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# Modal Wavefront Sensorless Adaptive Optics with Karhunen–Loève Functions

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## ABSTRACT

In this work we propose an optimal modal decomposition technique for gradient-based wavefront sensorless adaptive optics. We implement statistically independent Karhunen-Loève functions for iterative blind correction, and analyze their optimal correction performance in various turbulence conditions in temporally evolving turbulence simulations.

**Keywords:** Wavefront sensorless adaptive optics, Karhunen–Loève functions, Dynamic turbulence simulations

## 1. INTRODUCTION

Gradient-based sensorless wavefront correction is based on achieving the best possible compensation with very few correction steps. Time scales are short, as the correction window given by the atmosphere before conditions change is about 1 ms. After this time, turbulence decorrelation reduces the correction capability of any adaptive optics (AO) system with a loop bandwidth lower than 1 kHz. For iterative blind search correction, this time frame is divided by the number of required iterations for convergence, which renders temporal system response paramount, and imposes more rigid requirements on system design. There are two characteristics which can be adjusted in order to match temporal requirements. First, one can increase the correction bandwidth of the integrated hardware. However, devices with frame rates above 40 kHz are currently not available on the market, imposing an upper limit to this approach. The second option is to improve the efficiency of the correction algorithm itself in order to decrease the required iterations for convergence.

In this work we focus on the second option by including a priori knowledge about the Kolmogorov spectrum of refractive index fluctuations, and employing an optimal method to manage this knowledge over the course of a full correction cycle. We implemented modal instead of zonal correction for all simulated turbulence compensations. Karhunen-Loève (KL) functions are used as an alternative basis to Zernike polynomials here because they form an optimal modal decomposition of atmospheric wavefronts in the sense that the squared residual phase error over the aperture is minimum when compared to any other orthogonal set with the same number of corrected modes. KL functions overcome the statistical dependence between Zernike modes, and thus increase correction performance of the blind search algorithm.

We present a new method to handle the a priori knowledge in order to maintain accurate spatial frequency representation. This optimized modal basis is then compared to the traditional Zernike modes in order to demonstrate the advantages to the former. The comparisons are done in temporally evolving turbulence, for which we simulated both single-layer and multi-layer Kolmogorov turbulence. We provide an analysis of the achievable Strehl ratio of the tested methods when operating a deformable mirror with a finite bandwidth in different turbulence scenarios.

## 2. ZONAL VS. MODAL STOCHASTIC PARALLEL GRADIENT DESCENT

Wavefront sensorless AO uses iterative algorithms which “guess” various combinations of optical deformations until an improvement in a performance metric is observed. Naturally, when applied to strong atmospheric turbulence, the methods must be exceptionally fast in their convergence rate. The most popular method, the stochastic parallel gradient descent (SPGD),<sup>1</sup> is inherently “blind”, i.e. it does not make any assumptions about the nature of wavefront aberrations.

In order to improve the convergence rate of SPGD the modal version of the algorithm, M-SPGD, was developed

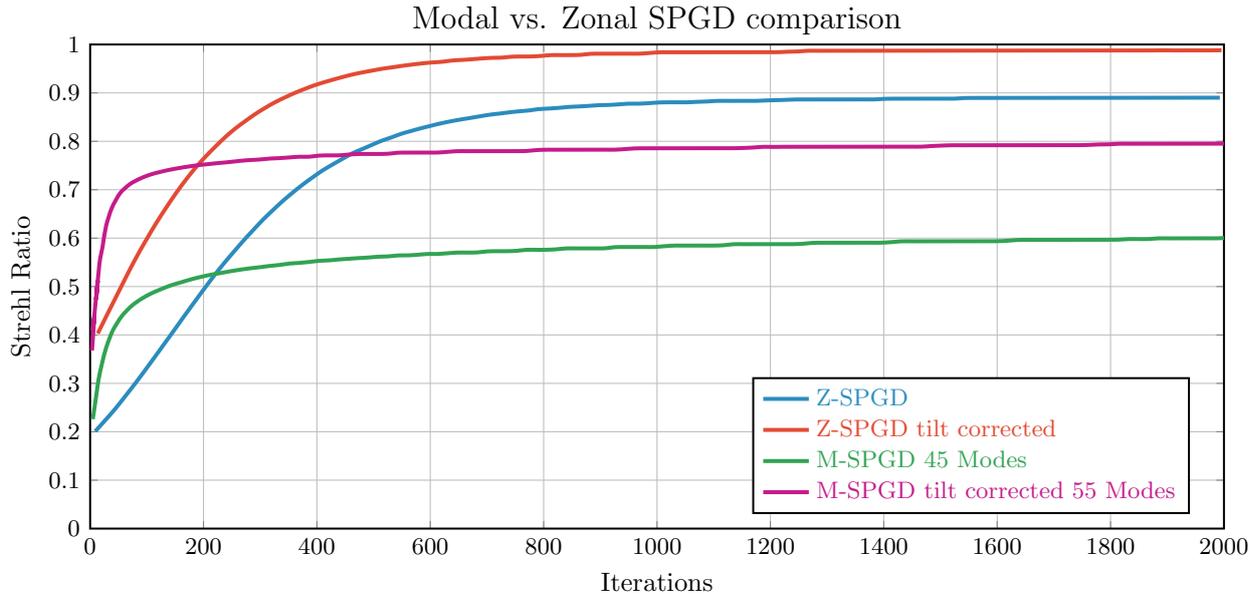


Figure 1: Comparison of performance of M- vs. Z-SPGD on static, simulated Kolmogorov phase-screens. Zernike basis was used for M-SPGD. Single-layer pupil-plane simulation was implemented using the subharmonics method.

at Fraunhofer IOSB.<sup>2</sup> In conventional SPGD, one randomly perturbs the actuators on a deformable mirror, and a beam quality metric is monitored for improvement. This can become a highly-dimensional problem for modern deformable mirrors with many actuators. To reduce the number of degrees of freedom one can project the actuator space onto an orthogonal modal basis, e.g. Zernike polynomials, and perturb the related mode coefficients rather than the actuator displacement. An additional advantage of this approach is that one can incorporate known turbulence statistics into the algorithm e.g. by optimizing gain of the algorithm for each mode. This method has been tested with success at Fraunhofer IOSB.<sup>3</sup>

In Figure 1, which is a result of static phase screen simulations, we show the main differences between modal and zonal SPGD approaches. It can be seen that M-SPGD achieves significantly lower Strehl ratio than Z-SPGD, but it converges much faster. The convergence can be increased when using fewer Zernike modes than the device actuator counts. This is inherent to the modal correction principle as any correction device is only capable of supporting a limited number of modes. Similar results to Figure 1 have been obtained in a laboratory environment.

### 3. SENSORLESS CORRECTION IN DYNAMIC TURBULENCE WITH KL FUNCTIONS

The modal KL basis minimizes the root-mean-square wavefront error in Kolmogorov turbulence as previously stated in Section 1. These functions are obtained naturally when solving the eigenvalue problem for the wavefront covariance function in Kolmogorov turbulence.<sup>4</sup> In this work we employ a different approach by diagonalizing Noll's covariance matrix and obtain numerical KL functions directly from the Zernike basis.<sup>5</sup> After limiting the number of synthesizing Zernike modes, in order to prevent diverging phase values and numerical precision errors, we are able to generate 397 accurate KL modes. In order to push the correction efficiency even further, we weight each mode with its individual eigenvalue, thus enabling the preservation of the Kolmogorov spectrum. Correction of 100 phase screens is executed for both weighted and unweighted M-SPGD configurations when operating in temporally evolving turbulence. Here we present the correction performance of the different mode configurations for single-layer phase screens, as well as the more accurate multi-layer turbulence simulations.

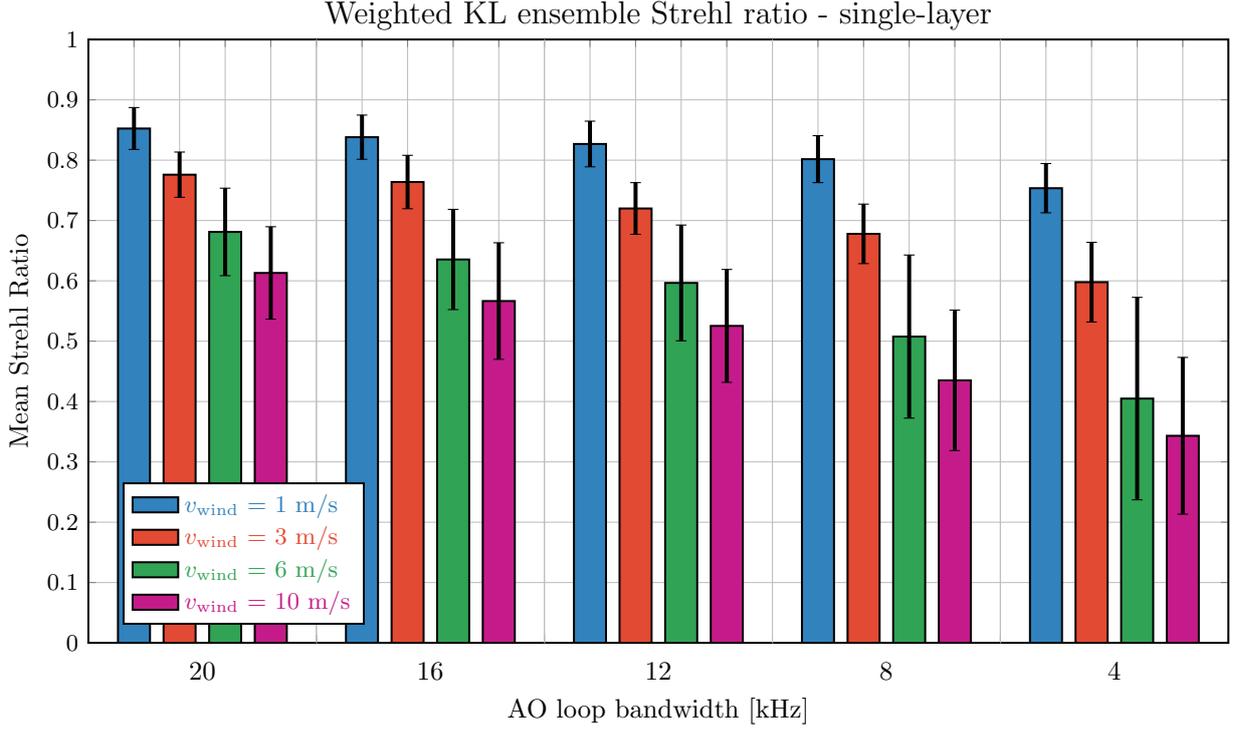


Figure 2: Ensemble Strehl ratio study in dynamic turbulence conditions for the optimized KL M-SPGD mode configuration. Here we compare the correction performance vs. AO loop bandwidth for different wind speeds  $v_{\text{wind}}$ . Kolmogorov phase screens with  $D/r_0 = 4$  were used in the single-layer turbulence simulation.

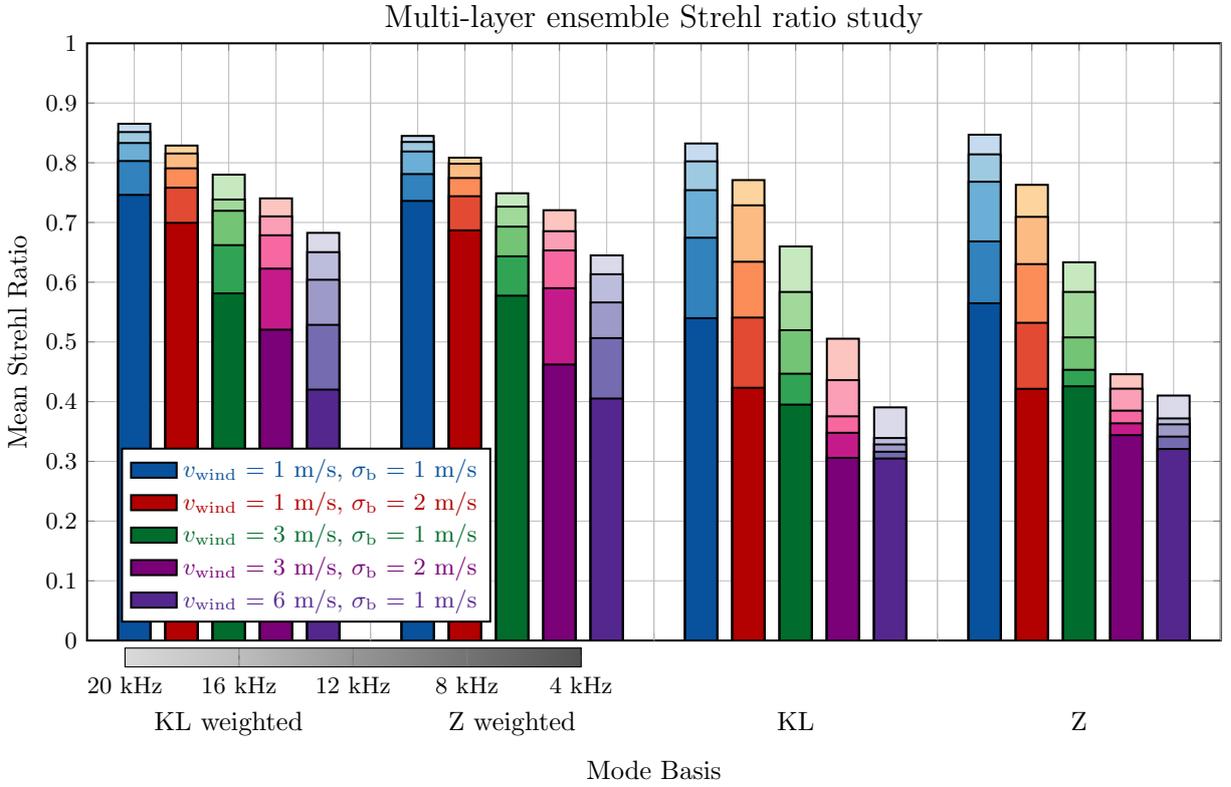


Figure 3: Multi-layer turbulence simulation with  $D/r_0 = 4$  in different wind speed  $v_{\text{wind}}$  and boiling  $\sigma_b$  scenarios for the four tested M-SPGD configurations. Here the saturation of the coloured bars depicts the provided correction bandwidth from 20 kHz (light) to 4 kHz (dark).

In Figure 2 an overview of all simulation results obtained with temporally evolving single-layer turbulence is shown, when the weighted KL basis is used. Here we simulated a finite bandwidth of a deformable mirror which cannot keep up with evolving turbulence for high wind speeds. Decreasing AO loop rates obviously decrease the correction performance and increase the variance of the Strehl ratio. For strong wind conditions, bandwidth requirements for achieving a particular Strehl ratio increase as well, leading to a large discrepancy in performance when comparing e.g. 20 kHz with 4 kHz loop rate at 10 m/s. Since 20 kHz loop rate is close to the achievable limit of currently available technology, it is worth highlighting the 50% average Strehl ratio obtained with a 12 kHz loop rate at 10 m/s, which can be provided by a wider range of deformable mirrors.

In Figure 3 we compare the correction performance of all M-SPGD configurations when applied to phase screens resulting from multi-layer turbulence simulation. Surprisingly, unweighted Zernike M-SPGD appears to be the best performing configuration for 1 m/s wind speed and weak boiling ( $\sigma_b = 1$  m/s), but quickly falls behind when the wind speed increases. In general both unweighted configurations perform better when the wind is weak and the correction speed is maximal, with Zernike M-SPGD outperforming the KL version. If, however, wind speed increases, or the provided correction bandwidth decreases, the weighted configurations clearly excel and weighted KL M-SPGD yields the best overall correction performance. Furthermore, we can observe that the efficiency of the weighted configurations at maximum loop rate decreases slower with increasing wind speed, while the performance of the equally weighted basis drops faster for wind speeds of 3 m/s and above. Finally, we can state that the constraint on accurate representation of the Kolmogorov spectrum enables the best utilization of the provided AO correction bandwidth.

#### 4. CONCLUSION

In this work an optimized implementation of the most popular gradient-based, sensorless wavefront correction method was presented. The advantages over the traditional correction method were highlighted and tested in realistic turbulence simulations. It was demonstrated that the weighted KL basis can give a result at least 5 % better than the Zernike basis for  $D/r_0 = 4$  in different wind speed and boiling scenarios.

#### ACKNOWLEDGMENTS

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