# Focal Plane and non-linear Curvature Wavefront Sensing for High Contrast Coronagraphic Adaptive Optics Imaging

Olivier Guyon
Subaru Telescope
640 N. A'ohoku Pl.
Hilo, HI 96720
USA

**Abstract**
Wavefronts can be accurately estimated directly from either focal plane images or defocused pupil plane images, in schemes similar to phase diversity. These wavefront sensing techniques offers fundamental advantages over more traditional techniques for high contrast Adaptive Optics. When combined with a high performance coronagraph, these techniques enable efficient detection of exoplanets.

## 1. Focal plane wavefront sensing

### 1.1. Principle

A pupil plane deformable mirror can be controlled to nearly perfectly cancel a focal plane speckle field and therefore produce a “dark hole” in the focal plane, provided that the number of degrees of freedom (actuators) is sufficiently high (Malbet et al. 1995). Several algorithms have been proposed to perform this task (Guyon 2005, Borde & Traub 2006, Give'on 2007) provided that the speckle field complex amplitude is known, and the same algorithms can be used to produce arbitrary speckle fields in the focal plane. Such speckle fields can be created to measure the complex amplitude, since they will interfere with the original speckles in the focal plane.

Focal plane wavefront sensing (FPWFS) therefore utilizes focal plane image(s) to derive the incoming pupil plane wavefront. In this technique, which is a generalization of phase diversity wavefront sensing, several images are obtained, each with a known phase or amplitude aberration (diversity) introduced in the incoming wavefront. For optimal sensitivity, this diversity is tuned to the wavefront sensing requirements, and, in closed loop high contrast Adaptive Optics (AO), is a small phase signal which can be applied to the Deformable Mirror (DM) used for wavefront correction.

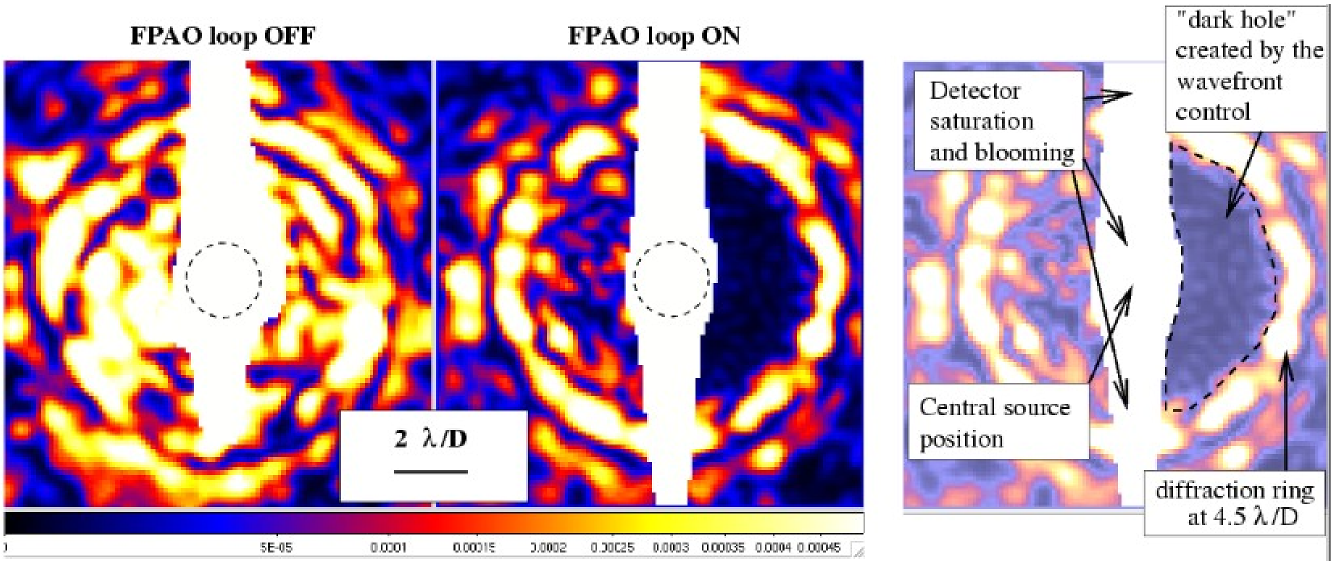


*Figure 1: Experimental result optained in the Subaru PIAA coronagraph laboratory testbed with Focal Plane Wavefront Sensing and control.*

### 1.2. Sensitivity in the small aberration regime

Comparison between wavefront sensing techniques shows that FPWFS offers in the small aberration regime fundamental advantages over more conventional wavefront sensing techniques for high-contrast adaptive optics:

(1) FPWFS offers excellent sensitivity (Guyon 2005). It transforms phase aberrations into intensity modulation with a greater efficiency than either Shack-Hartmann or Curvature wavefront sensors. This offers improved sensitivity, and therefore increased temporal bandwidth and imaging contrast for a fixed source brightness.

(2) FPWFS is naturally not prone to aliasing, since sensing is performed directly in the focal plane.

(3) FPWFS, if implemented at the science focal plane, does not suffer from non-common path errors. It is practical to perform FPWFS at the same wavelength as science imaging, in which case chromaticity terms are removed from the wavefront control error budget.

These features make FPWFS extremely attractive for high contrast "extreme-AO" imaging. The efficiency gain over more convential wavefront sensing schemes is then especially attractive since it leads to significant contrast improvements close to the optical axis, where there is the largest scientific return (exoplanets). The total number of pixel which need to be read for each wavefront sampling is similar to Shack-Hartmann requirements, and DM with sufficiently fast time response (MEMs) already exist. Fast reconstruction algorithms can be implemented with either "speckle nulling" schemes (different spatial frequencies are dealt with separately) or more comprehensive algorithms utilizing Fast Fourier Transform; both options could be implemented with current technologies to meet bandwidth requirements.

### 1.3. Considerations for use of FPWFS in Extreme-AO systems

FPWFS has been successfully tested in the laboratory in coronagraphic imaging by several teams, up to contrast levels approaching 1e-10 in the visible (Trauger & Traub, 2007). This performance level is much beyond what could be achieved in a ground-based telescope due to residual wavefront aberrations: a ~1e-5 contrast is a more realistic goal for such systems. FPWFS however holds the promise of delivering images largely free of "static" or "slow" speckles which are currently the main limitation to high contrast imaging.

The main limitations of FPWFS are:
(1)Chromaticity and field of view: In the focal plane, speckles are radially elongated in broadband. For a given spectral bandwidth, this limits the field of view over which the complex amplitude of speckles can be measured.
(2)Coherence requirements: For FPWFS to be able to measure the incoming wavefront, the coherence, within the time required to sense the wavevefront, needs to be high. The technique is poorly suited for faint targets.
These limitations are not a concern in "extreme-AO" where the source is relatively bright and little field of view is required.

## 2. Non-linear Curvature Wavefront Sensing

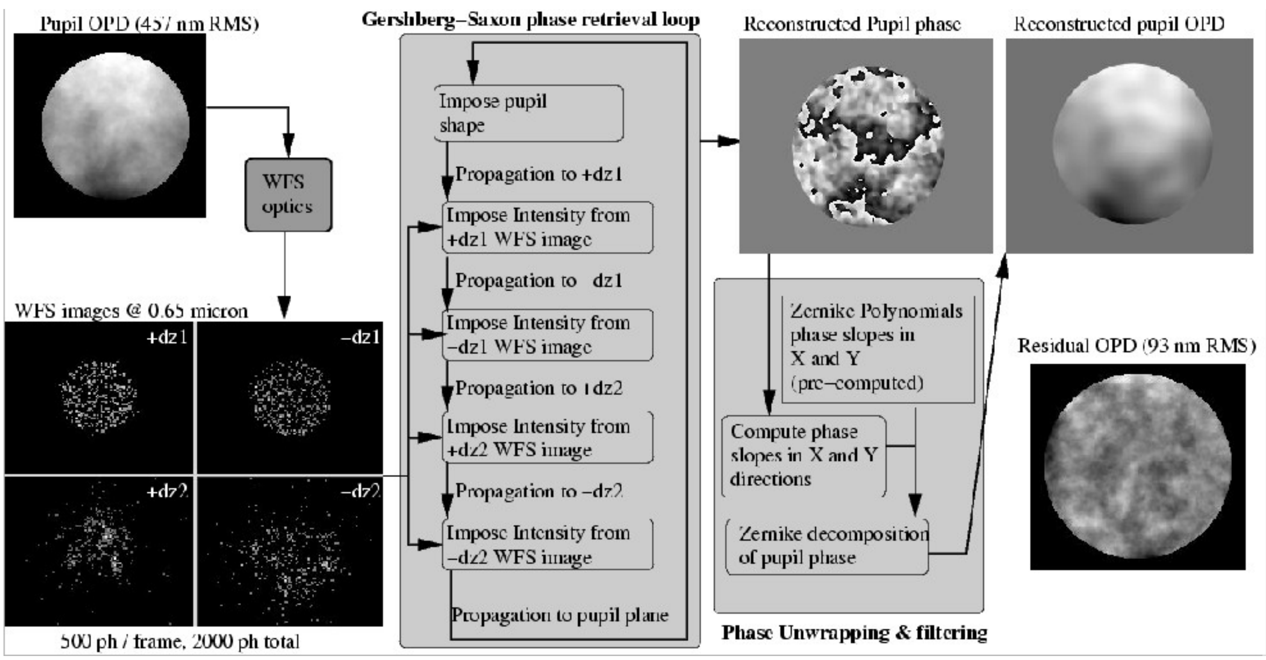

*Figure 2.: Wavefront reconstruction algorithm for non-linear curvature wavefront sensing. The 4 noisy defocused pupil images are shown in the lower left. An iterative non-linear algorithm is used to compute the wavefront phase with high sensitivitt, even with a moderate number of photons.*

These limitations are very efficiently overcome in non-linear Curvature wavefront sening (NLCWFS), a scheme derived from conventional curvature wavefront sensing. NLCWFS uses four defocused pupil images and a non-linear wavefront reconstruction scheme very similar to the reconstruction algorithms used in FPWFS. NLCWFS can be implemented easily with existing hardware, including beam splitters to achieve the required conjugation planes (more robust than the vibrating membrane technology currently used in conventional curvature wavefront sensors). Preliminary laboratory efforts and detailed closed-loop simulation support both the practical feasability and significant performance gain offered by this technique.

NLCWFS, since it is largely achromatic, can be used in broadband to offer high performance AO correction on mV~12 to 14 stars, and therefore nicely complements FPWFS (which is mainly geared at stars brighter than mV~12). NLCWFS is also much more robust, as it can operate even if the closed loop wavefront is far from offering diffraction limit. For bright stars, NLWFS could deliver extremely high contrast performance, and is therefore very suitable for Extreme-AO systems.

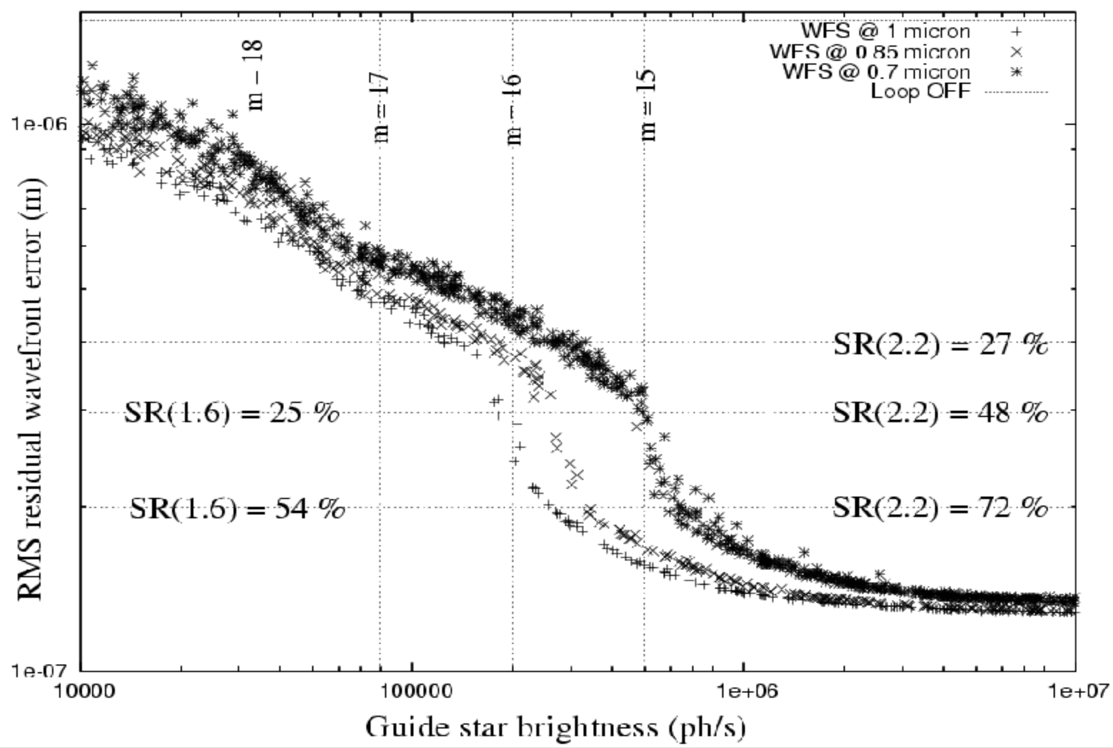


*Figure 3: Simulated closed loop performance of a non-linear curvature wavefront sensor-based AO system on a 8m telescope, as a function of guide star brightness.*

## 3. Conclusion

Both techniques presented in this paper are highly sensitive wavefront sensing schemes with excellent sensitivity to low order aberrations. Both techniques are extremely similar, as they are both non-linear phase diversity techniques. FPWFS is especially attractive because it operated directly in the focal plane, but it suffers from chromaticity and performs poorly if wavefront coherence is low. Non-linear CWFS is addressing both these issues, and it therefore seems that an optimal wavefront sensing architecture for high contrast imaging would be to first use non-linear CWFS in the visible to clean up the wavefront and then use

FPWFS for a finer correction.

**References**

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