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14. ABSTRACT
Studies of the behavior of partially coherent beams and other special beam classes on propagation through atmospheric turbulence were undertaken. A pair of new tools were developed to study the behavior of special beam classes in turbulence: a generator of partially coherent field realizations and an angular spectrum technique for propagating partially coherent fields in turbulence analytically. These tools were used in preliminary investigations of partially coherent fields and non-diffracting fields in turbulence. The stability and information-carrying ability of vortex beams were studied using multiple phase screen simulations of atmospheric turbulence. The tools developed during this project will facilitate future studies of special beam classes, and the simulation results demonstrate that special beam classes have significant potential for improving optical communications systems.

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Developing 'superbeams' for improved propagation through turbulence

Final Performance Report
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1. Summary

The objective of this project was to study the behavior of partially coherent beams and other special classes of optical beams, including vortex beams and nondiffracting beams, with the goal of developing a class of 'superbeams' which potentially have improved propagation characteristics in atmospheric turbulence. In particular, beam classes were studied which could potentially perform better in optical communications systems.

Atmospheric propagation is a very complicated topic of study, even for the simplest models of the turbulent atmosphere, and much of the project was focused on developing new tools which could be used to facilitate this study. Two major tools were developed for modeling of special beam classes in turbulence: a partially coherent field generator and a plane wave representation of partially coherent beams in atmospheric turbulence. Furthermore, computer software employing the multiple phase screen method of simulating extended turbulence was developed.

These tools were used to investigate special beam classes of three types. Partially coherent beams, beams which are partially 'pre-randomized' at the source, have been shown in a number of previous studies [1,2] to have better scintillation characteristics than the equivalent coherent beams. Nondiffracting beams (Bessel beams), beams which have been shown to propagate over significant distances without diffraction [3], had been theoretically demonstrated to possess some inherent resistance to phase distortions [4]. Vortex beams are known to possess orbital angular momentum [5] and it was suggested that this inherent momentum might provide turbulence resistance through a 'bicycle wheel' effect.

Preliminary simulations have been undertaken on each of these types. Partially coherent beams show the most promise, demonstrating a noticeable and often significant decrease in scintillation. The results for nondiffracting beams were more ambiguous, suggesting that there may be some slight improvement over ordinary Gaussian beams in some cases. Vortex beams were found to have scintillation characteristics on par with comparable Gaussian beams; however, further study has indicated that the vortex core of such a beam is quite stable under atmospheric distortion and might be used as an alternative or complementary information carrier in optical systems.

Each of these simulation tools and beam classes is discussed in more detail below.

2. New Simulation Techniques for partially coherent fields and atmospheric propagation

Studies of partially coherent field propagation in atmospheric turbulence are doubly hindered by the complexity of atmospheric modeling and the difficulty of simulating and calculating effects associated with the partial coherence of wavefields. Because of these difficulties, analytic calculations involving propagation through turbulence are typically restricted to the simplest atmospheric models (i.e. Kolmogorov turbulence or possibly von Karman turbulence) and correlation functions of simple analytic forms (Gaussian Schell-model sources). Furthermore, there is an additional ambiguity in studies of partially coherent fields in turbulence, especially when optical communications are considered. There are three time scales of interest, namely the rate of fluctuation of the turbulent medium, the rate of fluctuation of the partially coherent field, and the data transmission rate. For a partially coherent field to be effective in turbulence, its fluctuations must be far more rapid than both the fluctuations of the turbulence itself and the fluctuations associated with data transfer. Unfortunately, conventional coherence theory involves a long (idealized infinite) time average over the field and the fluctuating medium. Effects associated with fluctuations on a short time scale are averaged out in conventional coherence theory calculations.

The preceding observations suggested that two new, independent techniques were needed for studying partially coherent field propagation through turbulence: an analytic theory of beam propagation which could be used to investigate more complicated classes of beams, and a time-dependent theory which could be used to investigate and understand effects associated with fluctuations of partially coherent fields on short time scales without averaging.

A. Angular spectrum techniques for turbulence propagation

An angular spectrum technique [publication 1] was developed to study the propagation of arbitrary coherent and partially coherent beams in turbulence. The angular spectrum method is a standard tool in free-space physical optics problems, and works as follows. 1. One decomposes a complicated optical signal into a superposition of plane waves. 2. One propagates each plane wave independently through an optical system of interest. 3. One recombines the plane waves at the output of the optical system to determine the behavior of the original optical system at output. The technique works well because it is in general easier to analytically study plane wave propagation than other, more general, waveforms. Similarly, the propagation of plane waves through atmospheric turbulence has been studied for a long time and the results are well-understood [6]. These results were extended and applied to create a general analytic formalism for studying general partially coherent beam propagation through atmospheric turbulence. The results, when compared to known results for simple model beam classes, were in excellent agreement (see Fig. 1).

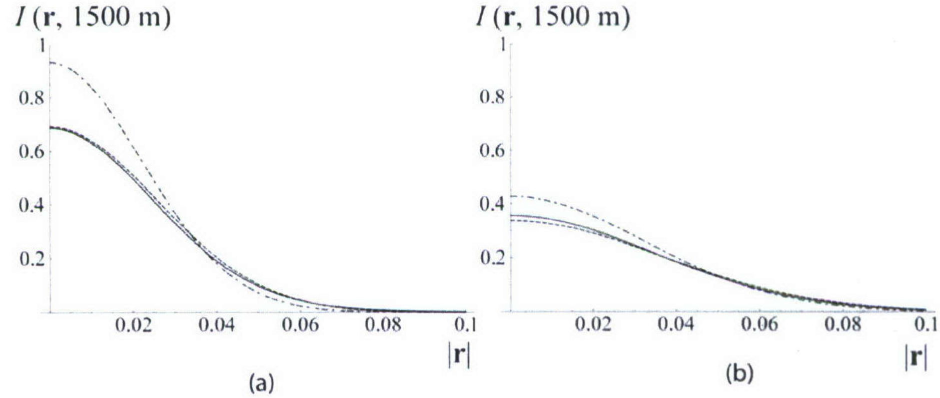


Figure 1. Intensity profile of a (a) coherent and (b) partially coherent Gaussian beam after propagation. In each case, the source beam width is 3 cm. The correlation length of the partially coherent field is 1 cm. The solid curve is the angular spectrum method result, while the dashed curve is based on a standard propagation method for Gaussian beams. The dashed-dotted curve shows the profile of the beam in the absence of turbulence. After [publication 1].

The technique was extended to the study of partially coherent *electromagnetic* beams in turbulence [publication 2]. Although it is well-known that polarization is not typically an important factor in atmospheric propagation, it has been shown that over long propagation distances there can be significant changes in the degree of polarization of the field, followed later by a 'revival' of the initial polarization state that is still not completely understood [7]. Results for the angular spectrum technique for electromagnetic beams were compared to established analytic results, and found to be in excellent agreement (see Fig. 2). Both angular spectrum techniques were applied to the study of special beam classes, which will be discussed in the next section of this report.

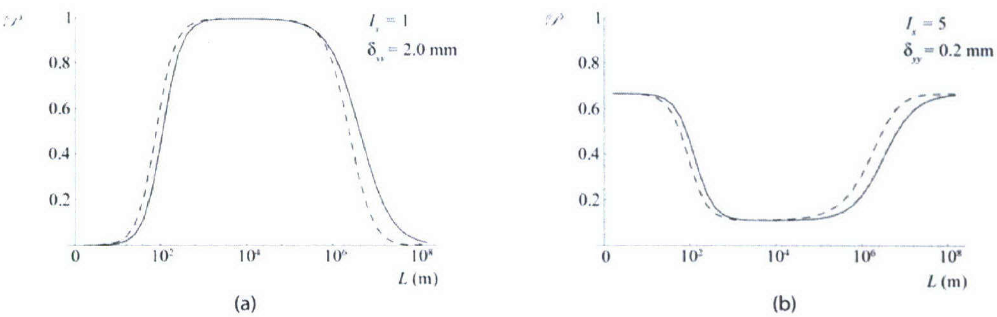


Figure 2. On axis degree of polarization of a Gaussian Schell-model beam as a function of propagation distance L for different values of spatial coherence and source degree of polarization. In all cases, the *y*-component of intensity is taken to be $I_y = 1$. The correlation length of the *x*-component of the field is taken to be 0.1 mm, and the beam width is taken to be 5 cm. After [publication 2].

The major limitation of the angular spectrum technique for studying turbulence propagation is that calculations still require a significant amount of numerical integration. If one is interested in the average intensity profile of the beam, the integrals are fourfold, but scintillation calculations require in general an eightfold integration, which is difficult even for high-power computing systems. For this reason, the angular spectrum technique is currently being used primarily to gain physical insight into the behavior of certain beam classes. General studies of beam propagation in turbulence are now being undertaken by numerical techniques, such as the multiple phase screen method [8].

B. A partially coherent field generator

Traditional coherence theory deals with long time averages of the field fluctuations. This is generally not a problem for most calculations, but when the system in question involves fluctuations of the field and the system in general over different time scales, this time average can potentially obscure important physical effects. In particular, in optical communication through turbulence, at least three time scales are relevant: namely the rate of fluctuation of the turbulent medium, the rate of fluctuation of the partially coherent field, and the data transmission rate. The fluctuation rate of the medium is typically slower than the other two and may be neglected, but even this is not the case if the optical field is sufficient narrowband, in which case the field fluctuations might be comparable in speed to the turbulence fluctuations.

These considerations are important for the following reason: a partially coherent field is assumed to have lower scintillation than a coherent field in turbulence because it propagates energy through multiple independent modes (Fig. 3). Each mode propagates differently in the turbulence, and the presence of more modes (i.e. less coherence) increases the likelihood that at least one of those modes will impinge upon the detector. The intensity fluctuations at the detector are consequently expected to be lower. This scheme only works, however, if the field fluctuates much more rapidly than the turbulence, i.e. for a fixed realization of the turbulence, the field must fluctuate through multiple realizations, in order that it makes several 'attempts' to propagate through the turbulence.

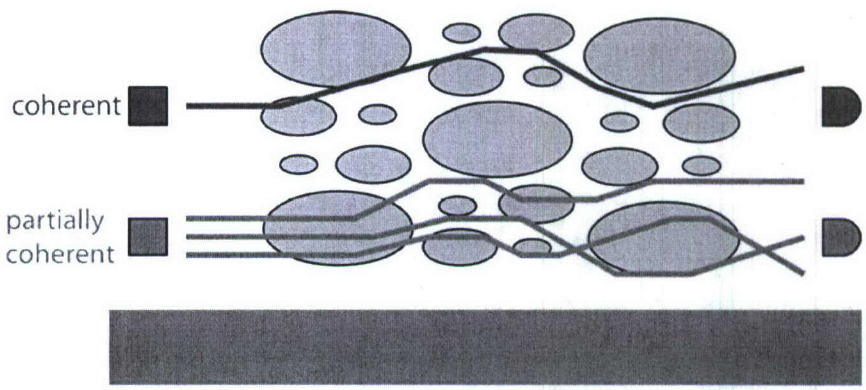


Figure 3. A qualitative explanation of the behavior of partially coherent beams in turbulence. A coherent laser propagates its energy through a single coherent mode, which is subject to distortion on propagation through the inhomogeneous medium. The partially coherent beam sends its energy through multiple (independent) modes, each of which propagates differently in the turbulent medium. After [publication 3].

Qualitatively, one can say that the field must fluctuate faster than the turbulence fluctuation rate and the date communication rate. Quantitatively, one needs a method for studying time-dependent realizations of partially coherent fields.

A new technique for generating such realizations of partially coherent fields has been developed [publication 3]. Based on an early simulation method for broadband signals [9], it involves decomposing a partially coherent field into a randomly oriented and randomly generated series of pulses. The choice of the pulse shape and the distribution of orientations uniquely defines the average temporal and spatial coherence properties of the field, respectively.

A simple illustration of the technique in action is shown in Fig. 4. Several realizations of a Gaussian Schell-model field in the source plane are pictured. The pictures are separated in time by 5 cycles of the field center frequency. One can clearly see the continuous evolution of the field profile. Numeric simulations confirm that this technique produces a field with the desired average coherence properties.

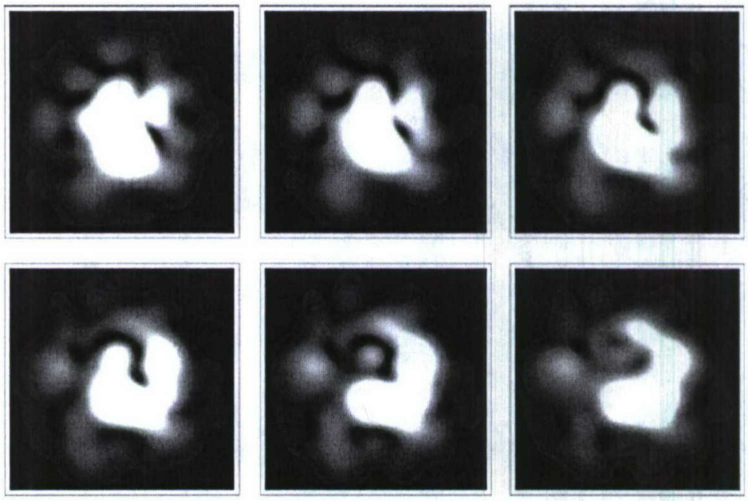


Figure 4. Illustrating several realizations of the intensity of the field generated by the new method with a beam width of 2 cm, a correlation length of 1 cm, and a spectral bandwidth of 1%. The pictures show the gradual evolution of the field in time; the frames are each separated by 5 periods at the center frequency. The window size is 10 cm on a side. After [publication 3].

This technique, which was originally developed for homogeneous and isotropic correlation functions, has also been extended to the case where the field consists of a finite number of incoherent modes [publication 4].

3. Investigation of nondiffracting and partially coherent beam classes

The previously mentioned techniques have been used to perform preliminary investigations of the behavior of certain special beam classes.

The angular spectrum technique was used to investigate the spreading of nondiffracting Bessel beams in atmospheric turbulence [publication 1]. Two examples are shown in Fig. 5. In both cases, the beams are ideally free-space nondiffracting, which means that all changes in beam shape come from turbulence distortion. It can be seen that the wider beam has better performance characteristics in turbulence. This is in marked contrast to an ordinary Gaussian beam, for which a wider beam corresponds to a shorter degradation-free path. These preliminary results suggest that nondiffracting beams have nontrivial differences in behavior from ordinary Gaussians, but that the parameters of the beam need to be chosen carefully.

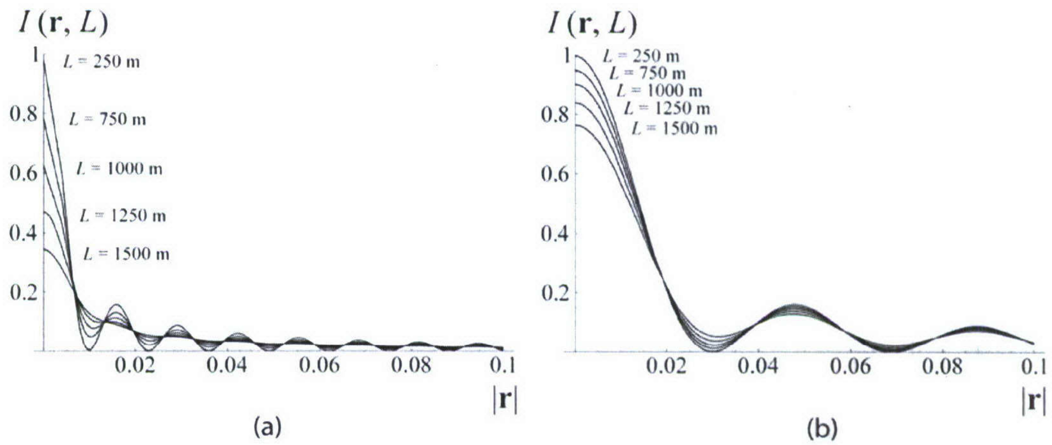


Figure 5. Intensity profile of several nondiffracting beams on propagation through atmospheric turbulence, for different propagation distances. The radial distance of the first zero from the source is taken to be (a) 1 cm, (b) 3 cm. After [publication 1].

It is to be noted that a direct comparison between a Gaussian and a nondiffracting beam is somewhat ambiguous. There is no obvious way to define a nondiffracting beam which is 'comparable' in width to an equivalent Gaussian. The best strategy, then, seems to be to look at the best performing Gaussian and nondiffracting beams in turbulence, and this is currently being pursued.

The angular spectrum method was also used to study beams of unusual correlation and polarization properties. In particular, 'mixed' correlation beams were studied, in which the x-component of the field was taken to be Gaussian correlated and the y-component exponentially correlated. The results are shown in Fig. 6. It is possible, by a careful choice of the correlation and polarization properties of the field, to produce a beam which has more than one 'polarization revival' on propagation.

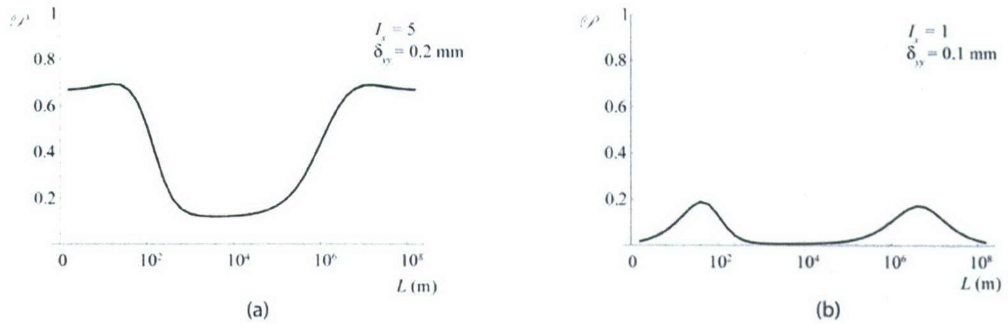
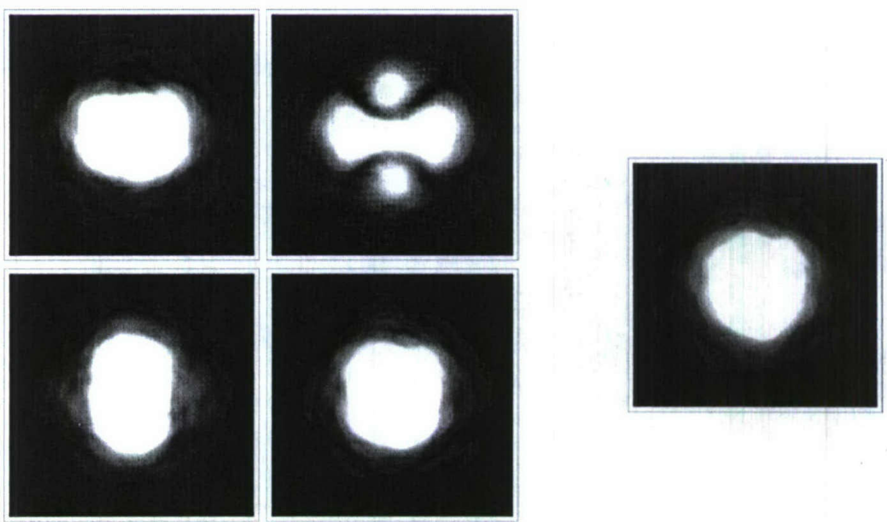


Figure 6. On-axis degree of polarization of a beam of mixed-correlation type as a function of propagation distance L. In all cases, $I_y = 1$, the correlation of the x-component is 0.1 mm, and the beam width is 5 cm. After [publication 2].

The partially coherent field generator was used to study the behavior of two-mode partially coherent fields in turbulence [publication 4]. The turbulence was simulated by a multiple phase screen method. An illustration of one such simulation is shown in Fig. 7. The simulations demonstrate that the field 'switches' rapidly between different modes, and the average intensity profile at the detector is a uniform, symmetric spot. This is a partial confirmation of the qualitative model of Fig. 3.



(a) (b)

Figure 7. a) Snapshots of the field intensity at the detector, at intervals separated by 5 cycles of the center frequency. The plots are 50 cm on a side. (b) The average field intensity at the detector, calculated over 25 snapshots. After [publication 4].

Future studies will involve a detailed investigation of the relationship between the performance of an optical communications system in turbulence and the relative magnitudes of the fluctuation rate and data communications rate. In addition, multiple phase screen simulations will be employed to search for partially coherent beam classes which have optimal performance in atmospheric turbulence.

4. Vortex beams in turbulence and topological charge conservation

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. The study of such vortices is now a subfield of optics in itself, known as singular optics [10]. 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 [11,12]. However, no author had yet studied the overall stability of such vortex beams in atmospheric turbulence.

One problem immediately arose in such considerations. On propagation through atmospheric turbulence, an optical field becomes effectively partially coherent, and it is well-known that partially coherent fields do not in general possess zeros of intensity. Evidently, on average, the core of a vortex beam is 'hidden' by the averaging process, which raised the possibility that a slow detector might not be able to see the vortices at all. However, it has been shown that there is an intimate connection between optical vortices and vortices of the correlation function of the corresponding partially coherent field. Analytic work was done [publication 5] to show, quite generally, that an optical vortex always transforms into a correlation vortex as the spatial coherence of the field is decreased. Such a result suggests that, even in the case of a slow detector, the presence or absence of a vortex in a partially coherent field could be detected.

The next step was to study the overall stability of topological charge on propagation of an optical field through turbulence of varying strength [publication 6]. A multiple phase screen method was again used to simulate the effects of turbulence, and the average value of the topological charge and its standard deviation was studied. The results for a number of different values of turbulence strength are shown in Fig. 8. It can be seen in each case that the topological charge is perfectly transmitted over a significant distance, after which it decreases rapidly along with a corresponding increase in the standard deviation.

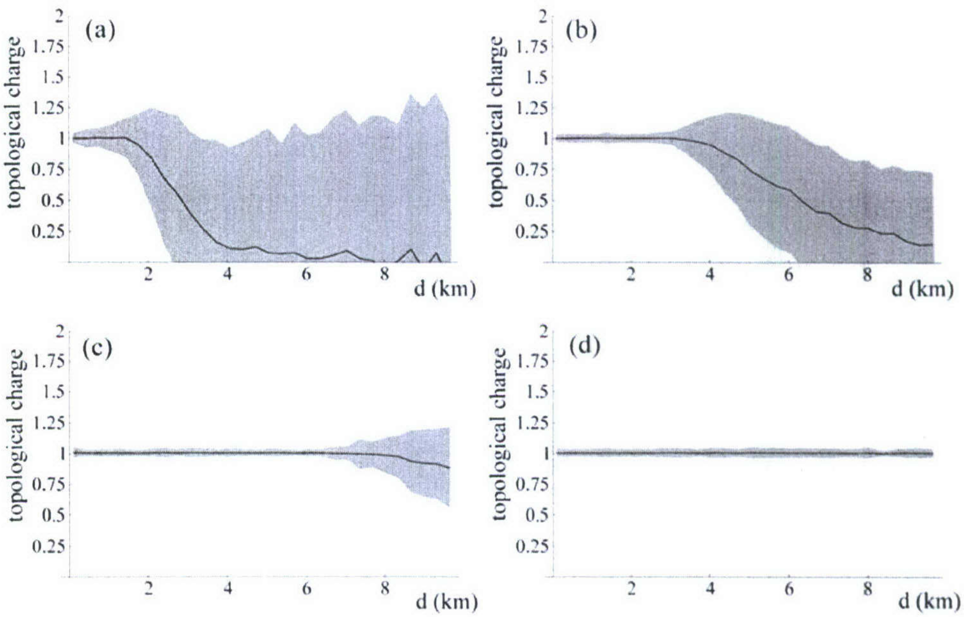


Figure 8. Simulation of the average topological charge for a Laguerre-Gauss beam of order m = 1, n = 1, for various turbulence strengths. (a) $C_n^2 = 10^{-14}$ m$^{-2/3}$, (b) $C_n^2 = 10^{-15}$ m$^{-2/3}$, (c) $C_n^2 = 10^{-16}$ m$^{-2/3}$, (d) $C_n^2 = 10^{-17}$ m$^{-2/3}$.

This degradation of performance can be shown to arise from 'wandering' of the vortex core outside of the detector aperture. This limitation can be improved by two strategies: 1. increase the aperture size, 2. increase the topological charge (more likely that some charge remains in the aperture). By a combination of these strategies, a reasonable discrimination between the presence/absence of topological charge can be achieved, even in strong turbulence (Fig. 9).

These results show that it is at least in principle possible to use topological charge as an information carrier. However, this charge is a phase property of the field and is somewhat harder to measure than a simple intensity measurement, though techniques have been and are being developed. The topological charge might be used as a channel of communication complementary to the amplitude modulation of the signal used in standard optical communication schemes.

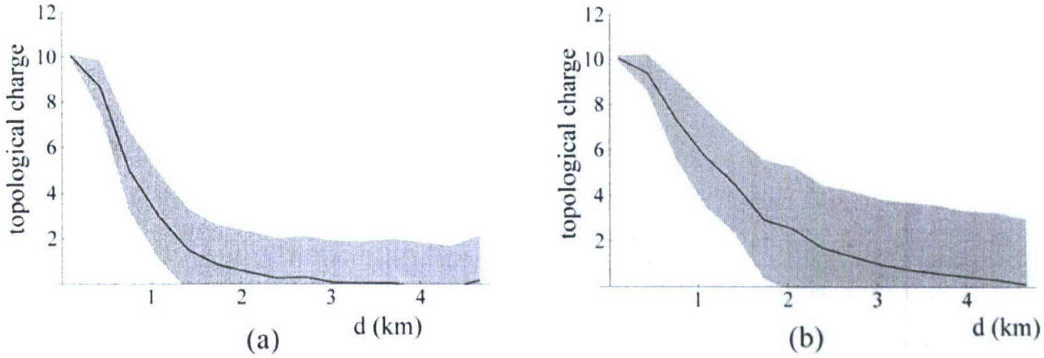


Figure 9. Simulation of the average topological charge for a LG beam of order m = 10, n = 1 in strong turbulence ($C_n^2 = 10^{-14}$ m$^{-2/3}$). Figure (a) represents a fixed detector radius and (b) represents a detector whose size increases as a function of propagation distance.

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[2] 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.

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[6] 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.

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9. G. Gbur, "*Vortex beam propagation through atmospheric turbulence and topological charge conservation*," Photonics West 2008.