Estimating the complex atmospheric wave front from speckle images

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ABSTRACT

Speckle image data contain information on both the object being viewed and the complex atmospheric wave front responsible for the degradation of the image. If we can extract the latter information from the raw speckle data, we can use it to produce a high-contrast image of the object. The challenge is we only measure intensity information. Here we investigate a possible approach for decoding the complex atmospheric wave front information from the measured intensity data.

BACKGROUND

Surveillance of the near-space environment using ground-based telescopes plays an important role in space situational awareness. Ideally, each telescope should be capable of both monitoring the entire the sky above it, from zenith to the horizon, and producing high-resolution, high-contrast imagery of any target, at any distance, from low-earth orbit to geosynchronous orbit.

Resolution and contrast are the two main ingredients for high-fidelity satellite identification and the detection of any closely spaced objects that may be in the vicinity. Of course, the maximum resolution provided by a telescope is dictated by the size of its aperture, and to acquire high-resolution imagery of targets in geosynchronous orbit will require apertures in excess of 40m. We will therefore focus here on low-earth orbit where the imaging of targets can be achieved with meter-class telescopes.

The main obstacle to overcome for acquiring high-resolution, high-contrast imagery of space-based targets using ground-based telescopes is the Earth's turbulent atmosphere. In order to recover from the image blur caused by the distortion of the wave front as it passes through the atmosphere we need to be able to accurately measure or model the atmospheric point spread function (PSF) over a large dynamic range. With this information we can then provide high-quality restoration of the recorded imagery through real-time wave front compensation using adaptive optics (AO), numerical post-processing, or, optimally, a combination of the two. We note that when AO compensation is not available we need to image at frame rates commensurate with or faster than the temporal coherence time of the atmosphere [1,2] in order to preserve diffraction-limited resolution information in the images.

Our earlier research has shown that a high-quality estimate of the complex wave front associated with each image can be achieved with a phase-diversity imaging system and analysis [3]. It can also be achieved by acquiring contemporaneous Shack-Hartmann (SH) wave front sensor (WFS) data along with the speckle image data [4] and using both data sets in the restoration process. In this latter case the emphasis to date has been on recovering accurate wave front phase, however, information on the wave front amplitude is encoded in the intensities of the spots in the images acquired with the Shack-Hartmann sensor and should be straightforward to retrieve.

Unfortunately, the majority of the Air Force's meter- and sub-meter class telescopes are not equipped with phase diversity systems, wave front sensors, or adaptive optics systems. In addition, future field-deployable telescope systems for observing "targets of opportunity" will, by necessity, need to have a minimalistic design. Therefore, there is a need for the development of restoration algorithms that can provide high-resolution, high-contrast, images from only single channel image plane speckle data.

RECOVERY OF WAVE FRONT PHASE

As we generally don't know the form of the object or the PSFs we turn to multi-frame blind deconvolution (MFBD) for the processing of our single channel speckle image data [5,6]. This algorithm has been a cornerstone for ground-based space situational awareness of near-Earth satellites, since the early 2000's.

When modeling the data in the MFBD algorithm, we typically use a Fourier optics model to describe the atmospheric PSFs via the wave front phase and amplitude because this model injects prior knowledge that observations are band limited and positive [7]. However, the wave front phases estimated via MFBD are typically not physical in any sense and tend to provide a solution that only captures the general morphology of the dominant speckle structure in the PSF. The low-amplitude speckle structure is not well modeled [8] and use of the resulting PSFs in the image restoration process thus leaves a low level "fog" in the restored image. To remove this fog requires accurate estimation of all of the speckle structure in the PSFs. This requires wave front phase estimates that are physical which in turn requires the inclusion of the inherent temporal correlations in the wave fronts in the Fourier Optics model for the PSF. It was shown over a decade ago that, for at least low levels of atmospheric turbulence, $D/r_0 \sim 2$, where D is the diameter of the telescope aperture and r_0 is the spatial coherence length of the atmosphere [1], that the information on the wave fronts that is encoded in the temporal correlations can be decoded using a Gaussian kernel to correlate the estimated wave front phases in time during the recovery of the PSFs [8]. Now, this level of turbulence does not drastically alter the resolution of the image from diffraction-limited resolution and is not of much practical interest. However, we show in Fig. 1 that the algorithm used in [8], with some slight modification in how the initial wave front phase estimates are seeded (see caption to Fig. 2), can in fact provide physical wave front phases out to a slightly more realistic level of turbulence, i.e. D/r_0 up to ~ 5.

Since the initial work it has been shown that the temporal correlations in the atmospheric wave fronts can also be modeled by using a multi-layer model for the atmospheric phases where the layers propagate across the telescope pupil at the local wind velocity at the height of the layer. Not only is this approach to incorporating the temporal correlations more in tune with what is physically happening, it also requires fewer variables to describe the wave front phases. However, in order to use this approach we need to know the number of atmospheric layers to be modeled and their wind velocity vectors. This is normally achieved by acquiring simultaneous SH WFS data and auto-correlating the recorded wave front phase gradient information [4]. However, as we show in Fig. 2, the information on the atmospheric layers can also be acquired by using the recovered phases obtained with the simple modeling of temporal correlation using the Gaussian kernel. We can then take these "level 0" phase estimates as a starting point for a "level 1" estimation of the phases using a multi-layer model with frozen flow behavior.

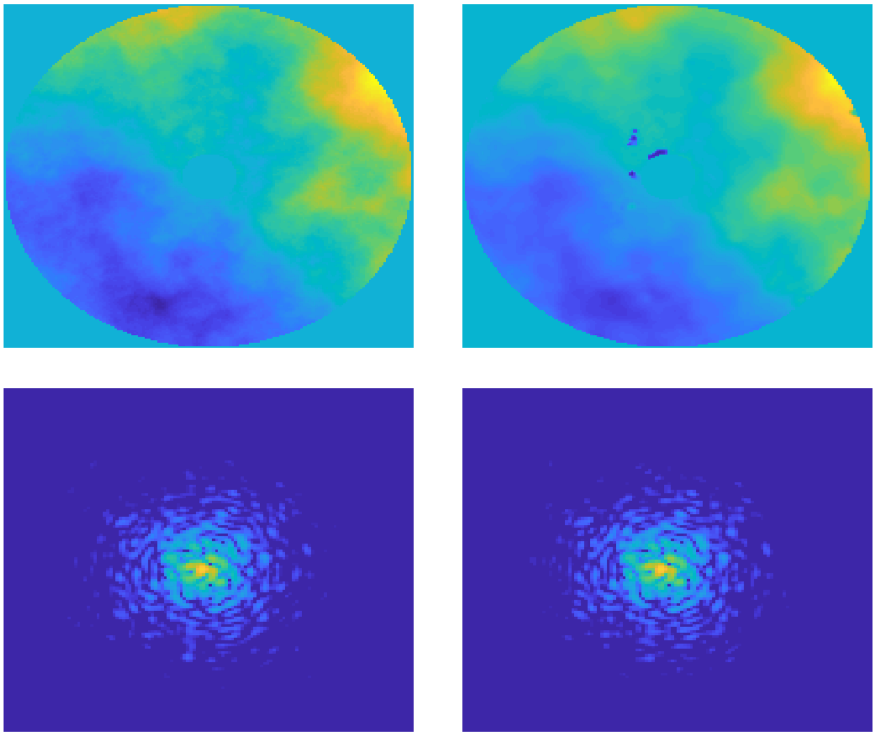

Fig 1. Top row: truth phase for $D/r_0=5$ (left) and recovered "level 0" phase (right). Images are on a linear scale. Bottom row: PSFs corresponding to above wave front phases above. Images are on a square root scale to highlight the low amplitude speckles. The root-mean-square error (r.m.s.e.) in the recovered wave front phase is 0.61 rads: this corresponds to a Strehl of ~0.7.

RECOVERY OF WAVE FRONT AMPLITUDE

Next we come to the estimation of the wave front amplitude. In practice, we often assume that variations in the wave front amplitude are negligible and we only estimate wave front phases in our restoration of the speckle image data.

For observations at low zenith angles this is not an unreasonable assumption: variations in the wave front amplitude will be small and the impact on our estimate for the PSF by ignoring them will primarily show up as small errors in the recovered speckle amplitudes. The general speckle morphology, which is most sensitive to accurate phase estimation, will be well recovered. For high zenith angles this is not necessarily the case. Moreover, to obtain the best contrast in our restored image we need to get not only the morphology of the speckle structure correct, but also the amplitude of the structure.

To estimate the wave front amplitudes we turn to the algorithm used in [3] which has already been validated as a way to recover the full complex wave front when good initial phase estimates are available, to accommodate the multi-layer model for the atmosphere. This part of the research is work in progress.

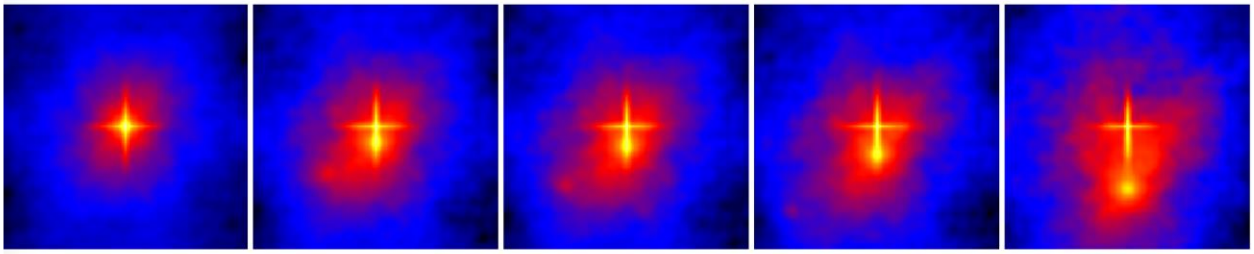

Fig. 2. Autocorrelation function for the x-gradients of the time series of recovered wave fronts. From left to right we have the ACF at increasing time lags. You can clearly see the moving spots at the 7 o'clock (fast layer) and 6 o'clock (slow layer) of the two component wind layers. Here we recovered the wave front phases using the approach of [8] slightly modified to provide better initial PSF estimates: we added some defocus to the tip/tilt estimate to give some width to the initial PSF.

DISCUSSION

We have verified that for turbulence levels of up to $D/r_0 \sim 5$ we can use a MFBD algorithm to obtain physically meaning estimates for the atmospheric wave front phases from single channel speckle image data. This is an important step in the recovery of the full complex atmospheric wave front. By recovering physically accurate estimates for the complex wave front amplitude and phase we will be in a position to generate high-contrast imagery of the objects being imaged. We have also shown that we can extract information on the number of atmospheric layers and their velocity vectors from the speckle intensity data.

Finally, we note that by being able to use a multi-layer/frozen flow model to describe the atmospheric wave fronts, we can recover estimates of the wave fronts in the individual layers, not just the composite wave front in the telescope aperture. The ability to estimate the individual layers allows us to recover the full tomographic solution [9]. This means that we will eventually be able perform high-quality correction of speckle images with spatially varying blur [10] without any additional hardware outside of a speckle camera.

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REFERENCES

1. Roddier, F., "Adaptive Optics in Astronomy", Cambridge University Press (1999).
2. Fried, D. L., "Time-delay-induced mean-square error in adaptive optics", *J. Opt. Soc. Am. A,* 7, 1224-1225 (1990).

3. Jefferies, S. M., Lloyd-Hart, M., Hege, E. K. and Georges, J., “Sensing wave-front amplitude and phase with phase diversity”, Applied Optics, 41, 2095 (2002).
4. Jefferies, S. M. And Hart, M., “Deconvolution from wave front sensing using the frozen flow hypothesis”, Optics Express, 19, 1975 (2011).
5. Schulz, T. J., “Multi-frame blind deconvolution of astronomical images”, JOSA A., 10, 1064 (1993).
6. Jefferies, S. M. and Christou, J., “Restoration of Astronomical Images by Iterative Blind Deconvolution”, ApJ, 415, 862 (1993).
7. Miura, N., “Blind Deconvolution under band limitation”, Optics Letters, 28, 2312 (2003).
8. Jefferies, S. M. and Giebink, C., “Temporal constraints in the blind restoration of high-cadence imagery obtained through atmospheric turbulence”, in *AMOS 2005*, AMOS Technical Conference, Kihei HI (2005).
9. Willson, M., Jefferies, S. M., and Hope, D. A., “Tomographic wave front sensing using a single imaging Shack-Hartmann wave front sensor and multi-frame blind deconvolution”, n *AMOS 2018*, AMOS Technical Conference, Kihei HI (2018).
10. Bardsley, J., Jefferies, S. M., Nagy, J., and Plemmons, R. 2005, “Blind iterative restoration of images with spatially varying blur”, in *AMOS 2005*, AMOS Technical Conference, Kihei HI (2005).