AN IMAGE RECONSTRUCTION FOR CAPELLA WITH THE STEWARD OBSERVATORY/AFGL INTENSIFIED VIDEO SPECKLE INTERFEROMETRY SYSTEM

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I. BASIC TECHNIQUES

In the decade since its invention by Labeyrie in 1970, speckle interferometric techniques have evolved from simple optical processing of photographic images to high-speed digital processing of quantum-limited video data. This progress has been summarized in preceeding papers by McAlister and Weigelt in this colloquium.

The basic hardware of our system has been described in Hubbard, *et al*. (1979 - The basic speckle camera) and in Hege *et al*. (1980 - The intensified video system). These capabilities have been successfully applied to observations over a dynamic range of 16 magnitudes, from Betelgeuse (Goldberg, *et al*. 1982) and Capella (this paper), at one extreme, to Pluto/Charon (Hege, *et al*. 1981a) and the 16th magnitude resolved QSO system PG1115+080 (Hege, *et al*. 1981b) at the other. To accomodate this dynamic range two distinct data-recording/data-processing modes have been implemented. The *Analogue mode* records the image intensity for each pixel in the speckle interferogram. This is applicable for objects brighter than 7th to 10th magnitude, depending upon telescope aperture, observing band-pass and detector image scale. For fainter objects the *Event mode* records individual photoelectron addresses in the speckle interferogram.

The usual speckle interferometric data reductions produce time-averaged Power Spectra by Fast Fourier Transform (FFT) techniques, or equivalently time-averaged autocorrelation functions (ACF), from the individual short-exposure speckle interferograms (I). For Analogue mode the power spectrum is given by

$$PS = \langle \left| FFT(I_i) \right|^2 \rangle_T \qquad (1)$$

For the Event mode the ACF is accumulated directly as the sum of the histograms of the event-address differences in each I (Hege, *et al*, 1980).

In both modes an energy-centroided long-exposure image (LE) is accumulated. Following a suggestion of Worden, *et al*. (1977), a seeing correction can be estimated using the long-exposure autocorrelation function (LEA) defined as

$$LEA = FFT\left(\left| FFT\left(\sum I_i \right) \right|^2 \right) \qquad (2)$$

Then a seeing-corrected autocorrelation function (SC-ACF) is produced by

$$SC\text{-}ACF = ACF - n\ LEA \quad (3)$$

where n is chosen such that LEA(r) = ACF(r) at radial distances r such that both distributions sample only the seeing distribution. This condition is applicable only for objects such as stars, satellites, and asteroids, i.e. objects with sharp boundaries and image scale small compared to that of the seeing.

The effectiveness, as well as the principle limitations, of this method are illustrated in Figure 1. The SC-ACF for an unresolved star, SAO 36615, observed with the Steward 2.3 m telescope is shown. This result is dominated by the expected point-spread function of the annular aperture defined by the telescope mirror. There are two principle departures from the expected response, i) an excessive central spike, the so-called noise bias, and ii) residual excess intensity (imperfect seeing correction) at r = 0.1-0.3 arc-sec.

An alternative seeing correction but which appears to be subject to the same conditions of applicability, is

$$SC\text{-}ACF = ACF/LEA - n \quad (4)$$

which was suggested by our interpretation of the model calculations of Bonneau, et al. (1980) and Roddier (1980) and the simulations for binary stars by Dainty (1978). We find the result to be the equivalent of the Worden method. In this case the constant n is produced directly by the quotient for radial distances at which both distributions sample only the seeing and is readily inferred from inspection of the result.

A better seeing correction is obtained using a calibration PS obtained by observing an unresolved star. Then the seeing corrected power spectrum is

$$SC\text{-}PS = PS_{Object} / PS_{Calibration} \quad (5)$$

Good observing practice requires that the calibration source be of similar brightness, in close proximity to the object, and that observations of the calibration source be interspersed with observations of the object to assure similar conditions of seeing.

For strictly astrometric purposes (e.g. ρ, θ for binary stars) the self-calibrating techniques (3) or (4) appear adequate. For photometric purposes (e.g. binary star intensity ratios) the point-source calibration (5) is essential.

A further complication, generally referred to as noise bias, is discussed in our following paper, Hege, et al., in this colloquium. The simple deconvolution (5) has been found to be applicable only to the very brightest objects for which the

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photon statistics are negligible.

II. IMAGE RECONSTRUCTION TECHNIQUES

An image I (x, y) is not uniquely determined by the image spectral amplitudes obtained from (5) or by FFT from (3) or (4). The full complex spectrum FFT (I), including phases as well as amplitudes is required.

We have implemented two methods for image phase retrieval, a phase unwrapping method developed by Cocke (1980) and the phase accumulation method of Knox and Thompson (1974).

In the phase unwrapping method (Cocke, 1980), the phase angle ambiguity $\phi \pm 2\pi n$ ($n = 0, 1, 2, \ldots$) is resolved by requiring the phase angles $\phi(u, v)$ to be as nearly continuous as possible as functions of the discrete wave-numbers (u, v). These phase angles are computed for each individual speckle frame, are "unwrapped" by adding appropriate values of $\pm 2\pi n$ to get the required near-continuity, and are accumulated in a storage array. Thus, after the required number of speckle frames is processed, an average unwrapped $\phi(u, v)$ is the result. Less ambiguity in n is obtained if the resolution in wave-number space (u, v) is improved by increasing the domain of the FT by padding out the speckle frames with zeros. This increases somewhat the amount of computer time and central memory required.

The Knox-Thompson method (1974) computes the phase factor ratios $\exp[i\phi(u+1, v) - i\phi(u, v)]$ for each speckle frame, at each value of (u, v), and accumulates them in an array, for averaging. The final result may be expressed, roughly as,

$$\exp[i\phi(u,v)]_{final} = \prod_{u'=1}^{u} \langle \exp[i\phi(u,v) - i\phi(u'-1, v]\rangle \quad (6)$$

This method also benefits from increased resolution.

The image phases are then combined with the spatial amplitudes to form a reconstructed complex image spectrum. The SC-PS, whether obtained by (3), (4) or (5), usually contains non-physical negative amplitudes as well as non-zero amplitudes beyond the aperture limit. We developed an iterative "cleaning" algorithm in which the SC-PS and SC-ACF pair are alternatively subjected to the appropriate non-negativity constraints, applied in both image space (ACF) and transform space (PS). Multiplication of the resultant cleaned PS by a suitable low-pass filter then suppresses the power beyond the aperture limit.

The reconstructed complex image spectrum, consisting of cleaned, filtered amplitudes and image phases, from either the Cocke or the Knox-Thompson method, is then further processed by the Fienup (1978, 1979) method to produce the final reconstructed image. This iterative method "retouches" the initial image estimate by using the cleaned, filtered SC-PS as a continuing constraint and further requiring that the image amplitudes produced be non-negative.

III. AN IMAGE OF CAPELLA

Analogue mode speckle interferograms for Capella and the unresolved star γ Ori were obtained using the KPNO 4 meter telescope on 3 Feb 81. About 200 frames of data for each object, using a 100A band-pass at 5200A, 15 ms exposure, and 0.014/pixel detector image scale were processed by FFT methods and (5) to produce the SC-PS shown in Figure 2.

We tested both phase-unwrapping and Knox-Thompson methods to produce images of the Capella system. In both cases the preliminary images were unrealistic in that some of the image amplitudes were negative. The Fienup retouching, however, cleaned these away and produced images which were indistinguishable except for subtle details in the noise background, which had in both cases an rms value about 4 magnitudes fainter than the stellar images. There is only one element of significant phase information in a binary star image with unresolved components - the resolution of the 180° orientation ambiguity. Both methods agreed, and further agreed with the orientation derived from the published orbit of Finsen (1975). Our final result, shown in Figure 3, yields

$$\rho = 0\overset{''}{.}042 \ (0\overset{''}{.}001)$$

$$\theta = 151^{\circ} \ (2^{\circ})$$

$$I_B/I_A = 0.63 \ (0.05)$$

$$\delta m = 0.5 \ (0.1)$$

which compare favorably with Bagnuolo's analysis by another method reported at this colloquium. The uncertainties in ρ and θ are principally limits in the precision of our image scale and camera orientation calibrations. The uncertainty in I_A/I_B is an estimate based on dispersion in measures obtained directly from the power-spectrum fringe visibility function and from the integrated amplitudes of the final reconstructed image components. The relative intensity determination may be subject to further systematic error due to image distortions produced by the electrostatic-focus image intensifiers. See the discussion in our following paper, this colloquium.

IV. CONCLUSION

The nature and systematics of real, astronomical speckle interferometric data acquired with linear, electronic detectors now appears to be well understood. Computer algorithms have been developed for producing aperture limited, deconvolved, debiased image power spectra and autocorrelation functions. These have been tested with observations spanning 16 visual magnitudes

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dynamic range (including detection of structure at m_v = 18.6). Methods for producing diffraction limited images for binary star systems have been demonstrated.

V. ACKNOWLEDGEMENT

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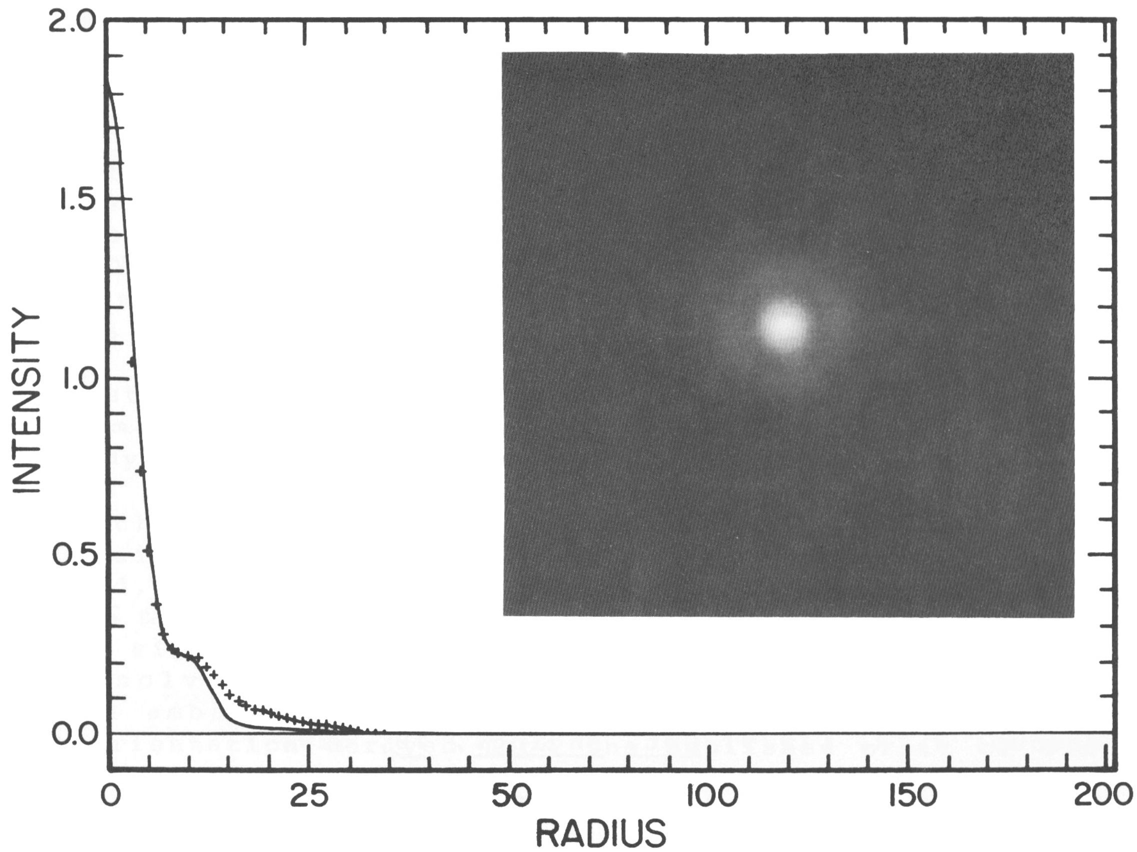

Figure 1. SAO 36615. The inset shows the two-dimensional seeing corrected ACF produced by (3). The azimuthally averaged radial function is plotted (+) against the ACF of the point spread function for a 3:1 annular aperture (line). Radial scale is $\approx$ 0".01 per pixel.

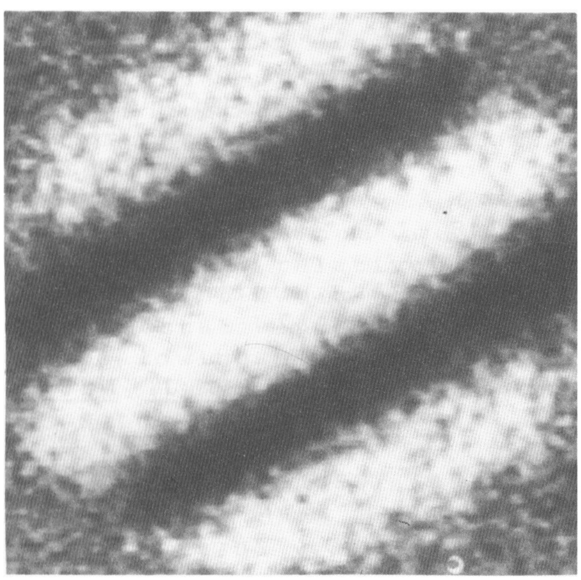

Figure 2. Capella. Deconvolved PS. Unresolved reference was γ Ori.

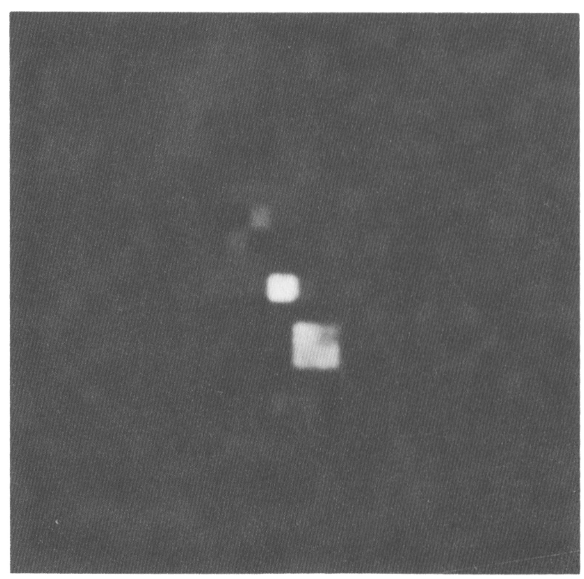

Figure 3. Capella. reconstructed binary image. Phases by Cocke method. Retouched by Fienup method.

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