SPECKLE INTERFEROMETRY IN THE NEAR INFRARED

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ABSTRACT

The use of Stellar Speckle Interferometry has been extended to the near infrared using a single element detector. Preliminary measurements indicate that diffraction limited information is available in this wavelength region.

1. INTRODUCTION

We shall describe here a method of performing stellar speckle interferometry in one dimension in the wavelength range 1-5μm.

2. METHOD

The technique involves sampling the spatial frequency power spectrum of the instantaneous image using a series of spatial frequency filters in the focal plane of the telescope (see figure 1). The filters are used sequenti-

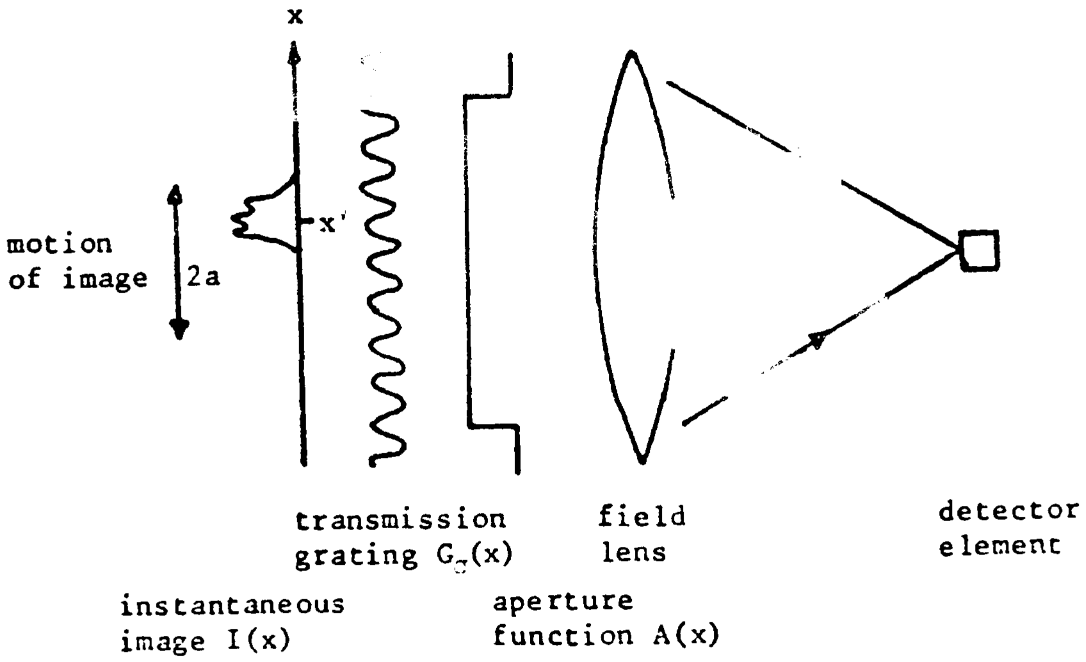

Figure 1. One dimensional spatial frequency filter $I(x)$, $G_o(x)$ and $A(x)$ all lie in the focal plane of the telescope.

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ally and consist of line gratings across which the image is oscillated so as to produce a modulated signal on the detector at a quasi-constant frequency. The power in this signal (after the DC and harmonics of the filter frequency have been rejected) is then proportional to the spatial frequency power in the image at the frequency of the grating.

3. INSTRUMENT

The detector used is a single element indium antimonide photoconductor and is cooled using liquid nitrogen. The infrared filters and gratings are also cooled, in order to reduce the background radiation falling on the detector. The arrangement inside the detector cryostat is shown schematically in figure 2.

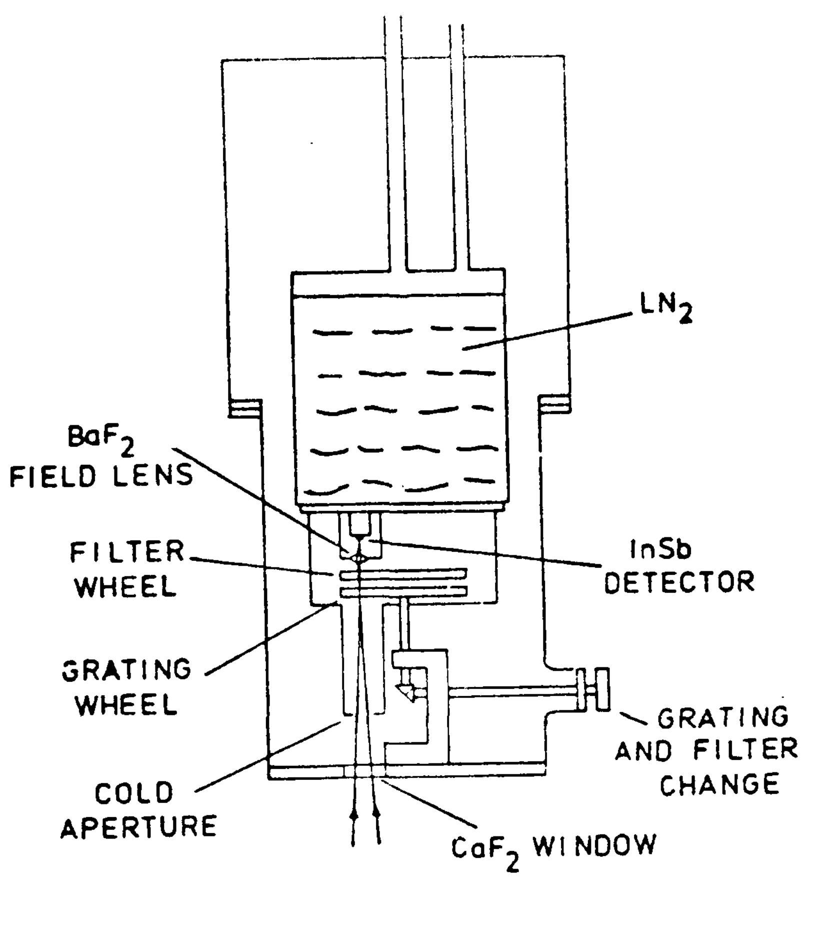

Figure 2. Detector Cryostat

The sawtooth motion of the image across the grating is produced by a servo-controlled two-mirror focal plane chopper[1], the principle of which can be seen in figure 3. The advantages of this type of chopper for this application

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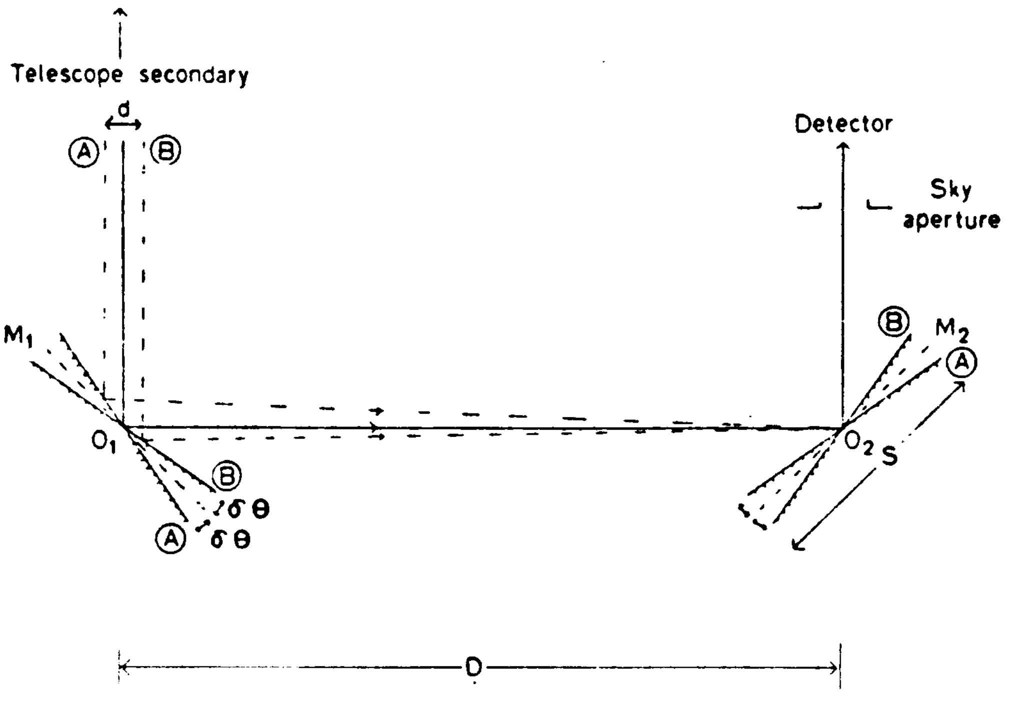

Figure 3. Two-mirror chopping system

are: a) the negligible amount of defocusing during the motion, and b) the highly accurate waveforms obtainable. The chopper control is programmed to give the same modulation frequency on the detector for all gratings, the fr quency chosen being 120 Hz. The oscillatory motion of the chopper produces periodic signal on the detector so that the power spectrum of this signal i line spectrum, the harmonic spacing being equal to the frequency of the cho With the coarse gratings this line spectrum is easily observed, see figure whereas for the fine gratings the spectrum is of the form shown in figure 4 The bandwidth here is produced predominantly by changes in the image which occur over a characteristic time t_o so that the bandwidth $\Delta B \simeq 1/t_o$; our measurements indicate that at $\lambda = 2.2\mu m$, $t_o \simeq 60$ ms.

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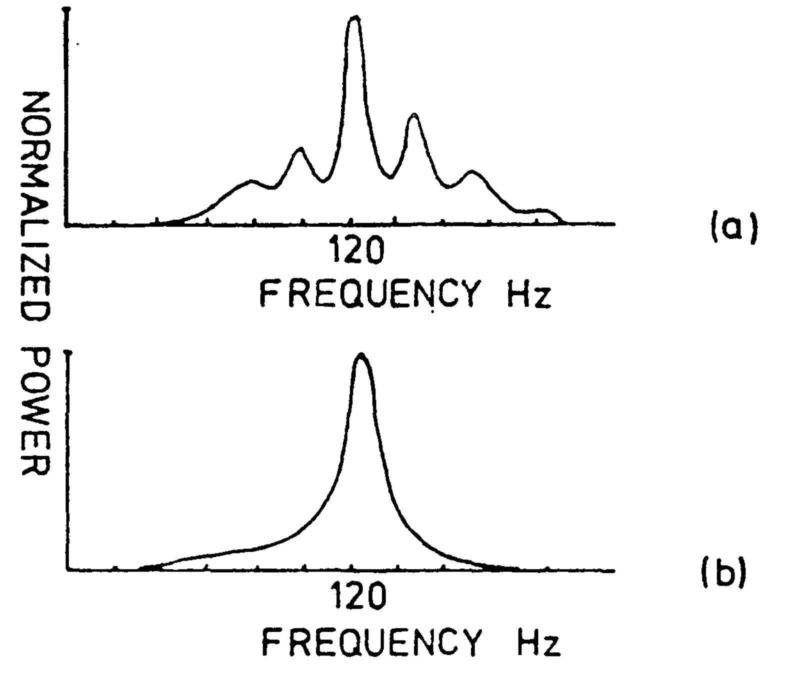

Figure 4. Power spectrum of signal from detector for
a) grating with 2 lines per mm
b) grating with 7 lines per mm
The star was μUMa at 2.2μm

4. DATA REDUCTION

The signals from the detector are recorded in analogue form on magnetic tapes which are analysed using an Interdata 70 computer with CAMAC interfacing and two 2½ mega-byte magnetic discs.

On-line analysis at the telescope has not been possible due to the high data rates required, although a computer-controlled spectrum analyser provides a "quick look" facility during the observations.

All data reduction computer programs have been written in the high level interactive language FORTH. After digitization at a rate of 400 samples sec^{-1}, the data is stored in 512 number blocks on magnetic disc. The autocorrelation function is then calculated for each block, co-added and then Fourier trans-

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formed to give the power spectrum. The integrated power spectrum over the modulation passband is used as a measure of the power in the image at the appropriate spatial frequency.

5. OBSERVATIONS

Observations have been made at the Cassegrain focus of the 1.5m Flux Collector on Tenerife, Canary Islands. The standard J, H, K, L, M photometry filters were used, the effective wavelengths and bandwidths of which are listed in table 1. In order to give high visibility speckles the filter bandwidths should meet the criterion[2].

Table 1

Details of infrared filters used.
The dispersion is for zenith distance = 60^o
while the resolution $\Delta\theta_D = \lambda/D$ where D = 1.5m

	J	H	K	L	M
λ_{eff} (μm)	1.23	1.65	2.23	3.45	4.94
$\Delta\lambda_{phot}$ (μm)	0.24	0.30	0.41	0.57	0.80
$\Delta\lambda=\lambda^2/D\Delta\theta_s$ (μm)	0.12	0.24	0.46	1.20	2.65
Dispersion ($\hat{\pi}$)	0.123	0.062	0.033	0.021	0.0034
Resolution ($\hat{\pi}$)	0.17	0.23	0.31	0.47	0.68

$$\Delta\lambda < \lambda^2/D\Delta\theta_s$$

where D is the telescope diameter and $\Delta\theta_s$ is the seeing angle. This ideal bandwidth is also listed in table 1 for each wavelength. As can be seen, the shorter wavelength filters are wider than required. Also given in the table are the resolution limit for the 1.5m and the atmospheric dispersion at zenith distance 60^o for each filter.

Figure 5 shows spatial frequency power spectra obtained using a point

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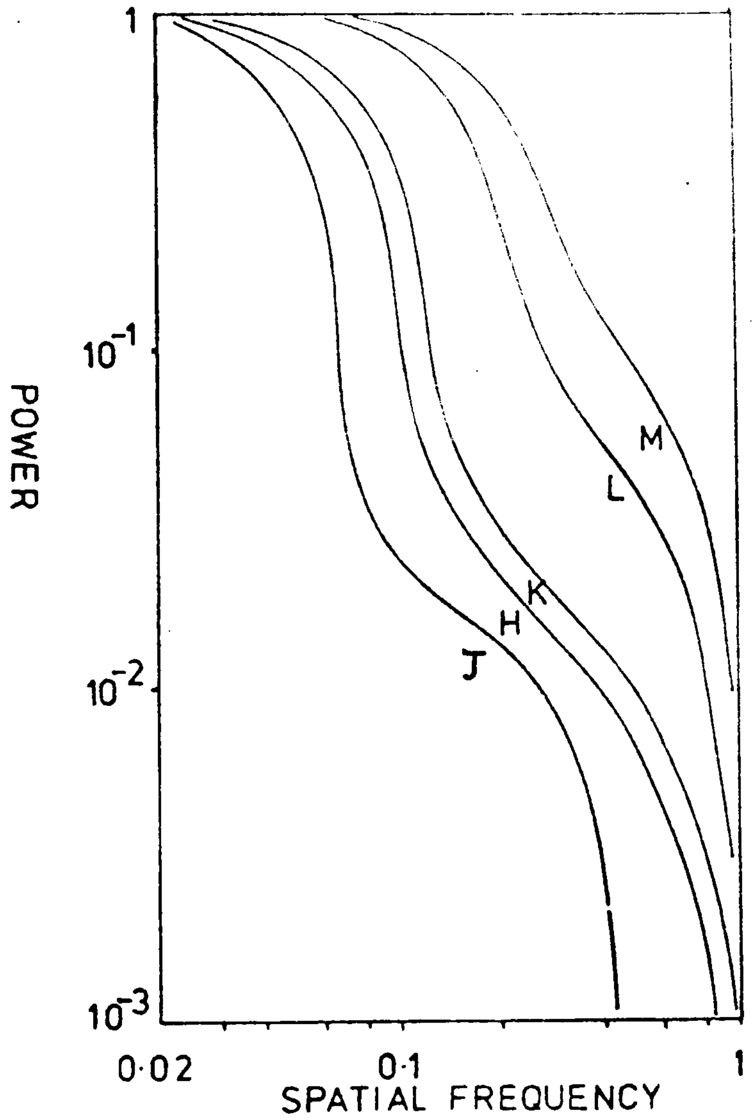

Figure 5. Spatial frequency power spectra of the point source μUMa at five infrared wavelengths. Spatial frequency normalized to 1 at $\sigma = D/\lambda$

source calibration star, for each of the five wavelengths. Diffraction limited information is retrieved on all but the J-filter; the loss of speckle visibility at this wavelength is predominantly caused by using a filter which has twice the required bandwidth.

Values of correlation scale r_o have been obtained by fitting point source power spectra to theoretical short exposure MTFs, for each wavelength. A set of such data is shown in figure 6. The data can be seen to be in agreement with the 6/5 power law predicted by Fried[3]. Young[4] suggests (based on the 6/5 power law) that the size of the seeing disc should be proportional to $\lambda^{-1/5}$, so that at $\lambda = 2.2\mu m$ it should be reduced by a factor of 0.74 compared to $\lambda = 0.5\mu m$. The values of infrared seeing predicted from our measurements of r_o are in fact in reasonable accord with those predicted from visual estimates of the seeing.

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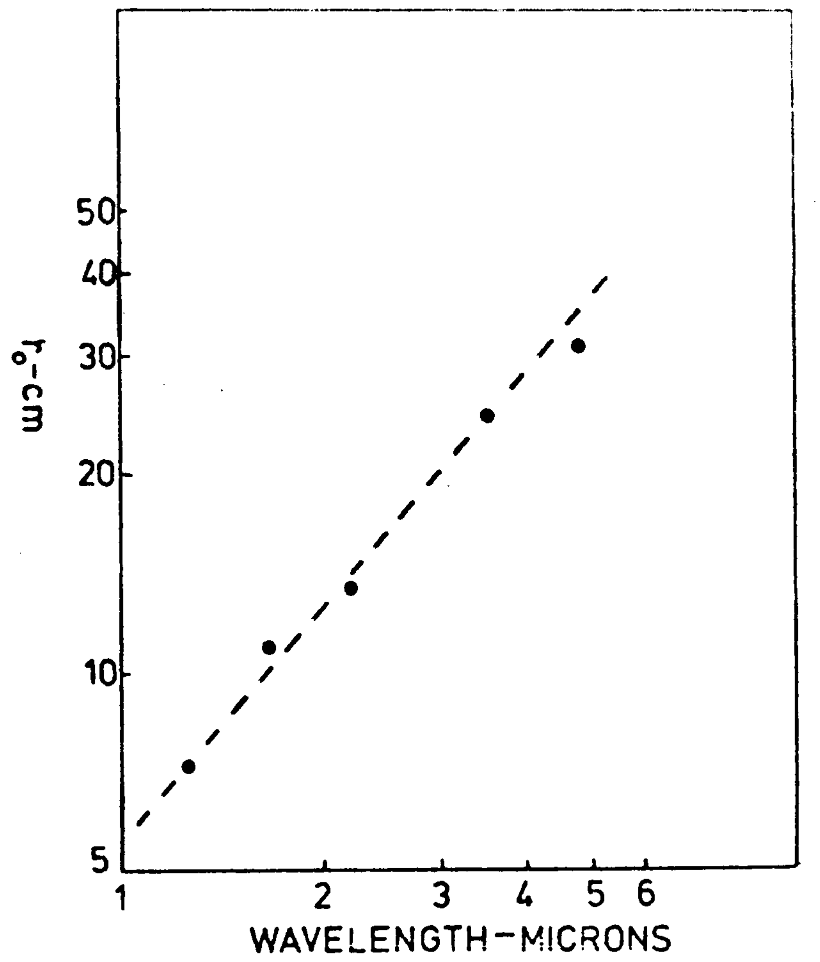

Figure 6. r_o vs λ; the line shown represents a $^6/_5$ power law.

In order to determine an object's power transform, the normalized power spectrum of its image intensity must be divided by the normalized power spectrum of a nearby point source. The feasibility of this method must ultimately depend on the stability of the atmospheric fluctuations during the measurement of the source and more importantly over the period including the calibration. Stars within 10^o of the source were selected and frequent comparisons made.

As a test the mean was taken of the normalized power spectra of four calibration stars. Each power spectrum was then divided by this mean so that the spread in these points around unity represents changes in the atmospheric transfer function over a typical observation period. The results of these tests are represented by the error bars of figure 7. Also shown in figure 7 is a set of data, divided by the appropriate point spread transfer function, for the extended source IRC+10216 at 2.2μm. Toombs et al[5] have measured this source using the lunar occultation technique and have fitted their data to a

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two shell model with shells of diameter .36" and 2" with 10-20% of the radiation at 2.2μm coming from the outer shell. Although several geometries can be made to fit the data of figure 7, we have found the best fit to be a single gaussian profile of equivalent width .35", as shown in figure 7.

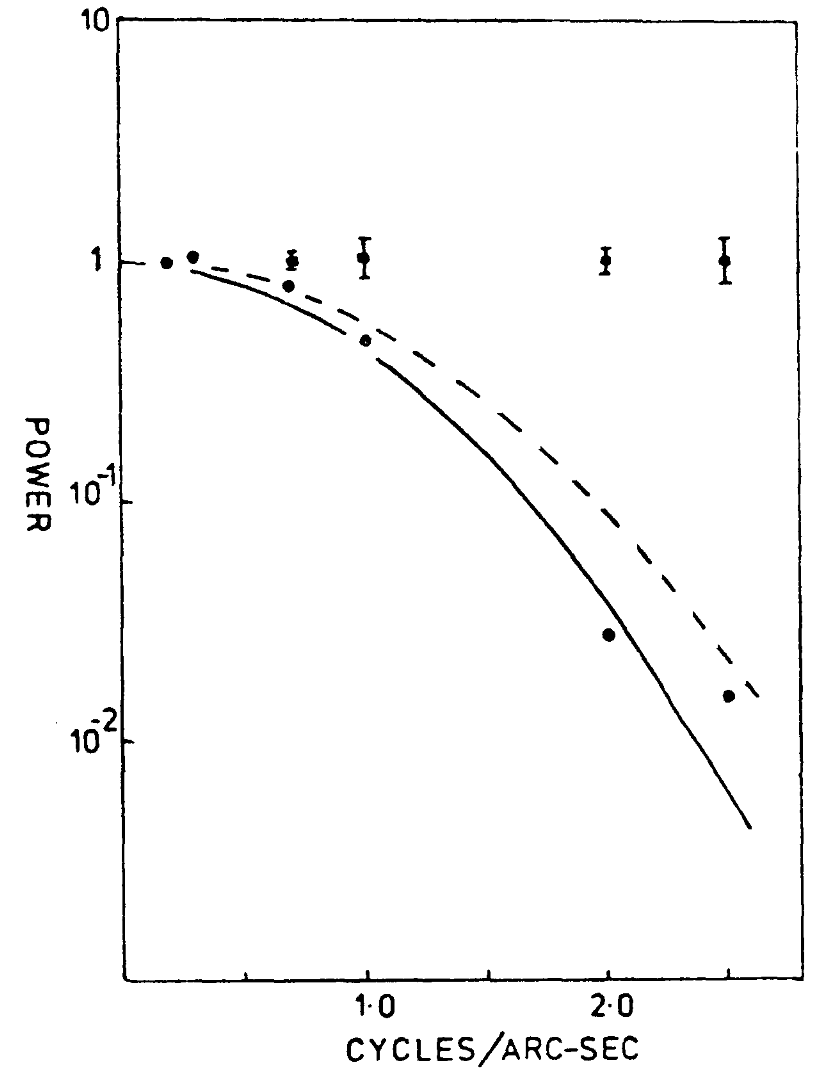

Figure 7. Theoretically predicted power spectra for

a) source extended to diffraction limit at 2.2μm (---)
b) source extended to .35" (—), compared with experimental points for IRC+10216 at 2.2μm.

Error bars represent typical change in normalized MTF over period of observation, determined by ratioing the power spectra of four calibration stars.

6. LIMITING MAGNITUDES

The limiting magnitude, m_s, for this method may be defined as the magnitude of a source with angular diameter $\Delta\theta_D = \lambda/D$ which can be resolved with a signal to noise of unity. It can be shown[6] that in the background limited case the limiting magnitude is given by:-

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$$m_s = m_{BL} + 1.25 \log_{10} \left[0.2\, r_o^2 \; (\beta t_o \tau)^{\frac{1}{2}} \right]$$

where m_{BL} is the background limited photometric limiting magnitude for a one meter diameter telescope using an integration time of one second and the standard photometry filters. τ is the total integration time and β is a factor which takes into account the width of the filter used where

$$\beta = \left[\frac{\Delta\lambda}{\Delta\lambda_{phot}} \right]^2 \quad \text{for } \Delta\lambda < \Delta\lambda_{phot} \qquad \text{otherwise } \beta = 1$$

The value of m_s is essentially independent of telescope diameter D but is a function of the seeing parameters r_o and t_o. Values of m_s and m_{BL} (calculated from measurements made on the 1.5m) are given in table 2.

Table 2

Speckle limiting magnitudes for the infrared filters J, H, K, L and M.

	J	H	K	L	M
m_{BL}	15.4	15.3	14.0	10.0	7.0
m_s	11.3	11.8	12.0	9.6	7.1

7. AN ALTERNATIVE SPATIAL FILTER

Instead of using gratings as spatial frequency filters Lena[7] has used a single slit as a broad band filter. The slit is made narrow compared to the diffraction limit of the telescope so that all spatial frequencies in the image are multiplexed. Since the resolution in the spatial frequency power spectrum is $\simeq 1/\Delta\theta_s$ and the total bandwidth is $\simeq 1/\Delta\theta_D$ then we have $N \simeq \Delta\theta_s/\Delta\theta_D$ spatial frequency information channels.

We may now compare the signal to noise available for the simple measurement of an extended source, with that available using the grating method, for the same total integration time. Two cases are of interest; detector noise limited and background noise limited situations. Now for the slit, although

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we have N times the number of spatial frequency channels, the signal power in each is reduced by N^2. In the detector noise limited case then the ratio of S/N (grating) to S/N (slit) is of order $N^{3/2}$. In the background limited case the noise is reduced in the slit method by a factor N so that the ratio becomes $N^{1/2}$. This simple argument indicates that the grating method offers greater signal to noise than the slit method when used for simple size determination.

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DISCUSSION

F. Roddier: Infrared speckle interferometry seems very promising to me. We have compared speckle MTF's observed by Pierre Lena's group with theoretical ones computed with Korff's model and have found that they agree to within 1-2%. This means that good calibration should be possible by using this model and, for instance, the method Claude Aime used on solar granulation.

M. Miller: Recent data reported by Schneiderman and Karo indicate that low frequency data from the object of interest, combined with theory (i. e., Korff's), should allow an internal calibration. This would eliminate the need for a reference point source.

D. W. McCarthy: Under what seeing conditions were your 2.2 μm measurements of IRC+10216 obtained?

R. Wade: About 2"

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