Adaptive pupil masking for quasi-static speckle suppression

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ABSTRACT
Quasi-static speckles are a current limitation to faint companion imaging of bright stars. Here we show through simulation and theory that an adaptive pupil mask can be used to reduce these speckles and increase the visibility of faint companions. This is achieved by placing an adaptive mask in the conjugate pupil plane of the telescope. The mask consists of a number of independently controllable elements which can either allow the light in the subaperture to pass or block it. This actively changes the shape of the telescope pupil and hence the diffraction pattern in the focal plane. By randomly blocking subapertures, we force the quasi-static speckles to become dynamic. The long-exposure point spread function (PSF) is then smooth, absent of quasi-static speckles. However, as the PSF will now contain a larger halo due to the blocking, the signal-to-noise ratio (SNR) is reduced requiring longer exposure times to detect the companion. For example, in the specific case of a faint companion at $5\lambda/D$, the exposure time to achieve the same SNR will be increased by a factor of 1.35. In addition, we show that the visibility of companions can be greatly enhanced in comparison to long exposures, when the dark speckle method is applied to short-exposure images taken with the adaptive pupil mask. We show that the contrast ratio between the PSF peak and the halo is then increased by a factor of approximately 100 (5 mag), and we detect companions 11 mag fainter than the star at $5\lambda/D$ and up to 18 mag fainter at $22.5\lambda/D$.

Key words: instrumentation: adaptive optics – instrumentation: high angular resolution.

1 INTRODUCTION
Detecting the faint reflected or the self-luminous signal from extrasolar planetary companions close to a bright parent star is a technically difficult task. With the development of sophisticated image analysis and adaptive optics (AO) systems on several modern large (8 m class) telescopes it is now possible. AO is required both to increase the peak intensity of the point spread function (PSF) and to concentrate the photons which are scattered into a diffuse halo by the atmosphere back into the diffraction-limited core. Dedicated high-contrast imaging instruments, such as HiCAIO (High Contrast Instrument for the Subaru Next Generation Adaptive Optics, Subaru; Hodapp et al. 2008), SPHERE (Spectro-Polarimetric High-Contrast Exoplanet Research, Very Large Telescope: Beuzit et al. 2008) and GPI (Gemini Planet Imager, Gemini; Macintosh et al. 2006), are designed to incorporate extreme AO (XAO) systems and sophisticated coronagraphs to reject the light from the star whilst conserving a few photons from the angularly separated companion. Quasi-static speckles, mimicking the signal of faint companions, are now limiting the detection capabilities of these instruments (e.g. Fitzgerald & Graham 2006; Soummer et al. 2007). Quasi-static speckles in the focal plane are caused by non-common path errors and uncorrected aberrations in the primary mirror and other optical and mechanical components. If these aberrations were entirely deterministic, then they could be subtracted. However, quasi-static speckles are slowly varying aberrations making calibration difficult.

The current most popular methods for quasi-static speckle reduction are PSF subtraction techniques such as PSF estimation (e.g. Lafrenière et al. 2007), angular differential imaging (ADI; Marois et al. 2006), simultaneous spectral differential imaging (SSDI; Smith 1987) and, in the case of the reflected light, polarimetric differential imaging (PDI; Seager, Whitney & Sasselov 2000). SSDI and PDI both require certain properties from the target. ADI is more generic, but if the speckles evolve during the observation the suppression provided by the technique reduces dramatically. The temporal decorrelation time-scale of these quasi-static speckles is an important factor when estimating the performance of image subtraction techniques which have proved themselves to be efficient at Strehl ratios of the order of 20–40 per cent (Martínez et al. 2012). At a high Strehl ratio (>80 per cent), the quasi-static speckles will become even more dominant as the PSF halo is reduced further. In this high Strehl regime, the speckle coherence time-scale is unknown. Martínez et al. (2012) show that the quasi-static speckles become unstable over a time-scale of a few seconds on a laboratory XAO test bench. It is thought that the evolution of the speckle pattern was primarily caused by temperature fluctuations and so, on a dedicated instrument, this could be more controlled.

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Several other interesting and inventive techniques are also being
developed in order to further enhance the probability of detecting
faint companions. Ribak & Gladysz (2008) demonstrate that it is
possible to enhance the contrast ratio by placing a rotating eccentric
mask in the pupil plane. This breaks the symmetry between the
telescope pupil and the focal plane causing the quasi-static speckles
to move; the companion will however stay fixed at the same location.
Gladysz & Christou (2008, 2009) use the statistical distribution
difference of on-axis and off-axis PSFs to differentiate between real
sources and speckles. It is likely that only the combination of several
of these techniques in conjunction with AO and a coronagraph will
result in the highest contrast ratios in modern instrumentation.

Here we propose to combine the idea of breaking the symmetry
of the optical system and the sensor by changing the pupil function
(similar to Ribak & Gladysz) with an adaptive pupil mask
(APM; Osborn, Myers & Love 2009). The APM is positioned in
the conjugate plane of the telescope pupil. This pupil mask consists
of a number of independently controllable elements. The simplest
design would be a segmented mirror where each segment can either
reflect the light on-axis into the remaining optical system or
off-axis into a baffle. This is also similar to the speckle decorrela-
tion (or phase-boiling) method (Saha 2002). The phase-boiling
method involves adding additional phase aberrations to the optical
path in order to force the quasi-static speckles to be more dynamic.
This was later disproven by Sivaramakrishnan et al. (2002) as the
original phase aberrations are still present and so the quasi-static
speckles, simply hidden within a field of dynamic speckles. Here
we boil the speckles by introducing amplitude aberrations instead
of adding phase aberrations, an important difference as the interfer-
ence pattern will no longer contain the same speckle pattern, but
will actually be completely different.

By changing the shape of the pupil, we modify the diffraction
pattern in the pupil plane. The light that once interfered construc-
tively to form a quasi-static speckle at a given location will now
not. However, speckles will be formed in other locations in the fo-
cal plane. The quasi-static speckles will be forced to be dynamic,
removing any dependence on the speckle time-scale. By changing
the pupil function many times during an exposure, these speck-
les will average out into a smooth PSF, albeit with an additional
halo due to diffraction through the pupil mask (Babinet’s prin-
ciple). This will mean that longer integration times are required for
a companion to become visible with the same signal-to-noise ra-
tio (SNR). However, the quasi-static speckles will be substantially
reduced, reducing the complexity of the companion identification
problem.

In addition to the APM averaging the static speckles into a smooth
halo, we can also expose after each configuration of the mask sepa-
ately. As the quasi-static speckles are now dynamic, we can use
other image manipulation methods to further enhance the image.
Dark speckle (DS) imaging, first proposed by Labeyrie (1995), is
a technique designed for the detection of faint companions in the
presence of dynamic speckles induced by the turbulent atmosphere.
Briefly, after a low-order AO correction to focus the majority of
the photons into the diffraction-limited core and a coronagraph to
reject the photons from the star, there still remain some atmospheric
turbulence-induced speckles in the PSF halo in short exposures. In
this speckle halo, at some locations the wavefront will interfere
destructively and result in a zero-photon event. As the atmosphere
evolves and traverses the telescope field of view, the position of
these nulls will change in the focal plane. However, at the pos-
tion of a faint companion, the probability of a zero-photon event
is considerably lower. Therefore, by counting the number of times
each pixel records a zero-photon event in each short exposure, we
can generate a ‘dark map’ where the position of the companion will
have a value lower than the rest of the image. Modern XAO systems
are designed with target residual wavefront errors (WFEs) of the
order of a few nanometres and so there is actually very little in the
way of residual atmospheric speckle. However, as the quasi-static
speckles are now dynamic, we can use the DS method to suppress
the dynamic quasi-static speckles.

The DS method is intended to be used to enhance AO-corrected
images. Each DS exposure must be short; otherwise, the AO residual
speckles will average, reducing the speckle nulls. Here we develop
the technique for quasi-static speckles, in which case the exposure
time no longer needs to be short, and we record the minimum value
over a number of mask configurations.

An additional advantage of the pupil mask is that it is a con-
figurable device allowing it to act in several different observing
modes. In ‘adaptive’ mode, the mask can also be used to put a
hard limit on the residual atmospheric WFE. APMs like this have
been shown to be able to reduce the PSF halo and actually in-
crease the PSF peak intensity despite removing photons (Osborn
et al. 2009), making it useful in scenarios where only low-order
AO or even no AO is available. The APM could be used in ‘static’
mode as a non-redundant aperture mask (e.g. Kopilovich 1984) or
partially redundant aperture mask (e.g. Buscher & Haniff 1993),
used in many modern high-contrast imaging instruments. If the
APM is of sufficiently high order, it can also be used to emulate
any binary shaped pupil-plane mask coronagraph (e.g. Nisenson &
Papaliolios 2001; Kasdin et al. 2003). The configuration of these
static masks can easily be changed to experiment with different
positions, element sizes and configurations, a current area of active
research.

In Section 2, we describe the simulation; in Section 3, we intro-
duce the APM and show how it will reduce the quasi-static speckles;
Section 4 describes the application of the DS method to APM; in
Section 5, we discuss the results, and we conclude in Section 6.

2 SIMULATION

2.1 Quasi-static speckles

The combined mirror and optical aberrations are simulated using the
method of Cavarroc et al. (2006) using the $\kappa^{-2}$ (where $\kappa$ is the spatial
frequency) power law in the spatial power spectrum, as defined in
Duparré et al. (2002). Fig. 1 shows a resultant static phase error,
the corresponding image and an example of the speckles found by
subtracting an image generated with quasi-static speckles from the
one generated without quasi-static speckles.

2.2 Adaptive optics

A Monte Carlo simulation has been developed to test the concept.
The simulation includes Poisson noise, sky background noise (as-
suming 14th magnitude) and $10^{-6}$ read noise. Residual AO phase
aberrations are also included in the simulations. We assume a Strehl
ratio of 90 per cent (a measure of AO residual error), consistent
with predictions for XAO systems. This residual WFE results in a
speckled intensity pattern around the diffraction-limited core; over
time this averages to a smooth halo.

There are a few choices for simulating this AO-corrected PSF.

(i) We can assume a basic two-part PSF, with a central
diffraction-limited core and a larger, to a spatial extent, Gaussian
The primary mirror phase aberrations and pupil including the telescope’s secondary support spiders. The RMS error is one fifth of a wavelength. On the right-hand side is a log-scaled simulated image of a star with AO residuals, photon noise, read noise, sky background noise and quasi-static speckles. The lower panel shows the speckles. Plotted is the absolute difference between two images, one with quasi-static speckles and one without.

(ii) We can use a fully analytical approach using statistical distributions to estimate the infinitely long-exposure AO-corrected PSF. As above, this will also result in a smooth PSF absent of residual speckles, but will be more accurate as it will include a deformable mirror model (subaperture sizes, mirror type, etc.).

(iii) We can use a complete end-to-end Monte Carlo simulation. This is more complicated and requires in-depth modelling of the whole optical system (including wavefront sensors, reconstructor, mirror dynamics, etc.) which is system dependent. This is a more complicated solution which is difficult to develop, test and calibrate.

(iv) The last option is a combination of the two points above. We use a statistical expression to generate AO-corrected phase screens – removing the need for wavefront sensors, reconstructor and deformable mirror dynamics, but retaining the non-deterministic nature of the PSF. This will be an approximation which is not reflected by any real system, but it will give an estimate of the AO-corrected PSF containing residual PSF speckles averaged over whatever timescale we desire.

Due to the instrument’s independent nature of this work, we only need an approximation to an AO-corrected PSF with the desired WFE. For this reason, the corrected PSF is generated using the last method in the list above.

The AO-corrected PSF is estimated by summing over a number of independently realized instantaneous PSFs. Each of which is generated by a semi-analytical method of spatially filtering a von Karman phase screen with an AO transfer function and Fourier transforming to form an image. An AO system will reduce the spatial power spectrum at low spatial frequencies, the effect of which can be modelled by a high-pass filter, $H(kd/2)$ (Greenwood 1978),

$$H(kd/2) = 1 - \left(\frac{2J_1(kd/2)}{kd/2}\right)^2 - 16(2/kd)^2 J_2^2(kd/2) \tag{1},$$

where $d$ is the diameter of the subapertures and $J_n$ is a Bessel function of the first kind of the order of $n$. The given equation is for a segmented mirror with tip/tilt and piston correction. This filter function only includes the deformable mirror fitting. Wavefront sensor errors (noise, non-linearity, etc.), deformable mirror dynamics, latency and reconstructor errors are not considered.

The AO residual phase spectral density, $\Phi_{AO}$, is then given by

$$\Phi_{AO}(k) = H(kd/2)\Phi_{atmos}(k) \tag{2},$$

where $\Phi_{atmos}(k)$ is the von Karman spatial phase power spectrum ($\Phi_{atmos}(k) = r_0^{-5/3}(k/2 + 1/L_o^2)^{-11/6}$, $r_0$ is the Fried parameter – a measure of the strength of the turbulence and $L_o$ is the outer scale of the atmospheric turbulence).

The AO-corrected phase screen is then given by (Ellerbroek 2002)

$$\phi_{AO} = \frac{0.1517}{\sqrt{2}} \left[ \frac{W}{r_0} \right]^{5/6} r_0 |\mathcal{F} \left[ \sqrt{\Phi_{AO}(k)}(\chi(k) + i\chi'(k)) \right]|, \tag{3}$$

where $W$ is the width of the phase screen and $(\chi(k) + i\chi'(k))$ is a randomly generated repeatable white noise field.

The filtered optical turbulence phase, $\phi_{AO}$, is added to the static phase aberrations, $\phi_{static}$. This assumes that the two are independent. In fact, the AO system will attempt to correct some of the static aberrations and so $\phi_{static}$ is also spatially filtered by the AO filter function. Therefore, $\Phi_{AO,static} = H(kd/2)\Phi_{static}$ can be used to replace $\Phi_{AO}(k)$ in equation (3) to generate the quasi-static phase aberrations. The PSF is given by

$$I(\rho, \theta) = \sum_{0}^{N} |\mathcal{F}[P(\xi) \exp(-i\phi_{static}(\xi, \eta) + \phi_{AO}(\xi, \eta, t))]|^2 \tag{4},$$

where $\mathcal{F}$ is the fourier transform operator, $P(\xi)$ is the pupil function and is equal to 1 when $\xi < D/2$ and 0 otherwise, $D$ is the diameter of the telescope aperture, $\rho$ and $\theta$ are the polar coordinates in the focal plane, $\xi$ and $\eta$ are the pupil-plane variables in the polar coordinate space, $N$ is the number of simulation iterations and $t$ denotes the time variable.

2.3 Simulation parameters

The process is repeated and a long-exposure image is built up for as many iterations as required. The telescope diameter is 8 m, $d = 0.18$ m, $r_0 = 0.12$ m, $L_o = 30$ m, the observing wavelength is 1.6 $\mu$m with a bandwidth of 0.23 $\mu$m ($H$ band), the exposure time is 30 s and the pixel scale is 0.25$\mu$m/$D$.

No coronagraph is included in the simulations, this is because modern coronagraphic techniques are as numerous as they are complicated. This means that any achieved contrast ratios cannot be directly compared to those from any high-contrast imaging instruments. Instead, we compare to a standard image with AO but without any other form of image manipulation.

Fig. 1 (top-right) shows the simulated focal plane image of a bright target and nine fainter companions. The companions are distributed from the centre to the bottom of the image. The central star has a magnitude of 4 and the companions have magnitudes 14–22, reducing by one magnitude for each step (2.5$\mu$m/$D$) outwards.
3 ADAPTIVE PUPIL MASKING

A reconfigurable mask is used to block the light of a chosen fraction, \( f \), of the pupil. This is done with a spatial light modulator with \( 44 \times 44 \) elements. In each iteration, a random selection of these elements is flipped to block an area of the pupil. The pupil function therefore changes in each iteration. As the image can be thought of as the interference pattern of the pupil function multiplied by the complex amplitude of any phase aberrations, the image in the focal plane will therefore also be modified. The random nature of the APM is important as this means that it is completely independent from any other optical component; it is modular. No additional information or optical components (e.g. wavefront sensors) are required.

The image is now given by

\[
I(\rho, \theta) = \sum_{\xi=0}^{N} |F[M(\xi, \eta, t)P(\xi)] \exp(-i\phi_{\text{dual}}(\xi, \eta) + \phi_{\text{AO}}(\xi, \eta, t))]|^2, \tag{5}
\]

where \( M(\xi, \eta, t) \) is the time-dependent mask function. In the simulation presented here, we block a random 15 per cent of the telescope aperture in each iteration. The actual fraction can be chosen and optimized by the user depending on system specific parameters. Here we choose 15 per cent as this is consistent with the throughput of many coronagraphic systems (Ribak & Gladysz 2008).

In the modified images, the quasi-static speckles are no longer quasi-static but are actually very different in each iteration. Fig. 2 shows two consecutive focal images and the modulus of the difference. In each individual frame, the speckle pattern is completely different. No atmospheric turbulence was included to generate these plots and so the speckle movement is entirely due to the changing pupil mask. Fig. 3 shows the sum of 1000 frames. We can define a metric for the magnitude of the quasi-static speckle as the normalized azimuthal variance,

\[
\sigma^2(\rho) = \frac{1}{2\pi\rho} \int_0^{2\pi} \left| I(\rho, \theta) - \langle I(\rho) \rangle \right|^2 \frac{d\theta}{I(\rho)}, \tag{6}
\]

where \( \langle I(\rho) \rangle \) denotes the expected intensity of the PSF at radius \( \rho \). The metric must be normalized by the azimuthal average or the variance will be biased by the radial intensity of the image. Fig. 4 shows the azimuthal variance for the original image and the APM image. We see that the radial intensity variance for the original image is approximately constant for all field angles; the speckle is dominant over the diffraction halo. The azimuthal variance for the APM image continues to reduce with separation. At small angles, the diffraction pattern from the central star is intense and the speckles are ‘pinned’ to the first diffraction rings (Bloemhof et al. 2001), even with the APM. At larger angles, the speckles are more free to move and so we achieve a greater suppression.

When we sum the images over a number of iterations, each with a different pupil pattern, the quasi-static speckles average out to a smooth PSF. However, as we are using square blocking elements, Babinet’s principle dictates that we can expect the diffraction-limited PSF to be a superposition of a square diffraction pattern of the blocking elements and the circular diffraction pattern from the pupil. The diffraction-limited PSF in polar coordinates is therefore given by

\[
\text{PSF}(\rho, \theta) = \frac{1}{(1 - \alpha^2)^2} \left( \frac{2J_1(\rho D/2)}{\rho D/2} - \alpha^2 \frac{2J_1(\alpha \rho D/2)}{\alpha \rho D/2} \right)^2 \left(1 - f\right) + 2\alpha^2 \sin\left(\frac{\rho a \sin(\theta)}{2}\right) \sin\left(\frac{\rho a \cos(\theta)}{2}\right) f, \tag{7}
\]

where \( \rho \) is related to the pupil-plane parameters by \( \rho = 2\pi \xi/\lambda f_1 \), \( \lambda \) is the wavelength of the light and \( f_1 \) is the effective focal length of the optical system, \( \alpha \) is the fractional radius of the central obscuration and \( a \) is the length of one side of one of the masking elements.

As the mask elements are smaller than the pupil, the diffraction pattern is broader, increasing the halo around the PSF. Smaller blocking elements will result in a broader diffraction halo, and a greater blocking fraction will result in a diffraction halo with a greater fraction of the total energy.

Although the sum of the individual frames does show a reduction in the quasi-static speckles, the disadvantage would be the decreased SNR due to the increased halo intensity and reduced peak intensity. This means that we would have to integrate for longer to achieve the same SNR, although the quasi-static speckles will no longer form a fundamental limit – we are now limited by the photon noise.

Figure 2. Two individual consecutive images after APM (left and centre). The speckle pattern in each image is different as shown by the modulus of the difference of the images (i.e. \( |I_1 - I_2| \), where \( I_1 \) and \( I_2 \) are the intensity patterns of the two frames) in the right-hand panel. In this example, we block a random 15 per cent of the pupil.

Figure 3. The sum of 1000 images. In this example, we block a random 15 per cent of the pupil.

\[
\text{Adaptive pupil masking} \quad 2287
\]
The theoretical form of the APM PSF is derived by Osborn, Myers & Love (2010). Here we briefly review the theoretical structure of the PSF for the case of random pupil blocking. The PSF, assuming on-axis observations, can be estimated from the modulation transfer function (MTF) of the residual atmospheric phase aberrations and of the telescope aperture. The PSF is given by

$$\text{PSF} = (F(M_{\text{tel}} \times M_{\text{tel}})) \times (1 - f),$$  \hfill (8)

where $M_{\text{tel}}$ is the atmospheric modulation transfer function and $M_{\text{tel}}$ is the telescope modulation transfer function. As the MTF is defined for unit total intensity, the PSF must be scaled by $(1 - f)$. We can see that the total intensity of the image is reduced by $f$, but the change in peak intensity is not so obvious. It has been shown that with careful pupil blocking the peak intensity can actually be increased (Osborn et al. 2009). However, here we choose to randomly block the pupil. In this case, we would expect the peak intensity to be reduced. The peak intensity is equal to the integral of the pupil,

$$I_0 = \int_0^\infty (M_{\text{tel}} \times M_{\text{tel}}) \, dv (1 - f),$$  \hfill (9)

where $v$ is the spatial frequency in the focal plane and is related to the separation in the pupil plane, $r$, by $r = \lambda f v$. The MTF is related to the phase structure function $D$ by

$$M_{\text{tel}}(v) = \exp \left( -0.5 D_{\text{tel}}(v) \right),$$  \hfill (10)

and (Rao, Jiang & Ling 2000)

$$D_{\text{tel}}(v) = 4\pi \int_0^\infty \left[ 1 - J_0(\kappa v) \right] \Phi_{\text{tel}} \, d\kappa.$$  \hfill (11)

Therefore,

$$M_{\text{tel}}(v) = \exp \left( -0.5 \times 4\pi \int_0^\infty \left[ 1 - J_0(\kappa v) \right] \Phi_{\text{tel}} \, d\kappa \right).$$  \hfill (12)

$M_{\text{tel}}$ is given by the autocorrelation function of the aperture function. This will be the product of the pupil function and the mask,

$$W(\xi, \eta, t) = M(\xi, \eta, t) P(\xi, \eta),$$  \hfill (13)

and so

$$M_{\text{tel}}(v) = \mathcal{F}\left[ \left[ W(\xi, \eta, t) \right]^2 \right].$$  \hfill (14)

The mask will act to reduce $M_{\text{tel}}$ due to the lower fill factor in the pupil (less redundancy in Fourier baselines), reducing the peak intensity of the image. Using the above, we can write equation (8) as

$$\text{PSF} = \left( F \left[ \exp \left( -0.5 \times 4\pi \int_0^\infty \left[ 1 - J_0(\kappa v) \right] \Phi_{\text{tel}} \, d\kappa \right) \right] \times \mathcal{F}[|W(\xi, \eta, t)|^2] \right) \times (1 - f)$$  \hfill (15)

and equation (9) as

$$I_0 = \int_0^\infty \left( \exp \left( -0.5 \times 4\pi \int_0^\infty \left[ 1 - J_0(\kappa v) \right] \Phi_{\text{tel}} \, d\kappa \right) \right) \, dv \times (1 - f).$$  \hfill (16)

This is solved numerically, and for a random blocking of 15 per cent we find that the peak intensity is reduced by $\sim 27$ per cent. To take a specific example, if we would like to observe a companion at $5\lambda/D$, the normalized halo would be increased by $\sim 16$ per cent in comparison to the non-blocked image.

The exposure time, $t_o$, to achieve a given SNR assuming that we are limited by the photon noise of the halo is given by

$$t_o = \frac{\text{SNR}^2 \epsilon}{SAc},$$  \hfill (17)

where $S$ is the signal from the planet, $A$ is the telescope area, $\epsilon$ is the efficiency of the optical system and $c$ is the contrast ratio between the intensity at the position of the image and the companion signal, $c = n_{\gamma,b}(\rho = 5\lambda/D)/n_{\gamma,\text{comp}}(\rho = 0)$, where $n_{\gamma,b}(\rho = 5\lambda/D)$ is the number of photons in the halo at the position $\rho = 5\lambda/D$ and $n_{\gamma,\text{comp}}(\rho = 0)$ is the peak number of photons from the companion.

As the mask will increase the PSF halo and reduce the companion signal, the contrast ratio will be increased, requiring longer exposure times to conserve the SNR. For the ratio $t_o/t_{\text{APM}}$, this simplifies to

$$t_o/t_{\text{APM}} = (1 - f)c/\epsilon_{\text{APM}}.$$  \hfill (18)

where $t_{\text{APM}}$ and $c_{\text{APM}}$ are the exposure time and the contrast ratio of the APM image, respectively. Using the figures found numerically above, we see that the contrast ratio is increased by a factor of 1.59 for a companion at $5\lambda/D$. The exposure time to achieve the same SNR in the noiseless case would be 1.35 times longer than the non-blocked image. This is confirmed by the Monte Carlo simulation with a value of 1.37. With noise (background, read and shot noise) the value is increased to 1.47.

4 DS IMAGING

As we have forced the quasi-static speckle pattern to be dynamic, we can use the individual frames to increase the image quality. One suggestion, developed here, would be to use the DS analysis of Labeyrie (1995).

In each frame, the speckle pattern will have minima in intensity. The location of these nulls will vary as the pupil mask changes shape. In the position of the faint companion, the probability of seeing a speckle null is considerably lower than anywhere else.

The proposed technique here is slightly different to that of Labeyrie. DS imaging is not applicable to long exposures as the atmospheric speckles will average over time, reducing the depth of the nulls. However, here we are not necessarily restricted to very short exposures and hence the readout noise, sky background and AO residuals will mean that the probability of measuring zero photons over an arbitrary time period is low. Instead, we record the lowest value of each pixel over all of the iterations of mask configuration. We have chosen to expose 1000 iterations at 3 s exposure time each, resulting in a total observing time of approximately 50 min. Fig. 5 shows the DS image. We see that eight of the companions are now easily visible. The companion closest to the bright star (at $2.5\lambda/D$) is still hidden in the halo from the bright star.

Figure 5. DS image. Plotted is the minimum count of each pixel over every iteration of the mask. Eight of the nine companions are now clearly visible. The ninth, the closest, companion is still hidden in the halo of the bright star.
A disadvantage of this technique is that the intensity at the location of the companion will be the minimum flux measured from the companion over an exposure time of one iteration. This will have the expected value of the intensity of the companion minus the shot noise. For this technique to work, a large number of readouts are required, although it should be noted that as we are only recording the minimum value of each pixel, we are essentially only including one readout per pixel.

A coronagraph would reject a large fraction of the photons from the parent star and improve the results at small angular separations. For example, if we assume the use of a perfect coronagraph (i.e. one which removes the diffraction-limited PSF but not the quasi-static speckles, noise or any diffraction effects due to the mask), then Fig. 6 shows the original image and the DS image. All companions are now visible with very little speckle.

5 DISCUSSION

For comparison, Fig. 7 shows the final images including the nine faint companions for the case of no manipulation, long-exposure APM and APM with DS image analysis. We can examine radial cuts of the final images to compare performance. In Fig. 8, we show a radial cut in the direction of the companions and the azimuthal average for the final APM+DS image (top), long-exposure APM image (middle) and the original image (bottom). The vertical lines indicate the position of the faint companion. Fig. 9 shows the radial profile of the original image, the long-exposure APM image and the APM+DS image on the same axis.

We can see that the effect of the companions is visible in the original and long-exposure images, but only the APM+DS method has been able to isolate all but the closest companion successfully in this case. At separations greater than 5λ/D, the contrast ratio between the PSF peak and the halo is increased by the DS method by a factor of approximately 100, corresponding to 5 mag. It is clear that not only have the speckles been suppressed but also the bright star diffraction pattern. This is because the speckle nulls are lower than the average intensity of the PSF halo for any given location. We are now able to detect companions 11 mag fainter than the star at the separation of 5λ/D and 18 mag fainter at 22.5λ/D. The inner working angle would be improved with the use of a coronagraph or other PSF subtraction methods which are not included here.

The performance of the technique is dependent on the parameters selected and on the properties of the system we wish to observe. Detection is modified if we increase the fraction that the APM
blocks, the number of iterations or the Strehl ratio of the AO system, of which only the blocked fraction of the mask and the number of iterations are controlled by the observer. If we increase the fraction which is blocked, then we generate more speckles in the focal plane, which means quicker averaging and more nulls. However, it will also mean reducing the throughput of the system; therefore, this will depend on the system to be observed. In the simulation, we blocked 15 per cent of the pupil. The number of iterations of the mask is also important. The more the number of iterations, the greater number of configurations of the mask are used. This means more averaging in the long-exposure APM image and means that more nulls are measured in the DS image, increasing detection. The number of iterations is a balance between the amount of time available for an observation and the exposure time of each iteration. In order to receive a significant number of photons from the companion, it may be necessary to increase the exposure time; this will limit the possible number of iterations. In the simulations, we assumed 1000 iterations of 3 s each. It should be noted that there is no limit to the exposure time of each iteration.

6 CONCLUSIONS

Atmosphere-induced phase aberrations (with or without AO) cause a halo of speckles to form around the PSF. This source of noise will average over time and, given enough time, faint companions can be observed above this halo. Current high-contrast imaging is limited by quasi-static speckles caused by the optics and structure of the telescope. This is because these quasi-static speckles do not average. They appear in the image as potential false-positive candidates for faint companions and are difficult to distinguish. Here we have presented a technique to turn these static speckles into dynamic speckles. This means that over time these static speckles will also average into a broad halo. The shape and magnitude of this halo will depend upon the geometry of each mask element and the fraction of the pupil that is blocked. This means that over time the PSF will converge to a smooth form allowing the companions to be seen above. However, as the APM adds more energy to the halo and the throughput of the system is reduced by a fraction equal to the fraction of the pupil which is blocked, the SNR is reduced. We would need to observe for a longer period of time to collect enough photons from the companion to be seen above the halo. For an example case of a companion at 5λ/D, we would need to observe for 1.35 times longer (1.47 defined by the simulation including noise) to achieve the same SNR. In this case, we do not need to expose the CCD between each mask state and so the mask frequency can be high allowing many mask states for an arbitrarily long exposure.

In addition to the smoother PSF, we can also use other conventional image manipulation techniques which are normally used for the dynamic speckling caused by atmospheric turbulence. Here we show the effect of implementing an adaptation of Labeuyre’s DS analysis. This is a simple technique where we record the minimum value of each pixel over all iterations of the mask.

Using this technique in a Monte Carlo simulation, we can detect faint companions with a higher magnitude difference from the central star. We find that at separations greater than a few λ/D, the PSF halo count is reduced by a factor of approximately 100, corresponding to a contrast increase of 5 mag.

Due to the APM, the diffraction rings from the bright star also move, this means that the diffraction pattern from the bright star is also suppressed by the APM when used with the DS imaging analysis. At small inner working angles, there is still some confusion between the companions and that of the parent star, due to the pinned speckles in the bright diffraction rings. However, we are now able to detect companions 11 mag fainter than the star at the separation of 5λ/D and up to 18 mag fainter at 22.5λ/D. The inner working angle would be improved with the use of a coronagraph or other PSF subtraction methods which are not included here. In order to perform the DS analysis, short-exposure images will have to be recorded. The length of the short exposures is arbitrary, but the optimal will depend on the number of iterations required during the exposure and the magnitude of the target.

The noise attenuation found here is comparable with the attenuation of the high-order test bench with ADI (Martínez et al. 2012). The advantage of this technique over ADI is that it does not rely on PSF subtraction and is therefore insensitive to any changes in the quasi-static pattern. It has an advantage over PDI and SSDI that it is also insensitive to the companion properties, i.e. it does not require the companion to have a specific emission spectrum or the light to be reflected and hence partially polarized. The disadvantage is the reduced throughput.

APM would benefit from a collaboration with other techniques. Currently, the inner working angle is limited by the diffraction pattern of the primary star. A coronagraph would reject light from the central star resulting in even higher achievable contrast ratios. Also, no additional image manipulation was performed. No attempt at PSF subtraction was made. The dynamic speckles will average into the predictable smooth long-exposure PSF, which could be subtracted. Therefore, compounding this technique with other instruments would further improve the noise attenuation and reduce the probability of false-positives.

It is also important to note that by including a high-order APM, in addition to quasi-static speckle removal, it would also be possible to reduce the residual WFE, emulate a non-redundant (or partially redundant) aperture mask and a binary shaped pupil-plane coronagraph, all of which would be completely and easily reconfigurable.

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