5/12/03 - 5/22/03

The monitor collected data across the Chesapeake Bay for several months. The probability density function in Figure 10 was generated from all of the data collected between April and July 2003. The median C_n^2 measured during these months was $2.8\text{x}10^{-15}$ $m^{-2/3}$. This figure does not include times of track loss due to the conditions described above. Such conditions occurred about 15% of the time. Therefore, Figure 10 represents about 85% of all conditions observed during the months of April – July 2003. The NRL Chesapeake Bay Lasercomm Test Facility demonstrated a 622 Mbps lasercomm link with 10^{-10} bit error rate[2] at a turbulence level of $5 \text{ x } 10^{-15}$ $m^{-2/3}$. This is significantly above the median observed C_n^2 value. Link closure was not attempted at higher turbulence levels due to time constraints for experiments. This means that this is the minimum C_n^2 over which link closure is possible. Experiments are planned to determine the maximum C_n^2 at which the link can be closed.[2]

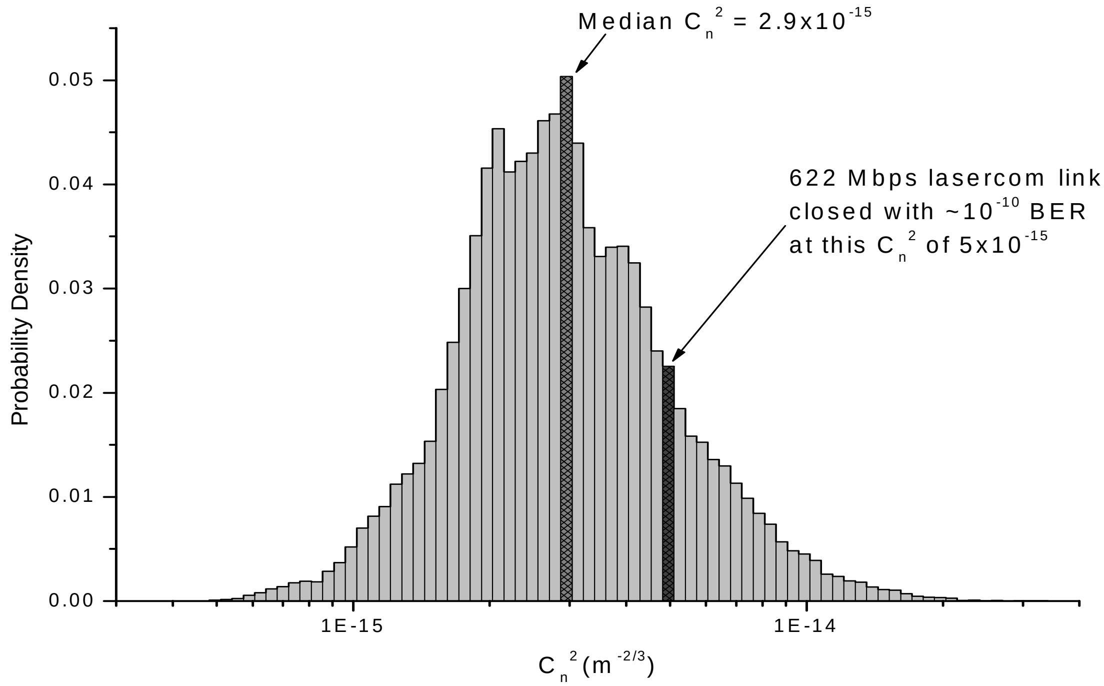

Figure 10: PDF of C_n^2 Data taken over a path across the Chesapeake Bay April 20 – July 17 2003

3.4 Frequency analysis and wind measurement

During the course of experimentation, a correlation between frequency content and wind speed was observed. This is not surprising since turbulent eddies move through the monitor's field of view faster at higher wind speeds resulting in higher frequency fluctuations. In order to obtain a numerical value for the frequency content, a frequency centroid based on the weighted mean of the frequency components was empirically determined and defined as follows:

$$freq.cent. \equiv \left(\frac{1}{\sigma_1^2 - \sigma_N^2}\right)\sum_{i=1}^{N-1}\frac{(f_i + f_{i+1})}{2} \bullet \left(\sigma_i^2 - \sigma_{i+1}^2\right) \quad (2)$$

where f_i is the frequency in the i^{th} bin and N is the total number of frequency bins (N=13). Figure 11 plots both the frequency centroid and the transverse wind speed taken at site 2. The frequency centroid was measured along a path across the Potomac River from NRL to the Alexandria power plant. Wind speed was taken from wind data reported on NOAA's website from a weather station at National Airport. The transverse wind speed was calculated by computing the component of the wind perpendicular to the line of site. This was very approximate since NOAA reported wind directions in 45^o intervals (N, NE, E etc). Furthermore, the point measurement of wind speed was taken approximately 4 km from the turbulence monitor's path averaged wind speed measurement. Despite all this, Figure 11 shows that the transverse wind speed did follow the same general trend as the AOA frequency centroid indicating a correlation with wind speed.

This investigation was repeated at site 3 – the path across the Chesapeake Bay. In order to obtain a more relevant wind speed measurement, a Davis Vantage Pro weather station was mounted on the rooftop of the NRL Chesapeake Bay Lasercomm Test Facility. Thus, this weather station was at the receiving end of the monitor's path. In order to reduce the effect of having a point rather than a path averaged measurement of wind speed and to simplify analysis, the only data selected was data where the reported wind speed and direction were constant for at least 10 minutes out of the North or South. Since, as shown in Figure 3, the Tilghman tower is due east of the NRL Chesapeake Bay Lasercomm Test Facility, such winds were predominantly in the transverse direction with relatively uniform wind speed over the test range. The results of this analysis are plotted in Figure 12. Since only a small portion of the data was considered, this result is preliminary. However, Figure 12 does show there is a very strong linear correlation between transverse wind speed and the frequency centroid. This means this monitor can be used as a transverse wind speed monitor as well as a turbulence monitor. Future work will involve a more extensive calibration of this monitor against measured wind speed.

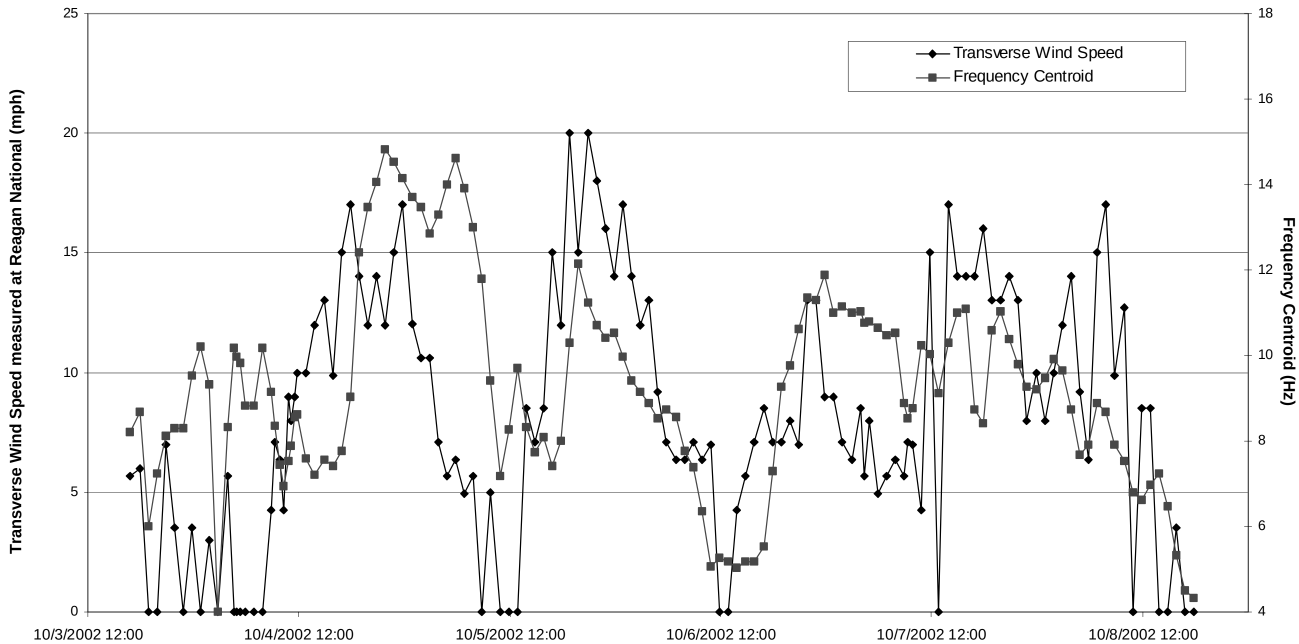

Figure 11: Frequency centroid of the AOA variance measured across the Potomac (Site #2) compared to transverse wind speed measured at National Airport (hourly averages)

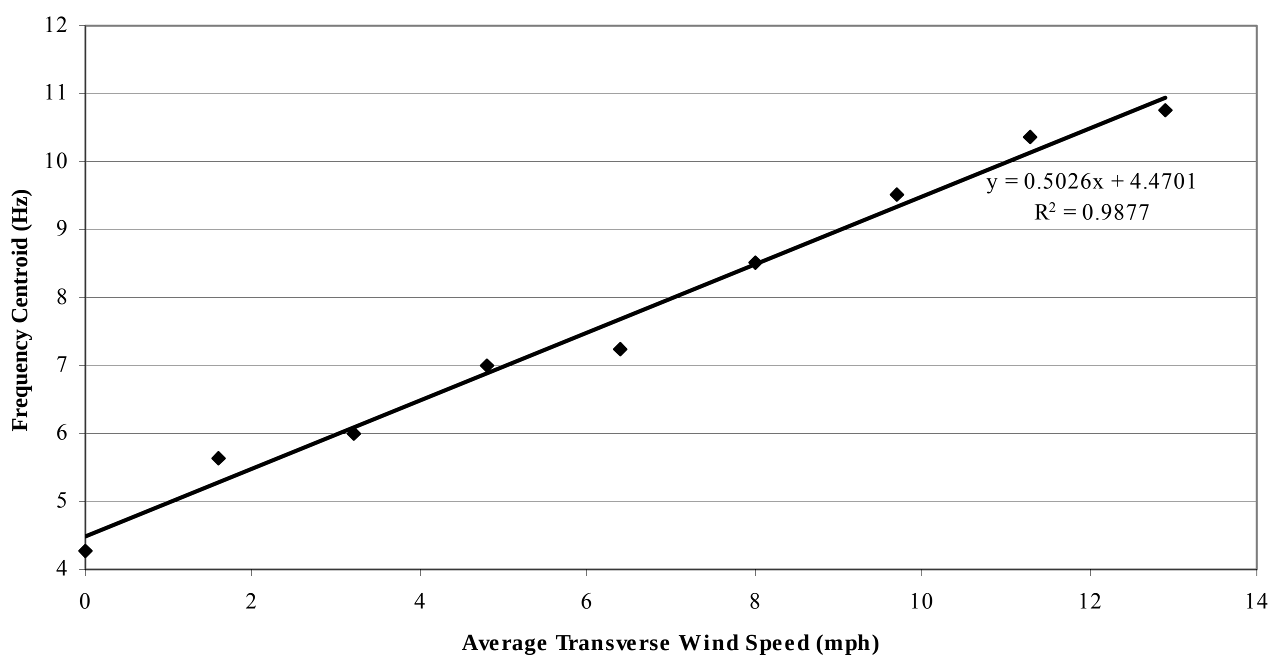

Figure 12: Frequency centroid of the AOA variance measured across the Chesapeake Bay (Site #3) vs. transverse wind speed

4. CONCLUSIONS

A passive optical turbulence monitor was developed and operated at ranges up to 10 miles. A comparison to a commercial scintillometer showed highly correlated C_n^2 measurements with a constant offset. Work is ongoing to reconcile this offset. Angle of arrival variance and its corresponding C_n^2 were measured over diverse terrains and under various atmospheric conditions. Temporal frequency analysis showed that angle of arrival fluctuations were dominated by low frequency components. Long-term monitoring over the Chesapeake Bay showed that the median value of C_n^2 was relatively low ($C_n^2 \sim 2.8\text{x}10^{-15}$ $m^{-2/3}$). Frequency components of the angle of arrival variance were shown to have a strong linear correlation with transverse wind speed. The monitor is an excellent means of measuring turbulence and wind conditions. Future inclusion of a PSD will greatly reduce the cost of the system allowing accurate and inexpensive long range turbulence and wind measurement.

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", *Proceedings of the SPIE.*, **4821**, pp. 474-485, 2002.

2. M.J. Vilcheck, H.R. Burris, C.I. Moore, M.F. Stell, M.R. Suite, M.A. Davis, R. Mahon, E. Oh, W.J. Scharpf, W.S. Rabinovich, A.E. Reed, and G.C. Gilbreath, "Progress in high-speed communication at the NRL Chesapeake Bay Lasercom Facility", *Proceedings of the SPIE*, **This issue**, 2003.

3. G.C. Gilbreath et. al. "Research in free space optical data transfer at the U.S. Naval Research Laboratory", *Proceedings of the SPIE*, **This issue**, 2003.

4. R. Mahon, H.R. Burris, W.S. Rabinovich, G.C. Gilbreath, P.G. Goetz, C.I. Moore, T.J. Meehan, M.F. Stell, M.J. Vilcheck, J.L. Witkowsky, L. Swingen, M.R. Suite, E Oh, and J. Koplow, "A free-space optical communications link at 1550 nm using multiple quantum well modulating retro-reflectors in a maritime environment", *Proceedings of the SPIE*, **This issue**, 2003.

5. M.R. Suite, H.R. Burris, C.I. Moore, M.J. Vilcheck, R. Mahon, M.F. Stell, M.A. Davis, W.S. Rabinovich, W.J. Scharpf, A.E. Reed, and G.C. Gilbreath, "Fast steering mirror implementation for reduction of focal-spot wander in a long-distance free-space communication link", *Proceedings of the SPIE,* **This issue**, 2003.

6. H. R. Burris, C.I. Moore, M.J. Vilcheck, R. Mahon, M.F. Stell, M.R. Suite, M.A. Davis, W.J. Scharpf, A.E. Reed, W.S. Rabinovich, G.C. Gilbreath, E. Oh, and N. M. Namazi, "Low frequency sampling adaptive thrsholding for free-space optical communication receivers with multiplicative noise", *Proceedings of the SPIE,* **This issue**, 2003.

7. Andrews, Larry C. and Phillips, Ronald L., <u>Laser Beam Propagation Through Random Media</u>. SPIE Optical Engineering Press, 1998.