Reconstruction of extended objects from their speckle images

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Introduction

Reconstruction techniques of speckle imaging have been demonstrated to approach diffraction-limited resolution of ground-based telescopes since 1970s. There are two kinds of reconstruction techniques, one is working in spectral domain, such as Speckle Interferometry and Speckle Masking. The other is working in spatial domain, such as Shift-and-Add (SAA) and Weighted Shift-and-Add (WSA).

The former technique has a weakness of complication of calculating phase spectrum, while the latter one can avoid the complicated phase reconstruction which makes data processing much easier. But SAA needs to deal with the "ghost" and WSA is difficult to realize for extended objects, such reasons make them can't be applied widely. The key point to use SAA or WSA is to find the right datum point for shifting.

A model of high-resolution spatial reconstruction, "the greatest diffraction-limited information of object speckle image", is presented in this paper. The PSF of this model and a method--Iterative Shift-and-Add (ISA) is given. Two modified methods of ISA, Deconvoluted Shift-and-Add (DSA) and Filter Iterative Shift-and-Add (FISA), are used to reconstruct extended objects.

Theory of ISA

Through quite a few observations, LIU Zhong et al[7] come to a hypothesis about the instantaneous point spread function $p_k(x)$

$$p_k(x)=a_{mk}h(x+x_{mk})+f_k(x)$$

Where, x is 2-D coordinate, h(x) is telescope diffraction limited point spread function, a_{mk} and x_{mk} are the intensity and position of the greatest diffraction-limited information of object speckle image, $f_k(x)$ is generally called noise.

If we know the position of x_{mk}, and take this point as the point for shifting, and add lots of speckle images, then the PSF of ISA will be got, i.e.

$$\begin{aligned} p_I(x) &= \frac{1}{N}\sum_{k=1}^{N} p_k(x-x_{mk}) \\ &= \frac{1}{N}\sum_{k=1}^{N}[a_{mk}h(x+x_{mk}-x_{mk})+f_k(x-x_{mk})] \\ &= ah(x)+g(x) \end{aligned}$$

Where, $ah(x)=\frac{1}{N}\sum_{k=1}^{N}a_{mk}h(x+x_{mk}-x_{mk})$. According to convolution theorem of linear space-invariant system:

$$\begin{aligned} i_k(x) &= o(x)*p_k(x) \\ &= o(x)*a_{mk}h(x+x_{mk})+o(x)*f_k(x) \end{aligned}$$

So, $a_{mk}h(x+x_{mk})$ is the greatest diffraction-limited information of object , which is swallowed up by the other part $o(x)*f_k(x)$.

$$\begin{aligned} i(x) &= \frac{1}{N}\sum_{k=1}^{N} i_k(x-x_{mk}) \\ &= o(x)*\frac{1}{N}\sum_{k=1}^{N} p_k(x-x_{mk}) \\ &= o(x)*ah(x)+o(x)*g(x) \\ &= o(x)*p_I(x) \end{aligned}$$

Use $p_I(x)$ to deconvolve $i(x)$, we will get high-resolution object image reconstruction $o(x)$. We can observe a point stellar near the object, and use ISA to calculate $p_I(x)$.

Usually, we can take the maximum value point of the autocorrelation of the object as the greatest diffraction-limited value of object speckle image, because the position of the maximum value point of the autocorrelation of the object and the object have fixed position relation.

Theory of FISA

ISA has been proved to be effective in reconstruction of point objects such as binary stars, but 'magnified phenomena of high frequency noise' and 'correlation failure' make ISA not very successful when reconstruct extended objects. So a modified method --FISA was presented [9].

FISA uses a high-pass filter on the speckle images, in order to weaken the smoothing effect. Then takes the maximum value point of the correlation of the object speckle image as the point for shifting, and add all the shifted speckle images, to get the reconstruction of the object. Here the maximum value point of the correlation of the object speckle image was obtained from the filter and the estimate of the object. Usually the result of SAA is regarded as the estimate of the object.

Theory of DSA

DSA is another modified method of ISA[9]. First, an estimate of the object is created by SAA. Then deconvolve it from the speckle images. The remaining part after deconvolving can be looked as the atmospheric instantaneous point spread function. The pixel of the maximum of the remaining part can be taken as the point for shifting.

Results without Noise

Results of different methods on simulated data without noise are listed in the following figures. Here Gaussian method[1] is used to generate the phase screen and get the simulation of the wavefront distortions caused by atmospheric turbulence.

Fig 1.simulated Object

Fig 2. Diffraction-limited image

Fig 3. Phase screen

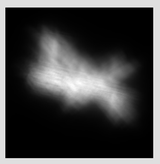

Fig 4. one example of Speckle image

Fig 5. Estimate of object by SAA

Fig 6. reconstruction result of ISA

Fig 7. reconstruction result of DSA

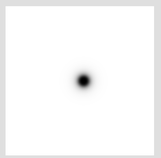

Fig 8. High-pass filter

Fig 9. reconstruction result of FISA

From the results, it can be seen that ISA is not very suitable for extended objects since it can't provide more details. While both DSA and FISA can reconstruct a near-diffraction-limited image. It's worth noting that the choice of high-pass filter is very important, it will influence the reconstruction result. In addition, some preprocessing work are needed to get a better result, such as getting rid of background and some filtering.

Arithmetics are not quite sensitive to the estimate of object, as long as it has the general shape of the object.

Results with Noise

Here some results of simulated data with noise are given (with SNR=100 and SNR=10).

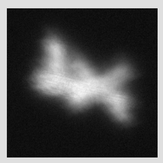

Fig 10. Speckle image with SNR=100

Fig 11. Result of DSA

Fig 12. Result of FISA

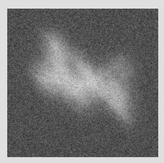

Fig 13. Speckle image with SNR=10

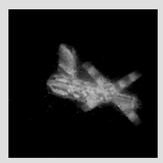

Fig 14. Result of DSA

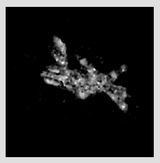

Fig 15. Result of FISA

Analysis

When SNR=100 the result of DSA is very good, the near-diffraction-limited image can be obtained. The result of DSA is better than that of FISA. That's because DSA estimate atmospheric instantaneous point spread function directly. The higher SNR is, the better the estimate, so that we can get a good result. While for SNR=10, FISA can get more details.

Apart from the Gaussian noise, there are other noise in real observation. So FISA should get a better result than DSA. But if we can find the noise and eliminate it, we'd better choose DSA.

DSA and FISA is much easier than speckle masking, and they can get similar reconstruction result. So they are more suitable to be applied.

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