OBSERVATIONAL SPECKLE INTERFEROMETRY

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ABSTRACT

Speckle interferometry techniques have improved appreciably during the past few years. Current progress to be reviewed includes: steps towards a fully digital analysis in the photon counting mode allowing for high resolution on faint astrophysical objects (i.e. quasars), practical prospects for phase recovery procedure, and the design of compact, self-contained interferometers for on-line results at remote sites.

1. INTRODUCTION

The general availability of sensitive receptors such as photon counting television cameras and image intensifiers has resulted in a widespread use of speckle interferometric techniques by astronomers. Since the first results by A. Labeyrie et al.[1], these techniques have evolved from systems based solely on optical processing to on-line digital devices which allow real time, diffraction limited observations and measurements to be made.

2. DIGITIZED SPECKLE INTERFEROMETRY

The speckle device that we use averages the autocorrelations of the frames rather than the Fourier transforms. With 20 m sec exposures made by a photon counting camera, processing is faster using an autocorrelation algorithm adapted for low light levels. The computation time of the algorithm depends on the number of events per frame, not on the number of picture elements.

We recall the basic formulae of speckle interferometry as applied to the image, Fourier transform and autocorrelation planes, respectively, in Eqs. (1-3):

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$$I(\underset{\sim}{x}) = O(\underset{\sim}{x}) \otimes T(\underset{\sim}{x}) \tag{1}$$

$$<|\tilde{I}(\underset{\sim}{\omega})|^2> = |\tilde{O}(\underset{\sim}{\omega})| \;.<|\tilde{T}(\underset{\sim}{\omega})|^2> \tag{2}$$

$$<AC_I(\underset{\sim}{a})> = AC_o(a) \otimes <AC_T(\underset{\sim}{a})> \tag{3}$$

where

$$AC_f(\underset{\sim}{a}) = \int f(\underset{\sim}{x}) f(\underset{\sim}{x}-\underset{\sim}{a}) d\underset{\sim}{x} \tag{4}$$

In the photon counting case, if there are N photons per frame, one has

$$f(\underset{\sim}{x}) = \sum_{i=1}^{N} \delta\ (\underset{\sim}{x}-\underset{\sim}{x}_i) \tag{5}$$

where x_i are the photon coordinates and δ is Dirac's distribution.
Eq.(3) now becomes

$$AC_I(\underset{\sim}{a}) = \sum_{i=1}^{N} \sum_{j=1}^{N} \delta\ (\underset{\sim}{x}_i - \underset{\sim}{x}_j - \underset{\sim}{a}) \tag{6}$$

A "hard-wired" correlator computes the difference in coordinates for each pair of factors in a frame according to Eq.(6); it also integrates and displays the autocorrelations in real time. Binary stars can be observed with diffraction limited resolution with up to three magnitudes difference in brightness between the components and a limiting magnitude of +9 is reached in five minutes.

3. FAINT OBJECTS

At very low light levels, e.g. those that are reached in the case of a 13th magnitude quasar (3C273), the TV camera remanence and poor homogeneity in the photon event sizes become troublesome and special preprocessing is required. Consecutive clipped images are stored in the memory of a computer and the remanence is removed by the operation

$$I(t) \leftarrow I(t) \cdot \overline{I(t-20)} \tag{7}$$

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where t is in milliseconds, "·" denotes a logical "and", and $\bar{I}$ is the logical complement of the clipped image. Barycentric coordinates of the remaining photon patches are computed and used for the correlation.

A one hour sequence of 20 ms exposures on 3C273 with the 5 m (200 inch) Hale telescope has been processed this way and the quasar appears unresolved with a 2×10^{-2} arc sec resolution. Other results have been recently published.[2-4]

4. PHASE RECOVERY

Speckle imaging techniques such as the Knox-Thompson algorithm are experiencing their first successes and will allow high resolution observation of non-simple objects. The Knox phase recovery method involves computing the function

$$\langle g(\omega)\rangle = \langle \tilde{I}(\omega)\tilde{I}^*(\omega + \gamma)\rangle \tag{8}$$

where $\tilde{I}(\omega)$ is the Fourier transform of the image I(x) and γ is a small, constant frequency shift.

In the case where it would prove efficient on low level or clipped images, Eq.(8) can be computed in the autocorrelation plane; the algorithm can be computed with a speed similar to that required for Eq.(6).

Fourier transformation of Eq.(8) yields:

$$g(a) = \int \tilde{I}(\omega)\tilde{I}^*(\omega+\gamma)e^{i\omega a}d\omega \tag{9}$$

Let $\tilde{K}(\omega) = \tilde{I}(\omega+\gamma)e^{i\omega a}d\omega$:

$$g(a) = \int \int I(x)e^{-i\omega x}dx\tilde{K}^*(\omega)e^{i\omega a}d\omega$$

and $g(a) = \int I(x)K(x-a)da$

Now let $\omega' = \omega+\gamma$, and as

$$K(x) = \int \tilde{I}(\omega+\gamma)e^{i\omega a}d\omega$$

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we have

$$K(x) = e^{i\gamma a}\int \tilde{I}(\omega')e^{i\omega' x}d\omega' = e^{i\gamma x}I(x)$$

Then

$$g(a) = \int I(x)I(x-a)e^{-i\gamma(x-a)}dx$$

$$g(-a) = \int I(x)I(x-a)e^{-i\gamma x}dx$$

Assuming that photon counting is used, I(x) will be given by Eq (5) and

$$g(a) = \sum_{i=1}^{N}\sum_{j=1}^{N} \delta\,(x_i - x_j - a)e^{-i\gamma x_i} \qquad (10)$$

The computing time for Eq.(10) is proportional to N^2, and after averaging a single Fourier transform will yield $\langle\tilde{g}(\omega)\rangle$.

5. CONCLUSION

What can be imagined for future speckle interferometers is a plug-in, portable element, which when placed at the focus of a telescope will change it into a diffraction limited imaging instrument. Pending this somewhat Utopian situation speckle devices will probably invade the field of large or medium sized instruments in the next few years, leading in general to a 3- to 10-fold increase in resolution.

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