# Robotic Speckle Interferometry Studies of WDS 04215-2544

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### Abstract

The separation and position angle of the known binary system WDS 04215-2544 was measured using the Speckle Interferometry method with the fully robotic 1.0-meter Planewave Instruments telescope, located at the El Sauce Observatory in the Atacama Desert of Chile. The November 2022 results are Separation $\rho = 0.5 \pm 0.1$ and Position Angle Theta $\theta = 246.3° \pm 0.3$. These are in line with 6th Orbit Catalog (Mason et al 2023) ephemeris projections for 2022 and 2023.

## Introduction

### Binary Stars

Binary star systems provide a unique opportunity to study stellar evolution. By observing the interaction between the two stars in a binary system, astronomers can better understand how stars evolve, exchange mass, and transfer energy (Tauris & Heuvel 2023). This knowledge contributes greatly to modern astrophysics.

Astronomers identify and catalog binary star systems through various surveys and observations. These systems are discovered through direct imaging, spectroscopic measurements, photometric variations, or astrometric techniques. Each binary is classified by its properties, such as spectral type, component star separation, period, eccentricity, and component masses. Photometric observations can track brightness, spectroscopic observations can measure radial velocities and determine orbital parameters, and high-resolution imaging can resolve the individual stars within the system.

### Known Binary Stars Project

The Known Binary Stars project (Genet et al 2023) obtained observations of WDS 04215-2544 using a robotic 1.0-metre Planewave Instruments telescope, one of the largest aperture research telescopes currently in production. Located at the telerobotic El Sauce Observatory in Chile's Atacama Desert, this telescope is one of a growing array of remote access telescopes in one of the best astronomic viewing locations on Earth.

*Figure 1: Left: Fully automatic El Sauce Observatory powered with solar panels. Right: The 1.0-meter Planewave Instruments robotic telescope used for these studies is located in one of the enclosures.*

The purpose of the overall project was to determine the accuracy, precision, and limitations of robotic astrometry for 1-meter telescopes. Binary star data from the Sixth Catalog of Orbits of Visual Binary Stars (Matson et al 2023) was used as the starting point. A spreadsheet list (McCudden et al 2022) was filtered to obtain observable candidates, and a number of these were observed in the fall of 2022. WDS 04215-2544 was selected from the observed binaries based on a review of the orbital plots of past observations.

## Speckle Interferometry

Speckle interferometry (Labeyrie 1970) is a technique used to study binary or multiple stars using high magnification. It involves obtaining many short-exposure images and analyzing the changes or "speckles" caused by atmospheric turbulence, as shown in Figure 2.

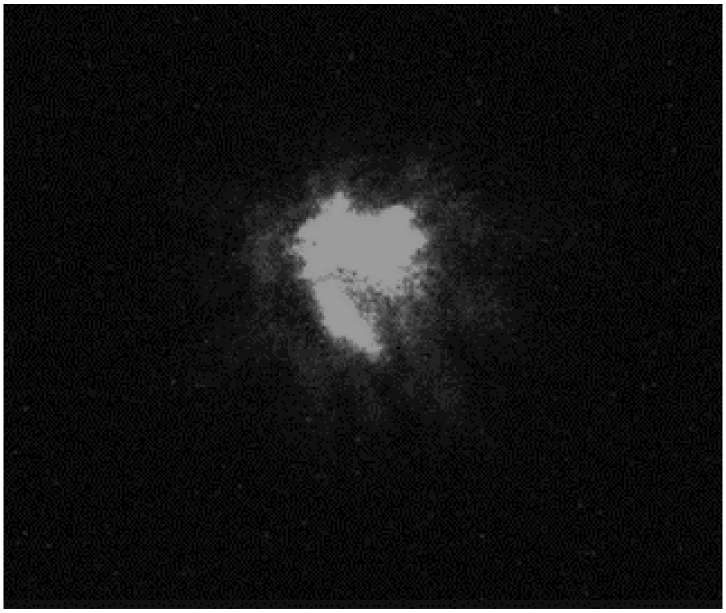
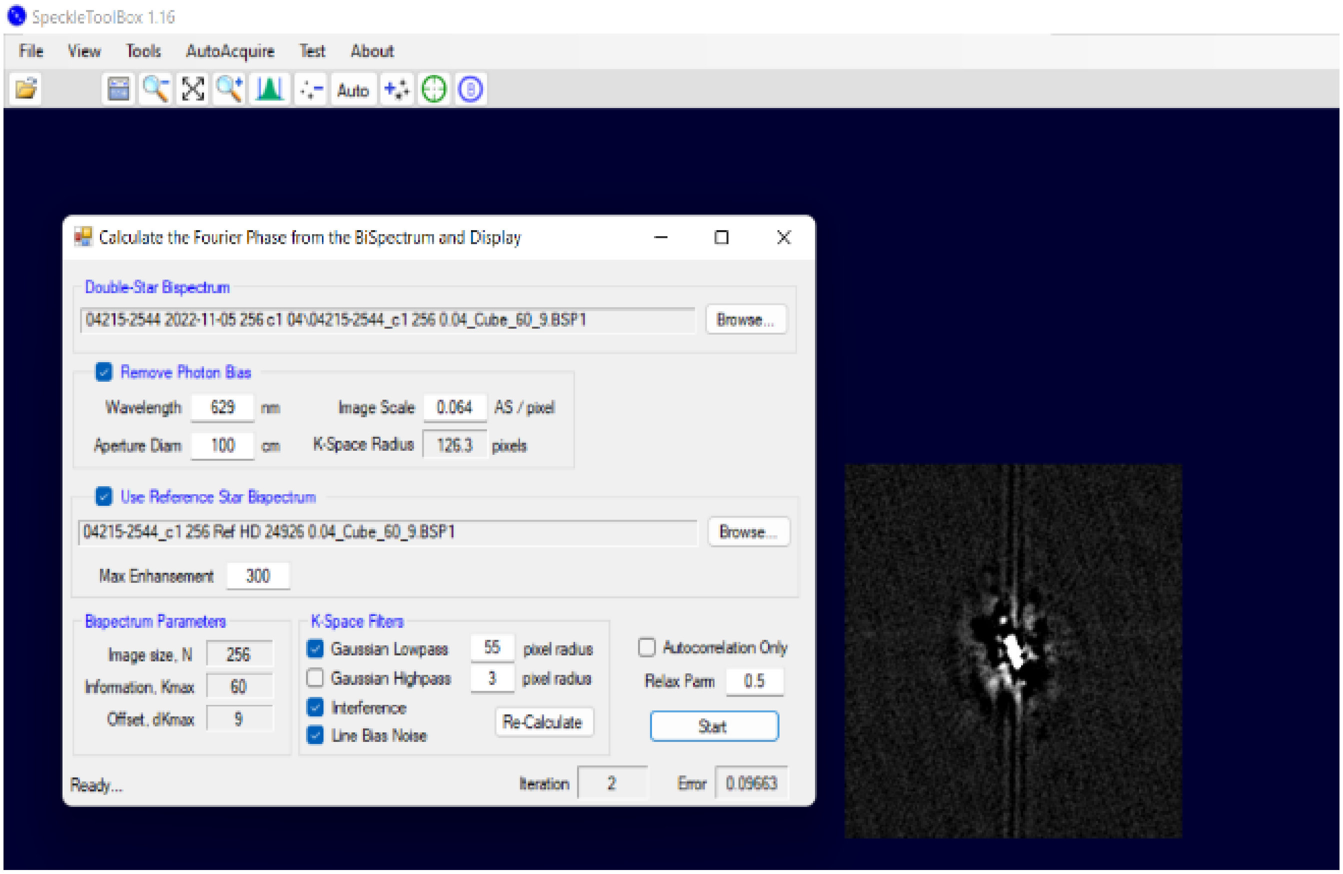


*Figure 2. Example of a short exposure speckle image of WDS 04215-2544.*

The speckle analysis process includes collating thousands of such speckle images and using multiple Fourier transformation steps and correlation to re-construct images. This process effectively removes much of the atmospheric turbulence of an Earth-based telescope system. The re-construction of the optical image comes close to reaching the optical diffraction limit of the telescope, given the telescope's aperture and camera system configuration, with most of the atmospheric turbulence effect removed by the special mathematical processing. The Speckle Toolbox software developed by Dave Rowe (Harshaw et al. 2017) was used to process the speckle images. Astrometric measurements of key binary star parameters were produced including component separation (Rho) and position angle (Theta).



Double-Star Bispectrum: 04215-2544 2022-11-05 256 c1 04\04215-2544_c1 256 0.04_Cube_60_9.BSP1

☑ Remove Photon Bias
Wavelength 629 nm
Image Scale 0.064 AS / pixel
Aperture Diam 100 cm
K-Space Radius 126.3 pixels

☑ Use Reference Star Bispectrum: 04215-2544_c1 256 Ref HD 24926 0.04_Cube_60_9.BSP1
Max Enhansement 300

Bispectrum Parameters
Image size, N 256
Information, Kmax 60
Offset, dKmax 9

K-Space Filters
☑ Gaussian Lowpass 55 pixel radius
☐ Gaussian Highpass 3 pixel radius
☑ Interference
☑ Line Bias Noise

☐ Autocorrelation Only
Relax Parm 0.5

Ready...
Iteration 2
Error 0.09663

*Figure 3: Bi-spectrum Phase Reconstruction of WDS 04215-2544 using the Speckle Toolbox enables special processing of high-resolution imaging at high magnification.*

The main steps and associated equipment involved in the speckle interferometry process are as follows:

**FITS Cube**: A high-speed camera is used to capture short exposure images of the binary star system. These images document the continuous changes caused by air turbulence. The software pulls these images into an overall matrix of all the FITS speckle images.

**Bispectrum Processing**: Double Fourier transform and correlation processing is performed on the acquired speckle images to eliminate the atmospheric turbulence effects, including deconvolution using a single reference star automatically selected during the speckle observing session (Genet et al 2023).

**Bispectrum Phase Reconstruction**: Reconstruction step uses an interactive procedure to reproduce the image.

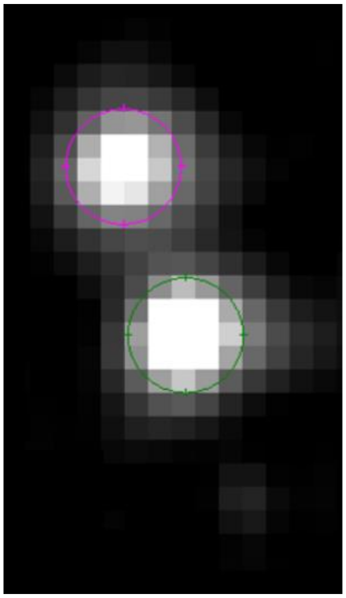


*Figure 4. Final Phase Reconstruction of WDS 04215-2544 showing the Primary A star closest to the middle of the image and the Secondary B star to the top left. A small faint artifact of the Speckle Interferometry process is shown towards the bottom right.*

### WDS 04215-2544

The spectral class of a star is determined by its surface temperature and spectroscopy which categorizes stars into different types represented by letters (Cannon. 1895). The spectral class of the components of a binary star system can vary significantly. Each component star can have its own spectral class.

WDS 04215-2544 was discovered in 1879 by Sherburne Wesley Burnham with a 0.2-meter telescope equipped with a micrometer. Both component stars (Table 1) are F-type stars, and the binary currently has a projected orbital period of 81 years. The key system and component parameters are as follows (Matson et al 2023):

Table 1: Key parameters of WDS 04215-2544

| **WDS 04215-2544** | Value | Spectral Class | Magnitude | Rho $\rho$ " | Theta $\theta^0$ |
|---|---|---|---|---|---|
| 6th Orbit 2022.0 Projection | | | | 0.487 | 243.6 |
| 6th Orbit 2023.0 Projection | | | | 0.5 | 246.4 |
| Primary Star | | F2V | 7.26 | | |
| Secondary Star | | F2V | 6.56 | | |
| Constellation | Eridanus | | | | |
| Discoverer | BU 744AB | | Alternative Names | HIP 20347 | |
| RA (Decimal) | 65.38038 | | Tycho 2 6460-03129-1 | HD 27710 | |
| Dec (Decimal) | -25.72844 | | CP-26 520 | HR 1374 | |
| Distance | 191.64 ly | | CD-26 1642 | ADS 3159 | |

## Instrumentation, Automation, and Methods

Speckle interferometry observations of WDS 04215-2544 were obtained with a PlaneWave Instruments PW1000 telescope with a 1-meter aperture, using the Known Binary Project configuration set up by Hardy et al (2023). The filters (Sloan g', r', z', and i' filters) and the QHY600MM-Pro CMOS camera are installed on their own speckle interference port. The focal length of 12,038 mm provides an image scale of 0.065 arcseconds/pixel. The AltAz telescope's image is stabilized with a field counter rotator that maintains a nearly constant direction with respect to celestial north. Small night-to-night deviations require a plate solution each night to determine the exact camera angle for that night. Software includes Night Imaging 'N' Astronomy (NINA), PWI-4 telescope control software, and a new NINA Speckle Interferometry Plug-in developed by Hardy and Bewersdorff (Hardy et al 2023). A full-frame image is created so that a region of interest (ROI) can be clearly defined around the target. A plate solution from the full frame is used to obtain the plate scale and camera angle for subsequent analysis. The NINA speckle plugin automatically calculates the optimum exposure time for images based on stellar magnitude. After taking 500 speckle images of the target star, the telescope moves to a nearby automatically selected reference star and repeats the whole process; taking 300 images with the same ROI size, before heading to the next target.

## Data

### Past Observations

An amateur astronomer, Robert Burnham was a court recorder in Chicago and searched for new double stars in his spare time. Almost 70 observations of 04215-2544 were made exclusively by refracting telescopes with micrometers between Burnham's discovery in 1879 and 1975. The majority of these observations were made by W. S. Finsen and W. H. van den Bos on the 0.7-meter Union Observatory refractor in Johannesburg, South Africa, and J. G. Voute on the 0.6-m refractor at Bosscha Observatory in Lembang, West Bangdung Regency, West Java. These observations are shown with + in Figure 1.

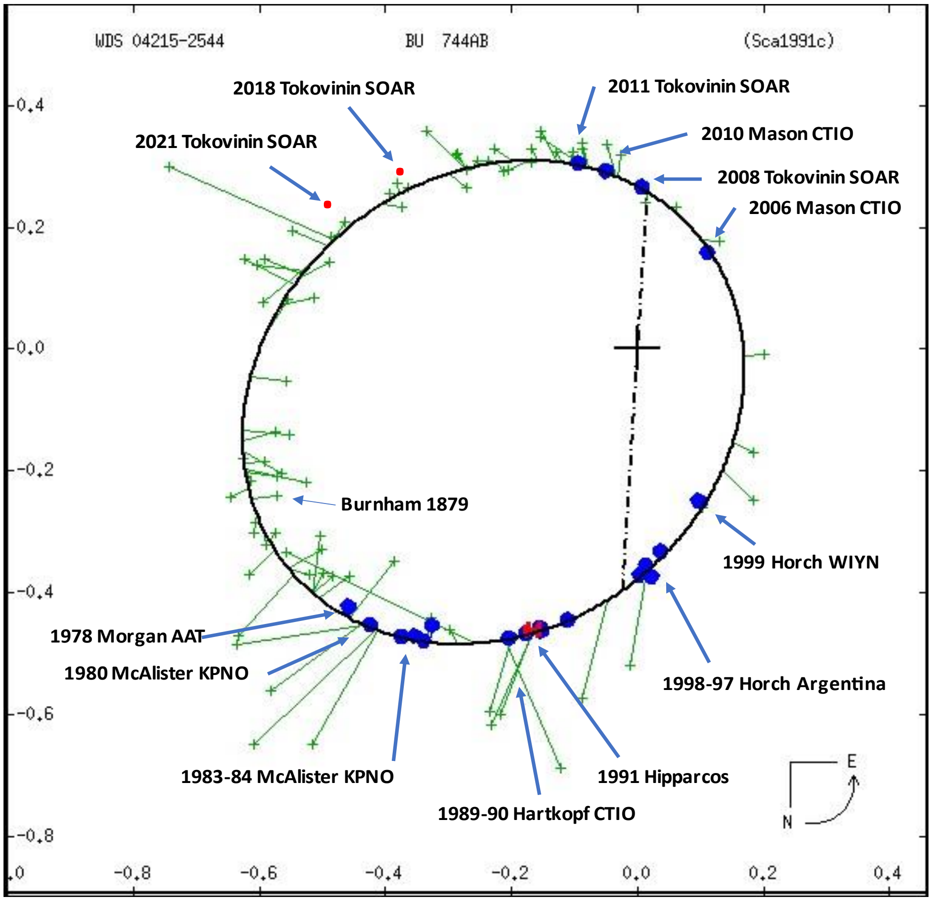


*Figure 5: Orbital plot from the Sixth Catalog of Orbits of Visual Binary Stars (Matson et al 2023). Marco Scardia (1991), a French astronomer, calculated the orbit. We have added annotations and the two dot observations in the top left of Figure 5, using data from the Washington Double Star Catalog (2023) supplied to us by Rachel Matson.*

The first speckle interferometry measurement of this binary was made in 1978 by B. L. Morgan et al (1982) from the Imperial College of Science and Technology in London. Their observations were made on the 3.9-meter Anglo Australian telescope at the Siding Spring Observatory in Australia. When it was commissioned in 1974, it was the largest telescope in the southern hemisphere. Observations were made with a high-speed film camera, while reduction was via a laser that illuminated each of the 500 or so frames.

*Figure 6: The 3.9-meter Anglo-Australian telescope at the Siding Spring in Australia. It was one of the last large telescopes with an equatorial mount. Later large telescopes utilized alt-az mounts as they are much more compact.*

The next speckle observations were obtained in 1980 by Harold McAlister et al (1983) with observations made on 35mm Tri-X film with a high-speed camera while riding in the Cassegrain focus of the 4.0-meter telescope at Kitt Peak National Observatory (KPNO). Similar observations were made in 1989 and 1990 by William Hartkopf et al (1993) with the 4.0-meter Victor Blanco telescope at Cerro Tololo Interamerican Observatory (CTIO) in the Chilean desert. These two 4.0-meter telescopes are twins. Their design and construction were supervised by David Crawford, Assistant Director of KPNO.

The Hipparcos astrometric space telescope was launched by the European Space Agency in 1989 and operated until 1993. It took four years to analyze the data with what was then the world's largest computer complex. The result was the *Hipparcos Catalog* (1997) which contained precise astrometric data (including distances) of over 100,000 stars. One of these was WDS 04215-2544.

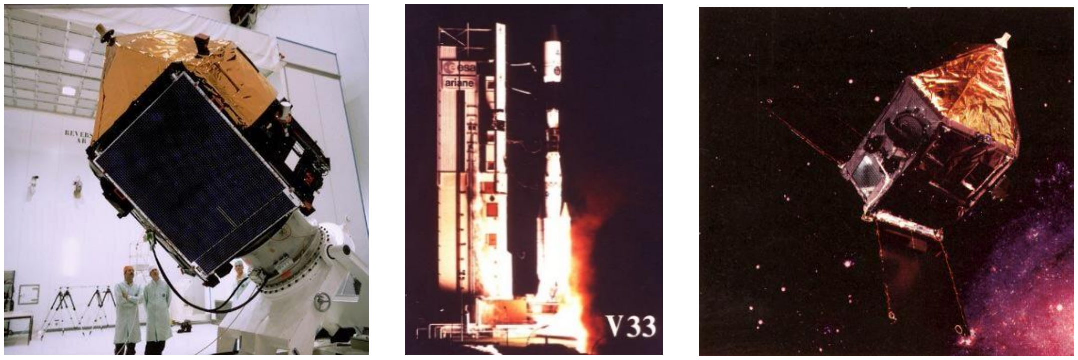


*Figure 7: The Hipparcos space telescope, which was launched in 1989, obtained precise astrometric measurements of over 100,000 stars.*

Elliot Horch made speckle observations in Argentina in 1998-97 and in 1999 with his advanced speckle camera on the 3.5-meter WYIN (Wisconsin, Yale, Indiana, National Optical Astronomy Observatories) located on Kitt Peak (Horch et al.). This pioneering telescope, devised by R. Kent Honeycutt at Indiana University, utilized an alt-az mount and had a thin primary mirror that was warped into exact shape by 66 computer-controlled actuators.

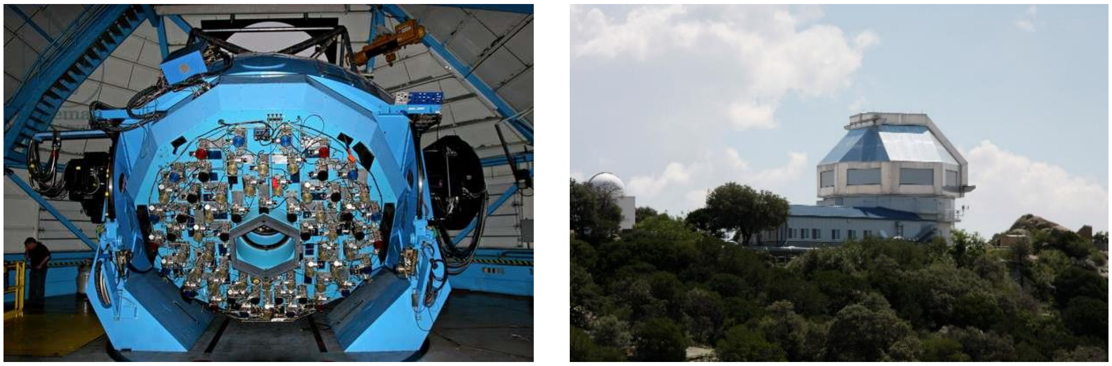


*Figure 8: The rear of the WYIN telescopes is covered with actuators that shape the mirror. The octagon-shaped dome is small for a telescope this size thanks to the alt-az mount and short-focus primary mirror.*

In 2006, Brian Mason et al (2009) used the 4.0-meter telescope at Kitt Peak National Observatory to observe WDS 04215-2544. In 2008, Andre Tokovinin made his first speckle interferometry observation of this binary with the 4.1-meter Southern Astrophysical Research (SOAR) telescope in Chile, located near CTIO. Tokovinin's initial SOAR speckle observations were made with the same, small, front illuminated Andor Luca emCCD camera used by several astronomers on much smaller telescopes.

*Figure 9: The Southern Astrophysical Research (SOAR) telescope in Chile.*

Further speckle interferometry measurements were made in 2010 by Hartkopf et al (2012) and in 2011 by Tokovinin et al (2012). The last two speckle measurements were made in 2018 by Tokovinin et al (2019) and in 2021 by Tokovinin et al (2022). These observations are shown in the top left-hand side of the original plot (Figure ~~1~~5).

## Our New Observation

The equipment and procedures used to obtain our observation have been described in Section 2 and in much detail by Hardy et al. The image in Figure 10 is a full frame, 60-second exposure with the Sloan Red r' filter. Because of the high magnification the field is small, just 10.37 x 6.92 arc-min. The plate scale and plate rotation angle were obtained through a long exposure image analyzed with the Plate Solve application developed by Dave Rowe (Harshaw et al period 2017). As shown in Figure 10, the stars were matched to catalogues, resulting in an image scale of 0.0650″/pixel and a plate rotation angle of 266.656°.

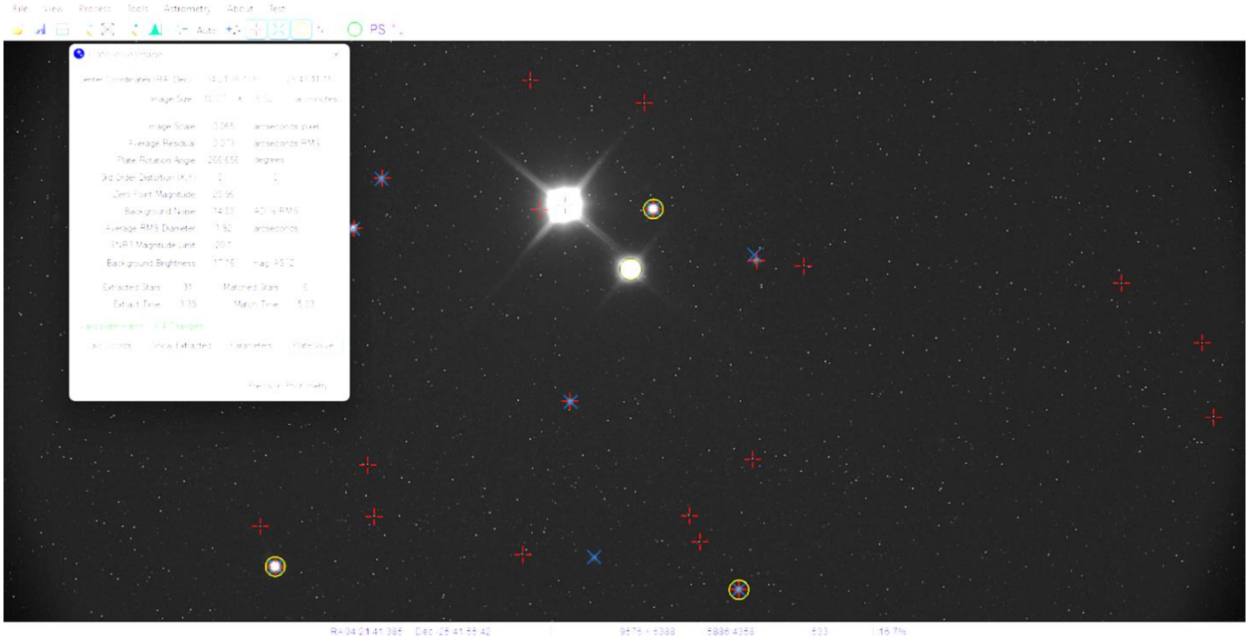
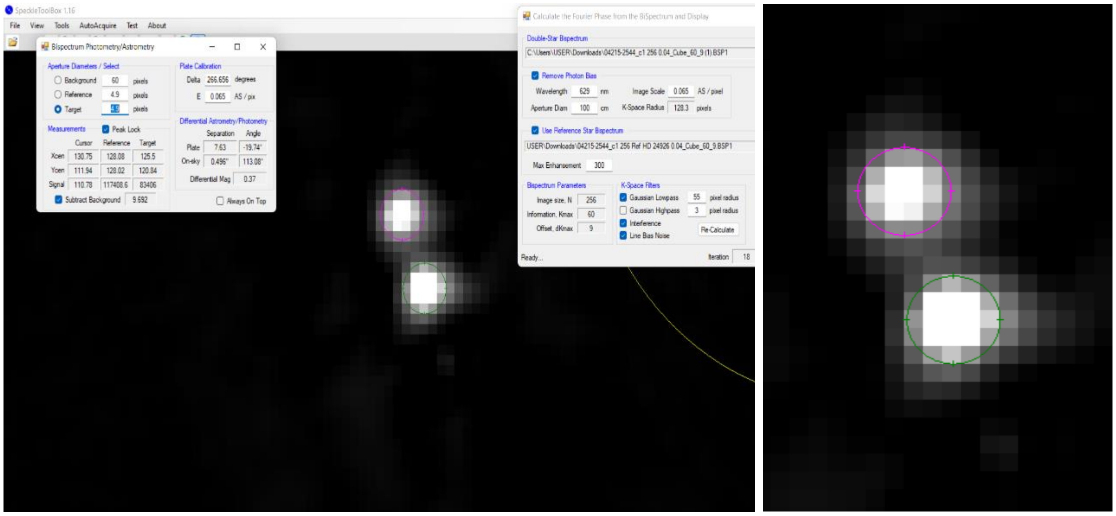


*Figure 10: Plate solution for WDS 04215-2544, BU 744AB obtained 6 November 2022. The seeing (RMS FWHM Diameter) at that time was 1.92 arcseconds. The bright sky background was 17.16 mag per square arc second.*

The final stage of the Speckle Interferometry process is running the bispectrum phase reconstruction or data reduction part of the process, as shown in Figure 11. Figure 11 also shows the measurement results by applying the Astrometry tool in the Speckle Toolbox, with centroids being applied around the component stars and a reference background area. Figure 12 shows the result tables of the measured parameters of the Astrometry Tool (left-hand side), along with the Reconstruction parameters used on the right-hand side.



Bispectrum Photometry/Astrometry

Aperture Diameters / Select
○ Background 60 pixels
○ Reference 4.9 pixels
● Target 4.9 pixels

Plate Calibration
Delta 266.656 degrees
E 0.065 AS / pix

Measurements ☑ Peak Lock

| | Cursor | Reference | Target |
|---|---|---|---|
| Xcen | 130.75 | 128.08 | 125.5 |
| Ycen | 111.94 | 128.02 | 120.84 |
| Signal | 110.78 | 117408.6 | 83406 |

☑ Subtract Background 9.692

Differential Astrometry/Photometry

| | Separation | Angle |
|---|---|---|
| Plate | 7.63 | -19.74° |
| On-sky | 0.496" | 113.08° |

Differential Mag 0.37
☐ Always On Top

Calculate the Fourier Phase from the BiSpectrum and Display

Double-Star Bispectrum
C:\Users\USER\Downloads\04215-2544_c1 256 0.04_Cube_60_9 (1).BSP1

☑ Remove Photon Bias
Wavelength 629 nm
Image Scale 0.065 AS / pixel
Aperture Diam 100 cm
K-Space Radius 128.3 pixels

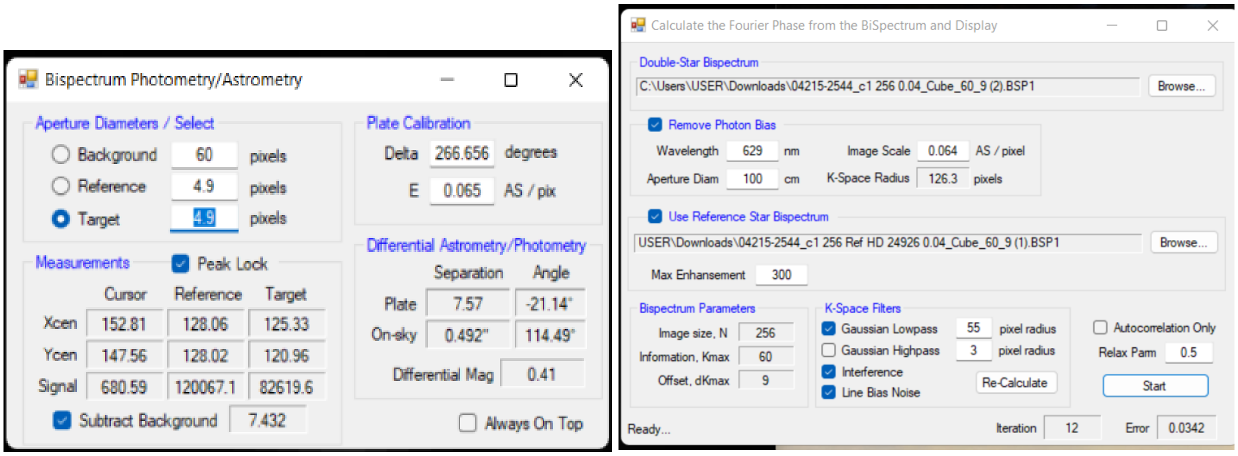
☑ Use Reference Star Bispectrum
USER\Downloads\04215-2544_c1 256 Ref HD 24926 0.04_Cube_60_9.BSP1
Max Enhansement 300

Bispectrum Parameters
Image size, N 256
Information, Kmax 60
Offset, dKmax 9

K-Space Filters
☑ Gaussian Lowpass 55 pixel radius
☐ Gaussian Highpass 3 pixel radius
☑ Interference
☑ Line Bias Noise

Ready...
Iteration 18

*Figure 11: The Speckle Toolbox bi-spectral data reduction provides control and feedback to the user, as well as monitoring of integration and effective bi-spectral convergence results during recovery (Hardy et al 2023) The false autocorrelation lobe disappears. Image on right-hand side is after 18 iterations of the process.*


Bispectrum Photometry/Astrometry

Aperture Diameters / Select
○ Background 60 pixels
○ Reference 4.9 pixels
● Target 4.9 pixels

Plate Calibration
Delta 266.656 degrees
E 0.065 AS / pix

Measurements ☑ Peak Lock

| | Cursor | Reference | Target |
|---|---|---|---|
| Xcen | 152.81 | 128.06 | 125.33 |
| Ycen | 147.56 | 128.02 | 120.96 |
| Signal | 680.59 | 120067.1 | 82619.6 |

☑ Subtract Background 7.432

Differential Astrometry/Photometry

| | Separation | Angle |
|---|---|---|
| Plate | 7.57 | -21.14° |
| On-sky | 0.492" | 114.49° |

Differential Mag 0.41
☐ Always On Top

Calculate the Fourier Phase from the BiSpectrum and Display

Double-Star Bispectrum
C:\Users\USER\Downloads\04215-2544_c1 256 0.04_Cube_60_9 (2).BSP1

☑ Remove Photon Bias
Wavelength 629 nm
Image Scale 0.064 AS / pixel
Aperture Diam 100 cm
K-Space Radius 126.3 pixels

☑ Use Reference Star Bispectrum
USER\Downloads\04215-2544_c1 256 Ref HD 24926 0.04_Cube_60_9 (1).BSP1
Max Enhansement 300

Bispectrum Parameters
Image size, N 256
Information, Kmax 60
Offset, dKmax 9

K-Space Filters
☑ Gaussian Lowpass 55 pixel radius
☐ Gaussian Highpass 3 pixel radius
☑ Interference
☑ Line Bias Noise

☐ Autocorrelation Only
Relax Parm 0.5

Ready...
Iteration 12
Error 0.0342

*Figure 12: The measurement window provides inputs for calibration and measurement apertures, yielding astrometry and photometry results. The primary, secondary and background apertures seen above were manually centered on the image, guided by star centroid indicators when "peak lock" was checked.*

Our repeated manual measurements of the final bispectrum image resulted in the following results for Rho and Theta as shown in Table 2.

Table 2: Our New Observation Results for Rho and Theta

| | **Measurements** | | | | | **Range** | | |
|---|---|---|---|---|---|---|---|---|
| **Researcher** | **Ref Pixels** | **Target Pixels** | **Rho "** | **On-Sky Theta** | **Theta °** | **Stat** | **Rho "** | **Theta °** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| RSC | 4.9 | 4.9 | 0.489 | 113.72 | 246.28 | N | 4 | 4 |
| RSC | 4.9 | 4.9 | 0.492 | 114.49 | 245.51 | Mean | 0.49 | 246.3 |
| RSC | 4.94 | 4.9 | 0.496 | 113.08 | 246.92 | | | |
| RSC | 4.9 | 4.9 | 0.497 | 113.53 | 246.47 | | | |

### Orbital Period

Using much of the recent Speckle data, including our new observation, we re-calculated the estimated orbital period going as far back as we could in whole orbits from the most recent measurement epochs, measuring the epoch back in time where the position angles are next matched. The mean of these results provided a new estimated period of 80.3 ± 0.5 years, slightly shorter than the current 6th Orbit catalog's value of 81.0 years**.**

## Discussion

Our new Rho and Theta measurements plural are in line with the 6th orbit catalog projections as shown in Table 3. After adding our 2022 speckle interferometry observation, shown as the X in the top left of Figure 13, we calculated a possibly slightly shorter orbital period using the latest speckle interferometry results.

Table 3: New Observation Measurements compared with 6th Orbit Projections

| **Measurement Source** | **Theta °** | **Rho "** |
|---|---|---|
| 6th Orbit Projected Ephemeris for 6th Nov 2023 | 246.0 | 0.5 |
| Our New Observation Result on 6th Nov 2023 | 246.3+/0.3 | 0.5+/0.1 |

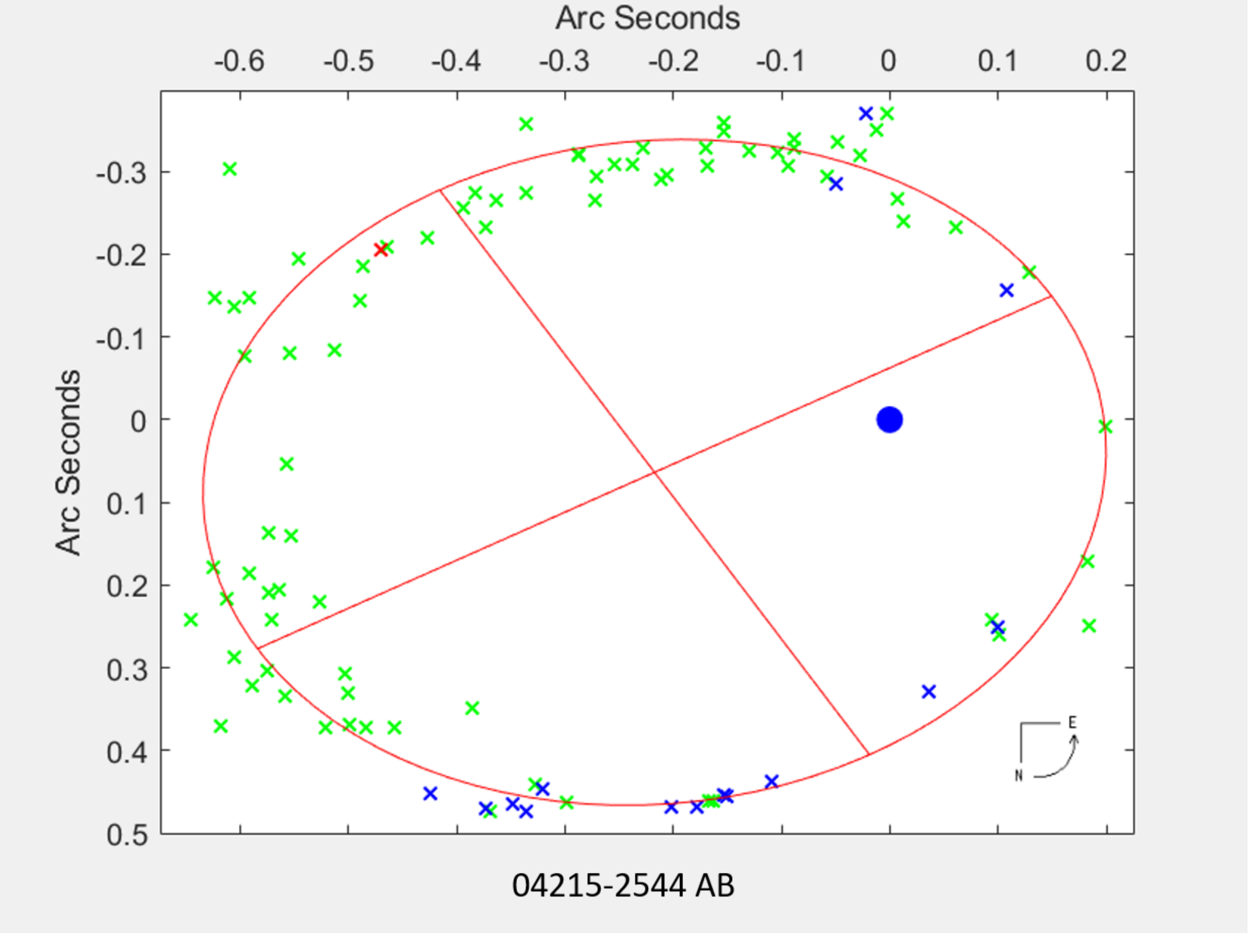


*Figure 13: Our observation, shown as X is near the top left of the image close to the ellipse.*

## Conclusion

In conclusion, our new Rho and Theta measurements are very close to the 6th Orbit Catalog projections, even though the orbit might be slightly shorter overall than older historical data has previously shown.

Given that the measurement results are so close to the 6th Orbit Catalog projections, and the high signal to noise ratio in the reconstructed images, there are clear advantages in using speckle interferometry to measure binary stars with smaller telescopes.

Given the relatively short period of this star system it will be well worth repeating images over the coming years to provide further improved projections of the orbital period.

## Acknowledgements

We are grateful to Mike Selby for granting us access to the 1.0-meter telescope and the El Sauce Observatory and for keeping the telescope in good shape. We also acknowledge the United States Naval Observatory for supplying us with the past data on WDS 04215-2544.

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