Digital Holographic Characterization of Atmospheric Wavefront Perturbation

Stephen Crouch[a], Zeb W. Barber[b], Jason Dahl[b] and Randy R. Reibel[a]
(a) Blackmore Sensors and Analytics, Inc., 3991 Valley Commons Dr., Bozeman, MT 59718
(b) The Spectrum Lab and Department of Physics, Montana State University, Bozeman, MT 59717
crouch@blackmoreinc.com

Abstract: Atmospheric turbulence is a fundamental limiter of long-range coherent ladar aperture synthesis imaging. We demonstrate a novel approach to high resolution measurement of wavefront perturbations caused by atmospheric turbulence. The approach features a simple optical design, minimal processing, and the ability to use diffuse surfaces as the wavefront characterization target. By deriving a local oscillator from the impinging beam, digital holography is used. Inspired by phase gradient autofocus, coherent processing techniques are used to extract the common mode phase gradient from a set of digital holographic images, each with a unique atmospheric realization. The common mode phase gradient is then subtracted from the phase gradient of each image to reveal the phase gradient of each atmospheric wavefront perturbation. This is used to reconstruct the perturbation. Experimental and algorithmic considerations as well as the potential for the technique to support turbulence agnostic coherent aperture synthesis are discussed.

Keywords: Coherent Laser Radar, Atmospheric Sensing, Wavefront Reconstruction

1. Introduction

Coherent laser radar aperture synthesis offers a pathway to cross-range resolution beyond the diffraction limit of physical optics. Specific schemes such as synthetic aperture ladar (SAL), holographic aperture ladar (HAL), and 3D variants have all been demonstrated. However, atmospheric turbulence introduces perturbations to the backscattered speckle field which destroy the spatial coherence of sequentially captured data and practically limit the applicability of such approaches to within the coherence time of the atmosphere.

The deleterious effects of atmospheric turbulence on coherent aperture synthesis are well studied.[1] In the digital holography/HAL field, simulation typically proceeds via the split-step beam propagation method which supports the insertion of phase screens along the propagation path with representative statistics. Such methods are also a starting point for attempts to correct for atmospheric turbulence whereby a corrective phase screen can be computed and applied.[2]

An *in situ* method to measure phase aspects of a propagated laser beam imaging a diffuse target would be a powerful tool in the effort to understand and correct atmospheric turbulence in coherent imaging scenarios. We present a method for the measurement of atmospheric turbulence induced phase perturbations to a wavefront. The approach relies on the analysis of digital holographic images, works with diffuse surfaces, and utilizes modest computational resources. We believe this approach will support the study, characterization and removal of unwanted atmospheric effects in coherent laser radar imagery.

2. Imaging Scenario

Consider the experimental scenario of Figure 1 where a 793nm CW laser beam with 15mW of optical power illuminates a diffuse target along an optical path including turbulence induced by an electric space heater. A local oscillator is run, via fiber, down to the target to enable digital holographic imaging of the spot on the target. A Point Grey USB 3.0 camera array records the speckle field at 110Hz frame rate and a processing station executes the processing of the digital holograms. A short exposure time helps to "freeze out" the speckle field which is evolving due to the turbulence induced by the space heater. We seek to derive information about the wavefront from this set of digital holographic images.

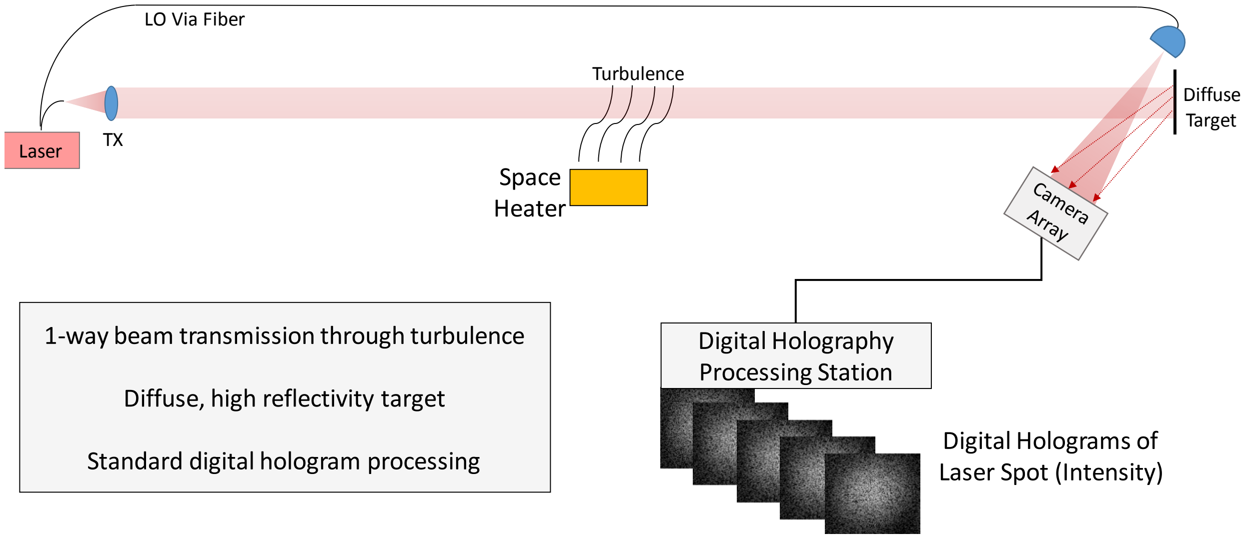

Figure 1. The experimental layout is illustrated in the schematic.

3. Theory and Algorithmic Approach

As a first step, consider the digital interference (i.e. phase differencing) of sequentially collected frames on the camera. This process is depicted in Figure 2. As the aberrations, divergence, and diffuse speckle pattern seen by the camera are constant, the phase difference observed by this digital interference is attributed to the changing atmospheric conditions. As a control, cases with no space heater present (no turbulence) were observed and generated essentially flat phase differences (not shown in this paper).

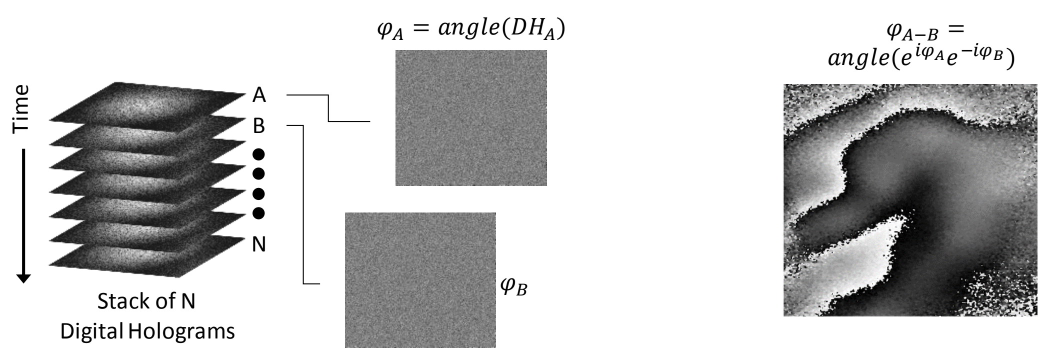

Figure 2. (Left) A set of digital holograms is collected. Pairs of digital holograms can be extracted and digitally interfered. (Right) The result of pairwise interference of digital holograms with changing atmospheric conditions reveals structure in the phase difference due to the turbulence.

The differential measurement alone is not an insightful measurement as an infinite combination of atmospheric conditions could give rise to the observed wavefront difference. However, the differential measurement described demonstrates potential conditions for the extraction of more useful information. Inspired by Warren, Ghighlia, et al.[3] we formulated a gradient based approach to extracting the atmospheric wavefront perturbation. We define the wavefront perturbation as the difference between a given frame's wavefront and the average wavefront over a set of beams. Through careful experimental control, we argue that this perturbation is only due to atmospheric turbulence. The average wavefront includes beam divergence and aberration. The digital hologram of the diffuse target also picks up a random speckle phase which is also common mode.

Our algorithm proceeds as in Figure 3. A set of several digital holograms is collected over time, each with a unique atmospheric realization. The phase gradients of each image are computed and then averaged over the set to extract the common mode aspects of the phase gradient. These are assumed to correspond to persistent features in the phase such as beam divergence, aberration, and random speckle from the diffuse target.

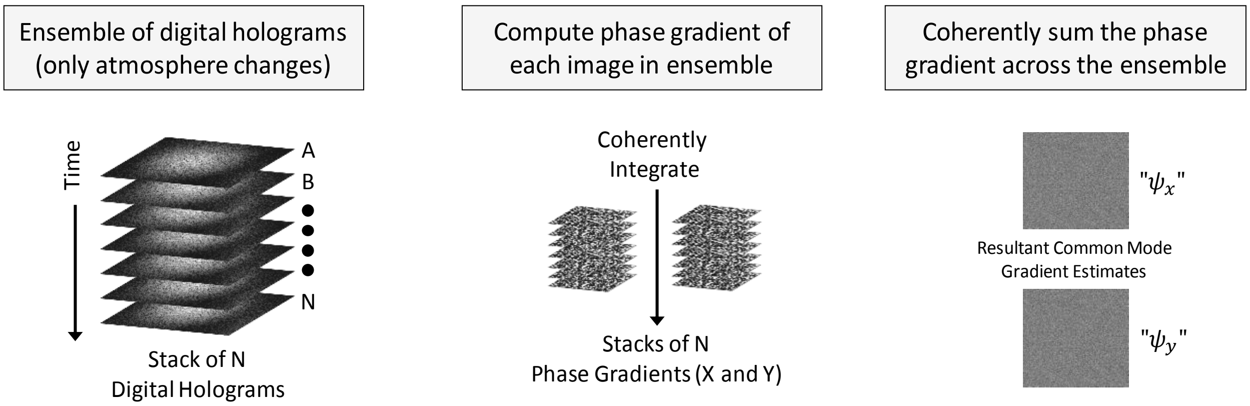

Figure 3. (Left) A stack of digital holograms is collected under changing atmospheric conditions. (Center) The gradient is computed and averaged over the set of digital holograms. (Right) The result is an estimate of the common mode aspects of the phase gradient.

Next we subtract the estimated common mode phase gradient from the phase gradient of each image in the set as in Figure 4. The residual phase gradient corresponds to the atmospheric perturbation. This gradient is ideal for input into any general purpose algorithm designed to reconstruct a function from gradients of the function. We chose to use an open source algorithm and software for convenience and were happy with the results.[4]

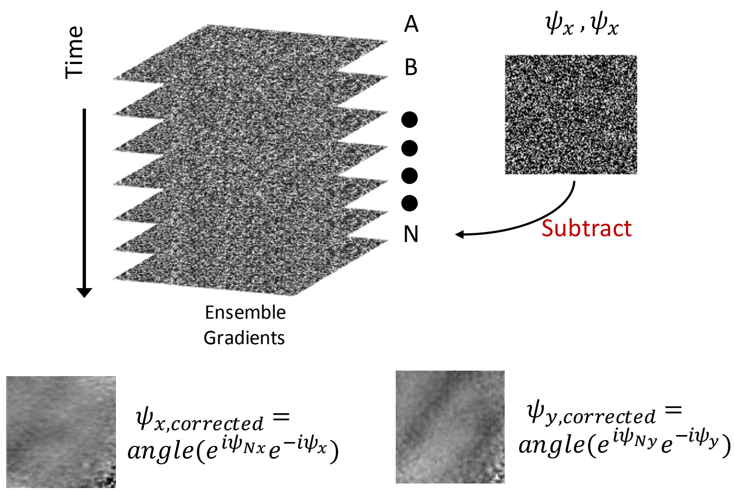

Figure 4. The common mode phase gradient can be subtracted from the phase gradient for each individual image to reveal the phase gradient corresponding to that image. This gradient corresponds to the atmospheric perturbation at that point in time on the beam.

As a final note, we modified the above algorithm to process sub-regions of the original camera array in parallel. This allowed the atmospheric perturbation gradient estimates to be coherently averaged after common mode gradient removal to mitigate speckle effects. This approach is valid as the atmospheric perturbation information is globally encoded in the speckle field sampled by the camera array. This approach trades in some spatial resolution for overall stability to good effect. We tested the number of speckle realizations and found that breaking up the camera array into 20 sub-regions produced a good tradeoff.

4. Experimental Results

The results of our approach were verified by comparing the phase difference of sequential reconstructed wavefront perturbations with phase differences of the same pair of sequential holograms. The phase difference should be identical up to a global constant phase. In Figure 5 we observe this self-consistency. A series of movies of the reconstructed wavefront will be presented in the oral presentation.

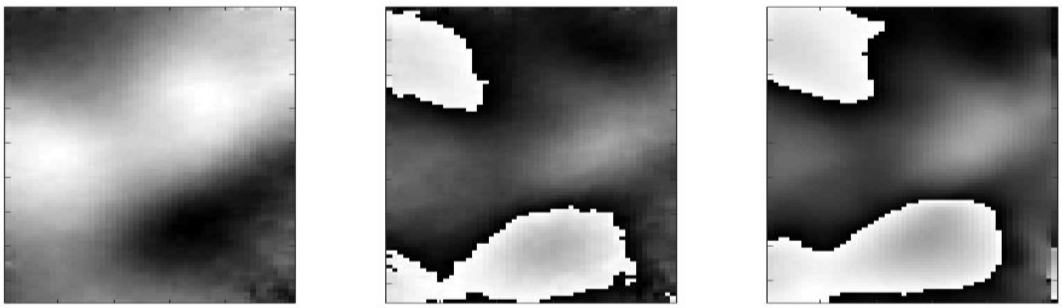

Figure 5. (Left) Reconstructed wavefront (-5pi to 5pi). (Center) Phase difference between reconstructed wavefront and the previous reconstructed wavefront in the image series (-pi to pi). (Right) Phase difference between the unprocessed digital hologram and the previous digital hologram (-pi to pi, same pair as center). Note the clear similarity between the two approaches. The important aspect is that the image at center is from actual derived wavefronts.

5. Conclusion

We demonstrated a novel wavefront characterization tool to measure atmospheric turbulence wavefront distortion. The approach relies on the static phase contribution of all factors except the changing turbulence. This contrivance could be overcome by use of speckle field tracking and appropriate speckle field registration as a pre-processing step. The computationally efficiency and overall effectiveness of the approach in extracting useful phase information for an *in situ* diffuse imaging scenario should underscore the potential of the approach. Next steps include transition to longer range imaging scenarios, larger beam diameters, and exploration of the potential for image correction. We gratefully acknowledge support from AFRL under contract number FA8650-15-C-1871.

6. References

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