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A High Speed Photometer in the Optical Region for Lunar Occultation Studies

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Abstract. High speed photometry during the lunar occultation of a stellar system provides an effective means of achieving high angular resolution in one dimension at the sub arc second level which is well suited for resolving close binary projected separations in the range of 10–100 milliarc seconds. An optical fast photometer designed for such a purpose is described and some results from the initial observations taken with the system including the resolution of a projected separation of 55 milli arcsecond in one binary system are detailed.

Key words: lunar occultation—fast photometry—photomultiplier—binaries—angular resolution.

1. Introduction

High angular resolution is one of the most challenging goals for the next generation of large ground based telescopes. Over the last few years interferometric methods for high angular resolution have reached new heights of sophistication (Alloin, D. M. and Mariotti, J. M. (Eds.), 1989). While long base line optical interferometry achieves milliarcsecond angular resolutions the major impact of speckle interferometry has been in resolving close binaries in many stellar systems (McAlister, 1985). A favourable alternative to these sophisticated techniques for achieving high angular resolution in the optical and near infrared domains is offered by the relatively simpler technique of lunar occultation. The technique consists in recording the straight edge diffraction pattern of the star light produced by the sharp edge of the moon. As the moon moves to occult the source the diffraction pattern sweeps rapidly (~ 1 km/s) across the earth's surface and can be recorded by a fast photometer. The event is over, typically in about a hundred milliseconds—hence the need for a fast photometer. The limitations of the technique are that lunar occultations are fixed-time events occurring in the zodiacal belt. It is also a one-dimensional technique as high angular resolution is obtained only along the direction of occultation. The advantage is that milliarcsecond resolutions are achievable.

Apart from the more challenging task of determining stellar angular diameters for bright stars, lunar occultation high speed observations in the optical region can also readily resolve binary and multiple systems at the level of tens of milliarcsec. The first double star discovery from a photoelectric occultation trace was made as early as 1950 (O'Keefe, 1950) when the star 22B Aur was found to be double with a projected separation of 53 milliarcsec and 0.5 mag brightness difference between components. Subsequently a triple star (BD + 27°943) was discovered by this technique which was not known to be a double (Beavers & Eitter, 1971). Single occultation measurement of a binary system provides only the vector separation between the components of the binary system and therefore multiple occultation measurements are required to get the plane of the sky separation. A discussion of discovery and measurement of occultation doubles is given by Nather and Evans (1971).

A program for observing lunar occultations in the visible and near infrared (1-5μ) region has been initiated at the 1.2 m telescope at Gurushikhar, Mt. Abu. In this paper a photomultiplier based fast photometer system which has been developed for high speed photometry for lunar occultation in the visible region is described. Some initial results pertaining to the binary nature of the occulted sources obtained with the instrument are also presented.

2. Instrumentation

2.1 *Optics*

Figure 1 shows the schematic diagram of the optical system of fast photometer designed and fabricated at PRL. The f/13 Cassegrain beam is brought to a focus at the aperture (A) where the scale size (for the 1.2 m Gurushikhar telescope) is 13 arcsec/mm. The aperture wheel has diaphragms of various sizes (Table 1) so that different fields of view on the sky can be selected as required. The filter wheel (F) has UBVRI Schott glass filters along with a clear glass filter through which initial adjustments of centring and focussing the object on the aperture can be made. Object acquisition is done through the flip mirror (M) and field eyepiece (E) arrangement. The post focal plane

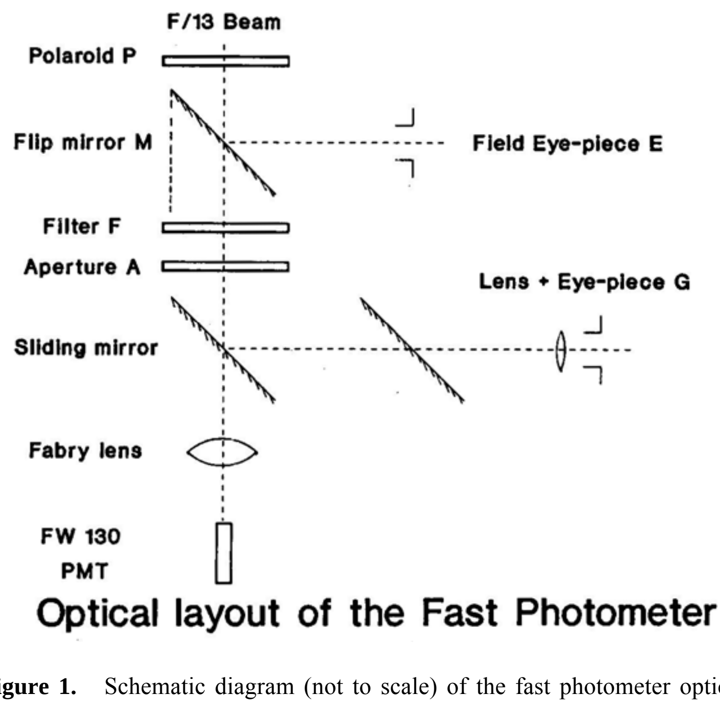

Figure 1. Schematic diagram (not to scale) of the fast photometer optics.

beam can be directed into a small lens-eyepiece assembly (G) to check on the centring of the object in the aperture whenever required. A fabry lens (focal length = 30 mm) images the telescope aperture on the sensitive surface of the photomultiplier. The optical parameters of the system are summarized in Table 1. A special requirement of the fast photometer used for lunar occultations is its ability to handle large light levels due to the scattered light from the moon. In occultation measurements what is of interest is not the absolute signal level but the changes in the signal level corresponding to fringe modulation especially during the last 50–100 millisec before the event (disappearance event) and corresponding time after the event in case of reappearance events. We have adopted a two-fold approach to tackle this problem. On the optical side a polariser – analyser assembly (P) is introduced at the entrance to the photometer to adjust the light level to be within the saturation limits of the detector electronics. The polariser approach of light attenuation is preferred over the step neutral density filter method as it offers a continuous smooth control of the light level during the crucial few minutes before an occultation. Electronic offset controls are used to further fine tune the signal level.

Use of narrow band filters like the Strömgren y filter along with smaller entrance apertures can also significantly reduce the sky background and improve S/N ratio. It is proposed to incorporate these changes in future.

2.2 *Detector*

The detector used for optical occultation measurements is an ITT FW130 (S20) photomultiplier tube. The details of the detector are given in Table 1.

In general, in the visible region, noise of the sky background from scattered moonlight dominates over the detector noise (at room temperature) even for occultation events occurring on the darklimb. Cooling the detector is therefore not necessary and the tube is operated at room temperature. Earlier a solid state stellar photometer employing a silicon PIN photodiode was used (SSP, Optec Inc.). Its time response was relatively poor for occultation measurements (~ 50ms), but it was nevertheless successful in recording the first diffraction fringe of the bright star α Leo during the occultation of 19 March 1989.

2.3 *Data Acquisition System* (*DAS*)

The data acquisition system has evolved over the years in our instrumentation starting from an 8 bit A/D used for the α Leo occultation of 1989. Presently two modes of data acquisition are being used.

a) An SR400 based system which has a large dynamic range but with a dead time of 2 millisec.

b) A frequency to voltage converter, offset controlled output system.

Mode a: The SR400 is a gated photon counter (Stanford Research Systems) and can be interfaced with a computer. It has two channels each of which can count up to a rate of 200 MHz. There are two independent gates which enable the counters and the gate width can be varied from 5 ns to 999.2 ms. The sampling intervals as well as the number of sampling can be predefined. Analog output of the digital input is available. In this

Table 1. Fast Photometer Specifications.

1. Detector			
Type		ITT FW130 16 stage Photomultiplier	
Effective photocathode size		2.5 mm (dia)	
Spectral response		S20	
Quantum efficiency		20% at 400 nm	
Photoelectron counting efficiency		> 80%	
Dark count		< 350counts/sec at 23°C	
2. Apertures			
Aperture size (mm)		Field of view in arcsec. (1.2 m f/13 Cassegrain focus)	
0.50		06.5	
0.99		13.0	
1.57		20.6	
1.95		25.6	
2.90		38.0	
3. Filters			
Size		25 mm	
Thickness		7 mm	
Filter	Central wavelength	Bandwidth	Peak transmission
	nm	nm	%
U	370	30	30
B	440	90	62
V	540	80	75
R	660	200	80
I	880	230	90
4. Polaroid Attenuator			
Size		35 mm (diameter)	
Thickness		5 mm	
Max. Transmission (%) (in V Filter)		30	
Min Transmission (%) (when crossed in V Filter)		0.5	

mode of operation, the light level is controlled optically (by polaroids) without any electronic offset.

Mode b: In this mode, which has been more extensively used than Mode a, a pre-amplifier discriminator device (A-101 PAD, Amptek Inc.) is used with the photomultiplier for a pulse output. A Frequency to Voltage converter (100 KHz/10 V) converts the pulses to an analog form which is then fed to a signal conditioner. The signal conditioner has a variable gain (0–1) and a step gain of 10,100 and also an offset facility by which the voltage level corresponding to the large lunar background can be substracted. In practice the signal due to the star in the predetermined filter is taken long before the event under low background conditions. Then as the background light level builds up with the approach of the moon, the offset is continuously adjusted to keep the signal (star + sky) within saturation limits. The star is drifted in and out of the aperture periodically to ensure that it is being properly tracked and recorded. The use of F/V converter and subsequent A/D conversion has so far been necessitated by the absence of a pulse input module which could directly record the photomultiplier pulses. This improvement is to be effected shortly.

The output of either Mode a or Mode b is an analog signal which is fed to a Keithley (Micronics Inc.) 570 data Acquisition System. The System 570 is a Data acquisition and control system interfaced with an IBM like PC-AT. It can accommodate 32 channels of single ended or 16 channels of differential analog inputs and provides two channels of high speed analog outputs. The system has hardware selectable amplifier with gain steps of 1,10 and 100 and software controllable amplifier with gain steps of 1,2,5 and 10 for analog input signals. The system uses a 12 bit A/D converter for analog data acquisition and can be sampled as fast as 33 KHz. Presently data recording at 1 millisec sampling rate is for 30 sec. centred on the predicted time of the event. A change in signal in the monitoring scope signifies a successful run. The system 570 incorporates a powerful graphics program which enables any portion of the 30,000 samples acquired during a run to be displayed and studied. Presently the data acquisition routine is triggered manually. It is proposed to make it an automatic start at a predetermined time in the near future.

So far event time has been recorded only with about 1 second accuracy. Absolute time has not been recorded at the millisec level so far. The emphasis has been on accurate relative time samples at rates of ~ 1 KHz. Efforts are underway to record absolute time also with the accuracy of ~ 1 or 2 milliseconds. A few trials have been made to synchronise with NPL (National Physical Laboratory) time signal with appropriate propagation corrections. A time signal is to be derived from this synchronised quartz clock and recorded along with the data.

3. Observations

All the observations reported here were carried out at the 1.2 m telescope at Gurushikhar (72°47'E, 24°39'N). The details of the observations are given in Table 2.

Several difficulties such as sudden power failures, instrumental failures, detector saturation due to strong moon's background light and occasionally cloudy sky were encountered in occultation observations. In some cases the object was lost, at the crucial moments before the event and could not be centered due to the strong background

Table 2. Observational details of the occulted sources.

Source	SAO Number	Date	Time (IST) h	m	s	m_v	Sp type Class	Filter	FPA[1]	P.A.[2] Deg.	Alt Deg.	Instrument
αLeo	098967	19 Mar 89	21	10	42	1.30	B7 V	clear	6	111	62	SSP[3]
ZC1466	098876	15 April 89	23	58	36	5.26	B9 IV	clear	6	132	46	SSP
ZC0089	109369	31 Jan 90	21	17	09	6.50	F5	B	21	49	23	FP[4]
ZC0518	075999	03 Feb 90	23	41	34	5.90	A3 V	B	12	96	30	FP
ZC0701	076682	05 Feb 90	00	36	33	6.50	F0	B	12	62	34	FP
ZC0840	077295	05 Feb 90	21	01	46	6.50	K2	I	12	66	86	FP
ZC1549	118376	06 April 90	20	36	00	5.1	G8 I–III	V	12	55	61	FP
ZC1336	098247	27 Feb 91	01	43	16	5.20	A3	V	12	138	53	FP
ZC1015	078557	23 Mar 91	23	16	04	6.40	A2	V	12	43	35	FP
ZC1019	078572	23 Mar 91	23	32	27	6.70	A5	V	12	67	32	FP

[1]Focal Plane Aperture (arc sec) [2]Position Angle of occultation
[3]Solid State Photometer [4]Fast Photometer

light. So far the efficiency factor of observing an event successfully is only about 50% but it is likely to improve with system tuning and experience. Further, so far only disappearance events at the dark limb have been recorded. For reappearance events, the telescope tracking must be good enough for a star to remain in aperture of < 10 arcsec for ~ an hour. It is to be tried out in the near future, which will then double our observational capability.

Since the horizontal parallax of the moon is approximately 1°, occultation predictions have to be generated for particular observing sites. We generate our own occultation prediction for any object. These predictions agree very well with the predictions supplied by International Lunar Occultation Centre (ILOC, Tokyo) for bright stars ($m_v < 8$). As a precautionary measure we acquire data for 30 seconds at 1 KHz rate (1 millisec sampling) ±15 seconds centered on the event. The event is also visually observed at the finder telescope and analog output voltage fed to the data acquisition system is also monitored on a scope.

The occultation of α Leo on March 19, 1989 was one of our earliest attempts in recording a lunar occultation. A Solid State Photometer (SSP–I) was used without any filter. The detector used was a 0.5 mm Silicon PIN diode (OPTEC Inc.). The data was recorded with an 8 bit A/D converter. Inspite of these drawbacks the sytem did record the first diffraction maximum from α Leo (Fig. 2). The fringe patterns obtained with this relatively crude system provided the encouragement for building a more sophisticated system for occultation measurements in the visible region using a

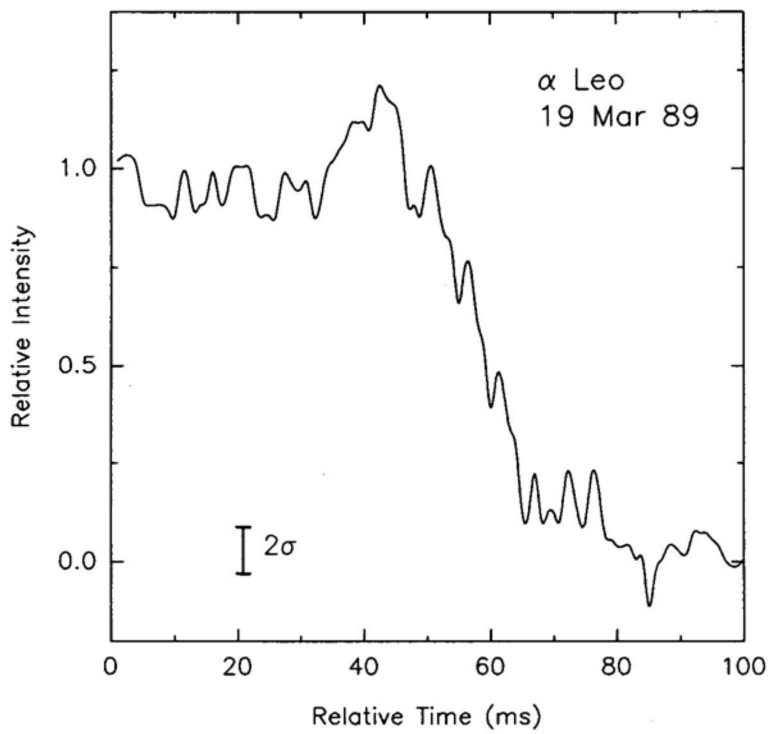

Figure 2. Occultation trace of α Leo observed on 19 March 1989. The large noise level is due to imperfect stellar image over filling the detector area. First fringe maximum can however be seen.

photomultiplier based system. Subsequently eight other optical lunar occultation events have been observed successfully, the details of which are given in Table 2.

4. Discussion

Observations of a single occultation event involving a multiple star produces a trace in which diffraction patterns of the components, separated in time, are added linearly. Analysis of the trace provides the difference in occultation times of the individual components and their relative brightness. From the geometry of occultation, knowing the velocity (V) of the lunar limb perpendicular to itself at the position occultation occurs, these time differences can be converted into angular separations. A single occultation provides only a projection ρ (in the direction perpendicular to the lunar limb) of the true separation ρ_0 (Fig. 3) such that $\rho_0 \cos(\theta - \theta') = \rho$ where θ' is the position angle defining the point of occultation and θ true position angle of the binary system (White, 1977). Observations of the same occultation from several sites provides a range of θ'. Repeated observations of occultations of a given star from a single site during many lunations or even during an 18.6 year nodal rotation period can provide a range of θ' and lead to true separation ρ_0 Details of the technique are discussed in Evans *et al.* (1977). However a large number of double stars measured by lunar occultation have been observed only once.

In the catalogue of photoelectric occultation observations prior to 1981 provided by Evans (1983) out of 3074 stars observed 224 (7%) were detected as double. For stars brighter than V= 6.7, 17% of the 342 stars were found to be double. The mean vector separation of double stars was 260 milliarcsec (mas) decreasing to 150 mas for stars brighter than V= 6.7. Internal errors were 13 mas.

The details of the optical occultation events observed successfully by us are as follows: Two of them (SAO 075999, SAO 076682) are multiple systems.

SAO 075999 is a triple star system with the fainter (10^{th} mag) third star well separated

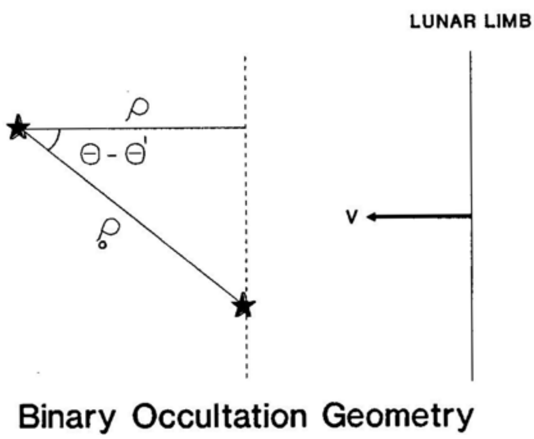

Figure 3. A simplified picture of a binary occultation. V is the velocity component of the moon perpendicular to the limb at the position angle (θ') of occultation assumed the same for both components of the binary. Position angle of the binary system is denoted by θ. θ and θ' are measured from celestial North through East.

(22.4 arc sec) from the double stars. The bright stars are almost of equal brightness, m_1= 6.6, m_2 = 6.7, m_1+ m_2 = 5.9, B – V= 0.13. The absolute visual magnitude is M_V = 1.7, the spectral type is A3 V and the distance to the system is ~ 65 pc (spectroscopic parallax). Orbital elements of the binary system suggest a period of revolution of 568 years and a semi major axis of 650 milliarcsec in 1990. As the position angle of the binary system is very small presently (θ_3 = 3°) the observable separation by lunar occultation technique is a small fraction of the actual value. The star system had been observed earlier by Evans (1971) [Run no. 1226 on 17 Jan 1970]. The timing for the second star was recorded, the first having gone 1.5 sec sooner and failed to register.

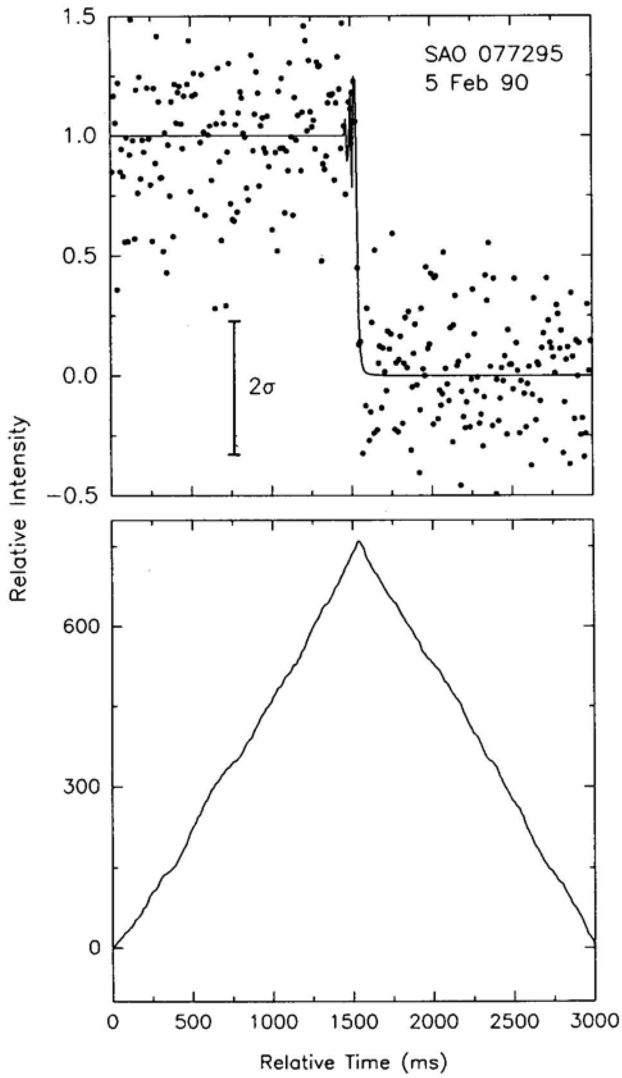

Figure 4a. Occultation data along with the integral curve are given for the observations of SAO 077295 (m_v = 6.5, K2). The source is not a binary as can be seen from the triangular shape of the integral curve. The main source of noise in the data is the sky photon noise due to the bright sky near the moon. 2σ error bar corresponding to this noise is shown.

A sensitive method of detecting binaries in occultation traces, in the presence of noise, involves computing the so called 'integral curve' (Dunham *et al.* (1973), Feirman (1987)). This curve is the running sum of deviations from a segment's mean raw data value ($\bar{I}$), plotted against time. A point $A(t)$ on the integral curve can be represented by

$$A(t) = \sum_{n=0}^{n=N} (I(t) - \bar{I})$$

where $t = t_0 + n\tau$ and τ is the sampling interval. The starting time t_0 is chosen to be typically several seconds before the occultation.

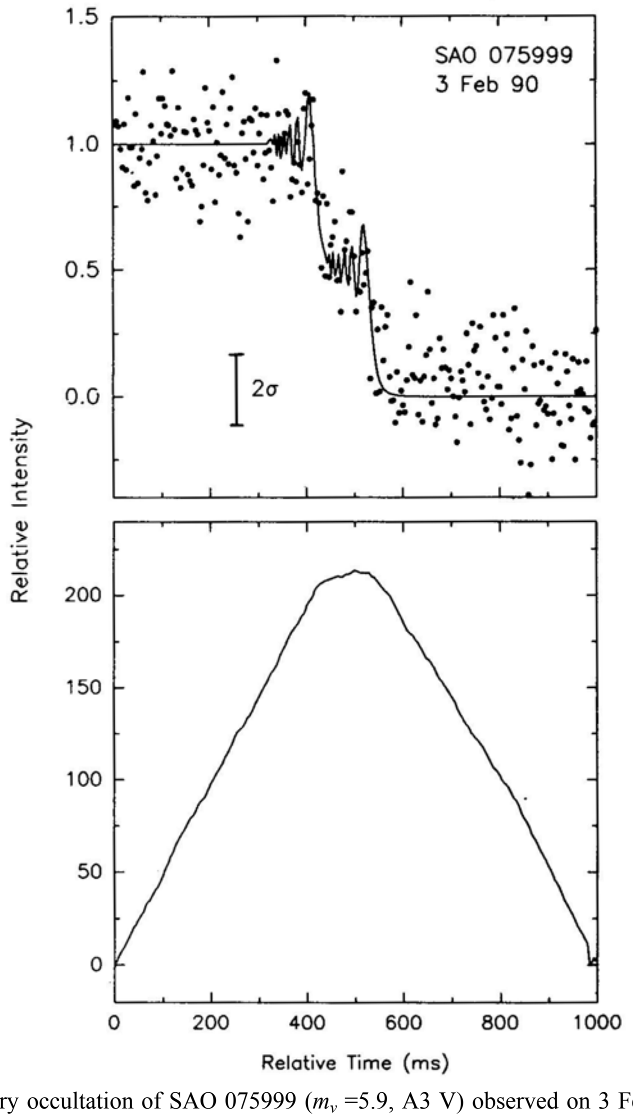

Figure 4b. Binary occultation of SAO 075999 (m_v =5.9, A3 V) observed on 3 Feb 1990 in the B filter. The component stars are of equal brightness and are seen clearly separated by 108 milliseconds corresponding to 55 milliarcsec. A composite point source diffraction pattern is fitted to the data.

The curve exhibits a positive slope before occultation which changes sharply to a negative slope after occultation in the absence of a binary. Fig (4a) depicting the occultation of SAO 077295 illustrates this case. For a binary system, the steeply rising curve before occultation flattens out before changing to negative slope. The extent of the flat portion is a measure of the projected binary separation in the direction of occultation. The integral curve is plotted as calculated and is not the result of any least square analysis. The error involved is unlikely to exceed a few milliseconds. From the integral curve of SAO 075999 (Fig. 4b) we find a binary separation of ~ 108 millisec corresponding to 55 milliarc sec. The observed values are consistent with the known

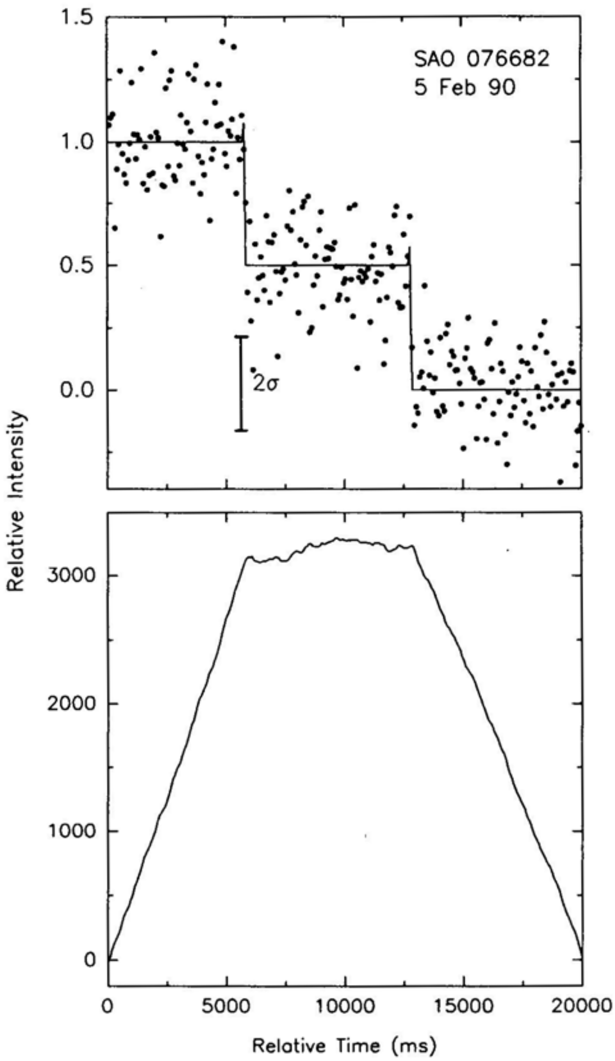

Figure 4c. Occultation data along with the integral curve are given for the observations of SAO 076682 (m_v = 6.5, F0). Integral curve clearly shows the binary with a separation of 4.4 arc seconds. The stars are of equal brightness. A composite point source diffraction pattern is fitted to the data, but the fringes are not evident in the figure as the time span covered is 20,000 milliseconds.

binary separation of 650 mas, position angle of the binary system of ~ 3° and a lunar slope of ~ – 2°.

SAO 076682 is a visual binary of visual magnitude 6.5 and of spectral type F0. The individual stars are of equal magnitude $m_1 = m_2 = 7.3$. From our observation (Fig. 4c) it is seen that the system has a binary separation of ~ 4.4 arc seconds. This binary system was earlier observed by Evans (1971).

Apart from SAO 075999 and SAO 076682 we find from the integral curves that the observed sources are not occultation binaries. SAO 118376 ($m_v = 5.1$, G8I–III) (Table 2) had been observed earlier (Eitter and Beavers (1974) and Evans (1971)). The lunar background noise in visible wavelengths through the 12 arc second focal plane aperture is large enough to mask the optical fringes except in bright sources like α Leo and hence the angular diameter information of the occulted optical objects could not be obtained. This minimum focal plane aperture size was necessitated by the optics of the Gurushikhar telescope. Presently the contrast factor in detecting binaries is not large due to the large focal plane aperture. Companions fainter than about magnitude $m_v \sim 8$ are unlikely to show up in the occultation traces. A significant improvement in S/N is likely when the telescope optics is improved sufficiently to allow us to see limited, smaller apertures of a few arcsec. It is also proposed to use the instrument at the 1 m telescope at Kavalur soon, to make use of its better optics. It is significant to note that even with the present limitation of the telescope optics we could obtain angular resolution of ~ 55 milliarc seconds in one multiple star system in the visible wavelength which is much below the seeing limit.

5. Conclusions

A high speed photometer has been developed for occultation measurements. Initial observations with this instrument have been encouraging and have led to the following results.

1. The projected observed angular separation between two close stars in the triple star system SAO 075999 is ~ 55 milliarc seconds and the slope at the point of occultation is ~ – 2°.
2. The projected observed angular separation between the visible binary system SAO 076682 is ~ 4.4 arc seconds.
3. The other occulted objects do not have companions brighter than about magnitude $m_v \sim 8$.

While the photometer has been primarily built for observations of lunar occultations of stellar systems in the optical region, the flexibility of the data acquisition system permits its use as a high speed photometer in other areas of astronomy. High time resolution studies of flare stars, millisec pulsars, some cataclysmic variables and optical counterparts of rapid varying X-ray sources are some of the other areas where the instrument will find use in the near future.

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References

Alloin, D. M., Mariotti, J. M. 1989 (Eds.), *Diffraction-limited imaging with very large telescopes,* Kluwer Academic Publishers.

Beavers, W. I., Eitter, J. J. 1971, *Astr. J.,* **76,** 1131.

Dunham *et al.* 1973, *Astr. J.,* **78,** 482.

Eitter, J. J., Beavers, W. I. 1974, *Astrophys. J.,* **28,** 405.

Evans, D. S. 1971, *Astr. J.,* **76,** 1107.

Evans, D. S. 1983, in *Proc. IAU Coll.* **62,** p. 63.

Evans, D. S., Africano, J. L., Fekel, F. C., Montemayor, T., Palm, C., Silverberg, E., Citters, W. V., Wiant, J. 1977, *Astr. J.,* **82,** 495.

Feirman, B. H. 1987, *I. A. P. P. P. communication* No. **28,** 1.

McAlister, H. A. 1985, *A. Rev. Astr. Astrophys.,* **23,** 59.

Nather, R. E., Evans, D. S. 1971, *Astrophys. Space Sci.,* **11,** 28.

O'Keefe, J. A. 1950, *Astrophys. J.,* **55,** 177.

White, N. M. 1977, *Revista Mexicana de Astronomia y Astrofisica*, **3,** 43.