REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
09-19-2011	Final Performance Report	February 2008 -- May 2011

4. TITLE AND SUBTITLE
Generation and use of `superbeams' in turbulence and scattering applications

5a. CONTRACT NUMBER
FA9550-08-1-0063

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Greg Gbur

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The University of North Carolina at Charlotte
9201 University City Blvd.
Charlotte, NC 28223-0001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
USAF, AFRL
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington VA

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-OSR-VA-TR-2012-0647

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution A

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The objective of this project was to study the generation and optimization of special beam classes in turbulence and scattering applications, with the goal of combining the beneficial properties of such special beam classes to create what are loosely referred to as “superbeams”. Particular emphasis was given to beam classes that could perform well in free-space optical communications with errors due to optical scintillation (intensity fluctuations) significantly reduced from conventional coherent Gaussian beams. Simulations demonstrated that incoherent beam arrays can perform as well as more general partially coherent fields, therefore simplifying the optimization process significantly. Pseudo-Bessel correlated beams, Airy beam arrays, nonuniformly polarized beams, and vortex beams were each shown to possess advantages in propagation through turbulence.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE		15	19b. TELEPHONE NUMBER *(Include area code)*

Reset

Generation and use of `superbeams' in turbulence and scattering applications

Final Performance Report

Greg Gbur
University of North Carolina at Charlotte
Department of Physics and Optical Science
Charlotte, NC 28223

Award: FA9550-08-1-0063

1. Summary

The objective of this project was to study the generation and optimization of special beam classes in turbulence and scattering applications, with the goal of combining the beneficial properties of such special beam classes to create what are loosely referred to as "superbeams". Particular emphasis was given to beam classes that could perform well in free-space optical communications with errors due to optical scintillation (intensity fluctuations) significantly reduced from conventional coherent Gaussian beams.

The most important beams studied in this project are partially coherent (PC) beams, whose fields fluctuate randomly in space and time. Such "pre-randomized" fields have been shown in many previous studies (e.g. [1,2] and the review in [3]) to be less susceptible to the fluctuations of the turbulent atmosphere. Beams with Gaussian correlations have been extensively studied, and this project took a look at more unconventional Bessel-correlated fields. Coherent Bessel beams had previously been shown to possess non-diffracting characteristics [4] and inherent resistance to phase distortion [5], so Bessel-correlated fields seemed like a natural topic of investigation. Not only was it demonstrated that Bessel-correlated beams have good scintillation reduction properties, but it was also discovered that these characteristics can be easily achieved with an incoherent array of a finite number of beamlets. This suggests that incoherent beam arrays are "good enough" for scintillation reduction via partial coherence, and will lead to easier attempts to optimized such beams.

With this in mind, incoherent arrays of Airy beamlets were also studied for their scintillation reduction capability. Airy beams were experimentally confirmed relatively

recently [6], and possess both diffraction-free propagation as well as the ability to "accelerate" along a curved trajectory. In this project, this acceleration was shown to be robust in atmospheric turbulence and it was also shown that arrays of such beams, designed to "curve" into a detector, can produce scintillation reduction close to the theoretical minimum.

Polarization is typically not considered in theoretical studies of turbulence propagation. It is well-known that the state of polarization of a coherent beam does not change appreciably on propagation, even in moderately strong turbulence conditions. However, it has been shown that the degree of polarization can change appreciably on propagation in turbulence [7], and that unpolarized beams can have scintillation lower than fully polarized beams [8], suggesting that polarization can play a role. In this project, the propagation of coherent but *nonuniformly polarized* beams was studied in turbulence. It was found that such a nonuniformly polarized (NUP) beam can act as an effective partially coherent source, with corresponding scintillation reduction. This suggests that such NUP beams could be used as the fundamental beamlets in the PC beams studied above.

A final intriguing class of beams are those with orbital angular momentum [9] and a circulating or helical phase structure, known as "vortex beams". Vortex beams possess a "rip" in their phase at the central axis, and it is well-known that this phase singularity is a conserved quantity that is persistent on propagation through significant atmospheric turbulence, as demonstrated in a paper published during a previous AFOSR grant [10]. In the current project, the statistical properties of vortex beams were further investigated, and it was also shown that such beams could be used to measure the characteristics of a random medium. Considering the optimization of scintillation reduction requires knowledge of the medium, this tool could be used in conjunction with the other strategies described in this project.

2. Partially coherent beam arrays

Free-space optical (FSO) communications systems typically transmit information via variations in the intensity of light. However, variations in the temperature, humidity and pressure in the atmosphere, turbulent or not, can distort an optical beam on propagation, leading to fluctuations in the intensity arriving at the detector and consequently errors in the transmitted data. These *scintillations* are one of the most significant limitations in the development of robust FSO systems.

Partially coherent beams are generally expected to have lower scintillation than their fully coherent counterparts. A simple explanation of this effect is shown in Fig. 1. A partially coherent beam can be interpreted as an incoherent superposition of multiple independent beamlets. Though any individual beamlet may not make it to the detector, there is an increased likelihood that some combination of beamlets will; the result is, on average, a more regular distribution of intensity.

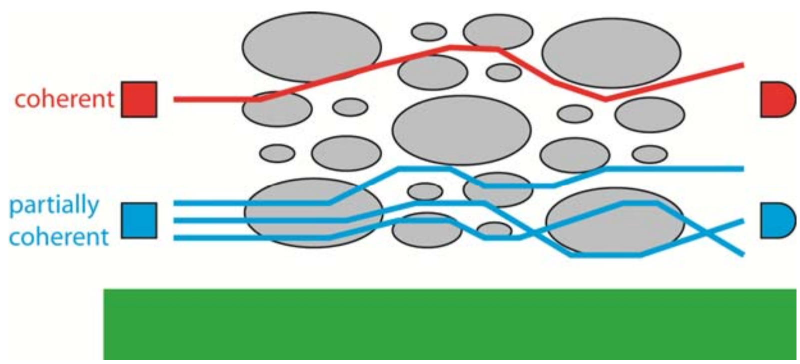

Figure 1. Illustration of the physics behind the improved performance of partially coherent beams in turbulence. A coherent beam sends all of its energy through a single mode, while a partially coherent beam sends its energy through multiple independent modes. The latter is more likely to send a regular amount of energy to the detector.

The scintillation of Gaussian-correlated beams in turbulence has been well-studied; for instance, see [1,2]. Beams with other correlation properties have not been investigated as thoroughly, however, or at all, and it was a natural course of action to look at the scintillation properties of beams with other correlation properties.

A. Bessel correlated beams and pseudo-Bessel correlated beams

The first class considered were so-called Bessel correlated beams, in which the spatial correlation function of the optical beam is of Bessel function form. Coherent beams with a Bessel function amplitude are also known as non-diffracting beams, as they can propagate long distances without an appreciable change in their intensity profile [4]. Fields with Bessel correlations were shown to have similar characteristics [11], and it was deemed worthwhile to look at the behavior of such beams in turbulence.

The propagation of Bessel correlated beams was studied both analytically and computationally [publication 6], the former with the Rytov approximation and the latter with a multiple phase screen method [12]. A true Bessel correlated field can be decomposed as a collection of Gaussian beamlets whose wavevectors lie on a cone centered on the direction of propagation; for computational and analytic tractability this was approximated by a finite collection of Gaussian beamlets lying on a cone – a "pseudo-Bessel correlated beam" (PBCB), whose configuration is shown in Fig. 2(a). The scintillation results for just two beamlets are shown in Fig. 2(b), and indicate that there is a degree of coherence (cone opening angle) for which the scintillation is reduced by half.

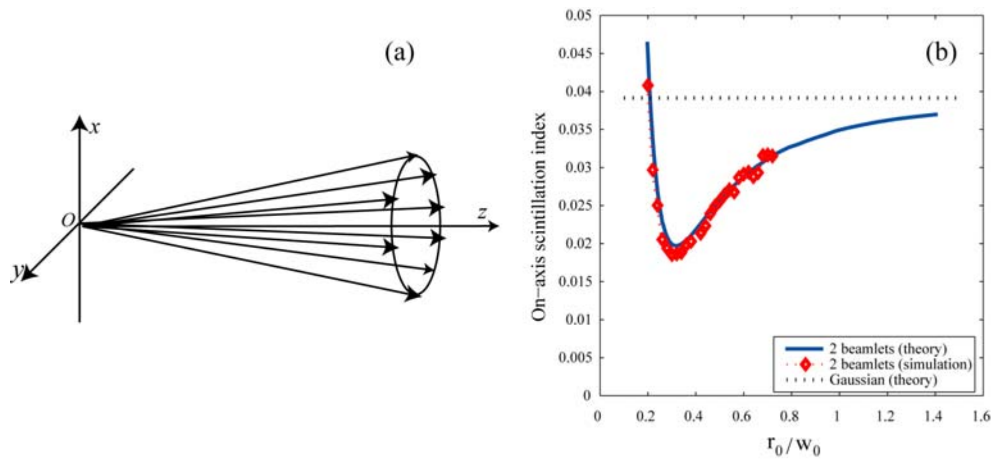

Figure 2. (a) The concept of a pseudo-Bessel correlated beam: the beam consists of an incoherent array of identical beamlets whose directions lie on a cone. (b) Scintillation of a 2 beamlet PBCB, as a function of the ratio of coherence length r_0 to beamlet width w_0. After [publication 6].

For high coherence (large r_0), the beamlets are all nearly parallel to the z-axis and the on-axis scintillation approaches the limit of a single Gaussian beam. In the low coherence limit (low r_0), the beamlets lie on a very divergent cone and tend to miss the axis completely, resulting in a very high scintillation. In between, there is an optimum degree of coherence for which the scintillation is minimized.

The large increase of scintillation for low coherence can be mitigated by adding an additional Gaussian beamlet on the z-axis, which makes up for the decrease in intensity on axis. With an appropriate chosen amplitude for this beamlet, the sharp increase in scintillation for small r_0 disappears completely for this "modified pseudo-Bessel correlated" beam.

As the number of beamlets is increased, one would intuitively expect that the scintillation of the beam to gradually approach that of an ideal Bessel correlated field. However, as shown in Fig. 3, something quite surprising happens: the scintillation saturates with only four beamlets! Though the average intensity profile of such a beam looks nothing like that of a true Bessel correlated beam, its scintillation is exactly the same on axis.

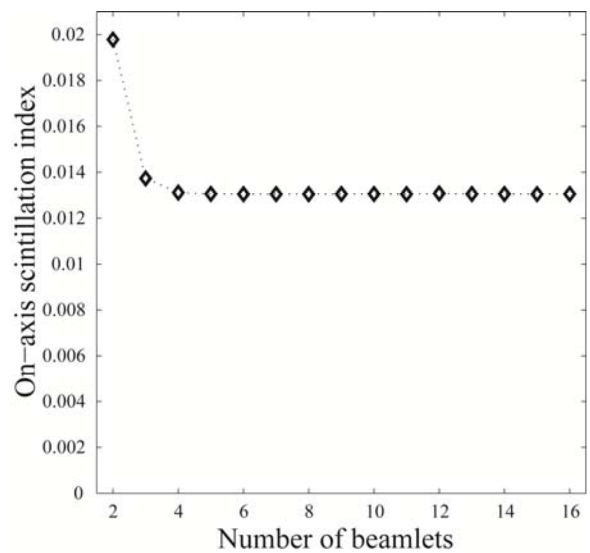

Figure 3. On-axis scintillation index of a pseudo-Bessel correlated beam as a function of the number of beamlets, after [publication 6]. Increasing the number of modes above 4 gives no significant decrease in scintillation.

This result can be understood by a little physical reasoning. If we superimpose two identical Gaussian beams on one another – same width, propagation direction, wavelength – they will be distorted in exactly the same way by the turbulence, produce identical interference patterns at the detector and consequently there is no scintillation reduction. In order for two or more beams to produce independent interference patterns at a detector, they must be sufficiently *diverse*; that is, they must propagate in a significantly different manner through the turbulent media. Three ways are possible to get diversity: *directional diversity*, in which the beamlets propagate in different directions, *spatial diversity*, in which the beamlets start at different positions, or *modal diversity*, in which the transverse profiles of the beamlets are different and therefore affected differently by turbulence.

This observation marks a rather dramatically different way of thinking of partially coherent beam propagation. Though it is not completely proven, the Bessel beam results suggest that the scintillation properties of any partially coherent beam can be sufficiently reproduced by a finite beam array. This allows us to focus on the question of optimizing finite beam arrays, rather than attempting to find an optimal partially coherent beam solution for a given turbulence application.

B. Incoherent Airy beam arrays

Pseudo-Bessel correlated beams employ directional diversity to reduce scintillation; however, this results in much of the energy of the beamlets propagating away from the central axis and the detector. It is reasonable to look at beam arrays which start spatially separated and instead converge to the detector; in fact, much research has been done on such beam arrays.

An alternative method of achieving spatial diversity is to use beamlets that start spatially separated and curve to the detector plane. Such Airy beams have been studied in optics since 2007 and have been confirmed to exist; in this project the use of such beams in turbulence was considered [publication 5].

The intensity of an Airy beam is shown as a function of propagation distance in turbulence in Fig. 4. The characteristic bending of the field can be seen, and it is clearly robust over several kilometers of propagation.

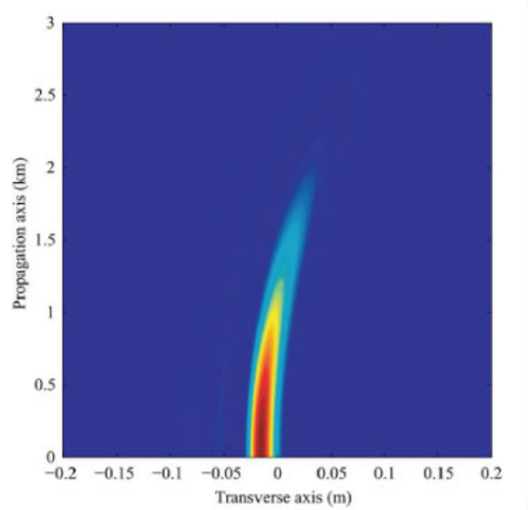

Figure 4. Intensity of a typical optical Airy beam on propagation through moderate turbulence, after [publication 5].

For scintillation reduction, an incoherent array of four Airy beams is employed, with parameters chosen to make the beam curve to the detector at 3 km. The idea is illustrated in Fig. 5.

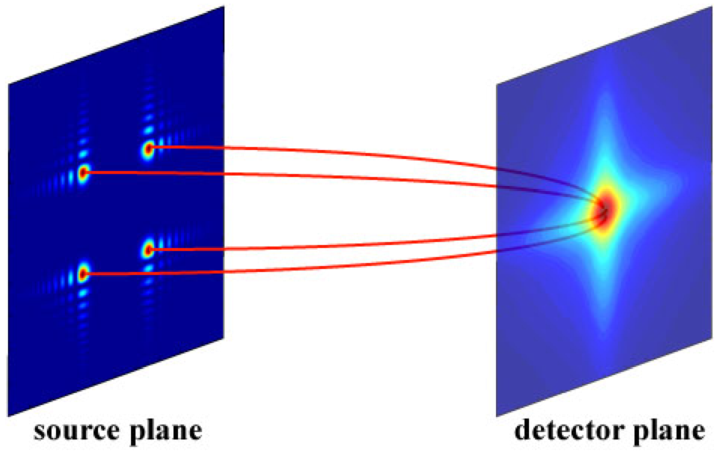

Figure 5. Simulation of the array intensity in the source plane and in the detector plane after propagation through 3 km of turbulence. The red lines roughly indicate the manner of propagation. It can be seen that the peak of intensity lies on the central axis.

Simulations of the scintillation of such Airy beams indicate that the scintillation of a four beam array is roughly ¼ of the scintillation of an individual Airy beamlet, in agreement that the theoretical minimum for an array of N incoherent beams is 1/N the scintillation of a single beam. For the arrangement considered, this 1/N behavior continued for Airy beams through N=6, and then saturated as for the Bessel-correlated beams.

The potential advantage of such Airy beam arrays over Gaussian arrays is the ability to manipulate the trajectory of the beams simply by manipulating the wavelength, without any reorientation of optical elements. Future studies will be needed to investigate the viability of such schemes.

3. Nonuniformly polarized beams

In studies of optical propagation through clear air atmospheric turbulence, the polarization of light is typically neglected. This is acceptable because the polarization state of a *uniformly* polarized beam (beam with same polarization at every point) does not change appreciably on propagation, even in quite strong turbulence and over long distances. However, if we coherently superimpose two beams with different spatial profiles (modal diversity) and orthogonal polarizations, each beam will propagate differently in the turbulence due to their different mode structures. They will not form an interference pattern at the detector due to their orthogonal polarization, and the two modes will act effectively as a two-beamlet incoherent beam array, even though they are fully coherent.

This idea was tested using the beamlets shown below in Fig. 6. A horizontally polarized Gaussian beam was coherently superimposed with a vertically polarized Laguerre-Gauss beam of order n=0, m=1, producing a beam with a polarization ellipse whose orientation depends on position.

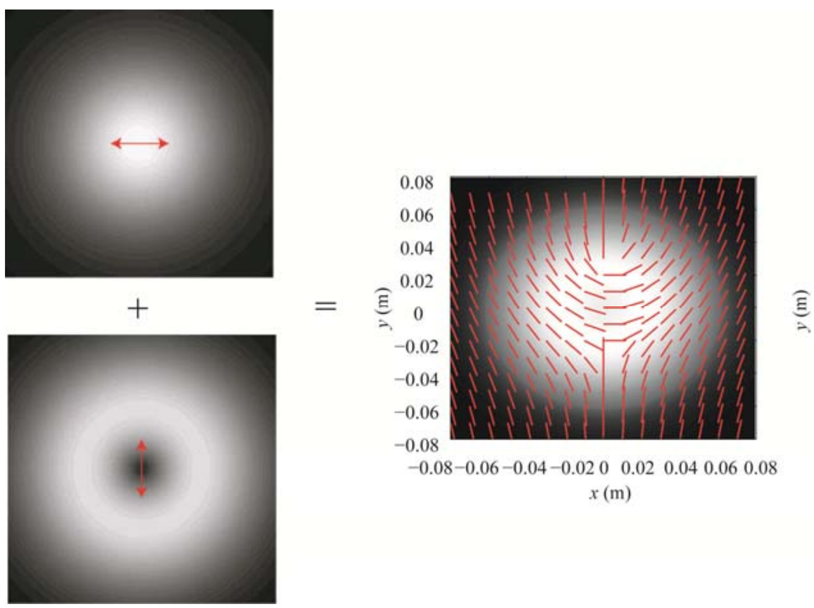

Figure 6. Construction of the nonuniformly polarized beam. A horizontal Gaussian mode is combined with a vertically polarized LG_{01} mode.

The scintillation characteristics of the beam as a function of Rytov variance σ_1 (turbulence strength, or distance) are shown in Fig. 7. The nonuniformly polarized beam has scintillation roughly 33% lower than that of the Gaussian beam alone. The combination of the two modes with the same polarization state is seen to be much higher, demonstrating that this is in fact a polarization effect, and not a fortunate combination of different modes.

The 33% reduction in scintillation is a modest improvement, but one that relatively easy to achieve. Nonuniform polarization can be achieved by passing a single coherent Gaussian beam through a tailored polarization-sensitive filter or liquid crystal filter. Furthermore, these nonuniformly polarized beams could be used as the beamlets in any incoherent beam array scheme, such as the pseudo-Bessel correlated beams described earlier. Preliminary investigations suggest that an array of nonuniformly polarized beamlets outperforms a comparable array of Gaussian beamlets.

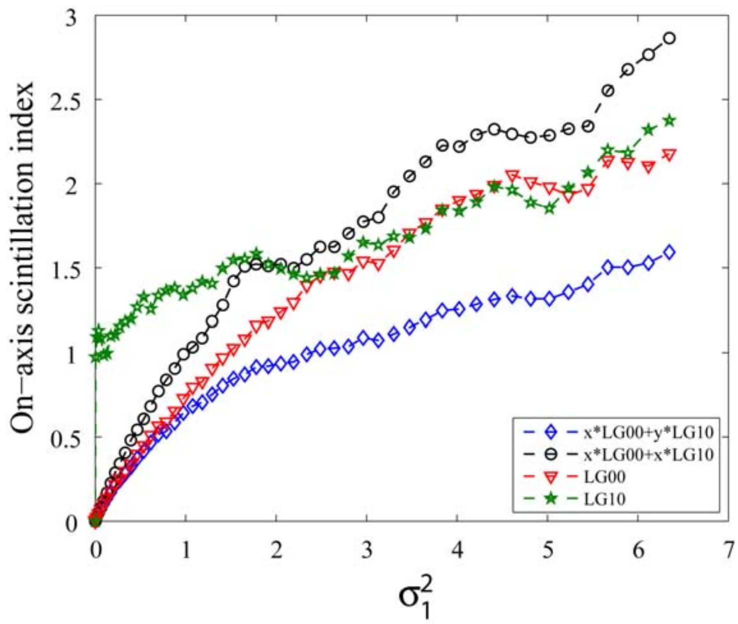

Figure 7. Numerical simulation of the on-axis scintillation of nonuniformly polarized beams in turbulence, as a function of turbulence strength. The blue diamonds indicate the nonuniformly polarized beam, while the red triangles indicate the Gaussian beam alone. The black circles indicate the same modes combined with parallel polarizations.

4. Statistical properties of vortex beams

For several decades now there has been significant interest in the study of optical beams which possess orbital angular momentum. These fields, which possess a central intensity null (phase singularity) about which the phase circulates, are known as optical vortices. An illustration of the cross-sectional intensity and phase of a typical vortex beam, a Laguerre-Gauss beam of order n=0 and m=1, is shown in Fig. 8. The study of such vortices is now a subfield of optics in itself, known as singular optics [13]. The 'order' or *topological charge* of a vortex beam, which is a measure of the field's orbital angular momentum, is a discrete quantity and is conserved under small perturbations of the field.

This discreteness and stability has made a number of authors suggest that this topological charge might be used as an alternative carrier of information for optical communications systems [14,15]. In a previous AFOSR grant, the PI and collaborators showed that the topological charge is a robust information carrier, within limits [10].

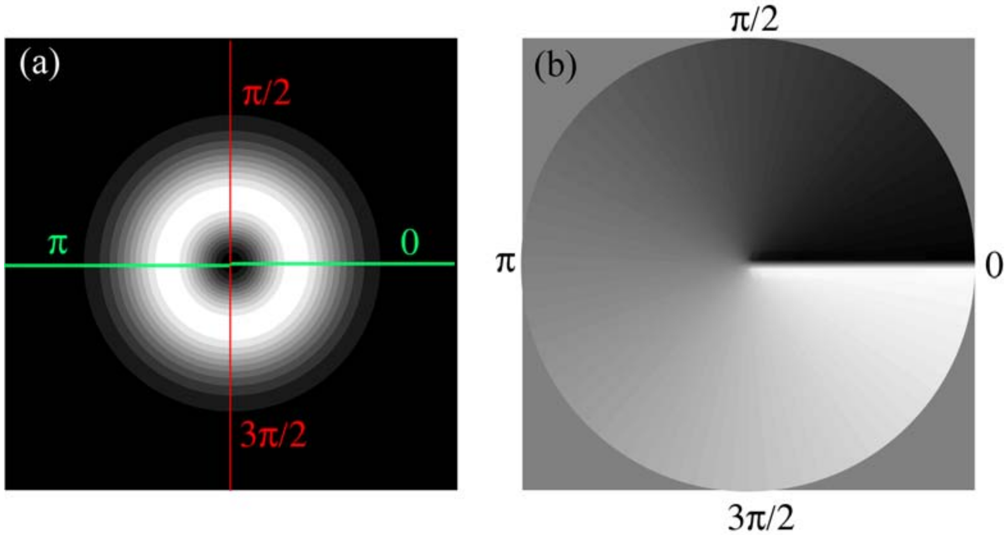

Figure 8. The (a) intensity and (b) phase of a Laguerre-Gauss beam of order n=0, m=1 in the waist plane of the beam. Several equiphase contours are shown in color in (a) for comparison. It can be seen that the phase increases continuously from 0 to 2π as one traces a continuous path around the central singularity.

A significant question involving the use of vortex beams in turbulence is the relationship between their instantaneous and average properties. A vortex is a persistent quantity on propagation, even through atmospheric turbulence, but a partially coherent beam produced on propagation through such a random medium does not generally possess zeros of intensity, as discussed in Ref. [16]. The correlation function of a partially coherent field may possess zeros, however, but questions remain about the relationship between the zeros of a fully coherent field and a partially coherent field derived from it.

A study of the general structure of a "correlation singularity" (zero of the correlation function of a partially coherent field) was undertaken in [publication 1]. For the first time, the general structure was mapped out as a function of the two transverse vector coordinates in the source plane. It was found that the zeros represent a two-dimensional hyperbola in a four-dimensional coordinate space, and this model agrees with all known observations of correlation singularities.

As correlation singularities possess the same robust characteristics as their fully coherent counterparts, it may be possible to use them as information carriers in optical communication systems as well. Very little has been done to study the possible topological reactions of such correlation vortices, such as the break-up of a high-order vortex into a smaller one, the creation/annihilation of such vortices, and their propagation. All three circumstances were investigated in [publication 2].

Among the noteworthy results of this study was the observation that the spatial size of a correlation "ring singularity" directly depends upon the spatial coherence of the wavefield. This result was put to use in [publication 4] as the basis of a new method to measure the strength of atmospheric turbulence. It was shown that the radius of a ring dislocation depends in a monotonic way upon the turbulence strength, and could therefore be used as a straightforward technique to measure it. Simulations of this effect are shown in Fig. 9; though the ring dislocation radius saturates at a sufficiently high turbulence strength, a variation of the beam radius and/or initial state of coherence allows one to change the saturation limit.

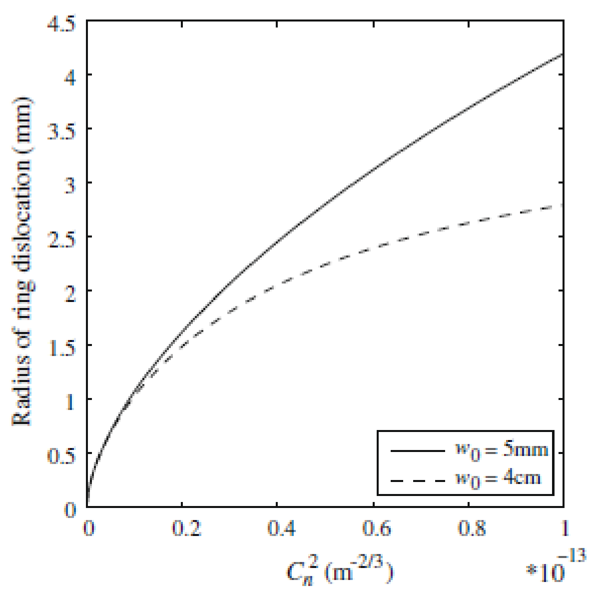

Figure 9. Showing the radius of a correlation singularity ring as a function of turbulence strength, for a given propagation geometry. Variations of the initial beam radius allow one to modify the relationship between ring size and turbulence strength.

All methods of scintillation reduction described in this project require some knowledge of the turbulence characteristics in order to produce the best reduction possible. The vortex method of turbulence measurement described here potentially allows one to measure these characteristics at the same time a communication link is active.

No-cost extension

A five month no-cost extension was requested at the end of the grant period to complete research and publication of [publication 4] and [publication 5], and to present these results at Photonics West 2011.

References

1. J.C. Ricklin and F.M. Davidson, "Atmospheric turbulence effects on a partially coherent Gaussian Beam: implications for free-space laser communication," J. Opt. Soc. Am. A 19 (2002), 1794-1802.

2. O. Korotkova, L.C. Andrews and R.L. Phillips, "A model for a partially coherent Gaussian beam in atmospheric turbulence with applications in Lasercom," Opt. Eng. 43 (2004), 330-341.

3. G. Gbur and T.D. Visser, "The structure of partially coherent fields", in E. Wolf (Ed.), Prog. in Optics, vol. 55 (Elsevier, Amsterdam, 2010), p. 285.

4. Z. Bouchal, "Nondiffracting optical beams: physical properties, experiments, and applications," Czech. J. Phys. 53 (2003), 537-578.

5. Z. Bouchal, J. Wagner and M. Chlup, "Self-reconstruction of a distorted nondiffracting beam," Opt. Commun. 151 (1998), 207-211.

6. G. A. Siviloglou, J. Broky, A. Dogariu, and D. N. Christodoulides, "Observation of accelerating Airy beams," Phys. Rev. Lett. 99 (2007), 213901.

7. O. Korotkova and G. Gbur, "Angular spectrum representation for propagation of random electromagnetic beams in a turbulent atmosphere," J. Opt. Soc. Am. A 24 (2007), 2728-2736.

8. O. Korotkova, "Scintillation index of a stochastic electromagnetic beam propagating in random media," Opt. Commun. 281 (2008), 2342-2348.

9. L. Allen, S.M. Barnett and M.J. Padgett, eds., Optical Angular Momentum (IOP, 2004).

10. G. Gbur and R.K. Tyson, “Vortex beam propagation through atmospheric turbulence and topological charge conservation,” J. Opt. Soc. Am. A 25 (2008), 225-230.

11. J. Turunen, A. Vasara, and A. T. Friberg, “Propagation invariance and self-imaging in variable-coherence optics,” J. Opt. Soc. Am. A 8 (1991), 282–289.

12. J.M. Martin and S.M. Flatte, “Intensity images and statistics from numerical simulation of wave propagation in 3-D random media,” Appl. Opt. 27 (1988), 2111-2126.

13. M.S. Soskin and M.V. Vasnetsov, “Singular optics,” in Progress in Optics, Vol. XLII, E. Wolf, ed. (Elsevier, North Holland, 2001), pp. 219-276.

14. Z. Bouchal and R. Celechovsky, “Mixed vortex states of light as information carriers,” New J. Phys. 6 (2004), 131.

15. G. Gibson, J. Courtial, M.J. Padgett, M. Vasnetsov, V. Pas'ko, S.M. Barnett and S. Franke-Arnold, “Free-space information transfer using light beams carrying orbital angular momentum,” Opt. Exp. 12 (2004), 5448-5456.

16. G. Gbur, T.D. Visser and E. Wolf, “ ‘Hidden’ singularities in partially coherent wavefields,” J. Opt. A 6 (2004), S239-S242.

Publications produced from grant

[1] G. Gbur and G.A. Swartzlander, Jr., "Complete transverse representation of a correlation singularity of a partially coherent field," J. Opt. Soc. Am. B 25 (2008), 1422.

[2] Y. Gu and G. Gbur, "Topological reactions of correlation vortices," Opt. Commun. 282 (2009), 709.

[3] Y. Gu, O. Korotkova and G. Gbur, "Scintillation of nonuniformly polarized beams in atmospheric turbulence," Opt. Lett. 34 (2009), 2261-2263.

[4] Y. Gu and G. Gbur, " Measurement of atmospheric turbulence strength by vortex beam," Opt. Commun. 283 (2010), 1209-1212.

[5] Y. Gu and G. Gbur, "Scintillation of Airy beam arrays in atmospheric turbulence," Opt. Lett. 35 (2010), 3456-3458.

[6] Y. Gu and G. Gbur, "Scintillation of pseudo-Bessel correlated beams in atmospheric turbulence," J. Opt. Soc. Am. A 27 (2010), 2621-2629.

Presentations produced from grant

1. G. Gbur, “Partially coherent and vortex beam propagation through atmospheric turbulence,” TCATS meeting, Dayton, OH, March 2008.

2. G. Gbur and G.A. Swartzlander, Jr., “Complete transverse representation of an optical correlation singularity,” 2008 OSA Annual Meeting in Rochester, NY.

3. Yalong Gu and Greg Gbur, “Topological reactions of optical correlation vortices”, 2008 OSA Annual Meeting in Rochester, NY.

4. G. Gbur, “Strategies for reduction of scintillation in atmospheric beam propagation,” AFOSR EM Workshop, San Antonio, TX 2009.

5. G. Gbur, “Studies of special beam classes in atmospheric turbulence,” Workshop on Waves in Complex Media, Napa Valley, June 2009 (invited).

6. Yalong Gu, Olga Korotkova and Greg Gbur, “Scintillation of nonuniformly polarized beams in atmospheric turbulence”, 2009 OSA Annual Meeting in San Jose, CA.

7. G. Gbur, “Optimizing incoherent arrays of beams for turbulence applications,” AFOSR EM Workshop, San Antonio, TX 2010.

8. Yalong Gu and Greg Gbur, “Measurement of atmospheric turbulence strength by vortex beam”, 2010 OSA Annual Meeting in Rochester, NY.

9. G. Gbur and Y. Gu, “Scintillation of Airy beam arrays in atmospheric turbulence,” Photonics West 2011.

10. Y. Gu and G. Gbur, “Scintillation of pseudo-Bessel correlated beams in atmospheric turbulence,” Photonics West 2011.

11. G. Gbur, “Special beam arrays for scintillation reduction,” OSA Application of Lasers for Sensing & Free Space Communication (LS&C) 2011, Toronto (invited).