Demonstration of nulling using delay line phase shifters

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ABSTRACT

We present results of experiments obtained using a new nulling technique that enables deep nulling without the use of achromatic phase shifters. The experimental set-up consists of a three-beam interferometer that should provide a nulling depth of several thousands over a wavelength range of 500 to 650 nm. The intended depth of null was not achieved and further experiments on determining the spectrum of each beam revealed why. We describe a method of obtaining accurate beam spectra in a multi-beam interferometer. The insights on the need of spectral shape control were tested with our nulling theory and proved the sensitivity of this nulling approach with respect to spectral mismatches.

Keywords: Interferometry, Nulling

1. INTRODUCTION

Direct detection of exo-planets is possible by using a technique called nulling interferometry,¹ which is based on destructive interference of light from a bright star and constructive interference of a faint planet near it. The light of a star must be attenuated by a factor, the so-called rejection ratio, which typically is of the order of 10^6 , for the infrared wavelength region. Nulling interferometry is basically the destructive combination of light from different telescopes. Object areas for which the arms of the interferometer have an equal pathlength, will be attenuated. This is only true for a general white light emitting star when the phase shift is π for all wavelengths simultaneously. Generally, deep nulling is achieved by using achromatic phase shifters (APSs). Unfortunately, the technology needed to build these APSs is not yet fully developed. Our method is a way to perform deep nulling, based on delay lines only. The use of delay lines only allows for a relatively simple interferometer layout. After a short explanation of our nulling concept in Sec. 2, the experiments will be described in Sec. 3. The outlook is presented in Sec. 4 and conclusions are made in Sec. 5.

2. THEORY

Recently, an alternative family of nulling interferometers was found that was less sensitive to phase shift errors that are produced by the 'achromatic' phase shifters.²⁻⁴ As a consequence, the tight constraint of achromaticity of several milliradians could be relaxed to such a level that delay lines are possible candidates to function as phase shifter for DARWIN.⁵ A small summary on this idea is given below.

In a nulling interferometer, each telescope provides a beam with a relative amplitude f and phase ϕ . After recombination of the beams of each telescope, the final transmittance of the star is expressed in terms of rejection. Even without any phase and amplitude noise, the achievable rejection depends strongly on the choice of f and ϕ . The following amplitude and phase distribution was proposed by Mieremet⁴:

$$\begin{aligned} f_i &= \binom{N-1}{i-1} \\ \phi_i &= [i-1][\pi - \epsilon(\lambda)]. \end{aligned} \quad (1)$$

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Figure 1. The advantage of applying more than only one chromatic phase shift of approximately π . When more beams get a shift, the residual in complex amplitude of the combined beams will be smaller. The sum of complex vectors of the DAC interferometer (a) clearly has a much larger vertical component left over as compared to the optimised configuration (b).

N	$f_1 \dots f_N$	$\phi_1 \dots \phi_N$
2	1 1	0 π
3	1 2 1	0 π 2π
4	1 3 3 1	0 π 2π 3π
5	1 4 6 4 1	0 π 2π 3π 4π
6	1 5 10 10 5 1	0 π 2π 3π 4π 5π

Table 1. Overview of the values of f_i , ϕ_i for $N = 2, \dots, 6$ (for simplicity, the ϵ terms have been left out)

In this distribution, N represents the number of telescopes, $\epsilon(\lambda)$ the wavelength dependent phase shift error introduced by the phase shifter and i the index of the telescope. Note that $\epsilon(\lambda)$ does not represent noise, but a systematic phase shift error with respect to an achromatic phase shift. In table 1 an overview of f and ϕ is shown for several values of N .

It can be derived that for this case the rejection ratio R is given by

$$R_N(\lambda_1, \lambda_2) \approx \binom{2N-2}{N-1} \langle \epsilon^{2(N-1)}(\lambda) \rangle^{-1}, \quad (2)$$

where the $\langle \rangle$ represent the average of the wavelength region $[\lambda_1, \lambda_2]$. The approximation sign has been used because higher order effects have been neglected.

The main result is that the influence of $\epsilon(\lambda)$ becomes much less for larger N , since $R_N \propto \langle \epsilon^{2(N-1)}(\lambda) \rangle^{-1}$, which implies that the achromaticity requirement is strongly reduced for increasing N . This has not been the case for other nulling interferometers. For $N = 2$, a rejection ratio of 10^6 requires that ϵ must be of the order of milliradians. This level of achromaticity is mentioned in literature.

To understand why the influence $\epsilon(\lambda)$ becomes much less for larger N , we show as an example the comparison between a $N = 3$ configuration and the Degenerate Angel Cross⁶ (DAC) nulling interferometer, see Fig. 1. Below each telescope, the complex representation of each beam is drawn. The state of the recombined beam can be obtained by adding the vectors. For the DAC nulling interferometer, the vertical component is far from perfectly 'nulled' and causes the DAC interferometer to have a $\langle \epsilon^2 \rangle^{-1}$ dependence. If this is compared with the 3 telescope configuration, it becomes clear that for that case the vertical component is much better nulled causing the $\langle \epsilon^4 \rangle^{-1}$ dependence.

Figure 2. Schematic diagram of the previous delay-line-only nulling set-up. Region A is the star simulator. Region B is the actual interferometer and C is the detection stage

3. EXPERIMENTS

3.1. The set-up

The goal of the experimental setup was to give a proof-of-principle. This is achieved when a higher rejection ratio was measured for the proposed configuration than for any other. We chose to simulate a three telescope system, which is the most simple configuration to take benefit from the nulling approach. As can be deduced from the theory, such an experiment could even in the case of perfect performance not reach a nulling depth of 10^6 , over the wavelength range of 500 to 650 nm. However, a depth of several thousands should be possible, whereas the combination of three beams with equal amplitude would yield a null of a few hundreds.

Our set-up (see Fig. 2) can be divided in three stages: the star-simulator, the interferometer and the detection stage.

The star simulator consists of a colour-filtered Xe arc light source (LS), focused on a pinhole (PH). From here the light is collimated so that flat wavefronts emerge as starlight. This light is then not collected by separated telescopes, but branched off by means of two beamsplitters (BS1, BS2) to produce three beams. Each of the beams is sent into another light path.

The nulling part is the heart of the set-up. Two of the three beams are directed onto retro-reflectors mounted on a piezo translation stage so to function as delay line. In this way, the optical path difference between all three beams can be controlled. The path of the third beam is used as a reference. The beams are recombined again by using beamsplitters (BS2 and BS4). Between BS2 and BS4 a diaphragm (DIA) or a functionally similar component is placed to be able to control the amplitude of beams 2 and 3 with respect to beam 1.

The recombined beams have a common path and are directed to a matched system of achromatic lenses and a single-mode fiber. The single mode fiber acts as a modal and spatial filter.⁷ The outcoming power after the fiber is detected with a sensitive power meter.

The setup allows us to investigate both different amplitude and phase distributions by changing the diafragm and delay lines, respectively. We can now record interferograms using the power meter and the known setpoints of the two delay lines. When both delay lines are used, a two dimensional 'interferogram' is produced, resembling a landscape with peaks and valleys aligned in some grid shape. This landscape represents the achieved null of the star as a function of different phase shift distributions. The deepest valley is the configuration that provides the best nulling performance.

3.2. Three beam nulling

Experiments have been performed with combining three beams to perform nulling, both according to 'conventional' schemes (all amplitudes equal and hence OPDs needed of fractions of a wavelength) as well as with 'optimised' schemes. For the latter, amplitude matching involved more than adjusting a few percent by placing a knife-edge in the beams.

Obtaining the prescribed amplitude ratio of 2 : 1 : 1 for the $N = 3$ case, which corresponds to a power ratio of 4 : 1 : 1, is not trivial. Placing neutral density filters in the paths is not an option: the third beam would also need extra optical path and all elements inserted should have exactly the same thickness and quality, to prevent dispersion effects. Alternatively, a knife-edge would have to be inserted far into the beam, causing its focus on the single-mode fiber to be displaced and hence have couple losses, which are chromatic and would distort the spectral shape. As a possible solution, a diaphragm was tried. It gives diffraction effects, but the focal shape and central position are not altered and it provides a power tuning possibility.

Two sets of spectra have been intensively investigated. The first set is the equal amplitude distribution, while the second represents the amplitude distribution as given in Equation 1. During the experiments, it was found that the three beam nulling experiments with beams with equal amplitude could quite nicely match the expectations from simulations (see Table 2). But the much deeper nulls that should come with the optimised strategy were never measured. It was suspected that the method of power reduction (that had to keep the spectral shape the same) was ruining the measurement. Either the reduction method adjusted the spectral balances in the beam itself, or it adjusted the chromatic coupling efficiency into the detection fiber, where the actual nulling takes place.

Power Balance	Theoretical null depth	Measured
1 : 1 : 1	275	188
4 : 1 : 1	3100	42

Table 2. Expected and measured nulling ratios for the combination of three beams for a wavelength range of 500 to 650 nm. The given value is the ratio of maximum and minimum total intensity.

In order to analyse the problem of proper beam attenuation further, the individual beam spectra were measured. Because of low light levels, it was done by Fourier analysis of pairwise interferograms (an explanation of this can be found in Appendix A). Figure 3 shows the derived spectra for three beams in two different cases, having power balances of 1 : 1 : 1 and 4 : 1 : 1. Clearly, these balances are not constant nor exact over the wavelength range.

Simulations that were used for the prediction of the null depth were adjusted to be able to process three different spectra. The results (see Fig. 4) show striking resemblance with what was measured: the deepest null measured in a two-delay-line scan was limited in the 1 : 1 : 1-case, but near to nothing in the 4 : 1 : 1-case.

Experiments were repeated, where the power ratio of 4 : 1 : 1 was realised in many different ways (knife-edges, density filters, irises and metal wire gratings) but the expected gain in null-depth was never found.

3.3. New insight — Sensitivity to mismatch

The investigation to ways of achromatically reducing the power present in two of the three beams led to the insight that it might not be the method of reduction that caused the lack of a deep null, but that the method itself simply was more vulnerable to mismatching amplitudes.

Figure 3. The top panels show the measured spectra of each beam for the equal amplitude distribution (top left) and the optimised distribution (top right). The three beam Fourier technique delivers the complex spectra per beam. The phase spectra were brought together at 633 nm, where a laser interferogram provided the zero OPD for that wavelength. The derived complex spectra are for the case that the three beams have equal power (lefthand side) and for the case that two beams pass through an iris, to limit their power (righthand side).

Figure 4. With the spectra (as given in Fig. 3) obtained at the set-up, a three-beam nulling simulation is performed. Figure (a) shows a pattern as expected, with a nulloptimum that is worse than expected. (Depth is 188, whereas exactly equal spectra would provide a depth of 275.) Figure (b) shows a pattern that is deteriorated from what was expected, but moreover has a null depth of only 42, where over 3000 was calculated for spectra having the same shape but a power ratio according to 4 : 1 : 1.

Figure 5. The sensitivity to amplitude or phase deviations when combining three beams, is much higher for the case of a power ratio of 4 : 1 : 1. Here we simulated putting together three spectra with unity amplitude over the wavelength range (for the second case fractions of unity). Figure (a) shows for both nulling configurations the achievable nulldepth with ideal spectra. Figures (b) and (c) respectively show what happens if white noise with an amplitude of 0.01 is put first on the amplitudes and then on the phases in the spectrum. The dashed red line indicates the wavelength for which the delay lines are set to provide best shifts in each case.

To verify this assumption, simulations of amplitude and phase deviations on the beams have been performed. The results of these simulations are shown in Fig. 5. In the left panel, the achievable rejection ratio as a function of wavelength is shown for the two distributions of interest in the case that no amplitude and phase noise are present. As a next step, an amplitude and phase noise of 1% are applied. The consequences of this are shown in the middle and right panel, respectively.

Figure 5 clearly shows that the optimised nulling technique is much more vulnerable to mismatching amplitudes or phases. The set-up we have constructed was not designed to attain much better matching than 1%, since the coatings on the beam splitters could not be applied at a tighter tolerance.

4. OUTLOOK

A way to overcome the spectral deformations that the beams acquire through the set-up, would be to construct a symmetrical beam combiner as for example described by Serabyn,⁸ where all beams interact all with the same optical elements for the same number of times. However, for a three beam nulling interferometer, realising a symmetrical lay-out is much harder than for a two beam case. When already in the design phase the need for spectra of equal shape is known, there might be a design possible that meets this need. It could even be designed to deliver *only* spectra according to the optimised amplitude balance, so that no objects have to be stuck in beams to correct this. The experimental work however, is stalled now.

5. CONCLUSIONS

We have presented the results of an investigation to why a promising nulling technique did not show the deep nulls that were expected. Theoretically, nulling with multiple beams that have amplitudes according to a defined distribution and relative phase-shifts of multiples of π , should provide deep nulls. However, the experimental set-up discussed here has a limited capability of delivering three beams with spectra that have amplitudes all over their wavelength range that match to the balancing that the theory requires. Since the method itself is more vulnerable to amplitude mismatches than the conventional method, we did not succeed in measuring the deep nulls. If accurate spectral shaping would be applied, the nulling method described here could enhance the performance of a nulling interferometer.

Figure 6. The spectra of the three individual beams (right panel) can be obtained from the Fourier transforms of three interferograms, obtained from pairwise combinations (left panel). The sharp spikes in the individual beam spectra are artifacts and result from division by a value close to zero in one of the spectra of combinations.

APPENDIX A. BEAM SPECTRA OUT OF THREE INTERFEROGRAMS

It is essential that the spectra of the three beams in the experiment are very equal. The power in each beam is rather low (typically 1 nW) and obtaining an accurate spectrum of the light emitting from the fiber is not feasible with general spectrometers, since the power even in relatively wide wavelength bins is in the region of picowatts. Another way was sought to obtain the spectra. This was achieved by performing some extended Fourier analysis of interferograms. The observation that we seek three spectra, and that we can successively measure interferograms resulting from three different combinations of beams, led us to the following procedure.

The spectrum of one beam of light in our system can be expressed as $S_i(k)$ where k is the wavenumber, i is the index to beam 1, 2 or 3. An interferogram resulting from interference of beams i and j as a function of optical pathlength difference x is then

$$I_{ij}(x) = \frac{1}{2} \int_{-\infty}^{\infty} \left[S_i(k) + S_j(k) + 2\sqrt{S_i(k)S_j(k)} e^{ikx} \right] dk \quad (3)$$

where $I_{ij}(x)$ is the recorded intensity. The Fourier transform $G(k)$ of this expression is written as

$$\begin{aligned} G_{ij}(k') &= \frac{1}{2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left[S_i(k) + S_j(k) + 2\sqrt{S_i(k)S_j(k)} e^{ikx} \right] e^{-ik'x} dk dx \\ &= \frac{1}{2} \left(\int_{-\infty}^{\infty} [S_i(k) + S_j(k)] dk \right) \delta(k') + \int_{-\infty}^{\infty} \sqrt{S_i(k)S_j(k)} dk \delta(k - k') \\ &= \frac{1}{2} \left(\int_{-\infty}^{\infty} [S_i(k) + S_j(k)] dk \right) \delta(k') + \sqrt{S_i(k')S_j(k')}. \end{aligned} \quad (4)$$

Equation 4 shows that the Fourier transformed interferogram is the sum of the DC values of both signals and a square root term of the product of both, per wavenumber. Application to three measured interferograms now gives us the three individual beam spectra:

$$G_{12}(k') = (P_1 + P_2)_{k'=0} + \sqrt{S_1(k')S_2(k')},$$

$$\begin{aligned} G_{13}(k') &= (P_1 + P_3) + \sqrt{S_1(k')S_3(k')}, \\ G_{23}(k') &= (P_2 + P_3) + \sqrt{S_2(k')S_3(k')}. \end{aligned} \quad (5)$$

where P_i is the total power in beam i , represented as the DC term of the transform. Rearranging these expressions yields for example the spectrum of beam 2:

$$\frac{[G_{12}(k') - (P_1 + P_2)][G_{23}(k') - (P_2 + P_3)]}{[G_{13}(k') - (P_1 + P_3)]} = \frac{\sqrt{S_1(k')S_2(k')}\sqrt{S_2(k')S_3(k')}}{\sqrt{S_1(k')S_3(k')}} = S_2(k'). \quad (6)$$

Likewise, each element of $S_1(k')$ and $S_3(k')$ can be calculated per k' . See Fig. 6 for the results. The total power P_i for each beam i can simply be measured before recording an interferogram or can be obtained from the zeroth element of the Fourier transform of this interferogram. With three FTs available, the different total powers or DC terms per beam can be obtained from a linear system of equations.

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