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Hypertelescope Approach: A Novel Method for Imaging of Stellar Objects

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Abstract: The diffraction limited phase retrieval of a degraded image is an important subject that is being implemented in other branches of physics too, for example, electron microscopy, wavefront sensing, and crystallography. A third-order moment (bispectrum) analysis yields the phase allowing the object to be fully reconstructed. This can be extended from the single aperture speckle interferometry to the multi-aperture long baseline interferometry as well. However, in order to obtain snapshot images of the astronomical sources, many-aperture optical array with arbitrarily diluted apertures is required to be built, what is known as Hypertelescope approach. A major challenge for building such a system is the development of adaptive phasing system. Modified wave sensing techniques such as dispersed speckle analysis are planned to be used with these systems. But development and installation of such advanced methods are not available at present. In such a scenario, speckle mode observations with hypertelescope becomes a viable alternative. A study of speckle techniques with such systems is thus of great interest. This lecture is aimed to describe some of these techniques and methods.

Introduction

The diffraction limited resolution of celestial objects viewed through the atmospheric turbulence can be achieved by employing post-detection processing of a large data set of short exposure images using Fourier domain methods. Certain specialized moments of the Fourier transform of a short exposure image contain diffraction limited information about the object of interest. This post-processing method, what is referred to as speckle interferometry [1], has made impacts in several important fields in astrophysics. Following its success, astronomers focused their efforts on developing post-detection image processing techniques and applied them to improve the resolution of astronomical images [2 and references therein]. In the last few decades or so, adaptive optics system that compensates in real time of the wavefront perturbations by incorporating a controllable phase distortion in the light path which is opposite to that introduced by the atmosphere, has become part and parcel of many large telescopes. However, since the resolution of any large telescope is limited by its diameter, diluted aperture interferometry became necessary to achieve high angular resolution information in optical astronomy. Some interferometers using diluted apertures equipped with adaptive optics system have been successful in producing results, but a new generation array, based on the concept of densified pupil imaging, has the potential of obtaining high angular resolution images. This article discusses the reconstruction ability using the afore-mentioned technique.

Tomographic Speckle Imaging

Several algorithms have been developed to retrieve the diffraction limited phase of a degraded image, of which the triple correlation technique [3], is a third-order moment (bispectrum) analysis yielding the phase allowing the object to be fully reconstructed. It is a generalization of closure phase technique where the number of closure phases is small compared to those available from bispectrum. This algorithm is insensitive to: (i) the atmospherically induced random phase errors, (ii) the random motion of the image centroid, and (iii) the permanent phase errors introduced by telescope aberrations; any linear phase term in the object phase cancels out as well. The images are not required to be shifted to common centroid prior to computing the bispectrum. The other advantages are: (i) it provides information about the object phases with better S/N ratio from a limited number of frames, and (ii) it serves as the means of image recovery with diluted coherent arrays. The disadvantage of this technique is that of demanding very severe constraints on the computing facilities with 2-dimensional data since the calculations are 4-dimensional. It requires extensive evaluation time and data storage requirements, if the correlations are performed by using digitized images on a computer.

Tomographic methods using Radon transform offer better alternatives since they are computationally efficient. Surya and Saha [4] have developed both Direct Bispectrum and Radon transform based triple correlation algorithms to process the speckle frames. Figure 1 displays the reconstruction of a close binary star, HR5747.

The specklegrams of this object were obtained from the 2.34 m Vainu Bappu Telescope (VBT), situated at the Vainu Bappu Observatory, Kavalur, India. Also, the developed algorithms were applied to the simulated speckle images from IMAGIN, which is a numerical simulation developed for multi-aperture imaging in cophased and speckle mode. The mode of beam combination used was Fizeau mode.

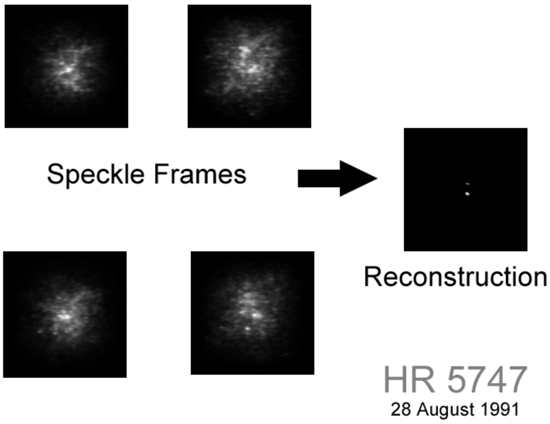

Figure 1: The reconstructed image of HR5747; the separation was found to be 0.23 arcseconds.

Speckle Imaging with Hypertelescope

Interferometric imaging through aperture synthesis with many baselines to reconstruct images, have been highly successful at radio wavelengths and also demonstrated at optical wavelengths. But it has been only recently that it was realized that many-aperture optical arrays can provide snapshot images, with arbitrarily diluted apertures. This hypertelescope approach to imaging may be viewed as a simple modification of the classical Fizeau interferometer by employing pupil densification. In order to obtain direct images, many apertures are needed, for a better sampling of the incoming wavefront. The coherent imaging thus achievable improves the sensitivity with respect to the incoherent combination of successive fringed exposures, heretofore achieved in the form of optical aperture synthesis. For efficient use of highly diluted apertures, this can be done with pupil densification. It has a vast potential, particularly since large arrays of relatively small apertures are easy to implement. Prototypes of such systems already have been developed [5] and large scale versions like CARLINA2 are under development.

A major challenge for these type of hypertelescopes is the development of adaptive phasing system. Modified wave sensing techniques such as dispersed speckle analysis are planned to be used with these systems. But development and installation of such advanced techniques will take time. In such a scenario, speckle mode observations with hypertelescopes becomes a viable alternative. Even in table top versions of hypertelescopes [6] speckle images have been observed due to phase variations in the subapertures. However, for imaging with hypertelescope, the incomplete output pupil filling provides a serious limitation. It is shown with the help of numerical simulations that even with smaller pupil filling rate in output pupil, high resolution imaging can be done with these interferometers by utilizing aperture rotation through the night.

Although best done with adaptive phasing, concentrating most energy in a dominant interference peak for a direct image of a complex source, such imaging is also possible with random phase errors such as caused by turbulent "seeing", using methods such as speckle interferometry and speckle imaging. We have simulated such observations using an aperture which changes through the night, as naturally happens on Earth with fixed grounded mirror elements, and found that the reconstructed images of star clusters and extended objects are of an unprecedented high quality. As with cophased imaging with these telescopes, speckle imaging is also constrained by the field of view limitations. Also it is shown that with utilizing the aperture rotation of the diluted array through night, reconstruction quality could be increased substantially. The results of the simulations of image reconstructions (see Figure 2) show that the tomographic speckle imaging provides a computationally efficient alternative to Direct Bispectrum technique with Fizeau imaging optical

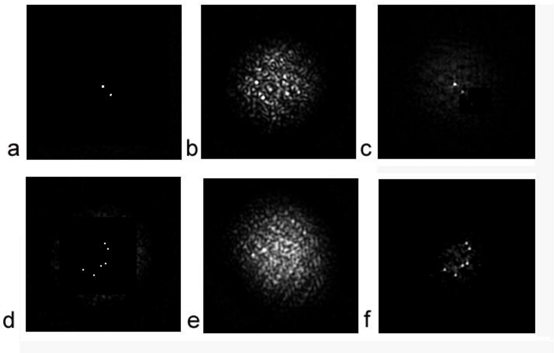

Figure 2; Bispectrum recovery from simulated speckle images of a binary system and a cluster of 6 objects of a hypertelescope: 40 frames of speckle simulations were taken for analysis: (a) binary system (brightness ratio 3:1), (b) a convolved speckle frame of the binary, (c) reconstructed image through speckle masking, (d) cluster of 6 objects of equal brightness, (e) a convolved speckle frame of the cluster, and (f) reconstructed cluster image [7].

interferometers. The bispectrum computes direct bispectrum of images. The speckle PSF (Point Spread Function) was convolved with the object distribution for object speckles. The simulation used 200 random apertures inside a disk, which was further densified with densified aperture diameter: disk diameter ratio is taken as 1:5.

Conclusion

The future of high resolution optical astronomy lies with the new generation arrays but its implementation is a challenging task. With improved technology, the interferometric arrays of large telescopes may provide snap-shot images at their recombined focus and yield improved images, spectra of quasar host galaxies, and astrometric detection and characterization of extra-solar planets. Although the Large Binocular Telescope (LBT), in which the mirrors are co-mounted on a fully steerable alt-az mount, offers unprecedented spatial resolution of the order of 8-9 mas at the near IR (1 micron), its baseline is limited to 22 m. In this system, the information in the (u, v)-plane can be continuously combined or coadded. In this respect, developing an array based on the hypertelescope technique, though it is a subtle technique, will have far reaching impact on astrophysics, thus offering the possibilities for direct measurement of all the basic physical parameters for a large number of stars. With instruments as powerful as the current generation of working or planned interferometers, the element of serendipity will bring many surprises to astronomy.

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