The NN-explore Exoplanet Stellar Speckle Imager: Instrument Description and Preliminary Results

Nicholas J. Scott\textsuperscript{1} \textsuperscript{©}, Steve B. Howell\textsuperscript{1}, Elliott P. Horch\textsuperscript{2} \textsuperscript{©}, and Mark E. Everett\textsuperscript{3} \textsuperscript{©}

\textsuperscript{1} NASA Ames Research Center, Moffett Field, CA 94035, USA
\textsuperscript{2} Dept. of Physics, Southern Connecticut State University, 501 Crescent St, New Haven, CT 06515, USA
\textsuperscript{3} National Optical Astronomy Observatory, 950 North Cherry Avenue, Tucson, AZ 85719, USA

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Abstract

A new speckle and wide-field imaging instrument for the WIYN telescope called NN-EXPLORE Exoplanet Stellar Speckle Imager (NESSI) is described. NESSI offers simultaneous two-color diffraction-limited imaging and wide-field traditional imaging for validation and characterization of transit and precision RV exoplanet studies. Many exoplanet targets will come from the NASA K2 and Transiting Exoplanet Survey Satellite (TESS) missions. NESSI is capable of resolving close binaries at sub-arcsecond separations down to the diffraction limit and >6 mag contrast difference in the visible band on targets as faint as 14th mag. Preliminary results from the instrument commissioning at WIYN and demonstrations of the instrument’s capabilities are presented.

Key words: binaries (including multiple): close – instrumentation: high angular resolution – instrumentation: interferometers – techniques: interferometric – techniques: photometric

Online material: color figures

1. Introduction

The NASA-NSF Exoplanet Observational Research (NN-EXPLORE) Exoplanet Stellar Speckle Imager (NESSI) is a new dual-channel speckle imaging instrument built at NASA’s Ames Research Center. It is primarily intended for high angular resolution observations for exoplanet validation and characterization but also includes the capability for wide-field and traditional CCD imaging in addition to speckle interferometry.

Speckle imaging removes the corrupting influence of the atmosphere upon the resolution of the telescope (Labeyrie 1970). If stars are close together on the sky, the light from them will pass through nearly the same atmospheric coherence cells above the telescope aperture, a condition known as isoplanicity. This leads to instantaneous distortions to the image of each star which appear nearly the same. The detailed nature of these distortions is determined by the interference of light between all possible cell pairs (Roddier 1988). The resulting image can be referred to as a speckle interferogram. The analysis of such images can be approached as a deconvolution problem. The technique requires an imaging detector capable of reading out frames at a a very fast rate in order to capture speckles. It has seen a resurgence in recent years with the advent of electron-multiplying CCDs (EMCCDs), which were first used in speckle work by Tokovinin & Cantarutti (2008). EMCCDs combine high quantum efficiency, low read noise, and fast readout speed to make them extremely sensitive and efficient devices for speckle imaging. Speckles may be correlated in Fourier space and used to produce a reconstructed image. This reconstructed image has an angular resolution equal to the theoretical diffraction-limit for a given telescope diameter and wavelength, effectively giving space-based resolution from the ground.

As a technique, speckle imaging is extremely efficient for detecting binary systems. A single short observation can give the separation, position angle, and magnitude difference of a binary pair. A scientific driver for this instrument is exoplanet characterization for the Kepler, K2, Transiting Exoplanet Survey Satellite (TESS), and many RV programs (Howell et al. 2011; Furlan & Howell 2017). Contrast ratios of 6 or more magnitudes are easily obtained. High resolution imaging enables the identification of blended binaries that contaminate many exoplanet detections, leading to incorrectly measured radii (Hirsch et al. 2017). In this way small, rocky systems and/or long period systems, such as Kepler-186f (Quintana et al. 2014) and the TRAPPIST-1 planet family (Howell et al. 2016), may be statistically validated and thus the detected planets radii are correctly measured.

NESSI is based on the successful performance and design of the Differential Speckle Survey Instrument (DSSI; Horch et al. 2009, 2012) but has several significant advantages over its predecessor. NESSI utilizes the latest generation of EMCCDs to obtain high speed image readout with minimal noise. Two
EMCCDs and two filter wheels provide simultaneous dual-color observations in either narrowband or Sloan Digital Sky Survey (SDSS) broadband filters. Obtaining dual-color observations greatly helps to characterize detected companions (Torres et al. 2015). NESSI is able to take advantage of the sophisticated speckle image reconstruction software that the DSSI team have developed over years of operation. NESSI also has a “wide-field” mode and is capable of regular and high speed CCD photometry applications. This makes possible high-cadence photometry for transit, occultation, pulsation, and asteroseismology studies.

NESSI has been commissioned at the 3.5 m WIYN telescope at Kitt Peak National Observatory (KPNO). It is available to the community via the peer review proposal process. Data are reduced using our speckle reduction pipeline that generates reconstructed images with a typical resolution of 0″04 and contrast limit curves that show detection limits for each observation. The optical parameters are given in Table 1. An example of NESSI binary star data are shown in Figure 1.

2. Instrument Description

Optically, the instrument is quite simple. Light enters NESSI after the telescope focus and is collimated by the first lens. The collimated beam is then incident upon an imaging-quality Semrock dichroic with an edge at 672.9 nm. This dichroic splits the input beam into blue and red components; the blue light is reflected into beam A and the red light is transmitted into beam B. Each resultant beam passes through a filter wheel. The filter wheels for each beam are model USFW-100, made by the Newport Corporation. Each filter wheel is capable of holding six one-inch round filters. The filters currently installed are listed in Table 2 with the overall system transmission given in Figure 2. After passing through the filter wheel each beam passes through a re-imaging lens. Each beam is focused on an independent EMCCD, providing simultaneous two-color operation.

2.1. Design

All lens elements are mounted on linear motion stages, enabling switching between speckle and wide-field modes.

![Figure 1](image_url) Observations of HIP 104858 from 2016 October 14 in the 832 nm filter. One of the thousand raw speckle frames taken (top right), each frame is a 40 ms exposure. The resultant power spectrum (bottom right) and reconstructed image (left) of the binary pair are shown. This binary system has a separation of 0″145. The image field of view is 4.6 × 4.6. (A color version of this figure is available in the online journal.)

### Table 1
NESSI Optical Design Parameters

| Mode       | Collimator (mm) | Reimager (mm) |
|------------|----------------|---------------|
| Speckle    | 30             | 200           |
| Wide-field | 100            | 150           |

| Detector image plane | Magnification | Plate Scale (″/pxl) | Unvignetted Circle Dia (″) | Detector FoV (″ × ″) |
|----------------------|---------------|---------------------|---------------------------|---------------------|
| Speckle              | 6.67x         | 0°0182              | 22                       | 19 × 19             |
| Wide-field           | 1.5x          | 0°0813              | 56                       | 83 × 83             |

### Table 2
NESSI Filters

| Element       | λ (nm) | FWHM (nm) |
|---------------|--------|-----------|
| Dichroic      | 672.9  |           |
| Filter Wheel A|        |           |
| SDSS/u′       | 354.3  | 32.7      |
| SDSS/g′       | 480.0  | 151.1     |
| SDSS/r′       | 620.0  | 143.5     |
| g-narrow      | 467.1  | 44.0      |
| r-narrow      | 562.3  | 43.6      |
| Filter Wheel B|        |           |
| SDSS/i′       | 765.4  | 146.4     |
| SDSS/z′       | 943.3  | 242.7     |
| i-narrow      | 716.0  | 51.5      |
| z-narrow      | 832.0  | 40.4      |
without disrupting observations. The instrument contains three such stages, one at the input, one for the blue re-imaging lenses, and one for the red re-imaging lenses. At the input, the speckle and wide-field collimating lenses share a stage, as do each of the speckle and wide-field mode re-imaging lens pairs. The three stages are identical Zaber Incorporated model X-LSM050 linear stages with USB input and are remotely operable.

In addition to EMCCD speckle observations, NESSI is capable of operating as a traditional high sensitivity CCD and with a wide-field mode. Speckle and “wide-field” mode observations may be made in standard SDSS or narrow-band filters. Typically, the narrow-band filters are used exclusively for speckle observations. Due to its narrow bandwidth the u-band filter is suited for either mode, providing a maximum angular resolution at WIYN of 0\(^{\prime\prime}\)025 though it will be slightly undersampled at 1.5 pixels per resolution element instead of Nyquist sampling. Modes and filters may be changed during nighttime operations, requiring only about 15 s for the linear stages and filter wheels to re-position. Figure 3 shows the components of the instrument as installed on the WIYN telescope Nasmyth port. The \(f/ratio\) at this port is 6.3. In order to keep cost low and development rapid, NESSI has been designed to be quite compact and to utilize as many off-the-shelf components as possible. Like DSSI, NESSI does not have any elements for atmospheric dispersion compensation (ADCs). To mitigate the effect of atmospheric dispersion: (1) known point sources are observed close in time and location to science targets (2) narrow-band speckle filters are used for
speckle observations and (3) targets are preferentially observed only at airmass <1.4.

To achieve the sensitivity and rapid readout rate necessary for speckle observations, NESSI utilizes two identical Andor Corporation iXon Ultra 888 EMCCDs cameras. These devices are not limited by output amplifier readout noise as would be dominant in traditional CCDs read out at high speed and are capable of single photon sensitivity and 30 MHz readout rates. This particular model features a $1024 \times 1024$ array with $13 \, \mu m$ square pixels and is capable of 26 fps when reading out the full chip, and up to 670 fps for a $128 \times 128$ subarray readout. Typical integration time for speckle mode is 40 ms with a windowed readout of $256 \times 256$ pixels that is read out at 25 fps. The cameras are operated in a variety of modes and combinations of modes, each with numerous settings, the most relevant of which are given in Table 6. In electron multiplying mode, the effective read noise, or the read divided by the electron amplification factor, is $<1e^−$ and the detectors are sensitive to single photons. The full well depth is $\sim 60,000 \, e^−$. The adjustable electron multiplication of the electron multiplying mode enables a larger dynamic range with suppression of the effective read noise. For typical speckle observations the cameras are operated in EM and kinetic modes which allows for fast readout of multiple frames all saved into a single FITS data cube. In addition to an EM amplifier, each camera also has a conventional amplifier with low readnoise (and correspondingly lower readout rates). This allows the detectors to be used as traditional CCDs for imaging. Another setting option for the Andor cameras is “accumulation mode,” in this mode individual acquisition frames are co-added in computer memory, increasing the signal to noise ratio and producing a single 32 bit FITS image with extremely high dynamic range. The EX coating gives $>80\%$ quantum efficiency from 420 to 780 nm and $>90\%$ QE from 550 to 720 nm. They may be cooled thermoelectrically to $-95^\circ$ C and as such require no consumables. Further details and the results of tests performed on the cameras are presented in the Appendix. Data is transferred to the control computer via USB3 with no internal cards. The control computer for the instrument is quite small with minimal heat dissipation.

For comparison to other available instruments, Figure 4 shows nominal contrast ranges expected with respect to angular separation and filter selection of NESSI and DSSI+Gemini-S speckle imagers compared with the near-IR adaptive optics instruments NIRCam2 and GPI (from Figure 3 of Macintosh et al. 2014). Infrared adaptive optics can reach to deeper contrast but can not reach comparable angular resolutions to optical speckle imaging and requires a natural or laser guide star and much greater time on target. For speckle, the angular resolution is set by diameter of the telescope while contrast is limiting by the seeing; for AO the angular resolution depends on the seeing.

![Contrast vs. Separation](image)

**Figure 4.** NESSI’s sensitivity with respect to separation and delta magnitude of a binary star system in the 692 and 880 nm filters (labeled WIYN). The line denoted by $(2n)$ represents data sets taken on the same object over two nights and combined into a single reduced data set. Based on preliminary results of combining data sets and assuming excellent seeing, the nominal limit is shown as a rough guide for the instrument in terms of contrast. For comparison, DSSI sensitivity at Gemini is shown. Also shown are the IR/AO detection limits for a 45 minutes Keck NIRCam2 observations and GPI from Macintosh et al. (2014). IR/AO reaches deeper contrast but at a lower resolution and much greater observing time requirement.

### 2.1.1. Future Upgrades

We are currently exploring possible uses for the presently unused filter wheel slots in each NESSI beam including the addition of one or more transmission gratings (grisms), an aperture mask, and/or a notch filter. The addition of grisms would allow for simultaneous two filter, fast grism spectroscopy. The addition of a notch filter is an option that would allow for simultaneous recording of speckles in multiple bandpasses per channel. An aperture mask would allow spatial resolution beyond the diffraction limit, reaching true interferometric resolution ($\lambda/2D$) (Baldwin et al. 1986). Achieving resolutions on this order could be especially interesting if used on next-generation extremely large telescopes (ELTs) and would approach angular resolutions previously only available to long-baseline optical interferometry.

The use of a lenslet array to make a dedicated wavefront sensor for recording atmospheric phase information is a technique known as Deconvolution From Wavefront Sensing (DFWS). While it has been shown that bispectrum image reconstruction is always more effective than DFWS (Roggemann et al. 1997), there remains the possibility that a hybrid technique where one camera records speckle interferograms and the other performs simultaneous DFWS could improve the reconstruction quality under certain conditions. This additional DFWS measurement of atmospheric distortion could increase
the effective signal-to-noise and remove degeneracies in the image reconstruction. NESSI could serve as a testbed for this experiment.

2.2. Data Reduction

The process for reconstructing a diffraction-limited image from the raw speckle data frames follows the same basic steps as with the data from the earlier DSSI camera Horch et al. (2009). The first element of this process is to obtain an estimate of the diffraction-limited modulus of the object’s Fourier transform. Frames are debiased using an ensemble of corner pixels, and then an autocorrelation of each frame is computed. These are summed and the result is Fourier transformed to obtain the spatial frequency power spectrum of the observation. The same process is done on a set of speckle frames of a bright, nearby point source taken close in time to the science observations. By dividing the power spectrum of the science target by that of the point source, we deconvolve the speckle transfer function from the science observation, and the result is a diffraction-limited estimate of the object’s true power spectrum. By taking the square-root, we arrive at the modulus of the object’s Fourier spectrum.

The speckle frames are also used to compute near-axis subplanes of the image bispectrum, which is the Fourier transform of the triple correlation function of the image. These are also summed. As detailed in Lohmann et al. (1983), these near-axis subplanes contain diffraction-limited information of the phase of the object’s Fourier transform. Each subplane can be used to estimate the derivative of the phase, and so with several subplanes, a more robust derivative function can be calculated, and then integrated to arrive at the phase function itself. We develop a phase map based on the subplanes computed using the relaxation technique of Meng et al. (1990). The phase is then combined with the modulus estimate derived from the autocorrelation analysis to obtain the complex-valued Fourier transform of the object. We low-pass filter this function with a Gaussian shape of width chosen to approximate the width of the diffraction limit on the image plane, and inverse-transform to produce the final reconstructed image.

2.3. Science Goals

NESSI was designed to fulfill a specific scientific role: the validation and characterization of Kepler, K2, and future mission exoplanet candidates. Speckle validation of transiting exoplanets is the use of a high angular resolution, deep image of a candidate host star to eliminate, at high probability, the existence of other close-by sources that could be the source of a false positive, transit-like light curve signal. NESSI provides photometric and astrometric data simultaneously at subarcsecond precision, ideal for the NN-EXPLORE program of ground-based support for space missions. NESSI is capable of validating an exoplanet candidate in a single observation sequence lasting ~40 s to record a 1000 frame data cube. Overhead such as pointing, ROI selection, and focusing adds to this by roughly a factor of 2. In general, we record 1–12 sets of fits data cubes, each with 1000 data frames. Multiple data cubes break the data files into manageable sizes and can be combined during processing. The number of sets is based on the observing conditions and the brightness of the object. For example, for a 12th mag star we would record 9 fits data cubes. On a good night we can observe 100 science targets. System performance for companion detection is limited by the contrast of the binary components, with a typical sensitivity on the order of 1% at a separation of 0°2 with sensitivity improving with greater separation. Ultimately, the instrument can achieve subdiffraction-limited resolution for binary separations. High observing efficiency and high spatial resolution, compared with options such as radial velocity studies, makes speckle interferometry with NESSI an optimal solution for exoplanet follow-up studies, particularly in light of the rapidly increasing numbers of exoplanet candidates.

2.3.1. Exoplanets

Binary observations with NESSI are particularly focused on exoplanet transit follow-up and characterization for Kepler, K2, and TESS, although the instruments are also very well suited to other high angular resolution observations. Speckle imaging assesses binarity, providing the position angle, separation, and contrast of the system in a single observation. The use of simultaneous observations in two colors helps unbiased exoplanet radii that are derived from blended binary sources by providing color information such that the relative brightness of the sources can be determined for the bandpass (Ciardi et al. 2015). Using two cameras to collect data in two colors simultaneously also provides: (1) twice the data during the same amount of time, (2) accurate photometric measurements, (3) calibration to compensate for atmospheric dispersion, a major source of error at the smallest spatial scales. The high angular resolution images produced by speckle imaging can reveal faint companions or closely aligned background objects that could produce false exoplanet detection due to the contribution to the measured flux of the brighter target star. This is especially true if the faint companions are eclipsing binary stars (Howell et al. 2011). For a full explanation of this technique see Horch et al. (2014). DSSI results have been used in numerous papers on exoplanet validation (Horch et al. 2012, 2015; Torres et al. 2015; Crossfield et al. 2016; Furlan et al. 2017; Hirsch et al. 2017) and we anticipate a steady demand for this type of validation.

The number of Kepler objects of interest (KOIs) alone reaches into the thousands and the number of exoplanets detected with K2 is steadily increasing. The upcoming TESS mission is anticipated to detect thousands of exoplanet candidates, all of which will require follow-up validation and
characterization. NESSI supports the following science cases: exoplanet characterization, exoplanet transit spectroscopy, exoplanet atmosphere detection, transient object classification and characterization. Simultaneous two-color transit photometry is possible and yields instant verification of exoplanets, given the same transit depth in both channels. The inclusion of standard imaging with SDSS filters provides accurate host star photometry.

### 2.3.2. Other Roles

Although NESSI was designed with exoplanet validation in mind, it was also designed to be modular and extremely versatile to address numerous scientific questions. Techniques like speckle imaging bridge the angular resolution between long baseline interferometry optical interferometers like the CHARA Array and traditional imaging. Figure 5 shows a comparison of long baseline optical and near-IR instruments at the CHARA Array, RoboAO, and NESSI. The NESSI data shown is from a single observation of T Tauri. The blue curve represents the NESSI 5σ detection limit for that particular data set, any companion lying below that curve would be detected.

In Table 3 we list many potential observations NESSI is suited for or that the community has proposed to address.

### 3. Results

#### 3.1. Observations of Two Well-known Binaries

Figures 6 through 9 each show a montage of data illustrating the data reduction process on two bright, well-known binaries. In both cases, the pair was observed with NESSI using wavelengths of 562 and 832 nm in the two channels of the instrument, and in the speckle mode. The results, presented in Table 4 are obtained from 1000 frames of data using a subarray of 256 × 256 pixels, taking approximately 1 minute to obtain. In each figure, we show a sample speckle frame (with 40 ms exposure), the reconstructed modulus and phase as obtained from the analysis of the summed power spectrum and bispectrum, and the final reconstructed image. In the cases of the speckle frame and the reconstructed image, only a 128 × 128 pixel portion of the 256 × 256 frame is shown, corresponding to an area on the sky of 2.3 × 2′/3.

To analyze these results further, we measured the plate scale in speckle mode with the use of a slit mask that was mounted to the tertiary mirror baffle. The bright single star HR 911 was then observed with the slit mask creating a fringe pattern on the image plane. Scale can be calculated from first principles with the known distance from the plane of the mask to the focal plane, the measured spacing of the slits, and the effective wavelength of observation. For verification, scale binaries with very well-known orbits were observed such as HIP 104858 (Figure 1). The determined plate scales were 0.0174 and 0.0182 pixel⁻¹ for the blue and the red channels, respectively. In the past it was found with DSSI that the uncertainty in the plate scale measurement is about 0.1%–0.2% and we expect similar uncertainty here.

The first binary system studied is A 1938 = HIP 19719, a system with total apparent V magnitude of 5.29 and spectral type F2V. The magnitude difference is modest; previous values in the literature put the value at approximately 0.8 for observations near 550 nm. Our results in the 562 nm filter are shown in Figure 6, while those in the 832 nm filter are in Figure 7. Based on the speckle frames, the seeing was 0.5′. For the 562 nm observation and 0′.46 for the 832 nm observation. Using the orbit of Muterspaugh et al. (2010), we find that the ephemeris separation of the system at the time of observation was 0′.1511 ± 0′.0002 and the ephemeris position angle was 311°6 ± 0°.1. These values are very consistent with our images, based on our preliminary plate scale and orientation values determined at the telescope. The magnitude difference in the reconstructed image is likewise consistent with previous measures appearing in the 4th Interferometric Catalog http://ad.usno.navy.mil/wds/int4.html (Hartkopf et al. 2001).

Our results for the second system, HO 296AB = HIP 111974, are presented in Figures 8 and 9. This G4V pair has total V magnitude of 5.71. In this case, the seeing estimates were 0′.91 for the 562 nm observation and 0′.77 for the 832 nm file. Using the orbit of Muterspaugh et al. (2010), we calculate that the ephemeris separation of the system at the time of observation was 0′.4602 ± 0′.0002 with an ephemeris position angle is 47°5 ± 0°.1. Previous measures in the 4th Interferometric Catalog give a magnitude difference of about 1 mag. Again, these numbers are all very consistent with our images.
The modulus and phase in Figures 6 through 9 are plotted with the origin of the Fourier plane in the center of the figure. They are masked at a certain spatial frequency to eliminate frequencies above the diffraction limit. Our results in the 832 nm filter clearly illustrate a round area of high signal in the Fourier plane, extending out to a certain radius. This corresponds to the expected location of the diffraction limit at this filter. This is somewhat inside the circular radius drawn in the modulus and phase plots at that wavelength. In contrast, the same plots for the 562 nm filter indicate that the region of high signal is more elliptical in shape, although the long axis the signal extends farther from the origin in the Fourier plane than for the 832 nm filter. This is as expected since the diffraction limit will occur at a higher spatial frequency for a shorter-wavelength filter. The loss of signal along the orthogonal direction is due to atmospheric dispersion, which will affect bluer wavelengths more than redder ones. The effect on the reconstructed image in any case is modest unless the zenith angle of the observation is large. In the case of our observation of A 1938, the zenith angle was 28°, while for HO 296AB, it was 35°.

Figure 10 shows the detection limit plots for these systems. The methodology behind these curves is detailed in Horch et al. (2011) and Howell et al. (2011). A series of annuli centered on the primary star are formed of increasing radii, from 0"05 to 1"2. We then identify all local maxima and minima that fit into each annulus, and compute their average value, or average absolute value in the case of minima, and their standard deviation. The detection limit is set to the average plus five times the standard deviation value. A cubic spline interpolation is then performed on the resulting values, assuming a value of zero at 0"05, close to the diffraction limit of the telescope. In the case of the panels shown in Figure 10, the secondary falls below the detection line when its intensity is converted to a magnitude difference relative to the primary star, indicating a clear detection in all cases. The peak of the secondary is not included as a local maximum in any annulus in the

| Mode       | Science                                                                 |
|------------|-------------------------------------------------------------------------|
| Speckle    | Constrain the diameter of extremely low albedo Near Earth Asteroids (NEAs) |
|            | Determine the multiplicity of M dwarfs. Does it vary across M dwarf spectral type? |
|            | Surveys for Binarity in Nearby Stars.                                    |
|            | Imaging of brown dwarfs and distant large planets, particularly ones around M dwarfs. |
|            | Investigate the differences in planetary system architectures between multiple versus not (known) multiple host stars. |
|            | Search for distant third bodies as a source of long-term trends in radial velocity (RV) curves. |
|            | Provide overlap in spatial resolution with optical long baseline interferometry and AO. ALMA, CHARA, coronography, etc. |
|            | K2, TESS, and WFIRST targets will need high resolution images. |
|            | Provide an unbiased sample for TESS, so statistical determinations of planet occurrence rates can be made. |
|            | Determine the binarity of RV planet hosts.                               |
|            | Imaging Solar System objects.                                            |
|            | Exozodiacal light validation.                                             |
|            | Asteroseismic survey of giants.                                           |
|            | Rapidly rotating stars and giant stars that are oblate to look for companions |
|            | Continue the long-standing use of speckle for getting accurate binary star orbits. |
| High Cadence| Occultations.                                                             |
|            | Transit photometry.                                                      |
|            | Observe pulsars to look for short timescale variations on the order of a few minutes. |
|            | Observe pulsating white dwarfs such as HL Tau 76 and certain KOIs.       |

Table 3: Observational Roles

Figure 6. Speckle frame, reconstructed modulus, reconstructed phase, and final reconstructed image for the well-known binary A 1938 = ADS 3064AB = HIP 19719. The wavelength of observation was 562 nm, and 1000 40 ms frames were used to reconstruct the image. Scale bars are shown for 1" and the Rayleigh diffraction limit.

(A color version of this figure is available in the online journal.)
3.2. Comparison of Wide-field and Speckle Modes

Using the bright, double star HR 7053 = STF 2383CD we sought to directly compare the wide-field and speckle modes of the instrument in terms of magnification and basic image properties. We took a short file of 510 frames of the target in speckle mode using the 562 and 832 nm filters, and analyzed the data in exactly the same way as described earlier for the well-known binaries. We then took a data file using the wide-field mode, but with the same frame time, namely 40 ms. Only the 832 nm data are presented here; the observation was taken in poor seeing at a substantial zenith distance, 58°, and exhibited the effects of dispersion, that is a stretching of the speckles themselves along the line leading to the zenith, which could have influenced the subsequent analysis. In addition, no point source close to the target was observed, with the closest match being HR 8178, which was observed at a zenith distance of 29°, further complicating the analysis for the shorter-wavelength filter in the deconvolution step of the image reconstruction. In contrast, the near-infrared data exhibited only modest dispersion, and the choice of point source was less crucial.

Example frames for both observations are shown in Figure 11, and a seeing-limited image made by summing all of the frames in the observation is shown for each in Figure 12. It is interesting to note two things about these images. First, there are speckles in a short-exposure image in wide-field mode. The speckles themselves were expected to be undersampled due to the larger pixel scale in wide-field mode, but nonetheless there is high-resolution information in the images as evidenced by the graininess of the stellar irradiance pattern. Second, by comparing the speckle patterns of the two stars in the subsequent analysis. In addition, no point source close to the target was observed, with the closest match being HR 8178, which was observed at a zenith distance of 29°, further complicating the analysis for the shorter-wavelength filter in the deconvolution step of the image reconstruction. In contrast, the near-infrared data exhibited only modest dispersion, and the choice of point source was less crucial.

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Figure 7. Results for A 1938 = ADS 3064AB = HIP 19719 in 832 nm filter, same as Figure 6.

(A color version of this figure is available in the online journal.)

Table 4: NESSI Results for the Known Binaries HIP 19719 and HIP 111974 and Ephemeris Predictions for the Time of Observations

| R.A. and Decl. | HIP Channel | Besselian Year-2000 | Position Angle (E of N) | Separation (arcsec) | Δm | Filter | θ_{eph} | ρ_{eph} |
|---------------|-------------|---------------------|-------------------------|---------------------|-----|--------|---------|---------|
| 04136+0743    | 019719 blue | 16.7955             | 311.5 ± 0.5             | 0.1507 ± 0.0016     | 0.89 | 562    | 311.6 ± 0.1 | 0.1511 ± 0.0002 |
| 04136+0743    | 019719 red  | 16.7955             | 312.1 ± 0.5             | 0.1500 ± 0.0016     | 0.73 | 832    | ...     | ...     |
| 22409+1433    | 111974 blue | 16.7923             | 48.5 ± 0.5              | 0.4587 ± 0.0016     | 1.05 | 562    | 47.5 ± 0.1 | 0.4602 ± 0.0002 |
| 22409+1433    | 111974 red  | 16.7923             | 47.9 ± 0.5              | 0.4558 ± 0.0016     | 1.21 | 832    | ...     | ...     |
the same frame directly, it can be seen that they are similar but not identical. This is clear evidence that the secondary, with a separation of 2"4, does not lie within the isoplanatic angle of the primary in the case of these observations. As reported most

Figure 8. Results for HO 296AB = ADS 16173AB = HIP 111974 in 562 nm filter, same as Figure 6.  
(A color version of this figure is available in the online journal.)

Figure 9. Results for HO 296AB = ADS 16173AB = HIP 111974 in 832 nm filter, same as Figure 6.  
(A color version of this figure is available in the online journal.)

Figure 10. Detection limit plots for the two well-known binaries discussed in the text. In all cases squares represent the positions of local maxima in the reconstructed image and dots represent local minima (where the absolute value of the minimum is used). The red line represents the estimate of the 5-sigma line as a function of separation. (a) A 1938, at 562 nm. (b) A 1938 at 832 nm. In this case, the sole point below the detection curve lies at separation of ~0"15 corresponding to the secondary location in Figures 6 and 7. (c) HO 296AB, at 562 nm. (d) HO 296Ab, at 832 nm. In this case, the detection is made at approximately 0"45.  
(A color version of this figure is available in the online journal.)
recently in e.g., Horch et al. (2017), this lack of isoplanicity will lead to a loss of correlations in the location of the secondary star in the correlation functions used to make a reconstructed image. Thus, the magnitude difference is expected to be systematically overestimated. In the case of observations in poor seeing, such as the ones here, this will be a particularly large effect.

The speckle plate scale was determined to be $0''0182$ per pixel, the scale in the same camera in wide-field mode is $0''0837$ per pixel. These are very close to the design values of $0''0182$ and $0''0813$ per pixel, implying a relative magnification of 4.47. Depending on the properties of the lenses used for the wide-field mode, the actual magnification may be a function of position on the EMCCD chip; this will be more thoroughly investigated in the future. These numbers also confirm that the wide-field pixel scale would undersample speckles, as the diffraction limit at 832 nm is 60 mas, and Nyquist sampling would be achieved with a pixel scale of 30 mas pixel$^{-1}$.

Next, we computed a reconstructed image for the speckle-mode data file, using a point-source calibrator observed close in time to the binary (HR 8178). Unfortunately, no point source was taken in the same fashion in wide-field mode, so the speckle-mode point source was rebinned using the relative magnification factor obtained above to approximate a wide-field point source. The results of both reconstructed images are shown in Figure 13. As expected for a source that is not isoplanatic, the secondary appears fainter than the original speckle frames would suggest; nonetheless, the image resolution is much higher in both analyses relative to seeing-limited data. Indeed, the standard image reconstruction algorithm functioned reasonably well on the wide-field data, producing a reconstructed image with stellar peaks of full width at half maximum of $0''17$, a considerable improvement over the seeing-limited result of $1''55$. A summary of results is provided in Table 5. Note that we do not report $\Delta$ magnitudes for a system this wide due to, as expected, a loss of speckle correlation as the secondary lies outside the isoplanatic angle. The magnitude difference in the literature for the pair is

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**Table 5**

| Parameter                  | Wide Field Mode       | Speckle Mode          |
|----------------------------|-----------------------|-----------------------|
| Observation date (UT)      | 2016 Oct 14           | 2016 Oct 14           |
| Pixel scale (arcsec/pixel)$^a$ | 0.0813 (design)       | 0.0182 ± 0.001       |
| Seeing (arcsec)            | 1.55                  | 1.55                  |
| Reconstructed Image FWHM  | 0.17                  | 0.06                  |
| (arcsec)                   |                       |                       |
| Separation$^b$ (\(\rho\), arcsec) | 2.440 ± 0.007       | 2.434 ± 0.0016       |
| Position angle$^b$ (\(\theta\), E of N ) | 76.7 ± 0.2           | 76.2 ± 0.04          |

**Notes.**

$^a$ The wide-field pixel scale was assumed here from the design. The speckle mode pixel scale is from the slit mask measurement and based on DSSI data the uncertainty on that measurement is $\approx 0.2\%$–$0.3\%$.

$^b$ The uncertainties for separation in speckle mode are determined in the standard way, while for WF mode they have not been directly measured, but are assumed based on the magnification factor, 4.47. For position angle uncertainties $\Delta \theta = \arctan \left( \frac{\text{separation}}{\rho} \right)$ (Horch et al. 2017).
approximately 0.24 according to Hoffleit & Jaschek (1982). The systematic error on \( \Delta \) magnitude is larger for speckle mode than for the wide-field mode, as one would expect given that in wide-field mode the differences between the speckle patterns for the two stars are less severe due to the sampling of the image.

This commissioning experiment opens the possibility of developing the wide-field mode with a “high-resolution” capability, if sufficient information about the speckle transfer function can be gained and can be applied locally throughout a wide-field frame. It is a significant undertaking to develop an algorithm that would overcome the systematic error in the recovered brightness of the source due to the finite size of the isoplanatic angle, but in theory, NESSI provides a unique platform with which to study this and our team’s initial tests are promising (D. I. Casetti & E. P. Horch 2018, in preparation). The results here indicate that, while the resolution obtained in wide-field is not diffraction-limited, it may nonetheless be possible to reconstruct wide field frames to a level of 0\('0\)2 or better.

### 3.3. Exozodiacal Dust Validation

Dust is common throughout stellar systems. The architecture of spectral type A through K main sequence stellar systems may be typically comprised of a distant cold debris disk (<100 K), a warm exozodiacal disk (≈300 K), and a hot inner disk (>1000 K). Dust in this exozodiacal region confounds exoplanet detections by scattering light or mimicking planetary emission. Interferometry at the Center for High Resolution Astronomy (CHARA) Array provides the angular resolution to directly detect near-infrared (NIR) excesses originating from warm and hot dust close to the host star (di Folco et al. 2007; Absil et al. 2008, 2013; Scott et al. 2013; Ertel et al. 2014).

NESSI was used to record speckle observations of \( \upsilon \) And (HD 9826) on 2016 October 14 and 16. The wider FoV of the speckle observations constrain the possibility of a companion at the edge of the interferometric beam combiner FoV (Nunez et al. 2017), removing the potential confounding influence of incoherent flux from a companion star infringing on the interferometric measurements of the flux thought to be from hot exozodiacal dust.

An upper limit of the flux ratio at 832 nm of a companion located 0\('0\)1 away was found to be 1.6%, which allows us to exclude any hypothetical companion of earlier spectral type than M8V/M9V (\( T \geq 2500 \) K). This contrast limit increases with increments of 0.05.
greater separation of the hypothetical companion, reaching 0.4% ($T = 2100$ K) at the extent of the JouFLU FoV and 0.06% ($T = 1700$, K) at the extent of the speckle FoV. These observations exclude stellar companions across a range of separation and provide clear supporting evidence that the observed JouFLU excess is not due to binarity or a line-of-sight companion (See Figure 14). Further observations of suspected exozodiacal dust host stars are underway.

### 3.4. WD Pulsations

Identifying the pulsation on a non-radial pulsating star (e.g., pulsating white dwarf and subdwarf B stars) is notoriously difficult because of the paucity of pulsations present at any one time. One way to discern information about mode identity is to observe the amplitude of the pulsations at different wavelengths Randall et al. (2010), Thompson et al. (2004), Kepler et al. (2000), Clemens et al. (2000). At bluer wavelengths, the effect of limb darkening results in observation of less of the stellar surface area. Similarly, the center of a deep spectral line is effectively equivalent to a smaller stellar surface area. With simultaneous, multi-wavelength coverage taken at a rapid cadence, as those provided by NESSI, one may be able to observe a large change in the amplitude which is indicative of large degree pulsation modes. If such results are combined with a long baseline data set to definitively resolve the pulsation modes, it will be possible for asteroseismology to uniquely model the interior of the star.

In Figure 15 we present such data from a trial observation of HL Tau 76. Sets of data were taken in the traditional sequence of binned frames and in the “accumulation” mode of the cameras that allows multiple frames to be stacked in camera memory.

### 3.5. Other Examples

NESSI’s capability for high resolution imaging without requiring long integration times is well suited to observations of many time-dependent astrophysical processes (See Table 3). We have begun initial trials on time series photometry. For instance, one could observe the variations on the order of minutes in the light curve of the Crab pulsar. Also, the high precision and sensitivity makes NESSI ideal for measurement of occultations. Solar System objects may also be observed and resolved, including moons, planets, and cometary or asteroidal bodies.

Along with photometric and astrometric data, we are developing our speckle resolution technique for use on extended sources such as Solar System objects and globular clusters (E. P. Horch et al. 2018, in preparation). Even without speckle techniques, NESSI can function as a traditional CCD imager with narrow or wide fields of view and good plate scales (See Figures 16 and 17).

### 4. Discussion

Our observing strategy for speckle has been developed based on the team’s past experience with the DSSI instrument. A single observation consists of 1000 frames taken at 40–60 ms saved as a single FITS (Flexible Image Transport System) data cube for each camera. For faint objects multiple framesets may be taken to improve the signal-to-noise ratio (S/N). Narrow (~40 nm) bandwidth filters are used to prevent chromatic blurring of the speckle pattern. A point source may be observed for calibration at the time of observation or, more commonly, one of the previously observed point sources is used and interpolated for the science object’s position in the sky.

#### 4.1. S/N when Adding Frames

To give a good indication of the performance of NESSI, we investigated the quality of results from the instrument as a function of observation time, or equivalently, number of frames captured.
4.1.1. Visual Inspection

We took a large number (31,000) of frames of a 12th mag star, HIP 12986, which is a double of separation \(~0''35\) and magnitude difference of \(~1.5\), followed by 8000 frames of a bright point source (HR 812). We present both the modulus and the final reconstructed image obtained when a varying number of frames of data were used, from 31 to 31,000. Figure 18 shows the results at 562 nm while Figure 19 is the same for the 832 nm data. These images show that the modulus and the final reconstructed image improve in parallel when more frames are added to the calculation. The fringes initially do not extend to the highest spatial frequencies above the noise for either filter, but eventually are seen throughout the region below the diffraction limit, albeit with some effects of dispersion in the case of the 562 nm image. Likewise the secondary star appears only marginally above the noise when few frames are used, but when many are co-added, it is well above the final noise level. The 832 nm images appear more robust primarily because the star itself is fairly red; judging from its $B - V$ color of about 1.1 and assuming it is a main sequence system as its apparent magnitude and distance would indicate, then it likely consists of a primary in the mid-K spectral range, with the secondary being either in the very late-K or early-M range.

4.1.2. Limiting Magnitude in Reconstructed Images

As shown in other figures in the paper, we can also characterize an observation where we are searching for a faint companion in terms of the limiting magnitude difference that could be seen at $5\sigma$ above the noise in the reconstructed image. We attempted to study this limit as a function of the number of frames as well as to compare the results with the signal-to-noise results obtained in the...
another observation of the same star was used as the point source calibrator. For HR 476, there is generally a lower limiting magnitude at all frame numbers, possibly due to residual atmospheric dispersion. There also appears to be an offset in limiting magnitude for small frame numbers; in theory, the limiting magnitude should go to zero as the number of frames approaches zero. This may indicate a systematic error in the determination of the limiting magnitude in this regime of small number of frames and/or very low S/N due to poor seeing. We will need to study this further as NESSI is used more.

5. Conclusion

At the time of this writing, there are 3605 confirmed exoplanets and Kepler has 4496 exoplanet candidates (https://exoplanets.nasa.gov/). Over 2800 of the confirmed exoplanets were detected by the transiting method. There are 200 K2 Mission exoplanets and 622 candidates and its mission is ongoing. TESS is expected to observe over 200,000 nearby stars. Following TESS, Wide Field InfraRed Survey Telescope (WFIRST) will observe on the order of 100,000 transits. The focus on covering large fractions of the sky to search for exoplanet transits drove the design of these space-based instruments toward large pixels: over 4" per pixel for Kepler and 20" for TESS. It is not possible to disentangle blended binaries from true transit events with these instruments. High resolution imaging to resolve binaries is a robust technique for confirming and characterizing exoplanet candidates. Wide-field two-color time-resolved series data taken during transits can serve as an initial precursor candidate vetting process for eclipsing binaries in crowded 20" TESS pixels.

Here we have presented a new instrument for simultaneous dual-channel speckle observations at WIYN telescope, NESSI. Speckle interferometry’s high angular resolution imaging enables the separation and position angle of binary systems to be determined directly. From this direct imaging of the binary orbit, individual stellar masses can be calculated. Stars can be fit to isochrones to prove true companions and determine the stellar properties. The determination of binarity is used to validate potential exoplanet detections and characterize the planets for the current and upcoming space-based observatories: K2, TESS, WFIRST, and others. NESSI also provides photometric data that can determine accurate stellar magnitudes and colors, that in turn can provide stellar parameter and structure information for stellar modeling. The limiting magnitude for speckle observations, will remain around 13–14th at WIYN, while wide-field, non-EM CCD mode will operate as a normal CCD imager. In addition to speckle interferometry, NESSI provides wide-field imaging and photometric capabilities. In the upcoming era of NEID at WIYN, NESSI could provide complementary use in proper conditions during bright moon and twilight observations. It is conceivable to even switch between NESSI and NEID in

Figure 20. Magnitude difference corresponding to a 5σ detection as a function of the number of frames averaged in the reconstructed image. The color of the plot symbol indicates the filter used, with green for 562 nm and red for 832 nm. (a) Results at a separation of 0''2 from the primary star. Filled circles are for HR 812, open squares for HR 476, and asterisks are used for HIP 12986. (b) Results at 1''0 from the primary star, with the plot symbols the same as in (a). In the low S/N regime, S/N builds approximately as √n, where n is the number of frames. There is some falloff from this relationship after a few thousand frames or more. This deviation is likely related to the expected variations in seeing conditions over the longer period of time (>few minutes).
Table 6
Common Camera Modes

| Output Amplifier | Traditional | Electron-multiplying |
|------------------|-------------|----------------------|
| Min. Exposure (s) | 1.1         | 0.015−0.04           |
| Kinetic series length | 1−1000+ | ... |
| Number of accumulations | 1+ | ... |
| Frame transfer | on/off | ... |
| Vertical shift speed (μs) | [0.6], [1.13], [2.2], 4.33 | ... |
| Readout rate (MHz@16 bit) | 0.1 or 1 | 1, 10, 20, 30 |
| Pre-amp gain setting | 1 or 2 | ... |
| EM gain | ... | disabled, 2-300-(1000) |
| Binning | 1 × 1, 2 × 2, 4 × 4 | ... |
| CCD Temp (°C) | 0 to −95, −60 | ... |

Note. Minimum exposure times are given for kinetic readout mode with frame transfer on. The typically used settings are shown in bold. Shared options between CCD and EMCCD modes are shown under the CCD heading. EM gains of >300 can lead to premature aging of the chip if used on bright sources.

roughly 5 minutes to obtain a diffraction limited speckle image of the NEID RV target. It has high utility for applications where high temporal resolution is needed for accurate time-series photometry. There is even use for telescope engineering purposes to characterize high frequency telescope vibration characteristics or calibrate guider performance.

NESSI is a highly versatile instrument and it services a number of science programs in addition to exoplanet validation. It is expected to continue to have high utilization and is open to community use via the proposal and peer review process of WIYN. Instrument support is provided; including queue mode observation; reduction of data using a software pipeline that takes raw speckle data to fully reconstructed images and observed contrast limit plots; currently some of the reduced data is archived at the NASA Exoplanet Science Institute (NExScI) with plans to expand to a full archive.

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Facility: KPNO:WIYN.

Figure 21. This plot shows the effect of changing the gain under constant illumination using a collimated light source. The gain was progressively increased for each point for two different neutral density (ND) filters. The top curve simulates a bright source where a high gain is not recommended as an EM gain of over 300 is outside of the linear region of camera response. Also, prolonged use of high EM gain in a non-photon counting regime can prematurely age the chip. High gain is only recommended for faint sources. The bottom curve shows the low illumination condition where the response is linear across the range of gain values. For these tests the exposure time was 40 ms, the camera temperature was -60 degrees C, and 3 frames were averaged for each point.

Appendix
EMCCD Characteristics

The Andor iXon Ultra 888 EMCCD cameras have been tested most extensively operating under the typical speckle mode (See Table 6). Both cameras exhibit similar characteristics. The frame-to-frame fluctuation in the mean bias level in the 25 fps speckle mode has a standard deviation that is 0.5% of the mean. The mean bias level for a rapid series of acquisitions is a relatively constant value, but the bias level of the first frame is systematically lower than subsequent frames, presumably due to warming of the readout electronics as a sequence is taken. There is a column-to-column pattern, and sometimes a row-to-row pattern, seen in biases at the highest readout rate of 30 MHz with periodic pixel-to-pixel variations of ~8 ADUs amplitude. Similar features are still present at much lower levels using some slower readout speeds (20 MHz readouts greatly reduce the pattern). Large-scale slopes to the bias pattern are present as well, especially at high clocking speeds. The nature of the bias pattern can change with different selections of the readout window. To remove the bias pattern, either a set of bias frames may be used or the bias pattern may be found directly from science target data. In the latter case, for long series of short exposures where bias patterns dominates sky noise, the 2D bias pattern may be estimated using source-free parts of the images averaged over the series.

Photon transfer curves were produced for speckle mode settings using dome flats (Figure 21). Using pairs of dome flats (to reduce the effects of non-flatness in the pattern on the
analysis), the variance of the count level is plotted versus the mean count level over a wide range of illumination. The detectors have a linear response up to a certain count level where the curve turns over (See Figure 22). This corresponds to the maximum charge in the linear range for the active pixels. The slope of the linear part of the photon transfer curve is inversely proportional to the gain of the pre-amplifier. Because electron multiplication is normally employed in speckle observations, the actual counts in images corresponding to the maximum level with linear response will vary. The bottom panel of Figure 22 shows this count level as a function of the EM gain. At low EM gains, the maximum count level is proportional to the EM gain. At higher EM gains, the maximum counts is limited to a constant value set by saturation of the 16 bit A/D converter.

The iXon cameras have a very large number of possible combination of settings and many can be expected to have different properties and applications. An important source of noise under EM is the clock induced charge (CIC), characterized by spurious single pixels with high counts (after amplification). The CIC is produced as the EMCCDs are clocked, either in the array or the readout and amplification register. It can be minimized by choosing the fastest possible clocking speeds, both
in the vertical shift and readout rate. It can also be minimized by choosing the lowest vertical shift voltage amplitudes, another selectable setting. Lower CIC, however, is achieved at the expense of lower charge transfer efficiency. To measure some of these effects, the number of CIC-affected pixels was counted in bias frames taken with a high EM gain and different camera settings. The CIC pixels were detected as those significantly higher than the mean of their neighboring pixels. The rate of outlier pixels attributable to readnoise was subtracted from the count by noting that the readnoise distribution is symmetrical around the mean. Figure 23 illustrates the significant variation in CIC with different clocking speeds.

Readnoise is minimal with these cameras. For typical speckle mode settings, it is 100–200 e− for each camera. At high EM gain settings, the effective readnoise, read noise divided by EM gain, can be ≲1 ADU and ≲1 e−. CIC creates spurious counts in individual pixels. It is evident if the EM gain is turned up high and the readnoise is minimal. CIC can be minimized by using the fastest possible readout rates and vertical shift speeds. At slow readout speeds, the CIC is 50,000–70,000 pixels per image with ~6% of the pixels affected. At the highest speeds this drops to ~300–500 pixels per image (<0.05%). Based on our experience on-sky, we recommend EM gain settings of 2–100 for bright stars with a magnitude of m < 6, 100–300 for 6 < m ≤ 7, 700–1000 for 7 < m < 10, and 1000 for faint stars with 10 < m. This may vary significantly with seeing conditions. The limiting condition on setting EM gain is avoiding saturation.

ORCID iDs
Nicholas J. Scott @ https://orcid.org/0000-0003-1038-9702
Elliott P. Horch @ https://orcid.org/0000-0003-2159-1463
Mark E. Everett @ https://orcid.org/0000-0002-0885-7215

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