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Diffraction Free Light Source for Ghost Imaging of Objects Viewed Through Obscuring Media

by Ronald E. Meyers

ARL-TR-5095 **February 2010**

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Diffraction Free Light Source for Ghost Imaging of Objects Viewed Through Obscuring Media

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14. ABSTRACT

Quantum imaging is a new science that is developing new technology such as Quantum Ghost Imaging (QGI) to exploit quantum optical information. This research experimentally demonstrated the ability of diffraction free light sources to penetrate partially obscuring media and ghost image opaque objects. The experiments using diffraction free light beams were successful, supporting the capability of QGI to reveal images of objects through partial obstructions of the illumination. The results of this effort also demonstrated the ability to perform Quantum Inspired Ghost Imaging (QIGI) using only a single sensor, that is, a distant single-pixel bucket detector to ghost image opaque objects. Randomly displaced nearly diffraction free Bessel beams were successful at providing illumination patterns for the QIGI and resolving a small distant target. QIGI successfully recovered the image of the object even when the coarse illuminating Bessel beam had re-formed after passing through the obstruction of a small aperture displaced transverse to the laser beam.

15. SUBJECT TERMS

Quantum, experiment, photons, ghost imaging, turbulence, Bessel beam, compressive imaging

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1. Objective

Quantum imaging is a new science that is developing new technology such as Quantum Ghost Imaging (QGI) to exploit quantum optical information. QGI increases versatility in imaging objects of interest to the warfighter. The Army fights in all types of adverse imaging situations and there is a benefit to exploiting quantum optical information to image objects through partially obscuring media, i.e., optical turbulence, obstructions, smoke, and fog. Imaging through obscuring media is difficult; consider the difficulty of driving in foggy weather. Attempts at solutions have involved using different wavelengths and polarimetry. In cases in which these techniques are not effective or when they cannot be employed, it would be helpful to have other imaging methods to penetrate obscuring media.

The primary objective of the current research is to exploit quantum optical imaging in adverse imaging conditions. Ghost imaging is a quantum optical technique that shows promise for imaging through smoke and fog. Ghost imaging exploits quantum optical information using photon coincidence measurements. In ghost imaging, photon energy is put onto a target and a bucket detector is used to measure reflected and scattered photons (*1*). Ghost imaging has been shown to be insensitive to scattering disturbances encountered by radiation going to the bucket detector (*2, 3*). The main problem that remains is putting illuminating energy onto the target through the obscuring media. This project investigates a means of achieving energy on target through obscuring media and combining it with the ghost-imaging technique to produce a ghost image.

2. Approach

Since photon intensity variation is used in thermal ghost imaging, the main risk factor was in replacing the Gaussian light source used in the interaction with the ground glass that produces the thermal light inhomogeneities. The new light source used a nearly diffraction free source rather than a Gaussian light source. The approach was to find diffraction free patterns that will propagate down beam with the self mending property. There are several probable fixes to mitigate this problem. One technique is to bundle a number of fibers in parallel that each launch self-mending solitons of light that substitute for speckles. Another technique is to use a fiber positioner on the diffraction free light source fiber and have it undergo a high speed random displacement and launch the light solitons in random transverse positions. Our solution to producing the variation of the signal source was to randomly displace the center of the Bessel beam projected through a spatial light modulator (SLM). A Bessel beam is nearly diffraction free and has a self-mending property upon interaction with particulate disturbances. This approach proved to be successful. The experiments used the Quantum Inspired Ghost Imaging (QIGI) setup displayed in figure 1.

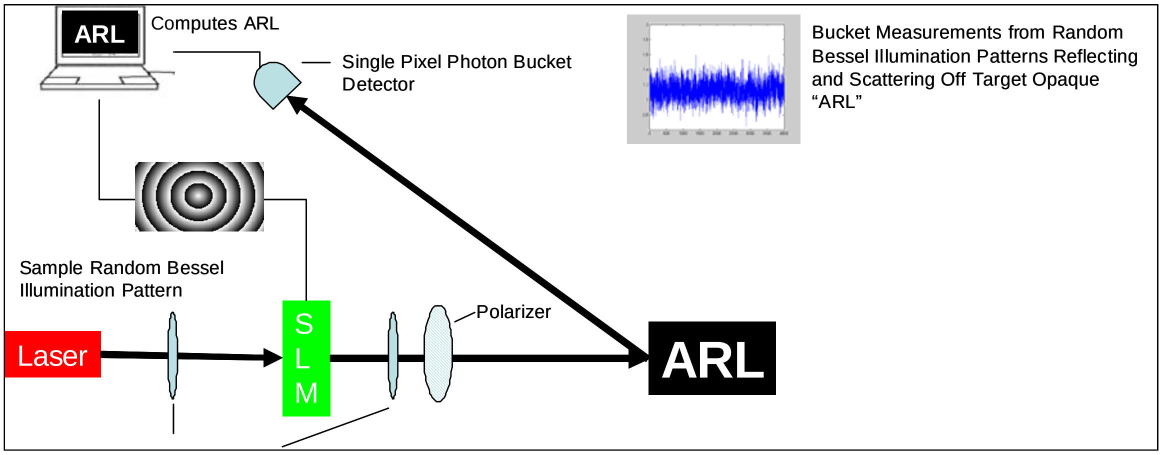

Figure 1. Schematic layout of the Bessel beam illumination ghost imaging experiments.

Normally, QGI uses two sensors. The first sensor is a camera that looks at the reference beam of the light source. A second sensor is a single-pixel photon bucket detector that collects photons from a separate test beam path that are scattered and reflected from the object to be imaged. The quantum ghost image is constructed from the Glauber $G^{(2)}$ coherence using the coincidence measurements of photons. QGI is quantum, since it can use entangled photons or thermal photons that have a nonlocal, nonfactorizable property (*3*). The current experiments are termed QIGI since only a photon bucket detector is used. The $G^{(2)}$ is computed using projected patterns of light for the reference beam and not the measured patterns of light. As the illuminating Bessel beam was displayed, each illumination pattern of the SLM was saved in computer memory so the QIGI could be computationally reconstructed using the additional photon bucket detector values.

This project was built on the U.S. Army Research Laboratory (ARL) ghost imaging experimental setup created by Ron Meyers and Keith Deacon (*1*), but used only a single-pixel distant photon bucket detector as the only sensor (*3*). A diffraction free laser light source was added to the setup in place of the usual transverse Gaussian or spatially random intensity beam. Diffraction free light beams penetrate though obscuring media far better than Gaussian beams (*4*). In fact, the Defense Advanced Research Projects Agency (DARPA) is funding their development for use in high energy laser sources. The diffraction free light beams have a self mending property in that when they encounter a small absorber their shape is temporarily distorted, but as they pass around the absorber they re-form into a self-similar shape. There is some loss of energy, but the concentrated light beam shape is maintained (*5*). This is a near ideal property for putting energy on target in the presence of the small and large particulates that occur in military smokes and fog. The diffraction free source can be fabricated from axicon lenses, special fiber optics, diffraction gratings, or an SLM and a laser. For our experiments, a diffraction free source was developed using an SLM and a laser.

3. Results

3.1 Unobscured QIGI Experiments

The schematic layout for the basic experiments using Bessel beams is shown in figure 1. A laser beam was expanded and transmitted through an SLM to impress on the laser beam profile the phase for a Bessel beam (figure 2).

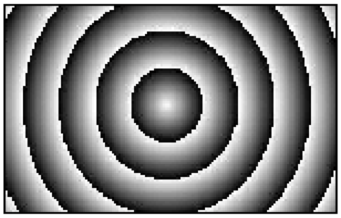

Figure 2. Bessel beam illumination pattern.

A single-pixel photon bucket detector was used to collect photons scattered and reflected from the object. This beam was then propagated to a target, in this case, the letters "ARL." Figure 3 presents an image of this target.

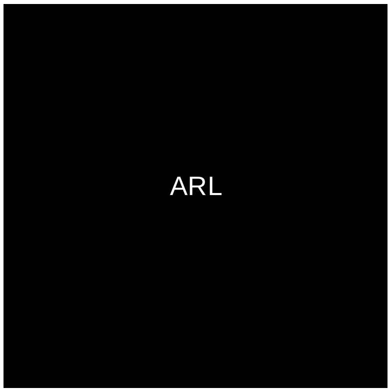

Figure 3. Image of the ARL target used in the experiment. The ARL is a 10-point font size.

To achieve reasonable illumination coverage over the ensemble of measurements of the target area, the Bessel beam patterns were randomly translated in *x* and *y* on the SLM. The sum, or equivalently the average, of all the Bessel beams used for illumination were computed and are displayed in figure. 4. The patterns were not quite uniform; rather they exhibited some structured variation, although most of the space was filled.

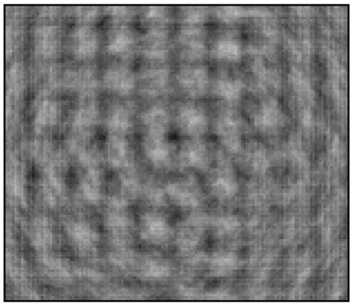

Figure 4. Sum of all Bessel illumination patterns used cropped to the area of interest.

Bessel patterns were randomly translated in *x* and *y* across the field of view by modulating the SLM for different illumination patterns on the target (figures 5 and 6).

Figure 5. Illustrative image of the coarse Bessel pattern illuminating the ARL target.

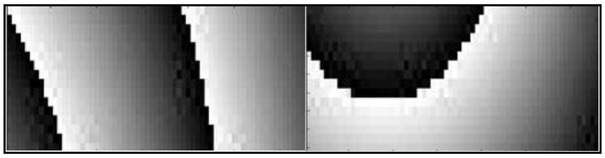

Figure 6. Sample randomly translated, coarse Bessel illumination patterns.

A single-pixel, photon-counting bucket detector collected and measured the light reflected from the "ARL" target (figure 7). These "bucket" measurements were then combined with the known Bessel illumination patterns (see figure 6) to generate an image of the object (figure 8). Fine-scale illumination patterns can be resolved with high resolution fine images. The current experiments, however, used coarse Bessel patterns in an attempt to see if they could resolve fine lettering. That is, the distance between maxima in the illuminating beam was greater than the size of the letter dimensions.

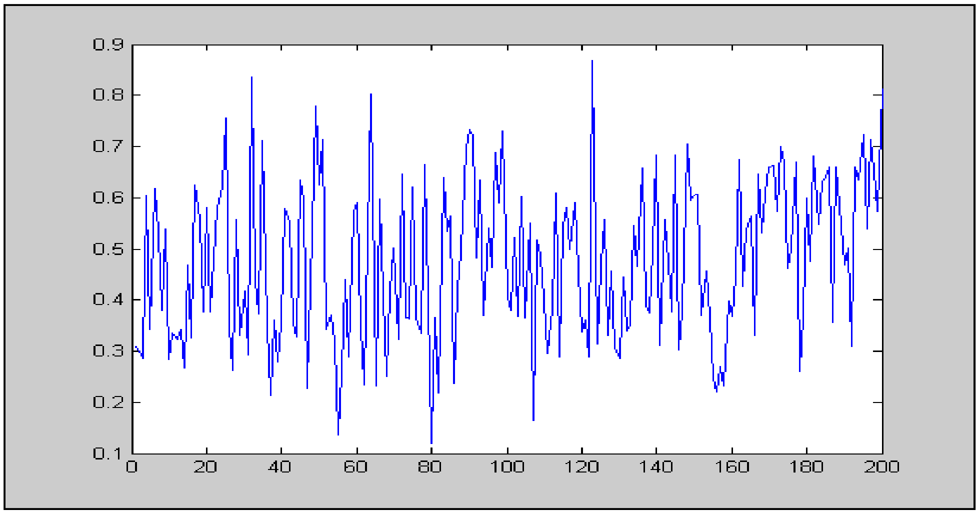

Figure 7. The 200 normalized "bucket" measurements from an experimental run.

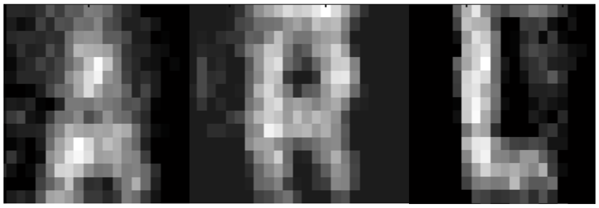

Figure 8. Computed "ARL" ghost image using random
Bessel beam illumination without obscuration.

This first set of experiments was performed without obscuration to align and test the optics and SLM properties. As shown in figure 8, even the coarse Bessel beams could resolve the fine letters.

3.2 Obscured Experiments

The next set of experiments used a modified layout as shown in figure 9, where an offset pinhole (less than 2 mm in diameter) was placed between the "ARL" target and the Bessel beam source. The target "ARL" was not in the direct line of sight from the laser to pin hole. The experiments were performed again using the randomly translated Bessel patterns similar the one use in figures 5 and 6. As was anticipated from the self-mending property of the Bessel beams, I was able to generate a ghost image (figure 10) under such an adverse condition that was only slightly degraded from the unobscured ghost image in figure 8.

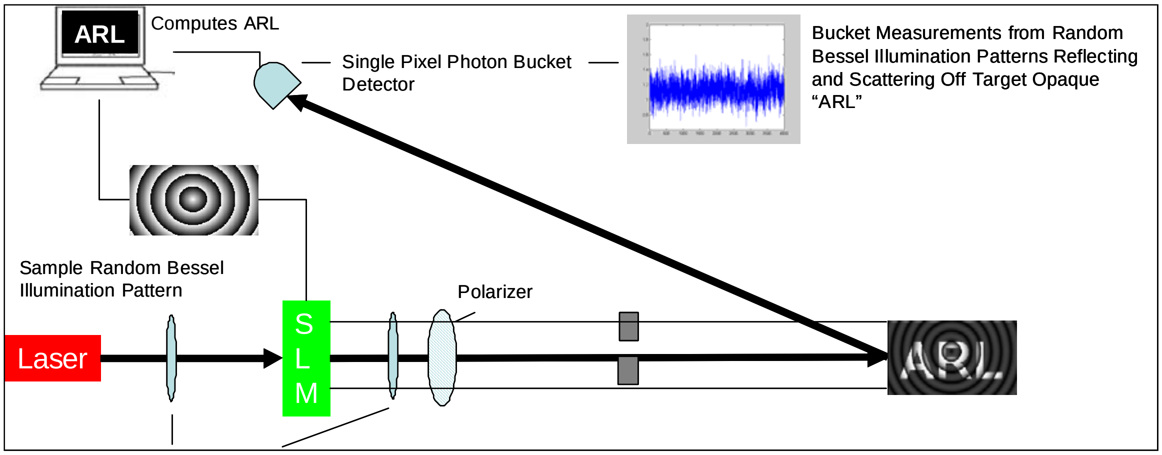

Figure 9. Schematic layout of obscured Bessel illumination ghost imaging experiment.

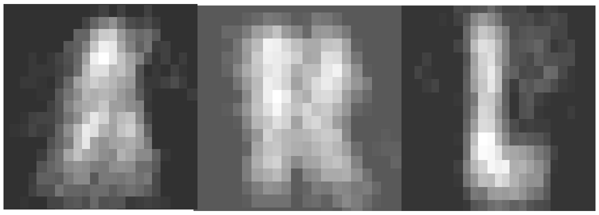

Figure 10. Computed "ARL" ghost image using random Bessel beam illumination with obscuration. The aperture diameter was 2 mm. The aperture was 27.8 cm from the SLM and 73.7 cm from the target.

3.3 Quantum Inspired Ghost Imaging

In other sets of experiments, a similar layout was used (figure 11). The SLM was used to project random illumination patterns onto a model soldier to generate ghost images of a three-dimensional (3-D) opaque object.

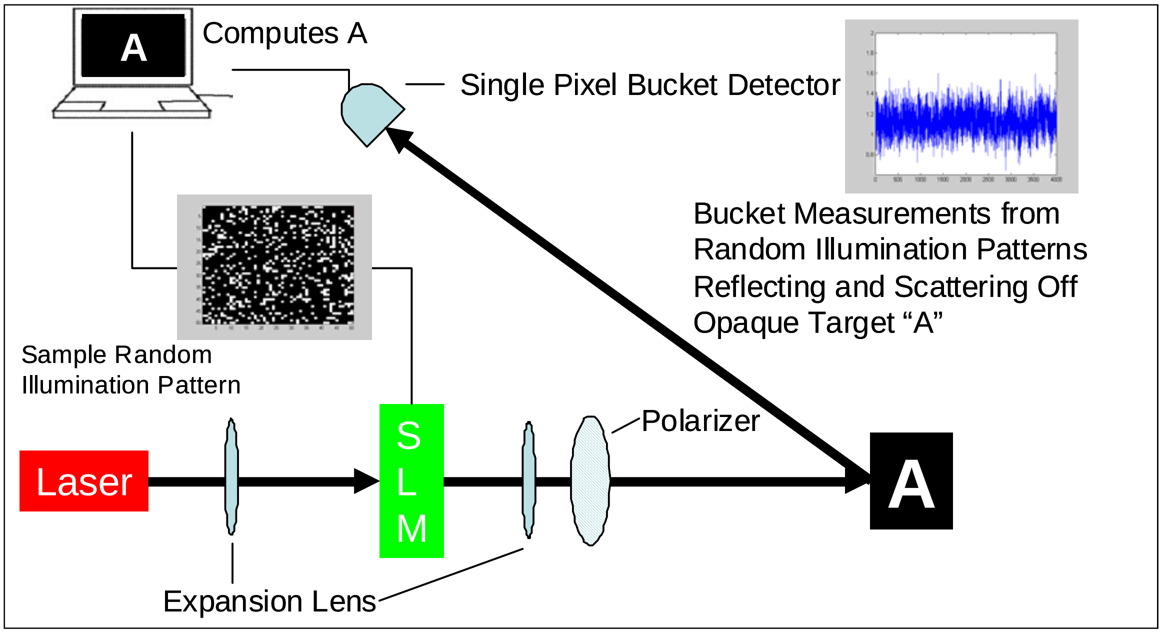

Figure 11. Schematic setup of the QIGI experiment.

Varying numbers of “on” illuminating pixels of the SLM were used in these experiments. The term “on” pixels means “macro-pixel illuminators” or “macro pixels.” The positions of the “on” macro pixels were randomly distributed in space from measurement to measurement. QIGI results using a 1 macro pixel illuminator are presented in figure 12 and similar results using 3 macro pixel illuminators are presented in figure 13.

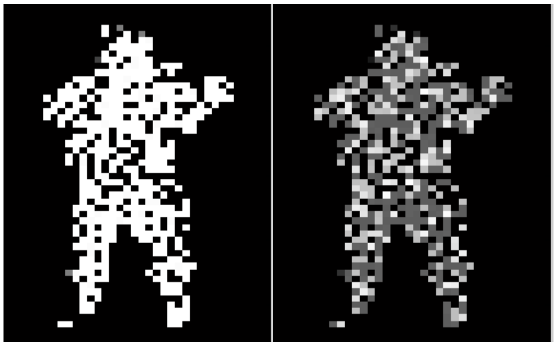

Figure 12. Computed opaque 3-D toy soldier image using 1 random single macro-pixel illuminator patterns and bucket measurements using 4000 illuminations patterns: (left) compressive imaging computation and (right) $G^{(2)}$, the inspired computation.

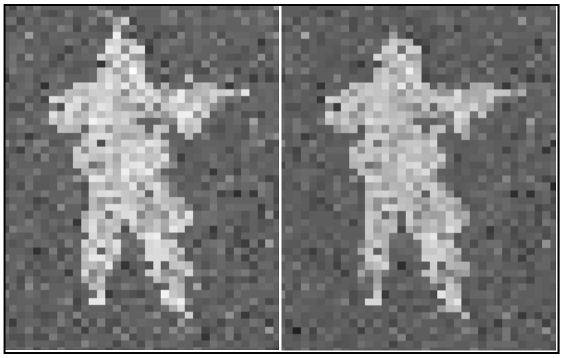

Figure 13. Computed opaque 3-D toy soldier image using 3 random single macro-pixel illuminator patterns and bucket measurements using 4000 illuminations patterns: (left) compressive imaging computation and (right) $G^{(2)}$, the inspired computation.

It should be noted that increasing the number of “on” pixels from 1 to 3 per measurement appeared to decrease the contrast of the generated ghost images, though the resolution may be greater.

3.4 Quantum Inspired Ghost Imaging Through Turbulence

Another set of experiments were run replacing the pinhole aperture of figure 9 with a heating element to generate strong optical turbulence. Random Bessel beams were propagated over this heating element onto the target. Results from these experiments are presented in figure 14. The strong turbulence decreased the signal received by the bucket detector and only slightly blurred the ARL images.

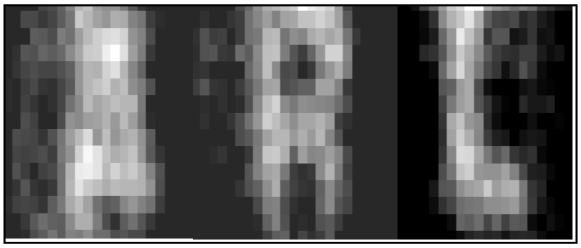

Figure 14. Bessel illuminated QIGI through laboratory generated turbulence.

3.5 Compressive Imaging

An imaging technique called compressive imaging was used to compute the QIGI images from the known illumination patterns and the bucket measurements. This technique follows the methods of Figueiredo et al. (*6*) to construct the image from an imaging integral equation. It is based on finding approximate solutions to the integral equations:

$$\mathbf{JR} = \mathbf{B}. \tag{1}$$

where

$$\mathbf{R} = R(x,y) \tag{2}$$

is the object reflectance.

The term **J** is a matrix, where the rows are the illumination patterns at time **k** and the **B** vector,

$$\mathbf{B} = [B_k] \tag{3}$$

represents the bucket values. In cases where the system is underdetermined (too few B_k), then L_1 constraints are used to complete the system and sparseness is used:

$$\arg\min_{R} = \frac{1}{2}\|B - JR\|_2^2 + \tau\|R\|_1. \tag{4}$$

The computational strategy takes advantage of the fact that it is normally true in images that not all pixels in an image contain new information and the system is said to be sparse on some basis since fewer degrees of freedom are needed to describe the system than the total number of pixels in the image. The parameter τ is often a constant.

4. Conclusions

The research tested the ability of diffraction free light sources to ghost image and penetrate partially obscuring media. The experiments using diffraction free light beams were successful, supporting the capability of QGI to reveal images through partial obstructions to the illumination. Given the results of other experiments performed through turbulence and obstructing paths, the technique using diffraction free photon beams such as Bessel beams appears to provide an advantage in imaging through other obscurants (*2*). The results of this effort demonstrated the ability to perform QIGI using only a single sensor, that is, a distant single-pixel bucket detector. Furthermore, randomly displaced nearly diffraction free Bessel beams successfully provided illumination patterns for QIGI and resolved a small distant target. Finally, QIGI successfully recovered the image of the object even when the coarse illuminating Bessel beam had re-formed after passing through the obstruction of a small aperture displaced transverse to the laser beam.

5. References

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6. Transitions

I have written a paper entitled “Quantum Inspired Ghost Imaging with a Distant Bucket Photo-Sensor” (*3*) that uses the research findings of this Director’s Research Initiative (DRI).

List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
ARL	U.S. Army Research Laboratory
DARPA	Defense Advanced Research Projects Agency
DRI	Director’s Research Initiative
QGI	Quantum Ghost Imaging
QIGI	Quantum Inspired Ghost Imaging
SLM	spatial light modulator

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