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Measuring Close Binary Stars with Speckle Interferometry

12 September 2014

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Astronomical Collaboration

21-23 October 2013 – short-exposure, high-frame rate images of close binary stars

The 2.1-Meter Telescope

Exterior of the 2.1-Meter Telescope

Kitt Peak Observatory

- i' filter – 771 nm
- IFOV = 0.0117"/pixel
- Airy half angle = 0.09"

Russell Genet is an astronomer at California Polytechnic State University and the University of North Dakota

Russell Genet provided the data from 3 binary stars taken on the 2.1-meter telescope

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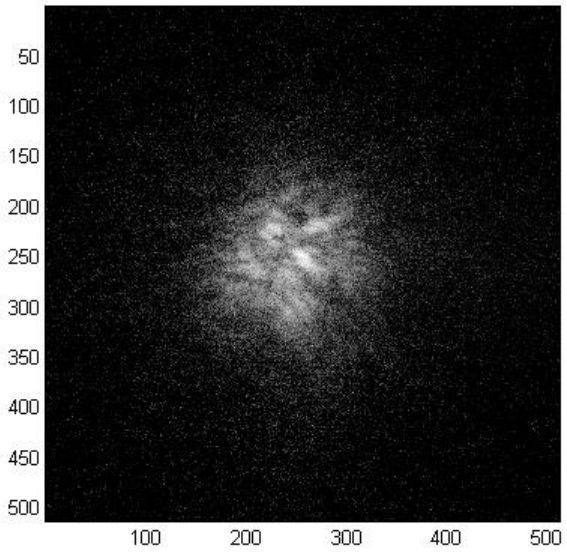
Binary Star Data

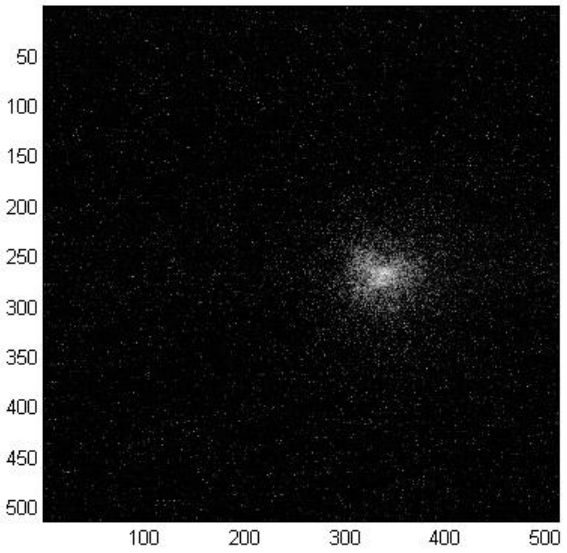
6“



WDS 01017+2518
7.75 m_v + 7.5 m_v

Separation = 0.074”

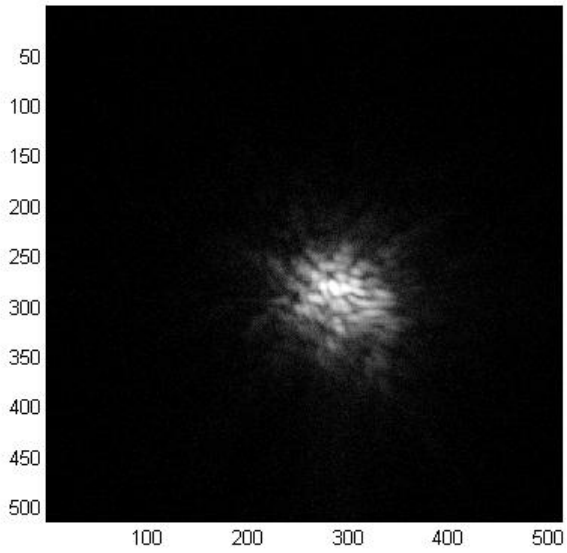
6”



WDS 21399+2737
11.95 m_v + 13.2 m_v

Separation = 0.154”

6”



WDS 23019+4220
3.7 m_v + 6.0 m_v

Separation = 0.191”

Airy Disk half angle = 0.09”

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Speckle Interferometry

Goal of Method

Determine angular separation and orientation of binary star

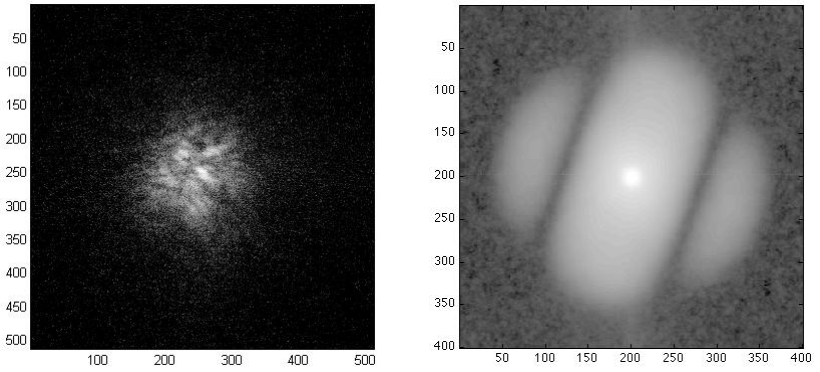
$$f(x) = psf(x - x_0) + a\,psf(x + x_0)$$

$$F(u) = OTF(u)\left(e^{-iux_0} + ae^{iux_0}\right)$$

$$|F(u)|^2 = |OTF(u)|^2\left[(1-a)^2 + 4a\cos^2(ux_0)\right]$$

Labeyrie's Technique (1970)

- Fourier transform each image
- Take square modulus
- Add all squared transforms together
- Measure cosine fringes



Fourier Transform of two identical patterns is multiplied by a cosine squared pattern

Goal of Effort

Automatically measure separation and orientation of cosine fringes

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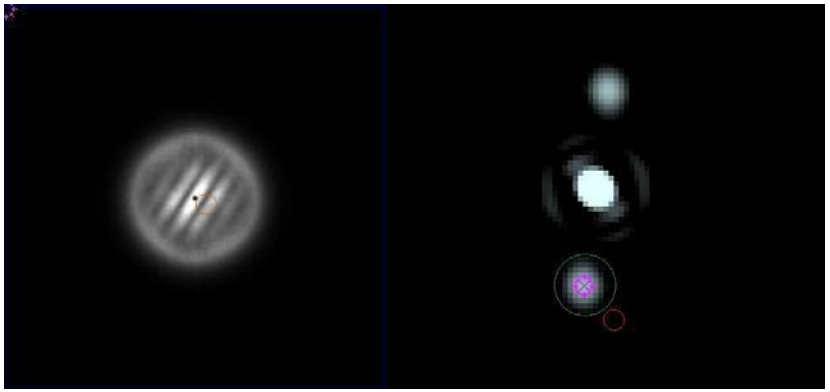
Measuring the Binary Separation

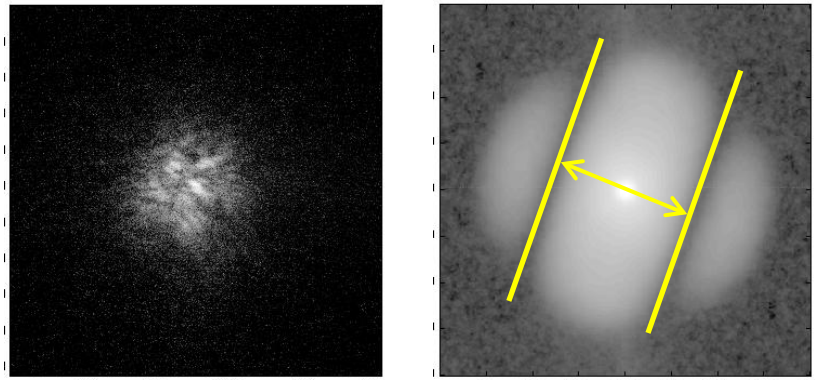
Compute the Autocorrelation



- Fourier transform each image
- Take square modulus
- Block central peak
- Trim outside diffraction limit
- Divide by single star spectrum
- Add all squared transforms together
- Inverse transform for autocorrelation

*Russell Genet, David Rowe, et al. "**Kitt Peak Speckle Interferometry of Close Visual Binary Stars**", Symposium on Telescope Science, Ontario, CA, June 2014*

Measure Fringe Separations



$$fringe\ separation = \frac{1}{star\ separation}$$

Without normalization by single star spectrum – minima and maxima can shift

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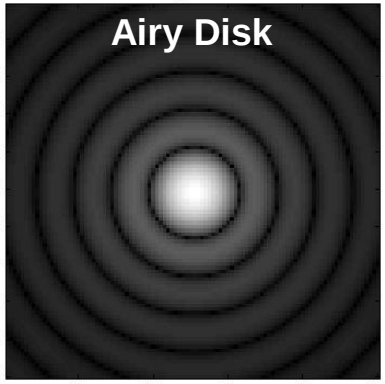
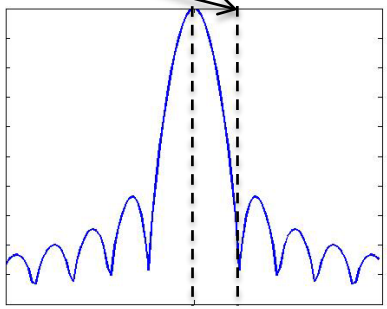
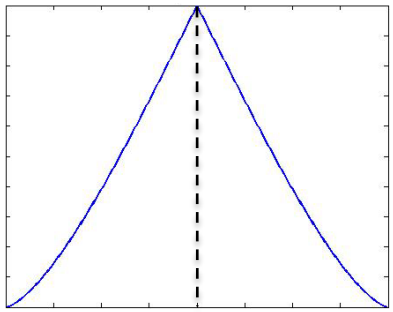
Rayleigh Criterion

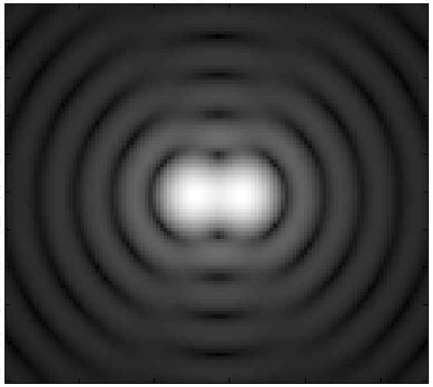


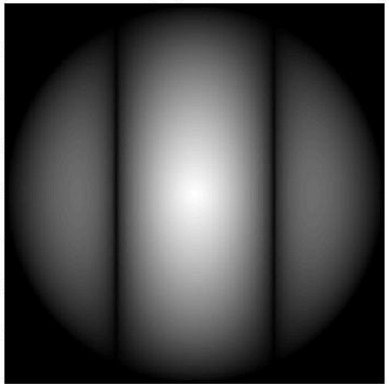
1.22λ/D





D/λ

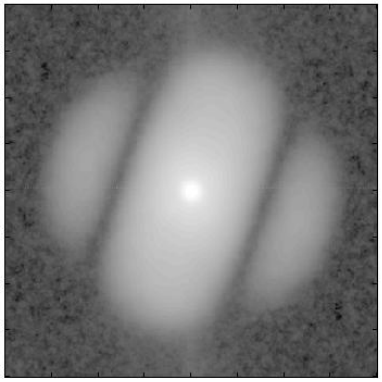




$$\left|F(u)\right|^2 = \left|OTF(u)\right|^2\left[(1-a)^2 + 4a\cos^2(ux_0)\right]$$

$$first\ fringe, \quad u/2\pi = \frac{1}{2}\frac{1}{2x_0}$$

Airy Disk
0.09”



Separation
0.074”

$$separation,\ 2x_0 = 1.22\,\lambda/D$$

$$first\ fringe,\ u/2\pi = \frac{1}{2.44}\frac{D}{\lambda}$$

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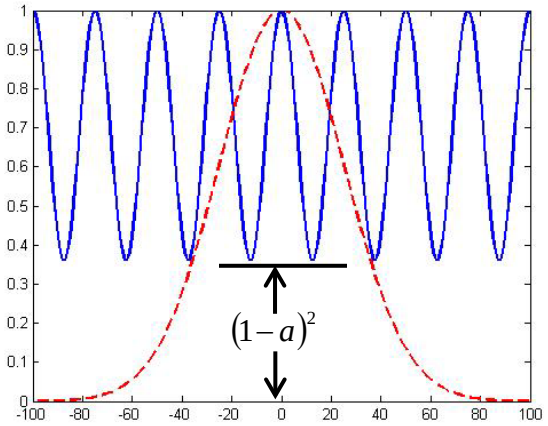
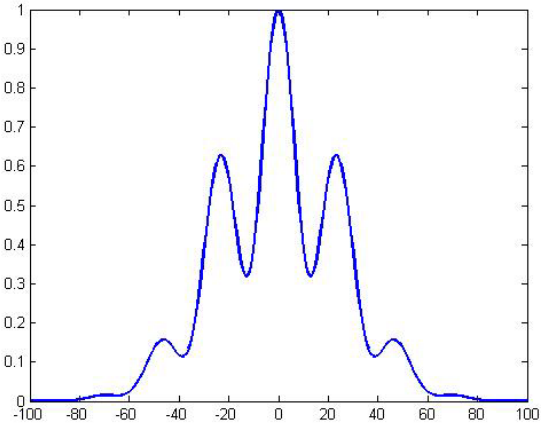
Envelope Causes Fringes to Shift

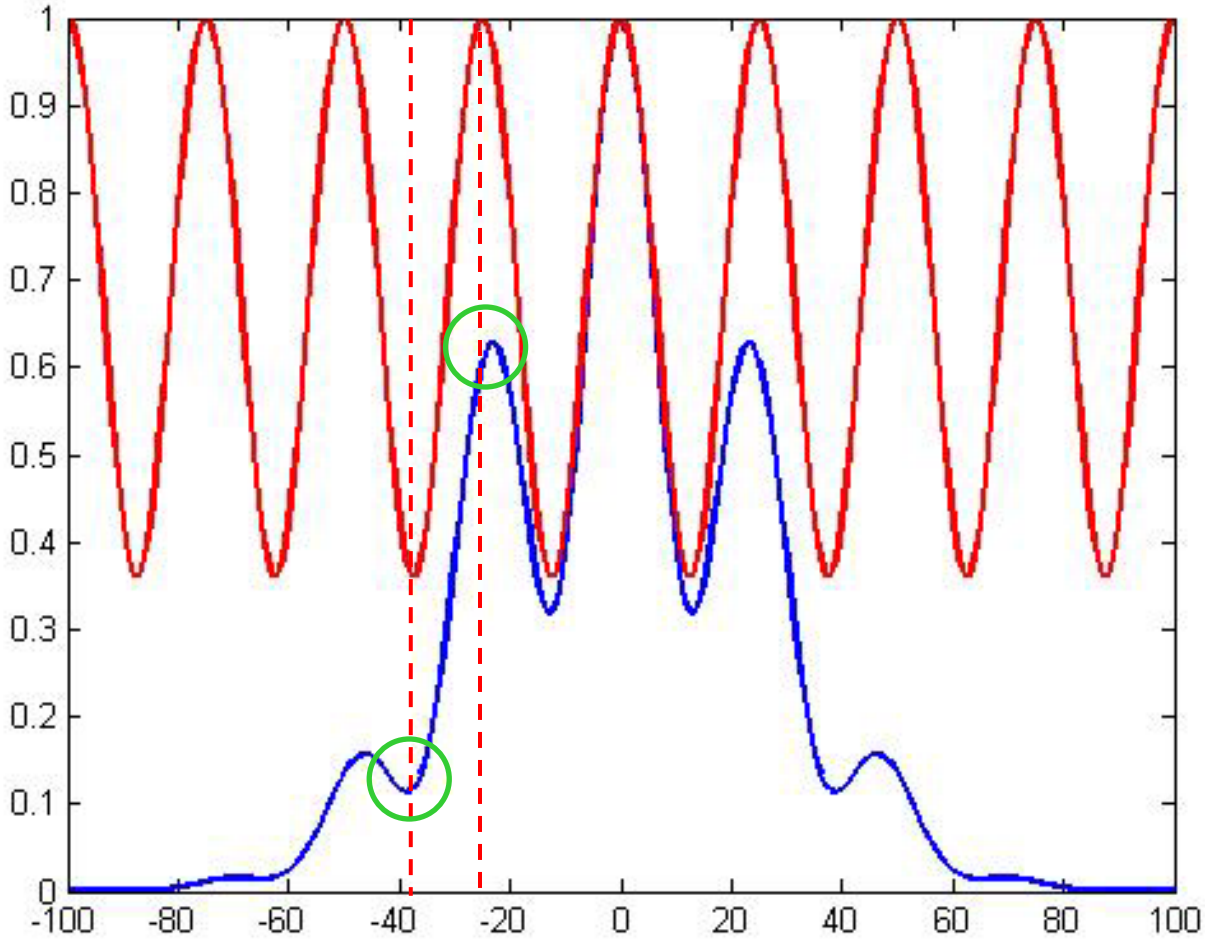
Cosine² and Envelope



No shift in minima when (a == 1)



minima ⟵ ⟶ maxima



Derivatives of the Fringes

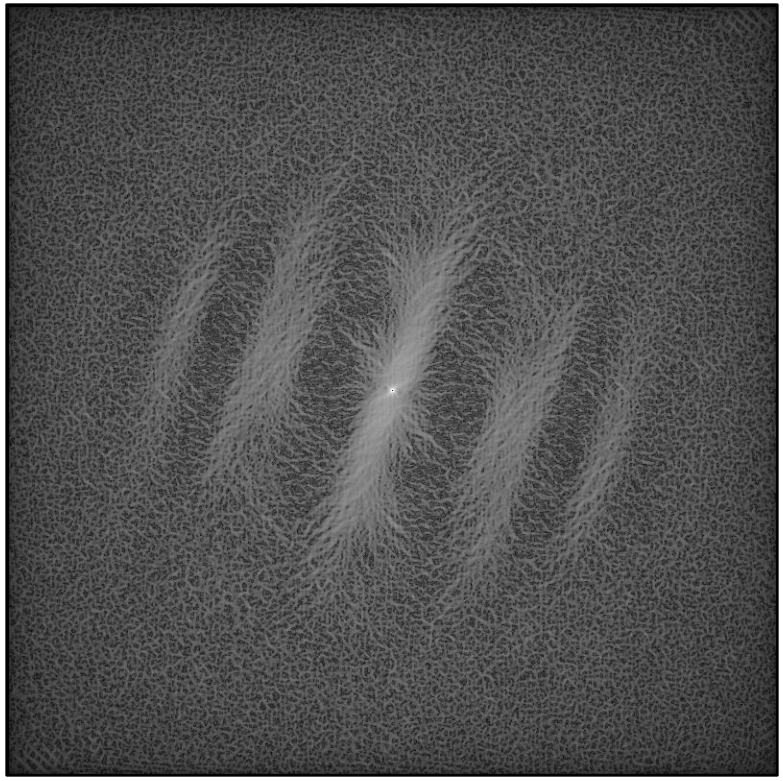
First derivative zero at maxima and minima

$$\left(\frac{\partial}{\partial x}\right)^2 + \left(\frac{\partial}{\partial y}\right)^2 = 0$$

Second derivative > 0 at minima

$$\frac{\partial}{\partial y} > 0, \quad \frac{\partial}{\partial x} > 0$$

Autocorrelation of second derivative produces fringes



Autocorrelation of second derivative

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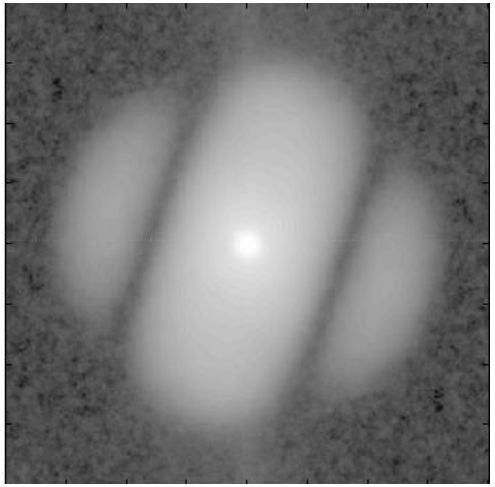
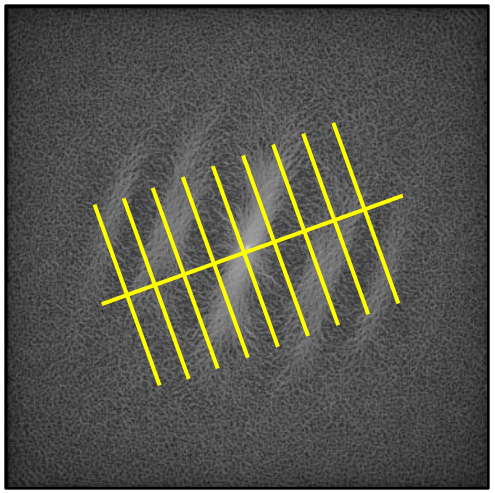
Automatic Method to Locate the Fringes

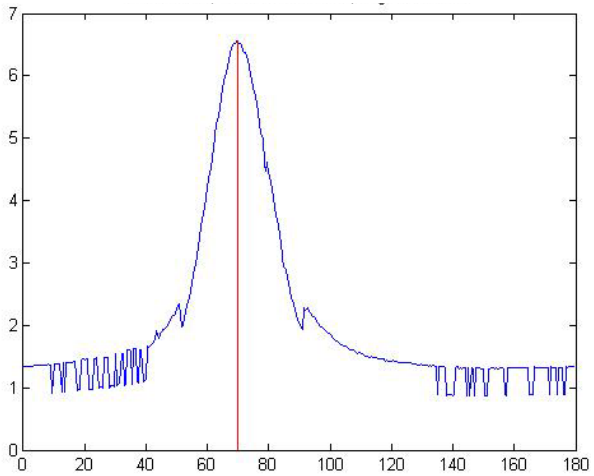
Fringes



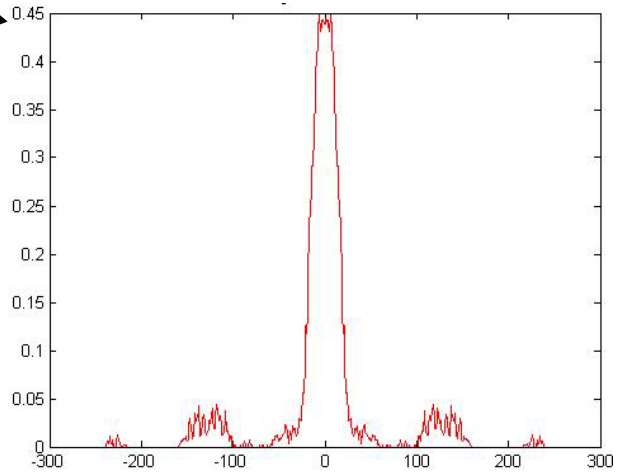
Integrate 2nd Derivative



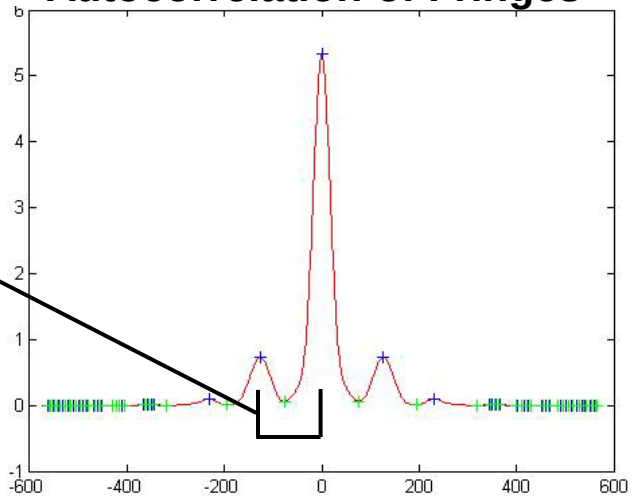
Angle of Max Modulation



Integrated Fringes



Autocorrelation of Fringes



Fringe Separation

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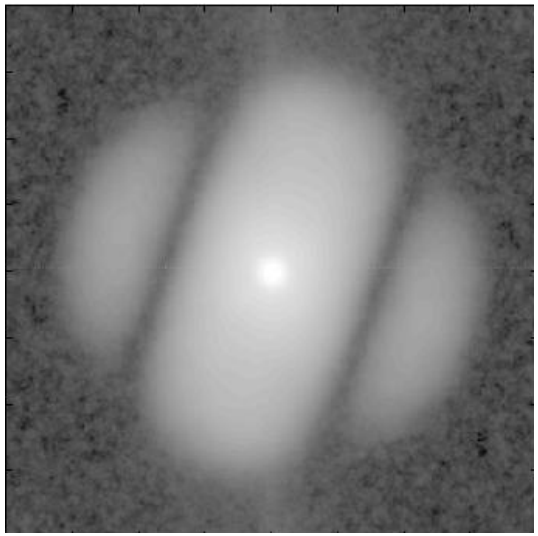
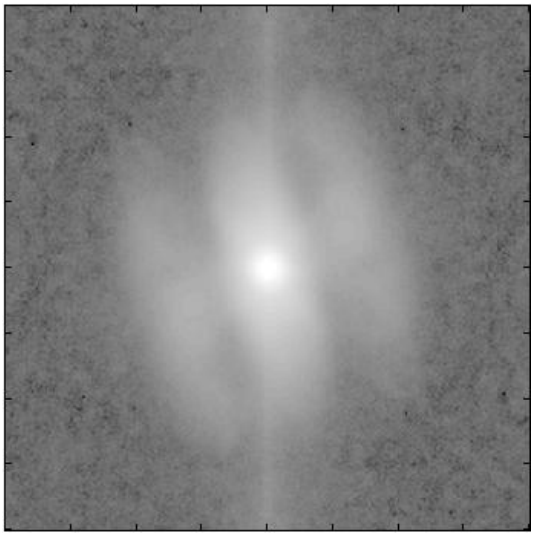
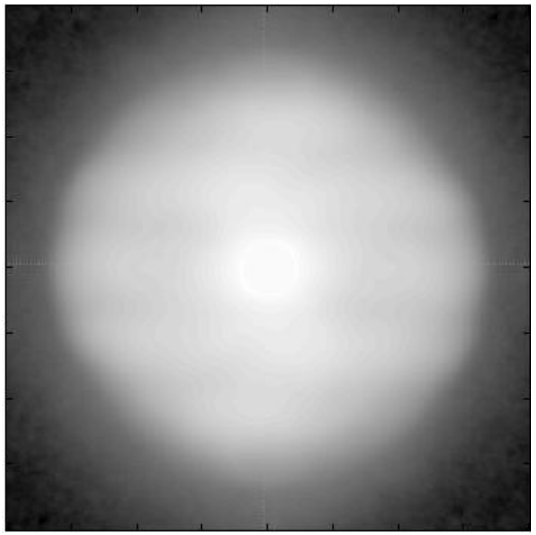
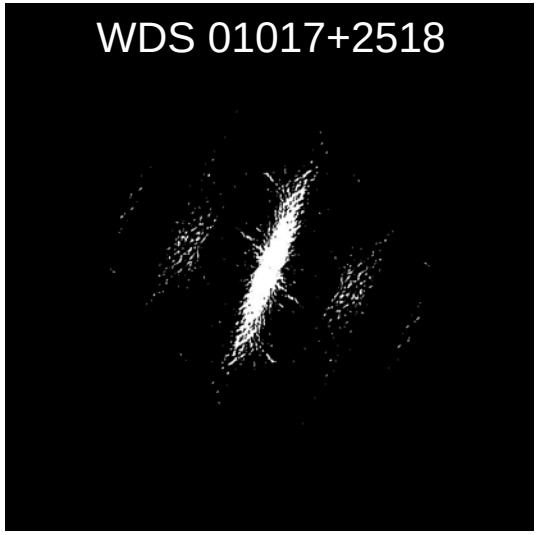
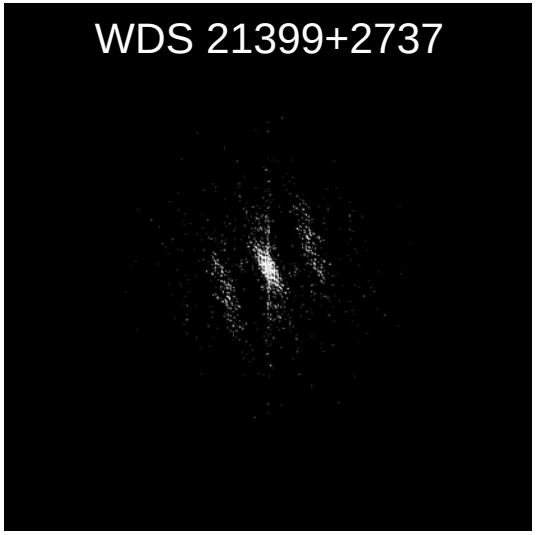
Results of Fringe Detection











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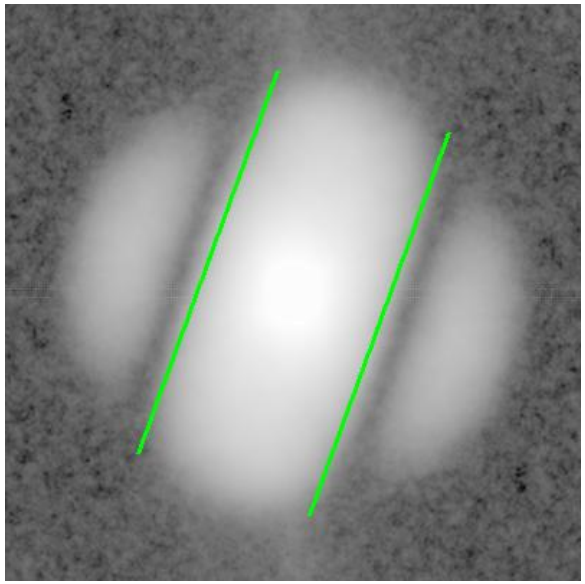
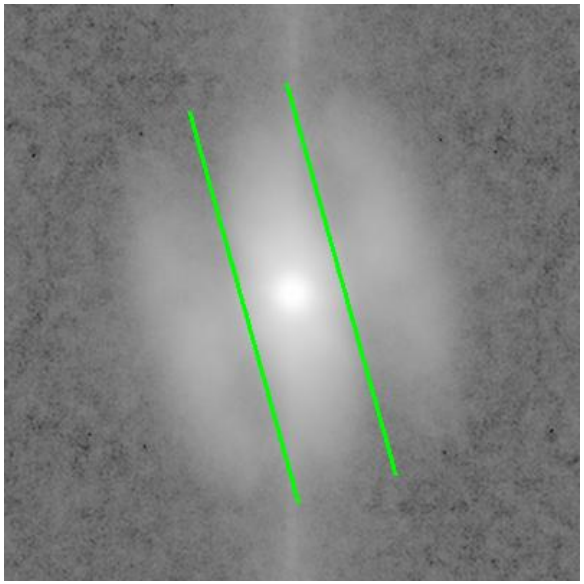
Measured Fringe Spacings Underestimated



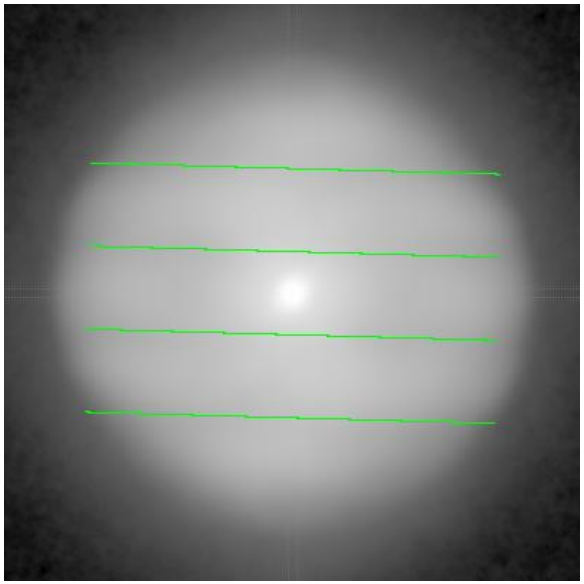
Measured = 0.095”

Published = 0.074”



Measured = 0.17”

Published = 0.154”



Measured = 0.208”

Published = 0.191”

Underestimated fringe spacings leads to slightly overestimated binary separations

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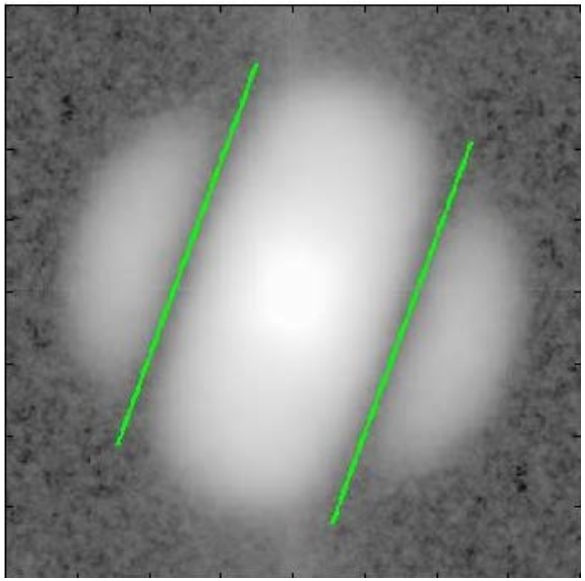
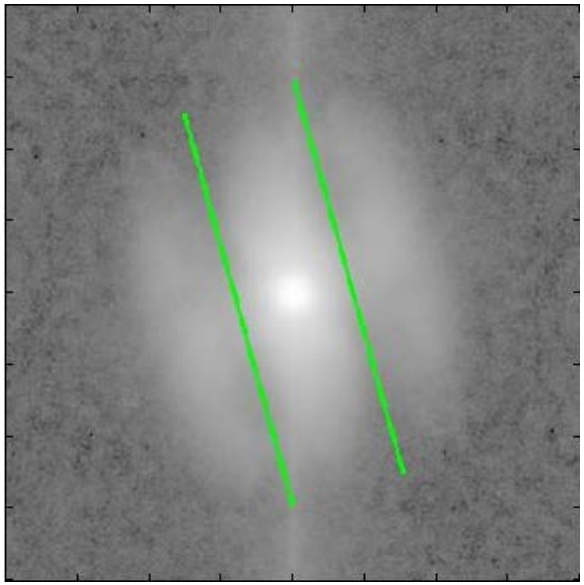
Fringe Spacings Manually Estimated



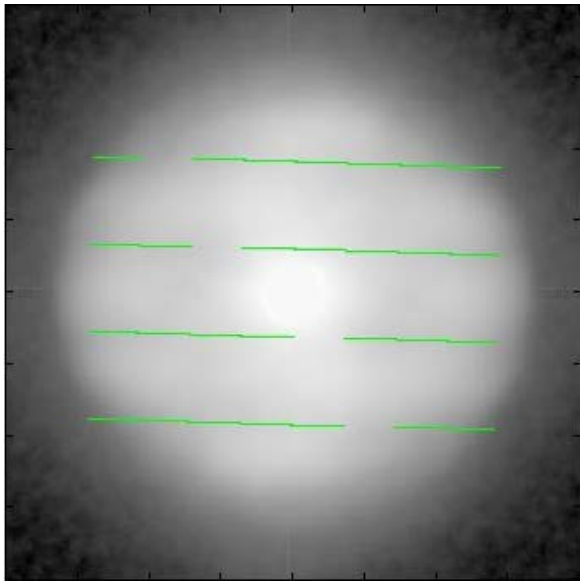
Measured = 0.075”

Published = 0.074”



Measured = 0.150”

Published = 0.154”



Measured = 0.196”

Published = 0.191”

Fringe spacings estimated by searching for minimum around original estimation

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Summary

- **Automatic fringe detection, based on regions where 2nd derivative is > 0**
- **Binary star separation estimates are slightly larger due to shifts in extrema and inflection points**
- **Analysis of systematic errors is underway**

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