LABORATORY PERFORMANCE OF THE KECK INTERFEROMETER NULLING BEAM COMBINER

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ABSTRACT

Now that regular visibility squared measurements are routinely achieved, mid-infrared nulling is the next observing mode to be implemented on the Keck Interferometer (KI). This mode’s main objective is the characterization of exo-zodiacal dust disks around nearby main sequence stars (Kuchner & Serabyn, 2003) in support of the TPF space mission. Keck Nuller also shares numerous characteristics with an interferometric TPF, and will then serve as a technical precursor for this mission. We report here the results obtained in the laboratory with the KI mid-IR nulling beam combiner, which is based on a dual polarization Modified Mach Zender (MMZ) combiner (Serabyn & Colavita, 2001), and dispersion compensation and achromatic nulling through zinc-selenide (ZnSe) dielectric plates (Koresko et al., 2002). Best broad-band dual polarization transient rejection levels obtained so far on thermal sources range from 7500:1 over a 29% bandwidth (FWHM from 9.20 to 12.35 microns) to 17000:1 with an 18% bandwidth (FWHM from 9.70 to 11.65 microns). These rejections are basically one order of magnitude better than the limit set by the stellar finite angular size, which is about 1000:1 at 10 microns for a 1 mas diameter star observed with KI 80 m baseline. These results then validate the optical concept chosen for the nulling back-end, which now needs to be properly integrated with the mid-IR nulling camera and the KI beam train.

Key words: nulling, interferometry, mid-infrared.

1. THE KECK INTERFEROMETER NULLING BEAM COMBINER

Figures 1 and 2 detail the KI nulling beam combination procedure. Two subapertures (“left” and “right” subapertures) are defined on each Keck telescope primary mirror. Sub-apertures are then nulled pairwise through one of two strictly identical sub-nullers (left and right sub-nullers). The two sub-nullers being identical, we will arbitrarily concentrate on the left one (figure 2).

Following the stellar path, the KI beam train and Keck AO systems provide two stabilized (in direction and K band opd) beams that enter the left nuller via two pick-off mirrors. Each beam goes through a pair of ZnSe prisms, which are translated to provide an adjustable optical path through glass. In addition to producing a static quasi achromatic null in the laboratory, this system will also be used on the sky as an Atmospheric Dispersion Compensator (ADC), providing active compensation of the time variable water vapor differential dispersion between the two beams to be nulled (Koresko et al., 2002). After going through the ADC, the two beams are recombined via a Modified Mach Zender (Serabyn & Colavita, 2001), which produces two nulled and two constructive outputs. Similarly, the right nuller produces two nulled and two constructive outputs. The resid-
Figure 2. Optical layout of the Ki nulling beam combiner. Note that the functions of achromatic phase shifting and beam combination are separate. Phase shifting occurs at the ADC (Atmospheric Dispersion Compensator) level, whereas beam combination occurs in the MMZ (Modified Mach Zender). The ADC uses wedged ZnSe plates.

Figure 3. Picture of the nulling beam combiner. One of the ADC's is visible to the right, with its 4 ZnSe prisms.

Figure 4. Autocollimation set-up used for the nulling beam combiner characterization.

from one of the nulled outputs. The cross-combiner of figure 2 is bypassed in order to increase the sensitivity of the experiment. The MMZ is first used to define two spatially distinct beams. The longitudinal position of the flat mirrors and the transverse position of the ADC prisms can be adjusted so that after their round trip through the ADC, the two beams come back with a quasi-achromatic \( \pi \) phase shift (see section 2 for more details). On the way back from the flat mirrors, the MMZ is used this time as a purely destructive beam combiner for the beams undergoing both a reflection and a transmission through the two beam splitters. The accessible nulled output is then detected via a single-pixel 77K cooled MCT detector, linked to a lock-in amplifier for demodulation of the signal.

2. A FEW PRACTICAL ISSUES

- Tip/Tilt adjustment. We did not find any real difficulties in zeroing the differential tip/tilt between the beams. An imaging mid-IR camera allows one to grossly "fluff out" the tilt fringes between the two beams. Final adjustment is done using PZTs to finely control the mirror positions.

- Shear adjustment. This is more tedious. Any residual shear will have three effects. Only the first one is an issue for sky observations, while the other two are more pronounced for the internal alignment/autocollimation set-up described above. Residual shear -even on a point-like source- first causes some leaks coming from the outer non overlapping region of the beams. This can be fixed to some extent by using masks or undersized optics, at the expense of sensitivity. A second effect is that residual shear will impact the overlap of beam profiles, which matters if the common source used to generate both beams has some spatial amplitude structure (e.g. gaussian laser beams). The third effect appears because of the finite source size. Although we use a
solution is obviously an even function of the differential glass thickness.

Figure 5. Best null achievable for a given differential glass thickness, adjusting the opd in air. Case of a 29% bandwidth filter (FWHM=9.20 to 12.35 microns), ADC made of a single glass (ZnSe). The solution is obviously an even function of the differential glass thickness.

A wavefront division scheme for the nuller internal alignment, any residual shear will partially resolve the white light source and limit the accessible nulls. On the sky, the star will be primarily resolved by the baseline between the KI telescopes, which will greatly dominate the effect of residual shear at the beam combiner level.

- Dispersion correction. It can be shown -both theoretically and experimentally-, that for any infrared bandpass and differential glass thickness introduced by the ADC, there is an optical path difference (opd) that minimizes the interferometric signal.

In addition, the curve giving the null level versus differential glass thickness is a cycloid with a set of local periodic minima. As an illustration, Figure 5 represents the theoretical curve obtained for a source with a white spectrum seen through the 29% bandwidth filter used in our laboratory, for ZnSe dielectric plates. The best theoretical rejection, strictly limited by residual dispersion across the 9.20-12.35 micron band is on the order of 20000:1. As expected, each local minimum corresponds to a very symmetric fringe pattern, which is observed experimentally as well. Local minima are regularly spaced and degrade rapidly as one goes off the best minimum - the closest to zero differential glass thickness.

- Spatial filtering. No single-mode filter is used -there is none available yet in the required wavelength range-, which is another challenge in getting good nulls. First the incoming beam is not strictly single-mode, so it can be resolved spatially (issues of residual shear, source size). Secondly null levels cannot be improved using a single-mode waveguide in the final focal plane, which is known to greatly reduce the effect of scattered light and amplitude profile mismatch on null depth (Mennesson et al., 2002). Yet the MCT single pixel is 30 microns large, and can then be considered as a spatial filter. This simple spatial filtering was enough to get to $10^4:1$ nulls in the mid-IR -where wavefront requirements are relaxed. In contrast, such levels of rejection in the visible could only be reached when using single-mode fibers (Serabyn et al., 1999; Wallace et al., 2000).

- Null levels measurements. The lock-in amplifier measures the amplitude of a modulated signal, at a reference phase and frequency. We then had to carefully baffle the optics to get rid of any back-reflection/emission that would cause a null floor level. At null the white light source signal is so low that it is comparable to the nitrogen cooled MCT noise level. Since the MCT noise has a random phase at the reference frequency, the lock-in may occasionally give negative null levels if only one of the quadrature components is measured, e.g. when the noise is in antiphase with your quadrature signal. To eliminate this spurious effect, we instead recorded the absolute signal at the reference chopping frequency regardless of its phase. To be on the safe side, we then added the maximum absolute excursion of the noise, which provides a very conservative estimate for the null level.

3. EXPERIMENTAL RESULTS

Figure 6 shows white light transient nulls obtained in the laboratory in March 2003. Results were obtained with two different mid infrared broadband filters, roughly 2 and 3 micron wide (FWHM). Nulls reported are for unpolarized white light, and 1" diameter beams. No active intensity control was necessary as the beam intensities matched within 1% (a natural property of the MMZ) which would be enough to get 1e-5 nulls. It is expected that intensity matching in the sky at the 4% level (to limit this null contribution to 1e-4) will be provided by rotating/translating "venetian blinds" currently tested. Although stabilization procedures - both software and hardware based- have been successfully tested on the nuller in the past few months, they were not available during the acquisitions reported here, showing transient nulls with quite large opd drifts manually corrected via a PZT activated mirror. Null signals were nevertheless steady at the 5000:1 level for periods of tens of seconds for both filters, without any active opd control, meaning that the environment is sometimes vibration free at the $\sim 50$ nm level over such timescales.

- 29% bandwidth filter, FWHM=9.20 to 12.35 microns. Figure 6 (left) is a time sequence showing successively the relative signals measured at a
constructive peak, at null, back to a constructive peak, and then looking at the detector noise. The best transient rejection levels measured - conservative estimates as described in section 3 - are 7500:1, or a null depth of 1.33 \times 10^{-4}. Rejections greater than 5000:1 are present for tens of seconds.

- 18% bandwidth filter, FWHM=9.70 to 11.65 microns. Same procedure as for the wider filter. Best transient rejection levels are 17000:1, i.e. null depths of 5.9 \times 10^{-5}. Mean levels are again around 5000:1 as fixed by the vibration environment.

4. SUMMARY

The Keck Interferometer nulling beam combiner has been assembled in the laboratory, and has successfully completed the validation phase, in which deep, broadband, dual-polarization extinction of white light has been demonstrated in the mid-infrared. The beam combiner now enters the phase of integration with the mid IR camera and the KI optical train.

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