Near-IR demonstration of adaptive nuller based on deformable mirror

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WHAT IS ADAPTIVE NULLING?

- An adaptive nuller is a compensator that will correct the intensity and phase of a beam at all wavelengths and each polarization across the nulling bandwidth.
- Adaptive nulling relaxes the requirements on the elements in the optical path and allows for deep robust nulling.

ABSTRACT

Deep, stable nulling of starlight requires careful control of the intensity and phases of the beams that are being combined. We are in the process of demonstrating a compensator based on a deformable mirror to correct the intensity and phase at each wavelength and polarization across the nulling bandwidth. We have demonstrated intensity and phase control at a single wavelength in the near-IR, and we are preparing to demonstrate control with our deformable mirror actuator in the near-IR. In parallel, we are also preparing a demonstration in the mid-IR.

INTRODUCTION

Adaptive nulling is a quasi-static correction to phase and intensity for each polarization (S & P) and at all wavelengths independently. Figure 1 is a diagram of our approach to this problem. The uncorrected beam enters at the upper left, passes through a pupil stop, and then through a birefringent element that splits the polarization states by a small angle. The light is then dispersed by a prism and is incident on a parabolic mirror that focuses the collimated beams onto a deformable mirror (DM). At this point the input light is spread into two focused lines, one for each polarization state, dispersed by wavelength. After reflection from the DM, the light is re-collimated by the parabolic mirror, de-dispersed and the two polarization states are re-combined before passing through the exit pupil stop.

The DM allows independent control of the intensity and phase for each polarization and wavelength as illustrated in Fig. 2. Piston of the DM adjusts the phase of the output beam (Figure 2-left); changing the local slope of the DM at the focal point introduces a shear of the outgoing collimated beam, which is then converted into a reduction of intensity by the exit pupil stop (Figure 2-right). The piston and local slope are adjusted independently for the different wavelengths and polarization.

This compensator is part of a control system for balancing the intensities and phases of the incoming beams. Also needed is a sensor for detecting the imbalances and an algorithm to make the appropriate adjustment at the DM. Since we are correcting for imbalances across the science band the sensor must operate over the same range of wavelengths. We intend to measure the intensities and phases of the different beams at regular intervals of time. This will require that the science observing be interrupted and the intensities will be obtained by measuring the photon rates for pairs of beams. Although this method will reduce the time available for science observations, the advantages of this method are there are no additional sensors needed, there are no uncommon path effects, and the intensity and phase can be measured separately.

#	Requirement	mid IR	Proof of Concept
1	Wavelength range of operation	7 – 17 µm	BW > 100 nm
2	Metrology wavelength	0.5 – 2 µm	N/A
3	# independent spectral degrees of freedom	> 5 (20)	> 5 (10)
4	# independent polarization states	2	2
5	Null depth across the band	$< 10^{-5}$	$< 2 \cdot 10^{-2}$
6	intensity correction range	> 5%	> 50%
7	intensity precision / stability (1 σ)	< 0.1%	< 5%
8	Phase correction range	> 2 µm	> 1 µm
9	Phase precision / stability (1 σ)	< 1 nm	< 15 nm
10	Throughput reduction	< 20 %	< 50 %
11	Polarization isolation	> 50 dB	> 20 dB

Table 1: Requirements for the mid-IR and proof-of-concept experiments

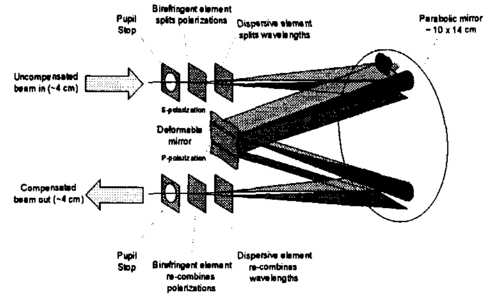

Figure 1: Parallel high-order compensator design based on a deformable mirror actuator

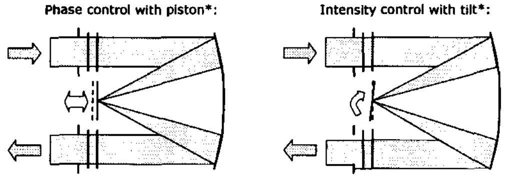

Figure 2: Phase and intensity control. *Side view, single wavelength and polarization

PROOF OF CONCEPT EXPERIMENT

While the adaptive nuller will be required to work in the mid-IR region from 7 to 17 µm, the optics required to do a full demonstration at these wavelengths can take a long time to be delivered. We decided to first conduct a proof-of-concept experiment in the near-IR centered around 850nm. This demonstration could be started quickly due to the availability of optical components for 850nm while we are in the process or procuring the mid-IR parts. The differences in requirements for the proof-of-concept and full mid-IR demonstration are given in table 1.

Due to the long development time for the DM electronics, the first tests of the proof-of-concept experiment were done with a PZT actuated flat mirror. By using a single flat mirror with tip and piston, we can simulate the adaptive nuller at one wavelength. The schematic for this experiment is shown in figure 3. The experiment is design with two beam paths set up as in figure 1. The first beam path has the actuated mirror, and the second beam path has a fixed mirror to act as a reference. A delay line allows us to equalize the beam paths, or introduce a small offset between the two. The two beam paths are combined and the signal is detected on a fiber coupled spectrometer.

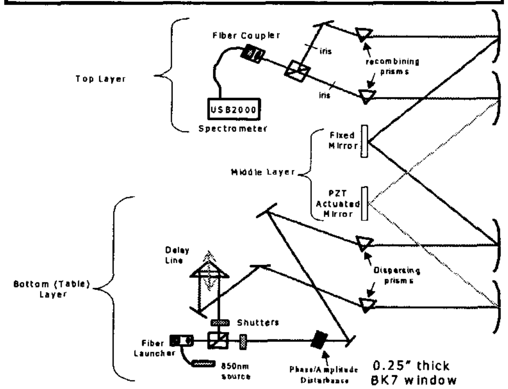

Figure 3: Schematic of the proof-of-concept adaptive nuller.

INTENSITY CORRECTION

We measure the spectrum of each beam by shuttering the other beam off. We then use the difference divided by the sum of the two spectrums as a measure of the intensity imbalance. Once the coupling loss vs. tip/tilt angle is calibrated we can apply the appropriate control signals to match the intensities at a particular wavelength. Figure 4 shows the intensity imbalance before and after compensation with the tip/tilt mirror for 850 nm.

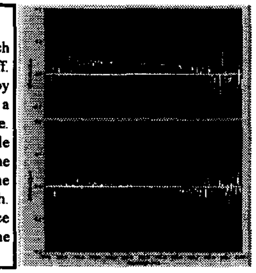

Figure 4: Intensity correction.

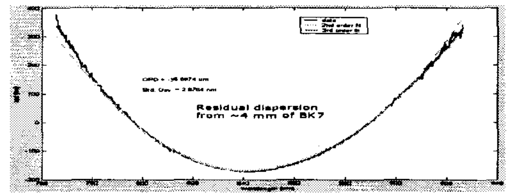

Figure 5: Residual phase measured with BK7 window in one beam arm. The calculated residual from ~4 mm of BK7 matches well with the data.

PHASE EXTRACTION

A variant of the Hilbert transform method is used as a quick and accurate means of determining the phase difference between the two beams as a function of wavelength. A known optical path length offset introduced using the separate delay line and the recorded spectrum is put through a fast Fourier transform, then the negative frequencies are filtered, and finally the filtered signal is inverse fast Fourier transformed to extract the phase. The linear part to the extracted phase tells us the offset of the delay line from the null, and the residual is or phase to be corrected. Figure 5 shows this residual with a BK7 window added to one beam path. The calculated residual from ~4mm of BK7 matches very well with the measured phase error.

Picture of the deformable mirror in the adaptive nuller proof-of-concept experiment. The small gold square at the center is the mirror membrane. The prisms to disperse and recombine the wavelengths can be seen on the left.

FUTURE WORK

We now have the DM in our proof-of concept experiment (picture above) and are in the process of building up our software to complete the proof-of-concept demonstration. The DM has 140 actuators and a 3mm x 3mm continuous gold membrane. The dispersion from the prisms put the light across a line of 10 actuators.

Our goal is to complete the proof-of-concept experiment by the end of this fiscal year. We have also already made significant progress on a mid-IR source and spectrometer and will then build up the mid-IR demonstration in FY'05, and finally we plan to integrate our adaptive nuller with a TPF nulling testbed in FY'06.

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

FURTHER INFORMATION

1. O. P. Lay and S. Dubovitsky, "Nulling interferometers: the importance of systematic errors and the X-Array configuration", this volume
2. Lay, O. P., Jeganathan, M., Peters, R. D., "Adaptive Nulling: A new tool for interferometric planet detection", 2003, ESA SP-539
3. Lay, O. P., Jeganathan, M., Peters, R. D., "Adaptive nulling: a new enabling technology for interferometric exo-planet detection", 2003, Proc. SPIE 5170