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Invited Paper

Many Interesting Things are Afoot at the Navy Precision Optical Interferometer

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ABSTRACT

The Navy Precision Optical Interferometer (NPOI) is currently undergoing a fundamental renaissance in its functionality and capabilities. Operationally, its fast delay line (FDL) infrastructure is completing its upgrade from a VME/VxWorks foundation to a modern PC/RTLinux core. The Classic beam combiner is being upgraded with the New Classic FPGA-based backend, and the VISION beam combiner has been upgraded over this past summer with low-noise EMCCD cameras, resulting in substantial gains in sensitivity. Building on those infrastructure improvements, substantial upgrades are also in progress. Three 1-meter PlaneWave CDK1000 telescopes are being delivered to the site, along with their relocatable enclosure-transporters, and stations are being commissioned for those telescopes with baselines ranging from 8 meters to 432 meters. Baseline-wavelength bootstrapping will be implemented on the facility back-end with a near-infrared beam combiner under development. Collectively, these improvements mark substantial progress in taking the facility towards realizing its full intrinsic potential.

Keywords: Navy Precision Optical Interferometer (NPOI), long-baseline optical interferometry

1. INTRODUCTION

The Navy Precision Optical Interferometer (NPOI) is an astronomical long-baseline optical interferometer located outside Flagstaff, Arizona, on Anderson Mesa. NPOI collects and combines light from up to six apertures simultaneously, to form a high-spatial-resolution synthetic aperture. The array has been in operation since the mid-1990's as previously described by Armstrong et al.[1] and updated recently by them.[2] Three institutions are involved in the operation and ongoing development of the NPOI. The US Naval Observatory (USNO) oversees operations and has a primary interest in astrometric observing; the US Naval Research Laboratory (NRL) provides engineering support and has a primary interest in interferometric imaging; the Lowell Observatory provides infrastructure support and observing staff under contract with the Navy, and is an active science partner; and amongst these integrated partners there is quite a bit of overlap in these particular roles.

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2. GENERAL DESCRIPTION OF THE CURRENT ARRAY

A brief description of the current configuration of the array can be broken up in the basic subsystem tasks: light collection, beam transport & array layout, beam delay, and beam combination.

Light collection. Light is collected at half-meter siderostat flats, which track objects in the sky for observation. This light is reflected upwards towards 12 cm fast tip-tilt narrow-angle tracking (NAT) mirrors, which can be used to rapidly follow angular errors in light caused by atmospheric turbulence and/or siderostat tracking errors; the 12 cm NAT mirror size is the effective limit for on-sky aperture for a siderostat station. The size of the NAT mirrors is the effective limiting aperture size of each array feed upon the sky. A wide-angle star acquisition (WASA) imaging system can be inserted in between the siderostats and the NAT mirrors via a translation stage. The WASA system is co-axial with the beam off the NAT towards the siderostat, and views the sky off the siderostat; the WASA system field-of-view is large (30 arcmin) and can be used for initial image capture when going on sky.

Six siderostats are 'imaging' type feeds for the array, consisting simply of the siderostat flats, and WASA & NAT subsystems. These feeds can be moved to different parts of the array, as noted below. Four of the siderostats are more elaborate 'astrometric' type feeds. These feeds are fixed in location near the center of the array, with the outer three forming a roughly $\sim$37 meter equilateral triangle, with the forth at the center of that triangle. These feeds are additionally equipped with laser metrology hardware which monitors the position of the siderostat position relative to the mesa bedrock; this position information, along with other pathlength monitoring hardware of the array, enables wide-angle all-sky astrometric measurements to be made. As of April 2018 this portion of the NPOI facility is currently mothballed; details on the astrometric experiment of NPOI are described by Benson.[3]

Beam transport and array layout. Light is reflected vertically downwards off the NAT mirrors through a window into a evacuated beam relay system. Beams in this system are reflected through the pipes towards the beam recombination laboratory. The beam transport system has 10 entry points along each of 3 array arms, laid out in a 'Y' shape, with each arm being 250 meters in length. As such, imaging siderostats can be flexibly located at these stations for configuring the array optimally for station-to-station baseline length.

Light that has entered the beam transport system is reflected along this vacuum system towards array center, with each arm fully symmetric in reflection to match image rotation and polarization properties; each arm can send up to 3 beams towards array center. At array center, repositionable mirrors inside large vacuum cans can be flexibly reconfigured to select six beams from among those available from the North, West, and East arms. The light is then reflected along a fourth set of six short vacuum pipes towards the beam recombination laboratory.

Beam delay. Entering the beam recombination laboratory, the six beams are directed towards six fast delay lines (FDLs). Each FDL consists of a vacuum-enclosed, rail-mounted cart whose direction of motion is coaxial with the light optical path; optics on the cart allow for the beam to be offset and retroreflected in the direction parallel but opposite from which it entered the FDL system. A staged servo arrangement of stepper motors, voice coils, and piezoelectric actuators allow each FDL system to provide 35 meters of delay at a positioning precision of $<$20 nm; laser metrology that is injected parallel to the beam light allows for nm-level position feedback on the servo loop. The FDL cart design is 'JPL heritage' and fundamentally similar to the systems originally designed by Colavita, Hines & Shao[4] and deployed at the Mark III, Palomar Testbed Interferometer, the Georgia State University (GSU) Center for High Angular Resolution Astronomy (CHARA) Array, and Keck Interferometer.

Light exiting the FDL system is then routed towards either the Classic or VISION combiners; before recombination, a portion of the light from each beam is utilized for narrow-angle tracking.

Narrow angle tracking. Tip-tilt errors will prevent the coherent recombination of the light collected on-sky by the siderostats; these errors can be caused by atmospheric turbulence, as well as tracking errors of the siderostats, and other errors introduced to the beam during beam transport. During Classic beam combiner operations, at the Classic optical table, 20% of each beam's flux is routed towards a quad cell of fibres, which in turn relay the light towards avalanche photodiodes (APDs). These APDs provide tip-tilt tracking information for each beam, which is relayed back to the NAT mirrors at each beam's corresponding siderostat station.

When the system is configured for VISION use, 70% of each beam is sent towards VISION, with the remainder continuing still towards Classic, where the standard layout once again sends 20% of that light towards the quad fiber-fed APDs. The net throughout for VISION tip-tilt tracking is a meager 6%, a compelling motivation for our planned tip-tilt upgrade (see below).

Beam combiner: Classic. The current 'workhorse' beam combiner for NPOI is its Classic combiner, a hybrid six-way combiner built on the basis of time-sampled fringe photometry of temporally modulated fringes. Classic interacts with the beam delay system noted above in two ways: first, each of the six delay lines is assigned a dither amplitude, whereby delay path length is modulated by up to 4 um with a 500 Hz triangle wave. Second, as fringes are sensed by the Classic system, atmospheric piston errors are tracked and delay path corrections sent to each delay line servo system for compensation.

Fringes are sensed by the Classic system as follows: each of the six beams is passed through a 50/50 beam splitter, and mixed with a neighbor; that mix pair is then passed through a second 50/50 beam splitter and mixed with a second pair. The result is 3 output beams, each with 4 mixed telescope beams; each of these beams is passed through a dispersive prism, with the 450-850 nm light then being spread and injected into 32 multimode fibers. These fibers then feed the light to avalanche photodiode detectors (APDs). The dither amplitudes for each beam line produce a unique fringe-scanning frequency for each of the six beam line pairs, or baselines. The time-series photometric signal on the APDs can be decomposed by a Fourier transform to produce interference fringe amplitude and phase information for each of the baselines. Triple products and closure phases can also be distilled from these time-series data (see the detailed discussion in §2 of Armstrong[1]). The bulk optics nature of the Classic system gives advantage in providing a wide field of view for multiple star observations.[5]

Current limitations on the Classic system include backend electronics that allow only 16 of the 32 spectral channels to be read, for 2 of the 3 output beams at a time, for a maximum of 30 seconds at a time; these and other aspects of the Classic system are being improved with the New Classic upgrade (see below).

Beam combiner: VISION. The Classic combiner has been a robust foundation for NPOI for many years, but reflects to a degree the strengths – and weaknesses – of its mid-1990's vintage. In particular, the advent of low-noise, high-speed electron-multiplying charged coupled device (EMCCD) array detectors have allowed NPOI to pursue a fundamentally different design architecture in beam recombination, as embodied in the VISION (Visible Imaging System for Interferometric Observations at NPOI) instrument.[6] VISION's layout is fundamentally similar to the highly successful near-infrared Michigan Infrared Combiner (MIRC) instrument on the CHARA Array.[7–9] Each of the six telescope beams is fed into a single-mode fiber, with those six beams arranged into a linearly non-redundant layout in a micromachined V-groove array; that light is launched from the fibers towards the fringe detector EMCCD. Before arriving at that detector array, a polarizing beam splitter sends half of the light towards a second EMCCD for contemporaneous photometric data on each individual telescope beam. The remaining light passes through a fringe-forming lens, and then


Figure 1. The first author with the first of three PlaneWave Instruments CDK1000 1-meter apertures for use at NPOI.

is spectrally dispersed in the direction orthogonal to the fringes via a spectrograph, before arriving at the fringe detector EMCCD.

This layout illuminates the EMCCD with fringes spatially along one axis, and as a function of wavelength in the orthogonal axis. By so doing, the mechanical-temporal nature of fringes in Classic is replaced in VISION by optical-spatially static fringes, which greatly simplifies the optomechanical control task for the delay lines above, as well as reducing the wear on the piezoelectric actuators.

The VISION architecture has additional benefits as well. In particular, the APD infrastructure – which includes custom electronics, and an elaborate & bulky chiller subsystem – is becoming increasingly problematic to sustain as it ages. APDs also exhibit afterpulsing, which complicates data calibration and analysis. The nature of the spectrograph optics allow an easily selectable spectral resolution between the two values of $R \sim 200$ and $R \sim 1,000$, whereas Classic is fixed at $R \sim 50$. The all-in-one combination nature of VISION allows all beam combinations of all telescopes to be formed and detected; the hybrid design of Classic does most but not quite all such combinations. The photometric channel of VISION promises improved data calibration over Classic as well.

3. ARRAY UPGRADES

A number of upgrades are ongoing at the NPOI site; an accounting of them in roughly chronological order follows.

Infrastructure improvements. Basic improvements to the system infrastructure are regularly being pursued. This includes assessment and improvement of essentials such as mirror mounting,[10] correction of (quasi-)static beam transport wavefronts,[11–14] and improvements to the optomechanics of the high-speed tip-tilt tracking system.[15–17]

FDL RTC upgrade. The increasingly aged control system of our real-time-control (RTC) hardware for our delay lines has been replaced with a modern real-time control system. The original system, based upon VME-based 680xx computers running VxWorks, was becoming increasingly unsupportable due to individual seat cost and unavailability legacy hardware. The new system, based upon Real-Time Linux on commercially available PCs, will deliver not just stainability into the future, but adds flexibility in supporting operations, particularly for temporally-based combiners such as Classic.

VISION: low-CIC EMCCDs. The VISION combiner noted above was originally implemented with Andor EMCCDs for both the fringe detection and photometric channels. Unfortunately, these particular camera heads had problematic levels of clock-induced-charge (CIC; see Figure 12 and the discussion in Garcia[6]) which reduced the expected on-sky sensitivity by 1-2 magnitudes. These detectors have been recently replaced with NüVü EMCCD detectors, selected for their favorable CIC performance. Optomechanical integration of these detectors has been completed, with software debugging ongoing; preliminary on-sky tests indicate these new detectors recover the originally expected sensitivity performance.

New Classic. The original mid-1990's vintage electronics of Classic (noted above) are a significant element in the limitations of that instrument, and as such, an upgrade project has been underway to replace the old hand-wired backend with a modern field-programmable gate array (FPGA) based system.[18] The New Classic (NC) electronics significantly enhance Classic operations in two ways. First, basic collection of photon data is improved: all 32 channels of each spectrometer output can be recorded, for indefinite durations (no 30 second buffer cap), and all 3 spectrometers can be simultaneously recorded (rather than just 2 of 3). Second, NC enables fringe tracking that includes multi-telescope 'baseline bootstrapping'.[19] This approach enables short baselines along a daisy-chain of apertures – with high-contrast, thereby high signal-to-noise (SNR) fringes – to be used to phase the array coherently upon the sky; as a result, the longer baselines in the chain are phased without active tracking, enabling measurement of their low-contrast, low-SNR fringes.

PALANTIR: 1-meter telescopes. The major upgrade going on at NPOI is the PALANTIR (Precision Array of Large-Aperture New Telescopes for Image Reconstruction) effort, which will add large-aperture telescopes to the array. PALANTIR is a \$3.26M project funded by NRL and has the following specific highlights:

- Three PlaneWave Instruments CDK1000 1.0-m telescopes. These are standard CDK1000 telescopes, with the addition of a Nasmyth instrument breadboard and Coudé train. The increase in effective aperture for NPOI will result in roughly 70× greater on-sky flux collection.
- The telescopes will be housed in 'enclosure-transporters' (ETs). The ETs consist of an Astro Haven Enterprises (AHE) 16-foot dome mounted on a movable trailer.
- The ETs will be relocatable to upgraded stations along the arms of the NPOI array. These stations will make use of existing entry points into the evacuated beam relay infrastructure. The evacuated piping will be extended to include a below-grade mirror that will be directly below the telescope azimuth axis – effectively the last mirror of the Coudé train. The stations slated for initial operations with the new telescopes will be a compact layout at the center of the array, with 8-m baselines, and a wide layout activating the ends of the east and west interferometer arms, with a 432-m baseline joined in the middle with a third telescope left at array center.
- Each of the telescopes will be equipped with a low-order adaptive optics (AO) subsystem. The AO will ride on the Nasmyth instrument breadboard of each telescope.

The PALANTIR project received funding in January 2017 and has been progressing rapidly since that point. The first CDK1000 had factory acceptance in January 2018, and first ET was delivered in early May 2018; on-site delivery of the first CDK1000 is slated for late May 2018. Delivery of the second & third telescopes & ETs will be complete by September 2018.

Upgraded tip-tilt beam tracker. The current tip-tilt sensor subsystem is based upon the APD infrastructure. Given the availability of the older Andor EMCCD cameras from the VISION upgrade to NüVü EMCCD cameras, one of those EMCCDs will be used as the basis of a new tip-tilt beam tracker for VISION. A significant improvement will be relocation of the tip-tilt pickoff mirrors to the VISION table, meaning 20% of the light will be available for tip-tilt tracking – a substantial improvement over the current 6% available currently for VISION operations. The optomechanical design of the upgrade tracker will direct the six beams onto a single EMCCD detector for centroiding.

Figure 2. The first Astro Haven Enterprises (AHE) 16-dash-1 trailer-mounted 'Enclosure-Transporter' domes after delivery to NPOI from AHE.

Near-infrared fringe tracker. Along with the PALANTIR upgrade, a second key element in extending the sensitivity of NPOI in the imaging domain is the development of wavelength-baseline bootstrapping (WBB).[20] The technique of WBB will leverage a near-infrared fringe tracker to extend the phase stabilization time for the VISION instrument by several orders of magnitude beyond the atmospheric coherence time. Towards that end, our NRL partners have funded a project to develop a near-infrared fringe tracker for NPOI; this project is in its initial stages.

Long delay lines. Initial operations of the array with its 432-m longest baseline will be possible with the FDL delay line current infrastructure; however, it will be limited in sky coverage due to the 35-m physical length of our current FDLs. Our current site includes the physical infrastructure for long delay lines (LDLs; see §6.4.1 of

Armstrong[1]), although it is not at present optically connected to the beam paths. The LDLs are designed to provide selectable, discrete amounts of optical delay in vacuum (akin to the CHARA 'pipes of Pan', or POPs) in 17 steps of 14.6-m of physical length, from 0-m up to 233.6-m (resulting in twice that in optical delay). Our current plans aim to fold the LDLs into the beam paths during a summer 2019 shutdown.

4. SCIENCE AND OPERATIONS AT THE ARRAY

Hardware development of a major facility such as NPOI is sustained in no small part by a steady stream of science results. Since the previous major survey of NPOI operations & prospects in 2013,[2] numerous notable astrophysical results have been published using data from NPOI. Asteroseismology and interferometry are becoming increasingly complementary approaches to finely establishing stellar fundamental parameters, as highlighted in Baines.[21] Hot Be star systems, including in particular their surrounding disk structures, are uniquely probed by the visible-light interferometry of NPOI, illustrated in the steady stream of results from Tycner and collaborators.[22–24] Stellar binaries, long the forte of NPOI, have seen results from Hummel on ζ Ori A,[25] with a revisit of that system in the collection of VISION commissioning data.[6] Major studies of angular diameters of evolved giants continue to highlight the ability of the NPOI to conduct large surveys;[26,27] the same strength has also been brought to bear on large samples of stellar multiplicity and exoplanet hosts.[5,28] Additional non-astrophysical on-sky efforts may be found in the literature.[29–34]

Finally, one area where the array distinctly shines in showing its utility is in the application of multi-facility observations. Such observations – combining the strengths of NPOI with other arrays such as CHARA, PTI, and VLTI – provide compelling constraints on astrophysical interpretations, through expanded reach in wavelength space, $\{u, v\}$ coverage, and temporal coverage. Over this time period, studies that leverage this approach include investigations of the post-AGB binary 89 Her,[35] the expanding fireball of Nova Delphini 2013,[36] observations of the unique eclipse of ϵ Aurigae,[37] and studies of Be stars.[38] All of these studies were enabled and enhanced by a multi-facility approach.

5. FUTURE PROSPECTS

Historically, NPOI was the first of the current major optical interferometers to go online, coming initially online in May 1996.[39] As such, there are aspects of the facility that are the subject of intensive rejuvenation efforts, noted above. However, the infrastructure of NPOI remains as a solid backbone for observational interferometry, an extensive scaffolding upon which the current and next generation of technology can rapidly and inexpensively incorporated into an operational facility. Of particular excitement is the PALANTIR upgrade, which will greatly increase the sensitivity of the facility, and allow it to realize its full spatial resolution potential.

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