Adaptive nulling for the Terrestrial Planet Finder Interferometer

Robert D. Peters*, Oliver P. Lay, Akiko Hirai, Muthu Jeganathan
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena CA 91109

ABSTRACT

Deep, stable starlight nulls are needed for the direct detection of Earth-like planets and require careful control of the intensity and phases of the beams that are being combined. We are testing a novel compensator based on a deformable mirror to correct the intensity and phase at each wavelength and polarization across the nulling bandwidth. We have successfully demonstrated intensity and phase control using a deformable mirror across a 100nm wide band in the near-IR, and are in the process of conducting experiments in the mid-IR wavelengths. This paper covers the current results and in the mid-IR.

Keywords: Nulling interferometry, planet detection, deformable mirror, dispersion compensator, nulling, amplitude and phase correction, adaptive nuller

1. INTRODUCTION

Direct detection of Earth like planets around nearby stars requires a combination of starlight suppression and high angular resolution (< 0.1 arcsec). The technique of nulling interferometry[1] has been proposed at mid-infrared wavelengths for both the European Darwin mission[2] and NASA's Terrestrial Planet Finder - Interferometer (TPF-I)[3]. The latter is also developing a visible coronagraph architecture (TPF-C).

For the case of the mid-IR interferometer, the light from the star must be suppressed by a factor of 10^5 or more over the bandwidth of interest, currently 7 - 17 μm. All designs under consideration include a single-mode spatial filter (SMSF) through which the combined light is passed before being detected. The wavefront from the star is incident on the collecting apertures of the instrument and delivered by the respective beam trains to a central beam combiner that couples the light into the SMSF. With just a single mode for each polarization state, the problem of nulling the on-axis light is simplified. The electric field within the SMSF is the vector sum of the electric field contributions from each collecting aperture. The starlight is nulled when the electric fields in the SMSF sum to zero requiring specific combinations of the electric field amplitude and phase.

Analysis has shown[4] that the stability of the null that drives the requirements on the accuracy of the amplitude and phase control. The detection of an earth-like planet around a sun-like star at 15 pc requires that the electric field amplitudes are matched to within ~0.1% (intensities equal to within 0.2%) and the phase is controlled to ~ 1mrad (1.5 nm at a wavelength of 10 μm) simultaneously at all wavelengths and both polarization states. A number of effects can perturb the amplitude coupling into the SMSF including reflectivity, beam shear, and wavefront aberration: tilt, focus, astigmatism, coma, etc. The phase is obviously impacted by changes in the optical path but also by birefringence and dispersion introduced by the ~ 30 optical elements present in each beam train.

One approach to architecting the instrument is to attempt to make the beam trains as identical as possible by applying very tight requirements to the alignment and specification of the optical elements. Error budgeting shows that the tolerances involved are prohibitive. Our solution is a technique that we call Adaptive Nulling in which a compensator is included in each beam train to correct for imbalances in the amplitude and phase independently at each wavelength and polarization[5,6].

In this paper, we present the current progress towards a demonstration of a DM-based compensator in the mid-IR. A 12x12 MEMS deformable mirror (DM) array was used to adjust the phase and intensity. A simple interferometer with an adjustable delay line was been built to measure phase and amplitude asymmetries and demonstrate nulling. In section 2,

* Robert.D.Peters@jpl.nasa.gov; phone 1 818 393-6263

we will present an overview of the Adaptive Nuller concept, and then in section 3 we will present progress on the mid-IR experiment. Finally, in section 4 we will discuss the ongoing mid-IR work.

2. CONCEPT OVERVIEW

Adaptive nulling is a quasi-static correction to compensate sources of asymmetry that are not changing on short timescales. The correction algorithm will depend on the nature of the sensor and will need to account for any cross-coupling effects between the amplitude and phase control.

The compensator should ideally act independently on the horizontal and vertical polarization states and support a null depth of 10^{-5}. The null stability requirement leads to the amplitude and phase stability requirements of 0.1% and 1 nm respectively. A maximum amplitude correction of 5% gives a dynamic range of 50 for amplitude and the 2 µm phase correction range corresponds to a phase of 0.6 radians at a wavelength of 20 µm. The compensator should have high throughput and it should not mix the polarization states at more than the 10^{-5} level.

Table 1 illustrates the requirements we have adopted for the laboratory demonstration compared to the flight requirements. The laboratory test is slightly relaxed from the flight requirements due to the SMSF, detector and light source used. However, the requirements are close enough that a successful demonstration in the lab will indicate that there is not likely to be something preventing extending the performance to the flight requirement levels.

#	Requirement	mid IR	Flight
1	Wavelength range of operation	8 – 12 µm	7-17µm
2	Metrology wavelength	1.319 µm	0.5 - 2 µm
3	# independent spectral degrees of freedom	> 5	> 5
4	# independent polarization states	1	2
5	Null depth across the band	$< 10^{-5}$	$< 10^{-5}$
6	Amplitude correction range	> 5%	> 5%
7	Amplitude precision / stability (1 σ)	< 0.12%	< 0.1%
8	Phase correction range	> 1 µm	> 2 µm
9	Phase precision / stability (1 σ)	< 5 nm	< 1 nm
10	Throughput reduction	< 50 %	< 50 %
11	Polarization isolation	NA	> 50 dB

Table 1. Performance requirements for adaptive nulling compensator for the mid-IR demonstration and flight.

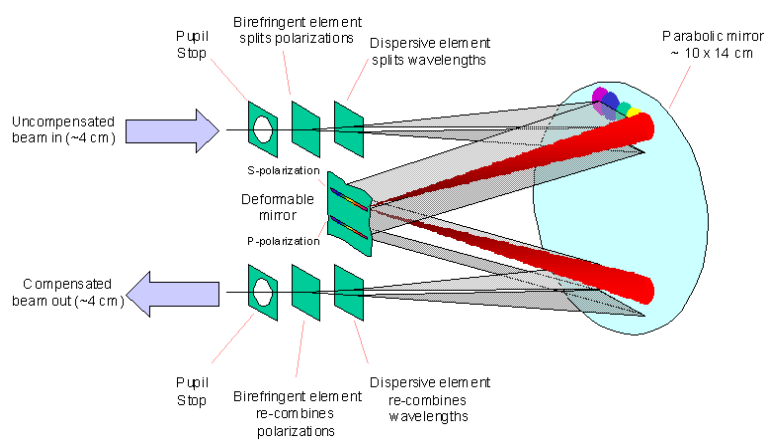

Fig. 1. Parallel, high-order compensator design using a DM to control amplitude and phase.

Our approach to implementing a compensator is to split the light into the different wavelength and polarization states and operate on them in parallel before recombining them. In principle, it is then possible to implement a high order compensator (many spectral degrees of freedom) without a large impact on throughput. Such a compensator is illustrated

in Fig. 1. 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 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.

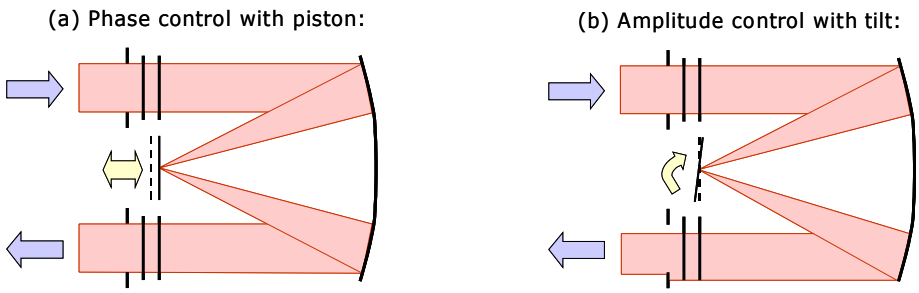

Fig. 2. a) Side view of phase control with a single wavelength channel on the DM using piston. b) Amplitude control of a single wavelength channel on the DM using tilt.

The DM allows independent control of the amplitude and phase for each polarization and wavelength as illustrated in Fig. 2. Piston of the DM adjusts the phase of the output beam (Fig. 2a); 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 amplitude by the exit pupil stop (Fig. 2b). 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 amplitudes 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. Although there are several approaches that may be used[5,6], we intend to measure the amplitudes and phases of the different beams at regular intervals of time. This will require that the science observing be interrupted and the amplitudes 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 amplitude and phase can be measured separately.

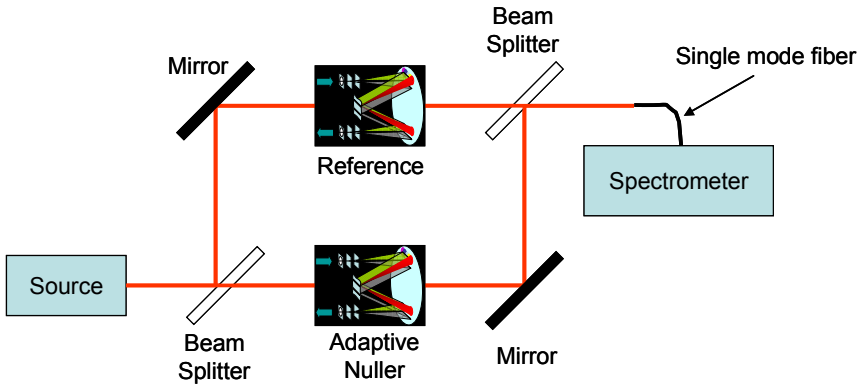

Fig 3: Schematic layout for the mid-IR demonstration. The adaptive nuller is in one arm, and a "reference" adaptive nuller in the other arm. The reference has all the same optics as the adaptive nuller with the exception of a fixed mirror in place of the deformable mirror.

3. MID-IR DEMONSTRATION

Fig. 3 shows the simplified schematic for the mid-IR demonstration. The source described below generates the light, which is sent through a Mach-Zehnder type interferometer. In one arm, we have the adaptive nuller as described above. In the other arm, we have a copy of the adaptive nuller with a fixed reference mirror in place of the deformable mirror. There is also a delay line (not shown) consisting of a large retro-reflector with two levels of actuation. The course actuation is accomplished by a computer controlled linear stage with 50 mm of travel and 0.1 µm resolution. The fine level is done with a PZT actuator, which is coupled with a simple metrology system to take out air-path variations. Finally, the output is recombined and sent through a SMSF before being detected by our spectrometer.

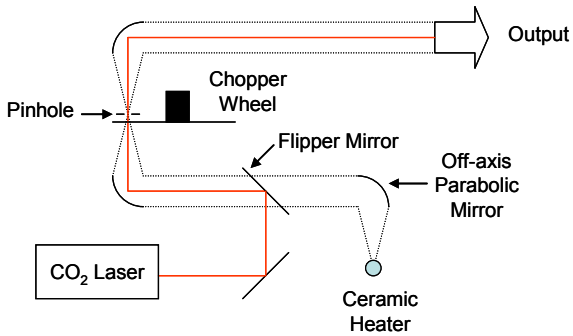

Fig 4: Schematic of the mid-IR source. Either the CO_2 laser or broadband output may be selected by the flipper mirror.

A more detailed schematic of the source is shown in figure 4. It consists of a ceramic heater, which is collimated by off-axis parabolas. A small CO_2 laser is co-aligned with the white light source to assist in alignment and calibration of the spectrometer. The source also contains a chopper wheel, which allows lock-in detection in the spectrometer. A small pinhole at the focus between two off-axis parabolas also provides some spatial filtering.

In the adaptive nuller wavelength separation and recombination was accomplished with zinc selenide (ZnSe) wedges with an angle of 7 degrees. The setup was modeled in Zemax, which predicted the wavelengths would be spread across eight pixels of the DM. Polarization separation using a cadmium selenide Wollaston prism was tested separately.

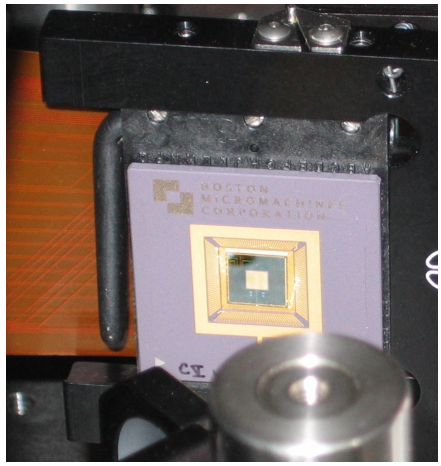

Fig. 5: Picture of a MEMS DM used in the demonstration. The small square in the middle is the 3mm x 3mm mirror surface.

The adaptive nuller arm contains the DM as shown in figure 5. The actuator we chose was a 3mm square 140 pixel MEMS DM from Boston Micromachines. The DM consists of a thin gold coated membrane that is deformed with electrostatic actuators driven by a custom 12 bit resolution digital high voltage controller system. Total stroke of any one actuator is approximately two micrometers.

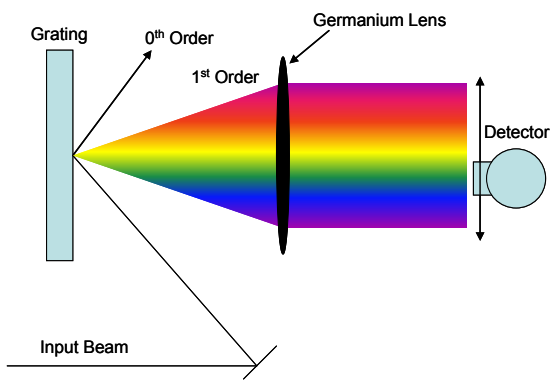

Fig. 6: Schematic of the spectrometer. The detector is translated by a computer controlled translation stage.

The output of the interferometer is coupled into a SMSF obtained as part of a separate development of TPF-I. The signal is then detected by our spectrometer as shown in figure 6. The spectrometer takes the output of the SMSF and disperses the wavelengths with a reflective grating with 60 grooves per millimeter blazed for 10μm. The 1st order reflection is focused by a germanium lens and detected by a mercury-cadmium-telluride detector with a 0.1mm square aperture. This detector is scanned through the spectrum with the same type of linear actuator used for the delay line with 50mm of travel and 0.1 μm resolution. This configuration allows us to scan the 8 to 12 μm wavelengths within the range of the linear stage. The output of the spectrometer is detected intensity versus position. The known wavelengths from the CO_2 laser can be used to calibrate the spectrometer, and software converts the position into wavelength based on the equation

$$x = f \times \tan\{\arcsin[\lambda \times 60 \times 10^{-3} - \sin(\alpha)] - \arcsin[60 \times 10^{-2} - \sin(\alpha)]\} + x_{10}$$

where x is the position of the focus, f is the focal length of the lens, λ is the wavelength, α is the grating incident angle and x_{10} is the position of the 10 μm light.

To create a null we combine the adaptive compensator and the reference arm with a pi phase shift between the two arms. A ZnSe window can be added to one arm to introduce lambda dependant amplitude and phase errors for us to correct. A PC running LabVIEW was used to control the source, delay line, shutters and DM, as well as take and process the data.

To measure the amplitude error, a spectrum of each beam is taken 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. A positive intensity

imbalance indicates more light in the adaptive nuller arm, while a negative imbalance indicates more light in the reference arm. As the adaptive nuller can only decrease the light coupled into the SMSF, we must begin with a positive imbalance. To force the imbalance to be positive, we can use an adjustable iris on the reference arm to decrease the light. Once the imbalance is positive, and the coupling loss vs. tip/tilt angle is calibrated we can apply the appropriate control signals to match the intensities at each particular wavelength. Figure 6 shows the intensity imbalance before and after compensation. The corrected intensity imbalance is <0.06% RMS while the uncorrected imbalance is >1% RMS.

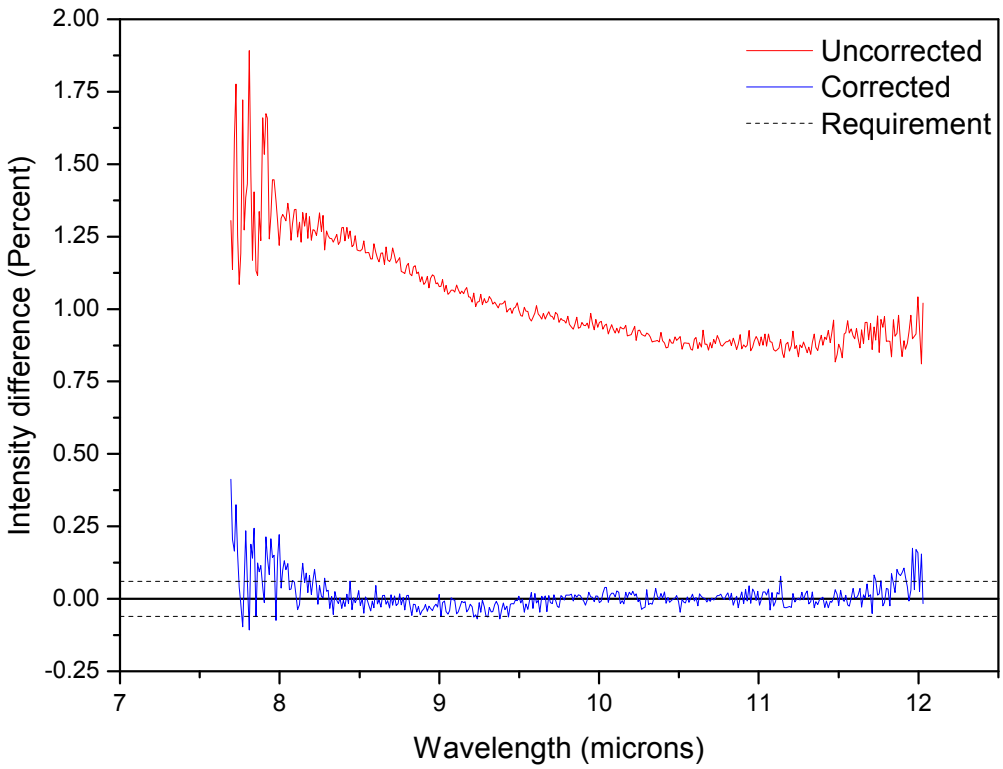

Fig. 6: Correction of intensity dispersion. The upper plot is before correction, the plot near zero is after correction. The dashed lines indicate our minimum requirement for correction as indicated in table 1.

4. FUTURE WORK

This demonstration is scheduled to be completed by the end of September 2006. We have demonstrated the amplitude correction within the requirements, however, we still need to implement phase correction and measure the corresponding null depth.

Phase dispersion is measured with a variant of the Hilbert transform[7]. This measurement requires the delay line be set a distance away from the null to produce spectral fringes. We measure the spectral fringes with the spectrometer and output of our algorithm is a phase error versus wavelength, which is then used to calculate the appropriate piston settings for each actuator on the DM. This method has worked very well in previous near-IR experiments[8]; however, it requires the optical path remain stable as the spectrum is read. Our single-pixel scanning spectrometer requires 45 seconds to complete a scan, so to stabilize the path we are currently working to implement an optical metrology system at 1.319 µm.

Some cross coupling is also expected in the form of amplitude correction causing phase dispersion, and vise versa. However, in the near-IR we found that if we iterate between phase and amplitude correction, the two corrections converge after 3 to 5 iterations. The cross coupling may also be decreased by choosing an output aperture that is

elliptical instead of circular. This would make the shear in the phase correction direction less sensitive than the shear in the intensity correction direction.

5. SUMMARY

We are continuing our development in the mid-IR of a system that confirms a DM can be used to correct both the amplitude and phase dispersion of the electric field coupling into a SMSF. We have shown that the amplitude can be corrected within the requirements needed for a 10^{-5} null depth. We are currently working to correct the phase and measure the null improvement. We expect to have full results by the end of September 2006. Once complete, this compensator will ease the tight requirements on symmetry; such a compensator also enables more flexibility in the optical design and the use of much simpler, asymmetric nulling beam combiners.

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