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Binary Star Observations in Selected Instants of Good Seeing

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Abstract: Video recordings of images of binary stars at the focus of a 0.36 m telescope have been used to select images recorded in instants of good seeing. The selected images have been analysed to give separations and position angles for the binary systems which are in good agreement with values predicted from previous observations. In these exploratory observations it has been shown that separations of 0.9 arcseconds can be measured with an accuracy of ~2% and position angles to ~1–2 degrees when the average seeing was ~1.3 arcseconds. These observations demonstrated that the diffraction limit of the telescope could be reached when the seeing was a factor of 2–3 greater than it. A binary with three magnitudes difference in the brightness of its components has been measured with comparable accuracy although difficulties are anticipated for binaries with components closer than ~2 arcseconds with this magnitude difference. The limiting magnitude is determined by the need to limit exposure times of individual frames to be comparable with or less than the atmospheric coherence time.

Keywords: atmospheric effects — stars: binaries — techniques: image processing

1 Introduction

The images produced at optical wavelengths by telescopes with aperture diameters greater than a few centimetres are generally distorted as a result of turbulence in the Earth's atmosphere. The magnitude of the image distortion, known as *seeing*, is a function of site, meteorological conditions, and time, and generally limits the angular resolution of a telescope. For telescopes with aperture diameters much larger than r_0, the coherence length of the distorted wavefront (Fried 1966), short exposure images consist of a number of 'speckles'. Each speckle has dimensions of the order of the Airy disk corresponding to the full aperture of the telescope convolved with the intensity distribution of the source. Speckle interferometry (Labeyrie 1978) uses Fourier techniques to process short exposure images consisting of multiple speckles to extract angular information on single and binary stars. However, it is well known that for modest sized telescopes there are moments of excellent seeing when the images approach the diffraction limit of the telescope even when the average seeing is poor, and Fried (1978) has analysed the probability of getting a 'lucky' short-exposure image in terms of the aperture D of the telescope and r_0. Visual observers of binary stars take advantage of these moments of good seeing and instruments have been developed to do the same.

Dantowitz (1998) has demonstrated that moments of good seeing giving near diffraction limited images can be selected from high quality video recordings made at the foci of modest size telescopes. Dantowitz describes observations made with telescopes with apertures in the range 0.3 m to 0.6 m and presents a number of resolved images including Jupiter's moons, a binary star, and a composite image of a space shuttle recorded in daylight.

We have made some preliminary observations using the technique described by Dantowitz to explore its potential for binary star observations to complement the programme of the Sydney University Stellar Interferometer (SUSI) (Davis et al. 1999a; 1999b). Some of the binary systems to be included in the SUSI programme have faint companions and, in planning the SUSI observations, it is desirable to know where these companions lie with respect to the binary systems being studied, and accurate separations and position angles are not always available in the literature. Our motivation in exploring this technique was to see if it was a viable method for determining this information.

2 Instrumentation

The telescope employed was a 0.36 m Celestron Schmidt Cassegrain carried on a custom built altazimuth mount. A 2× Barlow lens was employed to give an effective focal length of 7.82 m for the telescope–Barlow combination. An Astrovid 2000 low light, black and white CCD video camera was mounted at the focus giving a field of view of 210 × 170 arcseconds. The camera has 811 horizontal and 508 vertical picture elements resulting in a scale of four picture elements per arcsecond horizontally and three per arcsecond vertically. The choice of scale was a compromise between resolution, which requires a large number of picture elements per arcsecond, and sensitivity, which requires a minimum number of picture elements per stellar image. Images of selected binary systems were recorded continuously on Fuji Super-VHS video tape with a JVC Super-VHS VCR. During observations the images were displayed on a TV monitor but the selection of high quality images was carried out post observations in the laboratory.

3 Observations

For the purpose of the investigation a number of known binary systems were selected to give a range of angular

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Table 1. Binary stars observed in the programme

HR	Star	V	ΔV	Spectral class	VR	Δt (ms)	Images
1879/80	λ Ori	3.66	1.90	O8e + B0.5V	1	1	30
3890/1	υ Car	2.96	3.07	A8Ib + A8Ib	1	1	29
4057/8	γ Leo	1.98	0.03	K1-IIIbCN-0.5 + G7IIICN-1	1	1	48
4730/1	α Cru	1.58	0.51	B0.5IV + B1V	1	0.5	62
4819	γ Cen	2.17	0.1	A1IV	2	1	43
4844	β Mus	3.05	0.2	B2.5V	3	1	67
5459/60	α Cen	−0.01	1.34	G2V + K1V	11	0.1	458
5605/6	π Lup	4.72	0.10	B5V + B5IV	3	2	56

The three right hand columns give the number of ~5 minute video recordings made for each star (VR), the exposure times of individual video frames, and the total number of single frame images selected from the recordings (Images). Further information is given in the text.

separations and of magnitude differences between the component stars. The programme systems are listed in Table 1 together with details of the observations made of each system. The visual magnitudes (V), magnitude differences between the components (ΔV), and spectral classes in Table 1 have been taken from the Bright Star Catalogue (Hoffleit 1982). The exception is γ Leo for which V and ΔV have been taken from Lanz (1986). The V magnitudes are those of the primary component, except for γ Cen and β Mus, where it is the combined magnitude (separate magnitudes were not available).

α Cen was included in the programme to provide a calibration of the angular scale and origin for position angle determinations in the recorded images. It was chosen as the calibrator because its separation and position angle are well-known and, as a result of its ~80 year period, changes in them are negligible during the observing period. The relatively large separation of ~14 arcseconds at the epoch of the observations enabled an accurate calibration to be carried out, and this is discussed in Section 4.1.

Observations were made on the nights of 17 and 18 February 2000. Calibration observations of α Cen were made at the start, in the middle, and at the end of each night. The TV monitor displaying the video output of the camera was used during the observations to facilitate acquisition and centring of the binary images on the camera. Each observation consisted of a ~5 minute video recording, the duration based on trial runs and chosen to give an average of ~30 acceptable images. The mean time of each observation was recorded to allow the determination of the hour angle so that the field rotation angle, resulting from the use of an altazimuth mount, can be calculated.

The Astrovid camera controller allowed exposure times of individual frames in the range 0.1 to 16 ms to be selected. Exposure times as short as possible, consistent with obtaining images of both components, were selected to minimise temporal blurring of the images and depended on the brightness of the components. Thus, exposure times of individual video frames were in the range 0.1 to 2 ms and the exposure times used for each binary system are listed in Table 1.

4 Analysis

The selection of acceptable images was carried out by viewing the video tape on a TV monitor, stepping through it frame by frame. A frame was regarded as acceptable if the components of the binary star were clearly visible with little or no smearing. Each selected frame was digitised using a frame grabber and stored as a JPEG image file. Acceptable frames appeared singly amidst frames blurred by seeing. Figure 1 shows a sequence of five consecutive video frames showing images of α Cen illustrating the typical rapid variations in image quality due to seeing effects. The individual exposures were of 0.1 ms duration and only the central exposure was regarded as acceptable for analysis.

The JPEG image files were converted to FITS format and the Meade IP2000 image processing software package was used to obtain pixel values of the centroids of the images of the component stars in each image file. A limitation of this approach was the need to have non-overlapping images for the determination of the individual centroids. The resulting horizontal and vertical pixel positions of the components in each image must be converted to the conventional visual binary parameters of separation ρ and position angle θ (Heintz 1978). For this the angular scales in the horizontal and vertical directions and the orientation of the meridian relative to the frame are needed. Ideally the angular scales would be identical in the horizontal and vertical directions. However, because the pixels on the CCD chip are rectangular, and the digitising transforms the pixel scales, and the image processing software assumes the pixels are square, a calibration of the relative magnitudes of the horizontal and vertical scales is required. The orientation of the meridian relative to the frame depends on the orientation of the camera on the telescope, and this also requires calibration.

4.1 Calibration

The calibration of the angular scale and orientation of the meridian relative to the video frames was carried out with the observations of the α Cen binary system.

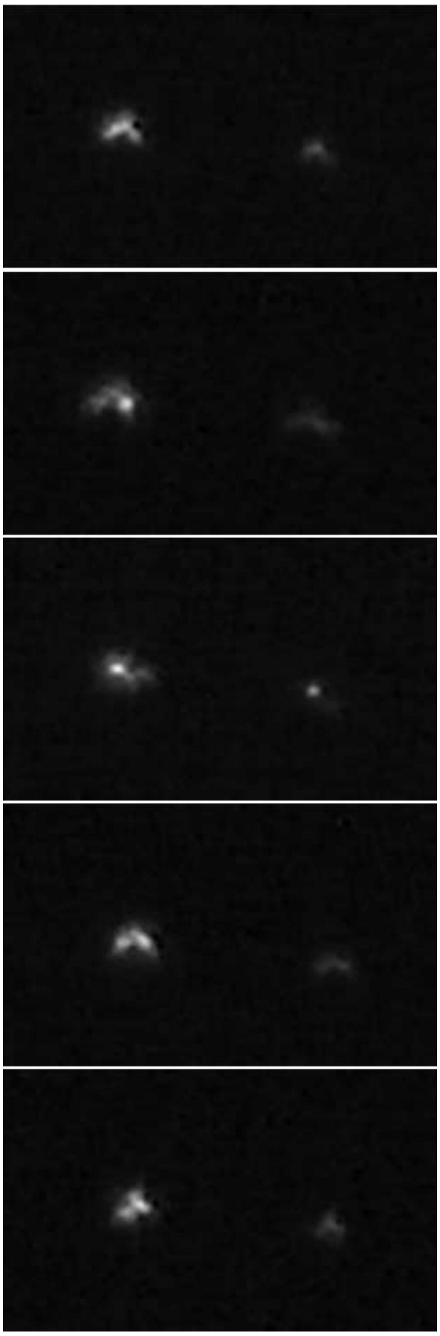

Figure 1 A 200 ms sequence of images of α Cen illustrating the effects of seeing variations. Each image had an exposure time of 0.1 ms with 40 ms between exposures. The separation of the component stars was 14.1 arcseconds.

Pourbaix, Neuforge-Verheecke & Noels (1999) have published the most comprehensive analysis of visual and spectroscopic observations for the orbital parameters of the α Cen system and, based on them, the separation of the components of α Cen was 14.08 arcseconds and the position angle was 222.43 degrees at the time of the observations (17–18/2/2000). Because of the long period of the α Cen system (79.90 years), the separation changes by only 0.002 arcseconds per day and the position angle by 0.003 degrees per day, and these changes can be ignored.

In principle, the known separation and position angle for the α Cen system combined with the hour angles for the observations of the system are sufficient for the determination of the horizontal and vertical angular scales and the orientation of the meridian. However, the transformations from the camera video frames to the final image frames is dependent on unknowns in the digitising and image processing software and therefore an independent but direct calibration of the relative angular scales in the horizontal and vertical directions was carried out. This was achieved in the laboratory with the aid of a mask consisting of a five-by-five grid of pinholes with 5 mm horizontal and vertical spacings drilled in a thin aluminium plate. The mask was illuminated with collimated light and imaged onto the camera's CCD chip using only the central part of an achromatic lens with a maximum off-axis angle of <2 degrees. This arrangement ensured that only paraxial rays were used and eliminated potential field distortion due to the imaging lens. The resulting array of images was recorded and digitised in exactly the same way as the stellar images and, in combination with a survey of the centres of the pinholes in the mask made with a travelling microscope, was analysed to give the scaling factor that had to be applied to the vertical pixel difference. This scaling factor, which was determined with an accuracy of $\pm 0.05\%$, ensures that the horizontal and vertical angular scales are identical.

The separation of the components of α Cen, after the correction had been applied to the vertical pixel difference, was found to be 60.01 ± 0.05 pixels. Thus, for the known separation of 14.08 arcseconds, the scale of the corrected images is 4.262 ± 0.004 pixels per arcsecond on the sky. The uncertainty reflects only the uncertainty in the calibrated ratio and does not include allowance for any uncertainty in the separation of the components of α Cen. It is emphasised that this scale applies to the image pixels only and differs from the camera pixel scales due to the transformation of the scales in the digitising process.

The image coordinates in each selected frame enable the 'image' angle from the primary to the secondary to be determined. This angle is the sum of three component angles — the position angle, the field rotation angle due to the altazimuth mount, and the misalignment angle between the meridian and the vertical axis of the frame when the telescope is pointing at the meridian. For each frame the field rotation angle was computed and combined with the position angle and the measured image angle to determine a value for the misalignment angle. The average of the values for the misalignment angle was found to be 358.4 ± 0.3 degrees.

4.2 *Results*

The vertical pixel differences for the components of all the programme systems were corrected as described in the previous section and the separations and position angles were determined for each image frame. The mean calibrated separations and position angles for the programme stars are listed in Table 2. α Cen is not included in Table 2

Table 2. Observed and predicted separations ρ and position angles θ for the programme stars

HR	Star	Observed		Predicted	
		$\rho \pm \Delta\rho$	$\theta \pm \Delta\theta$	$\rho \pm \Delta\rho$	$\theta \pm \Delta\theta$
1879/80	λ Ori	4.37 ± 0.07	44 ± 1	4.3 ± 0.1	43 ± 1
3890/1	υ Car	4.96 ± 0.04	129 ± 1	4.9 ± 0.1	128 ± 2
4057/8	γ Leo	4.61 ± 0.03	126 ± 1	4.6 ± 0.1	125.2 ± 0.3
4730/1	α Cru	3.89 ± 0.07	114 ± 1	4.0 ± 0.1	113 ± 1
4819	γ Cen	0.89 ± 0.02	347 ± 2	0.9 ± 0.1	347 ± 2
4844	β Mus	1.06 ± 0.10	40 ± 2	1.2 ± 0.1	40 ± 1
5605/6	π Lup	1.58 ± 0.02	71 ± 2	1.6 ± 0.1	66 ± 1

The units for ρ and $\Delta\rho$ are arcseconds and for θ and $\Delta\theta$ degrees.

since it was used for the calibration. The uncertainties are those calculated from the scatter in the values determined from the individual image frames. In the case of the position angles, the uncertainty in the camera alignment has been taken into account in the listed uncertainties. For both the separations and the position angles the uncertainty in the scaling of the vertical pixel differences and in the angular scale are negligible compared with the statistical uncertainties. However, the results are all subject to any systematic error in the values for the separation and position angle of α Cen. These are believed to be small compared with the listed uncertainties, judging from the uncertainties in the orbital parameters of α Cen given by Pourbaix et al. (1999). Predicted values for the separations and position angles of the programme stars are also included in Table 2. These have been extrapolated from existing data on the systems provided by Brian Mason of the United States Naval Observatory, from The Washington Double Star Catalog and from the Fifth Catalog of Orbits of Visual Binary Stars.

5 Discussion

The effective wavelength of the observations was ~700 nm, and Johnson R magnitudes would be more appropriate than the V magnitudes listed in Table 1 for discussing the results. However, R magnitudes are not available for the individual component stars except for γ Leo. The binaries included in the programme have components of similar spectral class and it follows that the ΔR values will generally be the same as the ΔV values or nearly so. Furthermore, estimates of the R magnitudes determined from $(V - R)$ colour indices obtained from a plot of $(V - R)$ versus $(B - V)$ for single stars, using the known $(B - V)$ values, shows that the R magnitudes for the programme stars in general show only small differences from the V magnitudes in Table 1. The results will therefore be discussed in terms of the V magnitudes.

Inspection of the data in Table 2 shows that the agreement between the measured values and the predicted values for separation and position angle is generally excellent. Agreement is within the uncertainties except for the position angle of π Lup which shows a difference approaching twice the sum of the individual uncertainties. We note that π Lup was the faintest system observed by more than a magnitude but have no explanation for the apparent discrepant result. The values for the position angle obtained from the selected images for the three separate observations were self consistent.

Figure 2 A sample image of γ Cen, the binary system with the smallest separation included in the programme. The angular separation of the components was found to be 0.89 ± 0.02 arcseconds on a night when the average seeing was 1.3 arcseconds.

The binary system with the closest separation was γ Cen (0.89 ± 0.02 arcseconds) and a sample image is shown in Figure 2. The two components are well resolved. The diffraction limit for the 0.36 m Celestron telescope for the effective wavelength of ~700 nm is ~0.5 arcseconds, and inspection of Figure 2 indicates that the diffraction limit could be very closely approached by the technique. The software used in the present image analysis, requiring non-overlapping images for determining the individual image centroids, would prevent the measurement of separations close to the diffraction limit and this is an area where an improvement could be made by the development of more sophisticated software to handle overlapping images.

SUSI observations include measurements of the average seeing and also provide values for the spatial and temporal scales of wavefront distortion at a wavelength of ~440 nm. Unfortunately there was only a small overlap in time with SUSI observations but the average seeing parameters on the second night of observation (18 February 2000), taken from SUSI records, were 1.3 arcseconds and 2 ms for t_0 as defined by Buscher (1994). The observations of γ Cen, which were made on the night of 18 February 2000, clearly do significantly better than the average seeing for the night and indicate the potential of the technique.

The separations of some of the wider spaced binaries in the programme, and certainly for α Cen, exceeded the isoplanatic patch size, meaning that the images of the component stars moved randomly with respect to one another due to seeing. The separations and position angles that we have determined are the averages of several values and, providing the relative motions are truly random, represent valid measurements of these quantities.

The binary system with the largest difference in brightness between its components is υ Car ($\sim$3.1 magnitudes in V) and the results show comparable accuracy with the other systems. However, it should be noted that systems with the components separated by $\leq$2 arcseconds, and with this brightness difference, would present difficulties. Exposure times long enough to record the fainter component in moments of good seeing would result in overexposure of the primary image which could overlap the image of the secondary.

Fried (1978) has given a formula for the probability of obtaining a 'lucky' short-exposure image, but states that it is only valid for $D/r_0 > 3.5$, where D is the telescope aperture diameter and r_0 is the coherence length of the distorted wavefront as defined by Fried (1966). Fried predicts that the probability will decrease exponentially as the aperture diameter increases. The mean value of D/r_0 for the observations on 18 February 2000 was $\sim$3.2 to which Fried's result does not apply. However, our average rate of obtaining sharp images of one per 230 exposures with a 0.36 m telescope, or approximately one frame in $\sim$9 seconds of recording, is comparable with the figure of one per 100 exposures given by Dantowitz (1998) for a 0.30 m telescope. The process adopted in this preliminary study of selecting acceptable images by viewing the video tapes frame by frame is extremely inefficient and time consuming, and an obvious improvement would be the development of software to select images. This would improve the efficiency of the technique and eliminate the subjective nature of the image selection.

6 Summary

It has been demonstrated that the position angle and separation of binary systems close to the diffraction limit of a 0.36 m aperture telescope can be obtained by selecting images recorded in instants of good seeing in conditions where the average seeing is $\sim$2–3 times the diffraction limit.

While the parameter space explored in this preliminary programme was limited by the characteristics of the binary systems selected, it has been shown that separations of 0.9 arcseconds can be measured for systems with components of comparable brightness with an accuracy of $\sim$2% and position angles to $\sim$1–2 degrees. Binaries with three magnitudes difference in the brightness of their components can be measured with the same accuracy, at least for separations of $\sim$5 arcseconds, although difficulties are anticipated for binaries with this magnitude difference and separations $\leq$2 arcseconds. The primary limitation of the technique is the limiting magnitude since exposures comparable with and preferably shorter than the atmospheric coherence time t_0 are required to freeze the instants of good seeing. The limiting magnitude was not determined but π Lup with a visual magnitude of 4.72 was the faintest system observed and was judged to be close to the limit for the telescope/camera combination employed. The components of π Lup differ by only 0.1 magnitudes in V but generally the limiting magnitude will be set by the brightness of the secondary component. Within these limitations the technique will be a useful adjunct to the SUSI binary star programme.

The careful calibration of the angular scales in the image frames and of the orientation of the meridian relative to the video frames is crucial for useful determinations of binary separations and position angles, and the importance of this is emphasised. The main improvement in the technique would be the development of software to automatically select good frames since manual selection is inefficient. A shortcoming of the image processing software employed was the need to have distinct non-overlapping images in order to determine the image centroids. While this did not affect the binary systems included in the programme it would be unsuitable for systems separated by angles close to the Rayleigh limit. The use of a polar mounted telescope would simplify the analysis by avoiding the field rotation associated with altazimuth mounts.

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