Building the Next Generation Science Camera for the Navy Optical Interferometer

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ABSTRACT

VISION is the next generation science camera for the Navy Optical Interferometer (NOI). In comparison to the current beam combiner of NOI, VISION will deliver higher precision data products and better flexibility by incorporating single mode fibers for spatial filtering and by using low-noise detectors. VISION can coherently combine up to six telescope beams using an image-plane combination scheme. This results in simultaneous measurement of 15 visibility amplitudes and 10 independent closure phases that can be used to reconstruct multipixel images of stars.

Keywords: Optical interferometer, Interferometeric observation, Beam combiner

1. INTRODUCTION

The Navy Optical Interferometer (NOI) is an established facility for astrometry and high resolution imaging;[1] it is capable of a maximum resolution $\sim 200\times$ higher than possible with either the Hubble Space Telescope or the largest ground based telescopes. The existing beam combiner at NOI is a free-space, pupil-plane design.[2] It is a hybrid scheme incorporating features of both pair-wise and all-in-one beam combination. It produces interfered outputs of the six input beams on three spectrometers, each of which can accommodate beams from up to four telescopes.

The Visible Imaging System for Interferometric Observation at NOI (VISION) is a science imaging camera for the NOI, developed by Tennessee State University. VISION is a fiber-based image-plane beam combiner, that can combine up to six telescopes with an all-in-one combination scheme. In comparison to its current beam combiner, VISION is able to achieve higher precision data products and better flexibility. VISION has the potential to improve the quality and reliability of observable data products from NOI by a factor of 10. This factor arises from an improved ability to calibrate data. The current NOI beam combiner can be calibrated at only the 10% level. The improved mechanical stability, use of spatial fringe modulation, incorporation of spatial filtering, and photometric taps will enable data calibration at a level better than 1%. Advanced visible-wavelength EMCCD detectors are used featuring minimal to zero read-noise, allowing the science camera to operate optionally without an external fringe tracking combiner, without significant sensitivity loss. VISION was inspired by the Michigan Infrared Combiner (MIRC)[3] which is used for infrared imaging at the CHARA array.[4] Imaging at visual wavelengths, at which the contrast between hot and cool regions is higher, will allow VISION to uniquely characterize stellar features less accessible to MIRC. We stress the complementarity of VISION and its infrared counterpart. There is much to be gained from joint investigations using both devices.

The addition of VISION to NOI improves its capability to perform unique science programs, including the following cases:

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- For imaging stellar surfaces, arrays with equal spacing between elements are superior to arrays that have been laid out to optimize imaging coverage and that therefore have unequal spacing. The imaging subarray of NOI provides a number of equally spaced configurations. Coherence across either type of imaging configuration is maintained by baseline bootstrapping. This allows imaging with many effective pixels across a resolved source.[5]
- The high spatial resolution imaging capability coupled with a good field of view enables the study of hierarchical triple star systems; where one of the two pair of stars is itself a much more narrowly separated binary. This allows full characterization of the structures and dynamics of these systems.[6,7] The relatively large interferometric field of view is enabled by the optional use of medium to high resolution spectral dispersion of the fringes.
- The unique capability of NOI to spatially resolve emission line regions around stars[8] will be preserved by using VISION in moderate dispersion mode. This will be used to isolate spectral regions containing strong emission lines.
- The long baselines at NOI give it enough resolution to measure visibilities beyond the first null of the visibility function. This will make it possible to measure[9,10] —rather than calculate— the limb darkening of several bright Cepheids.

2. DESIGN

VISION is an image-plane beam combiner, that can combine up to six telescopes. A schematic layout of the VISION instrument is shown in Fig. 1. The details of the components are described below in the order seen by the star light.

2.1 Light Gathering

Array siderostats direct starlight through vacuum pipes to the central beam combining facility. It is passed through long and fast delay lines which move to match optical path-lengths. The result is 6 coherently-phased collimated beams of light with 35 mm diameters.

2.2 Visible Wavelength

NOI operates at visible wavelengths and so does VISION. Many modern optical interferometers operate at near infrared wavelengths where atmospheric turbulence is reduced. Visible operation has its own advantages. Shorter wavelengths allow for the highest spatial resolutions. Detector technology at visible wavelengths is more advanced. There are science features at visible wavelengths not present in the infrared. The long history of visible wavelength observational astronomy, particularly on bright stars targeted by interferometry, offers better auxiliary support data at visible wavelengths.

2.3 Fiber-Feed Unit

The 35 mm collimated star light is focused into single-mode fibers using high quality off-axis parabolas. For a single mode fiber with NA=0.12 the optimum focal length for NOI seeing condition of 9 cm was calculated using the method of Shaklan & Roddier[11] and found to be 165 mm (f/4.7). High precision positioners are employed to accurately place the fiber at the focus point to maximize the coupling efficiency. This alignment is remotely controllable.

2.4 Single Mode Fibers

The light is spatially filtered by single mode fibers to remove residual wavefront errors. These errors are caused by atmospheric turbulence and optical imperfections. The spatial filtering enhances the minimum visibility contrast that can be observed which increases the data precision. Thorlabs PM630-HP polarization maintaining fibers have been chosen which operate over a spectral range of 570-850 nm. The polarization maintaining fibers are employed to avoid polarization drift which can be caused by temperature change or other effects.The mode-field diameter and beat length of this fiber are respectively 4.5 μm and 1.8 mm at 630 nm and the numerical aperture is 0.12.

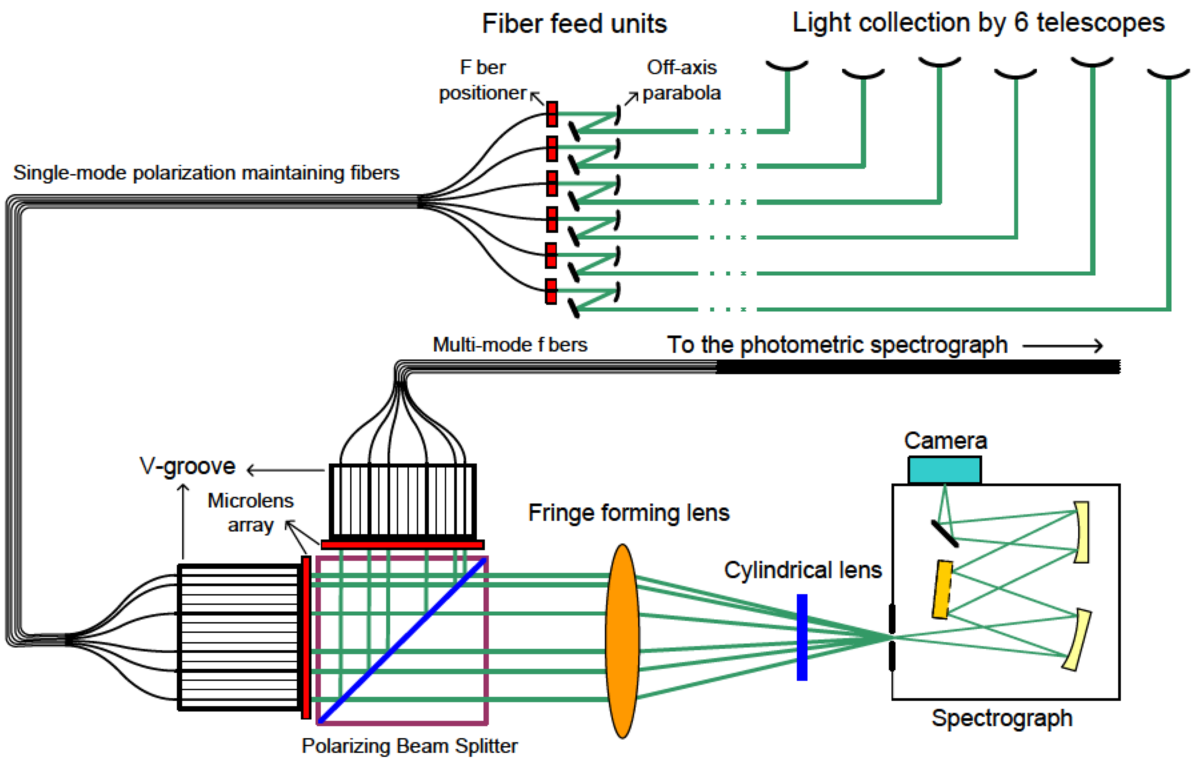

Figure 1. Schematic layout of VISION.

2.5 Beam Combiner

The outputs of the fibers are arranged in a non-redundant linear pattern on a V-groove array, with base spacing of 250 μm. This is an image-plane combination and spacing between the fibers will translate to the spatial frequency (see Fig. 3) of the resulting fringe pattern. A fiber arrangement similar to MIRC[3] with fiber spacing of 2-6-5-4-3 was chosen. These spacings result in fringes with spatial frequencies (multiples of the base frequency f_0) of 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 15, 17, 18, 20. As it can be seen, each pair form fringes of unique spatial frequency for demodulating the signals between all telescope pairs.

The polarization axis of all the fibers are aligned in the V-groove array. A lenslet array recollimates the light exiting each fiber to a 250 μm beam. The six collimated beams are focused by a doublet to form fringes between the six beams. This is a six-element version of the classic Young's double slit experiment. VISION uses an all-in-one combination scheme, all the six telescope beams are combined which result in simultaneous measurement of 15 visibilities and 10 independent closure phases. The doublet has a long focal length ($\sim$ 1 m) in order to produce fringes large enough to be resolved by the 24 μm pixels in the science camera. A cylindrical lens with 50 mm focal length focuses the beam in the direction orthogonal to the linear array, in which fringes are not formed. This results in an image 24 μm by 3.5 mm, fringing in the long dimension.

2.6 Spectrograph

The fringing image is fed to a spectrometer dispersing the light in the non-fringing dimension and reimaging it onto the detector. At least two options for the dispersing element are available: a low dispersion (R $= \lambda/\Delta\lambda =$ 200) element allowing all the light across an effective 570-900 nm bandpass to fit on the detector, and a higher (R=2000) dispersion option which can select a smaller bandpass from within that range. A commercial system has been used (Princeton Instruments Acton Spectrograph Model SP2156) to minimize design costs, simplify use, and increase flexibility by having a range of dispersing elements. Switching between the gratings can be done in a few seconds.

2.7 Science Camera

The spectrally dispersed and spatially modulated fringes are imaged onto a Andor Ixon DU-860 camera. The new electron multiplication technology built into these cameras allows zero read noise operation at frame rates faster than temporal variations in the atmospheric turbulence (500 Hz). The zero read noise functionality enables the light to be spread over many pixels without penalty, meaning our design with spatial modulation of fringes and spectrally dispersing the fringes is equally sensitive as other combination schemes, while it offers many advantages for stability and data calibration.

2.8 Photometric tap

A polarizing beam splitter cube redirects one of the polarizations to feed multimode fibers. The output of these multimode fibers is also on a V-groove, and is placed in front of second spectrograph and camera to monitor photometric fluctuations. Note that this happens after spatial filtering and enables precision visibility amplitude calibration. Although the light after the first V-groove is collimated by the lenslet, it expands due to diffraction. Hence the multimode fiber has to be placed as close as possible to the output of the single mode fibers. In our design this distance is 12 mm.

3. CHARACTERIZATION

VISION was completely developed and tested at Tennessee State University (TSU) and then it was transported to NOI for deployment in May 2012.

3.1 Coupling Efficiency

The theoretical coupling efficiency for a 12 cm aperture with r_0 =9 cm at 800 nm (typical for NOI) for coupling starlight to a single mode fiber with f/4.7 optics is shown in Fig. 2. The first-light test of the coupling efficiency of the fiber feed unit was measured at NOI to be 20%. Measuring a throughput lower than expected value (55%) can be attributed to seeing conditions, optical quality, and optical alignments. This will be investigated further.

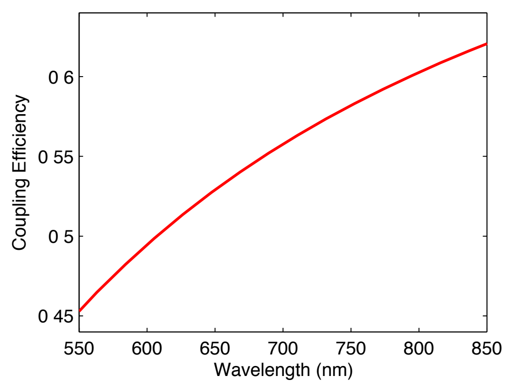

Figure 2. Theoretical coupling efficiency of the fiber feed unit with f/4.7.

3.2 Instrumental Visibility

The instrumental fringe contrast (V_{inst}) can suffer degradation resulting from imbalances of dispersion, polarization, photometry, and a poor spatial overlap of the images from different telescopes of the array.[12] It can be written as

$$V_{inst} = V_{ph}.V_{pol}.V_{spatial}.V_{disp} \tag{1}$$

Each of these degradation mechanisms was characterized and in the end high contrast (>90%) white light fringes were demonstrated at TSU.

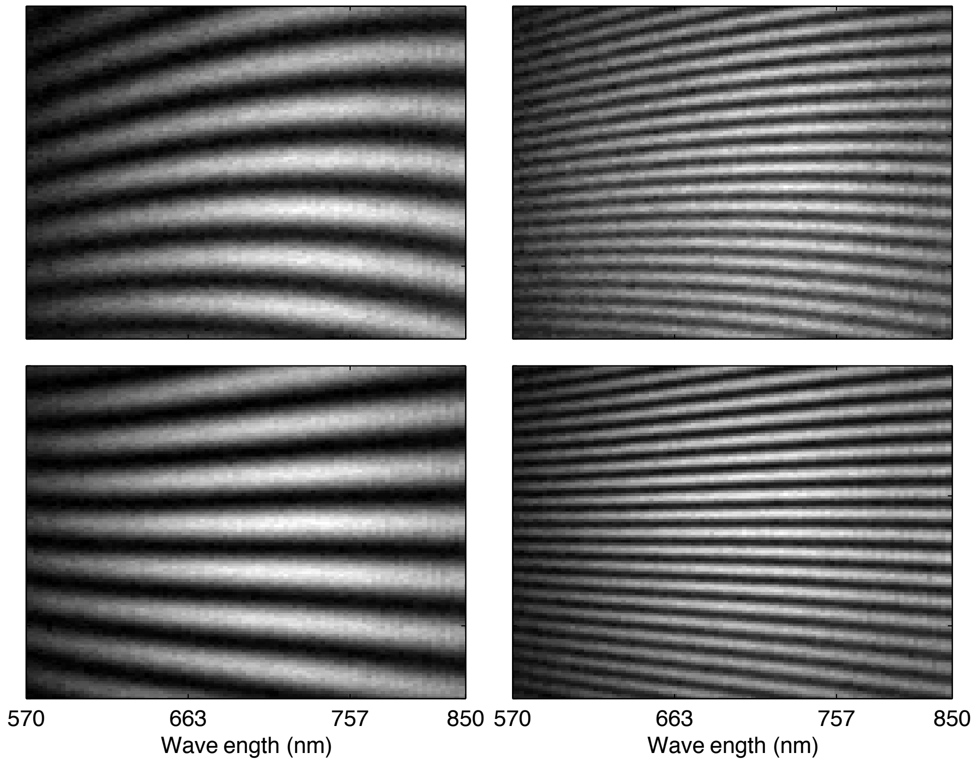

Figure 3. White light channeled spectrum produced by VISION for two different pairs with spatial frequencies of $7f_0$ and $18f_0$. The horizontal axis is the spectral direction. Top: Fibers were cut with equal length. Bottom: Differential dispersions were minimized.

Photometry: The photometric unbalance between the two interfering beams will reduce the contrast by

$$V_{ph} = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} \tag{2}$$

Using the photometric tap this term can be correctly measured and a correction can be applied.

Polarization: The differential polarization effects are automatically minimized by the polarization maintaining fibers. The polarization axes set by these fibers is fixed and all of them are aligned in the V-groove. The light emerging from a polarization maintaing fiber generally has a polarization phase-shift between the fast and slow axes. This phase-shift which is in the order of 1 fringe can reduce the fringe contrast. In the current design a polarizing beam splitter is used to guarantee that only one set of fringes will be detected, ensuring high polarization contrast, so $V_{pol} \cong 1$. The reflected polarization is used for photometry. Hence the light is divided 50/50 between the two cameras.

An alternative option that may be considered later is to cancel the polarization phase shift induced by the fibers using a birefringent component before injecting light into the fibers. A similar approach is used by PIONIER[13] by using Lithium-Niobate plates. The advantage is that the division ratio can be changed to increase the light going to the fringing camera. The drawback is that the polarization phase-shift drifts and that means the cancellation has to be checked and corrected before each run.

Differential Dispersion: VISION's polarization maintaining fibers were cut to equal length by applying tension during the cut.[14] Then the channeled spectra was analyzed to measure differential dispersion. The result showed a differential dispersion greater than what can be caused by a cut error. The same values were measured when the fibers were cut again. The measured differential dispersions for fibers of 1.5 m length corresponded to fiber length differences ranging from 50 μm to 600 μm. This unbalanced dispersion is a result of inhomogeneity of the

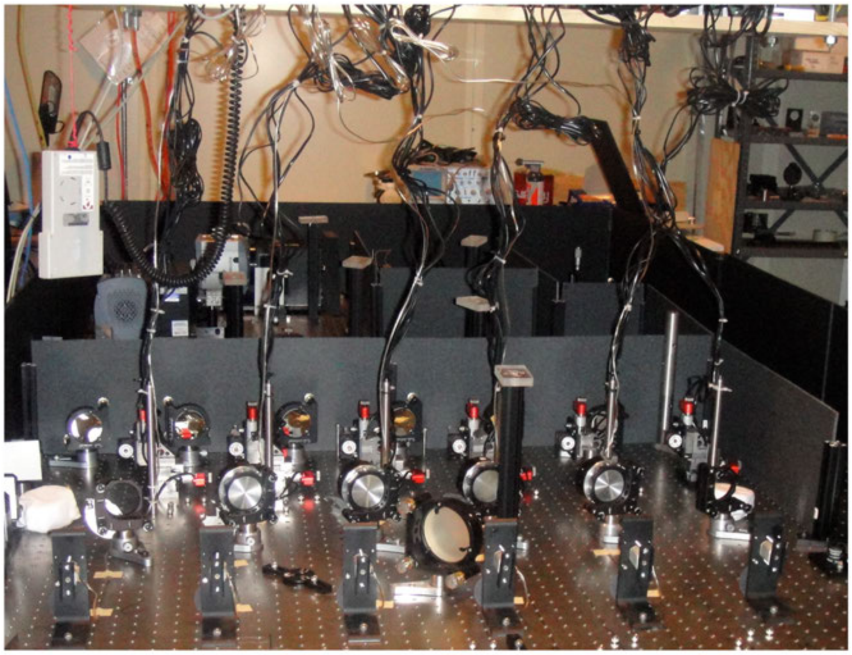

Figure 4. Fiber feed units of VISION deployed at NOI.

polarization maintaining fibers.[15] To balance the dispersion we measured the imbalance and then cut them again after moving the cut point. Figure 3 shows white light channeled spectra produced by VISION in the spectral range of 570 nm to 850 nm. The horizontal axis is the spectral direction. Left side fringes are resulting from fiber spacing of 7 and fringes on the right side are from fiber spacing of 18. The top two channeled spectra are when the fibers were cut with equal length. Differential dispersion in these can easily be seen as curved fringes. The bottom two channeled spectra are when the fibers were cut with correction of the measured unbalance. The final differential dispersion between all the pairs was equivalent to fiber length differences of 40 μm RMS.

Spatial Overlap: The optical alignment of the lenslet array, fringe forming lens, and cylindrical lens can affect the spatial overlap of the beams. The most sensitive alignment among them is the lenslet array. In order to ensure a good and stable overlap of the beams the lenslet was glued to the V-groove.

4. CONTROLS AND INTERFACING WITH NOI

Control of VISION is implemented in the $C/C{+}{+}$ language on a Linux computer. Data from the fringe and photometric cameras will be recorded and analyzed in real time. The fringe signals are processed to provide feedback to the NOI delay lines for phasing the array; tentatively, these signals will be communicated by ethernet sockets to the delay lines. The text based control that coordinates all the main components of VISION (camera, spectrograph, fiber positioners, delay line, shutters) is completed and the GUI equivalent of that is being developed.

VISION uses the current NOI star trackers for fast tip/tilt wavefront correction. A 70/30 beam splitter is used to direct light to VISION and the star trackers. In its current configuration, active fringe tracking at NOI is accomplished by two main VME subsystems, a delay line subsystem and a fringe engine system. The fringe engine system reads the photon counts and computes fringe tracking error signals. These error signals are sent to the delay line subsystem over a reflective memory link. When VISION is operational, the fringe tracking error signals will be computed in realtime by the new VISION control computer then passed to the delay line subsystem. The existing reflective memory link will be replaced by ethernet socket communication for the VISION instrument.

5. CURRENT STATUS AND FUTURE MILESTONES

The hardware of the VISION instrument was transported to NOI in mid May 2012. Initial interfacing steps were completed. The VISION system for two beams was phased with the NOI fast delay lines to get white-light fringes. The first attempt for star fringes is planned for the end of July 2012. Figure 4 shows fiber feed units of the VISION instrument deployed at NOI.

Future steps include phasing the full VISION system with NOI, the combination of more beams, measurement of closure phases, and evaluating its stability. The NOI long delay lines will be operational soon. This allows for a better sky coverage which is critical for pursuing the science plans listed in the introduction.

6. CONCLUSION

The deployment of VISION as the next generation science camera for NOI is reported. VISION is a fiber-based image-plane beam combiner, that can combine up to six telescopes with an all-in-one combination scheme. In comparison to the current beam combiner of NOI, VISION will deliver higher precision data products and better flexibility by incorporating single mode fibers for spatial filtering and by using low-noise detectors. VISION was completely developed and characterized at Tennessee State University resulting high instrumental contrast for white light fringes. The hardware of the VISION instrument was transported to NOI in mid May 2012 for deployment. Initial interfacing steps were completed. The VISION system for two beams was phased with the NOI fast delay lines to get white-light fringes. The first attempt for star fringes is planned for the end of July 2012.

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