Effects of Atmospheric Turbulence on Laser Propagation

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Abstract:

New technologies in direct line of sight wireless communication systems are being developed at the University of Maryland. These are hybrid systems that use both free-space optical (FSO) communication links and radio frequency links (RF). The focus of this summer's project is to characterize the affects of atmospheric turbulence on laser beam (FSO) communication links. To acquire and analyze atmospheric data a Helium-Neon laser is directed at a distant Schmidt-Cassegrain telescope. The optical data is then gathered from the telescope by a high performance CCD camera connected to a laptop. LabVIEW software is used to capture the desired data and analyze it using the appropriate statistics including the calculation of intensity correlation functions.

Introduction:

The Maryland Optics Group is currently researching and developing wireless direct line-of-sight free-space optical (FSO) communication systems. In order to optimize these systems an understanding of the channel medium (the atmosphere) is requisite. The concern of the current research is the characterization of the effects of atmospheric turbulence on the propagation of electromagnetic waves at optical wavelengths.

One effect of atmospheric turbulence is that it scatters light. The current method of research into the characteristics of atmospheric turbulence is the analysis of this scattered light. It is this resultant scattered light that brings up two essential questions. What does the turbulence do to the light i.e. how does it scatter the light? What does the scattered light tell us about the atmospheric turbulence? It is hoped that the current research will help to answer both questions.

The answer to the first question is important for engineering applications like a FSO communication systems. Specifically our current research will look to optimize the receiver or aperture size for a FSO communication system. The answer to the second is important to the development of formal mathematical theories on the behavior or physics of the atmosphere. Our current research will aid the development of these physical theories.

Turbulence Theory:

The atmosphere can be described as a moving fluid of air. As such it can be modeled by the Navier-Stokes equations (shown below) that describe the behavior of moving fluids.

$$\partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{\rho}\nabla p + \upsilon \nabla^2 \mathbf{v} \qquad \nabla \cdot \mathbf{v} = 0$$

Navier-Stokes Equations (NSE)
(Assuming incompressibility)

ρ is density, $\upsilon = \dfrac{\eta}{\rho}$ is called the kinematic viscosity. η is called the dynamic viscosity

These equations show that atmosphere can move as either as turbulent flow or laminar (non-turbulent) flow. Turbulence occurs when a fluid flow exceeds a critical Reynold's number ($R \equiv lu/\upsilon$) which causes the non-linear term ($(\mathbf{v} \cdot \nabla)\mathbf{v}$) of the NSE to dominate which is characterized by the flow's chaotic behavior (as shown below).

$$\frac{(\mathbf{v} \cdot \nabla)\mathbf{v}}{\frac{\eta}{\rho}\nabla^2 \mathbf{v}} \sim \frac{u^2/l}{\eta u/\rho l^2} = \frac{ul}{\upsilon} = R$$

The non-linear nature of the equations makes them difficult to with since there are no known solutions or families of solutions to the Navier-Stokes equations. This forces one to look at other mathematical observations to take something meaningful from these equations.

In low turbulence (when the non-linear term, $(v \cdot \nabla)v$, is much less than $\upsilon\nabla^2 v$) significant symmetries arise. These symmetries are space and time translation, Galilean transformation, parity, rotation, and scaling. In extreme turbulence, Kolmogorov predicted and proved that the symmetries of the Navier-Stokes equations that exist in non-turbulent systems re-appear. The extreme complications of the Navier-Stokes equations, arising from the nonlinearity, force us to use statistical methods to characterize the behavior of a turbulent fluid as such the atmosphere. Fortunately, the symmetries give us insight into the statistics.

Experimental Setup:

To acquire and analyze atmospheric data, a Helium-Neon laser is mounted on a portable optical breadboard behind a 30x Melles Griot beam expander with two mirrors (Fig. 1) used to aim the expanded beam at the distant Schmidt-Cassegrain telescope. The intensity pattern at the front of the telescope is transferred to the telescope by a high performance CCD camera that is connected to a laptop by a frame-grabber interface (Fig. 2). The acquired data is written to the laptop as a .AVI file.

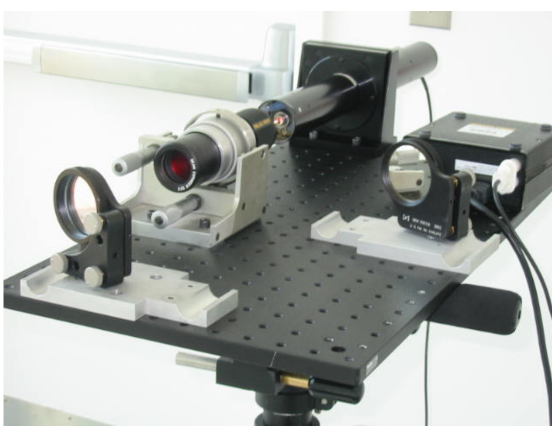

Figure 1: Propagating laser setup

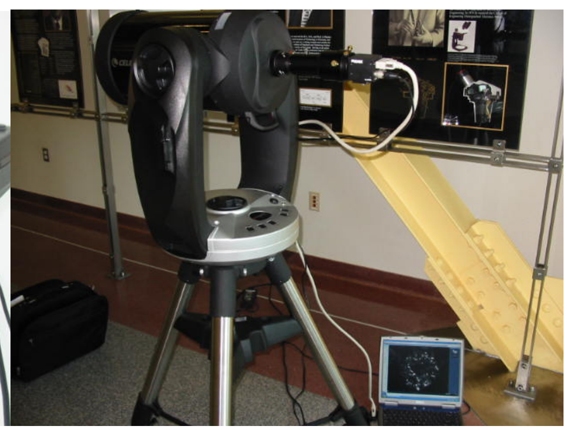

Figure 2: Telescope, camera, and laptop setup

The analysis of the data from the Schmidt-Cassegrain telescope was performed by a LabVIEW Virtual Instrument (VI). This VI was designed to take the acquired data in the form of an .AVI file and convert it to 8-bit 3D-dimensional array to allow the VI to properly analyze the data. The data is analyzed by the calculation of various statistics, and correlation functions.

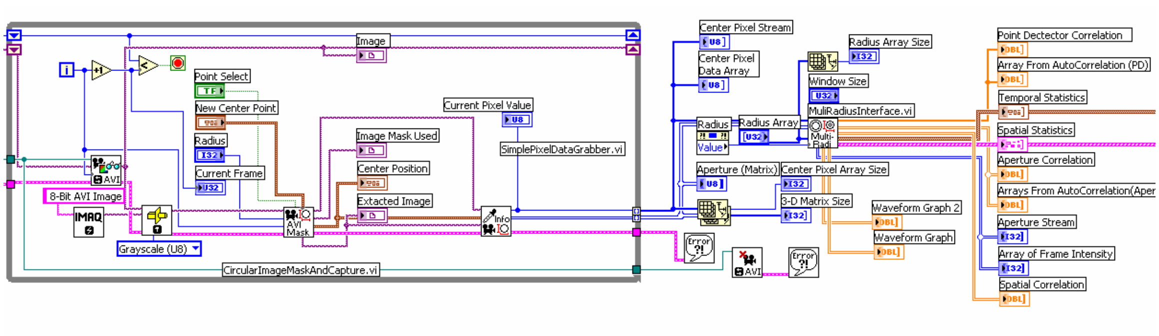

Figure 3: Screen shot of LabVIEW programming used

Atmospheric Effects:

The effects of atmospheric turbulence are easily seen by the propagation of the laser through the atmosphere. As can be seen on figure 4 the turbulence induces intensity random fluctuations in the beam known as scintillation. This is an effect of the many random changes in the index of refraction along the path of beam propagation due to turbulence.

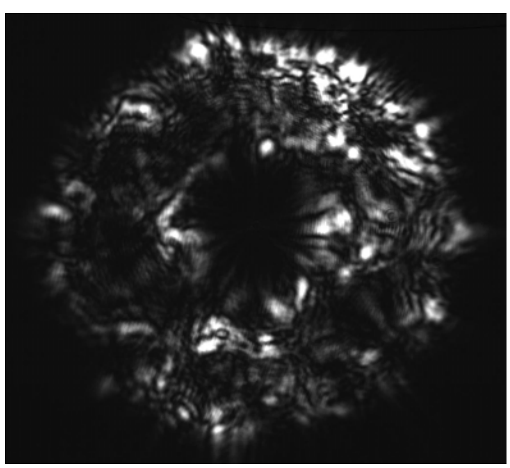

Figure 4: Screen shot of image at the front of the telescope

Analysis:

The statistical methods used in the data analysis included aperture averaging, the calculation of temporal and spatial correlation function, and various other statistics such as the mean, variance, and standard deviation of pixels used to calculate the aperture averaging factor.

Aperture averaging is a statistical method that is useful for the optimization of the receiver size or aperture size in a FSO link. In a FSO link the scintillations of the received beam causes signal degradation. A large receiver will collect all the transmitted data and see no atmospheric-turbulence-induced intensity variance, but is expensive. An optimized receiver aperture size is desired to reduce intensity scintillations and be cost effective. The aperture averaging factor (F) is a measure of aperture averaging and it is a ratio of normalized intensity variance of a receiver of some size to that of a point detector.

$$F = \frac{\left(\frac{\sigma^2}{\mu^2}\right)_{PD}}{\left(\frac{\sigma^2}{\mu^2}\right)_{Aperture}}$$

Figure 5 shows the results of calculating the aperture averaging factor for apertures of various diameters. To take advantage of the best aperture size for least intensity variance one should select an aperture size with an ‘F’ within that range when the slope begins to stop falling off so quickly.

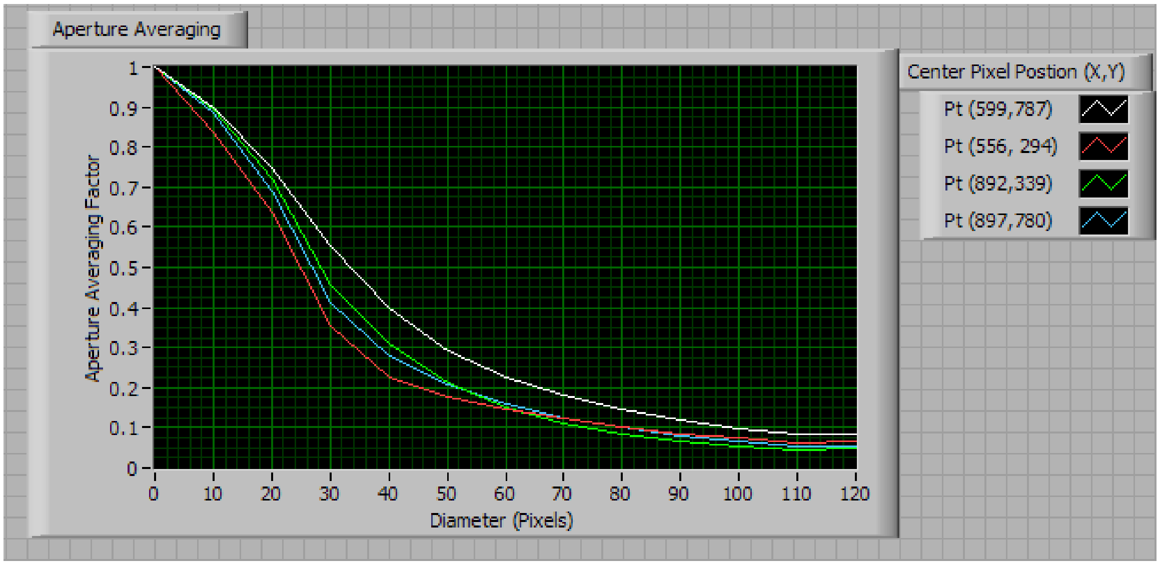

Figure 5: Graph of aperture averaging factor for various aperture diameters

The other major statistical method used in the analysis of the optical data was the calculation of correlation functions. Correlation is a measure of how neighboring (in time or space) pixels have related intensity values. Spatial and temporal correlation functions are calculated to gain an understanding to time and space evolution of the atmospheric turbulence so that formal mathematical descriptions can be later developed. One of the important applications of the correlation function is that they tell you the expectation for the size of optical patterns.

Figure 6 shows that results of a spatial correlation function for a various lengths of pixels that have averaged in time. From the graph 1/e point of the spatial correlation gives you an idea of the size of the optical pattern for this particular .AVI shoot (around 20 pixels) though some amount of atmospheric turbulence. Further understand the turbulence this spatial correlation needs to be calculated from variable amounts of turbulence.

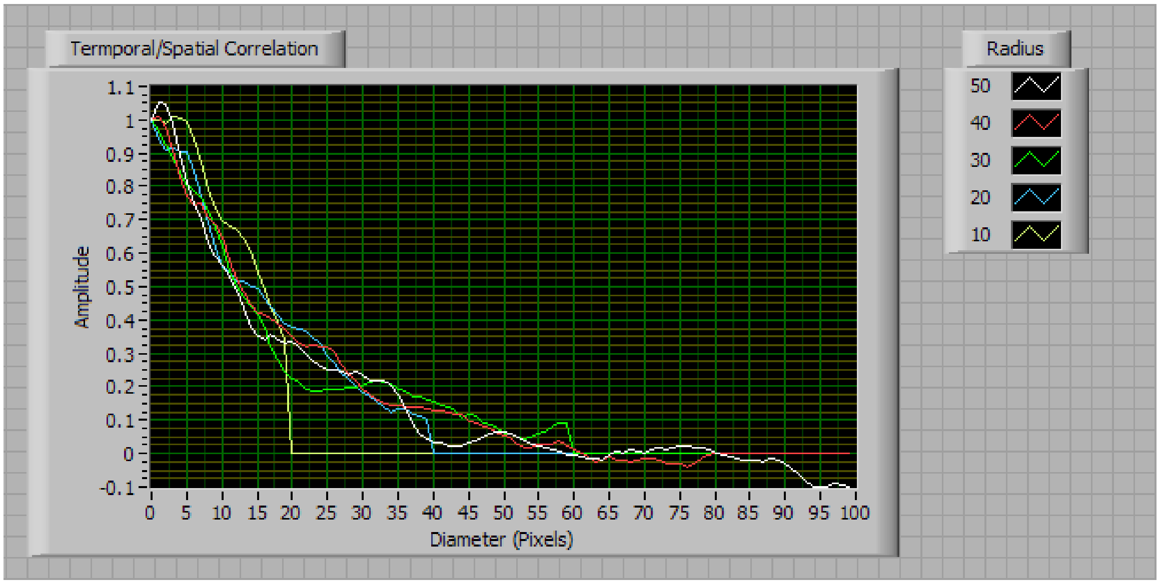

Figure 6: Graph of spatial correlation function

Conclusion:

The current research has development a system that allows the effects of the atmosphere on a laser beam to be studied. This system uses Schmidt-Cassegain telescope to collect scintillation patterns that develop when a laser beam propagates a long distance through the atmosphere. In particular, scintillation pattern analysis has allowed determination of aperture averaging effects and both spatial and temporal correlation functions. This analysis will allow for the development of future mathematical frame work to describe the behavior of atmospheric turbulence.

Sources:

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