Direct exoplanet detection is limited by speckle noise in the point-spread function (PSF) of the central star. This noise can be reduced by subtracting PSF images obtained simultaneously in adjacent narrow spectral bands using a multi-channel camera (MCC), but only to a limit imposed by differential optical aberrations in the MCC. To alleviate this problem, we suggest the introduction of a holographic diffuser at the focal plane of the MCC to convert the PSF image into an incoherent illumination scene that is then re-imaged with the MCC. The re-imaging is equivalent to a convolution of the scene with the PSF of each spectral channel of the camera. Optical aberrations in the MCC affect only the convolution kernel of each channel and not the PSF globally, resulting in better-correlated images. We report laboratory measurements with a dual-channel prototype (1.575 and 1.625 μm) to validate this approach. A speckle noise suppression factor of 12–14 was achieved, an improvement by a factor ~5 over that obtained without the holographic diffuser. Simulations of exoplanet populations for three representative target samples show that the increase in speckle noise attenuation achieved in the laboratory would roughly double the number of planets that could be detected with current adaptive optics systems on 8 m telescopes.

Subject headings: instrumentation: adaptive optics — planetary systems — stars: imaging — techniques: high angular resolution — techniques: image processing.

1. INTRODUCTION

Direct detections of faint exoplanets near bright stars are essential to extend the census of planetary companions to separations that are beyond the reach of radial velocity surveys and to enable measurements of exoplanets' physical properties through follow-up multicolor photometry and spectroscopy. This difficult endeavor, already being tackled by many, is one of the major goals for next-generation instruments on 8 m class telescopes and future 30–100 m telescopes. The main difficulty stems from imperfections in the optics that produce bright quasi-static speckles in the point-spread function (PSF) of the central star (Marois et al. 2004; Biller et al. 2005; Masciadri et al. 2005). The subtraction of reference PSF images is a very efficient way of reducing this speckle noise. A good example is angular differential imaging (ADI; Marois et al. 2006; Lafrenière et al. 2007), in which images of the target, obtained while the field of view rotates, are used for subtracting the stellar PSF. This technique is among the most successful at suppressing speckle noise for ground-based imaging; however, it is inefficient at small angular separation (<1") because the time required for sufficient natural rotation of the field of view is too long.

Simultaneous spectral differential imaging (SSDI) is a PSF subtraction technique that is efficient at all angular separations. It consists in the simultaneous acquisition of images in adjacent narrow spectral bands within a spectral range where the stellar and planetary spectra differ appreciably (Racine et al. 1999; Marois et al. 2000; Smith 1987; Rosenthal et al. 1996). Judicious image combination and subtraction removes the stellar PSF and leaves that of any companion. Note that because the PSF images are acquired in different bandpasses, they must be rescaled prior to subtraction (diffraction scales as λ). At larger separations, this scaling allows the technique to work even in the absence of differential spectral features, since a companion would not overlie itself in the rescaled images.

The standard implementation of SSDI is done with a multi-channel camera (MCC). The speckle noise suppression achievable with such instruments is hampered by differential aberrations between the spectral channels (Marois et al. 2005). For the triple imager TRIDENT (Marois et al. 2005; Canada-France-Hawaii Telescope) and the quadruple imager SDI (Lenzen et al. 2004; Very Large Telescope), the subtraction of two images obtained simultaneously through different channels yields a speckle noise attenuation of only ~2–2.5 (Marois et al. 2005 and Appendix). In light of the differential aberrations problem, new implementations of SSDI which should enable a better speckle noise attenuation have been proposed, such as the multicolor detector assembly (Marois et al. 2004) or the use of a microlens array at the focal plane of an MCC (Lafrenière et al. 2004). As for existing cameras, strategies such as multiple rotations of the instrument or observation of reference stars (Marois et al. 2005; Biller et al. 2004) have been used to further attenuate the residuals left by the incomplete simultaneous multichannel subtraction, and 5 σ contrast limits for magnitude differences of ~9 and ≥10 have been achieved at an angular separation of 0.5" with TRIDENT and SDI, respectively (Marois et al. 2005; Biller et al. 2006). However, the approaches used to circumvent the problem of differential aberrations often complicate data acquisition and decrease the observing efficiency at the telescope. As several MCCs are currently being developed by major observatories for future exoplanet searches, e.g., NICI (Toomey & Ftaclas 2003) for Gemini South, SPHERE/IRDIS (Dohlen et al. 2006) for the VLT, or HiCIAO (Tamura et al. 2006; Hodapp et al. 2006) for Subaru, the development of...
techniques to improve the PSF subtraction performance of MCCs is of great interest.

In this paper, we propose to minimize the effect of differential aberrations by introducing a holographic diffuser (HD) at the focal plane of an MCC (see also Lafrenière et al. 2006). This simple approach provides a direct gain in speckle attenuation without the need to modify the observing strategy. The concept and performance estimates are presented in § 2. Measurements and results using a laboratory prototype are reported in § 3, and § 4 presents estimates of the detection limits that such a device should reach on 8 m telescopes using current adaptive optics (AO) systems, along with an assessment of the corresponding exoplanet detection efficiency. Improvements in performance for a dedicated camera, implications of the laboratory results for other types of SSDI instruments, and considerations for implementation of this concept in an existing camera are discussed in § 5.

2. MULTICHANNEL IMAGER WITH HOLOGRAPHIC DIFFUSER

2.1. Concept

A light-shaping HD is a random surface relief hologram that diffuses the light incident on it into a controlled angular distribution. When a coherent wave front goes through an ideal HD, large phase errors are introduced over small scales and spatial coherence is lost; thus, every point of the wave front effectively becomes an independent source emitting with an angular distribution controlled by the HD. Hence, an HD located at a focal plane converts the PSF image into an incoherent illumination scene, which can then be re-imaged by an MCC. This is equivalent to a convolution of the scene with the PSF of each channel of the MCC. Optical aberrations in the MCC affect only the convolution kernel of each channel rather than the PSF globally; the effect of differential aberrations is merely a convolution of the same PSF image with different kernels. Hence, contrary to standard MCC imaging, the speckle pattern remains the same in all channels and it is only the light distribution within each speckle that may vary slightly depending on the size of the convolution kernel and on the amount of aberration present in the MCC. If the size of the convolution kernel is smaller than the size of a speckle in the incident PSF image, then most of the light will remain inside the same speckle after convolution and the correlation between the different channels will be high.

An HD is a better choice than other diffuser types for use with an MCC because its diffusing cone angle can be made small, allowing efficient coupling to relatively large focal ratios ($f/D \sim 8-32$), typical of existing cameras. Moreover, the diffusing properties of an HD are wavelength independent. It should be noted that since the diffuser breaks the coherence of the wave front, it precludes the use of a coronagraph downstream from it. However, the diffuser poses no problem for a coronagraph placed in front of it.

A real HD does not behave exactly as described above because the size of the structures on its surface is not negligible compared to the full width at half-maximum (FWHM) of the incident PSF. The surface of an HD can be thought of as a random collection of microlenses, each refracting light slightly differently, such that the overall diffusion of light results in the desired angular distribution. A real HD thus transforms the wave front incident on it into a random collection of sources, or micropupils, of finite size rather than ideal, infinitesimally spaced, point sources. Accordingly, the image recorded by an MCC equipped with a focal-plane HD would correspond to the smooth illumination scene incident on the HD broken up into many tiny spots whose position and intensity are determined by the position and amount of light intercepted by the corresponding microlenses (see Fig. 1). As the micropupils produced by the microlenses are usually not resolved by the MCC, the shape, or FWHM, of each tiny spot is determined by the focal ratio of the MCC. This breakup of the smooth illumination scene into a collection of tiny spots is problematic, but a simple solution exists. If the HD is moved slightly in a plane tangent to its surface, then each tiny spot will move on the detector by a corresponding amount, and the intensity of each spot will change according to the new amount of light intercepted by the corresponding microlens. In the limit where the HD moves continuously during an exposure, the detector is smoothly illuminated and, effectively, the image recorded by the MCC corresponds to a convolution of the
illumination scene incident on the HD with the PSF of the MCC (see Fig. 1).

The imaging process described above can be understood mathematically as follows. If $I_1$ and $I_2$ represent the PSFs of the two channels of a dual imager for a point source located at its entrance focal plane, and $I_{\text{inc}}$ represents the PSF incident on the HD, then the resulting image in each channel is given by the convolution $I_{\text{inc}} * I_1$ or $I_{\text{inc}} * I_2$. The residual image $R$ obtained by subtracting the images of both channels is then given by

$$R = (I_{\text{inc}} * I_1) - (I_{\text{inc}} * I_2) = I_{\text{inc}} * (I_1 - I_2).$$

(1)

The residual image can thus be viewed as being equal to the difference of the two MCC PSFs, convolved with the PSF incident on the HD. As the spatial scale of the residual noise in $(I_1 - I_2)$ is the FWHM of $I_1$ and $I_2$, denoted $\theta_{\text{MCC}}$, and the width of the convolution kernel is the FWHM of $I_{\text{inc}}$, denoted $\theta_{\text{inc}}$, the above convolution should reduce the amplitude of the residual noise in $(I_1 - I_2)$ by a factor dependent on the ratio $\theta_{\text{inc}} / \theta_{\text{MCC}}$. This ratio represents the number of characteristic lengths over which the residuals are averaged by the convolution. A larger ratio $\theta_{\text{inc}} / \theta_{\text{MCC}}$ should lead to a larger attenuation of the noise.

It was demonstrated in Marois et al. (2005) that the noise attenuation achieved by a dual imager is given by $\sigma_{\text{MCC}} / \Delta \sigma_{\text{MCC}}$, where $\sigma_{\text{MCC}}$ is the amount of aberration in each channel and $\Delta \sigma_{\text{MCC}}$ is the amount of differential aberration. Thus, when using an HD one can expect based on equation (1) that the residual noise also scales as $\sigma_{\text{MCC}} / \Delta \sigma_{\text{MCC}}$, but with an additional factor due to the convolution. While one should still minimize differential aberrations to maximize the attenuation, important leverage is introduced through the ratio $\theta_{\text{inc}} / \theta_{\text{MCC}}$, or equivalently through $(f/D)_{\text{inc}} / (f/D)_{\text{MCC}}$, where $(f/D)_{\text{inc}}$ and $(f/D)_{\text{MCC}}$ are the focal ratios of the beam incident on the HD and of the MCC. For better performance, these ratios should be made as large as possible. This would also minimize the loss in spatial resolution resulting from the convolution of $I_{\text{inc}}$ with $I_1$ or $I_2$. From convolutions of Airy functions, it can be shown that the loss in resolution is $\sim 12\%$ for $(f/D)_{\text{inc}} / (f/D)_{\text{MCC}} = 2$ and less than $5\%$ for $(f/D)_{\text{inc}} / (f/D)_{\text{MCC}} \geq 3$.

2.2. Speckle Noise Attenuation Estimation

Numerical simulations were done to estimate the speckle noise attenuation that may be achieved with a dual-channel camera equipped with an HD. For each simulation, three PSFs were created: the PSF incident on the HD ($I_{\text{inc}}$) and the PSFs of both channels of the MCC ($I_1$ and $I_2$). Arrays of $2048 \times 2048$ pixels were used for all calculations. The PSFs were obtained as the square modulus of the Fourier transform of the complex pupil function. The MCC PSFs FWHM, $\theta_{\text{MCC}}$, was fixed to 5 pixels, and the incident PSF FWHM, $\theta_{\text{inc}}$, was varied to test the effect of the ratio $\theta_{\text{inc}} / \theta_{\text{MCC}}$. Wave front aberrations having a power-law power spectrum of index $-2.7$, a value appropriate for AO systems and astronomical cameras (Marois et al. 2005), were included in the simulations. Different values of the wave front error of the incident PSF $\sigma_{\text{inc}}$, of $\sigma_{\text{MCC}}$, and of $\Delta \sigma_{\text{MCC}}$ were tried to see their effect.

Once the three PSFs have been obtained, $I_1$ and $I_2$ are normalized to a sum of unity and are subtracted from each other. This difference is then convolved with $I_{\text{inc}}$ to obtain the residual image. The noise attenuation is finally determined. The PSF noise is defined as the standard deviation over an annulus of the PSF image after subtraction of an azimuthally averaged profile. The noise attenuation $\eta$ is defined as the ratio of the PSF noise in one channel over the noise in the residual image. Many values of $\theta_{\text{inc}} / \theta_{\text{MCC}}$, $\sigma_{\text{inc}} / \sigma_{\text{MCC}}$, and $\Delta \sigma_{\text{MCC}}$ were tried; the results are presented in Table 1 and Figure 2. We note that the total amount of static aberration for TRIDENT at the CFHT was estimated at 130 nm, of

| Optical Aberrations | Speckle Noise Attenuation from Numerical Simulations | Fit of Eq. (2) |
|---------------------|-----------------------------------------------------|---------------|
| $\sigma_{\text{inc}}$ | $\sigma_{\text{MCC}}$ | $\sigma_{\text{MCC}} / \Delta\sigma_{\text{MCC}}$ | 1 | 2 | 3 | 4 | $\alpha$ | $\beta$ |
| 80.............. 50 1 | 2.1 | 6.9 | 15.2 | 25.3 | 2.1 | 1.80 |
| 80.............. 50 2 | 4.1 | 13.4 | 29.5 | 49.3 | 2.0 | 1.80 |
| 80.............. 50 3 | 6.1 | 20.0 | 44.2 | 73.8 | 2.0 | 1.81 |
| 80.............. 25 1 | 4.1 | 16.2 | 37.6 | 65.7 | 4.1 | 2.01 |
| 80.............. 25 2 | 8.1 | 32.1 | 74.5 | 130.3 | 4.0 | 2.01 |
| 80.............. 25 3 | 12.2 | 48.0 | 111.6 | 195.2 | 4.0 | 2.01 |
| 120............ 50 1 | 3.8 | 13.4 | 27.3 | 45.4 | 3.9 | 1.76 |
| 120............ 50 2 | 7.4 | 26.0 | 54.1 | 83.7 | 3.8 | 1.76 |
| 120............ 50 3 | 11.0 | 38.8 | 81.0 | 125.8 | 3.7 | 1.77 |
| 120............ 25 1 | 8.2 | 31.9 | 70.7 | 115.5 | 8.3 | 1.92 |
| 120............ 25 2 | 16.2 | 63.0 | 139.9 | 228.2 | 8.2 | 1.92 |
| 120............ 25 3 | 24.3 | 94.3 | 209.4 | 342.3 | 8.2 | 1.92 |

![Fig. 2.](image-url) — Speckle noise attenuation from numerical simulations as a function of $\theta_{\text{inc}} / \theta_{\text{MCC}}$, the ratio of the FWHM of the PSF incident on the HD over that of the intrinsic MCC PSF. The values of $\sigma_{\text{inc}}$ and $\sigma_{\text{MCC}}$, in nm, are respectively 80 and 50 (crosses), 80 and 25 (squares), 120 and 50 (diamonds), and 120 and 25 (triangles). All results are for $\sigma_{\text{MCC}} / \Delta\sigma_{\text{MCC}} = 2$. The curves are the fit of eq. (2) to each set of points.
which 50 nm originated from the camera and 120 nm originated from the AO system and telescope (Marois et al. 2005); the
values of \( \sigma_{\text{inc}} \) and \( \sigma_{\text{MCC}} \) tested here are therefore representative of real systems. The results indicate that the noise attenuation increases with \( \sigma_{\text{MCC}} / \Delta \sigma_{\text{MCC}} \) and with \( \theta_{\text{inc}} / \theta_{\text{MCC}} \), in agreement with the previous discussion.

Using a dual-channel camera, the maximum value of the attenuation, limited by chromaticity of the PSF, is equal to \( \lambda / \Delta \lambda \) (Marois et al. 2000, 2005), where \( \lambda \) is the wavelength of the first channel and \( \Delta \lambda \) is the difference in wavelength of the two channels. The maximum attenuation is thus \( \sim 30 \) for bandpasses located just outside and just inside the methane absorption feature in the spectrum of cold dwarfs at \( \sim 1.6 \) \( \mu \)m (e.g., \( \lambda_1 \sim 1.575 \) \( \mu \)m and \( \lambda_2 \sim 1.625 \) \( \mu \)m). From Table 1, the attenuation should be limited by chromaticity of the PSFs rather than by differential aberrations for \( (f/D)_{\text{inc}} / (f/D)_{\text{MCC}} \approx 3-4 \).

It is found that the attenuation is very well approximated by the function

\[
\eta = \alpha \left( \frac{\sigma_{\text{MCC}}}{\Delta \sigma_{\text{MCC}}} \right) \left( \frac{\theta_{\text{inc}}}{\theta_{\text{MCC}}} \right)^\beta, \tag{2}
\]

where \( \alpha \) and \( \beta \) are parameters that depend on \( \sigma_{\text{inc}} \) and \( \sigma_{\text{MCC}} \) (see Fig. 2); their values are indicated in Table 1. Thus in a regime representative of real AO systems and MCC cameras, the attenuation that may be achieved with a system equipped with an HD roughly scales as the square of \( \theta_{\text{inc}} / \theta_{\text{MCC}} \).

3. EXPERIMENTAL RESULTS

3.1. Dual Imager Testbed

A simple testbed operating in the 1.55–1.65 \( \mu \)m wavelength range was assembled on an optical bench to validate the concept presented in the last section. The experimental setup consists of a PSF-generating system followed by a two-channel camera.

The PSF-generating imaging system is composed of a biconvex and a plano-convex lens (Thorlabs, LB1056 and LA1172) and a 6.3 mm diameter pupil stop, which is located immediately before the first lens. The system is telecentric and has an exit focal ratio of \( f / D = 64 \). This focal ratio was chosen based on the results of the previous section and the \( f / 16 \) focal ratio of the dual imager described below. The PSF is generated by imaging a 25 \( \mu \)m pinhole illuminated from the back by a white light source. Due to the small number of optical components in this system and to the small dimension of the beam, the Strehl ratio achieved is very high, and no speckles are visible in the resulting PSF image. This is problematic for testing a technique aimed specifically at reducing speckle noise; it was thus necessary to introduce more aberrations in the system. This was achieved by placing an \( H \)-band filter just before the pupil of the system, resulting in a Strehl ratio of \( \sim 92\% \), or \( \sim 75 \) nm rms of aberrations.

The exit focal plane of the PSF-generating system corresponds to the entrance focal plane of the two-channel camera. An HD can be put in/taken out of the light path at this precise location without altering any other part of the setup. For reasons explained in § 2, the HD is mounted inside a ball bearing coupled to a small electric motor by a gear belt and spins at a rate of \( \sim 10 \) Hz. The rotation axis (center) of the HD is offset by \( \sim 6 \) mm from the optical axis to maximize the effective area of the HD seen by the dual imager. The rotation rate was chosen to ensure that at least a few complete rotations would occur during a single exposure.

A diagram of the two-channel camera is shown in Figure 3. The camera consists primarily of two plano-convex lenses (CVI Laser, PLCX-38-1-64.4-C and JML Optical Industries, PPX12925/000); an 8 mm pupil stop is located immediately before the second lens. This camera has an entrance focal ratio of \( f / D_{\text{MCC}} = 16 \); this is roughly the smallest focal ratio that could be realized easily using simple commercially available lenses. A magnification of unity was chosen for simplicity. Beam splitting is made directly after the second lens with a 50/50 beamsplitter cube (Thorlabs, BS012). The beam reflected at \( 90^\circ \) is folded back toward the detector by a right angle prism (Bernhard Halle, UB0.30); the side dimension of this prism was selected such that the extra path length in glass compensates precisely for the increased physical path length of this channel, allowing both channels to reach focus in the same plane. The detector used is a Hawaii-1 (Rockwell Scientific Company), which is housed inside an IRLab cryostat. A square filter mosaic consisting of two abutted rectangular filters of bandwidth 3%, centered on 1.575 and 1.625 \( \mu \)m respectively, is located in front of the detector and allows imaging through different bandpasses in the two channels. An additional \( H \)-band filter is placed inside the cryostat to block radiation longward of 1.8 \( \mu \)m, as the narrowband filters are not blocked outside of the \( H \) band. This dual imager has a square field of view 4 mm on a side and a Strehl ratio >95% over the entire field of view in each channel, as estimated from Zemax. The FWHM of the PSF at the detector is 5.5 pixels. There is no antireflection coating on any of the optical components; hence, many ghosts are present.

3.2. Data Acquisition and Reduction

The speckle noise attenuation capability of the testbed MCC was first quantified without the HD. These measurements were made by acquiring a sequence of images in the same bandpass
for both channels by rotating the filter mosaic by 90°, which made both channels fall on the same side of the mosaic. This eliminates chromatic effects and ensures that any decorrelation between the PSFs of the two channels is induced by differential aberrations. Then we obtained a sequence of images in the same configuration but with the HD in place. This sequence was obtained only a few hours after the first one, the only difference being the presence of the HD. It thus provides a direct measurement of the improvement in speckle noise attenuation provided by the HD. Finally, a third sequence was acquired with the HD using different bandpasses for the two channels, which is more representative of astronomical observations. Two diffusers (1° and 5° FWHM) from Physical Optics Corporation were tried and no significant difference in speckle attenuation was found between them; however, the 1° diffuser barely fills up the MCC pupil stop and yields a transmission of 85%, while the 5° one largely overfills the MCC pupil stop and yields a transmission of 30%.

All sequences of images were acquired in a similar fashion. Five images with the illumination source ON and OFF were alternately obtained for a total of 40–50 PSF images and darks. Each image consisted of ~5 minutes of co-additions. The intensity of the illumination source was adjusted to saturate the PSF center out to ~3–4 λ/D to improve the signal-to-noise ratio of the speckles at large separations.

Basic image reduction consisted in dark subtraction and division by the flat field. Bad pixels were replaced by the median value of neighboring pixels. For each sequence of images, the center of the first image was found by cross-correlation with a theoretical PSF having the same FWHM in an annulus where the image is not saturated. Then the other images of the sequence (including images of the second channel) were registered to the first one by cross-correlation in the same annulus. The image areas affected by ghost artifacts were masked out for cross-correlation and noise reduction.
calculation purposes. When images were acquired in two band-passes simultaneously, the short channel images were spatially scaled up to compensate for the change in diffraction scale with wavelength; the scaling factor was found by cross-correlation. In performing the subtraction, the second channel PSF intensity was normalized by the ratio of the radial profiles of the two channels. For each sequence, all images and all differences were finally median combined.

3.3. Attenuation Results

A comparison of the images before and after subtraction is shown in Figure 4 and the corresponding attenuation curves are shown in Figure 5. The single bandpass attenuation without HD is \( \sim 3.5 \) on average; this is slightly better than, but of the order of, what is achieved with TRIDENT and SDI. The addition of the HD boosts the attenuation to \( \sim 25 \), and even \( \sim 40 \) on Airy rings, an improvement by a factor \( \sim 7–10 \) over the configuration without the HD. This is a clear demonstration that the effect of differential aberrations is indeed reduced by using an HD. Even though the residual noise in this case is dominated by pixel-to-pixel noise, some residual speckles are present. The attenuation achieved with our testbed may be limited by a combination of interpolation errors (when shifting the images), flat-field errors, differential pixel cross talk, differential persistence, slight optical distortion of the MCC, or differential aberrations. Misalignment of the cube and prism may also result in slight field rotation and focus differences between the two channels.

Using the HD and two bandpasses, the speckle noise attenuation achieved is \( \sim 12–14 \). For the two wavelengths of our filter mosaic, the maximum attenuation possible for identically shaped bandpasses is \( \lambda/\Delta \lambda \sim 30 \). However, the transmission profiles of our filters have slopes in opposite directions; this decorrelates the two PSFs further. When taking this into consideration, the maximum attenuation attainable with our mosaic is \( \sim 25 \). Our results show an attenuation lower than this. One possible explanation for the difference, in addition to the ones mentioned previously, is an inadequate calibration of the structures produced by the irregular surface of the HD. During our measurements, we noticed a slow drift of the detector with respect to the pinhole as a function of time. This drift is likely correlated with the level of liquid nitrogen in the cryostat. Hence, the flat field could not be acquired in exactly the same configuration as the PSF images and slight calibration errors may be present. Such residuals, in the form of arcs due to the rotation of the HD, are noticeable in the residual image. The calibration of the surface of the HD is important only when different bandpasses are used because the images have to be rescaled, i.e., a given structure produced by an irregularity on the HD surface will not spatially coincide with itself after rescaling. For this reason, the performance of the two-bandpass configuration can be regarded as a lower limit; a larger attenuation could be achieved using a more stable setup.

4. PROJECTED ON-SKY PERFORMANCE

4.1. Detection Limit

Numerical simulations were done to estimate the detection limits that currently could be achieved by a dual-channel camera under three possible scenarios: (1) without an HD; (2) with an HD added to an existing MCC, requiring the addition of a focal enlarger (\( \S 2 \)) that reduces the field of view; and (3) with an MCC designed with an HD ab initio, avoiding the focal enlarger and the reduction of the field of view. For case (2), a 4× magnification was assumed, yielding \( f'/D_{\text{MCC}}/(f'/D_{\text{loc}}) = 4 \) as in the laboratory experiment. The baseline camera was assumed to be similar to NICI (Near-Infrared Coronagraphic Imager), i.e., featuring a 1024×1024 pixel detector with a pixel scale of 0.018″ and installed on an 8 m telescope equipped with an 85-actuator AO system. The simulation was done for a wavelength of 1.587 μm, the central wavelength of the first differential imaging filter of NICI. Coronagraphy was not considered as it does not provide significant gain in contrast for Strehl ratios typically achieved today, i.e., \(<50\% \) (Sivaramakrishnan et al. 2001).

A pupil of diameter 456 pixels, placed at the center of a 2048×2048 pixel array, was used to produce a PSF with a FWHM equal to 4.5 pixels; the corresponding pixel scale is 0.009″ at the wavelength of the simulation. Atmospheric phase screens were generated for \( r_0 = 20 \) cm at 0.5 μm. In addition, a static wavefront phase error having 80 nm rms and a power-law power spectrum of index −2.7 was used. AO phase filtering was simulated by multiplying the amplitude of the phase Fourier transform by a high-pass filter equal to \((k/k_{\text{AO}})^n\) for \( k < k_{\text{AO}} \) and to 1 for \( k \geq k_{\text{AO}} \), where \( k \) is the spatial frequency of the phase aberration and \( k_{\text{AO}} \) is the AO cutoff frequency (Sivaramakrishnan et al. 2001). The filter index \( n \) was set to 1.55 to produce an average Strehl ratio of 0.3, the baseline value expected for NICI. A long-exposure monochromatic PSF was obtained by co-adding the result of 5000 independent atmospheric wave front realizations. A polychromatic PSF image was then obtained by co-adding 101 spatially scaled versions of the monochromatic image, each representing a different wavelength within the 1% bandwidth of the filter. This PSF image was then either spatially scaled up by a factor of 2, or its pixels were binned 2×2 to obtain proper sampling for the configuration with the 4× magnification module (0.0045″ pixel−1), or without this module (0.018″ pixel−1), respectively. The speckle noise profiles were computed from these images.

The residual speckle noise was then obtained by assuming attenuation factors of 2.5 and 14 for the configuration without and with HD, respectively. The pixel-to-pixel noise was computed for a star of given \( H \)-band magnitude assuming a total system efficiency of 24% and 19% per channel without and with the HD, respectively, a sky background of 14 mag arcsec−2 in \( H \), a dark
current of $0.15 \, \text{e}^{-} \text{s}^{-1} \text{pixel}^{-1}$, 30 exposures of 120 s and a read noise of $10 \, \text{e}^{-} \text{pixel}^{-1}$ per exposure. Since the statistical distribution of static speckles is non-Gaussian, a $5 \sigma$ detection limit is not appropriate; rather, to reach a confidence level similar to that of a $5 \sigma$ Gaussian confidence interval, the detection limits were obtained as the quadratic sum of $10 \, \sigma_{\text{speckle}}$ and $5 \, \sigma_{\text{pixel}}$ (C. Marois et al. 2007, in preparation), where $\sigma_{\text{speckle}}$ is the speckle noise (dominating at small separations) and $\sigma_{\text{pixel}}$ is the pixel-to-pixel noise (dominating at large separations). A correction was applied to these limits to account for the partial loss in planet flux from the two-channel subtraction; this loss is maximal at zero separation and decreases to zero at a separation where the spatial scaling of the images displaces sufficiently (by $\sim 1 \, \lambda/D$) the planet. The results for an $H = 6$ star are shown in Figure 6. The higher asymptotic limit for the HD with $4 \times$ magnification is due to the higher relative importance of read noise for this largely oversampled configuration. The slightly higher asymptotic limit of the HD without magnification compared to the configuration without HD is explained by the 20% loss in throughput caused by the HD.

The detection limits presented in Figure 6 should not be regarded as predictions of the best contrast that a dual-channel camera could reach in practice, since other speckle suppression strategies, such as angular differential imaging or subtraction of images obtained after rotation of the instrument, could be used to attenuate the noise further. We note, however, that the detection limit without HD presented in this figure is very similar to the estimated baseline performance of NICI.

4.2. Detection Efficiency

A Monte Carlo simulation was done to investigate the impact of using an HD in terms of actual planet detections. First, realistic target samples were constructed for three representative populations of interest for planet searches. In particular, the distance, the age, and the $H$-band magnitude of each star of the samples were determined. The three samples are:

1. **NYS.**—Nearby young stars ($\leq 150 \, \text{Myr}, < 50 \, \text{pc}$). This sample includes 72 stars at a distance less than 50 pc from the Sun, obtained from Tables 3 and 4 of Wichmann et al. (2003); these stars have ages similar to those of the Pleiades stars ($20–150 \, \text{Myr}$), based on lithium abundance measurements. The stellar distances were taken from the same reference. Since the precise age of most of these stars is not well known, the stars were randomly assigned an age from a Gaussian distribution of mean 2.0 and standard deviation 0.15 in log (age/Myr).

2. **TWA.**—TW Hydrae Association ($\sim 8 \, \text{Myr}, 30–60 \, \text{pc}$). This sample includes 23 stars from Table 1 in Zuckerman & Song (2004). The stellar distances were taken from the same reference. The stars were randomly assigned an age from a Gaussian distribution of mean 0.9 and standard deviation 0.04 in log (age/Myr).

3. **$\rho$ Oph.**—$\rho$ Ophiuchus star-forming cloud ($\sim 2 \, \text{Myr}, < 135 \, \text{pc}$). This sample includes 27 stars with $R < 15$ from Table 4 of Wilking et al. (2005). The ages were taken from the same reference. The stellar distances were uniformly sampled in the $120–150 \, \text{pc}$ interval (Knude & Hog 1998).

In all cases the $H$-band magnitudes were taken from the 2MASS All-Sky Point Source Catalog (PSF, R. M. Cutri et al. 2003$^3$). For the simulation purpose, all samples were artificially increased to a total of 50,000 targets by reusing the same stars with different values for the random parameter. A population of exoplanets (one planet per star) was then generated using a mass distribution following $dN/dM \propto M^{-1}$ with $0.5 < M/M_{\text{jup}} < 12$, a semimajor axis distribution following $dN/da \propto a^{-0.5}$ with $0.1 < a/AU < 50$, and a Gaussian eccentricity distribution of mean 0.25, standard deviation 0.19, and with $0 \leq e \leq 0.8$; these properties were taken from Marcy et al. (2005), except for $dN/da$, which was set according to a minimum-mass solar nebula. All distributions are consistent with the exoplanet population from radial velocity surveys. The orbital inclination and phase were obtained by uniformly sampling, respectively, the orbital orientation and the orbital area

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$^6$ A maximum loss of 12% was assumed; this is the expected flux loss for a T8 dwarf ($T_{\text{eff}} \sim 800 \, \text{K}$) using the narrowband filters of NICI. According to the models of Baraffe et al. (2003), giant planets of $5 \, M_{\text{jup}}$ or less and older than a few 10 Myr should have $T_{\text{eff}} < 800 \, \text{K}$, and thus methane absorption redward of 1.6 $\mu$m is expected to be at least as important for such objects as for T8 dwarfs.

$^7$ See the NICI Campaign Science documentation at http://www.gemini.edu/sciops/instruments/nici/niciCampaign_orig.html. When comparing both curves, one should keep in mind that the detection limits of Fig. 6 assume a $10 \, \sigma_{\text{speckle}}$ criterion, whereas the curve in the NICI documentation is for $5 \, \sigma_{\text{speckle}}$, this translates into a difference of 0.75 mag.

$^8$ R. M. Cutri et al. 2003, 2MASS All-Sky Point Source Catalog (NASA/IPAC Infrared Science Archive; see http://irsa.ipac.caltech.edu/applications/Gator).
work well. In such a system, a microlens array is placed at the
IFS, Dohlen et al. 2006; or PFI, Macintosh et al. 2006b) should
also offers a good indication that an integral field spectrograph based
on all surfaces to reduce ghost artifacts, with a better alignment of
parameters, the apparent separation in arcseconds was computed
for all planets. Models of Baraffe et al. (2003) were used to derive
the apparent H-band magnitude of the planets given their mass,
age, and distance. The magnitude difference between the planets
and their primary star was finally compared to the detection limits.
The results are shown in Figure 7 and the corresponding detection
efficiencies are presented in Table 2. The detection efficiencies
for the configuration without an HD are 6%, 17.5%, and 12.5%
for the NYS, TWA, and ρ Oph samples, respectively. The use of
an HD roughly doubles these numbers. In all cases it is interest-
ing multichannel cameras and instruments dedicated to exoplanet
detection.

It was previously mentioned that an existing MCC could be
adapted for use with an HD; we take NICI as an example and
briefly state the type of work that would be needed to do so. The
NICI system (see Toomey & Ftaclas 2003)\(^9\) consists of a complete
AO system followed by a dual-channel camera operating in the 1–
5 μm wavelength interval. The focal plane of the camera is located
outside of the cryostat. At this focal plane, a wheel mechanism is
used to select between various occulting masks for coronagraphy.
To implement an HD in this system it would thus be necessary to
replace the occulting mask wheel by a mechanism to hold the HD
and make it rotate or move continuously as explained in § 2. This
mechanism would not be technically challenging to realize, as it
would be warm. The entrance focal ratio of the camera \(f/D_{\text{MCC}}\)
is 16, and thus a diffuser diverging light within a cone of half-
angle equal to 1.8° would be needed; a custom HD matched to
this angle should be manufacturable, as this is within the range of
angles available from Physical Optics Corporation. As explained
previously, it would be necessary to enlarge the exit focal ratio of
the AO system \(f/16\); based on our numerical simulations and
experimental results, a factor of 3–4 appears adequate. This mag-
nification would be provided by a system of lenses placed be-
 tween the dichroic of the AO system and the HD mechanism;
these lenses would be warm. Accordingly, the field of view would
be reduced by the same factor. These modifications would pre-
clude the use of coronagraphy and would increase the thermal
background at longer wavelengths. However, the latter is irre-
relevant for planet searches as SSDI observations are made in the
H band, and the loss of coronagraphic capabilities would be largely
overcompensated by the increase in speckle noise suppression
given the modest Strehl ratios expected.

5. DISCUSSION

The experiment presented in this paper validates the concept
of breaking the wave front coherence before separating it into mul-
tiple wavelengths for SSDI. It is clearly demonstrated that this
strategy reduces the limitations imposed by differential aberrations.
Still, the two-bandpass attenuation obtained with our testbed could
have been as high as 25, considering the wavelengths of the filter
mosaic used. We do not believe that the attenuation achieved was
limited by differential aberrations, nor that it represents a funda-
mental limit to the attenuation achievable with such a system. The
fact that the single-bandpass attenuation was higher offers evi-
dence for this claim. We believe that a dedicated MCC built with
more care, i.e., with baffles to reduce scattered light, with coatings
on all surfaces to reduce ghost artifacts, with a better alignment of
the prism with respect to the beam splitter to minimize differential
rotation and distortion between channels, with a more precise con-
trol of co-focality between channels, and with better mechanical
stability, would provide better noise attenuation. The design of
NICI correctly addresses these issues and thus NICI should not
suffer from these shortcomings. For completeness, we estimated
how the planet detection efficiency would improve with better
speckle noise attenuation. It was previously mentioned that the
maximum attenuation is ~30 for bandpasses appropriate for exo-
planet searches. With such an attenuation, the planet detection ef-
ficiency would increase further by ~25%.

The experimental validation of the concept that we presented
also offers a good indication that an integral field spectrograph based
on a microlens array (e.g., GPL, Macintosh et al. 2006a; SPHERE/
IFS, Dohlen et al. 2006; or PFI, Macintosh et al. 2006b) should
work well. In such a system, a microlens array is placed at the
focal plane to spatially sample the PSF. Each microlens produces a
small pupil that is dispersed and re-imaged onto a detector by a
spectrograph; a spectrum of each spatial sample of the PSF is thus
obtained. Data processing allows the construction of a PSF data
cube, containing a spectrum for each spatial pixel. Similarly to the
HD, the spatial sampling of the PSF made by the microlens array
breaks the coherence of the wave front, and each “micro pupil”
becomes an independent source for the spectrograph. In this case,
differential aberrations in the spectrograph affect only the light
distribution within the spectra and not the speckles of the PSF im-
aged. Hence, images of the PSF at different wavelengths should be
highly correlated. Preliminary laboratory tests of an integral field
spectrograph prototype seem to corroborate this hypothesis
(Lavigne et al. 2006). Based on a similar argument, the use of a
microlens array at the entrance focal plane of an MCC, a concept
presented in Lafrenière et al. (2004), should be a good alternative
solution.

6. CONCLUSION

The concept of placing an HD at the entrance focal plane of an
MCC to minimize the impact of differential aberrations in SSDI
was presented. This concept was shown experimentally to im-
prove significantly the speckle noise attenuation: our dual-beam,
dual-bandpass experimental testbed produced a speckle noise at-
tenuation of ~12–14, a factor of ~5 improvement over existing
SSDI cameras. Using Monte Carlo simulations of realistic exo-
planet populations, it was shown that such an improvement in
speckle noise attenuation could yield an increase by a factor ~2
of the number of potentially detectable exoplanets. The option
presented in this paper should be considered seriously for upcom-
ing multichannel cameras and instruments dedicated to exoplanet
detection.

\(^9\) See also http://www.gemini.edu/sciops/instruments/nici/niciIndex.html.

| Configuration | Target Sample |
|---------------|---------------|
|                | NYS | TWA | ρ Oph |
| No HD          | 0.063 | 0.175 | 0.125 |
| HD with 4× magnification | 0.113 | 0.299 | 0.256 |
| HD without magnification | 0.128 | 0.295 | 0.244 |
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APPENDIX

VLT SDI TWO-CHANNEL SUBTRACTION ATTENUATION

Since the speckle noise attenuation resulting from a two-channel subtraction of images using SDI is unavailable in the literature, it is estimated here. Observations of the star AB Dor obtained on 2004 February 1 (Close et al. 2005) were retrieved from the European Southern Observatory science archive and used to quantify the performance of SDI. This data set consists in two sets of images at five dither positions obtained at position angles differing by 33°. SDI produces four simultaneous PSF images: one at 1.575 μm, one at 1.600 μm, and two at 1.625 μm. The reduction steps consisted in the subtraction of a sky frame, division by a flat field image, and correction of bad pixels using the median of neighboring pixels. The PSF images of all channels were then spatially scaled to match the 1.625 μm channel and registered to a common center with subpixel accuracy. When two PSF images were subtracted, their intensity was adjusted to minimize the residual noise. The six possible two-channel subtractions were performed and a noise attenuation 2.0–2.5 was obtained for all cases. Figure 8 shows the mean attenuation curve over the 10 images for the subtraction of the two 1.625 μm channels. We stress that this attenuation is not the best achievable with the SDI device; subtraction of simultaneous multichannel difference images obtained at different instrument rotation angles have been shown to attenuate further the residuals; see Biller et al. (2004) for more detail.

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