Noise as a Design Constraint in Broadband Wavefront Coded Optical Systems

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Abstract: Simulated results demonstrate the impact of detector noise on the design of a broadband wavefront coded optical system. We conclude that noise must be included as a first-order design constraint in cubic phase-encoded systems.

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1. Introduction

The performance of wavefront coded systems under ideal, noiseless conditions is well-documented [1]. A cubic phase contribution is placed in the pupil plane to engineer the point spread function (PSF), such that the optical transfer function (OTF) has particular properties over the image that enable image reconstruction through post processing [2]. This engineered PSF has the same shape throughout the image field, i.e. the system must be designed to have a much larger isoplanatic region than without wavefront coding, and the PSF is later deconvolved using digital signal processing.

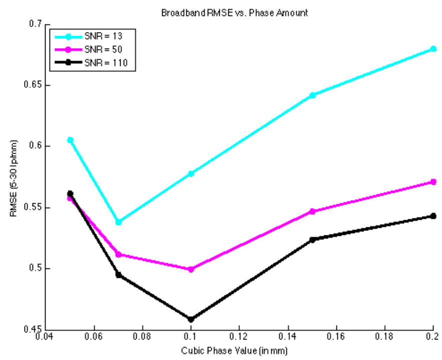
An increase in the added phase allows for an increased depth of focus after image processing and, consequently, a larger bandwidth of in-focus wavelengths for a single focal plane [3]. In a noiseless system, this increased depth of focus is only limited when the signal flux approaches zero. However, with the presence of noise, which is intrinsic to all image acquisition systems, the detected image is degraded, causing a loss of information where the signal flux approaches the noise level and resulting in artifacts in the reconstructed image. Wavefront coded systems are especially susceptible to noise since the point spread function irradiance is spread out into a larger area, due to the deliberate aberration of the phase element, decreasing the signal to noise ratio (SNR) throughout the image. We investigated the impact of this increased noise susceptibility on the optical system design and determined whether noise drives the optimal amount of cubic phase to be added in a broadband system.

2. Simulated noisy optical system

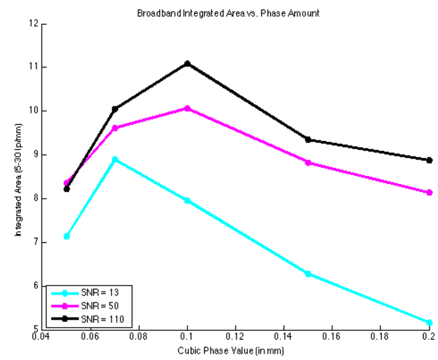
Phase was added in the pupil of a singlet lens optical system, depressing the MTF across a 350-1100 *nm* wavelength band, but simultaneously making the MTFs for each wavelength more uniform. Increasing the sag of the added cubic phase increases this effect: MTF curves become more uniform across an increased bandwidth at the expense of a lower average contrast. This increased uniformity among MTF curves in a cubic phase-encoded system is what allowed for performance improvements after applying the deconvolution algorithm. However, depressing the MTF curves too much caused the noise effects to be amplified, resulting in a worse overall performance. Thus, the phase surface design is a trade-off between increasing the useful wavelength band of the system while maintaining an MTF level high enough to remain above the noise floor. We simulated a cubic phase system to determine the optimal amount of phase that will provide the best recovered image while minimizing noise amplification.

3. Optimal amount of cubic phase

Our optical system simulations were based upon a model that incorporated the lens design software Zemax, developed by the company Radiant Zemax (Redmond, WA), with the processing capabilities of MATLAB®, developed by MathWorks, Inc. (Natick, MA). Images were simulated and reconstructed using the singlet lens and a cubic phase plate with varying phase amounts combined with a deconvolution algorithm. The recovered image was evaluated by two error metrics: the root mean squared error (RMSE) between the recovered MTF curve and the diffraction limit, and the integrated area under the recovered MTF curve. Results of each error metric were then plotted to determine the optimal phase amount. This simulation was repeated for different SNR values to show how the optimal phase amount changes with noise in the nominal system.



(a) RMSE evaluation; minimum value indicates best performing system.



(b) MTF integrated area evaluation; maximum value indicates best performing system.

Fig. 1: Wiener filtered images evaluated from an optical singlet with varying amounts of cubic phase added and 350-1100 *nm* broadband illumination were evaluated using two performance metrics.

Figure 1 shows the results of our simulation using spectral broadband illumination and varying SNRs. The minimum RMSE value in Figure 1a designates the optimal amount of phase for each curve. We see that the blue curve, representing the system with the highest amount of noise, shows a clear optimal value of phase of 70 microns sag. The pink and black curves, representing systems with lower noise levels, have a higher optimal phase value of 100 microns. Figure 1b shows results for the same system, using the MTF integrated area metric, and arrives at the same optimal phase values. These results support our hypothesis that there is a trade-off between adding enough phase to correct the full wavelength range, while not adding too much phase that the MTF curves drop below the noise floor. This simulation highlights the need to consider detected image noise during the optical system design process.

4. Conclusion

The addition of noise to our optical system model effected a change in the simulated optimal cubic phase value in a broadband system. In a noiseless system, the designer must only take care to avoid zero or near-zero values in the deconvolution filter. However, in a noisy system, we conclude that the designer must also avoid letting the deconvolution filter fall below the noise floor or noise will be amplified in the final image. Noise, then, reduces the optimal phase value, and systems with more noise have a lower optimal phase than systems with less noise. This result implies that lens designers must understand the expected noise level of their nominal system image *prior to* designing the optical system.

References

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