DIGITAL SPECKLE INTERFEROMETRY TO MEASURE THE ANGULAR DIAMETERS OF FAINT OBJECTS

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ABSTRACT

We have developed a digital speckle camera for use on the University of Arizona 90-inch telescope. This camera uses a CID detector to provide photon locations in an image, or an analog image for brighter objects. We have used this system to observe Saturn's satellites Rhea and Iapetus. Using a correlation speckle technique, we have determined the angular diameter of these objects to be 1487 ± 40 km for Rhea, and 1200 ± 132 km for Iapetus.

1. INTRODUCTION

Speckle interferometry has been well demonstrated as a method for obtaining near-diffraction limited information from large astronomical telescopes[1-4]. However, results are often difficult to calibrate. Moreover, the necessity of obtaining exposures short enough to freeze turbulence in the Earth's atmosphere ($t \lesssim .03$ sec) has limited speckle reductions to brighter objects. The development of self-calibrating data reduction schemes[5-6] and fast two-dimensional photon counting detectors has enabled us to apply speckle techniques to fainter objects.

In this paper we describe the Steward Observatory Digital Camera and data reduction method. We have used this system to measure angular sizes for Saturn's moons Rhea and Iapetus. Previous size determinations of these objects are based on lunar and stellar occultations. Speckle interferometry can be an useful check on these results, and can be applied at any time,

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so that specific interesting objects and occurances may be observed at the ideal time. For example, in this paper we report observations of Iapetus at its minimum brightness (Iapetus varies by over 1 magnitude from one side to the other).

2. DATA AQUISITION

The instrument and detector system have been described by Strittmatter and Woolf[7]. The speckle instrument package consists of: 1) a rotating, gravity aligned prism system to correct for atmospheric refraction, 2) a main module containing a microscope objective to expand the image scale, a guide and alignment system, and filter trays, 3) the image intensified package consisting of two three stage Varo image tubes coupled by a transfer lens. The detector system consists of a General Electric TN2200 CID camera with a 128 x 128 element pixel array on 46 μm centers giving a square sensor 5.9 mm on a side. A computer supervised camera control which contains a four micro-second 8 bit A/D converter manages the CID array. This controller has a selectable clock rate and other controls for a high speed shutter and auxiliary equipment. Between the camera control and the actual interface to the control computer there is a high speed 8 bit multiplier which can be bypassed or inserted into the digitized video data path or may be made available directly to the processor for high speed 8 bit multiply operations.

The control computer is an 8 bit Z-80 microprocessor capable of 4 MHz operation coupled to a 64K 300 nsec static RAM memory. This memory is sufficient to hold image acquisition and analysis programs and still have room for two completely digitized frames of data. Also included is an on-line video display consisting of a simple XYZ (X, Y, Intensity) monitor capable of displaying 8 bit digitized data on all three axes. This image acquisition system is linked by a data-interface to a host computer for recording frames on disk and magnetic tape and for other data reductions. With the micro-processor running at its 4 MHz clock rate, the system is capable of acquiring and storing 8 bit digitized pixel data for a complete 16,384 element frame in 80 msec.

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When the camera is operated at -25°C the camera noise is significantly less than the least significant bit (l.s.b.) of the 8 bit A/D converter. In the configuration used with the speckle camera application, the primary camera image was acquired with a three-stage 40 mm Varo image intensifier. The phosphor output of the image intensifier was reimaged on a second three-stage 40 mm Varo image intensifier using an f1.0 Repro-Nikkor 1:1 transfer lens. To reduce dark emissions, the image intensifiers were operated at about -15°C. With both transfer lenses at f/1.4, single photoelectron events can be imaged on single pixels with amplitudes of more than 100 l.s.b.

This system may be programmed to output either an analog image, or X and Y coordinates of photon events. At about 10th magnitude crossover to single photon coordinates mode becomes feasible, since there are few enough photon events in a 40 ms exposure to prevent overlap of photons.

The data used in this analysis were obtained in analog mode on the nights of 16 and 17 April UT 1978, using this system with the Steward Observatory 229 cm telescope. A log of observations for these data is provided in Table 1. An example of these data is shown in Figure 1, a speckle image of Rhea. These data all have 40 ms exposure times. 400 frames of Rhea were obtained on 17 April, 240 frames of Rhea on 16 April and 240 of Iapetus on 17 April. To provide a check of our reduction method, point source stars were observed on both nights. To obtain an accurate measurement of the effective image scale we placed a double slit mask with a known slit separation over the primary baffle. This effectively made the 90" telescope a double slit interferometer. We used speckle data on bright stars obtained through this mask to calibrate the image scale as described by McAlister[8]. We found we could determine the image scale to ± 2% in this manner. For both nights we used image scales such that there were 2-4 resolution elements per diffraction spot size.

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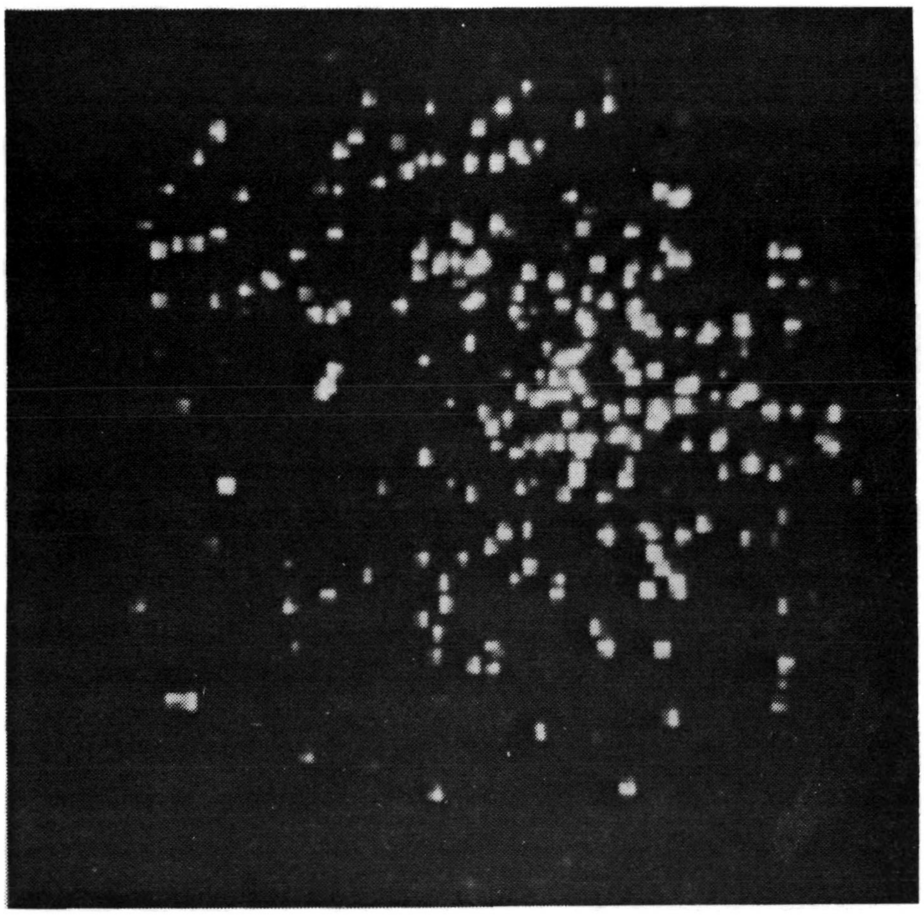

Figure 1: Digital Speckle frame of Rhea taken on 17 April 78 with the Steward Observatory speckle camera and 90-inch telescope. Data taken in analog mode.

Table 1

Log of Observations

Date	Time (UT)	Object	Wavelength (Å)	Number of Frames
16 Apr 78	05:32 - 05:43	Rhea	6500	160
16 Apr 78	06:15	α Boo (Double Slit Calibration)	6500	40
17 Apr 78	04:40	α Leo (Double Slit Calibration)	6500	50
17 Apr 78	05:20 - 06:00	Rhea	6500	400
17 Apr 78	07:10 - 07:40	Iapetus	6500	240
17 Apr 78	09:43	SAO 098777 (point source)	6500	80

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3. DATA ANALYSIS

Our data reduction method is that described by Worden *et al.*[5]. This method is a self-calibrating method which yields a telescope diffraction limited autocorrelation of an object. We briefly summarize this method here. A subset of our data containing 80 consecutive speckle frames constitutes as independent data set for estimating the object diameter. We compute the digital autocorrelation of these 80 frames using the Sacramento Peak Xerox Sigma 5 computer, where the autocorrelation of an image $I_n(x)$ is given by the following

$$AC(\Delta x) = \int_{-64}^{+64} I_n(x) \cdot I_n(\Delta x - x)dx \qquad (1.)$$

We then compute the cross-correlation between consecutive frames I_n and I_{n+1} by replacing $I_n(x)$ in (1) by $I_{n+1}(x)$

$$XC(\Delta x) = \int_{-64}^{64} I_{n+1}(x) \cdot I_n(\Delta x - x)dx \qquad (2.)$$

We sum the auto- and cross-correlations over the 80 frame set, and subtract the latter from the former Welter and Worden (1978) have shown that the result is a telescope diffraction limited autocorrelation. An example of these data for Rhea, Iapetus and a point source star is given in Figure 2. We note that the cross-correlations must be between frames obtained far enough apart in time so that atmospheric perturbations are uncorrelated. Our data was obtained with 3 sec between frames. With this delay the diffraction limited portion of each frame should be completely uncorrelated with subsequent frames. The resulting function, the autocorrelation of seeing free telescope image, may then be used to extract size and shape information on the object.

We derive the angular diameter by computing diffraction limited autocorrelations of various size uniform disks until the result matches the program object autocorrelation. This fitting may be accomplished in several ways. In this analysis we noted that both our results and the theoretical profiles showed a linear fall-off with angular distance. To

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derive angular diameters, we fit straight lines to both the theoretical data and our results. We note that it was necessary to avoid the large spike due to photon events correlating with themselves at zero, as well as to avoid using the values near zero at large angular distances, since these values showed a small tail not present in the theoretical results. This procedure had proved to work as well on asteroid data in a more sophisticated analysis used in previous work[5]. The uniform disk which best fits the observation is then adopted as the object size. Our results for Iapetus and Rhea are listed in Table 2. Errors were determined from the variation between diameter determinations for each independent data set. The data for 16 Apr 78 is less accurate due to an uncertainty in the image scale determination. Therefore, we have separated this data from the 17th April data and have not included it in our adopted diameters.

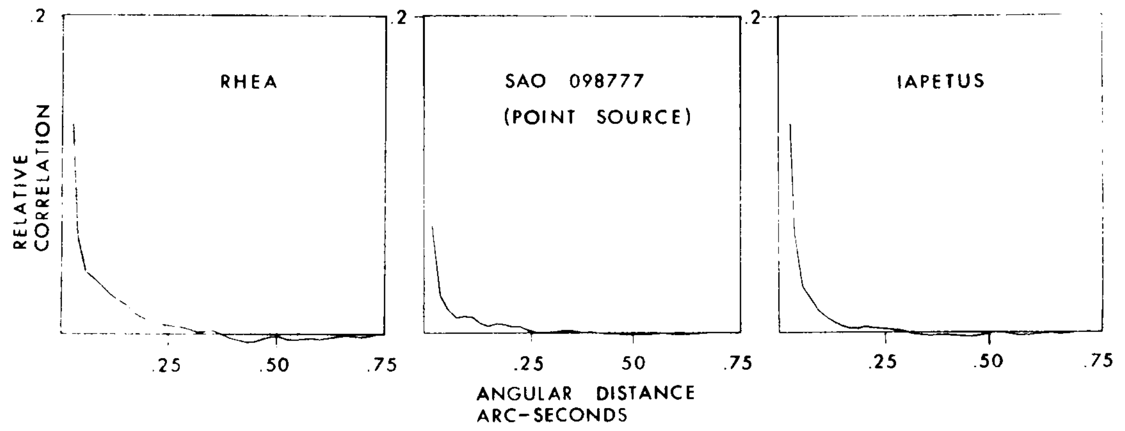

Figure 2: One-Dimensional profiles of the derived diffraction limited autocorrelation for a) Rhea, 17 Apr UT, b) SAO 098777, (point source) 17 Apr UT, c) Iapetus, 17 Apr UT.

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Table 2

Diameter Results

Object	Date (UT)	Angular Diameter Uniform Disk (Km)	References
Rhea	16 Apr 78	1230 ± 120	this work
Rhea	17 Apr 78	1487 ± 40	this work
Iapetus	17 Apr 78	1200 ± 132	this work
Rhea	30 Mar 74	1407 ± 78	Elliot *et al.*[9]
Iapetus	30 Mar 74	1388 ± 115	Elliot *et al.*[9]

4. SUMMARY

Our diameters for Iapetus and Rhea match the lunar occultation results (Elliot *et al.*[9]) to within the errors in the previous work. The occultation results of Elliot *et al.*[9] indicate substantial limb darkening for these objects. However, we were unable to determine limb darkening due to lack of enough data to perform a two parameter (diameter and limb darkening) fit to our results. We hope to obtain sufficient data in the future to determine limb darkening

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DISCUSSION

F. Roddier: I would like to make a comment about your calibration method. It can be correct for large values of D/r_o but may give spurious results for small values of D/r_o, as shown by computer simulations we have made using a log normal model for the complex amplitude of the distorted wavefront.

S. P. Wordern: This is true.

P. Nisenson: Doesn't the cross-correlation subtraction depend on accurate image-to-image centering?

S. P. Worden: Yes, with a suitably large number of photons, say more than 20, we can and must center each photograph before processing. Otherwise a spurious signal at large angular distances ($\sim$ 0."5) results.

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