"DIFFERENTIAL SPECKLE INTERFEROMETRY", A NEW TOOL FOR DOUBLE STAR RESEARCH

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ABSTRACT

Speckle interferometry is a powerful tool for close binary star research allowing angular resolutions as small as 20 milliarcsecond. A technique is proposed to resolve spectroscopic binaries with even smaller separations. It uses the fact that speckle images taken in one or the other of the Doppler shifted spectral lines give a different intensity weighting of the two components of the binary. The location of the speckles in the two speckle images is therefore different, the direction of the displacement being related to the position angle of the binary, the amount of the displacement being related to its separation. Since the location of speckles can be determined with a much higher precision than their diameter, this creates the possibility for submilliarcsecond observations. This paper describes an experiment being started now to use this so-called "Differential Speckle Interferometry" technique for the study of binaries, stellar rotation, stellar chromospheres, Ap stars and other objects.

I. INTRODUCTION

Speckle interferometry has found its most successful application in the study of close binaries. Two dimensional autocorrelation analysis or Fourier analysis of the binary speckle images results in a direct measurement of the binary separation and position angle. Its capabilities and results will be discussed elsewhere in this colloquium. It has been applied to binaries with separations larger than the speckle diameter ($\geq$ 25 msa, msa = milliseconds of arc). Accuracies of better than 1 msa have been reported (McAlister 1977, 1978), the limit being set by noise in the observations, the difficulty of separating the two images when the separations are unfavorable or when the intensities are very different, and by inaccuracies in the image scale calibration.

In the proposed Differential Speckle Interferometry technique, I plan to use the fact that known spectral variations occur across the object under study to generate two speckle images corresponding to two slightly different wavelengths which show a slight relative shift in position. As is the case with close binaries the position of the speckles, and thus their shift, can be determined with sub-

*The Multiple Mirror Telescope Observatory is a joint venture of the Smithsonian Institution and the University of Arizona.

https://doi.org/10.1017/S0252921100009982 Published online by Cambridge University Press

milliarcsecond accuracies even though the speckle size is substantially larger. The higher effective angular resolution of Differential Speckle Interferometry is therefore due to the fact that the location of an object (speckles, stars, spectral lines, etc.) can be determined with an accuracy many orders of magnitude better than its size. By encoding qualitatively known surface structure of the object into variations in speckle location, it is thus possible to derive quantitative information on that surface structure at the submillisecond of arc level.

Figure 1 demonstrates the concept in case of a spectroscopic binary whose two components B and R have substantial blue and red shifts respectively. An image taken at wavelength λ_R (corresponding e.g. to the H_α wavelength of R) will show B at a higher brightness than in an image taken at λ_B. The opposite is the case for star R so that the location of center of gravity (cg) of the combined binary intensity will be different at λ_B and λ_R. The amount of the shift δ will be a fraction of the actual binary star separation, the fraction depending on such factors as the line strength, and the relative intensities of the binary components. In the analysis later in the paper, I will assume this fraction to be 20%. The direction of the shift is identical to the position angle of the binary.

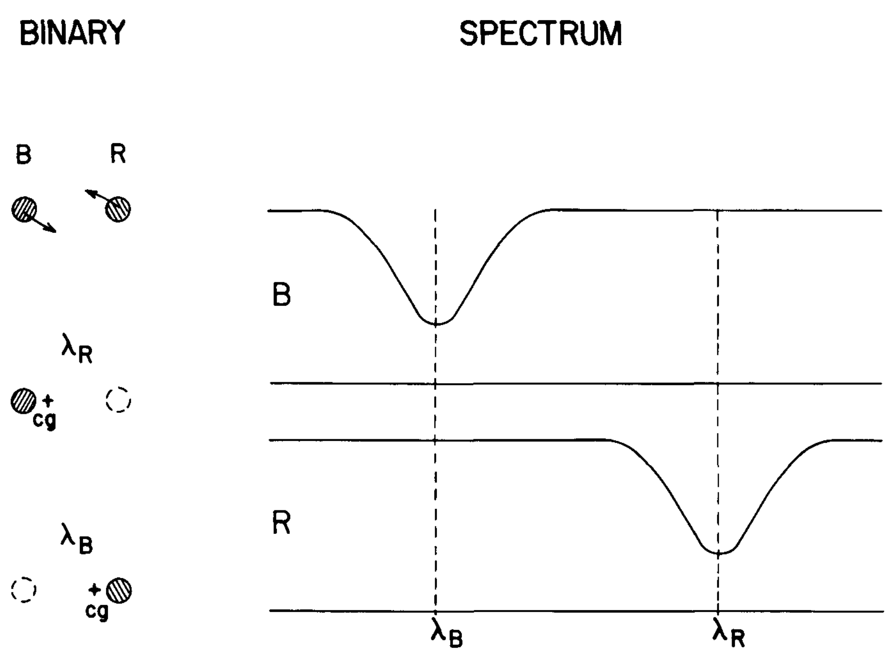

Figure 1. Hypothetical spectroscopic binary with B and R being the blue and red shifted components. The light center of gravity (cg) of an image taken at λ_R will be shifted slightly with respect to that of an image taken at λ_B.

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In the unresolved speckle images of the binary, the shift of the object's light center of gravity will cause a shift in the speckle image of a fraction of the speckle size. Differential speckle interferometry is the technique to generate the two images and to measure their displacement. In the remainder of this paper, I will describe the technique and its anticipated accuracy. Applications will be discussed. Results are, however, a matter of the future.

II. INSTRUMENTATION

Figure 2 shows the configuration of the differential speckle experiment. In the telescope prime focus is a reflecting aperture

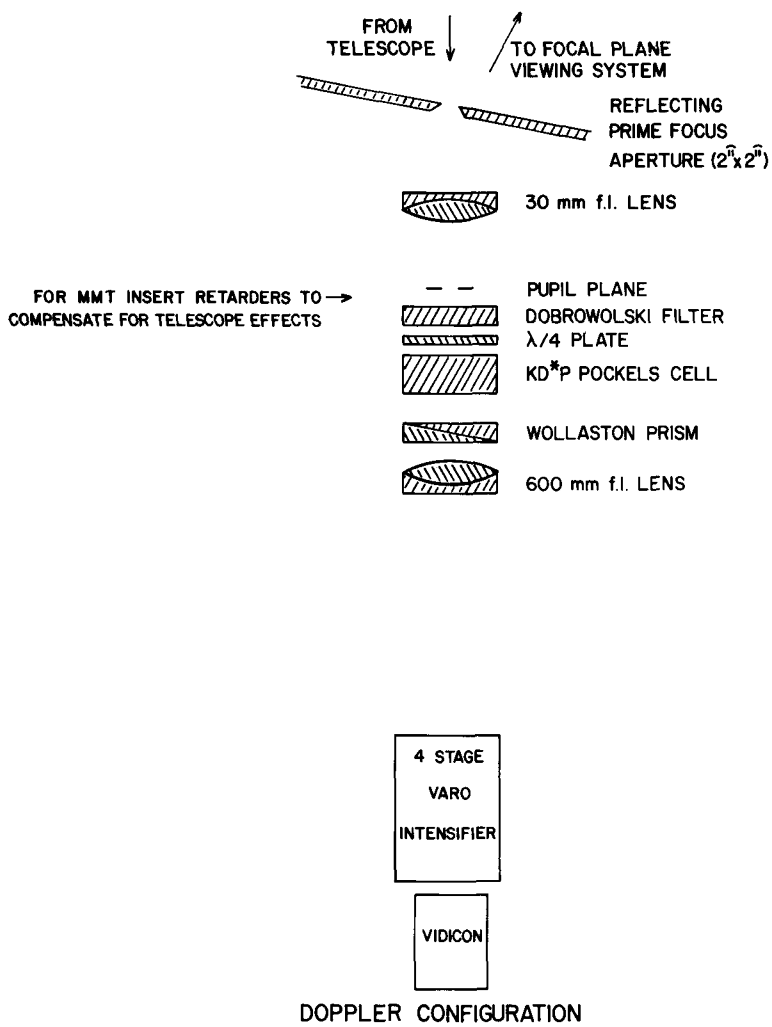

Figure 2. Instrumental configuration.

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plane with an aperture a few arc seconds in size. The reflected image will be used by the acquisition and guidance system of the telescope used. The transmitted image will be collimated and imaged again by 30 mm and 600 mm focal lengths lenses which together provide for an image magnification of 20x onto the speckle camera consisting of an image intensifier and vidicon camera described in this colloquium by E. K. Hege et al. While collimated the light passes through a mica narrow band interference filter, a quarter wave plate, a KD*P Pockels cell and a quartz Wollaston prism. These components have the following properties and functions:

(a) The interference filter has a bandwidth of approximately 0.75Å and a transmission of 25%. Because of the mica spacer, the filter is very stable with time. Its transmission wavelength can be chosen by varying the temperature. Since mica is a birefringent material the filter can be made to transmit two different wavelengths for the two orthogonal linear polarizations of the Wollaston. Ideally these wavelengths should correspond to λ_R and λ_B in Figure 1, in reality one will correspond to either λ_R or λ_B whereas the other will be located in the nearby continuum since these filters are quite expensive and since a different filter would be needed for each transmission wavelength difference. The properties of mica filters were described by Dobrowolski (1959).

(b) The quarter wave plate/Pockels cell combination will be used in conjunction with the Wollaston prism to switch the sense of the angular polarizing beamsplitting of the Wollaston around. With a minus quarter wave voltage on the Pockels cell, the combination will be neutral. With a plus quarter wave voltage, it will act as a half wave plate switching the wavelengths separated by the Wollaston.

(c) The Wollaston prism causes a doubling of the speckle image on the speckle camera by an amount determined by the wedge angle of the prism. This polarizing beamsplitter therefore effectively

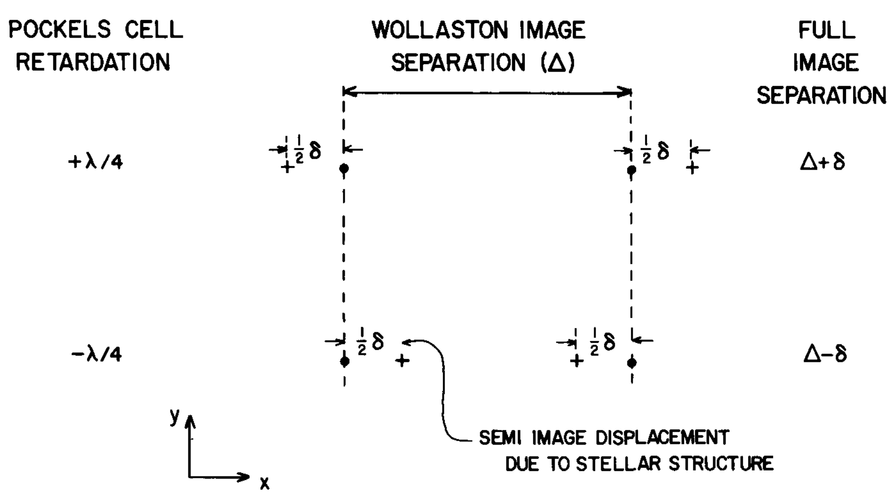

Figure 3. Speckle separations due to the Wollaston prism (Δ) and the differential speckle effect (δ).

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creates a speckle image of what appears to be a double star with a known approximate orientation and separation.

In Figure 3, I show the appearance of each image (speckle) element. The Wollaston prism alone, in the absence of the differential speckle effect, would give an image separation Δ. Figure 3 assumes that the differential speckle effect δ is in the same direction so that the actual image separation equals $\Delta + \delta$ and $\Delta - \delta$ depending on the sense of the Pockels cell voltage. The measurement of δ is then accomplished by measuring the artificial double star separation in opposite Pockels cell conditions by means of an autocorrelation function and then taking the difference of the separations which equals 2δ. The separation Δ is chosen as 300 msa. This separation places the double star autocorrelation peak well away from the central autocorrelation peak due to the speckle width themselves. A larger Δ would force me to correct for intensifier distortions before doing the correlation. The Wollaston prism/artificial double star technique was decided upon since it uses to some extent existing double star speckle techniques and because it records the two speckle images simultaneously, thus eliminating any noise resulting from temporal changes of the speckle patterns. Since we use TV recording the exposure times are 1/30 - 1/60 second. The time between opposite Pockels cell voltages is much larger, probably 0.5 - 2 seconds. Speckle changes of course do not affect the sequential $\Delta + \delta$ and $\Delta - \delta$ measurements. Intensifier/TV scale changes do, so that the detector system is to be made very stable in the $\sim$ 1 Hz time scale.

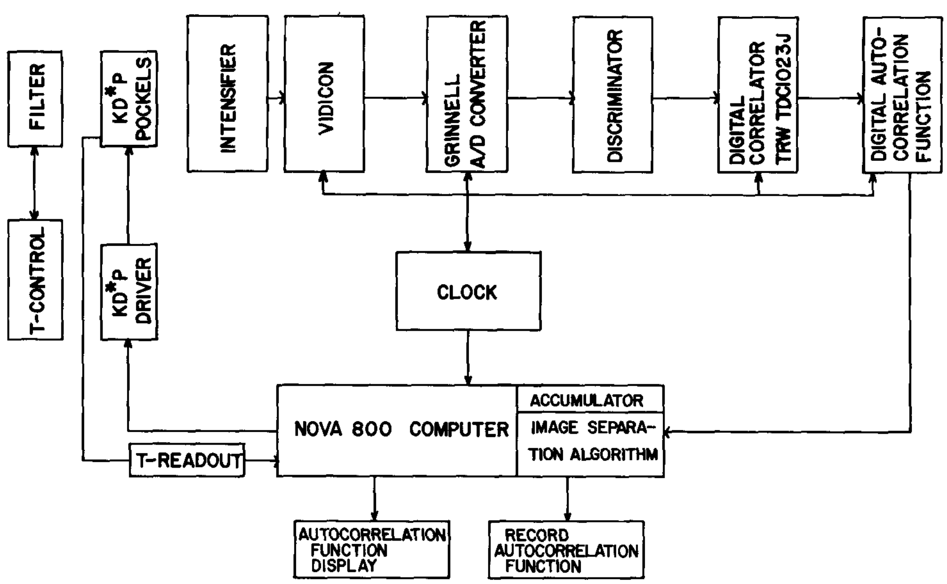

Figure 4. Digital analysis configuration.

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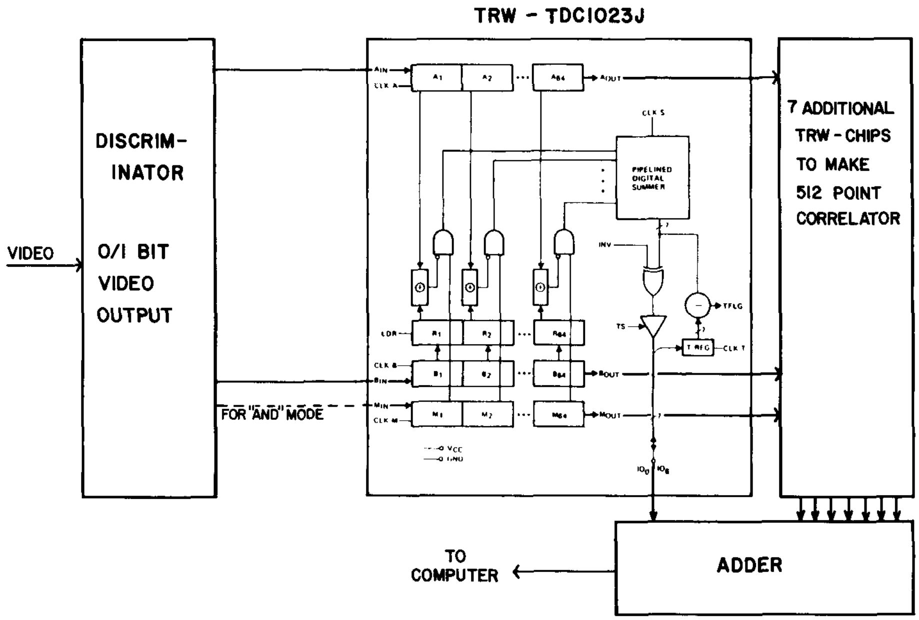

Figure 5. Autocorrelator.

Because of the narrow band filter, the photon flux is quite low even for rather bright objects so that the differential speckle interferometry will use individual photon event analysis. Photons are detected by means of a video A/D converter coupled to a threshold device which will generate a 0/1 digital video image with the photon locations corresponding to the 1 counts (Figure 4). A hardware autocorrelator consisting of TRW-TDC1023J autocorrelator chips will correlate this digital image in real time and will accumulate and display the results in a computer until sufficient accuracy is obtained. Figure 5 shows in more detail the functioning of this autocorrelator whose speed is high because the correlation is done simply by one bit XOR or AND circuitry.

In reality the differential speckle effect δ will generally not occur in the Δ splitting direction (or the x direction in Figure 3). Since δ in this experiment will be a fraction of the speckle size the displacement of the speckles in the y direction (δ_y) will hardly affect the autocorrelation so that a peak will be measured at a displacement $\Delta \pm \delta_x$. To obtain the δ_y displacement the entire package will be rotated over 90^o and the measurement repeated.

III. ACCURACY

Figure 6 displays the anticipated autocorrelation function with the main peak at zero displacement and a secondary peak at a displacement corresponding to the $\Delta \pm \delta$ splitting. The real autocorrel-

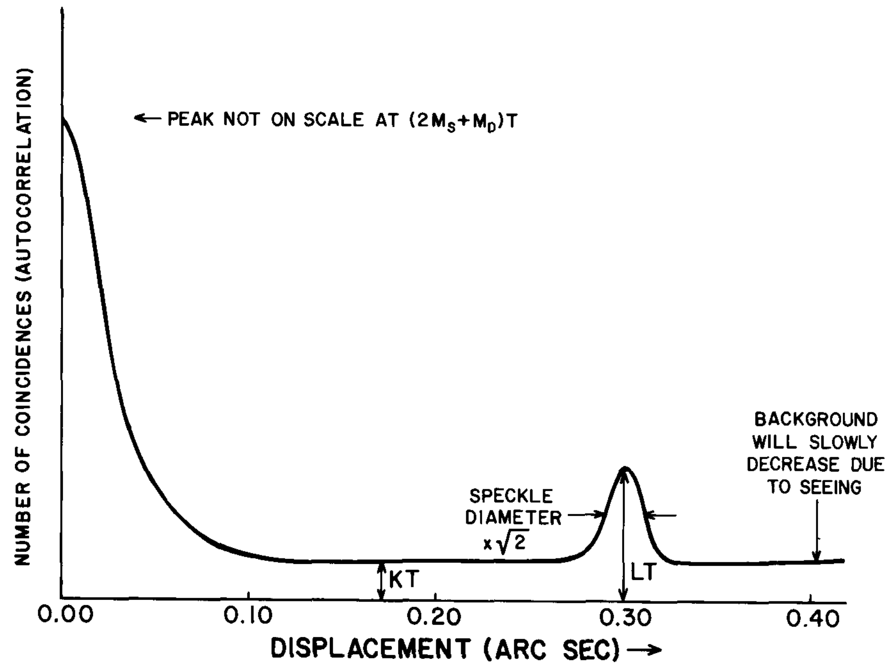

Figure 6. Sketch of anticipated autocorrelation function. See text for explanation of symbols. For a V = 5 star and 1 video frame (T = 1) $(2M_S + M_D)$ T = 201, KT = 11 and LT = 76.

ation function will be noisy, the noise depending on the photon statistics in the speckle images. I estimated the noise for the following conditions.

1.	Telescope collection area	150000 cm^2 (MMT)
2.	System Efficiency (photoelectron events per photon incident on the telescope)	0.2%
3.	Filter bandwidth (FWHM)	1 Å
4.	Speckle size (FWHM)	20 msa
5.	Seeing Disk (FWHM)	1 arc second

Under these circumstances, and for a V = 5 object, the number of photoelectrons per video frame (1/30 seconds) M_S equals 100 per image as compared to a dark count M_D of about 1. At zero autocorrelation function displacement the number of electron event coincidences equals therefore $(2M_S + M_D)$ = 201 per video frame as shown in Figure 6 (T = number of video frames). At a random displacement small compared to the seeing disk size the coincidence count equals K and at the secondary autocorrelation peak L. For V = 5 and for an approximate model for the speckle intensity distribution K = 11 and L = 76. From this I estimate the accuracy with which the secondary peak can be located as 1.3 msa RMS per video frame (or 7% of the speckle size). Allowing for a factor of 10 decrease of sensitivity because of unanticipated problems, I arrive at accuracies for the determination of δ shown in Table I.

TABLE I

RMS Accuracy in δ Measurement for Different Observing Times t

($\Delta\delta$ in milliseconds of arc)

V =	2.5	5.0	7.5	10.0
$\Delta\delta$ (t = 1 sec)	0.25	2.5	(25)	(267)
$\Delta\delta$ (t = 1 min)	0.03	0.3	3.2	(34)
$\Delta\delta$ (t = 1 hr)	0.004	0.04	0.4	4.4

Differential speckle interferometry is therefore capable of reaching very high precisions in a rather short time for objects brighter than V = 7.5.

IV. APPLICATIONS

In the context of this colloquium, the main interest is in the observation of close binaries. In Table II, I list a sample of bright spectroscopic binary stars which are unresolvable with normal speckle interferometry, but which are assessable by the proposed technique.

TABLE II

Examples of Spectroscopic Binaries

Star	V	Spectral Type	Period (days)	Velocity (km/s)	Semi-Major Axis (msa)	10δ Observing time (minutes)
i Ori	2.76	08III 09	29	115 192	0.3	1
ζ^2UMA	2.29	A2V	21	69 68	9.5	0.02
αVir	0.96	B2V B3V	4	117 194	1.4	0.1
ζCen	2.54	B2VI	8	111	1.2	3
βSco	2.63	B0V	7	129 215	1.2	4

In estimating the time required to reach a 10σ signal (σ = RMS error according to Table I,) I assumed that δ equalled 20% of the semi-major axis. Because the period of these close binaries is short, it should therefore be possible to determine their orientation and sep-

https://doi.org/10.1017/S0252921100009982 Published online by Cambridge University Press

TABLE III

Examples of Stars in the U Ma Group

HR	Name	Spectral Type	V	Angular Diameter*	v sin i (km/sec)	δ**	3σ observing time (minutes)
			NUCLEUS				
4191	37 U Ma	F1V	5.16	0.6	100	0.18	80
4295	β U Ma	A1V	2.37	1.0	32	0.20	0.3
4554	γ U Ma	A0V	2.43	1.1	165	0.44	0.1
4660	δ U Ma	A3V	3.44	0.9	178	0.36	0.8
4931	78 U Ma	F2V	4.89	0.6	90	0.18	40
5054	ζ U Ma	A2V	2.09	0.9	45	0.18	0.2
5062	80 U Ma	A5V	4.02	0.8	240	0.32	3
			STREAM				
68	σAnd	A2V	4.51	0.9	105	0.36	5
378	89Psc	A3V	5.28	0.9	130	0.36	20
1046	-	A2V	4.98	0.9	200	0.36	10
1383	ξEri	A2V	5.23	0.9	215	0.36	20
1872	38Ori	A2V	5.32	0.9	205	0.36	20
2763	λGem	A3V	3.65	0.9	165	0.36	1
3974	21 LMi	A7V	4.47	0.7	145	0.28	10
4865	29 Com	A1V	5.64	1.0	170	0.40	30
4900	41 Vir	A7III	6.34	1.0	65	0.30	300
5214	-	A5IV	6.57	0.8	120	0.32	400
5373	-	A2V	5.98	0.9	165	0.36	100
5634	45 Boo	F5V	5.03	0.5	40	0.10	200
5721	8 Ser	F0V	6.10	0.6	120	0.24	200
5867	β Ser	A3V	3.74	0.9	195	0.36	1
7215	16 Lyr	A7V	5.06	0.7	115	0.28	20
7312	59 Dra	F2V	5.06	0.6	65	0.18	70
8263	-	A2V	6.27	0.9	185	0.36	100
8291	76 Cyg	A2V	6.05	0.9	165	0.36	100
8407	-	A0IV	5.52	1.5	90	0.45	20
8984	λPsc	A7V	4.61	0.7	45	0.14	40

*Angular diameter in milliseconds of arc

**I took δ = 10%, 20%, 30%, and 40% of star diameter for v sin i in the intervals 0-20; 21-50; 51-100 and 101-250 km/sec respectively. Actual δ value will depend on the filter and spectral line used.

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aration over a complete orbit over a rather short time. Such observations in combination to the spectroscopic velocities will lead to a full orbit determination including the inclination i and thus to a determination of the masses and distances of the objects.

Another application of differential speckle interferometry of interest in binary star studies concerns stellar rotation. Speckle images taken in the blue and red wings of strong absorption lines will again show shifts if the star rotates appreciably. Differential speckle interferometry will result in information on this rotation specifically on the projected orientation of the rotation axis. When observed in resolved binaries or star clusters, the orientation of the rotation axis is of interest in understanding the evolution of the star system. Table III shows that for a star cluster like the U Ma group it should be possible to measure the rotation for a large number of members. The same is true for the Hyades and the Pleiades as well as for a large number of binaries.

Other applications of differential speckle interferometry concern peculiar A stars, flare stars, stellar chromospheres and prominences, and possibly other objects. They are, however, not relevant to the present topic of discussion.

V. CONCLUSION

This paper describes a concept which appears to be promising in giving information on bright stellar objects on the submilliarcsecond level. A proposal to implement a test of the concept has been submitted jointly with E. K. Hege to the U. S. National Science Foundation. We hope to report within the not too distant future about its feasibility and results.

References

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McAlister, H.A. 1977 Astrophysical Journal 212, 459.
McAlister, H.A. 1978 IAU Colloquium No. 48. "Modern Astronometry" p. 325.

DISCUSSION

McALISTER: If I understand correctly, you will essentially be measuring the maximum of an asymetric auto-correlation peak. It then seems that both separation and delta-m contribute to this asymetry, and I am wondering if you can unambiguously separate these effects.

BECKERS: The effect does not depend on the peak being asymetric. For most observations the differential speckle effect will be small compared to the speckle size, so there will be little or no asymetry. When I have the optical modulator in the plus-quarter-wave position, the peak will come at one location. If I switch it, it will come at a different location, and I measure a difference in displacement.

The interpretation of the data is going to be complex. You have to know indeed what the magnitude differences and what the spectral properties of the objects are. One thing that is unambiguous is the direction of the displacement. If I have the direction of the displacement, I know what the position angle of the binary is, and I know what the rotation axis of the star is.