Super Resolved Imaging with Adaptive Optics: Supplemental Document

Robin Swanson[1,2] Esther Y. H. Lin[1] Masen Lamb[3,4] Suresh Sivanandam[1,2] Kiriakos N. Kutulakos[1]

[1] University of Toronto [2] Dunlap Institute for Astronomy & Astrophysics
[3] International Gemini Observatory [4] University of Victoria

8. The Shack-Hartmann Wavefront Sensor

Here we include additional details on the operation of the Shack-Hartmann Wavefront Sensor (SHWFS) in Fig. 9 and how a new flat is applied to the AO system in Fig. 10.

9. Simulation Settings

Simulation Parameters		Values
Telescope	Diameter	8 m
	Sampling Frequency	800 Hz
	WFS Order	16×16
	WFS Readout Noise	$\approx 0e^-$
	DM Order	17×17
	NGS Band	R
	NGS Magnitude	$\mathcal{U}(8, 16)$
	POL Gain	0.35
Three Layer Atmosphere	r_0	$\mathcal{N}(0.15, 0.02)$ cm
	Layers	3
	Altitudes	0 km 4 km 10 km
	Fractional r_0	0.70 0.25 0.05
	Wind Speeds	$\mathcal{N}(5, 2.5)$ km/s $\mathcal{N}(10, 5)$ km/s $\mathcal{N}(25, 10)$ km/s
	Wind Directions	$\mathcal{U}[0, 2\pi)$ rad
Science Camera	Science Camera Band	K
	Science Camera Noise	1% Max Value

Table 2. *Simulation parameters used for generating point spread functions and the training of our reconstruction methods.*

10. Experimental Calibration

To calibrate the modal power needed to match simulation and experiment, we simply induce a change to the flat with a single mode applied with different amounts of power. We can then compare the output from our forward model with varying amounts of the same mode and find the scalar value that best matches. This process can be repeated for any number of modes to ensure linearity across each mode and their power. As previously mentioned, the PWFS response is linear only about some working point and so this may be more important when using one compared to the SHWFS used in these experiments.

We also use test-time augmentation in order to renormalize the network and match the new experimental data distribution. We employed a modified version of the popular TENT [61] algorithm where only the batch-normalization scalers are updated using cropped areas of the input data and their bilinear-upsampled values as input/training pairs.

11. Additional Experimental Results

Here we include additional simulated results in Fig. 11 as well as the larger, uncropped experimental results from Sec. 6.1 in Fig. 12.

Corresponding author: robin@cs.toronto.edu
Project website: www.cs.toronto.edu/~robin/aosr

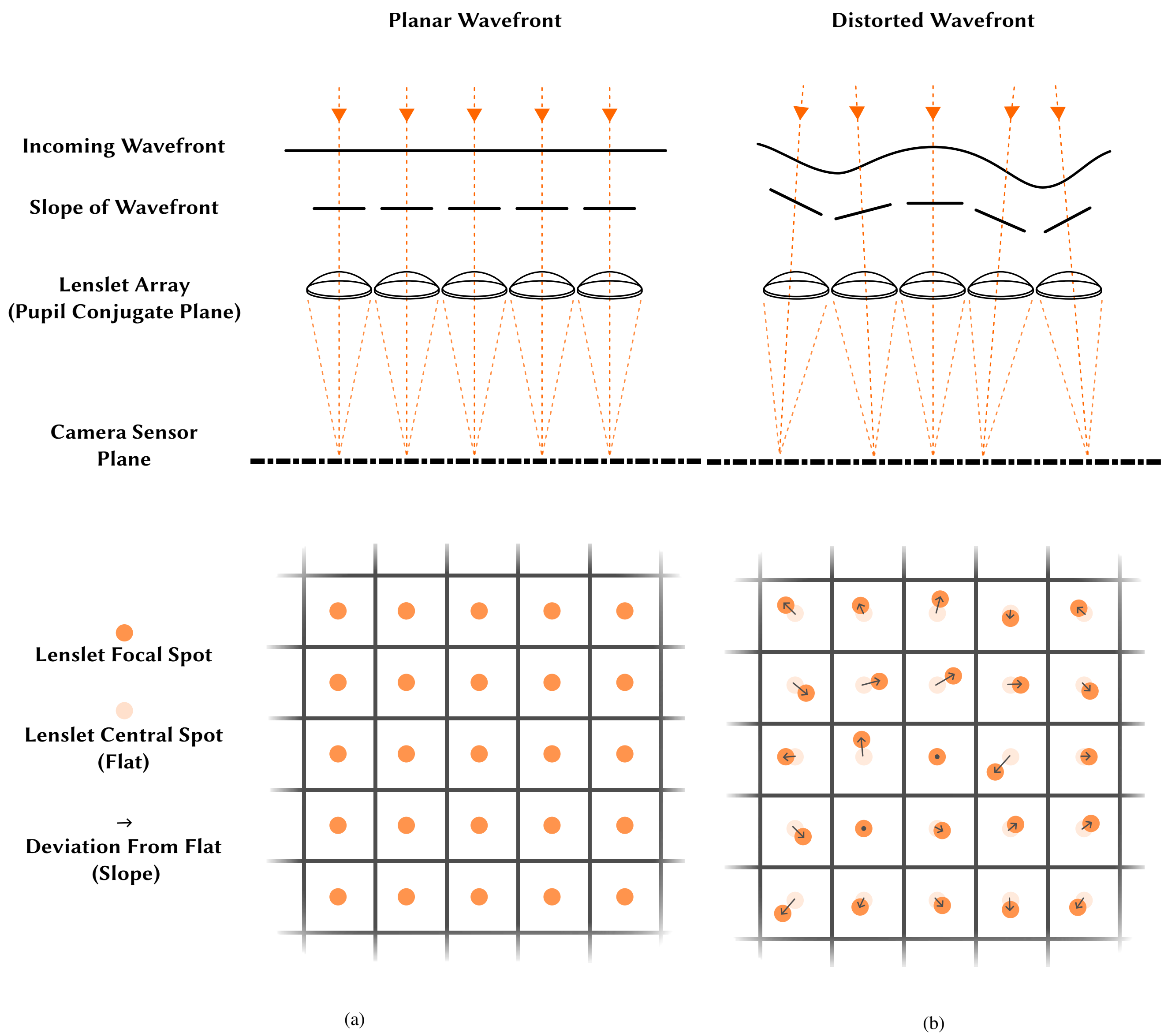

Figure 9. *Basic working principles of the Shack-Hartmann Wavefront Sensor.* If a perfectly flat wavefront reaches the SHWFS (a), each lenslet will focus the guide star as a point in the middle of its corresponding pixel grid. Any deviation to the wavefront (b) will result in an x and/or y shift in the sensor plane. These deviations directly correspond to the x and y "slope" (first derivative) of the wavefront.

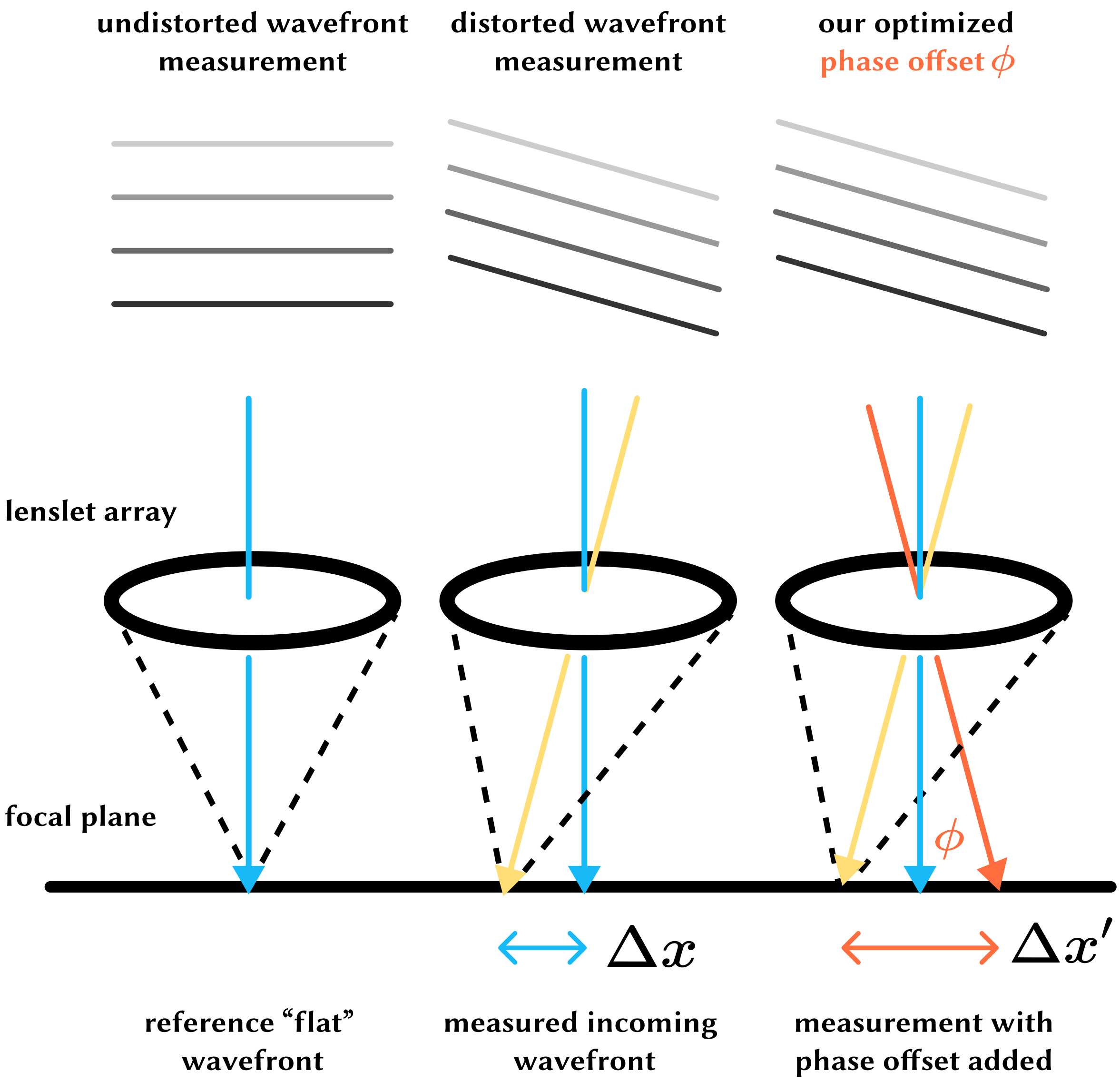

Figure 10. *The Shack-Hartmann Wavefront Sensor (SHWFS)*: Wavefront distortions can be measured by focusing incoming light to a point and measuring its (x,y) position with respect to a reference "flat" position. Using a grid of lenslets, the SHWFS can spatially sample the wavefront across the entire image sensor. This signal is sent to the control system which determines the ideal mirror positions to remove the deviations. Our method changes the reference positions, applying a small offset to each lenslet, inducing an optimized phase shift on the mirror.

Figure 11. *Simulated Scaled Results with 4 Sub-Exposures from the PIRM Dataset*

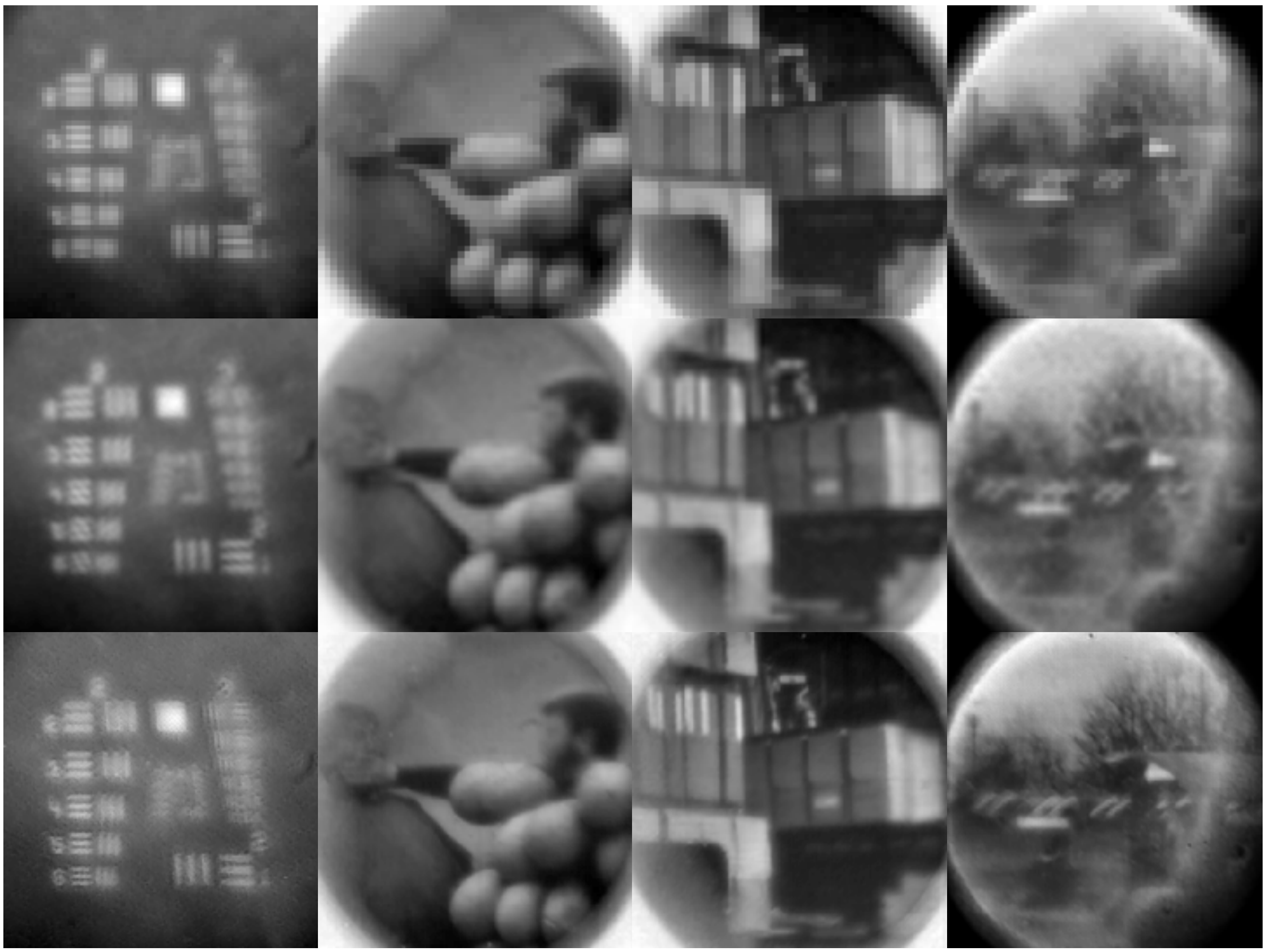

Figure 12. *Uncropped Experimental Results.*