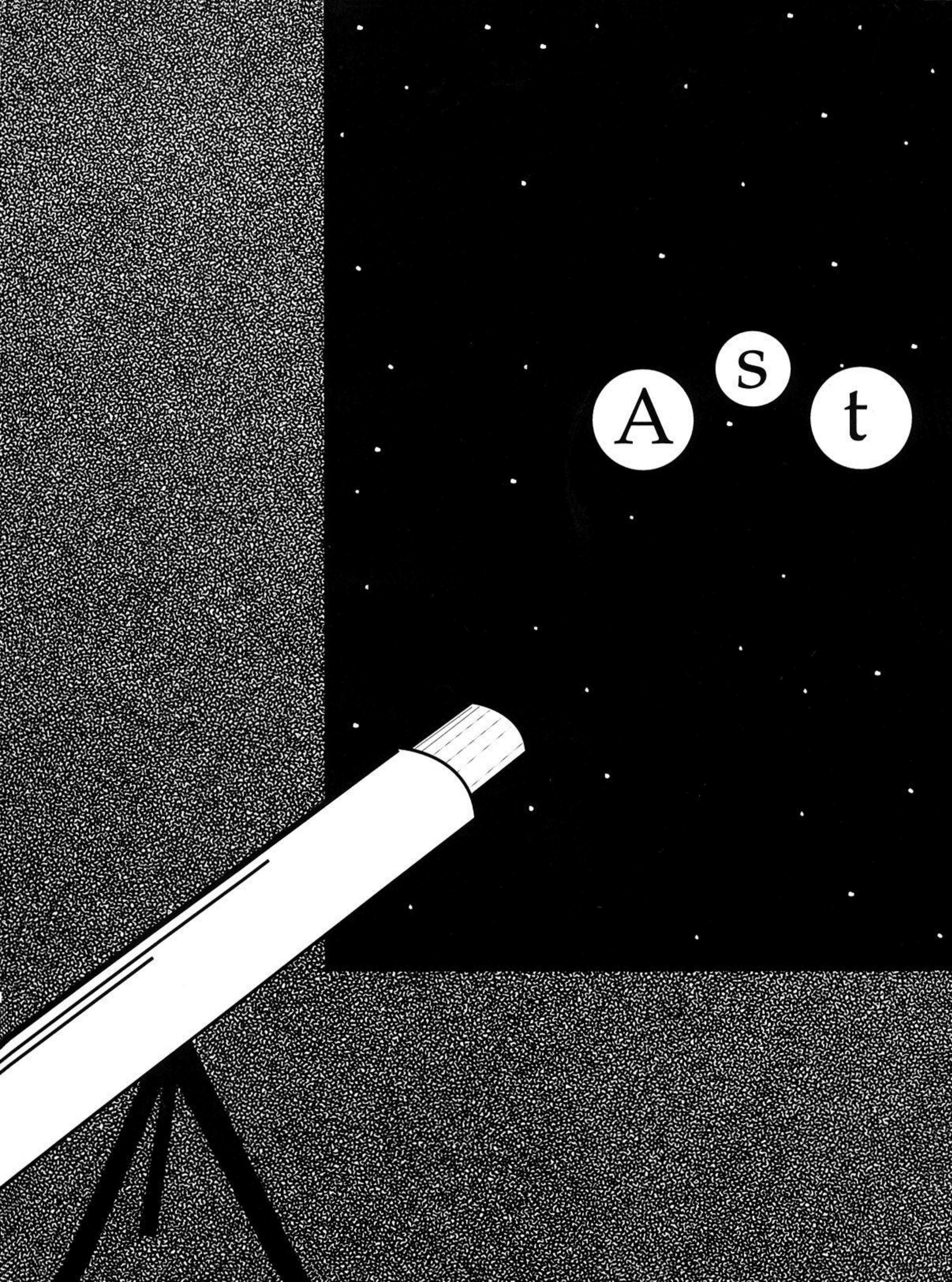
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Unconventional ronomical Imaging

BY MICHAEL C. ROGGEMANN AND DAVID W. TYLER

Unconventional imaging techniques have been studied to improve the ability to obtain high resolution images of distant objects viewed through a random medium such as the atmosphere. In this paper, the term "conventional imaging" refers to the common case of opening the shutter of a large telescope, collecting photons on film or an electronic detection device, and accepting the result as the final product of the measurement process. Unconventional imaging is distinguished from this definition by three key characteristics: (1) the need to obtain the highest possible resolution in the final image, (2) the use of clever measurement techniques, and (3) the use of post-detection image processing to reconstruct a high quality image from the measurements.

Unconventional imaging techniques can be categorized by how the effects of atmospheric turbulence are corrected. Uncompensated techniques, such as the so-called speckle imaging methods[1-6] use pure post-detection image processing to correct for turbulence effects. Real-time wavefront sensing and adaptive optics, referred to here generically as adaptive optics techniques, attempt to correct for turbulence effects before an image is measured.[7] Finally, hybrid techniques combine both pre-detection correction using adaptive optics and post-detection image processing.[8-10] All of these techniques have performance limitations imposed by the nature of the measurement, plus practical advantages and disadvantages. In this paper, we describe these three imaging techniques and give examples of their performance.

In this paper, we show contour plots of the binary star referred to in the Bright Star Catalog as HR #7882, observed with the 1.6 m telescope at the Air Force Maui Optical Station (AMOS) observatory. The brighter component of this binary

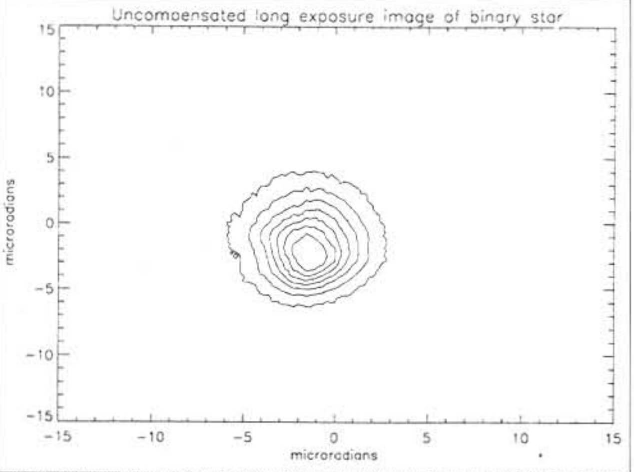

FIGURE 1. CONTOUR PLOT OF THE BINARY STAR HR #7882, UNCOMPENSATED LONG EXPOSURE CASE. SHOWN IS THE AVERAGE OF TWO HUNDRED 30 MSEC EXPOSURES TAKEN AT A RATE OF 15 FRAMES PER SECOND.

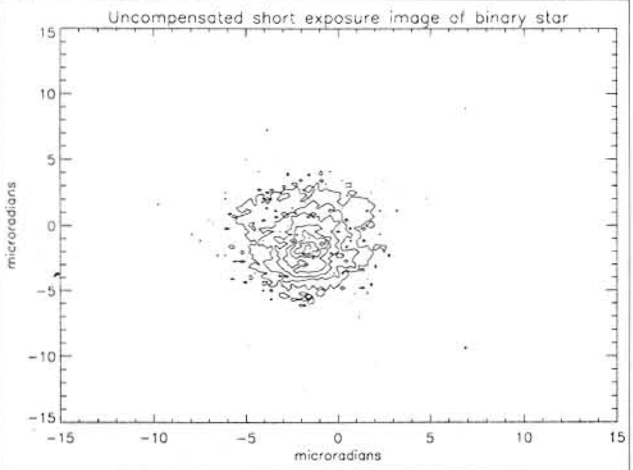

FIGURE 2. CONTOUR PLOT OF THE BINARY STAR HR #7882, UNCOMPENSATED SHORT EXPOSURE CASE. EXPOSURE TIME WAS 30 MSEC.

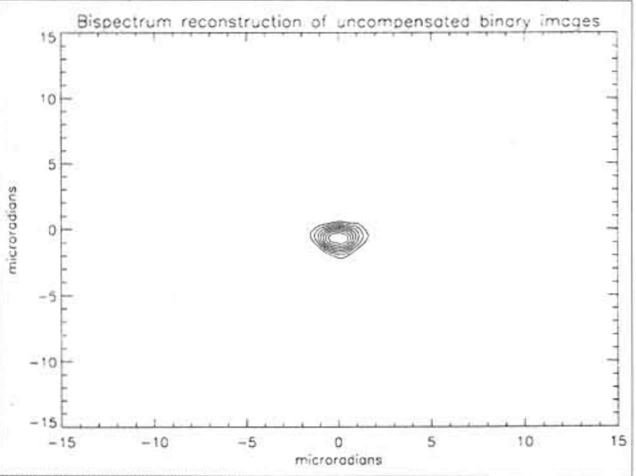

FIGURE 3. CONTOUR PLOT OF THE SPECKLE IMAGING RECONSTRUCTION OF THE BINARY STAR HR #7882. THIS RECONSTRUCTION WAS OBTAINED BY PROCCESSING AN ENSEMBLE OF TWO HUNDRED 30 MSEC EXPOSURES.

pair has visual magnitude 3.63; the dimmer component is approximately one visual magnitude dimmer. The AMOS observatory is located atop Mt. Haleakela, on the island of Maui, Hawaii. The observations used here were made on the night of August 2, 1991. Contour plots are displayed with eight levels equally spaced between the maximum and minimum values of the images.

The first section of this paper describes the effects of atmospheric turbulence on imaging systems. The following section describes speckle imaging techniques; the next two sections cover adaptive optics methods and hybrid techniques, respectively.

ATMOSPHERIC TURBULENCE EFFECTS ON IMAGING SYSTEMS

Turbulent motion of the atmosphere causes a random distribution of temperature which, in turn, causes the index of refraction of the air to vary randomly.[1] A plane wave entering the atmosphere must propagate through this random index distribution with the result that, by the time the wave reaches the ground, it is no longer planar. The random surface of the wave presents a random aberration in the pupil of the telescope that profoundly limits its resolution capability.[2]

The resolution of a large telescope looking through atmospheric turbulence using long exposure times is limited to the resolution obtained from a smaller telescope of diameter r_0. Exposures of a few hundred milliseconds or more force operation under long exposure conditions. The parameter r_0, called the atmospheric coherence length, is a function of the strength of the atmospheric turbulence.[1,2] Actual values for r_0 are a function of both the site and local weather conditions, but at visible wavelengths r_0 commonly varies between 5 cm and 20 cm—or more on rare occasions. A large telescope has the light gathering capability of its full clear aperture, but has the "conventional" resolution of a much smaller, r_0–sized, telescope. Large telescopes allow very dim objects to be imaged, but with much lower resolution than diffraction effects alone would impose.

A contour plot of the uncompensated long exposure image of the binary star described above is shown in Figure 1. If diffraction alone were limiting the resolution of this telescope, the individual components of the binary would be clearly visible and would each be about 0.5 microradians in diameter. The effects of turbulence are clear in this image: the individual components of the binary are lost, and the image is much larger than diffraction effects alone could account for.

A comment on the analysis methods used for unconventional imaging is appropriate. It is natural to describe the performance of these imaging techniques in the spatial frequency domain, that is, the domain given by the two-dimensional Fourier transform of the image. This is due to the relationship between the optical transfer function (OTF), $H(\rho)$, and the aberrated pupil function, $P(x)\exp\{\phi(x)\}$, given by:[11]

$$H(\rho) = \frac{\int P(x)P(x-\rho)\exp\{\phi(x)-\phi(x-\rho)\}dx}{\int |P(x)|^2 dx} \qquad (1)$$

where $P(x)$ is the telescope pupil function, $P(x)$ equals one inside pupil and zero outside the pupil, $\phi(x)$ is the phase aberration, and x and ρ, are two-dimensional position vectors. The shift vector, ρ, is related to the spatial frequency vector, ν, by $\nu = \rho / \lambda d_i$, where d_i is the distance between the exit pupil and the image plane. The statistics of the turbulence-induced aberration, $\phi(x)$, are well-known, and analytic techniques exist to compute the statistics of the OTF from the statistics of $\phi(x)$.[2] Standard linear systems analysis techniques can then be applied to the problem of image formation.[11]

SPECKLE IMAGING

Speckle imaging techniques are pure post-processing methods for overcoming the effects of atmospheric turbulence on imaging systems. Speckle imaging techniques derive their name from the appearance of uncompensated, very short exposure images of stars obtained with large telescopes. Such images are much larger than the diffraction limited spot and contain high spatial frequency modulation that gives the imagery a speckled appearance. The term "short exposure" refers to the use of exposure times that freeze the atmospheric turbulence-induced aberration during the exposure. An example of short exposure image of the binary star described above is shown in Figure 2.

Labeyrie was the first to recognize that the high frequency modulation in speckled images contains useful information,[4] and proposed a technique for estimating the power spectrum of an object (that is, the squared modulus of the Fourier transform of the object) called "speckle interferometry," which is widely used. Speckle interferometry works because the average power spectrum of short exposure images measured through turbulence is non-zero at spatial frequencies approaching the diffraction limited cutoff frequency of a telescope.[2]

The Fourier transform of an object is, in general, complex-valued. Thus, while Labeyrie's technique is useful for estimating the object power spectrum, the Fourier phases of the object, called its phase spectrum, must still be obtained to form an image. The approach to phase spectrum estimation most often discussed in current literature is called the "bispectrum" or "triple correlation" technique.[5] Phase spectrum recovery is based on the fact that the average Fourier transform of a specialized correlation of very short exposure images, called the bispectrum, is non-zero at spatial frequencies approaching the diffraction limit of the telescope.

Unfortunately, the average bispectrum does not yield the object Fourier phase spectrum directly, but rather a data object containing linear combinations of the object Fourier phases. The object Fourier phases must be extracted from the bispectrum, a difficult problem due, in part, to the fact that the bispectrum phase can only be known modulo 2π, and in part to noise inherent in the measurement process. Recent advances in phase spectrum reconstruction from the bispectrum may prove to have alleviated this problem.[6]

A reconstruction of the binary star obtained by using the Labeyrie and bispectrum techniques is shown in Figure 3. This reconstruction is much narrower than the uncompensated long exposure image. It is also elongated, hinting at the presence of a binary star, but the individual components cannot be resolved in this reconstruction.

A major factor limiting performance of speckle imaging techniques is the signal-to-noise ratio of the power spectrum estimate, $SNR(\nu)$. The power spectrum signal-to-noise ratio for a single realization of a speckled image, $SNR_1(\nu)$, is bounded from above by one for medium and high spatial frequencies for point sources, such as stars. For extended objects $SNR_1(\nu)$ can be quite small. To overcome this limitation, multiple frames are averaged to boost the power spectrum $SNR(\nu)$ according to:

$$SNR_N(v) = N^{1/2} SNR_1(v) \qquad (2)$$

where N is the number of image measurements in the ensemble. Ensembles of a few hundred frames to a few thou-

sand frames can be required to achieve good $SNR(\nu)$ at moderate spatial frequencies.

ADAPTIVE OPTICS

Adaptive optics systems use real time wavefront sensing and some type of active optical element to sense and correct for the turbulence induced phase aberration. Wavefront sensors, such as Hartmann sensors and shearing interferometers, sense local gradients in the phase aberration. Local gradient measurements are mapped to actuator commands through a reconstruction law and a control law. Active wavefront correction improves resolution by decreasing the variance of the phase aberration term in Eq. (1). Reducing this variance increases the average OTF and reduces the variance of the OTF, with the result that certain signal-to-noise ratios critical to imaging are greatly improved.[9]

An example of a compensated image of the binary star previously discussed is shown in Figure 4, where the effects of using adaptive optics are clearly visible. The image peak is sharper and the main lobe is considerably narrower than in the uncompensated case shown in Figure 1. The individual components of the binary star are not yet distinguishable; however, the image is clearly elongated, indicating the presence of a binary.

When adaptive optics are used, photons must be diverted from image formation to provide energy for the wavefront sensor elements. This creates the need for an engineering trade-off: large subapertures are desired to collect the maximum number of photons to allow viewing of the dimmest possible objects, but the pupil must be spatially well sampled by wavefront sensor elements to obtain a good estimate of the phase aberration. The conventional solution to this trade-off is to make the wavefront sensor elements approximately r_0-sized and to place deformable mirror actuators at the equivalent positions of the corners of the subapertures, when both the wavefront sensor and the deformable mirror are projected into the pupil of the telescope. This approach to designing adaptive optics is sometimes referred to as the "fully compensated" approach.

An alternative solution to the problem of providing signal for the wavefront sensor measurements has recently received attention: the use of laser guide stars.[12,13] A guide star is created by projecting a laser beam into the atmosphere and measuring the returned signal. Two methods of creating a guide star have been investigated: (1) resonance backscattering in the mesospheric sodium layer,[12] and (2) use of Rayleigh backscatter from the atmosphere.[13] One or both of these approaches may someday provide sufficient signal for the wavefront sensor to allow other considerations to drive the design of adaptive optics systems.

The fully compensated approach to designing an adaptive optics system can lead to the need for wavefront sensors and deformable mirrors with several hundred to a few thousand elements for the 3.5-8 m diameter telescopes of the future. The problems associated with fabricating and controlling hardware of this complexity have not yet been solved.

HYBRID TECHNIQUES

The problems associated with developing fully compensated

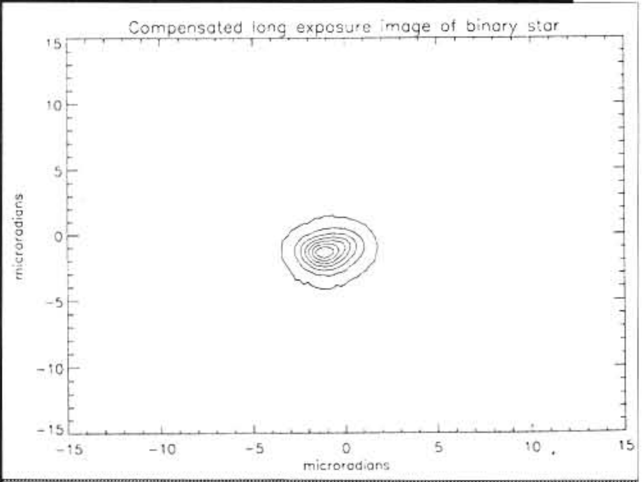

FIGURE 4. CONTOUR PLOT OF THE BINARY STAR HR #7882, COMPENSATED LONG EXPOSURE CASE. SHOWN IS THE AVERAGE OF TWO HUNDRED 30 MSEC EXPOSURES TAKEN AT A RATE OF 15 FRAMES PER SECOND.

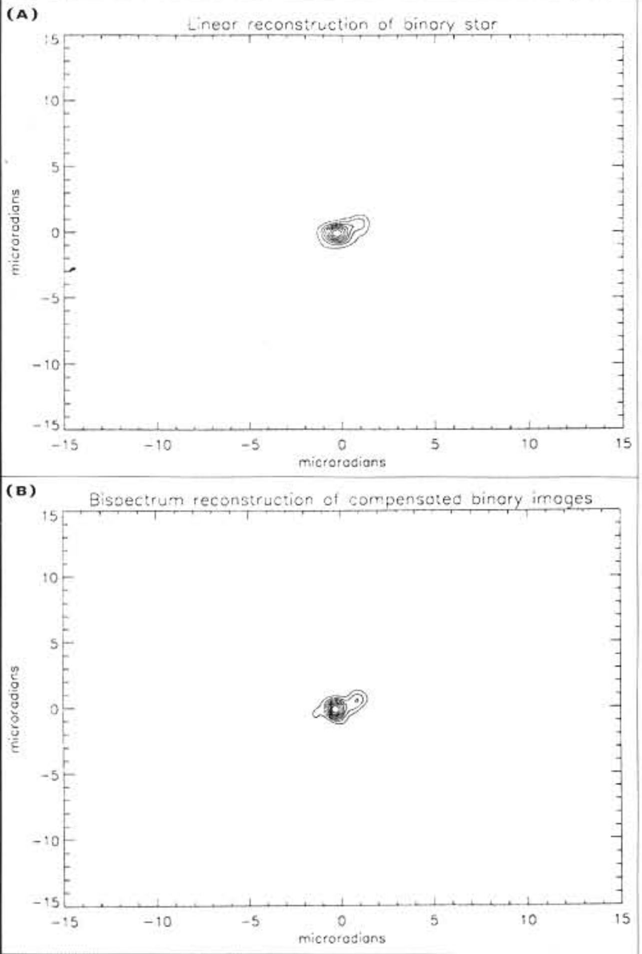

FIGURE 5. CONTOUR PLOTS OF THE POST PROCESSED COMPENSATED IMAGES OF THE BINARY STAR HR #7882: (A) LINEAR POST PROCESSING RESULT AND (B) SPECKLE IMAGING POST PROCESSING RESULT. THESE RESULTS WERE OBTAINED FROM AN ENSEMBLE OF TWO HUNDRED 30 MSEC EXPOSURES.

adaptive optics systems for very large telescopes has motivated the study of hybrid systems that combine limited amounts of predetection compensation using adaptive optics with image post processing to reconstruct a high resolution image. The idea is to trade adaptive optics hardware complexity for image post processing to obtain high resolution images. The approach to simplifying adaptive optics hardware examined most recently involves so-called "partially compensated" systems that have a reduced number of deformable mirror actuators compared to a fully compensated system.[9,10] Two image post processing approaches have been explored—a linear reconstruction technique[9] and speckle imaging post processing.[10]

Detailed analysis of the relevant signal-to-noise ratios has shown that even very limited amounts of predetection compensation provide large improvements in the performance of the estimators used in image reconstruction compared to the uncompensated case. [10] For fully compensated systems, speckle imaging post processing provides no improvement in image quality over linear post processing. However, as the amount of compensation is reduced, speckle imaging post processing outperforms linear post processing. The primary advantages of linear post processing are (1) it is conceptually quite simple while providing improved performance, (2) it is simple to implement, and (3) its execution on a computer can be quite fast.

Results of applying linear and speckle post processing to the binary star discussed earlier are shown in Figure 5. The linear reconstruction clearly shows the existence of a binary star. The speckle reconstruction shows even more clearly the location of the dimmer component of the binary. We estimate the angular separation of the binary components to be approximately one microradian.

SUMMING UP

Unconventional imaging techniques allow high resolution images to be obtained when looking through atmospheric turbulence from ground based observatories. We have described three unconventional imaging techniques and have illustrated their performance with binary star data measured on the compensated 1.6 m telescope at AMOS. Of the three techniques discussed, speckle post processing of uncompensated measurements has received by far the most attention in the literature. As adaptive optics systems for astronomical telescopes become more widespread, we expect to see more attention given to post processing of compensated images.

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