EXPERIMENTS IN DIFFERENTIAL SPECKLE INTERFEROMETRY

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ABSTRACT

We propose to develop a technique to achieve submillisecond of arc resolution on stellar objects. It uses the fact that the spectrum of the light emitted by such an object often changes across its surface either because of Doppler shifts, Zeeman splitting, abundance anomalies or changes in the stellar atmosphere. By an appropriately designed experiment using narrow band (0.5 - 1 Å) filters, it is then possible to obtain differences between the position of speckles in the stellar image when viewed in slightly different wavelengths. It is possible to determine these differences in the position of the speckles with an accuracy much higher than the speckle size itself using techniques which are already developed for binary star-speckle research. We propose to use the technique of "Differential Speckle Interferometry" to study stellar rotation, evolution of stellar systems, spectroscopic binaries, the mass-luminosity relation, and peculiar A stars.

INTRODUCTION

Atmospheric turbulence has classically limited the resolution of optical astronomical observations from earth to about 1 arc second until it was realized about a decade ago that the very small scale structures, called speckles, seen in stellar images obtained with short exposure times (∿ 10 millisecond) are caused by wave interference between sections of the incoming wavefront with distances comparable to the telescope aperture. Thus, these speckles contain information on the spatial structure of the object under study on scales comparable to the theoretical resolution limit of the telescope itself. For the Multiple Mirror Telescope (optical baseline 690 cm) this corresponds to 20 milliseconds of arc or an improvement of almost two orders of magnitude over the classical resolution limit as set for long exposures by the atmosphere. This very powerful technique for improving the resolution of ground based optical facilities has been exploited for studying the separation of close binary stars, for studying the angular diameters

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of giant stars and asteroids, and to improve the angular resolution of already resolved objects. Reviews of this technique and its results have been published by Dainty (1975), Labeyrie (1978), and Worden (1977).

Of particular interest in the present context is the study of close binaries by speckle interferometry because the technique for these studies is to some extent similar to that used for differential speckle imagery. The separation and orientation of the binary can be determined either by autocorrelation studies of the speckle image or by a fourier transform analysis. For binaries separated by more than the speckle diameter, the separation can be determined with an accuracy substantially better than the speckle size if sufficient photons are available. Accuracies of 0.5 milliseconds of arc have been reported (McAlister, 1978).

In "Differential Speckle Interferometry", the differences in two speckle images are studied which are obtained simultaneously in slightly different wavelengths and/or orthogonal polarizations. Because of the surface variations across the object under study, the two speckle images are slightly different. Specifically, the locations of the speckles in the two images may be different. If so, the displacement of the speckles between the two images contains information on the surface structure of the object. As is the case with binaries, it is possible, given enough photons, to measure the position of speckles with much higher precision than the speckle size. Differential speckle interferometry is a technique for generating and measuring these differences in speckle positions. It thus allows effective angular resolutions which are smaller than the speckle size.

An example of an astrophysical application is stellar rotation. A spectroheliogram taken of the sun in the blue wing of the Hα line shows the eastern hemisphere of the solar disk to be darkened as compared to the western hemisphere because of the 2 km/sec solar surface rotation rate (Figure 1). A red Hα wing spectroheliogram shows exactly the opposite effect so that the "center of gravity" of the intensity of the blue wing spectroheliogram is shifted towards the west by about 10% of the solar diameter with respect to that of the red wing spectroheliogram. When observed from a great distance as a star, a solar speckle image obtained in the blue Hα wing would therefore be shifted slightly with respect to that obtained in the red Hα wing. A measurement of this shift would give information on the (projected) orientation of the solar rotation axis and on the solar rotation velocity. Other examples of applications of differential speckle interferometry are spectroscopic binaries, magnetic variables, spectrum abundance variables, and flare stars.

INSTRUMENTATION

Figure 2 shows the optical configuration of the experiment. It is the quasi-cassegrain focus of the MMT is a reflecting plate which con-

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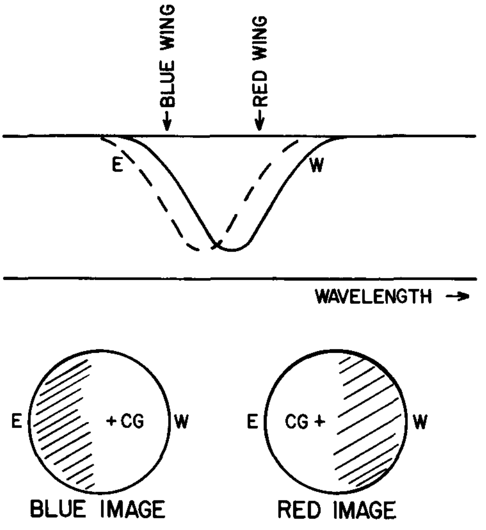

Figure 1. Effect of solar rotation on the location of the center of gravity (CG) of blue and red line wing spectroheliograms.

shown as if installed at the Multiple Mirror Telescope but it is not unique to that telescope. In the quasi-Cassegrain focus of the MMT is a reflecting plate which contains a 2 x 2 arc sec (0.556 x 0.556 mm) square aperture. The reflected light is used by the focal plane monitering system in the MMT top box. The transmitted light is collimated by a 30 mm focal length lens. This forms an image of the telescope pupil(s). Near this pupil image we will insert the narrow band filter which will transmit a different wavelength depending on the polarization used. This filter is followed by a Pockels cell which is biased with a $\lambda/4$ plate and a Wollaston prism. This assembly serves as a polarization switchable beamsplitter which causes the formation of a double image of the 2 x 2 arc sec field on the front face of the image intensifier by the 600 mm focal length camera lens. Each original single speckle is thus transformed into a speckle pair. The final speckle image is thus like that of a double star with a separation Δ and with comparable intensity components except that one of the images corresponds to one wavelength and the other to the other wavelength. Switching the Pockels cell causes the wavelengths to switch. If the differential speckle effect δ is present, this switching causes the separation of the apparent double star to change back and forth (Figure 3). Measuring the amount and direction of this dithering results, therefore, in the detection of the effect. We intend to use the Steward Observatory 4 stage extended red VARO electrostatic image tube coupled by lens to a vidicon as the detector (Hege et al 1980). The images will initially be recorded on videotape for later reduction on the Steward Observatory Grinnell digital television analyser. At a later date we plan to use a real time autocorrelation analysis system at the telescope.

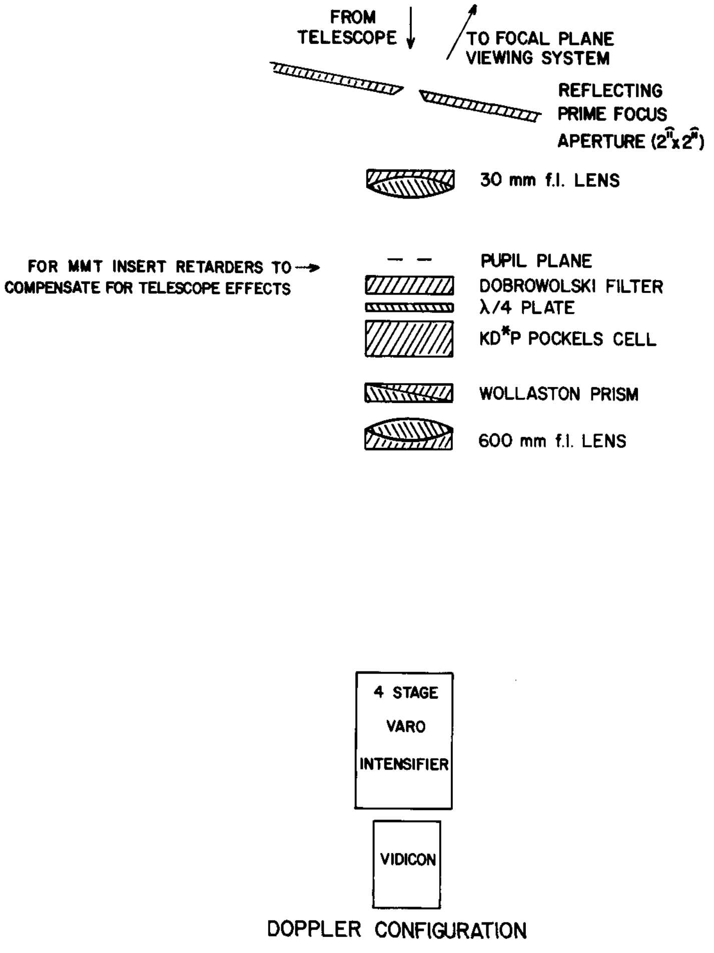

Figure 2. Schematic of the instrument.

The filter has a width 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. The properties of mica filters were described by Dobrowolski (1959).

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

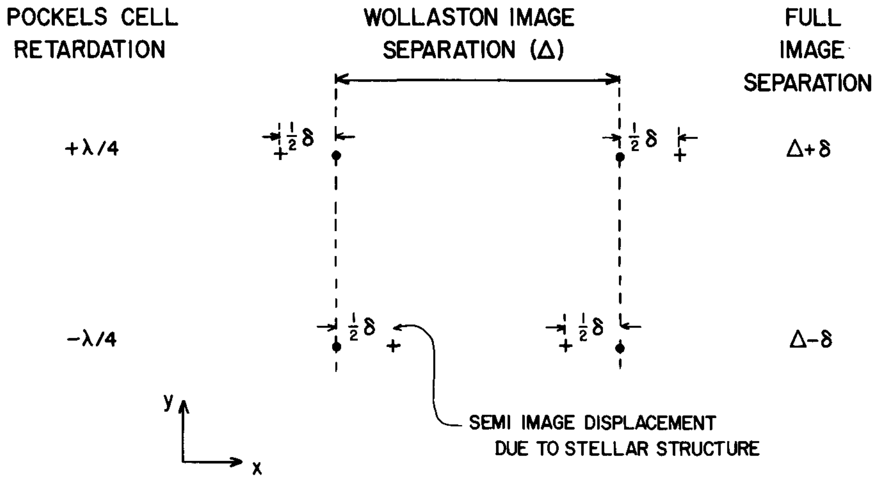

Figure 3. Speckle separations due to the Wollaston prism (Δ) and the differential speckle effect (δ).

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.

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 in the x direction 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.

ACCURACY

Figure 4 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 autocorrelation function will be noisy, the noise depending on the photon statistics in the speckle images. We 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

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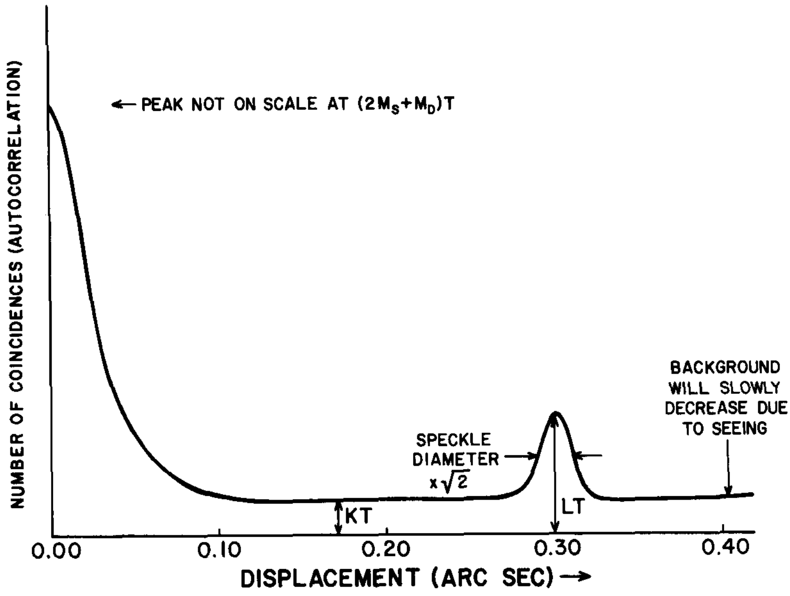

Figure 4. Sketch of anticipated autocorrelation function. See text for explanation of symbols. For a V = 5 star and 1 video frame (T = 1) $(2M_S + M_D)$ T = 201, KT = 11, and LT = 76.

Under these circumstances, and for a V = 5 object, the number of photo-electrons 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 4 (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 we estimate the accuracy with which the secondary peak can be located as 2.5 msa RMS per video frame (or 7% of the speckle size). Allowing for a factor of 5 decrease of sensitivity because of unanticipated problems, we arrive at the following accuracies for the determination of δ (in milliseconds of arc, msa):

RMS Accuracy in δ Measurement for Different Observing Times t

V =	2.5	5.0	7.5	10.0
Δδ (t = 1 sec)	0.25	2.5	(25)	(267)
Δδ (t = 1 min)	0.03	0.3	3.2	(34)
Δδ (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.

APPLICATIONS

Differential speckle interferometry will find applications wherever spectrum or polarization changes can cause displacements of the location of speckles. We emphasize here the application to stellar rotation and spectroscopic binaries. The following table lists a number of stars in the UMa Group nucleus and stream whose rotation effects can be measured in a relatively short time.

HR	Name	Spectral Type	V	Angular Diameter (msa)	v sin i (km/sec)	δ	3σ observing time (minutes)
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
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
68	σAnd	A2V	4.51	0.9	105	0.36	5
1046	-	A2V	4.98	0.9	200	0.36	10
2763	λGem	A3V	3.65	0.9	165	0.36	1
3974	21 LMi	A7V	4.47	0.7	145	0.28	10
5867	β Ser	A3V	3.74	0.9	195	0.36	1

It will therefore be possible to study stellar rotation axis orientations in some stellar clusters and binaries as well as in single stars. Stellar systems are of special interest because of the implications for the evolution of the properties of angular momentum.

The δ values for spectroscopic binaries are often in the 1 - 10 msa range which results in large differential speckle effects. These are often short period binaries so that the full orbital parameters can be determined by combining spectroscopy and speckle observations in a short time. This in turn will result in significant additions to the Mass-Luminosity relation.

CONCLUSION

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

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