A new low-noise high–quantum-efficiency speckle imaging system

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ABSTRACT

A design for a new-concept speckle imaging system is presented. The instrument, now under construction at Rochester Institute of Technology (RIT), will be able to use any large-format scientific-grade CCD as the imager. The high quantum efficiency, low noise, and linear response of current CCDs are attractive characteristics when compared with traditional photon-counting speckle imaging systems. The RIT system consists of an optics package, placed between the telescope and the imager, that contains a piezoelectric tip-tilt mirror capable of executing a timed sequence of movements to place many speckle patterns over the active area of the CCD. The system will either (a) place a series of speckle images in a row and then use the CCD electronics to periodically shift charge toward the serial register or, if the CCD electronics do not allow, (b) have the mirror perform a serpentine step-and-scan motion over the entire CCD. When the entire CCD is full of speckle images, the chip is read out as normal. This kind of "burst mode" speckle data collection effectively uses the large area of the CCD as a memory cache of speckle data frames, allowing large format scientific-grade CCDs that already exist at many observatories to be used efficiently and inexpensively in speckle imaging. The expected performance of the system, which is dependent on the CCD imager, is discussed. CCD speckle observations at the WIYN* 3.5-m telescope and simulation results indicate that, when used with a very low noise CCD, this system could obtain speckle data that are superior to those of even the best photon-counting cameras at the fainter magnitudes where such cameras are currently used.

Keywords: speckle imaging, CCDs, piezoelectric actuators

1. INTRODUCTION

Although some investigators[1,2] have used CCDs for speckle imaging, the vast majority of visible-light speckle data has been acquired with photon-counting imaging devices such as intensified-CCDs,[3,4] precision analog photon address (PAPA) detectors,[5] resistive anode detectors[6] and multi-anode microchannel array (MAMA) detectors.[7] These devices all use microchannel plates for signal amplification and, while their quantum efficiencies are much lower than CCDs, they are shot-noise limited and have large bandwidths. In contrast, the lack of these latter two attributes greatly decreases the effectiveness of using CCDs in speckle imaging. CCDs have read noise, which degrades the contrast of speckle patterns, and they have slow readout times, which is problematic in dealing with the bandwidth requirements of speckle imaging. On the other hand, the much higher quantum efficiency (especially in the red) and the broad wavelength response of CCDs are desirable characteristics for high-resolution imaging applications. As Tyler and Matson[8] have discussed, there are situations where CCDs can compete favorably with photon-counting cameras in terms of the quality of the speckle images detected. In their study, they chose to investigate the properties of a CCD with 20 electrons rms read noise and quantum efficiency of 50%, and achieved comparable or superior signal-to-noise ratio (SNR) in the spatial frequency power spectrum of speckle data frames by increasing the width of the wavelength band pass (usually kept narrow in speckle imaging to maintain high contrast in the speckle patterns) and by increasing the exposure time of individual frames.

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Since the publication of Tyler and Matson's findings, CCDs have continued to improve in terms of read noise, so that CCDs of only a few electrons rms read noise are now being used regularly at large observatories. CCDs with faster readout electronics (and somewhat higher read noise) are also becoming more common. The CCDs that currently exist at most observatories are typically large format (1024 × 1024 pixels or larger) and have slow readout times (less than 50 kpixel/sec), neither of which is optimized for speckle imaging. However, the low read noise of these CCDs in comparison to the figure used in Tyler and Matson suggests that if they were used to record speckle patterns, these patterns could have superior SNR compared to current photon-counting cameras. In addition, CCDs are extremely linear devices, as opposed to most photon-counting cameras, which are susceptible to channel saturation effects.[9] The problem with using current large-format CCDs in speckle imaging is observing efficiency. Even an appropriately magnified speckle pattern would not fill a large portion of a large-format CCD, nor could the device be read out rapidly enough to avoid a large amount of dead time while collecting a sequence of speckle frames.

A step forward in this regard was made last year in a paper by Horch, Ninkov and Slawson,[10] hereafter HNS. These authors took a [2033 × 2048]-pixel CCD with 200 kpixel/s readout and showed that, at a 60-cm telescope, a sequence of 1024 speckle images could be acquired in about 150 seconds by recording many speckle images in a strip and then reading these out together. This "strip mode" of speckle data collection dramatically increased the observing efficiency by using some of the large active area of the device as a physical memory cache of previous speckle images and reducing the number of times the chip had to be read out per observation. Moving the collected charge while the CCD is still exposed to the target introduces a low-level streak between speckle patterns, but HNS showed that this streak can be effectively removed in the analysis phase.

In this paper we extend the work of HNS in two ways. Firstly, we discuss the design of a new optics module which includes a tip-tilt mirror that will move the location of the image on the chip periodically so that speckle images can be recorded over the entire active area of a large-format CCD. Such a system could potentially allow many observatories to enjoy the benefits of diffraction-limited imaging without major expenditures on new hardware. Secondly, expected performance characteristics are presented based on tests using the strip acquisition method of HNS at the Wisconsin-Indiana-Yale-NOAO (WIYN) 3.5-m telescope and on simulated speckle observations. The data from the WIYN telescope suggest that a system such as the one proposed here would work well at this larger aperture, something that was not clear from the previous results in HNS. The simulation results suggest that, when used with the new optics module, the lowest-noise CCDs currently available would yield power spectrum SNRs that are greater than or equal to than those of current photon-counting cameras to *at least* magnitude 10.2.

2. DESIGN OF THE NEW SYSTEM

The success of using a large format CCD in speckle imaging with the technique of HNS leads immediately to the idea of using the entire active area of the CCD for collecting speckle images rather than just a thin strip. This could be accomplished with the use of a tip-tilt mirror, as shown schematically in Fig. 1. Such a tip-tilt mirror, placed between the telescope and the imager, could be operated in one of two ways. The first is in conjunction with the read-out electronics, where the electronics provide motion of the images in one direction (orthogonal to the serial register) and the mirror provides deflection of images in the other direction. The second is where the tip-tilt mirror provides deflection of images in both directions, performing a "raster" motion over the entire area of the CCD.

To perform this function we have the choice of a number of mirror systems. The most appropriate and well-studied of these available within our laboratory is a three-axis piezoelectric mirror (the PZ-80) obtained from Burleigh Instruments of Fishers, New York. The 4.4-cm clear aperture mirror and three piezoelectric actuators come in an easy-to-mount optical housing that is equipped with a high voltage quick connector. This connector is then attached to a three axis high voltage amplifier from Trek Corporation (the Trek 601B, 0-10 volts in, 0-1000 volts out). The input voltage is supplied using a National Instruments D/A board (the AT-AO-6) located in a PCI slot of the control computer. This mirror system has been reported on by Backer, Ninkov and Cirillo[11] where it was used in a closed loop, single-chip tip-tilt image correction system based on a random access charge injection device. A number of operational questions dealing with the use of these piezoelectric mirrors have been addressed, most notably the non-linear hysteresis effects. Backer, Ninkov and Cirillo showed that these can be calibrated. The PZ-80 mirror has an angular sensitivity of 0.075 arcsecond/volt and therefore can provide a maximum deflection of 75 arcseconds. For the WIYN 3.5 meter telescope, the diffraction limit at 5500 Å is 0.04 arcseconds, so critical sampling of the speckles on the focal plane would give a pixel scale of approximately 0.02 arcseconds/pixel and the full field of a 2048 × 2048 CCD array (a typical array that would be used with this system) would be 40 arcseconds. The PZ-80 will therefore

Figure 1. Two possible methods for recording speckle images on a large format CCD with a tip-tilt mirror. (a) "Tip-only mode." Here, the tip-tilt mirror provides deflection in the horizontal direction, and the CCD performs periodic row-shifts to advance rows of speckle images vertically. (b) "Full tip-tilt mode." In this case, the mirror provides deflections in both horizontal and vertical directions, executing a serpentine step-and-scan motion over the entire chip.

Figure 2. The major components of the CCD speckle optics box.

easily provide sufficient angular deflection to translate the speckle subarray across the entire CCD, and could nearly fill a 4096 × 4096 array. The use of the tip-tilt mirror will produce a low-level streak between speckle patterns as in the strip method, but we expect that it will be possible to calibrate this streak away, just as in HNS. The mirror has an operational bandwidth of approximately 1 kHz, so that the setting time between speckle exposures will be on the order of 1-2 ms.

In addition to the piezoelectric mirror for providing image deflection, all of the optical components traditionally used in speckle cameras will be placed in the optics box. These include a pair of Risley prisms for correcting atmospheric dispersion, two filter wheels, and a third wheel for providing different magnifications of the image with microscope objective lenses. For these components, we plan to use a design very similar to the speckle optics package described in Horch *et al.*[12] In particular, the system would include magnification of the image scale from 2× to 40×, the Risley prisms will be able to compensate for atmospheric dispersion for zenith angles of up to 60°, and filter wheels used will hold up to eight 2.5-cm diameter round filters. The general design of the box is shown in Fig. 2. The piezoelectric mirror is placed inside the collimated beam after the Risley prisms.

We are currently conducting tests of the PZ-80 tip-tilt mirror and finalizing the design specifications of the optics package. The machining will be completed in Rochester, and the assembly and bench testing of the system will be made in our optics laboratory at RIT. Initial astronomical tests will be made at the local C.E.K. Mees Observatory, where a 60-cm Boller & Chivens telescope is available for this purpose.

3. EXPECTED SYSTEM PERFORMANCE

3.1. CCD Speckle Tests at the WIYN Telescope

Although the results of HNS indicate that the strip method works well when used on a small telescope, it was not clear from that work that the same method could be applied to a much larger aperture. The main reason for this is that at a larger telescope, a larger subarray must be used in order to simultaneously oversample speckles and contain the seeing disk. As a result, the method will be less efficient, *i.e.* fewer speckle patterns will be recorded per second. In addition, although the number of photons per speckle is independent of telescope diameter,[13] a narrower filter is usually used at a larger telescope to maintain high contrast in speckle patterns. This decreases the light detected in each speckle, and makes it potentially harder to overcome the CCD read noise in recording speckle patterns.

To test the feasibility of CCD speckle imaging at a larger aperture, we mounted a large-format fast-readout CCD and the speckle optics package of a photon-counting system[12] on the WIYN 3.5-m telescope at Kitt Peak, Arizona. The CCD used was a 2033 × 2048 Kodak KAF 4200 chip with 9 micron square pixels. This is a front-illuminated device with a quantum efficiency of 40% at 7000Å (36% at 5500Å) and it has camera electronics capable of reading out pixels at a rate of 500 kpixel/s. The strip method of HNS was used, and for the data discussed here, a total of 120 [128 × 1024]-pixel strips of each target were taken, with each strip containing 8 separate images. It was therefore possible to divide each strip into 8 separate [128 × 128]-pixel speckle frames in the analysis phase for a total of 960 speckle frames per observation. We have also successfully used a subarray format of 112 × 128 pixels. A strip with the shutter closed is always recorded first to provide a bias estimate. With this mode of operation, each observation took approximately 6.5 minutes to acquire, providing an effective frame rate of $\sim$ 2.5 Hz.

Fig. 3 shows two diffraction-limited images reconstructed from speckle observations taken with the CCD camera. The images were produced from the raw speckle data with the technique of bispectral analysis.[14] Both objects are binary stars (Cou 14 and McA 77 AB), where the magnitude difference between the components was measured to be $\sim$1.3 for Cou 14 and $\sim$2.5 for McA 77 AB. The dynamic range of the images, defined as the maximum value divided by the largest spurious peak (positive or negative), is approximately 30 in both cases. The highest contour in the figures is drawn at the full-width at half-maximum (FWHM) level of the primary star, and therefore the diameter of this contour circle represents the resolution of the reconstructed image. The recovered FWHM is approximately 58 milliarcseconds (mas); a diffraction-limited profile at the wavelength of observation (7009Å) would be slightly narrower, 50 mas. The difference is due to the slight undersampling of speckles with the CCD camera. To generate Fig. 3, we placed the recovered [128 × 128]-pixel Fourier transforms of the reconstructed images inside 256 × 256 arrays prior to inverse-transforming. This procedure effectively doubles the sampling of the reconstructed image relative to the raw data frames, but does not contain any information (*i.e.* Fourier components) not directly derived from the data themselves. The lower contours of the images are not circularly symmetric, and there may be several factors contributing to this result. In the case of McA 77 AB, a third component in the system (oAnd Aa) has been intermittently revolved by speckle interferometry,[3,15,16] and although the Aa component is not resolved in

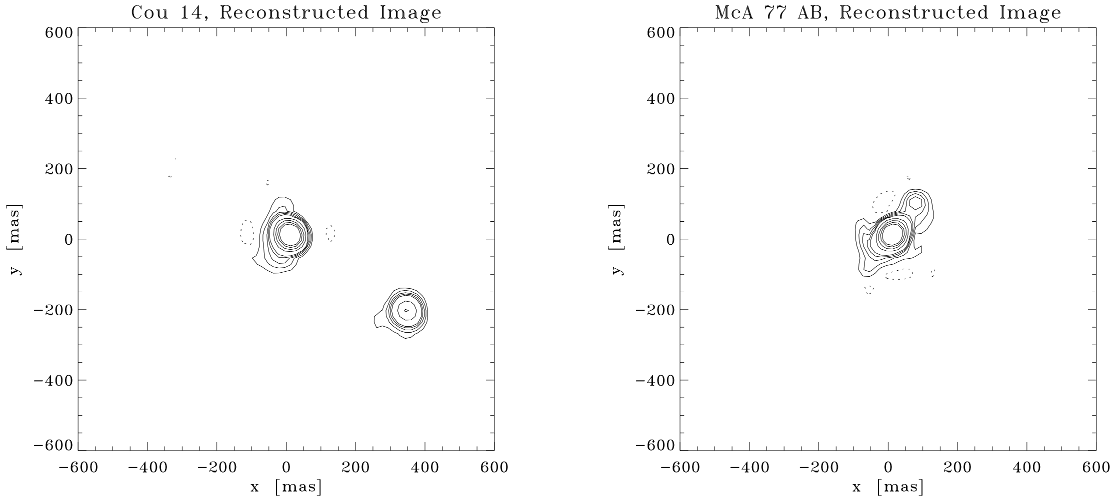

Figure 3. Two reconstructed images of binary stars from CCD data taken at the WIYN telescope. Left: Cou 14 = WDS 21502+1718 = HR 8344, right: McA 77 AB = WDS 23019+4219 = HR 8762. The contour levels are drawn at [-0.02, 0.02, 0.04, 0.06, 0.08, 0.10, 0.20, 0.30, 0.40, and 0.50] of the maximum. The negative contour is drawn as a dotted line. North is up, east is to the left.

our reconstructed image, it may be distorting the lower contours. More generally, the quality of the point source calibration data can significantly affect the appearance of the low contours. Despite these details, these images demonstrate that speckle imaging with large-format CCDs is possible even at apertures as large as 3.5 meters.

So far, we have observed objects with magnitudes ranging from 2 to 9 with the WIYN telescope, and our experience to date is that with a 100Å band pass, the signal-to-noise ratio of the power spectrum degrades significantly in the magnitude range 7.0-8.0. A band pass of 400Å can be used successfully to slightly fainter magnitudes, with the signal-to-noise ratio degrading significantly in the range 7.5-8.5. Further observations are needed in order to make more definitive statements, but these figures are in basic agreement with Simulation 3 presented in the next section, which is a good match to the read noise and quantum efficiency parameters of the chip used at WIYN.

3.2. CCD Speckle Simulations

In order to more fully develop a picture of the potential of a modern low-noise CCD used with the optics system described here, several simulations of the speckle/detection process were performed. The simulation program used here was that of Horch,[17] which is a simple phase screen model of the speckle process. The original version of the program was appropriate for using in simulating photon-counting cameras, but the more recent version used in HNS incorporates a section for the CCD detection and digitization process. It is therefore possible with the current version of the code to compare directly between the two kinds of detection systems, and rate their relative performance when used under the same observing conditions.

In this study, two photon-counter and three CCD simulations were performed; the relevant input parameters for each simulation are shown in Table 1. Each simulation was a 1000-frame sequence of speckle images, where the aperture size was assumed to be 3.5 meters, the wavelength of observation was set at 5500Å, and the band pass was assumed to be 220Å. Better results can be achieved in simulated CCD observations if the wavelength of observation is longer (where the seeing and CCD quantum efficiencies are better); nonetheless we thought it best to retain identical observing conditions for both CCD and photon-counter simulations. The seeing FWHM was set to 0.8 arcseconds, which is the median seeing at the WIYN telescope. Total losses of 50% in the number of photons reaching the detector are assumed from the combination of the atmosphere, telescope, and filter transmissions. We did not use the techniques discussed in Tyler and Matson[8] for increasing the SNR of CCD observations; the statistics of the speckle patterns hitting both detectors were identical. These data therefore represent a true head-to-head comparison between the CCD and photon-counter detection systems.

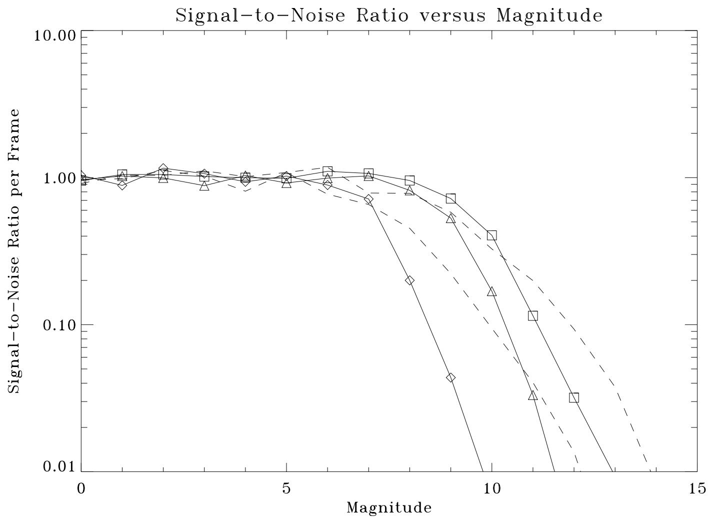

Figure 4. Performance curves several speckle simulations for a 3.5-m aperture in 0.8 arcsecond seeing. The symbols and parameters used for each simulation are described in Table 1. The upper dashed line is the simulation of a 10% quantum-efficiency photon-counting camera, the lower is of 2% quantum efficiency.

Table 1. Speckle simulations performed in this study.

Simulation	Detector	RMS Read Noise (e-)	Quantum Efficiency (%)	Symbol in Fig. 4
1	Photon-counter	0	10	Dashed Line
2	Photon-counter	0	2	Dashed Line
3	CCD	10	35	◇
4	CCD	4	80	△
5	CCD	2	80	□

After obtaining the raw images recorded by the detector in each simulation, we computed the average spatial frequency power spectrum for the frame sequence. The SNR of the power spectrum is a standard measure of the performance of a speckle imaging system. Fig. 4 shows the results of the five families of simulations, where we have plotted the power spectrum SNR at half the diffraction limit as a function of magnitude. The two photon-counter simulations (dashed lines) bracket the range of quantum efficiencies (2-10%) for devices of this type in current use.[6,7,18] (The quantum efficiency of a photon-counting detector is often somewhat lower than that of its photocathode material, due to losses in the detection process.) The other three curves represent CCD simulations of varying read noise and quantum efficiency. The first of these (Simulation 3 in Table 1) approximates the RIT CCD described in the previous section and used at the WIYN telescope. The second (Simulation 4) matches the current large-format CCDs available at Kitt Peak National Observatory. The third (Simulation 5), with 2 electrons read noise, matches the very best CCDs that exist today. The streaking effect between speckle images expected from the new system was not simulated.

All the curves in Fig. 4 are flat out to some magnitude where the SNR then drops off. This is a well-known feature of speckle SNR.[13] The two features that distinguish the various simulations are the location of the "knee" of the curve and the slope on the faint side of the knee. CCD simulations have a steeper slope since the read noise degrades the final SNR in faint speckle patterns when compared with the photon-counter simulations, which are shot-noise limited. However, the location of the knee is pushed to fainter magnitudes by increasing the CCD's quantum efficiency and lowering its read noise. For the lowest-noise CCDs, the simulations indicate that the location of the knee is fainter than even the best photon-counting cameras currently used in speckle imaging, yielding SNRs

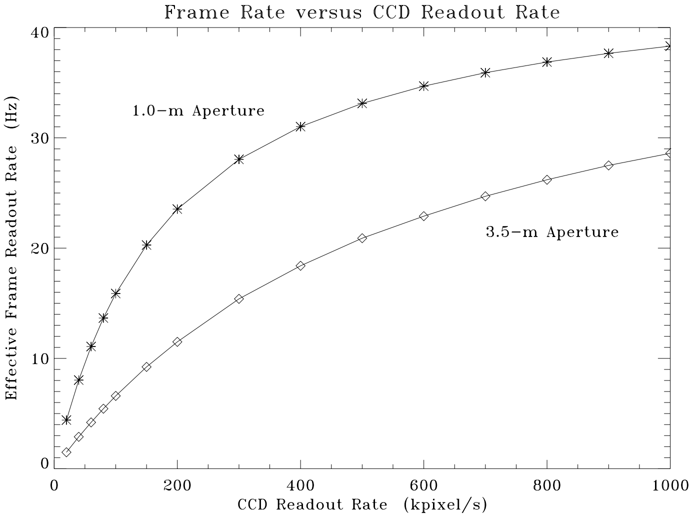

Figure 5. Effective frame rate as a function of readout speed for a 2048×2048 CCD, assuming observing parameters appropriate for a 1.0-m and a 3.5-m telescope.

that are 20 to 25% higher in the magnitude range 8 to 10. It must be stressed that these simulation results are intentionally conservative in that they have not optimized the observing parameters for the CCD. Both the seeing and the quantum efficiency of the detector would improve by working in the red, where the CCD has a natural advantage over the photon-counting devices. In addition, it may be possible to further improve the performance of the CCDs by using wider band pass filters and longer integration times than with photon-counting cameras, as suggested by Tyler and Matson. Despite these facts, we are led to the conclusion that many observatories already have excellent detectors for speckle imaging in their large-format low-noise CCDs, the potential of which could be fully utilized by coupling the CCD with an optics package such as the one described in Sect. 2. It is also reasonable to expect that CCDs will continue to improve in terms of read noise in the coming years, whereupon the knee of the performance curve in Fig. 4 will be pushed to even fainter magnitudes. Similar results are obtained if the simulations are carried out using a smaller aperture.

Another figure of merit for the proposed system is the expected observing efficiency. This is determined by the readout speed of the CCD used with the optics package and the telescope aperture. Using a [2048×2048]-pixel format, we have calculated the effective frame rates (*i.e.* the number of frames recorded per second) for CCDs of various readout speeds, from 20 kpixel/s to 1 Mpixel/s. A 20 ms exposure time is assumed, as is a 2 ms shift time for the tip-tilt mirror. Fig. 5 shows two curves of the effective frame rate as a function of CCD readout speed. The lower curve is appropriate for a 3.5-m aperture, where individual speckle exposures are assumed to be 114×114 pixels, allowing for a grid of 18 by 18 speckle images to be recorded over the active area of the chip. (The 114×114 size is similar to what we have used at WIYN with the strip technique.) A 972-frame exposure is assumed, so that the full chip would have to be read out 3 times. The upper curve in Fig. 5 is appropriate for a 1.0-m aperture, where the individual frames are [64×64]-pixel blocks, meaning that on a [2048×2048]-pixel CCD, 1024 images can be stored, and therefore only one read must be made per observation.

There are several points to make about Fig. 5. As alluded to earlier, the reason that aperture size makes a significant difference in the effective frame rate is that at a smaller aperture telescope, a smaller subarray is needed to both oversample the speckle size and contain the entire seeing disk. Since frames contain fewer pixels, more frames can be read out per second. However, because the images are taken in burst mode, the telescope could be setting to the next object during the final read of the chip, increasing efficiency. The plot shows that even at modest CCD readout speeds (less than 200 kpixel/s), effective frame rates of 20-25 Hz (comparable to video rates) are possible using this technique at smaller apertures. At larger telescopes, this is not so, but 1000-frame sequences can be obtained in under 3 minutes (frame rates greater than 5.6 Hz) with readout speeds of greater than 80 kpixel/s. Current CCDs at Kitt Peak National Observatory have readout rates in the 20 to 25 kpixel/s range, but the next generation devices will likely be substantially faster.

4. CONCLUSIONS

A design for an optics module that will use large-format CCDs in speckle imaging has been presented. The unit will feature a piezoelectric tip-tilt mirror to utilize the entire active area of the chip in recording speckle images and will be flexible enough to use with *any* existing large-format CCD imager. The piezoelectric mirror is currently being tested in the laboratory and the optics box will be assembled in the coming months. Both real and simulated data indicate that large-format CCD speckle observations of high quality are possible with telescopes at least as large as 3.5-m aperture. In fact, simulation results of the best CCDs that exist today suggest that these devices can record speckle patterns of higher signal-to-noise ratio than even the best photon-counting speckle imaging systems in the magnitude range of 8.0 to at least 10.2. The effective frame output rate, which is dependent on the CCD readout electronics and telescope aperture, is 24 Hz for a 2048 × 2048 CCD with 200 kpixel/s readout on a 1-m telescope, comparable to video rates that are typically used in current intensified speckle imaging systems. At a 3.5-m telescope, the system will be less efficient, but 1000-frame sequences can be obtained in under 3 minutes with a CCD that reads out at 80 kpixel/s.

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