# Speckle Interferometry of Close Visual Binaries

with the

# ZW Optical ASI 224MC CMOS Camera

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## Introduction

The most influential parameter by far, with respect to the life cycles of stars, is their mass. William Herschel (1803) provided evidence that some close visual doubles were actually gravitationally-bound "binaries," a term he suggested. Observations of close visual binaries over time can establish their apparent two-dimensional elliptical orbit (Kepler's First Law). Kepler's Second Law (of equal areas swept out in equal times) can then be applied to determine the actual three-dimensional orientation of the binary's orbit. If the distance to the binary is known (by Hipparcos or soon more accurately by Gaia), simple trigonometry provides the obit's minor axis in physical, astronomical units, as opposed to angular units. Kepler's Third Law relating orbital periods and semi-major axes can then be applied to determine a binary's dynamical mass, i.e. the sum of the two individual stellar masses. Finally, radial velocity curves can be applied to parse the dynamical mass into its two components.

Currently there are about 3000 binaries with published orbits. Most of these binaries have orbital periods of many decades, centuries, or even millennia. To establish accurate orbits (and hence stellar masses), it is necessary to have at least one nearly complete orbit, and two or more complete orbits are even better. Short orbital periods only occur when the physical separation of the two binary components is small. The result is small apparent angular separations. For a given binary, the further away it is from Earth, the smaller will be its apparent angular separation. The upshot is that the visual binaries of greatest interest—shortest periods—generally have separations below the seeing limit.

Antoine Labeyrie (1970) discovered that the seeing limit could be circumvented for close visual binaries within the isoplanatic patch, a small area of the sky (typically about 5″) where jitter movements are correlated (double stars dance about together). Circumvention was accomplished by taking short exposures that froze out atmospheric variations (the small air cells just not having enough time to change or move very far). Such short exposures produced a speckle pattern of many binary-pair images randomly superimposed on another. Labeyrie found, however, that the position angle and separation of a binary's two components could be recovered from a series of these short, jumbled exposures (typically many hundreds or a few thousand) through Fourier spatial analysis that produced an autocorellogram.

High-speed film was initially used to make speckle interferometry observations. When CCD cameras became available, they were not used in their "barefoot" mode because their read noise at high speed was very high compared to the few signal photons available in the short exposures. However, amplification of the light prior to the CCD camera, i.e. an intensified CCD (ICCD), in conjunction with early portable computers, ushered in the area of practical speckle interferometry of close visual binaries (McAlister 1985). See Figure 1. ICCD cameras were expensive, however, and their intensifiers were inherently nonlinear. Thus while astrometric measurements of position angles and separations could be made, it was difficult to make precise photometric ICCD measurements of close visual binaries.

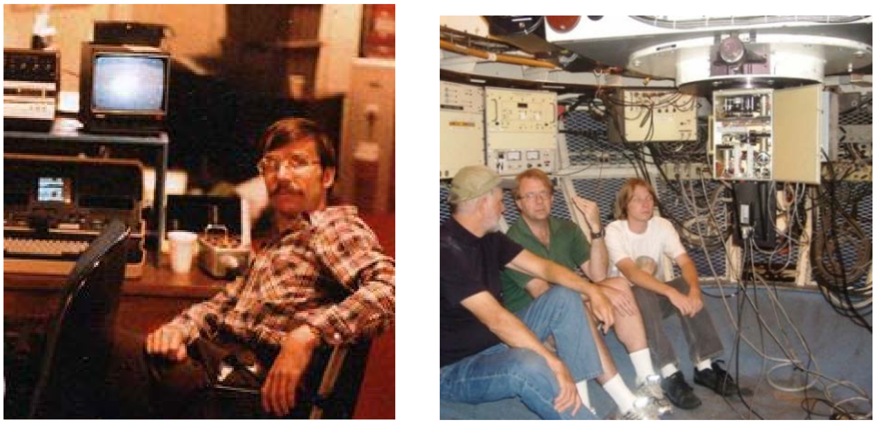

*Figure 1. William Hartkopf, in warm room comfort at Kitt Peak National Observatory (left), captures high-speed frames with an early Osborn portable computer from an intensified CCD (ICCD) camera located at the Cassegrain focus of the 4-meter telescope. Russ Genet, Brian Mason, and Jo Johnson in the 4-meter Cassegrain cage (right) with the US Naval Observatory's similar ICCD camera.*

Over a decade ago, electron-multiplying CCD (EMCCD) cameras were introduced. A gain register was added between the pixel array and the CCD chip's analog-to-digital (A/D) converter. The gain register, similar to a solid state photomultiplier, amplifies the signal to a level where the read noise, in comparison to other noise sources, becomes insignificant.

These cameras, however, with their back-illuminated, high quantum efficiency e2v chips, are expensive (currently about $40,000 for Andor's top-end iXon camera). They are also sizeable and somewhat heavy (about seven lbs.). While the size, weight, and cost of these EMCCD cameras do not pose a problem for most professional astronomers making speckle observations on large telescopes in funded programs, they do pose a challenge for small-telescope astronomers on a limited budget. Two successful small-telescope solutions were found for this size, weight, and cost problem.

*Figure 2. Florent Losse used his 0.4-meter telescope in France to obtain highly-precise measurements of the position angles and separations of many close visual binaries—many of them with separations well below the seeing limit.*

The first solution was pioneered by Florent Losse. He took a short exposures with a "regular" CCD camera (around 20 milliseconds), and then read it out at regular, several-second rate. Although his duty cycle (exposure time versus exposure plus readout time) was very low, he patiently took the time to obtain hundreds of short exposures on each target. He modified his popular double-star reduction program, REDUC, to process his results in Fourier space to obtain autocorrelograms.

The second solution was to use a lower cost, relatively small EMCCD camera made originally by Andor Technologies (the LucaS and LucaR) and now others (such as the Raptor) that use a front-illuminated EMCCD chip made by Texas Instruments. While still somewhat expensive (typically over $10,000), these cameras are relatively small and lightweight (about two lbs.). Genet (2013, 2014) used the Andor LucaS and LucaR cameras for observations made at various observatories in the western US, including Kitt Peak National Observatory, while Jocelyn Sérot (2015) used the Raptor Kite for speckle observations on a small telescope in France.

*Figure 3. Left: Eric Weise finishes the installation of an Andor Luca-S EMCCD camera on the 0.5-meter PlaneWave Instruments telescope at Rowe's Pinto Valley Observatory in the Mojave Desert Reserve. Right: Raptor Kite EMCCE camera on Jocelyn Sérot's Celestron C-11 telescope in France.*

Although these front-illuminated cameras were an important step forward for small-telescope speckle interferometry, they were still somewhat pricy for many amateur and student astronomers. Furthermore, Texas Instruments stopped making the front-illuminated chips used in these cameras. Thus the search continued for a truly low cost, small, lightweight, high speed camera.

## Discovery of the ZW Optical ASI 224MC CMOS Camera

Rapid improvements have been made in the design and manufacture of high-speed CMOS cameras with low read noise. Scientific CMOS (sCMOS) cameras appeared on the market a few years ago with performance approaching that of EMCCD cameras. Although sCMOS cameras remained expensive (typically over $10,000), there was hope that the cost of the low-noise CMOS chips would be reduced, allowing them to be incorporated into low-cost, mass-market cameras.


*Figure 4. ZWO's ASI 224MC low-noise CMOS camera. The Sony team that developed the IMX 224 chip: back row Mr. Torii, Mr. Azami, and Mr. Yano; front row Ms Tokunaga and Mr. Maruno.*

This happened recently. A team at Sony developed a low read-noise (less than 1 electron) chip that has been incorporated in a camera made by ZWO that only costs $359 US, and just weighs 120 g (4.2 oz). Benoit Shillings obtained one of these cameras, placed it on his 0.5-meter telescope in San Jose, California, and, using a list of targets supplied by Richard Harshaw, quickly demonstrated that the new ZWO camera could observe remarkably faint and close double stars. Within days of hearing about this breakthrough, Genet obtained a ZWO ASI 224MC camera from High Point Scientific (442 Route 206, Montague, NJ 07827, USA, 800-266-9590, www.highpointscientific.com), and also obtained remarkable results at his Orion Observatory in Santa Margarita, California.

*Figure 5. Left: Benoit Shillings, with his 0.5-meter telescope, made the first close double-star speckle interferometry observations with the ZWO ASI 224MC camera. Right: close-up of the instrumentation at Russ Genet's Orion Observatory. The ZWO camera is behind a Tele-Vue 2.5-power Barlow lens.*

Clif Ashcraft, at his Perrineville Observatory in New Jersey, quickly joined in the observations, and has, to date, made the most extensive close visual double star, speckle interferometry observation with the ZWO ASI 224 camera. Only a few of his observations are reported here, while his extensive observational results are presented in a companion paper (Ashcraft 2015).

*Figure 6. Clif Ashcraft and his Night Assistant, Boomer. Celestron C-11 telescope equipped with the ZWO ASI 224MC camera behind a 3X Barlow lens.*

## Data Reduction with Plate Solve 3.44

Plate Solve 3 (PS3) was initially developed by David Rowe to obtain place solutions, which it does with unusual rapidity. A speckle interferometry capability was added to PS3 in 2013 that included adjustable high and low pass filters, an interference filter, and, of critical importance, the capability to accommodate single deconvolution stars (Rowe & Genet 2015). PS3 has the capability of pre-processing (obtaining the Fourier transforms and averaging them) automatically in a batch mode, reducing file sizes from gigabytes to megabytes, and greatly speeding up the subsequent reduction and analysis process.

PS3 processes FITS data cubes, although it does have a routine for converting files of FITS images into data cubes. However, PS3 was only programmed to handle monochrome images, so to accommodate the ZWO ASI 224 MC color camera, Rowe developed a routine to parse Bayer FITS data cubes into blue, green, red, and total data cubes. Although the "total" data cubes were used in the results provided below, the other cubes may end up being useful for the speckle multi-band photometry of close double stars.

## Sample Results

The results described below were obtained by Clif Ashcraft on the night of October 8, 2015. See Ashcraft (2015) for more comprehensive results and a detailed discussion of how the observations were made, reduced, and calibrated. Here we briefly present selected results.

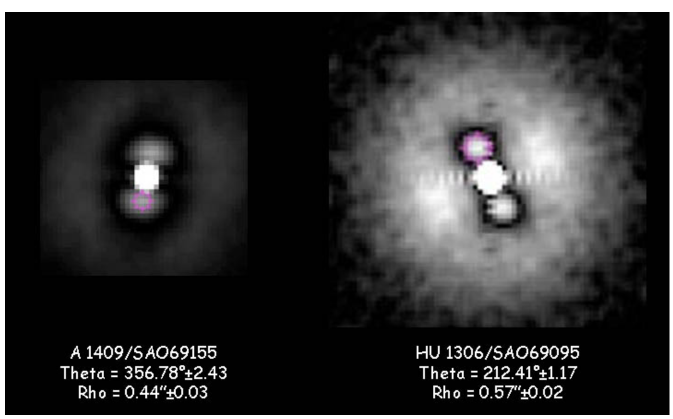


*Figure 7. Autocorellograms of A 1409 and HU 1306 deconvolved with a nearby known single star. Ashcraft obtained 10,000 frames of each with an exposure of 30 milliseconds for A 1409 and 50 milliseconds for HU 1306. The ability to obtain such results for 10th magnitude stars separated by less than 0.6" on a Celestron C-11 telescope with a CMOS camera costing $359 USD is quite revolutionary.*

A 1409 (WDS 19580+3840) is a very close double with components of magnitudes 8.7 and 10.7. Its last reported measure was θ= 0.1°, ρ = 0. 477 in 2007. Only six measures have been reported since 1906. 10,000 images were obtained of this double with the ASI224MC coupled to the C-11 telescope with a 3x Barlow lens using an exposure time of 30 ms. Some 2000 images of the nearby single star SAO69155 were also obtained. The 10,000 images were made into 10 FITS cubes of 1000 images each and the 2000 images of the reference star were made into a single FITS cube. These cubes were then processed in PS3 to obtain 10 deconvoluted autocorellograms from which the position angle and separation of the components of A 1409 were measured and the standard deviations determined. The result was θ= 356.78°±2.43, and ρ = 0. 44"±0.03. In rectilinear coordinates: x = 0.440"±0.027 and y = -0.025"±0.019.

HU 1306 (WDS 19558+3604) is a 10.16 and 10.13 magnitude pair. The last reported measurement on this system was θ= 209.1°, ρ = 0.596 in 2008. Fourteen measures have been reported since 1905. A set of 10,000 images of this system was obtained with 50 ms exposures with the same setup described above, and 2000 images were obtained from the nearby known single star SAO69095. The images were grouped into FITS cubes as described above and processed in PS3 to give autocorellograms from which the position angle and separation of HU 1306 were measured and the standard deviations determined. The result was θ= 212.41°±1.17, and ρ = 0. 39"±0.04. In rectilinear coordinates: x = 0.476"±0.014 and y = -0.303"±0.021.

In Figure 7 we give an example of one of the ten autocorellograms that were obtained from each of the double stars. For comparison with the autocorellograms, the best 10% of the 10,000 images were also aligned and stacked using Autostakkert2 to give the lucky imaging results shown in Figure 8 along with a single frame.

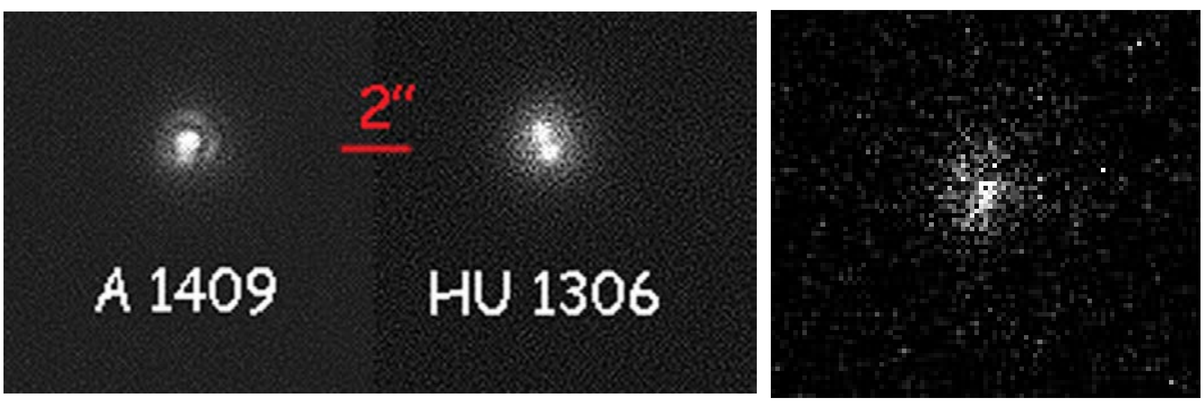


*Figure 8. Left: lucky image results on A 1409 and HU 1306 . The red bar is 2 arc seconds long for scale. Right: the central portion of a single pixel image of A 1409 taken with the ASI2245MC and 30 milliseconds exposure on the CPC-1100Edge HD with 3x Barlow at f/31.5.*

## The ZWO ASI 224 MC Camera

ZW Optical was created by Sam Wen in response to his dissatisfaction with the status quo imaging devices and telescope optics available in China and abroad. Sam is a lifelong amateur astronomer and astro-imager, currently living in Suzhou City, near Shanghai. His early astronomy endeavors took a back seat as he finished his degree in electrical engineering, then establishing a career in that field. Living in the city, planetary imaging became his astronomy area of interest. The Philips SPC 900NC and PCVC 840K were the starting imaging hardware.

*Figure 10. Sam Wen (left) and the team at ZWO. Front row Yi Tang, Zhenrong Gu and Vanessa Zhang. Back row: Xueming Lu, Yang Zhou, Yong Yu, Sam Wen, Hongwei Kan, and Junfeng Zeng.*

Seeing room for improvement, and with fresh ideas, Sam began making his own cameras and small telescopes, founding ZW Optical in the process. His first imager was the ZWO ASI 130MM which used the same sensor as its QHY5 counterpart, producing similar results. Looking for a higher QE sensor, he saw potential in Sony's Aptina's MT9M034, which delivered the desired improvement. The MT9M034 was at the heart of ZWO's second two offerings, the ASI 120MM (monochrome) / MC (color) cameras. Coupled with support within the SharpCap and FireCapture imaging software, he now had a camera that had the potential to outperform equivalent systems at a significant cost savings.

*Figure 11. Left: designing a circuit board. Right: assembling a camera in the clean room.*

The ASI 224MC discussed in this paper is ZWO's latest camera. A two-stage Peltier cooled version of this camera is scheduled to be released before year's end. These latest ZWO cameras are built around Sony's IMX224 sensor and are able to push read noise below 1 electron.

The response of this camera extends well into the near-IR. Although a monochrome camera would normally be preferred for scientific astronomical measurements, this color camera performs remarkably well and its color filters may allow it to be used for three-color photometry.

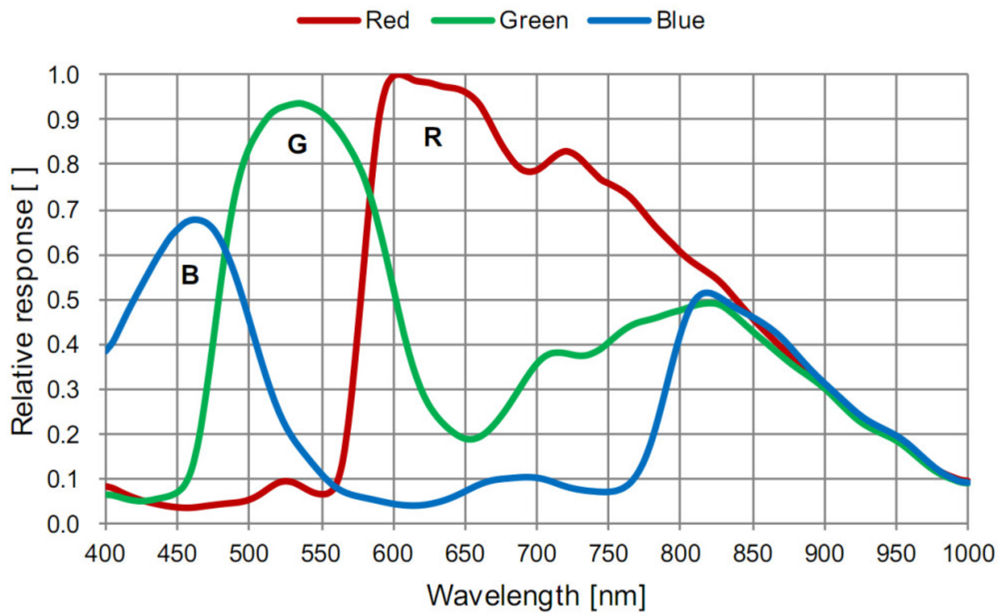


*Figure 12. Relative spectral response of Sony's IMX 224 CMOS chip used in ZWO's AST 224MC camera.*

## Discussion

Although the performance of the ZWO AST 224MC is remarkable, being in color as opposed to monochrome, it is not optimal for the speckle interferometry of close visual binaries. There is about a 2x filter loss on the color sensors, and another 4x loss for the doubling of the f/number, what with 1/4 of the photons per pixel yet the same read noise.

The architecture of CMOS differs from CCD sensors. The CCD sensors in this class have a single readout register, amplifier, and analog to digital converter (ADC). This architecture by its nature normalizes the resultant data, leaving only pixel sensitivity as a variant that is fully normalized with calibration. CMOS sensors have an amplifier and ADC converter for each row or column.

In the case of the IMX224, that is 1213 amplifiers and ADCs (one per column). To reduce the pattern variation produced by the per-column conversion, there is an on-sensor image processing pipeline/Digital Signal Processing system. Since raw data is not available from the CMOS sensor, actual "noise" levels cannot be determined. The term "Temporal Dark Noise" (TDN) is sometimes used to differentiate between this low level noise in CMOS sensors and the classic "Read Noise" from a CCD camera. In general these values cannot be directly compared. In the case of CMOS sensors with unknown processing algorithms, camera-to-camera TDN comparisons should also be done with some care. This pre-processing of data has other ramifications that are specific to a camera. In the case of the ASI224, no dark frame subtraction is used as it produces artifacts.

Jones demonstrated that a high-speed CCD camera could produce nearly as good results as those obtained by Ashcraft with the ZWO AST 224MC camera. Using a Celestron Skyris 618, a classic monochrome CCD camera, images were capture at approximately the same exposure as those with the ASI224 with similar results. Images were processed with dark frames. The Skyris 618 is well behaved, allowing a full calibration if needed.

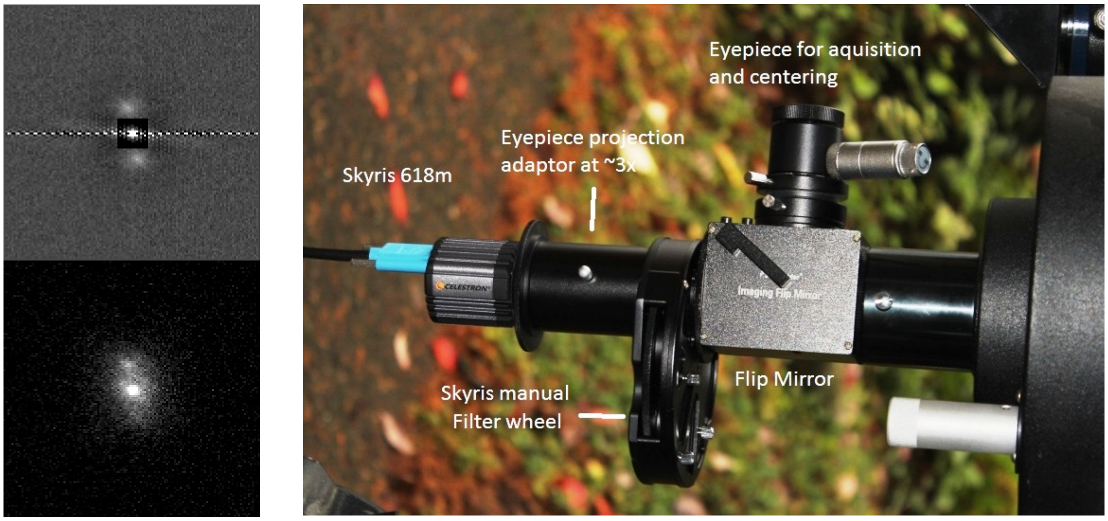


*Figure 13. Top left is the autocorrelation of 20449+4332 (rho 2", 10.4 and 10.8 magnitude pair) obtained with the Skyris 618m followed by a "lucky image" below. Both were obtained from the same data set captured without filters at 250ms exposure. A data set with 150ms exposure also yielded measurable results. The back of the 8" SCT and imaging train used to acquire the dataset is at the right. At f/32 the final f-ratio is slightly longer than the optimal f/28 for this camera.*

The ASI-224 uses the Sony IMX224LQR image sensor. This is an Exmor Starvis (progressive scan) CMOS sensor. Pregius is the Sony designation for their line of sensors with Global shutters. Both progressive and global shutter sensors are effective for speckle, with a slight benefit to the global shutter option if it does not affect limiting magnitudes.

Sony has announced several sensors and two new technologies beyond that in the IMX-224LQR. Exmor R moves to back side illumination and Exmor RS extends this with better NIR response, deeper well depth and a stacked configuration offering better fill (80%+ vs. ~50%). All these moves are to improve QE of the sensors. Further reduction in TDN is also expected.

The IMX 290, a monochrome Exmore RS Starvis sensor, is expected early in 2017. This sensor is expected to be as good as or better than a monochrome IMX224, which is not planned. The IMX273 Exmore RS Pregius sensor is also expected by the end of 2017 and may be the best senor for low cost speckle work if all else holds.

For speckle interferometry, both the delta mag and the sum of the intensities of the two components are important. Also important are the composite stellar spectra, the QE vs. wavelength curve, filtering, if any, and seeing. If a monochrome CMOS camera shows up with <= 1e- RMS effective read noise and at least 50% QE in-band, then a C-11 should get to about mag 12.5 composite intensity with 70 mS exposures, assuming the delta brightness is less than 1 stellar magnitude and the seeing is good (10 cm Fried cell diam). This should hold down to separations that are roughly the radius of the first diffraction ring. For a C-11, this is about 0.65 arcseconds at V-band. There are many parameters to consider, and they can affect the results by more than a stellar magnitude.

As read noise is reduced, a point will eventually be reached where other noise sources become dominant, and further reductions in read noise will not significantly improve performance for this particular application. Based on our observational data, we estimated that the read noise of the ZWO224 camera was approximately 0.85 e- RMS. In making this estimate, we made a number of assumptions about the transparency of the atmosphere, optical throughput, quantum efficiency, etc.

There are two dominant noise sources in speckle interferometry: read noise and photon shot noise. Even if the read noise were effectively zero, photon shot noise would still limit the magnitude of the double that can be observed. Rowe used his double star speckle interferometry simulation program

(ASD), which incorporates both read noise and Poisson shot noise statistics, to make simulated FITS cubes that were then processed by PS3.

Using Ashcraft's C-11 aperture and image scale, a camera with 0.85 e- RMS read noise, a Fried cell diameter of 10 cm, a double with a separation of 0.65", 1000 FITS images per cube, and a double star having a secondary/primary intensity ratio of 0.5 approximately, some 500 photoelectrons are necessary to detect and measure the double in PS3. If the read noise were zero, the necessary number of photoelectrons drops to ~150. This implies that the read noise is reducing the detection limit by about 1.5 magnitudes over a camera with no read noise.

For faint doubles, Ashcraft found, empirically, that the optimal integration times were upwards of 100 ms. Under conditions of good seeing and using an I-band filter, even longer integration times may be optimal. We speculate that as telescope aperture increases, the integration time must be reduced to avoid smearing images of the increasing number of high resolution speckles. It may be somewhat fortuitous that smaller telescopes can make longer integrations (at wider bandwidths), thus offsetting, to some extent, their lack of light-gathering power.

## Conclusion

The ZWO ASI 224MC low noise, low cost CMOS camera, with its Sony IMX224 chip, is a significant technical breakthrough for affordable speckle interferometry of close double stars on smaller telescopes. We are only beginning to explore the full capabilities of this camera, and invite others to join us in this exploration.

If a monochrome version of this Sony chip were incorporated into a camera, this would significantly improve the performance with respect to speckle interferometry. While further reductions in read noise will improve performance, a limit will eventually be reached where read noise becomes insignificant and photon shot noise, which cannot be reduced, will dominate.

## Acknowledgements

We thank Sony and its design team for developing the IMX224 chip. We thank the U.S. Naval Observatory for the use of the Washington Double Star Catalog to formulate our target lists.

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