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Poster Previews for Conference 9907: Optical and Infrared Interferometry and Imaging V

, "Poster Previews for Conference 9907: Optical and Infrared Interferometry and Imaging V," Proc. SPIE 10015, Poster Previews: SPIE Astronomical Telescopes and Instrumentation 2016, 1001505 (16 June 2016); doi: 10.1117/12.2248393

SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2016, Edinburgh, United Kingdom

Fundamental gain in high contrast imaging with the **LBT**.

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ABSTRACT

Numerical simulations for the LBTI have shown a fundamental gain in contrast when using two 8m adaptive optics telescopes instead of one. The LBTI provides an "in-between" PSF, combining both diffractive and interferometric properties (Fig. 1). The maximum intensity in the PSF is increased by a factor of four, accounting for the double flux and the fringe intensification. The imaging performance of the LBTI is limited by the AO-correction level, as for a single LBT aperture (Fig. 3,4). The PSFs are computed by using 2 time series of residual wavefronts with an RMS of ~ 100nm yielding an AO Strehl of 50% in R band (visible). The contrast gain map is defined as the normalised ratio of the PSF of a single LBT over the PSF of the LBTI. The contrast gain averaged across the field is improved by a factor 2 in contrast by using the long exposures and by a factor of 10 in contrast by using the short exposures (Fig. 5,6). Indeed, contrary to the long exposure where the fringes are blurred, a snapshot retains the fringes formed in a halo of speckles (Fig. 3), enabling speckle imaging. The speckle halo contains not only high angular resolution information but also high contrast imaging information. Thus, there is some gain in grouping some short exposures with high gain. A gain zone is produced in the valleys of the PSF formed by the dark Airy rings and/or the dark fringes. A huge contrast gain ($G \sim 100$ to 1000) in narrow zones (few mas) can be achieved when both a dark fringe and a dark ring overlap. The Earth rotation allows to exploit various area in the contrast gain map in which a planet passes through several gain zones. This makes the LBTI well suitable for the Angular Differential Imaging (ADI) technique. A rotation of 15° is sufficient to pass through at least one contrast gain zone (Fig. 7). A planet is located in a white or in a dark ring, depending on its radial distance. A planet is alternatively located in a white fringe ($G \sim 1$) or in a dark fringe ($G \sim 10$ to 100) as a function of the parallactic angle (Fig. 8,9).

Diffractive-limited PSF

Figure 1. Theoretical PSF in a focal plane. PSF distributions with a linear scale (top) of a 23m telescope (left), an 8m LBT telescope (middle) and the LBTI interferometer (right). PSF profiles (bottom) of a 23m telescope (dotted line), an 8m LBT telescope (dashed line) and the LBTI interferometer (solid line) in the Y direction perpendicular to the LBTI baseline (left) and in the X direction parallel to the LBTI baseline (middle and right). The fringes appear within an Airy envelope, due to the double-aperture nature of the LBTI. The PSF with a logarithmic scale (bottom right) shows that the theoretical contrast of the LBTI is better than the contrast achieved by a single 8m LBT telescope and decreases down to the noise level of a 23m telescope in some areas of the PSF.

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Contrast gain map = 4 x PSF(LBT) / PSF(LBTI)

Figure 3. Point spread function of a single aperture with the LBT (left) and of two apertures with the LBTI (right). Diffraction-limited exposure (top), seeing-limited short exposure (middle) and seeing-limited long exposure (bottom). Logarithmic scale.

Figure 4. Point spread function profile of two apertures with the LBTI (solid line) and of a single aperture with the LBT (dashed line). Diffraction-limited exposure (top) and seeing-limited long exposure (bottom). Logarithmic scale.

Figure 5. Contrast gain map of the LBTI vs the LBT. Ratio of a short exposure (top left), ratio of the long exposure (top right) and average of the ratio of the short exposure (bottom). Logarithmic scale.

Figure 6. Contrast gain map profiles of the LBTI vs the LBT. Ratio of the long exposure (dashed line) and average of the ratio of the short exposure (solid line). The contrast gain averaged across the field equals to $G_{LBT} \approx 2$ by using the long exposure and $G_{LBT} \approx 10$ by using the short exposures.

Figure 7. Integrated contrast gain map of the LBTI vs the LBT rotated over 15° and 90° (top to bottom). Ratio of the long exposure (left) and average of the ratio of the short exposure (right). Logarithmic scale.

Figure 8. Contrast gain map of the LBTI vs the LBT as a function of the radial distance and the parallactic angle over 90° . Ratio of the long exposure (left) and average of the ratio of the short exposure (right). Logarithmic scale.

Figure 9. Contrast gain map profiles of the LBTI vs the LBT as a function of the parallactic angle over 90° for few given radial distances: 20mas, 40mas and 120mas (top to bottom) from the central axis. Ratio of the long exposure (left) and average of the ratio of the short exposure (right). Logarithmic scale.

CONCLUSIONS

Compared to a standalone 8m LBT, the 23m LBTI can provide not only a gain in angular resolution (by a factor of 3 to 10 in the infrared vs visible) and a gain in sensitivity (by a factor of 4), but also a gain in contrast (by a factor of 10 to 1000), assuming a high AO Strehl and a co-phasing mode. A new ADI-like mode should be developed for high contrast imaging in the visible wavelengths in the framework of the LIVE project. Indeed, the visible PSF contains thinner structures than the infrared PSF, providing numerous dark fringes and dark rings where planets can be detected at low level.

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Sensitivity to piston & adaptive optics errors with the

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ABSTRACT

On-sky adaptive optics wavefront screens have been used and random optical path fluctuations – differential pistons – have been included in numerical simulations for the LBTI. The interferometric Strehl which can be achieved by the LBTI using two FLAO is close to the AO Strehl provided by a FLAO standalone, as long as other sources of aberrations can be mitigated (Fig. 1). The imaging performance of the LBTI is thus fundamentally limited by the AO-correction level. The tip-tilts induced by both AO systems onto each sub-aperture produce differential tip-tilts of the sub-beams and differential shifts of the sub-images (Fig. 2, 4, 5), so that the diffraction envelopes do not overlap properly and the beams do not fully interfere coherently. However, for piston fluctuations, the fringes move back and forth within the Airy disk (Fig. 3, 4, 5), reducing the fringe contrast for a long exposure, but not for a short one. A snapshot retains high angular resolution information by freezing the fringes. Few criteria have been evaluated as a merit function (Fig. 6, 7) to characterise the Point Spread Function (PSF) and the Optical Transfer Function (OTF). The R23 quantity is more sensitive than the interferometric Strehl to the contrast attenuation induced by the shift of the fringes in a long exposure (image blurring). The visibility should not be used as a merit function, but as a criterium for science applications. The contrast in the PSF enables to highlight two regimes depending on the location in the diffractive pattern, either in a side-lobe (low contrast) or in a valley (high contrast). The FWHM of the central peak of the MTF may be used to sense the low order aberrations from each AO systems. For instance, large tip-tilts produce fringes in the central peak affecting the FWHM in real-time.

FLAO wavefronts

Figure 1. Theoretical PSF, short exposure PSF and long exposure PSF (top to bottom) of the LBTI in the visible wavelengths obtained by numerically combining two on-sky FLAO wavefronts having an AO Strehl of 90% in H band. Logarithmic distribution, X profile parallel to the baseline, Y profile perpendicular to the baseline, profile integrated over 300° (left to right). The LBTI can provide an interferometric Strehl above 85% in H band, assuming no differential errors in the optical train of the LBTI.

Pistons & AO errors

Figure 2. PSF and MTF distributions with AO wavefront errors, given an RMS equal to $\lambda/24, \lambda/12, \lambda/8, \lambda/6, \lambda/4, \lambda/2$ (left to right). Short exposure (top) and long exposure (bottom). Logarithmic scale. Same PSF spatial scale as in fig. 1.

Figure 3. PSF and MTF distributions with piston errors. Same legend as in figure 2.

Figure 4. PSF profiles with AO wavefront errors (top) or with piston errors (bottom), given an RMS equal to $\lambda/24$ (solid line), $\lambda/64$ (long dash), $\lambda/32$ (dash), $\lambda/24$ (dash-dot), $\lambda/16$ (dash-dot-dot), $\lambda/12$ (dot), $\lambda/10$ (solid line), $\lambda/8$ (long dash), $\lambda/6$ (dash), $\lambda/4$ (dash-dot), $\lambda/3$ (dash-dot-dot), $\lambda/2$ (dot). Short exposure (left) and long exposure (right).

Figure 5. MTF profiles with AO wavefront errors (top) or with piston errors (bottom). Same legend as in figure 4.

PSF & MTF criteria

Figure 6. Merit functions for the PSF: Interferometric Strehl (top left), averaged contrast from 80mas to 100mas (top right), contrast at 80mas located in a local minima (bottom left), contrast at 80mas located in a local maxima (bottom right). AO wavefront errors (square symbol) or piston errors (circular symbol) for various RMS values. Short exposure (empty symbol, dashed line) and long exposure (filled symbol, solid line).

Figure 7. Merit functions for the MTF: Interferometric visibility (top left), R23-criteria (top right), FWHM X along the baseline (bottom left), FWHM Y perpendicular to the baseline (bottom right). Same legend as in figure 6.

CONCLUSIONS

These results provide an estimate of the performance and of the requirements of the LBTI extended to the visible wavelengths. For a long exposure, an interferometric Strehl of 85% corresponds to a residual piston RMS of $\lambda/8 \sim 100\text{nm}$ or to a residual AO wavefront RMS of $\lambda/18 \sim 40\text{nm}$. An interferometric Strehl of $0.85^2 = 72\%$ corresponds to both effects at a time. In other words, an interferometric Strehl above 70% is achievable in the visible wavelengths by providing a piston below 100nm RMS and an AO correction better than 40nm RMS. The AO errors – mainly the differential tip-tilt – are more critical than the piston errors, which do not blur the short exposures where the fringes are frozen.

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GRAVITY: the new metrology concept

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GRAVITY is a dual-feed four-telescope K-band combiner for the VLTI, aiming at precision narrow-angle astrometry. To this end, a metrology system traces the differential optical path difference between the science and the reference targets, backward from the instrument spectrometers to the telescopes. During the integration phase, it was discovered that GRAVITY suffers from extremely strong Raman and fluorescence back-scattering from its 20-m fluoride fibers, excited by the metrology laser. Stellar fringes were then contaminated on the spectrometers detectors by a strong incoherent light background, dramatically reducing the instrument sensitivity by more than 10 stellar magnitudes!

We present here the concept of the new metrology system that mitigates this back-scattering effect to a level such that GRAVITY can operate with optimal performance. More details on the implementation of this system can be found in Poster 9907-73.

3-BEAM OPTICAL AMPLIFICATION

- Interference of 2 metrology beams:
$$F = I_1 + I_2 + \sqrt{I_1 I_2} \cos(\phi_{12})$$
- Metrology phase SNR $\propto \sqrt{I_1 I_2}$
 - The addition of a 3rd high power carrier beam (>50 mW) allows decreasing the laser power in fibers down to fW level at constant SNR.
- Back-scattering and non-common path effects (e.g. differential fiber heating) reduced in proportion, by a factor 100-1000, hence are negligible now.

SYNCHRONOUS DETECTION

- Phase-shifters sawtooth modulation of amplitude 2π and frequencies f_{SCI} & f_{FT} between 10 and 20 kHz
 - Telescope fringe signal $F \sim$ pure sine harmonic $1f$
- Lock-In Amplifiers (LIA) demodulate the sine fringe signal and measure phase $\Phi_{SCI/FT} - \Phi_{carrier}$
- LIA = narrowband filter ($\Delta f < 100$ Hz) at frequency f
 - disentangle both metrology signals
 - Filter receivers white noise, improving metrology sensitivity by a factor "few" wrt ABCD
 - filter out the three-beam laser power fluctuations, vibrations, etc.
 - very flexible with the free choice of modulation frequencies wrt noises

RESULTS

This new metrology system mitigates the back-scattering issue, allowing optimal operations of GRAVITY. It also reduced NCP effects to a negligible level and proved to be more sensitive and flexible than a standard ABCD modulation.

The metrology system of GRAVITY has been upgraded in consequence with:

- 4 additional carrier laser beams of ~ 50 mW each;
- 40 Lock-In Amplifiers measuring the phase from the two metrology arms;
- All 40 metrology receivers were also modified to deal with too high laser power fluctuations.

See **poster 9907-73** for more details on the implementation.

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Reaching the Diffraction Limit

907-100

A new dual-channel speckle instrument for Gemini and WIYN, Paper Number: 9907-100

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Introduction

Speckle imaging allows telescopes to achieve diffraction limited imaging performance. The technique requires cameras capable of reading out frames at a very fast rate, effectively 'freezing out' atmospheric seeing. The resulting speckles can be correlated and images reconstructed that are at the diffraction limit of the telescope. These new instruments are based on the successful performance and design of the Differential Speckle Survey Instrument (DSSI) [2, 1].

The instruments are being built for the Gemini-N and WIYN telescopes and will be made available to the community via the peer review proposal process. We envision their primary use to be validation and characterization of exoplanet targets from the NASA K2 and TESS missions and RV discovered exoplanets. Such targets will provide excellent follow-up candidates for both the WIYN and Gemini telescopes [3]. Examples of DSSI data are shown in the figures below. We expect similar data quality in speckle imaging mode with the new instruments.

Additionally, both cameras will have a wide-field mode and standard SDSS filters. They will be highly versatile instruments and it is that likely many other science programs will request time on the cameras. The limiting magnitude for speckle observations, will remain around 13-14th at WIYN and 16-17th at Gemini, while wide-field, normal CCD imaging operation should be able to go to much fainter, providing usual CCD imaging and photometric capabilities. The instruments will also have high utility as scoring cameras for telescope engineering purposes, or other applications where high time resolution is needed. Instrument support will be provided, including a software pipeline that takes raw speckle data to fully reconstructed images.

Gemini North

Telescope f/#	16.0
Plate scale	1.592 "/mm

GemSpeck - Speckle mode

Focal Lengths

L1	35 mm
L2	75 mm

Detector Image Plane

Magnification	2.14x
Pixel Scale	0.0096 "/pxl
Unvignetted Circle Dia	6.7 "
Detector FoV	9.9 x 9.9 "

GemSpeck - Wide-Field mode

Focal Lengths

L1	75 mm
L2	-100 mm
L3	50 mm

Detector Image Plane

Magnification	0.285x
Pixel Scale	0.0725 "/pxl
Unvignetted Circle Dia	60 "
Detector FoV	74 x 74 "

WIYN

Telescope f/#	6.289
Plate scale	9.374 "/mm

WIYNPKL - Speckle mode

Focal Lengths

L1	30 mm
L2	200 mm

Detector Image Plane

Magnification	6.67x
Pixel Scale	0.0182 "/pxl
Unvignetted Circle Dia	22 "
Detector FoV	19 x 19 "

WIYNPKL - Wide-field mode

Focal Lengths

L1	100 mm
L2	150 mm

Detector Image Plane

Magnification	1.5x
Pixel Scale	0.0813 "/pxl
Unvignetted Circle Dia	56 "
Detector FoV	83 x 83 "

GemSpeck - top view, mounted at the GCAL port. From the pickoff mirror, the beam enters the collimating lenses and re-imaging lenses are mounted on motorized linear stages (green). After being collimated, the beam enters the detector. The collimating lenses and re-imaging lenses are mounted on motorized linear stages (green). After being collimated, the beam enters the detector. The collimating lenses and re-imaging lenses are mounted on motorized linear stages (green). After being collimated, the beam enters the detector.

Integrated
1'' image

Speckles

Reconstructed
speckle image

Reconstructed
speckle image

~60'' of M13 from HST archive. This is a higher resolution image than we expect from the ground, but at a scale comparable to what will be available in WF mode.

Detector QE/SDSS Filter Transmission. The Gemini and pickoff mirror transmission is only applicable to the Gemini telescope.

Dichroic Edge

685 nm

This allows the blue (447nm) and green (562nm) filters in the reflective channel and the red (692nm) and infrared (880 nm) filters in the transmissive channel.

Filter Wheel A

central λ , bandwidth

SDSS/g	480 nm, 140 nm
SDSS/r	625 nm, 140 nm
g-narrow	466 nm, 40 nm
r-narrow	562 nm, 40 nm

Filter Wheel B

central λ , bandwidth

SDSS/i	770 nm, 150 nm
SDSS/z	910 nm, 120 nm
i-narrow	692 nm, 40 nm
z-narrow	832 nm, 40 nm

Detectors

The instrument will use two identical Andor iXon Ultra 888 EMCCD cameras.

- 1024 x 1024 with 13 μ m square pixels
- Capable of 26 fps reading out the full chip, higher for subarray readout (speckle mode)
- EX coating, > 80% quantum efficiency from 420 to 780 nm, > 90% QE between 550 and 720 nm.
- Thermoelectrically cooled, require no consumables.
- Data is transferred to the control computer via USB3, no internal cards
- Control computer can be quite small with heat dissipation being minimal.

Maximum Resolution

Gemini	0.015'' FWHM @ 500 nm	0.025'' FWHM @ 800 nm
WIYN	0.036'' FWHM @ 500 nm	0.058'' FWHM @ 800 nm

Discussion

Possible Exoplanet Applications

- Simultaneous two color transit photometry yields instant verification (same depth in both channels).
- Standard imaging provides host star photometry
- Speckle imaging assesses binarity and yielding correct exoplanet radius

Future Expansion

The filter wheels each have two remaining empty slots, we are currently exploring possible uses for these including the addition of:

- Transmission Grating - Grism
- Aperture Mask

Possible science application include: exoplanet transit spectroscopy, exoplanet atmosphere detection, transient object classification and characterization.

An aperture mask would allow spatial resolution beyond the diffraction limit! Achieving true interferometric resolution (2.44x the diffraction limit). This could be especially interesting if used on next-generation ELTs.

Acknowledgments

We acknowledge the collaborations with the WIYN and Gemini observatory staff and the support for this project from the NASA Exoplanet Exploration Program and NASA headquarters.

Notes

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Chalcogenide Glass Planar MIR couplers for future chip based Bracewell Interferometers

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The fundamental goal of exoplanet research is to find Earth-like bodies. Already there are discoveries of rocky planets orbiting in their respective habitable zones. The inevitable future of exoplanet exploration is the characterisation of the atmosphere of these planets. To achieve this exoplanets must be imaged, using interferometry, with high angular resolution and extreme dynamic range. Here we present a photonic approach that enables such astronomy by using a Bracewell inspired nulling interferometer. The idea is to use a single photonic chip, made of layers of Chalcogenide glass, to null the star light enabling characterisation of the exoplanet light.

In the Mid Infrared (MIR) planetary light is in optimal contrast to the light emitted from the host star. The L' MIR band in particular is favourable and is highlighted in orange. Planetary formation is the key focus in the L' band but in the M' band absorption features, that indicate the existence of plant life, are present – a focus for future works.

The Multimode interference coupler (MMI) is the key mechanism for the nulling interferometer. The beauty of the MMI is the simplicity of allowing light to interfere with itself in mathematically predictable patterns that reimage the light into identical images of the original wavefront. A special case 2x2 MMI is displayed, fabricated with tapering inputs from 2 μm waveguides, maintaining a single mode, to 8 μm increasing the fabrication tolerances and bandwidth of the device.

The interferometer is created in three layers of Chalcogenide glass (ChG) on a silica wafer. Initially starting with an under layer of $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$ and core layer of $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$ the device is plasma etched and then overlaid with $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$. The light source used for the below tests was a custom built seeded optical parametric amplifier and a ND: YVO_4 picosecond pump laser with a wavelength of 1064 nm

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The interferometer combining the three MMIs in a 2:1 configuration indicating how the star light is interfered and nulled. The black lines are to help guide the eye.

The interferometer allows a planet to be found orbiting a star when otherwise the star light would be too bright. The combination of three MMIs in the figure above indicates the path of the star light allowing the third MMI to identify light not from the star, such as a planet or merely dust.

The Extinction Ratio is a measure of how effectively the star has been nulled. The right side picture provides an indication of the effectiveness of the device purely based on the simulations of the individual MMIs.

A simulation of the interferometer. The wavelength scan was taken for various MMIs each with randomly assigned width and length that are within an exaggerated tolerance of the expected 45 μm X 875 μm dimensions.

All-in-one 4-telescope beam combination with a zig-zag array of waveguides

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Abstract

In this work we propose a new geometry of discrete beam combiners (DBC) for spectrally-resolved stellar interferometry which overcomes the limitations of previous designs. The new beam combiner is based on an array of coupled waveguides arranged in zig-zag pattern. It has been numerically optimized for the combination of 4 telescopes and engineered to operate in the L-band. We manufactured a first sample by direct laser writing in Gallium Lanthanum Sulfide glass, a highly transmissive material in the mid-infrared (550 nm to 10 μm). Initial near-field characterization of the fabricated sample at a wavelength of 3.4 μm are encouraging, but highlighted the necessity of a better control of the polarization dispersion of individual waveguides, as well as induced stresses from manufacturing process.

Zig-zag discrete beam combiners

Discrete beam combiners (DBC) are 3D integrated optics multi-telescope, all-in-one interferometric beam combiners based on the properties of 2D arrays of evanescently coupled waveguides (photonic lattices) [1]. So far, only square or hexagonal waveguide arrays have been investigated both numerically and experimentally [2], which pose an obvious limitation as long as high-resolution spectro-interferometric applications are concerned [3]. Recent advance in the theory of DBCs [4], showed the necessity of diagonal (second order) coupling between waveguides in the 2D array in order to use the photonic lattice as a beam combiner. This discovery lead us to identify zig-zag photonic lattices (see Fig. 1) as ideal candidates enabling the interfacing of the DBC output to a spectrograph for high-resolution spectro-interferometry purposes.

Fig. 1: (Left): Spectrometer output of 4x4 DBC. (Right): Spectrometer output of zig-zag DBC.

We optimized the design of the zig-zag array for 4-telescope combination, by numerical search of the DBC input configuration and array length which could deliver the most well conditioned Visibility to Pixel Matrix (V2PM) [5] for the beam combiner. It turned out that an array of 23 waveguides with the input configuration as shown in Fig. 1 and length ~ 1.4 coupling lengths would result in the best beam combiner performance (condition number of V2PM = 3.6).

Manufacturing zig-zag DBC in Gallium Lanthanum Sulfide

Our first sample of the zig-zag DBC was manufactured by ultrafast laser inscription (ULI) [6] in Gallium Lanthanum Sulfide (GLS), as we are targeting the realization of integrated optics beam combiners for mid-infrared [7]. With ULI, structural material modification is induced by intense and highly localized laser irradiation, which can be used to manufacture single-mode waveguides, as long as laser irradiation induces positive refractive index changes (like in GLS) [7,8].

Fig. 2: (Left): Scheme of ULI setup. (Right): Image of a multi-pass waveguide & guided mode at $\lambda=3.4 \mu\text{m}$.

We manufactured waveguides supporting nearly circular mode fields at $\lambda=3.4 \mu\text{m}$ by multi-pass ULI [4,5] with the following writing parameters:

Laser source: Nd:KGW, 400 fs pulses Average power: 40 mW
Repetition rate: 500 kHz Translation velocity: 4 mm/s

Focusing objective NA: 0.35

Writing procedure: 21 parallel tracks with lateral separation of 300 nm.

From the guided mode profile (Fig. 2), we estimated that the core-cladding refractive index contrast is in the range of $\Delta n \sim 10^{-3}$.

To engineer the designed zig-zag DBC, we first estimated the coupling strength at $\lambda=3.4 \mu\text{m}$ of pairs of evanescently coupled waveguides, by measuring the splitting ratios of a set of 2x2 couplers (Fig. 3) with waveguide gaps between 20 and 30 μm and interaction length $L=0, 4$, and 8 mm. Waveguides were both arranged in horizontal and diagonal geometry.

Fig. 3: (Left): Schematic top view of the directional coupler. (Right): Image of the output intensities of a horizontal and diagonal directional coupler at 3.4 μm , separation ca. 23 μm , interaction length 4 mm.

According to the coupled mode theory, the splitting ratio of the coupled waveguide (cross) over the injected one (bar) is given by:

$$\frac{I_{\text{cross}}}{I_{\text{bar}} + I_{\text{cross}}} = \sin^2(kL)$$

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Estimates of the kL term from the measured splitting ratios have been plot as a function of the interaction length and fitted with a line to extract the coupling strength as a function of the waveguide gap (see Fig. 4).

Fig. 4: (Left): The ratio of $I_{\text{cross}}/I_{\text{bar}}+I_{\text{cross}}$ over the waveguide separation for 4 mm long interaction for horizontal and diagonal couplers. (Center): Fit of kL for several couplers. (Left): Results of coupling coefficients.

First results with zig-zag DBC

The measured coupling constants were used to engineer a sample of 4-T zig-zag DBC. We chose a horizontal period of 27 μm to fulfill the coupled mode approximation for light propagation in the array. The overall sample length was 25 mm. Output light distribution for input excitation of waveguides 5 and 19 of the manufactured component are shown in Fig. 5, for both vertically and horizontally polarized input laser beam. Comparison with numerical simulations showed however that manufacturing imperfections dominate light propagation in the array.

Fig. 5: Images of the output intensities of the zig-zag coupler with horizontal separation of 27 μm at $\lambda=3.4 \mu\text{m}$ from simulation and experiment.

Limitations of ULI

Experimental data (Fig. 5) indicate an asymmetry and a strong polarization dependence of the output excitation patterns of the DBC. A possible explanation lies in the accumulation of mechanical stresses induced by ULI during the manufacturing process (the next waveguide is written on a substrate already modified by the manufacturing of previous ones). To verify this hypothesis, we used polarimetric strain measurements to gauge the impact of ULI-induced mechanical stresses. As shown in Fig. 6, we found polarization rotation on a ca. 200- μm -wide butterfly shaped area surrounding each written waveguide. Quantitative estimates of the optical path differences between orthogonal polarization states amount to $\sim 60 \text{ nm}$ over 3-mm-long samples. This corresponds to a minimal stress-induced birefringence of $\Delta n \sim 2 \cdot 10^{-5}$ (assuming zero-order length).

Fig. 6: (Left, center): Images of the optical path difference of waveguides.

Conclusions and outlook

We have identified a new design of 4-T DBC, suitable for high-resolution spectro-interferometric applications (zig-zag DBC). However, manufactured samples of zig-zag DBC highlighted the need for a better control of ULI-induced mechanical stresses in the GLS substrate. We are currently investigating the possibility to cure stresses by a post-processing annealing [9]. Stress distribution by alternating the order of written waveguides is also being investigated.

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6- and 8-Telescope Discrete Beam Combiners

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Abstract

We conduct an extensive numerical study to single out the best performing rectangular array of evanescently coupled waveguides (discrete beam combiner) that can be used as an integrated optic beam combiner for 6-telescopes at once. We found that the performance of a discrete beam combiner only depends on the conditioning of the Visibility to Pixel Matrix (V2PM) describing it. However, we found that the condition number of V2PM pertaining to different beam combiner architectures cannot be compared. We further report on the possible input waveguide configuration of an 8-telescope discrete beam combiner featuring 8x8 or 9x9 waveguides.

Keywords: Integrated optics, coupled waveguides arrays, optical astrointerferometry

1. Discrete Beam Combiners

A Discrete Beam Combiner (DBC) is an array of evanescently coupled single-mode waveguides used to measure simultaneously the mutual coherence properties of light injected in selected sites [1]. Its application to astronomical interferometry could drastically reduce the complexity of multi-telescope integrated optics beam combiners [2]. For the efficient combination of the input fields A_k from N_t telescopes the DBC uses an array of $N_w > N_t \times N_t$ waveguides. Due to evanescent coupling, light propagating in one waveguide will leak to neighboring waveguides. At a given length of the array, the N_t input fields will interfere inside the waveguides with variable amplitude and phase depending on the observed waveguide and the length of the array (see Fig. 1). The intensities of the N_w waveguide modes at the end of the sample can be related to the complex visibilities $\Gamma_{ij} = \Gamma_{ji}^* = \langle A_i A_j^* \rangle$ by a real valued, $N_w \times N_t^2$ elements matrix, the so called Visibility to Pixel Matrix (V2PM [3]):

$$I_n = \sum_{i,j=1}^{N_t^2} |V2PM|_{ni} J_i$$

Here the complex visibilities Γ enter the equation in the form of their quadratures J_i defined as:

$$\vec{J} = [\Gamma_{1,1}, \dots, \Gamma_{N_t, N_t}, \Re \Gamma_{1,2}, \dots, \Re \Gamma_{1, N_t}, \dots, \Re \Gamma_{N_t, 1}, \dots, \Re \Gamma_{N_t, N_t}, \Im \Gamma_{1,2}, \dots, \Im \Gamma_{1, N_t}, \dots, \Im \Gamma_{N_t, 1}, \dots, \Im \Gamma_{N_t, N_t}]^T$$

Figure 1 – Cartoon illustrating the structure and basic setup of a 4T-DBC.

The quadratures J_i can be retrieved by multiplying the I_n vector by the pseudo-inverse of the V2PM (Pixel to Visibility Matrix, P2VM). The visibility modulus can then be calculated from:

$$V_{ij} = \sqrt{(\Re \Gamma_{ij})^2 + (\Im \Gamma_{ij})^2}$$

2. Goals and methods

Aim of our investigation is a numerical optimization of the discrete beam combiner scheme suitable for the combination of $N_t = 6$ or $N_t = 8$ telescopes.

The chosen optimization parameters are the number of waveguides in the array and the relative strength of the diagonal coupling in the array. This choice is motivated by two previous results related to the DBC architecture, namely:

- Arrays featuring more than $N_t \times N_t$ waveguides have a better conditioned V2PM [4].
- Besides the horizontal coupling C_h , the diagonal coupling C_d is a necessary condition for phase retrieval with arrays of waveguides [5].

As quality parameter for the optimal beam combination configuration, we chose the condition number (CN) of the V2PM. We verified (see Results 6T-DBC) that the conditioning of the V2PM is proportional to the error on the retrieved visibility amplitude in the photon-rich detection limit (inverse of the signal to noise ratio).

Two algorithms have been used in this work: a) a best DBC configuration finder, and b) a Monte-Carlo simulator of the visibility measurement procedure. Block diagrams of the algorithms are shown here below.

Algorithm (a)

Algorithm (b)

3. Results 6-T DBC

Figure 2 - We numerically investigated rectangular arrays of waveguides with increasing size to verify the existence of an array featuring a minimal CN of the V2PM ($C_d/C_h = 0.15$). In the investigated size interval (from 36 to 100 waveguides) we found a monotonic decrease of the CN (Fig. 2.a). We verified that the measurement error on the visibility (unresolved source) is proportional only to the CN of the V2PM (Fig. 2.b). We found that different types of beam combiners (ABCD and multi-axial) have different dependencies of the measurement error on the CN of their V2PM (Fig. 2.b). For a given array (7x7) we tested the effect of the diagonal coupling on the conditioning of the 6T-DBC V2PM (Fig. 2.c). For $C_d/C_h > 0.1$, diagonal coupling optimization has a relatively small impact on the conditioning of the V2PM (<15%).

4. Results 8-T DBC

Figure 3- Because of computational power limitations, we could only search for the 8T input configurations in 8x8 and 9x9 arrays. Despite the high CN of the V2PM (see Table below) we found that the visibility retrieval error is comparable to that of the best 6T-DBC (see Fig. 2b).

DBC Array	CN V2PM	min 1/SNR (10 ⁻⁵ detected photons)	max 1/SNR (10 ⁻⁵ detected photons)
8x8	29.2	0.020	0.038
9x9	10.7	0.010	0.019

5. Conclusions and outlook

- The CN of the V2PM is proportional to the error on the visibility amplitude retrieved from measurements.
- For DBCs larger arrays lead to smaller CN. For 6T-DBC we could not find a minimum.
- The CN of the V2PM of different beam combiner architectures cannot be compared directly.
- Tuning of the ratio C_d/C_h above ~0.1 can improve by ~10-20% the conditioning of the V2PM of the DBC.
- Scaling of DBC beyond 8T is limited by the factorial growth of the configurations to be tested.

We are currently investigating the performance of a new DBC geometry based on zig-zag arrays [6] and plan to manufacture and test first samples of 6T-DBC to verify numerical predictions.

6. Acknowledgments

S.M. acknowledges the support of the German Ministry of Education and Research – Project ALISI (Advanced Laser-Interferometry for Stellar Interferometry), contract number 05A1430A. Proceedings of SPIE on 31 Jul 2019

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HIGH FIDELITY IMAGING OF GEOSYNCHRONOUS SATELLITES WITH THE MROI

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1. Overview

Visible/infrared interferometry provides the only practicable way to image satellites in Geosynchronous Earth Orbit (GEO) with sub-meter spatial resolution. The Magdalena Ridge Observatory Interferometer (MROI) is being supported by the US Air Force Research Laboratory to determine the feasibility of imaging passively-illuminated GEO satellites with a ground-based interferometer, by means of two parallel activities:

- A demonstration of the 9.5 mag. sensitivity and baseline-bootstrapping capability that will be needed to realise a useful GEO imaging capability. This program will utilise the central three telescopes of the MROI and aims to validate routine acquisition of fringe data on faint well-resolved targets.
- Computational simulations to investigate the spatial resolution and imaging fidelity that can be achieved with different numbers of array elements.

Preliminary simulation results indicate that faithful imaging of the main satellite components can be obtained with as few as 7 unit telescopes, and that increasing the number of telescopes to 10 improves the effective spatial resolution from 0.75 meter to 0.5 meter and enables imaging of more complex targets.

2. Sensitivity Demonstration

We have begun a five-year program to mitigate the principal technical risks associated with developing a ground-based satellite imaging array. Under this program, three unit telescopes will be installed on the Magdalena Ridge, and used to secure interferometric data on GEO targets. These measurements will be used to validate models of the instrumental performance needed to predict the imaging capability of the full telescope array. The MROI sub-systems will be deployed and tested in sequence, starting with the unit telescopes, beam relay system, and delay lines. The program will culminate in measurements of co-phased visibilities (year four) and closure phases (year five) for GEO targets. MROI has been designed to accommodate up to 10 unit telescopes. For the simulations presented here, we have also considered a 19-telescope array – this would require changes to the existing designs and site infrastructure.

3. Imaging Simulations

Simulated interferometric datasets were prepared by evaluating the discrete Fourier transform of a suitably scaled model image at spatial frequencies corresponding to the MROI projected baselines. The assumed telescope array configurations and corresponding (u, v) coordinates are shown in Fig. 2. The configurations were optimized for baseline bootstrapping, with a constant 7.8 m spacing between adjacent telescopes. For simplicity, the target was assumed to have an identical appearance across the J (1.1–1.4 μm) and K (2.0–2.4 μm) wavebands (future plans include simulating the modest albedo variations expected in the near-IR). The model image used is shown in Fig. 3, and its visibility as a function of projected baseline length is shown in Fig. 1.

Figure 2: The telescope array layout for the proposed array configurations at different stages of development (left) and the (u, v) plane coverage of these arrays (right). Only the most compact configurations of these arrays are shown.

The Fourier data were then used to generate interferometric observables (squared visibilities and bispectra). Random errors were added to the data based on realistic assumptions of co-phasing accuracy at the assumed 9.5 mag. target brightness. In addition, uncorrelated calibration errors were added to the visibilities ($\Delta V^2/V^2 = 0.02$) and closure phases (0.8°). For the ten-telescope simulation, the mean SNR of the synthetic V^2 was 6.8, and the mean closure phase error was 3.1° . The largest closure phase errors were $\sim 40^\circ$. The simulated data were used as input to the BSMEM image reconstruction code.¹ For each dataset, a two-step reconstruction procedure was used. First, higher spatial frequency data were removed and BSMEM run with an uninformative circular Gaussian prior image. High spatial frequencies and noise were removed from the BSMEM output image by convolving with a circular Gaussian function and setting pixel values below a user-selected threshold to zero. The resulting image was used as a prior for a second run of BSMEM on the full dataset.

Figure 1: Object visibility as a function of baseline length at a wavelength of 2.2 μm for the satellite shown in Fig. 3, which has a "bus" of order 5 m in dimension and a 10 m long solar panel. Note the steep fall-off in visibility for baselines longer than about 8 m.

4. Simulation Results

The model spacecraft has structure on a range of scales from ~ 0.2 m to 17 m and is therefore a good test of the accuracy and effective resolution with which images can be reconstructed. For arrays of 7 or more telescopes, the simulation results (Fig. 3) show faithful reconstructions. The effective spatial resolution of the images increases as the number of telescopes, and hence the maximum baseline, is increased. These images exhibit "super-resolution" beyond the nominal λ/B diffraction limit. For example, the 1 m diameter structure at the tip of the boom is resolved in the seven-telescope image where the nominal resolution is just 1.6 m. Observations using fewer than 7 telescopes provide information on the size and orientation of the satellite but do not permit model-independent imaging.

Figure 3: Truth (top left) and reconstructed images using 19, 10, and 7 telescopes (clockwise from top right) for a simulated MROI observation of a GEO satellite. The axes are scaled in meters.

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USER-FRIENDLY IMAGING ALGORITHMS FOR INTERFEROMETRY

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Introduction

OPTICON currently supports a Joint Research Activity (JRA) dedicated to providing easy to use image reconstruction algorithms for optical/IR interferometric data. This JRA aims to provide state-of-the-art image reconstruction methods with a common interface and comprehensive documentation to the community. These tools will provide the capability to compare the results of using different settings and algorithms in a consistent and unified way. The JRA is also providing tutorials and data samples to introduce the principles of image reconstruction and illustrate how to use the software products.

JRA Deliverables

- User-friendly implementations of BSMEM, MiRA, and WISARD (see table below)
- A common graphical user interface for the above algorithms
- Example datasets
- User manuals and cookbooks

The specification (currently in draft form¹) for the interface between the algorithms and the common GUI will be made available to encourage the integration of other algorithms such as SQUEEZE² and the Building Block method.³

Name	Authors	Optimization	Regularization
BSMEM ³	Baron, Buscher	Trust region gradient	MEM-prior
MiRA ⁸	Thiébaud	VMLM-B	Many
WISARD ⁶	Meimon, Mugnier, Le Besnerais	VMLM-B + self-cal	Many

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Graphical User Interface

Figure 1: Screenshot of a prototype of the image reconstruction user interface. The GUI includes controls for selecting a subset of the interferometric data (by target, wavelength, and kind of data); the algorithm settings (starting image, maximum number of iterations, regularization); and the initial or reconstructed image.

The graphical user interface (Fig. 1) and the image reconstruction algorithm will run as separate processes, exchanging data by means of files. This approach works on any platform and allows algorithms written in any programming language to be integrated straightforwardly. The diagram in Fig. 2 shows how the two processes interact to reconstruct an image with the user-specified settings and display results.

Figure 2: UML activity diagram showing the steps involved in reconstructing an image using the common Graphical User Interface. The GUI process writes an input file and launches the algorithm process. After each iteration of the reconstruction, the algorithm writes updated intermediate results to an output file. The GUI watches for modifications to the output file and updates its displays after each iteration.

Algorithm Interface

The common interface to image reconstruction algorithms is a specification for their input and output files.¹ These files, which conform to the FITS standard,⁴ are exchanged between the GUI and algorithm processes as described in the centre panel. The input file provides the interferometric data and the algorithm parameters. The output file contains either intermediate or final results. The design of the specification is based on the following principles:

- The output file must also be a valid input file, for traceability and to permit the algorithm to be restarted from where it finished.
- The input and output files must conform to the OIFITS⁷ standard, with additional images/tables containing the image reconstruction parameters and results.
- The outputs must include model data corresponding to the intermediate/final reconstructed image.

Figure 3: Diagram of the FITS-based file format used for input and output to/from the algorithms. The image reconstruction input and output parameters are stored in dedicated FITS binary tables. For compactness, additional table columns (as permitted by the OIFITS standard) are used to store model data within the OIFITS data tables.

AGP (Astrometric Gravitation Probe) Optical Design Report

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9907-150

This paper describes the current opto-mechanical design of AGP, a mission designed for astrometric verification of General Relativity (GR) and competing gravitation theories by means of precise determination of light deflection on field stars, and of orbital parameters of selected Solar System objects. The optical concept includes a planar rear-view mirror for simultaneous imaging on the CCD mosaic detector of fields of view also from the direction opposite to the Sun, affected by negligible deflection, for the sake of real time calibration. The precision of astrometric measurements on individual stars will be of order of 1 mas, over two fields separated by few degrees around the Sun and observed simultaneously. We describe the optical design characteristics, with particular reference to manufacturing and tolerancing aspects, evidencing the preservation of very good imaging performance over the range of expected operating conditions.

The implementation of the AGP differential measurement scheme is achieved by means of a dual-line-of-sight telescope with a diluted pupil mask, used in order to reject the Sun light. Rear-view mirror picks-up the star light of sources opposite to the sun, and uses the non populated part of the mirrors in order to drive the light into the “front” optical path.

The AGP telescope is designed with two channels, but it is compatible with up to four/eight channels. The two channels are pointing symmetrically to about +/- 1deg with respect to the optical axis of the telescope, which in nominal operation is set on the Sun. This corresponds to a base angle of 2 deg. Each channel has a field of view of 16'x16'. Each channel has a similar and symmetric layout with respect to the telescope incoming beam.

- The AGP structure is composed by the following elements:
- Two circular extremities built from titanium
 - A large Carbon Fiber Reinforced Plastics (CFRP) central element.
 - A CFRP removable .
 - Two CFRP open boxes, obtained by the same mold. These two elements provide the housing for the two M4s and M5s
 - The four legs, built from stainless steel welded pipes. The extremities of three of the four legs end with flexible elements, to separate the thermal deformations of the AGP module from those of the satellite.

Primary mirror holes-set with footprint of pupil mask

Rear-view mirror displacement

Rear-view mirror: according to AGP measurements principles, star light coming from sources in the direction opposite to the Sun, are not affected by any deflection, and should improve the calibration issues of the experiment. The focal plane therefore images at the same time the two front and the two rear fields of view.

A first study of the structure has been performed by FEA. In the model the CFRP parts are modeled using an equivalent isotropic material. The interfaces to the mirror have a good level of detail and a first computation of the stress, even if still purely indicative, is thus realistic.

CONCLUSIONS: The present paper summarizes the Optical Design for the AGP mission, whose main goal is the measure of positions of stars for light deflection and high precision solar system dynamics. It is designed through the diluted pupil concept and beam combining of two fields separated by 2 degrees around the Sun. The design shows a good optical quality over the two 16' x 16' fields, and good tolerancing. The initial analysis