The VAMPIRES instrument: imaging the innermost regions of protoplanetary discs with polarimetric interferometry

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ABSTRACT

Direct imaging of protoplanetary discs promises to provide key insight into the complex sequence of processes by which planets are formed. However, imaging the innermost region of such discs (a zone critical to planet formation) is challenging for traditional observational techniques (such as near-IR imaging and coronagraphy) due to the relatively long wavelengths involved and the area occulted by the coronagraphic mask. Here, we introduce a new instrument – Visible Aperture-Masking Polarimetric Interferometer for Resolving Exoplanetary Signatures (VAMPIRES) – which combines non-redundant aperture-masking interferometry with differential polarimetry to directly image this previously inaccessible innermost region. By using the polarization of light scattered by dust in the disc to provide precise differential calibration of interferometric visibilities and closure phases, VAMPIRES allows direct imaging at and beyond the telescope diffraction limit. Integrated into the SCExAO (Subaru Coronagraphic Extreme Adaptive Optics) system at the Subaru telescope, VAMPIRES operates at visible wavelengths (where polarization is high) while allowing simultaneous infrared observations conducted by HICIAO. Here, we describe the instrumental design and unique observing technique and present the results of the first on-sky commissioning observations, validating the excellent visibility and closure-phase precision which are then used to project expected science performance metrics.

Key words: instrumentation: high angular resolution – instrumentation: interferometers – instrumentation: polarimeters – techniques: interferometric – planet-disc interactions – protoplanetary discs.

1 INTRODUCTION

The mechanism by which planets are formed within circumstellar discs is a key question in current astronomy. Flattened, cool discs of gas and dust surround most low-mass stars for their first several millions of years of existence, during which they gradually dissipate via photoevaporation, mass outflow, assimilation by the star, and condensation into planetisimals and eventually planets (Williams & Cieza 2011). Of particular interest are so-called transition-discs – protoplanetary discs exhibiting a partially evacuated gap, first identified via a distinctive dip in their infrared spectral energy distributions (e.g. Calvet et al. 2002). An exciting possibility is that these gaps are indicative of planetary formation (Bryden et al. 1999) and detailed observational characterization is of particular importance.

Although our understanding of the evolutionary processes involved is incomplete, in recent times spatially resolved observations have provided great insight into the structure and evolution of such protoplanetary discs, including the gaps, knots, and other density modulations that provide evidence of planetary formation. Sub-millimetre observations have resolved the inner cavities of transition discs (Andrews et al. 2011), as has long-baseline optical interferometry (Olofsson et al. 2011). Furthermore, infrared observations using coronagraphy and polarimetry have revealed fine sub-structure within protoplanetary discs. Spiral arms and complicated asymmetrical structure has been imaged using these techniques in several discs, such as those surrounding AB Aurigae (Fukagawa et al. 2004; Hashimoto et al. 2011) and MWC 758 (Grady et al. 2013).

While such infrared observations are extremely productive, the imaging of the innermost region (within ~100 mas) is highly challenging, due to the high contrast and angular resolution required as
well as the area occulted by the coronagraphic mask in traditional coronographs. However, this inner region is critical for the understanding of disc structure and planet formation (Williams & Cieza 2011). The main disc inner rim, the partially evacuated cavity (such as that characteristic of transition discs), and an inner-disc may all lie within this region. Here, we introduce a new instrument, the Visible Aperture-Masking Polarimetric Interferometer for Resolving Exoplanetary Signatures (VAMPIRES), specifically designed to directly observe this key inner region. Using a unique combination of aperture-masking interferometry and differential polarimetry, VAMPIRES will directly image the structure of the inner disc region in scattered starlight at visible wavelengths, revealing rim structure, disc geometry, and asymmetric density perturbations betraying the presence of an accreting planetesimal. Furthermore, polarimetric measurements reveal the distribution of dust grain sizes and species. Integrated into the SCExAO (Subaru Coronagraphic Extreme Adaptive Optics) system (Guyon et al. 2011; Jovanovic et al. 2013) at the Subaru 8 m telescope, it will enable observations at the telescope diffraction limit. The observational parameter space explored by VAMPIRES is distinct from – and complementary to – that of a coronagraphic polarimetric imager; it has no limitation on inner working angle (limited only by its resolving power, around 10 mas) and offers diffraction-limited imaging of this inner region while being robust against seeing and imperfect AO correction.

The remainder of this section will outline the technical background to the technique employed by VAMPIRES. Section 2 will describe the instrument itself. Section 3 describes the unique triple-differential interferometric calibration used by VAMPIRES. The results from the first on-sky observations are presented in Section 4. A qualitative demonstration of the expected data from science observations is given in Section 5 and a summary is included in Section 6. Appendix A explains the calibration procedure used for residual instrumental polarization not removed during the differential process.

1.1 Non-redundant aperture masking

Non-redundant aperture masking (Readhead et al. 1988; Tuthill et al. 2000), segments the pupil of a single telescope into a number of sub-apertures by placing an opaque metal mask with a carefully designed pattern of holes at a pupil plane upstream of an imaging instrument. This causes a diffraction pattern to form on the detector, with each set of fringes corresponding to a particular pair of sub-apertures (holes) in the aperture mask. Thus, each pair of sub-apertures forms a baseline of a Fizeau interferometer, with the visibilities and phases recovered by Fourier analysis of the diffraction pattern.

The key to the technique’s performance is that the layout of sub-apertures must be non-redundant – that is, the vector separation of every hole pair must be unique. This allows for the noise-process arising from seeing to be largely eliminated (see Readhead et al. 1988 for more detail). The power (or squared visibility) recorded for fringes on any baseline is intrinsically robust against phase errors caused by seeing, and this observable alone provides powerful constraint for diffraction-limited imaging from terrestrial telescopes. However, visibilities do not preserve any of the phase information of the image. Ideally, the phases recorded for each baseline would also be utilized, however these are completely dominated by random error from seeing. However, an alternate observable – the closure phase (Baldwin et al. 1986) – can be derived, which in the limit of small sub-apertures and short exposures, is immune to the effects of seeing. When starlight entering each sub-aperture is corrupted by a random phase error, then by taking the sum of phases around three baselines forming a closing triangle, phase errors cancel out and the resultant observable, the closure phase, is a function only of the source intensity distribution. The use of non-redundant masking along with these two observables has been highly successful in producing diffraction-limited, high-contrast images of such targets as stellar surfaces and atmospheres of evolved stars (Haniff et al. 1987; Tuthill, Haniff & Baldwin 1999a; Woodruff et al. 2008), dusty plumes surrounding Wolf–Rayet stars (Tuthill, Monnier & Danzi 1999b) and, most recently, protoplanetary discs (Eisner et al. 2009; Huélamo et al. 2011), and even suspected sub-stellar companions undergoing formation within (Arnold et al. 2012; Kraus & Ireland 2012).

Both visibilities and closure phases are subject to systematic errors arising from imperfections and instabilities in the instrumental point spread function (PSF). To combat this, the conventional approach in interferometry is to interleave observations of the science targets with observations of a calibrator star, usually an unresolved point-source (or sometimes an object with well-known structure). The calibrated visibilities are formed from the ratio of the science target’s visibilities to those of the calibrator star, and the calibrated closure phases are the difference between those of the science and calibrator stars. The success of this calibration assumes that aberrations encountered by the calibrator star are a good statistical representation of those for the science target. This can be a poor assumption if the two are at different airmasses or if conditions change between observations.

Current masking interferometry programmes usually deploy the aperture-mask in a beam corrected by an adaptive optics system. For such experiments (Tuthill et al. 2006), the AO system acts as a fringe-tracker, stabilizing the fringe phase so that visibility information is preserved for exposure times longer than the atmospheric coherence time (a fraction of a second). The precision calibration provided by non-redundant masking then allows the PSF of the AO-corrected imaging system to be accurately calibrated.

1.2 Astronomical polarimetry

Polarimetry and polarimetric imaging are well-established techniques in astronomy. Earlier polarimetric studies measured the overall polarization of light from a star using a polarimeter with a single pixel detector such as a photomultiplier tube (e.g. Hall & Mikessol 1950; Hiltner 1956; Gehrels & Teska 1960; Mathewson & Ford 1970). These instruments had polarization precisions as good as 0.01 per cent when used over narrow bands, with subsequent developments extending this precision to wide bandwidths (e.g. Tinbergen 1973.) Later, imaging polarimeters were developed that could measure the polarization of a spatially resolved field, using both photographic (Wolijer 1957) and electronic (Scarrott et al. 1983) methods. General-purpose imaging instruments on 8 m telescopes such as NACO on the VLT and AO188/HICAO on the Subaru telescope offer polarization modes, wherein the emphasis is on polarimetric differential imaging (PDI) – using the emphasis in polarization between starlight and scattered light to solve the contrast-ratio problem of imaging circumstellar discs – rather than high polarization precision (which is of the order of 1 per cent for NACO (Witzel et al. 2011)). Newly developed polarimeters such as SPHERE/ZIMPOL (Thalmann et al. 2008) promise sensitivities of the order of 1 part in $10^5$.

As in conventional imaging, all these polarimeters operate by forming an image of the science target on an array detector (such as a CCD), but with the addition of polarization optics which convert the polarization properties of the signal into intensity variations. In
the simplest case, this could be an analyser (linear polarizer), but in practice more complex systems are used to achieve the desired sensitivity and mitigate the effects of systematic errors resulting from instrumental polarization. Dual beam methods (where orthogonal polarizations are measured simultaneously using a polarizing beam-splitter) are often used, originally designed to improve polarimetric precision by removing the effect of seeing (Hiltner 1951). A related technique, channel switching (where polarizations are switched upstream with a rotating half-wave plate, HWP, or similar) is often used in combination with dual beam methods (Appenzeller 1967). Here, the channel-switching device is placed as far upstream as possible (before polarization-modifying elements just as mirrors and filters) allowing these systematic errors to be cancelled. Using either or both of these techniques, the differences or ratios of the intensities in the channels can be used to mitigate the effects of seeing and of instrumental polarization (Bagnulo et al. 2009).

High-precision instruments may use fast polarization switching (using a liquid crystal device or similar) to modulate the polarization on time-scales equal to or faster than atmospheric turbulence (Tinbergen 1973). Initially restricted to use with single-pixel detectors, advances have subsequently allowed this technique to be used with array detectors via some form of de-modulation at the detector, using an optical demodulator (Stenflo & Povel 1985) or an on-detector charge-shuffling technique (Thalmann et al. 2008; Bazzon et al. 2012). A particular challenge is the changing instrumental polarization at the Nasmyth focus of modern alt-az telescopes due to the changing angle of the M3 mirror with respect to the Nasmyth platform – a challenge that can be addressed by using a rotating compensator plate system (Tinbergen 2007). In all cases, proper characterization of and calibration for instrumental polarization is necessary.

In terms of exoplanet and protoplanetary disc studies, single-pixel polarimeters rely on detecting the small perturbations made to the overall polarization of the stellar system by the presence of a planet or other asymmetric body. They therefore need to be extremely sensitive to small polarizations; even systems with a close-in giant planet are expected to exhibit polarizations of only 10^{-5} or so (Seager, Whitney & Sasselov 2000). However, if the planet or disc is spatially resolved (as in an imaging polarimeter), then a much lower polarimetric sensitivity is required, assuming the surface polarization of the object is high. This methodology has been used successfully in the imaging of protoplanetary discs and the sub-structure therein, including around AB Aurigae (Perin et al. 2009), HD100546 (Quanz et al. 2011) and HD142527 (Avenhaus et al. 2014), in which fractional (surface) polarizations from several per cent up to several tens of per cent were observed in the near-IR. These adaptive optics observations provided imaging of the disc to within an inner working angle of (in the best case) 100 mas from the star.

1.3 A new approach: polarimetric differential non-redundant masking

The VAMPIRES instrument is based upon a recent extension to the aperture-masking technique: polarimetric non-redundant masking, initially demonstrated using the NACO instrument on the VLT to image the dust shells around asymptotic giant branch stars (Norris et al. 2012). This technique – and the VAMPIRES instrument – leverage the aforementioned switching and modulation methods from conventional polarimetry and recast them in an interferometric context. In contrast to proposed methods for full Stokes optical interferometry (Elias 2001), we take a different, differential approach. Rather than calibrating the instrumental transfer function using a nearby reference star, this technique instead records two orthogonal polarisations of the science target simultaneously. Differential polarized observables can then be extracted by calibrating these observations against one another. In practice, extreme care must be taken to avoid systematic errors which would otherwise overwhelm the science signal – see Sections 2 and 3. This technique offers three distinct advantages in imaging circumstellar regions which emit even a modest degree of polarized flux.

First, it allows direct observations of polarized circumstellar structures at very small separations from the star, at contrasts which are unachievable with conventional non-redundant masking. Dusty structures such as mass-loss shells and circumstellar discs scatter unpolarized light from their host star, a process which yields a polarized signal. The differential polarimetric observables produced by this technique describe the spatially resolved polarized intensity distribution, allowing faint, polarized structures to be clearly imaged in isolation despite the immediate proximity of the very bright (but unpolarized) stellar photosphere.

Secondly, imaging data for the two orthogonal polarizations are recorded simultaneously, as opposed to many minutes apart for more conventional stellar interferometry (the time taken to slew from science target to reference star). For the interferometric calibration, this is a profound difference. Rather than attempting calibration of the statistical properties of the telescope-atmosphere transfer function, starlight recorded simultaneously traversed identical optical paths (with the exception of a small instrumental leg immediately prior to the detector discussed later). Exact, frame-by-frame calibration then makes it possible to eliminate errors arising from temporal-variation such as seeing, imperfect AO correction, changing airmass, and flexure of the optics.

Thirdly, the polarimetric data produced can reveal important information about the scattering medium. By using multiwavelength studies of the degree of fractional polarization, quantities such as dust grain size and even chemical makeup can be accurately constrained.

It is also important to compare polarimetric aperture masking to conventional imaging polarimetry. The key distinction in technique is that the differential calibration – performed by subtraction or division of intensities in conventional polarimetry – is instead performed in the Fourier domain by the calibration of interferometric visibilities. The goal of this technique is analogous to that of PDI – to exploit the difference in polarization between a star and the surrounding circumstellar dust (such as a protoplanetary disc) to overcome the contrast ratio problem and directly image the circumstellar region.

However, the parameter space in which polarimetric aperture masking operates is quite distinct from that of conventional polarimetric imaging/PDI. High-contrast, high-angular-resolution imaging polarimeters generally employ a coronagraph to block out the light from the star to help achieve the desired contrast ratio between star and disc. This technique is thus limited by the coronagraph’s inner working angle, with the two newest instruments – SPHERE and Gemini Planet Imager (GPI) – having an inner working angle of ~100 and ~200 mas, respectively (Martínez, Aller-Carpentier & Kasper 2010). This puts the innermost regions of circumstellar discs – critical for proper understanding of the planetary formation process – out of reach for conventional imaging polarimeters. A polarimetric aperture-masking instrument such as VAMPIRES, however, has an effective inner working angle limited only by its resolving power, approximately 10 mas (with a field of view of only ~300 mas). Additionally, the spatial resolution of an imaging polarimeter
is limited by the performance of its adaptive optics system, while aperture masking can provide diffraction-limited performance even with high levels of wavefront error. Thus, this technique can explore a unique parameter space, unreachable with – but complementary to – conventional imaging or imaging polarimetry.

In the comparison between conventional polarimetry and polarimetric aperture masking, it is also important to note that the residual systematic errors in the differential visibilities (as shown in Section 4.1) do not represent the absolute polarization precision of the instrument. Rather, they arise from the difficulties in precisely calibrating visibilities common to all optical interferometry. Conventional aperture masking exhibits errors in calibrated visibilities of the order of 5–10 per cent (Monnier et al. 2004), while the polarimetric technique described here produces errors more than an order of magnitude better than this (see Section 4.1).

Polarimetric non-redundant masking offers one other advantage over a conventional imaging polarimeter: the Fourier transform of each interferogram is normalized with respect to the zero-baseline power, so the resulting visibilities are not a function of the total flux in the channel. This means that the derived observables are intrinsically immune to many forms of instrumental polarization systematic error, such as differing levels of transmission through the two channels of the polarizing optics. This automatically sidesteps a large fraction of instrumental challenges arising in more orthodox polarimeters, with the remainder being calibrated as described in Appendix A.

2 THE VAMPIRES INSTRUMENT

VAMPIRES is a purpose-designed instrument for performing polarimetric differential non-redundant masking. It is integrated into the SCExAO Extreme-AO system at the 8 m Subaru telescope, first tested on-sky in 2013 July. The concept grew from experience with the SAMPol mode commissioned by our group on the NACO instrument at the VLT (Norris et al. 2012) which enables near-infrared polarimetric masking interferometry. However, the new purpose-built VAMPIRES instrument offers a number of major advantages. While SAMPol relies on a strategy of slow-switching (every few minutes) of an HWP to swap polarization channels and thereby calibrate non-common path error, VAMPIRES features a fast-switching liquid-crystal variable retarder (LCVR) which allows channel switching every ~10 ms. This is part of a three-tiered differential calibration scheme that demonstrated on-sky polarized visibilities calibrated to a precision of 1 part in 10^5 and polarized closure phases calibrated to a fraction of a degree, as detailed in Section 4.

A Wollaston prism (first tier) provides simultaneous measurements of orthogonal polarizations, allowing precise calibration of all time-varying components (e.g. due to seeing) but introduces non-common path errors. The fast-switching LCVR (second tier) works in concert, calibrating non-common path errors and variability on time-scales longer than the switch time. Finally, an HWP (third tier) which is placed further upstream calibrates out residual instrumental polarization and non-common path error of all optics downstream, particularly the non-ideal performance (e.g. chromaticity) of the LCVR. The entire instrument has been designed with precision instrumental polarization calibration in mind, incorporating a polarization state injector and rotating quarter-wave plate (QWP) for instrumental characterization.

Whereas NACO/SAMPol operates in the near-infrared $J - K$ bands, the visible/IR region (from 0.6 to 1.0 μm) explored by VAMPIRES exploits the fact that the degree of polarization induced by scattering is a strongly rising function with shorter wavelengths. At the limit of small particle sizes, this can be seen in the $\lambda^{-4}$ term in Rayleigh scattering. Moreover, at shorter wavelengths, the dependence of scattering cross-section on particle-size (for Mie scattering) is more pronounced, allowing greater discrimination between grain sizes. Stronger scattered-light signals yield more benign contrast ratios between circumstellar material and bright unpolarized host stars, allowing a wider range of astrophysical targets to be observed. Furthermore, wavelengths shorter than 1 μm are favoured from the perspective of detector technology as sensitive, relatively inexpensive EMCCD cameras are available providing rapid-exposure frames that are essentially free of readout noise.

VAMPIRES operates in a ‘hitch-hiker’ mode, taking data concurrently with infrared observations. The SCExAO system delivers wavelengths longer than 1 μm to its coronagraphs and IR science instruments (such as the HICIAO camera). Meanwhile, wavelengths shorter than 1 μm are routed to a second ‘visible’ optical bench where the available band is further divided between SCExAO’s pyramid wavefront-sensor (PyWFS), VAMPIRES, and potentially other instruments. Therefore, VAMPIRES offers the opportunity to perform polarimetric aperture-masking observations simultaneously with HICIAO imaging during observations of protoplanetary discs and other suitable targets, delivering a supporting data stream without cost in additional observing time.

The parameter space explored by VAMPIRES is highly complementary to that of coronagraphs. VAMPIRES can deliver extremely high angular resolutions (of the order of 10 mas) over a limited field of view (~300 mas depending of choice of mask and wavelength). Thus, the outer working angle of VAMPIRES complements the inner working angle of traditional coronagraphs, which typically have occulting spots of a few hundred milliarcseconds (Grady et al. 2013). VAMPIRES small inner working angle (effectively defined by the telescope diffraction limit) is in line with SCExAOs core mission of small inner-working angle wavefront control and coronagraphy, as implemented by its PIAA coronagraph (Guyon et al. 2010, whose inner working angle is as small as 50 milliarcseconds in the near-infrared). This inner region also plays into the nature of expected astrophysical signals, in which scattered starlight is expected to exhibit a strong fall-off with disc radius.

Although the primary design driver for VAMPIRES is the differential polarized masking mode, the instrument does allow a more versatile set of observational configurations. For example, it is entirely possible to treat VAMPIRES as a standard masking interferometer and employ a separate PSF reference star (as in Section 1.1). This would then deliver standard complex visibility imaging data (rather than polarization-differential data), enabling normal interferometry science to be performed and sacrificing the exceptional differential calibration. The outcome of operational testing of this mode is briefly discussed in Section 4.2. An even more straightforward operational mode is to employ VAMPIRES as an imaging polarimeter. Reconfiguring so that the mask is removed from the beam, and an image-plane field stop deployed to prevent polarized-field overlap, then rapid exposure differential imaging polarimetry data can be recorded. However, the focus of this paper is on the novel interferometric polarimetry and further discussion of these more orthodox strategies is limited.

2.1 Instrument design description

A schematic diagram of the instrument is given Å in Fig. 1. VAMPIRES is integrated into the SCExAO extreme adaptive optics
A schematic diagram of VAMPIRES as configured on-sky in 2013 July, with all items relevant to the VAMPIRES beam train shown. Operation of each sub-system is described in the text. Abbreviations: M – Mirror; L – Lens; OAP – Off Axis Parabola; DM – Deformable Mirror; Dicr.M – Dichroic Mirror; HWP – Half-wave plate; BRT – Beam Reducing Telescope; LCVR – Liquid-Crystal Variable Retarder; LCC – LCVR Controller; TC – Temperature Controller; Cam – Camera; QWP – Quarter-Wave Plate; Depol – Depolarizer; OAP col. – OAP Collimator; Lin polz – Linear polarizer. In an alternative configuration, the HWP can be replaced with a pair of QWP to allow birefringence to be corrected as needed.

Next, the beam encounters the LCVR, a Thorlabs LCC1111T-B device controlled by a Thorlabs LCC25 liquid crystal controller. The LCVR acts as variable wave-plate, switching its retardance between 30 nm and $\lambda/2$ depending on the applied voltage. This switching takes place rapidly, with a rise time of $\sim10$ ms and fall time of $\sim250$ ms. The retardance is also a function of temperature, and specified values are required for successful calibration. Therefore, the temperature of the device is actively controlled (using a Thorlabs TC200 temperature controller) to a temperature 45°C (higher temperatures allow faster switching times). The two orthogonal polarizations are then separated using a custom-designed Wollaston prism (manufactured by Altechna), and focused on to the detector through a pair of lenses (Thorlabs AC254-200-B and ACN254-075-B) in a telephoto configuration. The detector is an Andor Ixon 897 Ultra EMCCD camera.

The system is controlled by custom software written in MATLAB on a Linux-based Intel i7 computer. This software allows control and scripting of all aspects of data acquisition (interfacing with the EMCCD camera, Arduino, and LCVR controller) as well as reconfigurable optomechanics. The software allows control of all functions via single graphical user interface, allowing simple remote operation and permitting the automation of lengthy calibration procedures.

A separate sub-system allows off-line characterization of the LCVR and calibration of residual polarization errors throughout the internal instrumental optical path. A calibration source (common to SLEXAO and VAMPIRES) can remotely inject a simulated telescope beam into SLEXAO with a specified polarization state. This consists of a supercontinuum source coupled into a single-mode fibre via a Thorlabs DPU-25-B achromatic depolarizer to remove any prior intrinsic polarization. The light is then collimated and passed through an achromatic linear polarizer (Thorlabs LPVIS100-MP) mounted in a CONEX-AG-PR100P rotation stage to allow linear polarized light at any specified orientation to be injected. A QWP (Thorlabs AQWP10M-980), also in a rotation mount, is also moved into the beam allowing a complete Mueller matrix of the instrument to be constructed as described in Appendix A.

Figure 1. A schematic diagram of VAMPIRES as configured on-sky in 2013 July, with all items relevant to the VAMPIRES beam train shown. Operation of each sub-system is described in the text. Abbreviations: M – Mirror; L – Lens; OAP – Off Axis Parabola; DM – Deformable Mirror; Dicr.M – Dichroic Mirror; HWP – Half-wave plate; BRT – Beam Reducing Telescope; LCVR – Liquid-Crystal Variable Retarder; LCC – LCVR Controller; TC – Temperature Controller; Cam – Camera; QWP – Quarter-Wave Plate; Depol – Depolarizer; OAP col. – OAP Collimator; Lin polz – Linear polarizer. In an alternative configuration, the HWP can be replaced with a pair of QWP to allow birefringence to be corrected as needed.
As described in Section 3, VAMPIRES employs three tiers of differential calibration, one of which is rapid channel switching using the LCVR. This requires alternate frames acquired by the camera to have the incident beam polarization rotated by 90°, thus swapping the state probed by the two Wollaston channels. Due to the high acquisition rate and short integration times used (≈17 ms in order to maintain high visibilities despite residual seeing after AO correction), it was not possible to directly control the LCVR switching and camera exposures using the computer, due to the non-realtime operating system and variable USB latency. Instead, the timing signals were generated by a dedicated Arduino Uno microcontroller. When a data acquisition cycle is initiated at the computer, the desired timing parameters and commands are sent to the Arduino. The Arduino sends the appropriate timing signals based on its internal clock (via 5V TTL pulses) to the LCVR controller and camera. The computer software and Arduino remain in communication to allow further user interaction. Other settings, such as the desired LCVR voltages, temperature, camera readout patterns, and gain, are sent directly to the devices over USB cables.

3 DIFFERENTIAL DATA ANALYSIS

They key to VAMPIRES’ performance is its differential measurement process, which is based on a calibration strategy adapted from conventional masking interferometry (see Section 1.1). However, rather than employing a separate PSF reference star, calibration is performed between Fourier observables extracted from images in simultaneously recorded orthogonal polarizations. This differential multtiered calibration process removes most sources of spatially and temporally dependent systematic error, producing a purely polarimetric set of observables.

Because calibration takes place on Fourier domain observables, the first step is the extraction of the two interferograms arising from each Wollaston channel in every camera frame to be windowed and Fourier transformed. The visibilities are then extracted from the power spectrum, and accumulated over a data cube (corresponding to a given LCVR and HWP state) consisting of around 200 frames. The bispectrum (the triple-product of the complex amplitudes of three baselines forming a closing triangle) is also accumulated, and the argument of the accumulated bispectrum gives the closure phase. For the non-redundant aperture masks, the complex visibility data are extracted at the \(uv\) coordinates corresponding to the set of known baselines formed by the mask. For the partially redundant annulus, discreet baselines are not present, but instead the Fourier domain is sampled uniformly while avoiding the regions of low power associated with gaps in the annulus (covering the secondary-mirror support structures as depicted in Fig. 2).

An overview of the calibration process is depicted in Fig. 3. The Wollaston prism allows measurements of orthogonal polarizations to be taken simultaneously and calibrated against each other, resistant to time-varying errors but subject to non-common path. Conversely, the fast channel-switching LCVR allows the two channels of the Wollaston prism to be switched, and calibration performed between channel-switched states. This removes the effect of non-common path in the Wollaston, although with switching time-scales longer than \(\tau_0\) (the atmospheric coherence time, due to seeing) it is subject to some time-varying error. The calibration of these two calibrated quantities against one another – forming a second tier of calibration – provides resistance against both these error types. Finally, channel-switching of the bulk of the instrument takes place via a rotating HWP upstream. This calibrates out spatially dependent systematic errors due to the intervening optics. The rotating HWP also allows both linear Stokes parameters (\(Q\) and \(U\)) to be measured by rotating the polarization 45°.

For example, the visibilities from the two channels of the Wollaston prism (\(V_{\text{Ch1}}, V_{\text{Ch2}}\)) may be calibrated against one another.
4 ON-SKY RESULTS

The VAMPIRES instrument was tested on-sky in 2013 July during SCExAO engineering time which allowed the calibration precision to be measured under real observing conditions. These tests were conducted with the standard AO 188 system. The system configuration at the time had relatively low throughput, with the visible beam being split between different instruments both spectrally and with a 50/50 grey beam-splitter. Therefore, we expect the precisions shown here to improve in subsequent observations. The goal is to demonstrate differential visibility precision of the order of $10^{-3}$ (or 0.1 per cent).

4.1 On-sky differential visibilities and closure phases

Two unresolved bright stars, Vega and Altair, were observed as part of the SCExAO engineering schedule, while the VAMPIRES instrument was able to obtain simultaneous observations in the visible. This provided an ideal test of VAMPIRES’ calibration precision, since these point-source\(^1\) stars should ideally exhibit a polarized-differential visibility of 1.0 on all baselines, and zero closure phases. This also allowed the evaluation of VAMPIRES’ multiple tiers of differential calibration, both individually and in combination.

The results of observing Vega with the 18 hole mask at $\lambda = 775$ nm (FWHM $= 50$ nm) with a total integration time of 109 s are shown in Fig. 4. The standard deviation of the differential visibilities is seen to increase with successive tiers of differential calibration. The Wollaston prism in (a) removes time-varying errors (e.g. due to seeing) so small random-errors are reflected in the error-bars, but non-common path error leads to large (up to 10 per cent) systematics. Conversely, the LCVR (b) removes non-common path error but is subject to time-varying error, resulting in a mean of $\sim 1$ but large random error. Double-differential calibration (c) with the LCVR and Wollaston mitigates both time-varying and non-common path error. Triple-differential calibration (d) with the HWP further removes static systematic errors (such as those arising from instrumental effects, and non-uniform retardance across the aperture of the LCVR due to thermal gradients). The resulting differential visibilities have a standard deviation of $4.2 \times 10^{-3}$, which is approaching our desired performance levels. At this point, the precision is limited by random noise processes (such as photon and Electron Multiplying (EM) gain noise) and would improve with longer integrations. It should also be noted that these data were taken without the Extreme-AO correction anticipated from SCExAO in the future, which will lead to further improvement (increased fringe visibility and hence increased signal/noise). A similar observational sequence on Altair was conducted with the 9 hole mask (which trades more sparse Fourier sampling for the gain of higher throughput) at $\lambda = 750$ nm (FWHM $= 40$ nm). Here, the triple-differential visibilities had a standard deviation of $2.4 \times 10^{-3}$.

The annulus mask was also tested while observing Vega at $\lambda = 775$ nm, but performed poorly due to a misalignment between the mask and telescope pupil (due to chromatic effects upstream). This mask is especially susceptible to such misalignments since the annulus is oversized, relying on the edge of the telescope pupil to define the outer edge of the masked aperture. One side of the annular opening was almost completely occluded, causing large errors at longer baselines (see Fig. 5). Performing the same analysis considering only baselines with lengths shorter than 4 m, then

\[^1\] The known disc around Vega is significantly too large to be seen with VAMPIRES.
Figure 4. The on-sky differential visibilities from an observation of Vega at 775 nm with the 18 hole mask, showing the effect of different tiers of calibration. Ideally, the visibility ratio should be unity on all baselines, since the source is unresolved. Baseline azimuth is plotted on the horizontal axis, while baseline length is represented by colour. The precision is seen to increase with successive layers of calibration, as discussed in the text. Data were taken without Extreme-AO correction.

Figure 5. The on-sky triple differential visibilities from Vega at 775 nm, with the annulus mask. Due to a misalignment between the mask and pupil, many longer baselines have extremely low visibilities, resulting in large errors (panel a). If these affected baselines are eliminated by only plotting shorter baselines, excellent precision (0.17 per cent) is observed (panel b).

A set of histograms of closure phases (for the same Vega observation as in Fig. 4) at varying levels of differential calibration are given in Fig. 6. As found for the visibilities, the precision – represented by a small mean and width of the distribution – improves with increasing levels of calibration. With the full triple-calibration applied, the closure-phase distribution has a standard deviation of 0.72 and a mean of 0.009. However, examination of the random error for each triangle (based on the error encountered across the set of all integrations) is large compared to the standard error of the ensemble of closure phases, indicating that statistical errors set the present limitation and precision will improve further with larger volumes of data.

4.2 Non-polarimetric on-sky results

As previously mentioned, VAMPIRES can also operate in a non-polarimetric mode, wherein it works the same way as conventional aperture masking (albeit at shorter wavelengths). In this case, signals from orthogonal polarization channels are simply combined together, thus discarding the polarization information. Calibration was now performed with respect to a separate observation of an unresolved reference star. During the 2013 July observations, VAMPIRES had the opportunity to observe χ Cygni, an S-type star expected to be spatially resolved, and the binary star η Pegasi.

χ Cygni was observed by VAMPIRES with the 18 hole mask at λ = 750 nm, and was resolved, allowing its angular diameter to be measured. The V magnitude was ~6 at time of observation, and total integration time was 54 s. No polarized signal was detected from this target during these observations within the sensitivity achieved in this observation (differential visibility precision of ~2 per cent due to the relatively short integration time and faintness of the

\[ \lambda = 750 \text{ nm}, \]  

\[ \sigma = 0.009. \]  

2 Observations from the AAVSO International Database, http://www.aavso.org.
Histograms of the on-sky differential closure phases recorded set to $1.125^\circ \pm \rho = \lambda$ code, together with Pegasi was observed with the 18 hole mask $1994^\circ T_\text{is calculated automatically.}$

The surface density exponent $2011^\circ 2894–2906 (2015)$ $\beta V_447, (6) 1998^\circ 9000 \text{K.}$ The dust in the disc is $1998^\circ \beta V_\eta - R_\text{7}$ HYPERION $H_\text{V1}$ $0.6 \text{mas.}$ $\pm 2005^\circ \pm 7$ and $30^\circ \pm 7$ was set to $775 \text{nm, again for a total integration time of 54 s.}$ Vega was

**5 SIMULATED DATA AND PERFORMANCE PREDICTIONS**

The differential Fourier visibilities (e.g. $V_{\text{Horiz}}/V_{\text{Vert}}$) obtained from VAMPIRES are not directly equivalent to the differential intensities (or fractional polarizations) obtained in techniques such as polarized differential imaging. Rather, the magnitude of each of these differential visibilities (i.e. of their departure from $V_{\text{Horiz}}/V_{\text{Vert}} = 1$) describes the amount of correlated polarized flux at the corresponding spatial frequency, and the differential closure phases describe the corresponding phase. Since these quantities are less intuitive than polarized intensities, simulated VAMPIRES data have been produced using a radiative transfer model of a representative flared axisymmetric protoplanetary disc, in order to give a qualitative example. This particular model demonstrates the ability of VAMPIRES to precisely observe the inner rim of such discs. The model was created using the HYPERION radiative transfer code (Robitaille 2011) using a parametric density function, with a power-law surface density profile and Gaussian vertical structure (Andrews et al. 2011). The disc density is given by

$$\rho(R, z, \phi) = \rho_0 \left( \frac{R_0}{R} \right)^{\beta - p} \exp \left( -\frac{1}{2} \left( \frac{z}{h(R)} \right)^2 \right). \tag{6}$$

where

$$h(R) = h_0 \left( \frac{R}{R_0} \right)^\beta. \tag{7}$$

Parameters were set to typical values, with an inner radius of 25 au and an outer radius of 300 au, and a disc mass of 0.01 $M_\odot$, from which $\rho_0$ is calculated automatically. The surface density exponent $p$ was set to $-1$ and the scaleheight exponent $\beta$ set to 1.125. $H_{100}$, the scaleheight of the disc at 100 au, was set to 20 au. The inclination and position angle are 57$^\circ$ and 30$^\circ$, respectively. The model disc surrounds an A0-type star with $T_{\text{eff}} = 9000 \text{K.}$ The dust in the disc is a mix of silicate and carbon species based on the KMH distribution (Kim, Martin & Hendry 1994). The observational wavelength is 800 nm and the disc is placed at a distance of 500 pc.

Polarized images produced by the HYPERION code, together with the corresponding polarized differential visibilities, are shown in Fig. 7. In this model scenario, starlight scattered by the inner wall dominates, and the VAMPIRES data are seen to be extremely sensitive to the structure of the inner region. A strong modulation of the differential visibilities as a function of azimuth and baseline length is apparent in Fig. 7(c). Along with the associated differential closure phases (not plotted here), these encode the detailed polarized
The VAMPIRES instrument

Figure 7. A modelled protoplanetary disc at 500 pc (see Section 5) and the derived VAMPIRES data for $\lambda = 800$ nm. (a) Image of the inner region of the disc, shown with a non-linear intensity mapping, in four polarizations: horizontal $H$ and vertical $V$ corresponding to Stokes $Q$, while $H_{45}$ and $V_{45}$ are the two orthogonal polarizations rotated 45° corresponding to Stokes $U$. (b) The differential power spectra for the two pairs of orthogonal polarizations. (c) Expected differential visibility signals as seen by VAMPIRES with an 18 hole mask.

structure of the inner 100 mas or so. If more complex structures were present, such as asymmetrical clumps or an inner disc, they would be clearly evident in these signals.

The on-sky sensitivity of VAMPIRES has been quantified based on laboratory testing, wherein flux levels matching various stellar magnitudes were used along with simulated atmospheric turbulence. The turbulence was simulated by reproducing a AO-corrected Kolmogorov screen (based on typical seeing and wind speeds) via active modulation of the wavefront using the 2K deformable mirror within SCExAO. Visibility precisions of the order of $10^{-3}$ were reliably obtained for targets as faint as fourth magnitude using the 18 hole mask for integration times of 15 min (plus overhead for wave-plate switching), or 5.5 mag in 1 h integration. For fainter targets, a mask with higher throughput is advantageous. The laboratory test data indicated that the 9 hole mask will achieve this precision in 1 h for 6.5 mag stars and the 7 hole mask will achieve it in 1 h for eighth magnitude. The annulus should theoretically achieve order $10^{-3}$ precision in 1 h integration for stars as faint as 8.5 mag; however, as discussed in Section 4.1, this is currently only realized on the shorter (<4 m) baselines due to pupil alignment drift, a problem that is currently being addressed. Additional overhead must be allowed for due to time taken for wave-plate switching – this can be anywhere between 25 and 100 per cent of the integration time depending on switching frequency.

The representative model presented in this section has differential visibilities with an average magnitude (deviation for unity) of approximately 2 per cent. With the demonstrated on-sky precision using the 18 hole mask of 0.4 per cent, the $V_{Horiz}/V_{Vert}$ of each baseline can be measured to 5σ. However, the actual uncertainties on a fitted model would be much smaller due to the relatively small number of free parameters involved.

6 SUMMARY

By combining non-redundant aperture-masking interferometry with differential polarimetry, the VAMPIRES instrument will directly image the innermost region of protoplanetary discs, providing critical insight into the processes of disc evolution and planet formation. Non-redundant aperture masking provides diffraction-limited performance by way of the established interferometric visibility and closure-phase observables. VAMPIRES’ triple-differential polarimetric calibration strategy exploits the polarization of scattered starlight, utilizing simultaneous differential measurements with a Wollaston prism, fast channel-switching with an LCVR and slow-switching with a rotating HWP to better remove instrumental systematics. The resulting signal encodes the resolved, polarized structure of the inner disc. These observables are largely immune to the effects of instrumental polarization, with the remainder being
removed by precise calibration of the instrumental Mueller matrix using an in-built characterization system.

VAMPIRES records data at visible wavelengths (where polarization from scattering is typically higher) in a hitch-hiker mode that does not affect simultaneous science operation of other (infrared) instruments. On-sky demonstrations of the VAMPIRES instrument yielded a differential-visibility precision approaching 10⁻³ and closure-phase standard-deviation better than 1°. Limitations to both performance metrics are presently provided by restricted statistical sample size and therefore further improvement is expected with longer on-sky integration times. Precise visibilities and closure phases will be used to accurately constrain disc models, and to detect the presence of asymmetries and density enhancements which rephase will be used to accurately constrain disc models, and to detect the presence of asymmetries and density enhancements which rephase will be used to accurately constrain disc models, and to detect

The instrument is now integrated into the SCExAO system and is ready for its first science observations, planned for mid to late 2014. Eventually, the instrument will be largely autonomous and capable of entirely remote operation, allowing simultaneous measurements with standard facility instruments SCExAO/HICIAO when required.

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APPENDIX A: CALIBRATION OF INSTRUMENTAL POLARIZATION

The differential calibration of VAMPIRES mitigates the effect of many instrumental polarization effects. Moreover, since the visibilities for each polarization channel are normalized with respect to the total flux in that channel, simple diattenuation has no effect on the measured observables (unlike the case for standard polarimetry). However, this does not take into account cross-terms in the instrumental Mueller matrix (which describes the polarization properties intrinsic to the instrument and how they alter each of the Stokes parameters of the incoming light (Goldstein 2011)). Q → U and U → Q mixing will lead to incorrect measurement of the relative magnitude of Stokes Q and U measurements. The Q ↔ V and U ↔ V cross-terms are even more problematic – since VAMPIRES does not measure Stokes V, it thus appears to the instrument that part of the Stokes Q and U components have ‘disappeared’, leading to an underestimation of the magnitude of the polarization. Since VAMPIRES itself is behind the pre-existing systems AO 188 (which includes a k-mirror image rotator) and SCExAO, significant instrumental polarization cannot be avoided, and instead must be mitigated by careful calibration and the tripe-differential measurement process.

To resolve these problems, a careful full characterization of the instrumental Mueller matrix is performed immediately before or after astronomical observations, which is then used to correct data during processing. This characterization procedure is fully automated and can be performed remotely. First, a linear polarizer on
a rotation stage is driven into the beam upstream of the SCExAO optical path, and a rotating QWP is positioned immediately before the Wollaston prism inside VAMPIRES – see Fig. 1. Any residual polarized structure in the light incident upon the linear polarizer is removed by first passing it (as a large-diameter beam) through an achromatic wedge depolarizer, allowing an arbitrary linear polarization to be generated. Alternatively, the halogen flat-field lamp, linear polarizer and HWP which already exist within the AO188 adaptive optics system may be used to inject the linearly polarized reference, which has the advantage of characterizing the optics within AO188 itself as well. By using the Wollaston prism as the analyzer, a rotating-polarizer/rotating-compensator+fixed-analysers (RP/RCFA) type Mueller matrix polarimeter (Haque 1980) is created. Data from such a setup can specify the first three columns of the Mueller matrix of the instrument. While the fourth column cannot be determined, if the assumption is made that the astrophysical source has a negligible circular polarization component, then the missing fourth column is inconsequential.

If the QWP and linear polarizer are rotated synchronously such that the angle of the QWP is three times that of the polarizer, then the first three columns of the Mueller matrix can be directly determined by Fourier analysis of the resulting intensity variation (Haque 1980). Alternatively, to provide more physical insight into the origin of the polarization effects, a polarization model of the instrument can be created, and then fine-tuned by fitting it to the measured calibration data (Witzel et al. 2011). In this case, the Mueller matrix of the instrument is created by combining the Mueller matrices of the individual components, with the appropriate rotations. The linear polarizer (and the Wollaston prism channels), with their polarization axis at angle \( \theta \), are represented by the matrix \( M_{LP} \):

\[
M_{LP} = M_{L(\theta)}^{-1} \times M_{P(h)} \times M_{L(h)},
\]

where \( \times \) signifies matrix multiplication, \( M_{L(h)} \) represents the matrix of an ideal horizontal linear polarizer, i.e.

\[
M_{L(h)} = \frac{1}{2} \begin{pmatrix}
1 & 1 & 0 & 0 \\
1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}
\]

and \( M_{L(\theta)} \) is the rotation matrix in Stokes space for angle \( \theta \):

\[
M_{L(\theta)} = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & \cos 2\theta & \sin 2\theta & 0 \\
0 & -\sin 2\theta & \cos 2\theta & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}.
\]

Similarly, the Mueller matrix for a wave-plate (retarder) can be represented as

\[
M_{WP} = M_{W(h)}^{-1} \times M_{W(P)} \times M_{R(\phi)},
\]

where \( M_{W(h)} \) is as before and \( M_{W(P)} \) is the matrix of a wave-plate with retardance \( \phi \):

\[
M_{W(P)} = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & \cos \phi & \sin \phi & 0 \\
0 & 0 & -\sin \phi & \cos \phi
\end{pmatrix}.
\]

Combinations of these matrices can represent VAMPIRES’ HWP, LCVR, and Wollaston prism, as well as the linear polarizer and QWP used for calibration. Instrumental polarization arises mostly from reflections off various mirrors in the system. Reflections from a metallic mirror cause both a change in transmission between linear polarization components and a change in phase between these components. The Mueller matrix for a metallic mirror can thus be constructed by combining the matrices for a partial-linear polarizer with a wave-plate, resulting in the following matrix (Clarke 1973):

\[
M = \frac{1}{2} \begin{pmatrix}
r_{\perp} + r_{\parallel} & r_{\perp} - r_{\parallel} & 0 & 0 \\
r_{\perp} - r_{\parallel} & r_{\perp} + r_{\parallel} & 0 & 0 \\
0 & 0 & \sqrt{r_{\perp}^2 \cos^2 \delta} & \sqrt{r_{\perp}^2 \sin^2 \delta} \\
0 & 0 & -\sqrt{r_{\perp}^2 \sin^2 \delta} & \sqrt{r_{\perp}^2 \cos^2 \delta}
\end{pmatrix},
\]

(A6)

where \( r_{\perp} \) and \( r_{\parallel} \) are the coefficients of reflection for the perpendicular and parallel polarizations, respectively, and \( \delta \) is the retardance between the components. For each metallic surface in the VAMPIRES optical model, these values are in turn calculated from the metal’s known complex refractive index \( n_i \) using the amplitude Fresnel equations (where \( n_i \approx 1 \) is the refractive index of air).

The complex amplitudes of the perpendicular and parallel reflected components, respectively, are given by

\[
r_{\perp} = \frac{n_2 \cos \theta_i - n_1 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t},
\]

(A7)

\[
r_{\parallel} = \frac{n_2 \cos \theta_i - n_1 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t},
\]

(A8)

where \( \theta_t \) is the angle of incidence and \( \theta_i \) is nominally the angle of transmission, and is calculated using Snell’s law, but in the case of a metallic reflection it is complex. The coefficients of reflection are then simply

\[
r_{\perp} = |r_{\perp}|^2, \quad r_{\parallel} = |r_{\parallel}|^2
\]

(A9)

and the relative retardance is just

\[
\delta = \arg(r_{\perp}) - \arg(r_{\parallel}).
\]

(A10)

A Mueller matrix for the entire instrument is thus created by combining the matrices of all polarizing elements, with the appropriate rotations. Using the Levenberg–Marquardt algorithm (or a simple parameter grid), a fit of the model to the measured calibration data is performed, in which the free parameters are the complex refractive indices of the metallic surfaces (starting at the tabulated value\(^3\) for the specific metal comprising the mirror coating). This fitting process also allows the dichroic mirror (of poorly known reflection characteristics) to be characterized. To reduce the number of free parameters, the SCExAO focusing mirror and the DM (which are both in the same plane of reflection) are combined into one component.

Finally, the instrumental polarization contribution from the telescope itself and the AO 188 system must be taken into account. In principle, it should be straightforward to probe this portion of the optical system with observations of polarized standard stars, but until such data can be obtained, detailed optical modelling must serve. Fortunately, a precise ZEMAX model of the system was made available to us, yielding precise knowledge of position and angle of all optical surfaces. Alternatively, the contribution from AO 188

\(^3\) Complex refractive indices obtained from http://refractiveindex.info/. Optics suppliers unfortunately do not provide this level of characterization.
can be measured by using its own flat-field lamp, linear polarizer and HWP. Exploiting this, an accurate matrix $M_{tel}$ can be calculated using the methods discussed above.

Thus, a final Mueller matrix for the instrument is constructed:

$$M_{VAMPIRES} = M_{Woll} \times M_{QWP} \times M_{LCVR} \times M_{PerM2}$$

$$\times M_{(\theta_{Per})} \times M_{HWP} \times M_{PerM1}$$

$$\times M_{OAP + DM} \times M_{LP} \times M_{tel},$$

where each matrix term incorporates its appropriate rotation matrix. $M_{OAP + DM}$ represents the combined in-plane mirrors on the bottom bench, $M_{PerM1,2}$ are the periscope mirrors, $M_{(\theta_{Per})}$ is the beam rotation of the periscope and $M_{Woll}$ the Wollaston prism, which in fact exists in two instances (with $\pm 45^\circ$ rotations corresponding to the two channels). The calibration polarizer and wave-plate ($M_{QWP}$ and $M_{LP}$) are included for fitting the model to the calibration data.

An alternative configuration under investigation replaces the HWP with a pair of QWP, which allows the polarization to be rotated (as with the HWP) but also the system birefringence to be compensated for (by differential rotation of these wave-plates). In this case, the $M_{HWP}$ term above is replaced by two $M_{QWP}$ terms.

A sample Mueller matrix for the instrument is given below – in this case, the matrix for the instrument at 775 nm in the dual-QWP configuration, for zero polarization rotation, Wollaston prism ordinary beam and LCVR retardance set to $\pi/2$.

$$M = \begin{pmatrix}
1 & -0.026 & -0.062 & -0.015 \\
-0.022 & 0.706 & 0.225 & -0.668 \\
0.059 & 0.130 & -0.973 & -0.189 \\
0.026 & -0.693 & 0.045 & -0.717
\end{pmatrix}.$$

Substantial off-diagonal terms are seen (while noting that this matrix includes the beam rotation by the periscope between benches), and as described in Section 3 the bulk of these effects are mitigated by the triple-differential measurement process and the inherent robustness of interferometry against diattenuation (since the signal in each polarization channel is normalized with respect to the total flux in that channel). (This full matrix, however, is still used for correction during data reduction to ensure any residual effects are calibrated for.) The effect of birefringence is most strongly seen in the $Q \leftrightarrow V$ terms rather than the $U \leftrightarrow V$ terms, due largely to the rotation of the beam by the periscope. This matrix includes the contribution of AO 188, which makes a sizeable contribution to the instrumental polarization due to its image rotator ($k$-mirror).

Polarized light of Stokes vector $S$ incident on the telescope is transformed by the instrument to emerge as $S'$, where

$$S' = M_{VAMPIRES} \times S.$$

To determine the signal measured by the camera (which only measures intensity), we apply the detector operator $D$, which is the row vector $[1, 0, 0, 0]$. The intensity measured is then

$$I = D \times M_{VAMPIRES} \times S.$$

To correct for instrumental polarization in the intensity domain, the inverse instrumental Mueller matrix $M_{VAMPIRES}^{-1}$ could simply be applied to the measured Stokes vector. However, VAMPIRES’ calibration precision relies on immediately transforming each frame of fringes into the Fourier domain and conducting all subsequent operations in this domain, making such a strategy impractical. Therefore, rather than applying the instrumental polarization correction to the data, instead we apply $M_{VAMPIRES}$ directly to the astrophysical model (e.g. a radiative transfer model) or image reconstruction before fitting to the data, which is the technique we will employ in future science observations.

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