RECOVERY OF INTENSITY INFORMATION FROM SPECKLE DATA

E. K. Hege, E. N. Hubbard, W. J. Cocke, P. A. Strittmatter
and S. P. Worden
Steward Observatory, Tucson, AZ 85712

R. R. Radick
Sacramento Peak Observatory, Sunspot, NM 88349

I. INTRODUCTION

The achievements of speckle interferometry in recovering diffraction limited spatial information, primarily by optical processing of photographic data, have been well summarized by McAlister in a preceeding paper. In general, the recovery of intensity information has received less attention mainly because of complications such as the need for accurate deconvolutions and noise bias corrections.

Methods for producing image power spectra (or the equivalent image autocorrelation functions) from digitally recorded speckle interferograms, as well as methods for correcting these functions for seeing effects, are described in our previous paper, Cocke, *et al*. in this colloquium. In this paper we discuss effects of instrumental response and photon statistics, the so-called noise bias, and procedures for correcting these effects in order to recover binary star relative intensity information from speckle interferometric data. We find for Capella $\delta m_v = 0.48$.

II. THE INTENSITY RETRIEVAL PROBLEM

We define the intensity ratio (relative intensity) for a binary star to be the ratio of the intensity of the fainter component to that of the brighter component: $\beta = I_B/I_A$. Then the relative magnitude difference (δm) equals $-2.5 \log \beta$. Unless carefully calibrated, absolute photometric information is not preserved by speckle interferometry. However, if certain assumptions discussed further in sections III and IV are valid, then relative intensity information can be recovered from speckle interferometry, and the intensity ratio may be inferred from either the visibility of the lobes in the autocorrelation function or the visibility of the fringes in the power spectrum. In both cases the visibility relation is non-linear in β and given by

$$V(\beta) = \frac{2\beta}{1 + \beta^2} \qquad (1)$$

and is physically valid in the interval $0 < V(\beta) < 1$.

(Note that $V(\beta)$ is equal to the ratio of intensities of the central and summed lobe components in the autocorrelation function; it is also equal to the amplitude of modulation of the fringe visibility function in the power spectrum.)

https://doi.org/10.1017/S0252921100010010 Published online by Cambridge University Press

III. THE NOISE BIAS PROBLEM

In the basic theory of speckle interferometry, a simple deconvolution using a similarly measured power spectrum (PS) for an unresolved source should produce the desired object power spectrum. If the speckle interferometric process can be characterized as a convolution of the object intensity distribution by a time dependent point spread function, so that

$$I_t(x, y) = O(x, y)*P_t(x, y) \qquad (2)$$

then the time averaged PS of many speckle images, obtained by Fourier Transformation (FT), is

$$PS = \langle |FT(I_t)|^2 \rangle_T = |FT(O)|^2 \cdot \langle |FT(P_t)|^2 \rangle_T \qquad (3)$$

This can in principle be deconvolved using a similarly derived PS of a point source to produce the desired object PS

$$|FT(O)|^2 = PS_{object}/PS_{point} \qquad (4)$$

The measured PS is, unfortunately, not given by the simple relation (3) but is complicated by the photon detection process itself; this phenomenon is usually referred to as the "noise bias" problem. The measured power spectrum is proportional to the square of the number N of events detected, and is in fact given by

$$PS = \{|FT(O)|^2 \cdot \langle |FT(P_t)|^2 \rangle_T + \bar{N}\} \cdot |FT(D)|^2 \propto N^2 \qquad (5)$$

where $\bar{N}$ is the average number of photons/frame and $|FT(D)|^2$ represents the detector transfer function (DTF).

If photoelectrons were detected as delta-functions (unique pixel events), and if the probability of detecting an event were uniform over the surface of the detector (no vignetting), then $\langle |FT(\delta)|^2 \rangle_T$ would be unity. These conditions are, however, seriously violated by our system. Thus it is necessary to correct both the measured power spectrum of the object and of the unresolved calibration star for the shape of the detector transfer function, $DTF = \langle |FT(D_t)|^2 \rangle_T$, and then to subtract the resulting bias (noise bias) from both PS before dividing. Then the bias corrected, seeing corrected PS is

$$PS_{BSC} = \frac{PS_o}{PS_p} = \frac{PS(M)_o/DTF - \bar{N}_o}{PS(M)_p/DTF - N_p} = |FT(O)|^2 \qquad (6)$$

We have found that for all except the very brightest objects, in which case the N^2 dependence of the PS dominates the N dependence of the noise bias, this noise bias correction (6) is crucial.

https://doi.org/10.1017/S0252921100010010 Published online by Cambridge University Press

IV. OTHER COMPLICATING FACTORS

Numerous complications ultimately limit the accuracy with which binary star intensity ratios may be determined.

If the instantaneous atmospheric transfer function appropriate to component A of the binary star differs significantly from that for component B, then the interferometric contrast, and consequently the apparent intensity ratio will be decreased. Significant degradation in isoplanicity may be detectable at separations of a few arc seconds (Hubbard, et al. 1979). Furthermore, if residual atmospheric dispersion errors exist in either the observation of the object or the calibrating point source, the power spectrum visibility will be altered again modifying the itensity ratio.

Errors in intensity ratio can also be introduced by changes in observing conditions between object and calibration measurements. Of these, changes associated with the seeing itself are usually the most important. Thus, for example, changes in the characteristic timescale of atmospheric changes, if shorter than the detector sampling time can distort derived intensity values. So also can changes in telescope focus. We are gradually accumulating a body of data to document the effects of such changes both on resolution and intensity derivations.

As a final example, we note that image distortions due to the image intensifiers or detectors can, if not appropriately corrected, reduce the visibility of power spectrum fringes and lead to incorrect interpretation of the data.

In order to produce properly calibrated binary star relative intensity ratios, it is therefore necessary that the above effects be well controlled through proper instrumental design and observation procedure. In particular, rapid chopping between standard and program star seems to be essential if accurate intensity information is to be obtained.

V. SOME PRELIMINARY RESULTS

Tables I and II summarize some of our most recent results. Unfortunately, not all of the stars studied to date have otherwise well established magnitude differences (such as lunar occultation observations) to which these results may be compared. In all cases, the uncertainties quoted for magnitude differences are subjective estimates based on ranges allowed by conservative interpretations of the data and are not formal statistical errors.

In Table I the calibration uncertainties are $\rho \pm 5\%, \theta \pm 5^{\circ}$ and $\delta m \pm 1$ magnitude unless otherwise indicated. The uncertainties in ρ are largely due to the anamorphic imaging properties of the 4 stage electrostatic inverter image intensifier which produce seeing-dependent and guiding-dependent image scale factors. Position angle uncertainties are due to

https://doi.org/10.1017/S0252921100010010 Published online by Cambridge University Press

uncorrected anamorphism in the video raster and to uncertainties in the absolute orientation of the detector. The major contributions to magnitude difference uncertainties are noise bias calibration errors due to lack of independent measures of the event detection point spread function (PSF) for many of the observations presented here. Elsewhere the DTF was modelled by an anamorphic transmission function fit to the wings of the PS beyond the high spatial frequency limit of the optical system.

The column labeled Method indicates PS or ACF, respectively, if the visibility was taken from a power spectrum or an autocorrelation function. I indicates a visibility determined from a reconstructed image. In all cases it was necessary to correct for noise bias. In PS measurements the DTF was modelled by an anamorphic Gaussian function fit to the wings of the PS outside the λ/D cut-off frequencey.

In both tables the observing band-pass is specified by the central wavelength and FWHM of the interference filter used for the observation. The image scale is given in arc-seconds per video digitizer pixel. The UT observing Date is listed. Magnitude difference δB and δR from lunar occultations taken from the summary compiled by Evans (1982) are quoted for comparison.

Results for the binary objects in Table II are obtained from power spectra which are properly debiased and (except for ADS 13449) deconvolved with debiased spectra of unresolved objects using our most recently developed observing and reduction methods. We believe the quoted uncertainties in ρ, θ, and δm reflect these improvements in technique.

For those cases in which m's have been observed by lunar occultations, the results from the two methods appear to be consistent but the agreement is certainly not overwhelming. It is our (optimistic) opinion that, given sufficient care in the design of observing programs to assure proper standardization and proper control of those phenomena known to cause complications, the problem of recovery of binary star relative intensities can be solved within limits set by photon statistics. Success in this endeavor is of course essential if valid image information on more complex objects is to be recovered by speckle techniques.

VI. ACKNOWLEDGEMENTS

This work was supported in part by Air Force Contract #F19628-78-C-0058. We gratefully acknowledge the contributions of M. S. Gresham in developing the data reductions software and J. Freeman in operation of the video data reductions systems. We thank D. Monet for supplying a list of candidate Hyades binaries for speckle interferometric observations.

https://doi.org/10.1017/S0252921100010010 Published online by Cambridge University Press

REFERENCES

1. Fienup, J. R., Feldkamp, G. B. (1980) Proc. S.P.I.E., 243, 95.

2. Evans, D. S. (1982) In Proc. IAU Colloq. 62, Flagstaff, 1981 ed. R. S. Harrington.

3. Frost, R. L., Rushforth, C. K. (1979) Private communication.

4. Hubbard, E. N., Hege, E. K., Reed, M. A., Strittmatter, P. A., Worden, S. P., (1979) Astron. J., 84, 1437.

5. Hege, E. K., Hubbard, E. N., Strittmatter, P. A. (1980) Proc. S.P.I.E., 264, 29.

6. Koechlin, L., Bonneau, D. and Vakili, F. (1979) Astron. Astrophys. 80, L13.

7. Wright, K. O. (1954) Astrophys. J., 119, 471.

TABLE I

SAO	ρ	θ(Mod 180°)	δm	Method	λ	δλ	Scale	Date	δB	δR
93925	0".104	118°	2.0	PS	5007Å	30Å	0.0109	10 Nov 79	0.31(.02)	
	0.095	112.5	1.0	ACF	5007	30	0.0109	5 Dec 79		
93926	0.248	18.0	0.71	ACF	7500	100	0.0198	9 Nov 79	(a) A=8.2,	B=8.8
	0.252	17.7	1.9	ACF	5500	100				
	0.249	17.7	3.4	ACF	4100	100				
93955 (77 Tau)	0.086	164	2.9	PS	4100	100	0.0109	10 Nov 79	3.2(.2)	
	0.203	0	3.3	PS					(b)	
93955 (77 Tau)	0.157	2	3.3		4100	100	0.0109	13 Sep 79	(b)	
94163	0.282	39.1	(c)	ACF	7500	100	0.0198	10 Nov 79	(a) A=7.8,	B=7.8
	0.27	42	1.5(d)	I	7500	100				
	0.288	38.5	2	ACF	4100	100				
94171	0.209	56.7	0.95	ACF	7500	100	0.0198	9 Nov 79	(a) A=6.8,	B=6.8
	0.214	55.9	0	ACF	7500	100	0.0198	10 Nov 79		
	0.211	56.0	1.5	ACF	5500	100				
	0.215	56.5	2.0	ACF	4100	100				
94554 (115 Tau)	0.104	78.2	1.5	ACF	7500	100	0.0198	9 Nov 79	1.13(.06)	0.90(.06)
	0.099	78.4	(c)	ACF	5500	100				
	0.094	78.2	0.73	ACF	4100	100				
	0.088	83.7	2.0	ACF	5007	30	0.0109	10 Nov 79		

TABLE II

Object	ρ	θ	δm	Method	λ	δλ	Scale	Date	Notes
Capella	0".042(.001)	151°(2)	0.48(.05)	I	5200Å	100Å	0.00723	2 Feb 81	(a) (e)
RY Tau	0.037(.003)	92(2)	3.7(.3)	PS	5200	100	0.00723	2 Feb 81	(a) (f)
ADS 13449	0.319(.015)	232.8(2)	0.3(.2)	I(g)	5500	100	0.0198	7 Jul 79	(a) A=7.3 B=7.6
PG1115+080A	0.54(.03)	18 (2)	0.1(.2)	I(h)	6000	2000	0.0615	5 Jun 80	(a)
Pluto/Charon	0.31(.05)	285(7)	2.2(.3)	I(i)	6000	600	0.0615	5 Jun 80	(i)

Notes for Tables I and II:

(a) No lunar occultation data for comparison. Visual magnitudes if quoted, are from an observing list supplied by Monet (private communication), or from ADS catalogue.

(b) Possible 3rd component. May have been detected in occultation by Radick.

(c) No physical solution: $V(\beta) > 1$ for this data set.

(d) Fienup and Feldkamp (1980).

(e) $\delta m = 0.48$ is not inconsistent since Capella is a two-lined spectrum binary. The 180° ambiguity is correctly resolved by this phase-constrained image reconstruction. Frost and Rushforth (1979) found $\delta m = 0.47$ by analysis of photographic speckle data. Koechlin, Bonneau and Vakili (1979) quote (indirectly) the historical spectrum binary result of Wright (1954) of $\delta m = 0.25$.

(f) $\delta m = 3.7$ suggests an M-dwarf companion.

(g) Hege, et al. (1980).

(h) Using unresolved point source within isoplanatic patch.

(i) Consistent with other speckle interferometric results.

https://doi.org/10.1017/S0252921100010010 Published online by Cambridge University Press