HOLOGRAPHIC ADAPTIVE OPTICS

Dr. Geoff Andersen
United States Air Force Academy

ABSTRACT

For the last two decades adaptive optics has been used as a technique for correcting imaging applications and directed energy/laser targeting and laser communications systems affected by atmospheric turbulence. Typically these systems are bulky and limited to <10 kHz due to large computing overhead and limited photon efficiencies. Moreover most use zonal wavefront sensors which cannot easily handle extreme scintillation or unexpected obscuration of a pre-set aperture. Here we present a compact, lightweight adaptive optics system that utilizes a hologram to perform an all-optical wavefront analysis that removes the need for any computer. Finally, the sensing is made on a modal basis so it is largely insensitive to scintillation and obscuration. We have constructed a prototype device and will present experimental results from our research.

1. INTRODUCTION

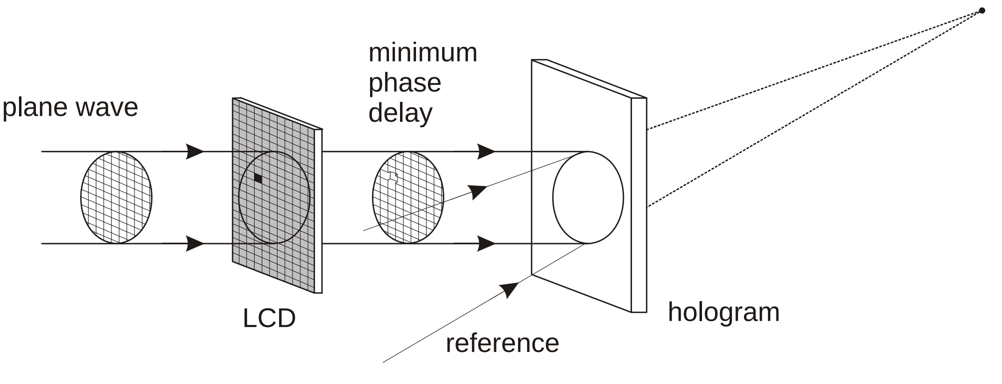
The transmission of light through the atmosphere suffers greatly from atmospheric turbulence effects. In the specific case of the Airborne Laser, the problem is compounded by thermal effects in the laser itself and aerodynamically induced turbulence outside the aircraft. These issues result in a system that routinely requires correction at bandwidths greater than 10 kHz. Typical AO systems[1-3] operate at around 100-200 Hz, with the fastest ones approaching 1-10 kHz under ideal conditions. The adaptive optics process is slowed due to computational loads imposed by the detection as well as requirements of control software to take the acquired phased data and convert this into control signals for the corrective optic. Dedicated circuitry in the form of FPGAs can be constructed but they are large and expensive custom items.

Here we present an alternative solution which involves using a hologram for the wavefront sensing. This hologram is created by recording the precise response function of the each individual deformable mirror actuator. The system detects the actual phase error at the actuator location using a photodetector - the output of which can be directly tied into the actuator control. The closed-loop system thus operates autonomously, *i.e.* without the need for any computer. Furthermore, since the correction is made on a modal basis instead of zonal, it is virtually insensitive to scintillation and obscuration.

2. HOLOGRAPHIC ADAPTIVE OPTICS

While any phase correction device can be used, it is simplest to understand the operation of the holographic adaptive optics system using a pixilated liquid crystal display. We begin by constructing an object beam consisting of a plane wave modified by applying a negative phase shift to a particular pixel on the LCD. A hologram is recorded between this wave and a diffraction limited reference beam focused to a distant point A (Fig. 1). On reconstruction, if the same phase delay were applied to the plane wave passing through the LCD it would reconstruct a beam focusing to the same point A.

a.



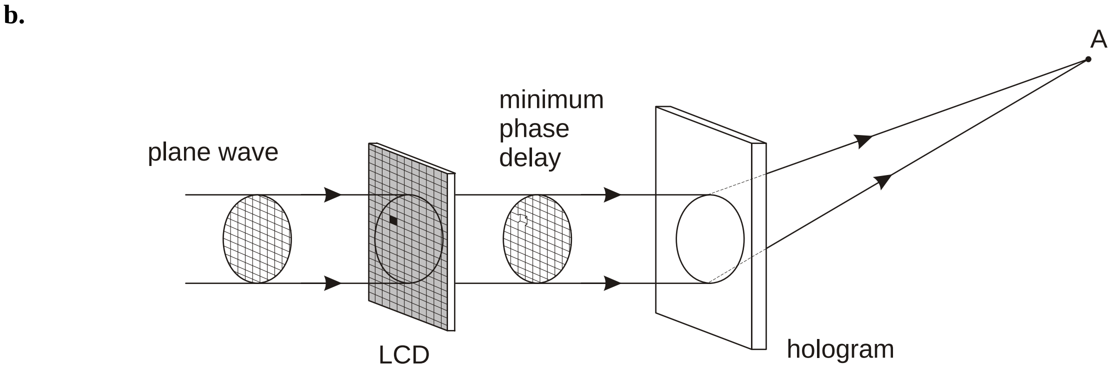


Fig. 1: a. Recording. A hologram is recorded with a single pixel element set to its minimum phase shift and a reference beam focused to distant point A. **b.** Replay. An input beam with the same phase shift at that pixel location will reconstruct a focused spot at A.

We then record a second hologram on top of the first, but this time with an object beam modified with the maximum phase delay applied to the same pixel on the LCD, and a reference beam focused to a different point B. The multiplexing of holograms is a very straightforward process and allows us to retain the information encoded in both. If we now send in some wave at the pixel location (shaded red in Fig. 2) with an arbitrary phase shift (between our maximum and minimum recorded values) there will be two beams reconstructed. The relative intensity of the two spots is a measure of the degree of phase matching obtained in the reconstruction process at that particular pixel. For example, if the input wavefront has a large positive phase shift then spot B will be more intense as it is a phase shift more related to that used to record spot B's hologram. So by simply measuring the ratio of light intensity in the two spot locations we can obtain a relative measurement of the actual phase shift at the particular pixel location. The relative measurement can be made an absolute measurement using a one-off calibration.

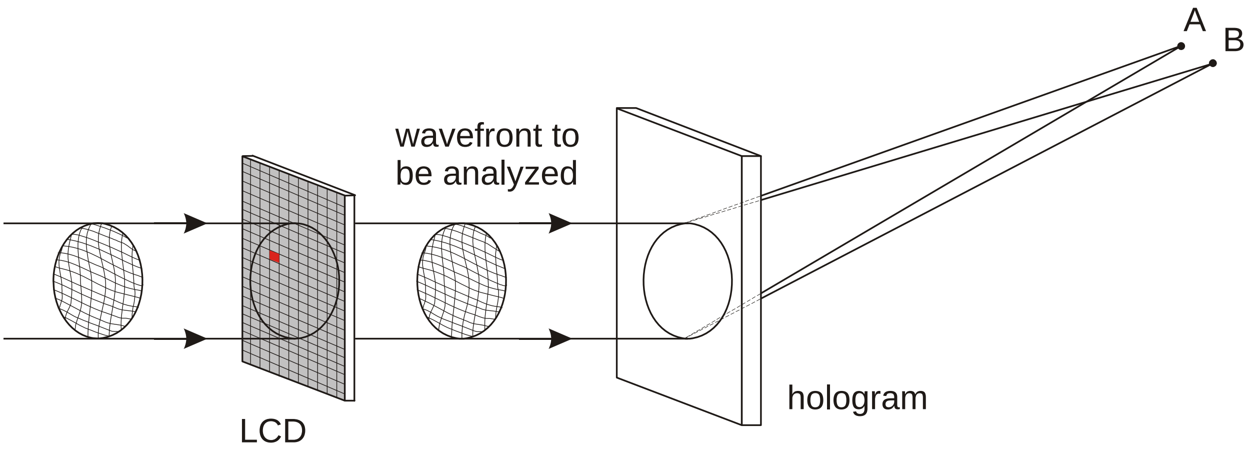


Fig. 2: An input wave with some arbitrary phase shift at the particular pixel location (shaded, red online) will reconstruct a pair of beams focused at A and B.

The simple description above describes how the phase shift at a particular pixel can be made with two holograms. In order to fully characterize the entire wavefront we only need to repeat this process with more pairs of holograms – one for each pixel on the LCD. In this case we configure the hologram construction to create the focal spot pairs into spatially separate locations on a distant image plane (Fig. 3).

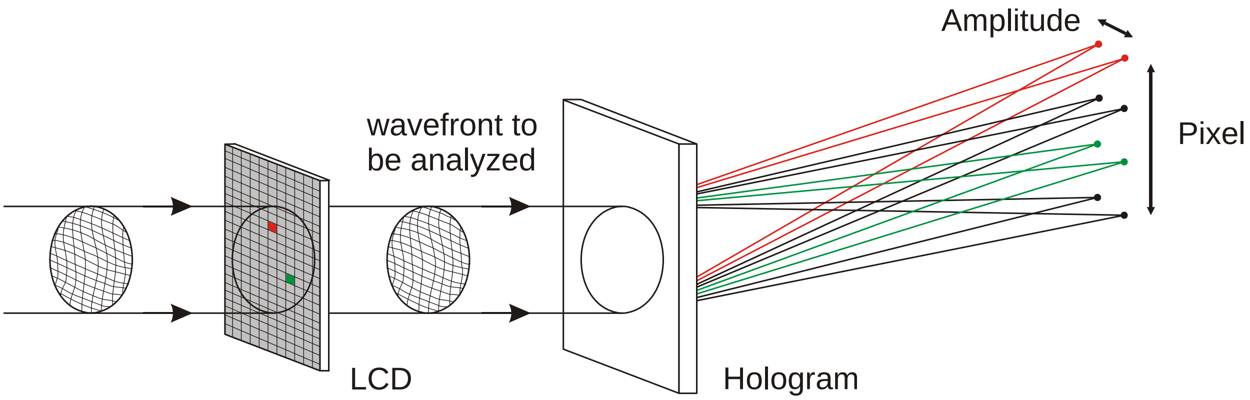


Fig. 3: A pair of holograms are recorded for each subaperture. Each pair of beams is spatially separated and the corresponding phase delay is measured by the intensity differences of each pair.

The important point to note is that the spatial resolution of the phase measurement (i.e. subaperture number or pixel size) has no effect on the bandwidth of the sensor. This is because the speed is not determined by any calculations but merely by the readout of the spot intensities which can be made to MHz rates given the appropriate choice of detector and sufficient input power. In our designs we are planning to use either multi-anode photomultiplier tubes (MAPMTs) or multi-pixel photon counters (MPPCs). These devices are far superior in sensitivity and efficiency to CCDs used in most conventional Shack-Hartmann or curvature wavefront sensors.

The ability for the holographic wavefront sensor to characterize the phase of an input wavefront without the need for calculations means that a fully computer-free closed-loop adaptive optics can be developed. A schematic of the basic closed-loop AO system is shown in Fig. 4, below. In this case, pixels in the LCD have been replaced by the more conventional actuators in a deformable mirror. However, the one-to-one correspondence between detector output and individual actuator remains. This means that a simple wiring system can permit direct control of the actuators by the detector elements themselves (most likely with some signal modification required but not shown). Thus a compact, self-controlled closed-loop system is possible with the only outside requirement being electrical power.

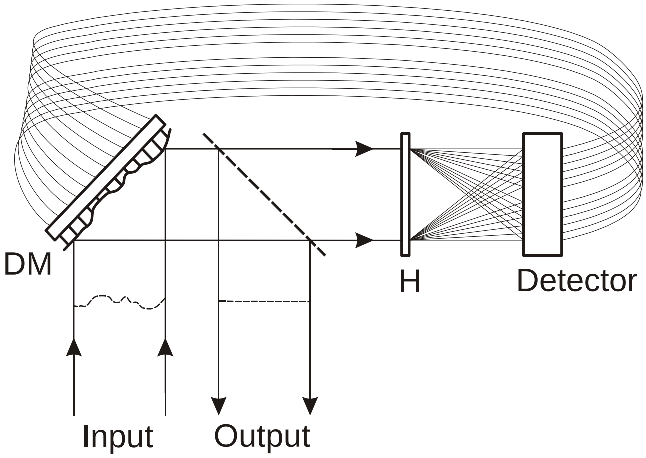


Fig. 4: A closed loop system takes the detector output from a pair of spots and converts this into a control voltage for the corresponding subaperture element in the deformable mirror (DM).

The critical design/performance issues of the holographic adaptive optics system can be summarized as follows:

1. Speed: Using photon counting multi-pixel photon counter (MPPC) arrays we can achieve wavefront measurements limited only by the detector response. The closed-loop performance is thus limited only by the deformable mirror bandwidth which for some MEMS-based systems can be over 1kHz.

2. Computational overhead: The key significance of the holographic adaptive optics system is the removal of the need for computations to assess the wavefront phase error. In the closed-loop system shown above, the entire wavefront correction is achieved autonomously. This not only reduces the footprint and mass but greatly improves the ruggedness and usefulness. Furthermore, increasing the number of actuators has no affect on speed as in conventional devices, so this system has many applications in areas of extreme turbulence where D/r_o can be very large.
3. Obscuration/Scintillation: Holographic AO utilizes a modal detection method, so unlike conventional zonal phase characterization, the system is virtually insensitive to obscuration or scintillation effects. Dramatic variations in intensity are all factored out when comparing the brightness of two spots because the measurement is based on the relative intensities rather than the absolute intensities.
4. HEL operation: Holographic adaptive optics can be configured for both high power applications and infrared wavelengths. While IR holograms are less commonplace, several photopolymers can provide reasonably high efficiency. Of course, there is still the possibility of sensing at one wavelength (with a visible illuminating laser, say) and correcting for another. The only requirement would be the use of a dichroic beamsplitter in the set-up.
5. Other applications: The high speed and scintillation insensitivity of holographic AO makes it ideal for directed energy weaponry where a laser beam travels through fast-changing, highly turbulent airflows. Spin-off applications include lightweight, compact image correction systems for UAVs, free-space optical communications, eye surgery systems and intra-cavity laser correction.

3. EXPERIMENTAL RESULTS

In previous research[4,5] we demonstrated the viability of a holographic wavefront sensor. That work incorporated a holographic optical element configured to sense low-order Zernike modes. In that case, the deterministic nature of the modes made it possible to design and create a computer generated hologram in etched fused silica. The measurement of focal spot intensity differences was made using linear position sensitive devices (PSDs). The resultant sensor was able to decompose the first 8 Zernike modes of any input wavefront. Phase measurements were demonstrated to be good to $\lambda/50$ over a $\pm 2\lambda$ range with minimal inter-modal cross-talk. The wavefront sensor was also incorporated into a closed-loop adaptive optics system using a 37-actuator MEMS-based deformable mirror. The bandwidth of the correction was around 30 Hz with a sample of the correction achieved shown in Fig. 5. The feasibility of a holographic wavefront sensor was clearly demonstrated and we have since devised the faster, cheaper, lighter and more efficient concept described here.

Fig. 5: An image of an aberrated beam before and after correction using the holographic wavefront sensor and MEMS mirror.

A more practical alternative to using Zernike polynomials as the basis set for phase deconvolution is to use the actuator response functions themselves. In this case there is a direct one-to-one correspondence between the measured amplitude and the required correction at each subaperture location. This removes the need for any calculations to convert measured phase information into actuator control as they are one and the same.

We constructed an experiment to record the response functions of 7 actuators in an OKOTech MEMS-DM. The 14 phase holograms were recorded optically in dichromated gelatin for the maximum and minimum applied voltages against 14 spatially separate focused reference beams. On reconstruction the power ratios in the pairs of focal spots were used to plot the 1st moment $((P_1-P_2)/(P_1+P_2))$ versus voltage as shown in Fig. 6. Once again the function is singly determined over virtually the entire actuator motion. This indicates that we can generate a unique control voltage for off-setting the wavefront error at a particular actuator location.

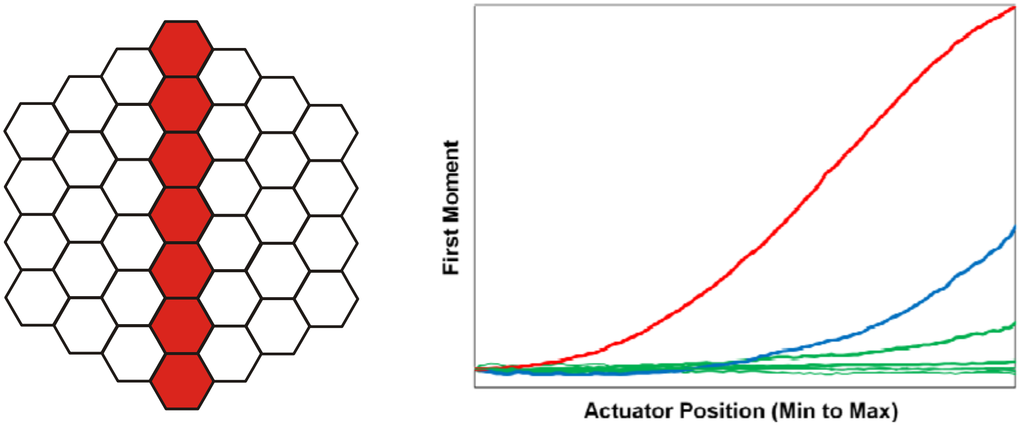


Fig. 6: Left: A schematic of the actuators recorded. **Right:** A plot of the 1st moment of intensities as voltage is varied to the test actuator. The test actuator is shown in red, while the cross-talk response from the adjacent actuator is shown in blue and the other actuators in green.

The cross-talk in this case is fairly significant as indicated by the fact that the neighboring actuator seems to change its response even though only the test actuator is being moved. Meanwhile a distant actuator shows no change as should be expected. This is an issue with some continuous facesheet MEMS-DMs and indicates that this particular model (from OKOTech) is not suitable for future experiments. The large overlap in influence functions is clearly evident in interferometric measurements made by moving a single actuator in this mirror (Fig. 7). In the future we propose to use a DM with lower cross-talk (and faster response times) available from several other manufacturers.

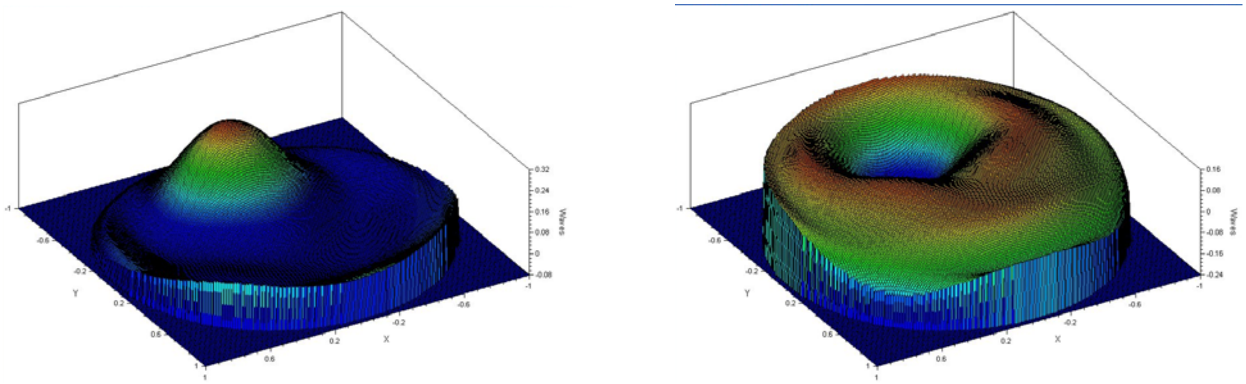


Fig. 7: Interferometric measurements of the effect of pushing and pulling on a single actuator show the large cross-talk this has over other actuators.

In spite of the cross-talk a closed-loop system was constructed to test the feasibility of the holographic adaptive optics concept. In this case, to lower the effects of cross-talk and prevent ringing we chose the 7 widely spaced actuators and the subsequent hologram reproduced in Fig.8. The system was run in closed loop via Labview software and was capable of self-correcting to a set initial calibrated plane wavefront as demonstrated in the screenshot reproduced in Fig. 8.

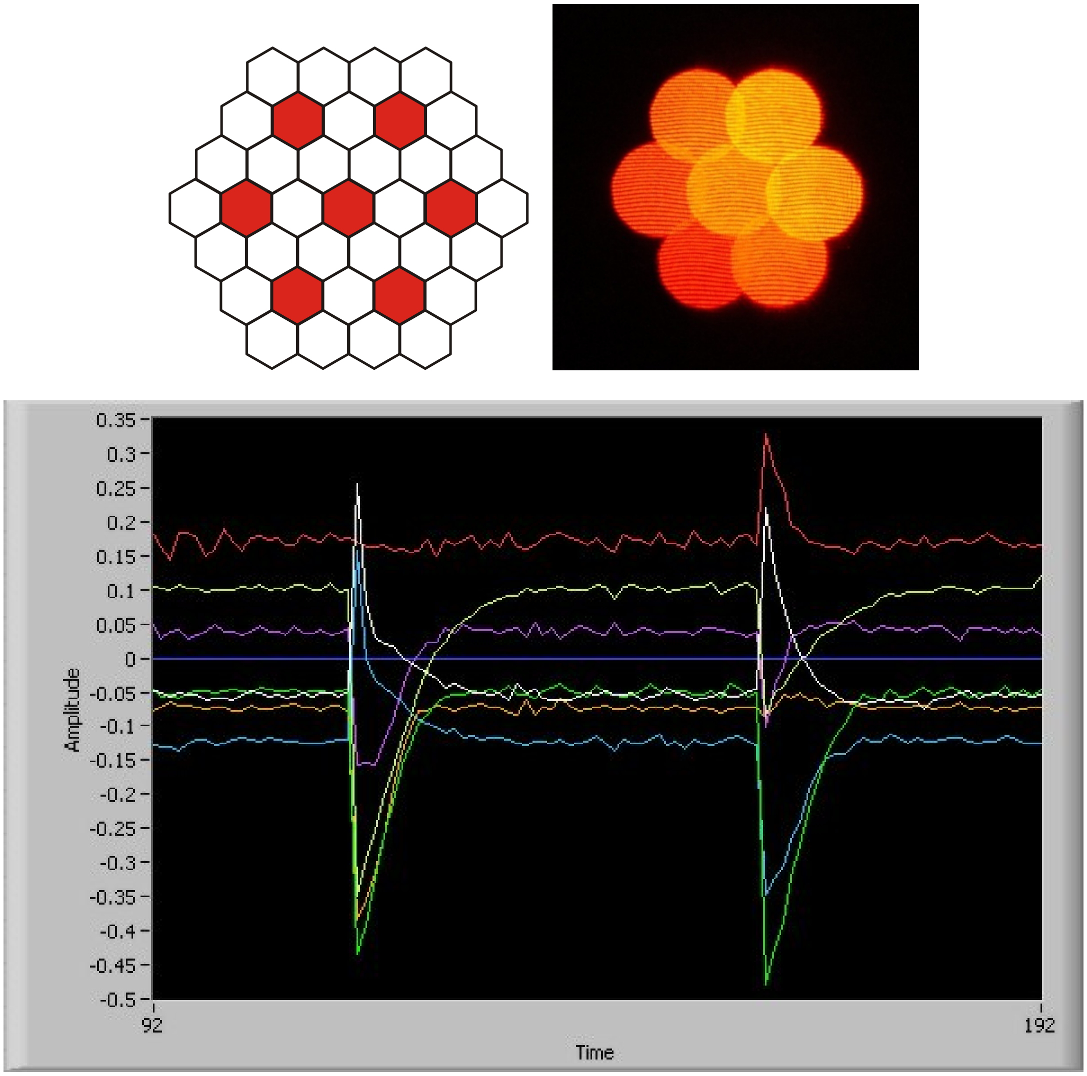


Fig. 8: Top: The actuators chosen for closed-loop operation (left) and an image of the recorded hologram (right). **Bottom:** A plot of the first moments over time. Any transient change is rapidly corrected as the system returns to the set values for a flat wavefront.

The closed-loop system as it operates is far from optimal. To begin with we have used a CCD for intensity measurements instead of an array of photodetectors. The latter would produce a simple signal that could be used to control the DM actuators directly, while the former requires software to make some intermediate calculations. This is quite computationally intensive and results in a very slow close-loop correction. However, the principle has been demonstrated so that when the appropriate detectors are purchased we feel confident we will be able to remove the computer from the loop altogether.

4. CONCLUSION

We have presented a novel holographic adaptive optics system that uses a hologram to deconvolve a wavefront phase in terms of the precise response functions of actuators in the corrective deformable mirror. We have constructed a working closed-loop prototype with a CCD and software control. Ultimately, however, the system will be configured to operate autonomously without any computer in the loop with the appropriate detectors. Beyond the significant speeds achievable the system offers improvements over conventional Shack-Hartmann or curvature-based AO systems in compactness, simplicity, ruggedness and insensitivity to scintillation.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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